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VIA EMAIL
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Re: Comments of Backcountry Against Dumps, Donna Tisdale and Joe E. Tisdale on the Campo Wind Project with Boulder Brush Facilities (PDS2019-MUP-19-002, PDS2019-ER-19-26-001) and the Final Environmental Impact Report for the Project

Dear Mr. Potter, Ms. Harris, Mr. Koutoufidis, and Honorable Members of the San Diego County Board of Supervisors:

On behalf of Backcountry Against Dumps, Donna Tisdale and Joe E. ("Ed") Tisdale (collectively, "Backcountry"), and pursuant to the California Environmental Quality Act ("CEQA"), Public Resources Code ("PRC") section 21000 *et seq*., we respectfully submit the following comments regarding the Campo Wind Project with Boulder Brush Facilities (the "Project;" PDS2019-MUP-19-002, PDS2019-ER-19-16-001) and the Final Environmental Impact Report ("FEIR") for the Project. Please include these comments in the public record for this Project and provide them to the members of the County Board Supervisors ("Board") before the public hearing for this Project on March 3, 2021.

These comments build on and incorporate by reference Backcountry's February 21, 2019 scoping comments on the Boulder Brush Project ("Scoping Comments"), its March 18, 2019 supplemental scoping comments ("Supplemental Comments"), its June 24, 2019 second supplemental scoping comments ("Second Supplemental Comments"), its February 3, 2020 comments on the draft environmental impact report ("DEIR") for the Project, and its November 11, 2020 comments on the FEIR.

I. It is Premature to Approve the Project

Because the Project will have significant unmitigated environmental impacts, including impacts to aesthetics, aviation safety, wildfire ignition and suppression, biological resources, groundwater and noise (FEIR at ES-8 and these comments), it cannot be approved without a statement of overriding considerations. CEQA § 21081; CEQA Guidelines § 15093; FEIR at ES-9. The statement of overriding considerations "shall be supported by substantial evidence in the record" showing that the benefits of the Project outweigh its unmitigated environmental impacts. CEQA Guidelines § 15093(b). The Project's purported benefits are to "generate and deliver to the grid renewable wind energy to meet the demands of consumers." FEIR at 1-1. However, those "benefits" would only materialize if the Boulder Brush Facilities have an energy generation source. The plan is for the Boulder Brush Facilities to connect to the Campo Wind Project, but that wind project might never be built. For one, the Federal Aviation Administration ("FAA") has stayed issuance of its potential approvals for the Campo Wind Project, as discussed further below in the context of the Project's aviation impacts. Unless and until the FAA completes its review and determines that the Project may proceed – which may never happen -- this stay remains in effect and the Project cannot proceed. The future of the Campo Wind Project also depends on the outcome of Backcountry's lawsuit against the Bureau of Indian Affairs in the United States District Court for the Southern District of California over its unlawful approval of the Campo Wind Project (Case No. 20-CV-2343-JLS). In sum, there is no substantial evidence that the Campo Wind Project or any other energy generation project will ever be built and allow the Boulder Brush Facilities to achieve their objectives. It would thus be premature for the Board to approve the Project before it is clear that the Boulder Brush Facilities will have an energy generation source.

II. The FEIR Fails to Analyze the Whole of the Project

CEQA forbids "piecemeal" environmental review. *Berkeley Keep Jets Over the Bay Commission v. Board of Port Commissioners of the City of Oakland* ("*Berkeley Keep Jets*") (2001) 91 Cal.App.4th 1344, 1358. CEQA mandates that "environmental considerations do not become submerged by chopping a large project into many little ones . . . [,] which cumulatively may have disastrous consequences." *Bozung v. Local Agency Formation Commission* (1975) 13 Cal.3d 263, 283-284.

Here, the FEIR acknowledges that the Project's 8.5-mile 230-kilovolt ("kV") gen-tie transmission line would "connect energy generated by [the 60-turbine Campo Wind Project] to the existing SDG&E Sunrise Powerlink," and it accordingly analyzes together the impacts of the Campo Wind Project and the Boulder Brush Facilities. FEIR at ES-3. But the FEIR, like the

DEIR, fails to analyze another wind energy project – the 30-turbine Torrey Wind Project – that the Boulder Brush Facilities would likewise enable. As the FEIR acknowledges, the Boulder Brush Facilities' "high-voltage substation would allow for the receiving and stepping up of electric energy from 230 kV to 500 kV for the proposed Torrey Wind Project, a separate wind energy project proposed on private lands under County jurisdiction." FEIR at 1-5. Despite the inextricable link between the Boulder Brush Facilities and the Torrey Wind Project, the FEIR merely treats the latter as a cumulative project. *E.g.* FEIR at 2.3-110. That violates CEQA. The County may not piecemeal the analysis of a project that *would not be constructed* but for the Boulder Brush Facilities' 500-kV substation and switchyard. *City of Antioch v. City Council of the City of Pittsburg* (1986) 187 Cal.App.3d 1325, 1337 (holding that approval of a road and a sewer line triggers a duty under CEQA to examine the impacts of the development that they will foreseeably serve).

III. The FEIR Fails to Meaningfully Analyze Numerous Significant Environmental Impacts

An EIR must include "enough detail to enable those who did not participate in its preparation to understand and to consider meaningfully the issues raised by the proposed project," particularly the potentially significant environmental impacts. *Sierra Club v. County of Fresno and Friant Ranch, L.P.* ("*Friant Ranch*") (2018) 6 Cal.5th 502, 513 (quote); CEQA Guidelines § 15126.2. The EIR "fail[s] to comply with the information disclosure provisions of CEQA" when it "omit[s] any meaningful consideration" of a potentially significant environmental impact identified in the record. *Bakersfield Citizens for Local Control v. City of Bakersfield* ("*Bakersfield Citizens*") (2004) 124 Cal.App.4th 1184, 1208. Here, the FEIR, like the DEIR, omits meaningful consideration of numerous potentially significant environmental impacts.

A. The FEIR Fails to Meaningfully Analyze the Project's Impacts to Aviation

As detailed in Backcountry's January 29, 2020 comments to the FAA on the Campo Wind Project, Wind Turbine C-69, Campo, California Aeronautical Study No. 2019-WTW-4585-OE (incorporated by reference and attached hereto as **Exhibit 1**), the Campo Wind Project would cause significant and life-threatening impacts to aviation that could not be avoided or sufficiently mitigated by the proposed mitigation measures. FAA's Southern California TRACON ("SCT") also identified numerous impacts to aviation safety and flight control operation in its written opposition to the Campo Wind Project.[1] For example, SCT notes that the wind turbines would compromise the safest flight route for crossing the mountains in winter – a "significant impact." **Exhibit 2** at 3. The presence of the wind turbines would increase the minimum en-route altitude ("MEA") on airway V317:

> This airway is commonly used, but more so during the winter months as a safe route for aircraft who cannot climb to higher altitudes due to icing conditions, this airway has the lowest MEA for crossing the mountains to the east. The aircraft

[1] The email chain detailing SCT's opposition is attached hereto as **Exhibit 2**.

> that use this are General Aviation fixed wing aircraft from all the San Diego area airports, and military rotary aircraft (who are very ice sensitive) from MCAS Miramar and NAS North Island. The loss of the 7,000 feet MEA would be significant as it [would] force all along the route to 8,000 feet MSL and higher.

Exhibit 2 at 3. The FEIR appears to assume that these aviation impacts will be insignificant, but in fact, they are very significant. For that reason, the FAA has found that Backcountry's Petition for Review is valid, and it is therefore actively reviewing the impacts of the Project on aviation. Pursuant to its finding that Backcountry's Petition for Review is valid, the FAA has stayed issuance of its potential approvals for the Project. Unless and until it completes its review and determines that the Project may proceed – which may never occur -- this stay remains in effect and the Project cannot proceed.

B. The FEIR Fails to Meaningfully Analyze the Project's Wildfire Impacts

The Project poses immense wildfire risks, both by increasing the risk of fire ignition and by impeding wildfire fighting. These risks are detailed in Mark Ostrander's professional review of the Project's wildfire impacts, which is attached hereto as **Exhibit 3**. Mr. Ostrander is a retired Battalion Chief and CEQA Environmental Coordinator with the California Department of Forestry and Fire Protection ("Cal Fire"), with 36 years of experience working in the field of wildfire suppression throughout Southern California, including eastern San Diego County. Based on his experience, Mr. Ostrander concludes that:

> construction and operation of the Campo Wind Project and its sixty 586-foot tall wind turbines, three 374-foot tall meteorological towers, collector substation, gen-tie line and associated electrical lines and facilities (including the Boulder Brush facilities) pose not only a significant fire-ignition risk, but also an extremely hazardous impediment to effective wildfire suppression in the Campo area. In my professional opinion, the only way to significantly reduce wildfire risk from these power generation facilities is to move them to an area not known for its wildfire hazards. And the only way to significantly reduce wildfire risk from the electrical transmission lines is to underground them . . . .

Exhibit 3 at 1-2.

The FEIR discusses, yet systematically understates, the Project's wildfire risks. In particular, the FEIR fails to analyze how the Project would impede firefighting efforts – both aerially and on the ground – beyond an off-hand note that the Project would "represent . . . challenges regarding rescue or firefighting within or adjacent to electrical facilities" (FEIR at 2.9-41) and an evasive, vague and short response to comments. This violates CEQA and precludes informed decisionmaking.

The nearly 600-foot-tall wind turbines would "make aerial delivery of retardant or water to the Project site extremely difficult, if not impossible. The mere presence of the 600-foot-tall turbine towers would create a large zone in which it is dangerous for low-flying aircraft to operate, either for fire-spotting purposes or to drop retardant and water." **Exhibit 3** at 3. Mr. Ostrander also explains that the Project would "impede effective ground attack against any wildfires in the vicinity of the Project. The deployment of fire crews within 100 to 1,000 feet (depending on conditions) of electrified structures is unsafe and forbidden by applicable safety rules and regulations due to the serious hazard of electrical shock from the wind turbines, substations, gen-tie lines and other electrified facilities." **Exhibit** 3 at 4. That means that "any fire in the area will generally get larger as the fire crew waits for it to pass through the Project area to a safer distance from which to work the fire." *Id.* Omitting these critical impacts violates CEQA.

The FEIR also fails to discuss the recent reductions in wildfire fighting capacity in the County:

> Due to state budget cuts, Cal Fire and the California Department of Corrections and Rehabilitation depopulated (eliminated) two fire camps in the county on December 12, 2020, including the camp closest to the Project (McCain Valley Conservation Camp in Boulevard) and Rainbow Conservation Camp in Fallbrook.

Exhibit 3 at 4. This development undermines the FEIR's conclusion that emergency response capabilities in the Project area are adequate and must be addressed. FEIR at 2.9-25 to 2.9-28.

C. The FEIR Fails to Meaningfully Analyze Impacts to Golden Eagles

Wind turbines kill birds, and so do power lines.[2] The Campo Wind Project's 60 turbines will be no different, just as will be the Torrey Wind Project's 30 turbines and the Project's miles of power lines. Indeed, in its responses to comments, the FEIR predicts that "one eagle fatality [will] occur[] every 8 years" with a "60-turbine design." FEIR at GR5-14. The risk to golden eagles from these wind projects is particularly concerning because golden eagles are "currently known to be at risk of *population-level* effects from [wind turbine] collisions," and must be afforded every possible protection. **Exhibit 4** at 306. Yet the FEIR, like the DEIR, brushes aside the risk to golden eagles as insignificant. FEIR at GR5-14.

The FEIR provides zero explanation for how the Project's direct impact to golden eagles qualifies as insignificant when the Campo Wind Project will likely kill at least 3 eagles over the course of its 25+-year life (at the forecasted rate of 1 eagle fatality every 8 years). FEIR at 1-2 (Project life), GR5-14 (fatality rate estimate). Nor does it discuss how the projected fatalities could affect the golden eagle population, which is at existential risk from wind turbines and other causes, as discussed. Even without considering population-level effects, the FEIR's conclusion that the killing of at least 3 eagles is insignificant contravenes the County's own thresholds of significance for impacts to biological resources. The most applicable threshold provides that a "significant impact would result if" the "project would impact one or more individuals of a

[2] Dwyer, J.F., M.A. Landon, and E.K. Mojica, 2018, "Impact of Renewable Energy Sources on Birds of Prey," in J.H. Sarasola *et al.* (eds.), 2018, *Birds of Prey*, Springer International Publishing AG (attached hereto as **Exhibit 4**).

species listed as federally or state endangered or threatened." FEIR at 2.3-45. The golden eagle is a special-status species and the FEIR itself forecasts that "one eagle fatality [will] occur[] every 8 years" with the Campo Wind Project. FEIR at GR5-14. That is a significant environmental impact.

D. The FEIR Fails to Meaningfully Analyze Impacts to Bats

Bats perform vital biological and economic functions. As detailed in a recent peer-reviewed scientific journal article:

> Bats play a key role in Earth's ecosystems. In North America, ecological services provided by bats have been valued at $3.7 to $53 billion USD per year. They are major predators of nocturnal insects and contribute to the regulation of epidemic outbreaks in agricultural fields and managed forests, as well as the control of insects transmitting diseases to humans.[3]

Exhibit 5 at 1.

But as with birds, wind energy facilities also kill bats, through both collisions and barotrauma (abrupt drop in air pressure behind turbine blades sucks bats into low pressure zone, causing bats' lungs to expand and hemorrhage). And with "continued wind energy expansion, there are increasing concerns that there could be population-level implications for bats."[4] **Exhibit 6** at 125. This is even more concerning given recent evidence that bats are *attracted* to wind turbines and associated infrastructure, and use them as night or foraging roosts. **Exhibit 6**. It is therefore essential to assess both project-specific bat impacts and the "*cumulative* effects of bat fatalities at wind farms." **Exhibit 5** at 2 (emphasis added).

Here, the FEIR fails to meaningfully analyze the Project's impacts on bats. The FEIR concludes that "there were low occurrences of bats during surveys within the Campo Corridor, particularly when compared to other areas with higher-quality habitat types in the region," and that bats were therefore "not anticipated to have a high number of collisions with [Project] turbines." FEIR at 2.3-52. But the FEIR fails to provide or even summarize the "surveys within the Campo Corridor." Instead, the FEIR belatedly discloses in its responses to comments that the "bat data is presented" in an appendix to the "Draft Environmental Impact Statement (EIS) prepared for the [Campo Wind] Project by the Bureau of Indian Affairs." FEIR at 05-4. That precludes informed public review. The EIR itself must disclose the data.

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[3] MacGregor, K.A., and J. Lemaître, 2020, "The Management Utility of Large-scale Environmental Drivers of Bat Mortality at Wind Energy Facilities: The Effects of Facility Size, Elevation and Geographic Location," *Global Ecology and Conservation* 21(e00871) (attached hereto as **Exhibit 5**).

[4] Bennett, V.J., A.M. Hale, and D.A. Williams, 2017, "When the Excrement Hits the Fan: Fecal Surveys Reveal Species-Specific Bat Activity at Wind Turbines," *Mammalian Biology* 87:125-129 (attached hereto as **Exhibit 6**).

In addition, the FEIR fails to meaningfully discuss the risk to bats of barotrauma in addition to turbine blade collision. Instead, it cites a study of pressure effects on rats. But as the FEIR acknowledges, the "actual relationship between rat thresholds and bat thresholds is not known." FEIR at 05-5.

E. The FEIR Fails to Meaningfully Analyze the Project's Audible Noise Impacts

The FEIR's analysis of audible noise impacts suffers from at least three sets of critical errors and omissions. First, the acoustical analysis on which the FEIR relies is plagued by numerous technical errors, which dBF Associates, Inc. ("dBF," a San Diego-based acoustical consulting firm) and Wilson Ihrig & Associates ("WIA," a national noise, vibration and acoustical professional consulting firm) detail in their respective technical reviews of the nearly identical Acoustical Analysis Reports ("AARs") on which the FEIR for the Project and the Environmental Impact Statement ("EIS") for the Campo Wind Project rely. dBF's February 3, 2020 review of the FEIR's AAR, dBF's February 3, 2021 review of the EIS and its AAR, and WIA's February 4, 2021 review of the EIS and its AAR are attached hereto as **Exhibits 7**, **8** and **9**, respectively. The technical errors include overstating the existing ambient noise conditions (thereby understating the Project's added noise) due to the "limitations of the noise logging instruments" used and "insufficient duration of measurements" (**Exhibit 9** at 3 (quote); **Exhibit 8** at 3), and relying on a modeling program (CadnaA) that "cannot accurately predict wind turbine noise." **Exhibit 9** at 8.

Second, the FEIR fails to meaningfully analyze the issue of amplitude-modulated wind turbine-generated noise. Amplitude modulation produces the characteristic "whoosh" sound that residents near wind turbines, including residents near the existing Tule and Kumeyaay wind projects in the Boulevard area, frequently identify as distressing, stressful, and sleep-disturbing. Recent peer-reviewed academic studies confirm that amplitude modulated noise is a health problem. For example, Pohl *et al.* (2018)[5] conducted a longitudinal study of wind turbine noise disturbance in Germany and found that a "cause for the WT noise annoyance might be the amplitude modulation (AM)." **Exhibit 10** at 126. Schäffer *et al.* (2019)[6] conducted a laboratory experiment with audio-visual simulations and likewise found that, even after accounting for visual impacts, amplitude modulation increased annoyance. And Hansen *et al.* (2019)[7] documented tonal amplitude modulation from wind turbines in southern Australia that was audible outdoors and indoors up to 3.5 kilometers away, which the authors concluded had "important implications for possible sleep disruption from wind turbine AM," particularly where

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[5] Pohl, J., J. Gabriel, and G. Hübner, 2018, "Understanding Stress Effects of Wind Turbine Noise – The Integrated Approach," *Energy Policy* 112:119-128 (attached hereto as **Exhibit 10**).
[6] Schäffer, B., R. Pieren, U.W. Hayek, N. Biver, and A. Grêt-Regamey, 2019, "Influence of Visibility of Wind Farms on Noise Annoyance – A Laboratory Experiment with Audio-Visual Simulations," *Landscape and Urban Planning* 186:67-78 (attached hereto as **Exhibit 11**).
[7] Hansen, K.L, P. Nguyen, B. Zajamsek, P. Catcheside, and C.H. Hansen, 2019, "Prevalence of Wind Farm Amplitude Modulation at Long-range Residential Locations," *Journal of Sound and Vibration* 455:136-149 (attached hereto as **Exhibit 12**).

ambient noise levels are low, as in the rural Backcountry area.

The AAR dismisses the risk of amplitude modulation from Campo Wind Project turbines by citing a 2016 study of "multiple operating wind turbine facilities" in unnamed locations. FEIR, Appendix G at 35. According to that study, most modulation was 2 decibels ("dB") or less. But as WIA concludes in its technical review, the 2016 "RSG study minimizes the severity of the phenomenon by understating the actual, measured differences in noise levels associated with infrasound." **Exhibit 9** at 8. Furthermore, the AAR *entirely ignores* the much more recent and relevant evidence of *frequent* amplitude modulation in the *5-6 dB* range (deemed "excessive modulation" by acoustics experts) at residences in the Boulevard area from the existing Tule and Kumeyaay wind project turbines located quite close to the proposed Campo and Torrey wind projects. That amplitude modulation is documented in WIA's 2019 report attached as Exhibit 1 to Backcountry's Supplemental Comments (and incorporated herein by reference) and in the December 16, 2019 report by dBF Associates, Inc. ("dBF Report"), which is attached hereto as **Exhibit 13**.

The FEIR attempts to critique the 2019 WIA Report and the dBF Report in the responses to comments. FEIR at GR4-16. And it ultimately concludes that "these reports fail to provide sufficient evidence that a significant environmental impact due to amplitude modulation would occur as a result of the Project." FEIR at 05-6. But that is the wrong standard. The public does not have the burden of proving that a project would cause a significant environmental impact as a precondition for CEQA analysis. Instead, it is the lead agency's duty to analyze in an EIR any impact for which there is "enough relevant information and reasonable inferences from this information that a fair argument can be made" that the impact might be significant, "even though other conclusions might also be reached." CEQA Guidelines §§ 15384 (quote), 15064. The 2019 WIA Report and the dBF Report both conclude from *empirical research* that existing wind turbines *in the Project vicinity* generate *excessive amplitude modulation* that is observed at the homes of nearby residents. That is the epitome of substantial evidence supporting a fair argument that the Project might cause a significant noise impact. CEQA thus requires the County to thoroughly analyze the Project's noise impacts from amplitude modulation, not merely nitpick the 2019 WIA Report and the dBF Report. It is immaterial that there might not yet be any "local, state, or federal standards of significance for determining the environmental impact" of amplitude modulation. FEIR at 05-5 (quote); *Berkeley Keep Jets*, 91 Cal.App.4th at 1370-1371.

Third, the FEIR fails to meaningfully describe the full panoply of wind turbine-generated noise impacts on health, including stress, sleep disturbance and reduced quality of life. This is similar to the EIR the Supreme Court found inadequate in *Friant Ranch*. There, "[a]lthough the EIR generally outline[d] some of the unhealthy symptoms associated with exposure to various pollutants, it [did] not give any sense of the nature and magnitude of the 'health and safety problems caused by the physical changes' resulting from the Project as required by the CEQA guidelines." *Friant Ranch*, 6 Cal.5th at. 522 (quoting CEQA Guidelines § 15126.2(a)).

The FEIR here entirely fails to *even mention* "stress" or "sleep" or otherwise connect the projected Project-generated noise levels to health outcomes, despite the fact that numerous wind turbine noise impact studies to date have established a correlation between noise and self-reported annoyance or sleep disturbance. Researchers are also increasingly studying the *physiological* responses to wind turbine noise during sleep. For example, a pair of recent pilot studies investigated the physiologically measured sleep effects of nocturnal wind turbine noise in a laboratory setting.[8] The results provided "evidence that participants had more frequent awakenings, reduced amounts of N3 ("deep") sleep, reduced continuous N2 sleep, increased self-reported disturbance and [wind turbine noise]-induced tiredness in exposure nights with [wind turbine noise] compared to [wind turbine noise]-free nights." **Exhibit 14** at 10. The increase in self-reported sleep disturbance also comports with the findings of numerous survey-based studies on the subject.

Morsing *et al.*'s (2018) results are also consistent with those of a cohort-based study in Denmark on the impacts on sleep and depression of long-term residential exposure to wind turbine noise.[9] Poulsen *et al.* (2019) found, based on their study of nearly 600,000 people during an approximately 20-year period, that "high levels of long-term nighttime exposure to outdoor" wind turbine noise (greater than or equal to 42 dBA) were "associated with redemption of sleep medication and antidepressants" (*i.e.* filling prescriptions for those medications), particularly amongst people aged 65 or older. **Exhibit 15** at 037005-6. The authors reported that their findings accord with most studies on the effects of wind turbine noise exposure on sleep and self-reported mental health. **Exhibit 15** at 037005-7.

The FEIR relies almost exclusively on the 2019 County Public Health Position Statement to support its conclusion that the Project's wind turbine noise impacts would not be significant. FEIR at GR4, 05-6 to 05-7. But that statement fails to consider numerous pertinent studies, data, and issues. For example, the statement omits numerous recent relevant studies, including Morsing *et al.'s* (2018) study and Poulsen *et al.'s* (2019) study. It also fails to mention or discuss the 2019 WIA Report and the dBF Report. In addition, the statement fails to discuss amplitude modulated noise *at all*, despite increasing academic and professional literature on the subject, as discussed above. Backcountry's April 12, 2019 comments on the 2019 County Public Health Position Statement are attached hereto as **Exhibit 16**.

F. The FEIR Fails to Meaningfully Analyze the Project's Infrasound and Low-Frequency Noise Impacts

The audible noise level, like that measured with the A-weighted scale used in Poulsen *et al.*'s (2019) study, is only one aspect of wind turbine-generated noise. For example, a 2018

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[8] Morsing, J.A., M.G. Smith, M. Ögren, P. Thorsson, E. Pedersen, J. Forssén, and K.P Waye, 2018, "Wind Turbine Noise and Sleep: Pilot Studies on the Influence of Noise Characteristics," *International Journal of Environmental Research and Public Health*, 15(2573) (attached hereto as **Exhibit 14**).

[9] Poulsen, A.H., O. Raaschou-Nielsen, A. Peña, A.N. Hahmann, R.B. Nordsborg, M. Ketzel, J. Brandt, and M. Sørensen, 2019, "Impact of Long-Term Exposure to Wind Turbine Noise on Redemption of Sleep Medication and Antidepressants: A Nationwide Cohort Study," *Environmental Health Perspectives*, 127(3) (attached hereto as **Exhibit 15**).

review of the scientific literature affirmed not only that "there is ample evidence demonstrating that a component of the sound energy produced by a [wind turbine] is in the low and infrasonic frequency range" ("ILFN"), but also that the literature presents a "strong prima facia case for neural transduction of low-frequency sound] and [infrasound]."[10] **Exhibit 17** at 2 (first quote), 6 (second quote).

Carlile *et al.* (2018) also noted that weighted noise measurements – like the A-weighted measurements typically done for audible noise impact analyses, and the C-weighted measurements required by San Diego County Zoning Code section 6952(f)(1) – "exclude crucial low frequencies" from wind turbines. **Exhibit 17** at 3. Poulsen *et al.* (2019) similarly noted studies "suggest[ing] that the characteristics of [wind turbine noise] relevant for annoyance may be better captured by metrics focusing on amplitude modulation or low-frequency (LF) noise, rather than the full spectrum A-weighted nose." **Exhibit 15** at 037005-1. That is one reason Backcountry commissioned two professional studies, one by WIA and a more recent one by dBF, on the wind turbine-generated infrasound, low-frequency noise and amplitude modulated noise in the Boulevard area.

WIA obtained noise recordings between November 13 and 17, 2018 in the Boulevard and Jacumba Hot Springs areas. The findings are documented in its aforementioned 2019 report that is attached as Exhibit 1 to Backcountry's Supplemental Comments. Among other things, the report and a predecessor 2014 report on earlier noise measurements "conclusively document the presence of [wind turbine] generated infrasound (IS) as measured at residential and other locations up to 8 miles from the wind turbines at the Kumeyaay and Tule [wind project] facilities," and up to 11 miles from the Ocotillo Wind Energy project. Supplemental Comments, Exhibit 1 at 1. dBF's more recent report, based on noise recordings in the same area from August 16, 2019, likewise "conclusively document[s] the presence of ILFN, at homes up to approximately 6 miles away, generated by the [wind turbines] at the Kumeyaay and Tule facilities." **Exhibit 13** at 1.

Rather than include a serious analysis of the levels and environmental impacts of ILFN produced by the Project, the FEIR and its AAR try to sweep the issue under the rug with spurious claims. The AAR dismisses the issue by citing a 2016 RSG report claiming that the wind turbines produce infrasound that is "at the least, 25 dB below ISO 7196 audible perception thresholds." FEIR, Appendix G at 36. But as Dr. Richard Carman explains in WIA's review:

> the RSG study is completely irrelevant to evaluating the effects on infrasound because the RSG study does not evaluate the effects of noise levels below the threshold of audibility. The RSG study presumes that a sound level has no effect on the human ear unless it is audible. But this premise has no basis in science, and ignores the relevant question. The relevant question is whether a sound level – whether infrasound or not – causes physiological changes in the ear. The research

[10] Carlile, S., J.L. Davy, D. Hillman, and K. Burgemeister, 2018, "A Review of the Possible Perceptual and Physiological Effects of Wind Turbine Noise," *Trends in Hearing* 22:1-10 (attached hereto as **Exhibit 17**).

> by Salt and others shows that humans could be negatively impacted by sound levels significantly below the threshold of audibility.

Exhibit 9 at 7. The FEIR ignores the issue for an equally unmeritorious reason – because the "County does not have any regulations or standards pertaining to infrasound levels." FEIR at 05-8. That violates CEQA. CEQA does not require a formal impact standard as a precondition for analyzing and determining the significance of an environmental impact. *Berkeley Keep Jets*, 91 Cal.App.4th at 1370-1371.

G. The FEIR Fails to Analyze the Project's Lifecycle Greenhouse Gas Emissions

The FEIR boasts that the "Project would avoid more [greenhouse gas (GHG)] emissions than it would generate, resulting in **less than cumulatively considerable** climate change impacts." FEIR at 3.1.4-32. But the FEIR fails to quantify the Project's *lifecycle* GHG emissions. Many authoritative published life cycle analyses demonstrate that wind energy projects like the proposed Campo and Torrey wind projects have many more sources of GHG emissions than just on-site construction and operation. As one recent study states, "due to GHG emissions produced during *equipment manufacture, transportation*, on-site construction, maintenance, and decommissioning, wind and solar technologies are not GHG emission free."[11] **Exhibit 18** at SI36. That same study concluded, based on a "systematic review and harmonization of life cycle assessment (LCA) literature of utility-scale wind power systems," that industrial-scale wind turbines produce 11 g CO_2-eq/kWh (median value, with a range of 3 g CO_2-eq/kWh to 45 g CO_2-eq/kWh). **Exhibit 18** at SI36, SI46. To meaningfully analyze the Project's global warming impact in compliance with CEQA, the County must conduct a lifecycle assessment of the Project's GHG emissions.

The FEIR cites *Save the Plastic Bag Coalition v. City of Manhattan Beach* (2011) 52 Cal.4th 155, 175 to support its assertion that a "lifecycle analysis is not required." FEIR at 05-9. That case involved a small city's proposal to ban plastic bags, and the relative environmental impacts of plastic bags versus paper bags. The Court concluded that lifecycle analysis would not be useful in that instance because one small city's ban on plastic bags would not increase the overall supply for paper bags enough to change overall supply. Here, by contrast, the production of wind turbines is often project dependent, with components made to order. The wind turbines for the Project might not be built absent the Project, making the turbines' manufacturing impacts indirect impacts of the Project that require analysis in the EIR.

H. The FEIR Fails to Analyze the Project's Impacts on Groundwater Supply

Construction and operation of the Project would require substantial water supplies – approximately 173 acre-feet just for construction – much of which is proposed to be pumped

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[11] Dolan, Stacey L. & Garvin A. Heath, 2012, "Life Cycle Greenhouse Gas Emissions of Utility-Scale Wind Power: Systematic Review and Harmonization," *Journal of Industrial Ecology*, 16(SI) (attached hereto as **Exhibit 18**).

from the well field on the Campo Band of Digueño Mission Indians Reservation. FEIR at 3.1.5-3. That is the same well field that SDG&E had planned to use to supply the water for construction of its East County Substation in 2013. However, pumping from the well field had to be stopped after only 36 acre-feet of groundwater had been extracted, due to lack of aquifer recharge. *Id*. The FEIR fails to analyze the likelihood that the well field would once again fail to provide sufficient water supplies and the resulting impacts both to the on-Reservation well field, the aquifer as a whole, and the additional water supply sources the Project proponents would need to tap to complete construction.

The FEIR and the Groundwater Resources Evaluation ("GRE") on which it is based also understate the Project's likely groundwater impacts in numerous other ways. Snyder Geologic identifies many of these deficiencies in its independent review of the nearly identical groundwater resources evaluation underpinning the Bureau of Indian Affairs' hydrologic impact analysis in its Final Environmental Impact Statement for the Campo Wind Project. Snyder Geologic's technical review identifies five principal errors in the GRE's analysis. The review, which explains these errors in detail, is attached hereto as **Exhibit 19**. In brief, the five errors identified by Snyder Geologic are as follows. First, the GRE understates the existing groundwater demand in the Project area. **Exhibit 19** at 1. Second, the GRE understates the impacts of the Project's groundwater demand on local well drawdown by averaging the 173-acre-foot demand over a 5-year period instead of the 14-month construction period. **Exhibit 19** at 3; FEIR, Appendix J-1 at 27-28. Third, the GRE omits "key variables or misappl[ies] key principles of hydrogeologic analysis" in at least four respects, which causes the GRE to understate the Project's groundwater impacts. **Exhibit 19** at 3-5. Fourth, as already discussed above, the GRE ignores the groundwater impacts caused by pumping a substantially smaller volume of water from the same aquifer for the East County Substation project. **Exhibit 19** at 5-6. Fifth, the GRE failed to examine the drawdown impacts of pumping from the on-Reservation wells with actual data on the hydrologic properties of the southern well field, let alone pump tests from the wells themselves. As Snyder Geologic concludes, "this unexplained omission does not meet the standard of care and is unacceptable." *Id*. All five of these errors in the GRE propagate to the FEIR and preclude informed review of and decisionmaking on the Project.

I. The EIR Must Analyze the Impacts of Any Planned Battery Storage

The EIR must analyze the impacts of any planned battery storage that would accompany the Project (either the Campo Wind Project or the Boulder Brush facilities) and its impacts, particularly on wildfire ignition and suppression. The FEIR currently does not even mention battery storage as a possibility. Large-scale battery storage is well known to pose such impacts.

IV. The Project Must Comply with CPUC General Order 131-D.

As discussed in Backcountry's previous comments, the Project requires a certificate of public convenience and necessity pursuant to the California Public Utilities Commission's General Order 131-D because it includes "major electric transmission line facilities which are designed for immediate or eventual operation at 200 kV or more." G.O. 131-D § III(A).

V. Conclusion

In sum, the Board should not approve the Project. It would be premature to approve a project whose utility depends on another project that might never be built and whose EIR violates CEQA. The Project cannot be approved without revision and recirculation of the EIR to remedy the numerous deficiencies documented above. The Project also requires additional permitting under the California Public Utilities Commission's General Order 131-D.

Respectfully submitted,

Stephan C. Volker
Attorney for Backcountry Against Dumps,
Donna Tisdale and Joe E. (Ed) Tisdale

Attachments:

Exhibit 1 – Law Offices of Stephan C. Volker, January 29, 2020, "Comments of Backcountry Against Dumps and Donna Tisdale on the Campo Wind Project," submitted to the Federal Aviation Administration.

Exhibit 2 – Email chain between Federal Aviation Administration employees re "FAA Study / Wind Farm / Campo, CA / 19-WTW-4517 thru 19-WTW-4592," February 7, 2020.

Exhibit 3 – Ostrander, M., February 1, 2021, "Review of the Wildfire Impacts from the Campo Wind Project with Boulder Brush Facilities."

Exhibit 4 – Dwyer, J.F., M.A. Landon, and E.K. Mojica, 2018, "Impact of Renewable Energy Sources on Birds of Prey," in J.H. Sarasola *et al.* (eds.), 2018, *Birds of Prey*, Springer International Publishing AG.

Exhibit 5 – MacGregor, K.A., and J. Lemaître, 2020, "The Management Utility of Large-scale Environmental Drivers of Bat Mortality at Wind Energy Facilities: The Effects of Facility Size, Elevation and Geographic Location," *Global Ecology and Conservation* 21(e00871).

Exhibit 6 – Bennett, V.J., A.M. Hale, and D.A. Williams, 2017, "When the Excrement Hits the Fan: Fecal Surveys Reveal Species-Specific Bat Activity at Wind Turbines," *Mammalian Biology* 87:125-129.

Exhibit 7 – Fiedler, S. (dBF Associates, Inc.), February 3, 2020, "Campo Wind Project Noise/Acoustical Review."

Exhibit 8 – Fiedler, S. (dBF Associates, Inc.), February 3, 2021, "Noise/Acoustical Review for the Campo Wind Project with Boulder Brush Facilities."

Exhibit 9 – Carman, R. (Wilson Ihrig & Associates), February 4, 2021, "Review of the Noise Analysis in the DEIS for the Campo Wind Project with Boulder Brush Facilities."

Exhibit 10 – Pohl, J., J. Gabriel, and G. Hübner, 2018, "Understanding Stress Effects of Wind Turbine Noise – The Integrated Approach," *Energy Policy* 112:119-128.

Exhibit 11 – Schäffer, B., R. Pieren, U.W. Hayek, N. Biver, and A. Grêt-Regamey, 2019, "Influence of Visibility of Wind Farms on Noise Annoyance – A Laboratory Experiment with Audio-Visual Simulations," *Landscape and Urban Planning* 186:67-78.

Exhibit 12 – Hansen, K.L, P. Nguyen, B. Zajamsek, P. Catcheside, and C.H. Hansen, 2019, "Prevalence of Wind Farm Amplitude Modulation at Long-range Residential Locations," *Journal of Sound and Vibration* 455:136-149.

Exhibit 13 – Fiedler, S. (dBF Associates, Inc.), December 16, 2019, "Wind Turbine Infrasound and Low-Frequency Noise Survey in Boulevard, CA."

Exhibit 14 – Morsing, J.A., M.G. Smith, M. Ögren, P. Thorsson, E. Pedersen, J. Forssén, and K.P Waye, 2018, "Wind Turbine Noise and Sleep: Pilot Studies on the Influence of Noise Characteristics," *International Journal of Environmental Research and Public Health*, 15(2573).

Exhibit 15 – Poulsen, A.H., O. Raaschou-Nielsen, A. Peña, A.N. Hahmann, R.B. Nordsborg, M. Ketzel, J. Brandt, and M. Sørensen, 2019, "Impact of Long-Term Exposure to Wind Turbine Noise on Redemption of Sleep Medication and Antidepressants: A Nationwide Cohort Study," *Environmental Health Perspectives*, 127(3).

Exhibit 16 – Law Offices of Stephan C. Volker, April 12, 2019, "Request of Backcountry Against Dumps and Donna Tisdale to Rescind or Revise the San Diego County Health and Human Services Agency's February 25, 2019 Public Health Position Statement on the Human Health Effects of Wind Turbines," submitted to the San Diego County Planning & Development Services.

Exhibit 17 – Carlile, S., J.L. Davy, D. Hillman, and K. Burgemeister, 2018, "A Review of the Possible Perceptual and Physiological Effects of Wind Turbine Noise," *Trends in Hearing* 22:1-10.

Exhibit 18 – Dolan, Stacey L. & Garvin A. Heath, 2012, "Life Cycle Greenhouse Gas Emissions of Utility-Scale Wind Power: Systematic Review and Harmonization," *Journal of Industrial Ecology*, 16(SI).

Exhibit 19 – Snyder, S. (Snyder Geologic), February 1, 2021, "Groundwater Impacts of the Campo Wind Project with Boulder Brush Facilities in Eastern San Diego County."

EXHIBIT
1

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January 29, 2020

VIA EMAIL AND U.S. MAIL

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Federal Aviation Administration
Southwest Regional Office
Obstruction Evaluation Group
10101 Hillwood Parkway
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Lan.norris@faa.gov

Re: Comments of Backcountry Against Dumps and Donna Tisdale on the Campo Wind Project, Wind Turbine C-69, Campo, California
Aeronautical Study No. 2019-WTW-4585-OE

Dear Mr. Norris:

On behalf of Backcountry Against Dumps and Donna Tisdale (collectively, "Backcountry"), we respectfully submit the following comments on the Campo Wind Project with Boulder Brush Facilities ("Campo Wind" or the "Project"), pursuant to the Federal Aviation Administration's ("FAA's") October 21, 2019 Public Notice for Aeronautical Study No. 20191-WTW-4585-OE ("Notice"). Please include these comments and all eight attached exhibits in the public record for this Project.

On July 8, 2019, Backcountry submitted comments to the Bureau of Indian Affairs ("BIA") addressing the many deficiencies in the Project's Draft Environmental Impact Statement ("DEIS").[1] In addition to the significant environmental impacts we document there, the Project would also create unacceptably dangerous aeronautical hazards as discussed below. Accordingly, we urge your agency to reject this Project because it is unsafe for aviation.

I. INTRODUCTION

The Project site currently supports actively utilized navigable airspace, but that airspace

[1] Backcountry Against Dumps and Donna Tisdale DEIS Comments on the Campo Wind Energy Project, July 8, 2019, attached hereto as **Exhibit 1**.

will be significantly impaired by the Project's structures because they exceed by a substantial margin FAA obstruction standards. The Project's structures will create collision risks and turbulence harmful to aviation, degrade aircraft safety systems, and impair pilot safety.

The Project's wind turbines and meteorological towers present significant aeronautical risks that have not yet been analyzed. The DEIS fails to discuss the Project's impacts to aviation and instead relies entirely on FAA-required lighting to mitigate impacts it does not even acknowledge, let alone address.

As we explain below, the Project's impacts to aviation pose serious safety hazards that mere lighting alone cannot eliminate. Therefore the Project proponent's claims that these impacts can be mitigated simply by including lighting on the wind turbine towers and meteorological towers are mistaken. As proposed, the Project poses unacceptable hazards to aviation safety and must therefore be rejected.

II. THE PROJECT SITE CURRENTLY SUPPORTS NAVIGABLE AIRSPACE

The Project site lies directly beneath, and the Project will directly impact, navigable airspace that is actively utilized for military, commercial and private flights. The site is located in the border zone (FAA Notice at 7) and is situated between and in proximity to numerous military bases and air stations in California, including the Naval Base in San Diego, the Naval Air Facility in El Centro, the Naval Special Forces Training Facility in nearby Campo, and the Marine Corps Air Station in San Diego. This same airspace is also in use by the Marine Corps Air Station in Yuma, Arizona.[2] The site serves as an active route between these military bases and air stations, and is regularly frequented by their low flying aircraft.

Our client Donna Tisdale and her family own 267 acres on Tierra Real Road near Boulevard that share a half mile-long boundary with the Campo Reservation and the Project site on the Reservation's southeastern border along BIA Road 10. Ms. Tisdale regularly observes homeland security and military aircraft, as well as commercial and private aircraft, flying over the Project site. These aircraft often pass directly over the Project site at very low altitudes. We attach as Exhibit 2 illustrative photographs taken by Ms. Tisdale that show examples of the many low-flying aircraft she routinely observes over the Project site.[3]

III. THE PROJECT WILL IMPEDE AIRCRAFT OPERATIONS

A. The Project's Wind Turbines Will Encroach Upon Existing Flight Airspace

The FAA Notice identifies approximately 76 wind turbines included in this Project that exceed the FAA obstruction standards outlined in the Code of Federal Regulations, Title 14, Part

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[2] Military Base List, available at: https://www.military.com/base-guide, last accessed January 8, 2020.

[3] Photographs of the airspace above the Project site taken by Donna Tisdale, attached hereto as **Exhibit 2**.

77. These turbines will each stand 586 feet tall. Notice at 4-6. Consequently, they will exceed by 87 feet the FAA height limit of 499 feet above ground level. Notice at 6, citing 14 CFR § 77.17(a)(1). Furthermore, at least four turbines will cause the minimum en route altitude and the minimum obstruction clearance altitude to increase by 200 feet, from 7,000 feet to 7,200 feet. Notice at 6.

This abrupt increase in minimum flight altitude in this mountainous area will pose aviation burdens on and hazards to military as well as commercial and private aircraft that utilize the air space overlying the Project site. For these reasons, as the Civil Aviation Authority has recognized, "[w]ind turbine developments can have a detrimental effect on military operations."[4] This hazard would be especially problematic because the Project area is frequently used by the military for training aircraft at low altitudes.

The Project Creates Aeronautical Hazards That Will Harm Aircraft Safety

Wind turbines and meteorological towers present a direct risk of collision with aircraft. Between 2003 and 2016 ten individuals were killed in the United States as a result of aircraft collisions with wind energy turbines and their towers.[5] This well-documented risk is multiplied in an area like the Project site where, despite the mountainous terrain, low flying aircraft are a regular occurrence. While the turbines and their towers are required to have lights indicating their location, those lights do not eliminate the aviation risk entirely. The turbines' blade sweep would extend 230 feet above the highest light, which would be located on the nacelle. The towers' blinking red lights may not be readily visible to pilots wearing night vision goggles. In at least one fatal incident, sun glare caused the pilot's inability to identify and avoid a meteorological tower, and in another the tower light was not functioning properly at the time. Exhibit 4, at 2. As these examples demonstrate, wind turbines and their towers pose a serious risk to aircraft that cannot be entirely eliminated through lighting.

Turbulence from wind turbines can impact aeronautic operations.[6] Exhibit 3, at 31-34. "Turbulence is caused by the wake of the turbine which extends down-wind behind the blades and the tower, from a near to a far field." Exhibit 3, at 31. "[W]ind turbines produce wakes of similar, but not identical, characteristics to aircraft" and for this reason "aircraft wake vortices can be hazardous to other aircraft." Exhibit 3, at 31.

Furthermore, radar systems may be impaired or disrupted by wind energy facilities. Radar systems are designed to filter out false information, or "clutter."[7] Where wind energy

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[4] Civil Aviation Authority, *CAA Policy and Guidelines on Wind Turbines, CAP 764*, Safety and Airspace Regulation Group, 6th Ed., February 2016, p. 37, attached hereto as **Exhibit 3**.
[5] Linowes, Lisa, *Wind Energy and Aviation Safety, Fatalities,* WindAction.org, April 4, 2017, attached hereto as **Exhibit 4**.
[6] Mulinazzi, Thomas E., Zheng, Zhingquan Charlie, *Wind Farm Turbulence Impacts on General Aviation Airports in Kansas*, Kansas Department of Transportation, Report No. K-TRAN: KU-13-6, January 2014, attached hereto as **Exhibit 5**.
[7] Novak, Andrej, *Wind Farms and Aviation*, Aviation, 2009, 13:2, 56-59, p. 57, attached hereto as **Exhibit 6**.

turbines create dense centers of stationary clutter, radar may be tricked into increasing the clutter threshold, effectively causing radar systems to miss other, actual obstacles that would normally appear on the radar. Exhibit 3, at 20-21; Exhibit 6, at 57. This hazard is particularly acute in mountainous areas such as the Project site.

Additionally, where the wind turbine blades are moving, the radar may "detect Doppler returns from moving wind turbine blades and display them as returns on the radar screen." Exhibit 3, at 21; Exhibit 6, at 57-58. Where there is more than one turbine – or in this case 76 – "the radar may illuminate a blade or blades from one turbine on one antenna sweep, then illuminate the blades of a different turbine on the next sweep." Exhibit 3, at 21; Exhibit 6, at 57-58. This "'twinkling' appearance or 'blade flash effect' . . . can appear very similar to those that would be produced by a light aircraft" "lead[ing] to degradation of radar tracking capability." Exhibit 3, at 21; Exhibit 6, at 57-58.

Degradation of radar function is extremely dangerous to aircraft operations because radar is one of the main tools on which instrumented pilots rely to navigate, particularly when visibility is reduced due to rain, snow, cloud cover or darkness.

Because the Project site is located in mountainous terrain where storm activity is more frequent and severe winds, including sudden up- and down-drafts associated with the steep eastern escarpment of the coast range, are more common, impaired visibility combined with degraded radar function pose particularly severe aviation hazards. Indeed, because of the area's high risk of severe winds, the east-bound (down-gradient) lanes of the adjacent Interstate 8 freeway are often unsafe for, and occasionally closed to, truck traffic.

For these reasons, the introduction of such a large wind turbine facility at the Project's mountainous site could severely impair safe aeronautical operations.

B. The Project's Turbines and Meteorological Towers Will Interfere With Emergency Services

The Project's 586-foot tall structures will also pose hazards to emergency services, including emergency medical flights and aerial firefighting. These emergency services often employ low-flying aircraft that will be forced to either take additional time to re-route around the Project or, if they are needed in proximity to the Project site, be forced to compromise their mission to prevent collision with the Project's towers.

This Hobson's choice is especially problematic for aerial firefighting in this wildfire-prone area. As noted above, the towers exceed FAA height limitations and certain turbines will increase minimum obstruction clearance altitudes for nearby aircraft. Notice at 6. Because aerial firefighting frequently requires low-level operations (i.e., below 500 feet above ground level), the 586-foot tall structures would directly interfere with firefighting safety and effectiveness. For example, incident mapping is often performed at 500 feet above ground level and firefighting ground crew support is performed at even lower levels.[8] Low-level flight

[8] National Wildlife Coordinating Group, *Interagency Aerial Supervision Guide*, PMS 505, NFES

operations are often needed "to ensure air tanker drop effectiveness and safety" and to identify "safe jump spots" for smokejumpers. Exhibit 7 at 101, 112. Helicopters frequently perform firefighting operations between 200 and 500 feet above ground level. Exhibit 7 at 82, 113. But none of these operations can be performed at safe and effective levels where turbines and meteorological towers rise well above these heights, as they would with this Project. Notice at 1.

Furthermore, the Project itself will introduce myriad new wildfire ignition sources. DEIS at 130 ("The Project would increase the risk of wildfires"). The presence of high voltage wind turbines—which have a documented history of erupting in flame when their motors burn or short out or their bearings wear out—together with a high voltage substation and gen-tie line, and other electrified Project facilities will dramatically increase the risk of wildfire ignition in the area. This greatly increased risk of ignition, in turn, exponentially increases the likelihood that firefighting resources will be needed at this location in the first place.

Moreover, because the Project's generating and transmission facilities are electrified with high voltage—necessitating the imposition of a no-fire-fighting buffer zone around them, which would be enlarged in smoky conditions—fire suppression activities both in the air and on the ground will be additionally impaired, further exacerbating the impacts to aerial firefighting discussed above.

C. The Project's Aeronautical Hazards Cannot Be Eliminated By Lighting

Both the Project's wind turbines and its meteorological towers are required to be fitted with FAA-compliant lighting. DEIS 7, 9, 123. The DEIS relies on FAA-compliant lighting as the sole means of protecting against any aeronautical hazards. DEIS 123. However, this lighting will not by itself eliminate all the aeronautical hazards that the Project creates. Lighting is typically placed only on the nacelle and not on the blade tips. Therefore, the actual height of the wind turbine is not evident to pilots. Because the Project's turbine blades are 230 feet in length from the nacelle to the blade tip—the height of a 15-story building—reliance by pilots on the location of the lighting creates an enormous blind spot in which the spinning blades are invisible to the pilot at night.

Furthermore, FAA-required lights are ineffective for pilots who use night vision goggles ("NVGs"). As the FAA notes, "pilots using NVGs are unable to acquire red-colored LED obstruction lights due to the light generated being outside of the combined visible and near-infrared spectrum of NVGs."[9] This is particularly problematic for military pilots and nighttime air ambulance operators, both of whom regularly utilize NVGs. Again, this concern is heightened because of the high density of military air facilities and traffic in the area.

002544, April 2017, pp. 68, 82, attached hereto as **Exhibit 7**.

[9] FAA, *Engineering Brief No. 98: Infrared Specifications for Aviation Obstruction Light Compatibility with Night Vision Goggles (NVGs)*, December 18, 2017, p. 1, attached hereto as **Exhibit 8**.

IV. CONCLUSION

It is clear that "the combined effect of numerous individual turbines or multiple wind turbine developments can be hard, if not impossible, to mitigate." Exhibit 3, at 30. The Project will indisputably have a significant adverse effect on aircraft safety and operation, by producing turbulence and degrading radar function. The Project will also pose an unacceptable risk of fatal aircraft collisions that cannot be eliminated by FAA-required lighting. This severe risk—exacerbated by the acknowledged fact that the area is frequently used by low flying military aircraft—is unacceptable.

The Project must be rejected because it poses unacceptable risks to aviation safety.

Respectfully submitted,

Stephan C. Volker
Attorney for Backcountry Against Dumps and Donna Tisdale

Index to Exhibits:

Exhibit 1 – Backcountry Against Dumps and Donna Tisdale DEIS Comments on the Campo Wind Energy Project, July 8, 2019

Exhibit 2 – Photographs taken by Donna Tisdale, at the Project site

Exhibit 3 – Civil Aviation Authority, *CAA Policy and Guidelines on Wind Turbines, CAP 764,* Safety and Airspace Regulation Group, 6th Ed., February 2016

Exhibit 4 – Linowes, Lisa, *Wind Energy and Aviation Safety, Fatalities,* WindAction.org, April 4, 2017

Exhibit 5 – Mulinazzi, Thomas E., Zheng, Zhingquan Charlie, *Wind Farm Turbulence Impacts on General Aviation Airports in Kansas*, Kansas Department of Transportation, Report No. K-TRAN: KU-13-6, January 2014

Exhibit 6 – Novak, Andrej, *Wind Farms and Aviation*, Aviation, 2009, 13:2, 56-59

Exhibit 7 – National Wildlife Coordinating Group, *Interagency Aerial Supervision Guide*, PMS 505, NFES 002544, April 2017

Exhibit 8 – FAA, *Engineering Brief No. 98: Infrared Specifications for Aviation Obstruction Light Compatibility with Night Vision Goggles (NVGs)*, December 18, 2017

01-29-20
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July 8, 2019

VIA EMAIL
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Dan (Harold) Hall
Regional Archaeologist
Pacific Region Branch
Bureau of Indian Affairs

Re: DEIS Comments, Campo Wind Energy Project

Dear Mr. Hall:

On behalf of Backcountry Against Dumps and Donna Tisdale (collectively, "Backcountry"), we respectfully submit the following comments on the Draft Environmental Impact Statement ("DEIS") for the Campo Wind Project with Boulder Brush Facilities ("Campo Wind" or the "Project"), pursuant to the Bureau of Indian Affairs' ("BIA's") May 24, 2019 Notice of Availability, and the National Environmental Policy Act ("NEPA"), 42 U.S.C. section 4321 *et seq.*. Please include these comments and all attached exhibits in the public record for this Project.

I. The DEIS Unlawfully Segments the Analysis of Connected Actions

NEPA forbids "segmented" environmental review. 40 C.F.R. § 1508.25(a)(1). Connected actions must be considered together in a single EIS. *Thomas v. Peterson*, 753 F.2d 754, 759 (9th Cir. 1985) (overruled on other grounds by *Cottonwood Environmental Law Center v. U.S. Forest Service*, 789 F.3d 1075, 1088-1092 (9th Cir. 2015)). Connected actions are those that (1) "[a]utomatically trigger" other actions, (2) "cannot or will not proceed unless other actions are taken previously or simultaneously," or (3) are "interdependent parts of a larger action and depend on the larger action for their justification." 40 C.F.R. § 1508.25(a)(1). Actions do not lose their "connected" status just because they are proposed by a different project applicant. *Alpine Lakes Protection Society v. U.S. Forest Service*, 838 F.Supp. 478, 482 (W.D. Wash. 1993).

Here, the DEIS improperly segments the analysis of connected actions in at least two ways. First, the DEIS fails to analyze the impacts of the connected Torrey Wind project. The Torrey Wind project is a proposed 30-turbine126-MW wind energy generation facility that the Boulder Brush facilities would enable. The DEIS acknowledges that the Boulder Brush "high-voltage substation would allow for the receiving and stepping up of electric energy from 230 kV to 500 kV for the Torrey Wind Project," which would be located on private lands northeast of the Reservation. DEIS at B-11. Because the Torrey Wind project would not proceed without the approval and construction of the Boulder Brush facilities, it is connected to the Campo Wind Project, and its impacts must be analyzed together in the same document.

Second, while the DEIS acknowledges that the Project "consists of both the Campo Wind Facilities on land within the Reservation and the Boulder Brush Facilities which are located on adjacent private lands within the Boulder Brush Boundary," it fails to fully analyze the impacts from and alternatives to the Boulder Brush transmission, substation and switchyard facilities being considered for approval by San Diego County (PDS2018-MPA-18-016). For example, the DEIS fails to consider alternatives to the Boulder Brush transmission facilities; it just considers alternatives to the form, capacity and location of electrical generation. DEIS at 23-25.

II. The DEIS Fails to Consider All Cumulative Projects

NEPA requires analysis of cumulative impacts. 40 C.F.R. § 1508.7. Yet the DEIS ignores numerous reasonably foreseeable projects that would contribute to the Project's cumulative impacts, including the Energia Sierra Juarez Phase II project in Mexico, the 90-MW Starlight Solar project near Boulevard and the 50-MW Tecate Solar Hybrid project also in the Boulevard area. The cumulative impacts analysis in Appendix N is also defective because it does not include a map of the cumulative projects.

III. The DEIS Fails to Evaluate a Reasonable Range of Project Alternatives

NEPA requires that an EIS "[r]igorously explore and objectively evaluate all reasonable alternatives" so that "reviewers may evaluate their comparative merits." 42 U.S.C. §4332; 40 C.F.R. § 1502.14. Alternatives should be wide-ranging and not exclude options just because they require other agency approvals. *Sierra Club v. Lynn*, 502 F.2d 43, 62 (5th Cir. 1974). Agencies may decline to study an alternative in detail on the grounds that it is "similar to alternatives actually considered, or . . . infeasible, ineffective, or inconsistent with the basic policy objectives for the management area," but only after providing a "reasoned explanation *in the EIS* for its rejection." *Northern Alaska Environmental Center v. Kempthorne*, 457 F.3d 969, 978 (9th Cir. 2006) (first quote; internal quotations and citation omitted); *Southeast Alaska Conservation Council v. Federal Highway Administration* ("*SEACC*"), 649 F.3d 1050, 1059 (9th Cir. 2011) (second quote; emphasis added). The existence of a viable but unexamined alternative renders an environmental impact statement inadequate." *Friends of Yosemite Valley v. Kempthorne*, 520 F.3d 1024, 1038 (9th Cir. 2008).

Here, the DEIS evaluates an unduly limited range of alternatives. It only evaluates two action alternatives: (1) a 252-MW capacity wind energy facility with 60 4.2-MW, 586-foot (ground to blade tip) tall wind turbines, and (2) a 202-MW capacity wind energy facility with 48 4.2-MW turbines. DEIS at 23. BIA considered but eliminated from detailed consideration in the DEIS a mixed renewable generation (wind and solar) alternative, a minimal build-out (63-MW capacity) alternative, an off-Reservation location alternative, a reduced-capacity turbine (2.5-

MW turbine) alternative, and a distributed generation alternative. Yet BIA failed to provide a "reasoned explanation *in the EIS* for its rejection" of those additional alternatives. *SEACC*, 649 F.3d at 1059 (emphasis added).

For example, the DEIS fails to list any "scientific [or] other sources relied upon" for its conclusion that the "distance and cost of connecting the scaled down [minimal build-out] project to the planned switchyard would be cost prohibitive and the delivered cost of energy from 15 turbines would be too expensive for a potential buyer to enter into a contract for such a scaled-down project based on current energy market conditions." 40 C.F.R. § 1502.24 (first quote); DEIS at 24 (second quote). The DEIS similarly fails to support its rationale for rejecting the reduced-capacity turbines alternative: that the "[i]mpacts to the environment would have been similar to those of the larger capacity turbines considered in Alternative 1." To the contrary, noise – and potentially other impacts – would likely be reduced with lower-capacity turbines.[1]

BIA must rectify these and recirculate the revised DEIS.

IV. BIA Failed to Take a Hard Look at the Project's Impacts in the DEIS

NEPA requires that agencies take a "hard look" at the environmental impacts of proposed major federal actions and provide a "full and fair discussion" of those impacts in an EIS. 40 C.F.R. § 1502.1; *National Parks and Conservation Association v. BLM*, 606 F.3d 1058, 1072-1073 (9th Cir. 2010); CEQA Guidelines § 15126.2(a) ("Direct and indirect significant effects of the project on the environment shall be clearly identified and described"); *National Parks & Conservation Association v. Babbitt*, 241 F.3d 722, 733 (9th Cir. 2001). That includes "insur[ing] the professional integrity, including scientific integrity, of the discussions and analyses in environmental impact statements" by "identify[ing] any methodologies used and . . . mak[ing] explicit reference by footnote to the scientific and other sources relied upon for conclusions in the statement." 40 C.F.R. § 1502.24. Here, BIA failed to take a hard look at numerous Project impacts.

A. Impacts to Biological Resources

The DEIS significantly downplays the Project's biological impacts on numerous species. By understating these impacts, the DEIS fails to accurately inform the public and decisionmakers of the Project's environmental harm, in violation of NEPA.

1. Golden Eagles and Other Avian Species

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[1] *See*, *e.g.*, Walker, Bruce, George F. and David M. Hessler, Rob Rand & Paul Schomer, December 24, 2012, "A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin," Public Service Commission of Wisconsin Report #122412-1 (attached hereto as **Exhibit 1**) (noting that the "Navy's prediction of the nausogenic region . . . indicates a 6 dB decrease in the criterion level for a doubling of power such as from 1.25 MW to 2.5 MW).

Wind turbines kill birds.[2] The Campo Wind Project's 60 turbines will be no different. A wealth of bird species have been documented inhabiting or otherwise using the Project area, including sensitive species like golden eagles. DEIS Appendix F. The risk to golden eagles is particularly concerning because they are "currently known to be at risk of *population-level* effects from [wind turbine] collisions," and must be afforded every possible protection. **Exhibit 2** at 306. Yet the DEIS brushes aside the risk to golden eagles because "[e]agle use on site is infrequent and the chance for collisions is low." DEIS at 86. It also brushes aside collision impacts to other migratory birds (protected under the Migratory Bird Treaty Act, 16 U.S.C. section 703 *et seq.*) because the Project would "conduct . . . bat and avian monitoring during construction and operation." DEIS at 87; DEIS Appendix P at P-5 (quote). Those conclusion are unsupported and insufficient to reasonably inform decisionmakers and the public for at least three reasons.

First, the DEIS fails to *quantify* the number of expected wind turbine collisions with golden eagles or any other bird species. It is impossible to know how significant the Project's impacts to birds will be without a collision quantification. For example, because the golden eagle *population* is at risk from wind turbines and other causes, as discussed, the loss of one golden eagle could have population-level consequences.

Second, after-the-fact monitoring of bird collisions and removal of bird carcasses (as proposed as part of MM-BIO-4) does nothing to mitigate the collision impacts. DEIS Appendix P at P-5. Monitoring cannot bring birds back from the dead.

Third, the DEIS fails to analyze the *landscape*-scale avoidance impacts that the Project's turbines would likely cause.[3] A recent longitudinal study of bird densities at 12 wind farms in Ireland and their paired control sites found that "densities of open-habitat species were lower at wind farms" than at the control sites "independent of distance to turbines." **Exhibit 3** at 7. This "suggests that for open-habitat birds, effects were operating at a landscape scale." **Exhibit 3** at 8. The Campo Wind Project could well have similar effects. While the bird species may be different near the Campo Wind Project site than at the study sites in Ireland, the terrain is more "open-habitat" than "forested" (the other type of habitat present at some of the Ireland study sites, and for which the authors found gradient rather than landscape effects).

Fourth, the golden eagle surveys that the DEIS relies on are deficient. While the DEIS claims that surveys were conducted "within the study area from October through December 2017, and in January 2018 to present" and "during the spring and fall periods and included three surveys each week at each point," the survey tables provide conflicting information. DEIS Appendix H 17-25 (surveys were conducted 10/2/17 through 12/1/17, and resumed on 10/2/18

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[2] Dwyer, J.F., M.A. Landon, and E.K. Mojica, 2018, "Impact of Renewable Energy Sources on Birds of Prey," in J.H. Sarasola *et al.* (eds.), 2018, *Birds of Prey*, Springer International Publishing AG (attached hereto as **Exhibit 2**).

[3] Fernández-Bellon, D., M.W. Wilson, S. Irwin, and J. O'Halloran, 2018, "Effects of Development of Wind Energy and Associated Changes in Land Use on Bird Densities in Upland Areas," *Conservation Biology* 0(0):1-10 (attached hereto as **Exhibit 3**).

through 10/29/18. There were "avian point count" surveys during some of the intervening periods; however, there was only one survey by one person (on 2/9/18) between 1/4/18 and 7/11/-18). The failure to complete avian surveys during the spring and early summer is especially concerning because many birds migrate north during the spring along the eastern side of the mountains in San Diego County.

Furthermore, the surveys did not comply with Land-Based Wind and Eagle Conservation Plan Guidelines which call for a minimum of two years of surveys across all seasons, 20 hours of survey per turbine per year which would equal 2,400 hours for this Project. Yet here, these protocol were not met. In fact, only 333 hours or 13.9% of the recommended survey hours were completed. No eagle nest searches have been performed since 2011 and the DEIS does not provide any information on the status of breeding territories in the region. Finally, even if the surveys had been performed, the survey methods cannot be evaluated because survey reports are not included in the DEIS.

In sum, the DEIS' analysis of the Project's impacts to birds fails to reasonably inform decisionmakers and the public as NEPA requires. The biological resources impact analysis must accordingly be revised and recirculated.

2. Quino Checkerspot Butterfly

The DEIS admits that "Alternative 1 would permanently remove 222.1 acres of suitable Quino checkerspot butterfly habitat," and Alternative 2 would remove "approximately 191.58 acres of potentially occupied Quino checkerspot butterfly habitat." DEIS 86 (first quote), 87 (second quote). But even these significant and adverse impacts greatly understate the Project's effects on this special-status species.

The information provided in the DEIS lacks detail and information necessary to provide the public and decisionmakers with the "hard look" that NEPA requires. The approximately one-page discussion of the Project's effects on the Quino checkerspot butterfly directs the reader to DEIS Appendix H for more information, but that Appendix does little to elucidate the issue. DEIS 86; DEIS Appendix H 85-89. Rather, Appendix H makes more vague statements. For example, Appendix H confirms that "[c]onstruction activities increase the number of humans within the area, which can deter wildlife from using an area," but entirely fails to consider how that would impact Quino checkerspot butterfly survival. DEIS Appendix H 86. Indeed, human presence in the area will increase collisions and noise, and increased construction equipment and vehicles can introduce nitrogen which could alter vegetation and the presence of Quino checkerspot host plants.

Appendix H also claims that "[a]pproximately 1,216 acres were considered potential suitable habitat within the Project Site," and that "[n]o Quino checkerspot butterfly or their host plants were observed during the 2018 focused surveys." DEIS Appendix H 61. Yet those figures are understated in the DEIS, which claims that the 2018 surveys found only "699 acres within the Project Area were considered suitable habit." DEIR 37. The public and decisionmakers are left wondering what impacts the Project will have on the Quino checkerspot butterfly, and unable to even determine how potential habitat was identified. Appendix H claims that it followed U.S. Fish and Wildlife Service guidelines to identify potential habitat, but it does not cite any source for those guidelines, or provide any definition for the terms used therein. This is not the "hard look" that NEPA requires and the FEIS must provide more information.

Furthermore, the DEIS admits that BIA does not have all the information it needs to determine what impacts the Project will have. "An additional set of Quino checkerspot butterfly surveys are being conducted within the Off-Reservation portion of the Project." DEIS 37, 86 (quote). Without this survey information, BIA cannot accurately determine the Project's impacts and how that would affect the DEIS' analysis and conclusions. Yet, while lacking this critical information, the DEIS somehow concludes that the "Off-Reservation portion of the Project would not adversely affect any federally listed plants or wildlife, because none are present." DEIS 86. But that assertion is patently incorrect because BIA does not have the evidence to support its conclusion. The DEIS only compound this failure by relying on that lack of information to support its claim that it did not need to model off-reservation habitat. DEIS Appendix H 62.

The DEIS also claims that "[b]ecause decommissioning would include restoration of the area to pre-Project conditions, it would ultimately not result in adverse effects on Quino checkerspot butterfly." DEIS 86. But restoration to pre-Project conditions – which is not even possible – does not negate adverse effects. The DEIS acknowledges that decommissioning activities will "result in temporary direct and indirect adverse effects on Quino checkerspot butterfly," including collisions with equipment and vehicles, human disturbance, and noise impacts. DEIS 86. Those adverse impacts are significant and cannot be ignored simply because the DEIS claims that the area will be restored to pre-Project conditions. Even if area restoration were possible, it cannot heal dead or injured Quino checkerspot butterflies.

All of these failures are exacerbated by the importance of project area to the Quino checkerspot butterfly. The Project falls within the La Posta/Campo Core Occurrence Complex for the Quino checkerspot butterfly, on the eastern edge of the species' range. 74 FR 28776-28862. The U.S. Fish and Wildlife Service has concluded that the maintenance of these core occurrence complexes is essential for recovery and survival of the Quino checkerspot butterfly in San Diego County. *Id.* Furthermore, the La Posta/Campo and Jacumba core occurrence complex habitats are warmer and drier than the Otay Mountain Core Occurrence Complex and differ substantially in other habitat characteristics, and contribute significantly to reducing the subspecies' extinction probability. *Id.* "The eastern edge of Quino checkerspot's range supports large and robust butterfly populations, abundant and diverse larval host plants and nectar sources, and relatively low levels of development and intensive agriculture. These areas may provide climate refugia that Quino checkerspot will require under future predicted scenarios of climate change."[4] Therefore, the Project area is not only important because it is a core occurrence area, but because it is imperative to species survival with the ongoing perils of

[4] Preston, Kristine L., et al, 2012, "Changing distribution patterns of an endangered butterfly: Linking local extinction patterns and variable habitat relationships," *Biological Conservation* 152:280–290, 289 (attached hereto as **Exhibit 4**).

climate change.

The DEIS erroneously claims that any adverse impacts "would be reduced to less than adverse with implementation of recommended MM-BIO-1 and MM-BIO-3." DEIS 86. But the BIA has not demonstrated that these significant impacts can be mitigated at all, let alone by the deficient mitigation measures that are proposed. MM-BIO-1 calls for development of a number of plans that it claims will protect biological resources in general, and the designation of a Project biologist to oversee construction efforts. DEIS Appendix P P-1 to P-4. But the implementation of those plans, even if perfectly executed, would not reduce the Project's impacts to less than significant. The nature of the Project is such that there will be significant adverse impacts to the Quino checkerspot butterfly and no amount of avoidance, short of denying the Project, could protect this imperiled species.

MM-BIO-3, which is more specifically directed toward the Quino checkerspot butterfly, is vague and unenforceable. That measure simply defers the development of any Quino checkerspot specific mitigations until after Section 7 consultation is complete. DEIS Appendix P P-4. The DEIS makes vague statements such as "[h]abitat mitigation ratios will be determined through the Section 7 consultation," and "mitigation shall focus on habitat preservation and creation for long-term conservation of metapopulation dynamics." DEIS Appendix P P-4. But the DEIS does not provide any specific information on what those measures may be, what they may apply to, or how they would be implemented. Without any detail, the DEIS cannot accurately conclude these unknown mitigation measures will reduce the Project's impacts. The only specific direction that is provided, is that fencing and signage will be used near butterfly habitat, habitat mitigation ratios will be developed, and that construction "shall occur when adult and larval activity is reduced and host plants are not generally flowering or germinating." DEIS Appendix P P-4. But those measures are not sufficient to mitigate the Project's significant impacts. NEPA requires more.

In sum, the DEIS' analysis of the Project's impacts to the Quino Checkerspot Butterfly fails to reasonably inform decisionmakers and the public as NEPA requires. The biological resources impact analysis must accordingly be revised and recirculated.

B. Noise Impacts

The DEIS fails in many ways to accurately and reasonably inform the public and decisionmakers of the Project's noise impacts, including audible noise, low-frequency sound and infrasound impacts. Acoustics expert Dr. Richard Carman details many of the DEIS' deficiencies in his July 7, 2019 Review of Campo Wind Project and Boulder Brush Facilities DEIS Noise Analysis ("Noise Impact Review," attached hereto as **Exhibit 5**). Dr. Carman's objective critiques, which are incorporated by reference herein, including the following:

- The DEIS fails to recognize the significant impact on noise-sensitive land uses of the magnitude of the *increase* in ambient noise that Project operation would cause. **Exhibit 5** at 4-5. Instead, it uses thresholds for the *ultimate* noise levels during Project operation. DEIS Appendix K at 23. In doing so, the DEIS ignores Federal Transit Administration

("FTA") guidance directly in point, which "recognize that changes in ambient noise can adversely affect local populations." **Exhibit 5** at 4. Had BIA applied the FTA guidelines, Dr. Carman concludes the analysis would have "indicate[d] a substantial increase in [ambient audible] noise resulting in a significant impact." **Exhibit 5** at 2.

- The DEIS fails to acknowledge, let alone correct for, a limitation in the instrumentation used to measure ambient noise conditions, which resulted in an "overstatement of the existing ambient noise resulting in an incorrect assessment of the impact of project noise." **Exhibit 5** at 2.
- The DEIS fails to "adequately address the effects of low frequency noise on [noise-sensitive land uses]." **Exhibit 5** at 2.
- The DEIS fails to "adequately address the effects on [noise-sensitive land uses] of 'amplitude modulation' associated with low frequency wind turbine noise." **Exhibit 5** at 2.
- The DEIS fails to "adequately address the effects of infrasound on [noise-sensitive land uses]." **Exhibit 5** at 2.
- The DEIS relies on a computer program – CadnaA – to model noise generated by the Project's turbines that was "not intended to be applied to prediction of noise generated by large wind turbines due to inherent limitations in the modeling methodology." **Exhibit 5** at 2.

Dr. Carman's Noise Impact Review examines each of those deficiencies in more detail. **Exhibit 5**.[5] The DEIS' noise impact analysis is further deficient in at least two ways.

First, the DEIS *entirely* fails to analyze the Project's infrasound noise impacts. DEIS Appendix K at 32 ("infrasound is not evaluated in this report"). And its rationale for not analyzing infrasound is inapposite. The DEIS relies on a study that concludes wind turbine-generated infrasound is below "audible perception thresholds." *Id.* But as Dr. Carman notes in his Noise Impact Review, that misses the point: The research indicates that "humans could be negatively impacted at sound levels significantly below the threshold of audibility." **Exhibit 5** at 13. A 2018 review of the scientific literature affirmed not only that "there is ample evidence demonstrating that a component of the sound energy produced by a [wind turbine] is in the low and infrasonic frequency range," but also that the literature presents a "strong prima facia case for neural transduction of low-frequency sound] and [infrasound]."[6] **Exhibit 7** at 2 (first quote), 6 (second quote).

Second, the sole evidence the DEIS relies on to conclude that the Project would not cause

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[5] Dr. Carman and his firm, Wilson Ihrig, a national noise, vibration and acoustical professional consulting firm, also separately obtained noise recordings between November 13 and 17, 2018 in the Boulevard and Jacumba Hot Springs areas. The findings are documented in a 2019 report that is attached hereto as **Exhibit 6**.

[6] Carlile, S., J.L. Davy, D. Hillman, and K. Burgemeister, 2018, "A Review of the Possible Perceptual and Physiological Effects of Wind Turbine Noise," *Trends in Hearing* 22:1-10 (attached hereto as **Exhibit 7**).

significant low-frequency noise impacts is distinguishable. DEIS Appendix K at 37. That study, Epsilon Associates, Inc.'s ("Epsilon's") 2009 study of the infrasound and low-frequency noise produced by GE 1.5-MW SLE and Siemens 2.3-93 wind turbines, was published by O'Neal *et al.* (2011) in the Noise Control Engineering Journal in 2011 (published paper attached hereto as **Exhibit 8**). According to the DEIS, Epsilon's study "determined that noise generated by the turbines at distances beyond 1,000 feet were below the interior low-frequency noise criteria for bedrooms, classrooms, and hospitals. DEIS Appendix K at 37. And because the proposed Project "provides a minimum setback for turbine units of 1,320 feet (i.e., 0.25 miles) from local residential uses," the DEIS concludes that "low-frequency noise would not result in adverse noise impacts." *Id*. This cursory analysis based on a single study is both inadequate and inaccurate for at least four reasons.

First, the DEIS fails to provide any information about what low-frequency impact criteria were used in the Epsilon study or justify why they would apply here.

Second, the DEIS glosses over the fact that the wind turbines studied by O'Neal *et al.* (2011) were smaller and had significantly lower electrical generation capacities (1.5 to 2.3 MW) than those proposed here (4.2 MW). Because larger and higher capacity wind turbines generate lower frequencies and greater amounts of ILFN, it is likely that the turbines proposed for the Campo Would Project would produce greater amplitude (decibels), lower frequency and more harmful infrasound and low-frequency noise than the turbines studied by O'Neal (2011). *See*, *e.g.*, **Exhibit 1**.

Third, even assuming that the Project's turbines would generate the same infrasound and low-frequency noise levels and frequencies as the turbines studied by O'Neal *et al.* (2011), and propagate them for the same distance, they would still cause negative health impacts on nearby residents. Based on the dB SPL data presented by O'Neal *et al.* (2011), the infrasound levels generated by a single Siemens SWT 2.3 wind turbine and a single GE 1.5 SLE wind turbine at residences located 305 meters (991 feet) away were 75 dBG and 72 dBG, respectively. This is well above the "sound level[] [threshold] of 60 dBG" that Salt and Kaltenbach (2011) have demonstrated "will stimulate the [outer hair cells] of the human ear."[7] **Exhibit 9** at 300.

Fourth, using an attenuation rate of -3 dB/doubling of distance from the sound source, it is clear that the infrasound levels produced by the turbines studied by O'Neal *et al.* (2011) would continue to surpass the 60 dBG physiologic impact threshold for well over 0.5 miles. Here, numerous residents live within 0.5 miles of at least one planned wind turbine, and would thus be exposed to infrasound levels greater than 60 dBG. *See* DEIS Appendix K at 37 (stating that the "proposed project provides a minimum setback for turbine units of 1,320 feet (i.e., 0.25 miles) from local residential uses).

In sum, the DEIS' noise impact analysis is not only inadequate, it is inaccurate, and it

[7] Salt, Alec, and James Kaltenbach, 2011, "Infrasound from Wind Turbines Could Affect Humans," *Bulletin of Science, Technology and Society*, 31(4):296-302 (attached hereto as **Exhibit 9**).

fails to reasonably inform decisionmakers and the public as NEPA requires. The noise impact analysis must be revised and recirculated.

C. Impacts to Water Resources

The DEIS fails in many ways to accurately and reasonably inform the public and decisionmakers of the Project's impacts to water resources, including impacts to the underlying Campo/Cottonwood Creek Aquifer. Understanding the impacts to the aquifer are particularly crucial to an informed understanding of the Project's impacts because the aquifer was designated as a sole source aquifer pursuant to section 1424(e) of the federal Safe Drinking Water Act on May 28, 1993, with the Environmental Protection Agency ("EPA") making the determination that "contamination of [the] aquifer would create a significant hazard to public health." 58 Fed. Reg. 31025 (May 28, 1993).

Hydrogeology expert Scott Snyder details many of the DEIS' deficiencies in his July 5, 2019 Draft EIS Review and Opinion ("Groundwater Impact Review," attached hereto as **Exhibit 10**). His review and the critiques and recommendations therein are incorporated herein by reference. In addition to the deficiencies identified in Mr. Snyder's Groundwater Impact Review, the DEIS' analysis of the Project's impacts to water resources is deficient in at least four other ways.

First, the DEIS concludes that the Project would not violate water quality standards during construction and decommissioning because it would conform with the stormwater pollution prevention plan ("SWPPP"). DEIS at 70. But the DEIS never specifies what best management practices would be adopted as part of the SWPPP. Instead, it merely provides a list of the stormwater control measures that "*could*" be included, without any analysis of the relative efficacy of the listed measures. DEIS at 14 (emphasis added). That violates NEPA, which requires that EISs describe mitigation measures with sufficient detail to assess how well they "will serve to mitigate the potential harm" they target. *Foundation for North American Wild Sheep v. U.S. Department of Agriculture* ("*Wild Sheep*"), 681 F.2d 1172, 1181 (9th Cir. 1982) (quote); *South Fork Band Council v. U.S. Department of Interior* ("*South Fork*"), 588 F.3d 718, 727 (9th Cir. 2009). Without more information on what stormwater control measures would be adopted, and the relative efficacy of each one, BIA cannot possibly "supply a convincing statement of reasons why [the] project's impacts are insignificant." *Blue Mountains Biodiversity Project v. Blackwood*, 161 F.3d 1208, 1212 (internal quotations and citation omitted).

Second, the DEIS fails to disclose whether any hazardous wastes generated by the Project and disposed of through the operation and maintenance facility's septic system. DEIS at 17 ("Sewage disposal is anticipated via an approved septic system on site or nearby on the reservation"). This is a critical omission because, as discussed above, the Project is located over a sole source aquifer, contamination of which "would create a significant hazard to public health." 58 Fed. Reg. 31025 (May 28, 1993).

Third, the DEIS presents conflicting estimates of the acreage of jurisdictional waters of the United States that the Project would impact. For example, Table 3.5-1 in the Appendix D shows 7.0 total acres, while Table 3.5-2 shows 10.78 acres. This discrepancy must be rectified.

Fourth, the DEIS presents conflicting information about where the Project would obtain its operational water supplies. Page B-7 of Appendix B lists the operational water supplies as "on-site groundwater" *or* water "trucked in from Jacumba Community Services District (JCSD) or Padre Dam Municipal Water District (PDMWD)." But Appendix B states on page B-8 that the "source of water during operation would be connection to existing On-Reservation facilities in the vicinity of the proposed O&M building." This discrepancy must be rectified.

In sum, the DEIS' analysis of impacts to water resources fails to reasonably inform decisionmakers and the public as NEPA requires. The water resources impact analysis must accordingly be revised and recirculated.

D. Global Warming Impacts

The DEIS paints a rosy picture of the Project's global warming impacts, but it is based on an incomplete analysis. DEIS Appendix G at 29-44. The DEIS fails to calculate the Project's entire *life cycle* greenhouse gas ("GHG") emissions. Instead, the DEIS focuses solely on the GHG emissions from *on-site* Project construction and operation. DEIS 4.5-1 to 3. Myriad published life cycle analyses demonstrate that wind energy projects have many more sources of GHG emissions that just on-site construction and operation. As one recent study states, "due to GHG emissions produced during *equipment manufacture, transportation*, on-site construction, maintenance, and decommissioning, wind and solar technologies are not GHG emission free."[1] **Exhibit 11** at SI36. That same study concluded, based on a "systematic review and harmonization of life cycle assessment (LCA) literature of utility-scale wind power systems," that industrial-scale wind turbines produce 11 g CO_2-eq/kWh (median value, with a range of 3 g CO_2-eq/kWh to 45 g CO_2-eq/kWh). **Exhibit 11** at SI36, SI46. To fully analyze the Project's global warming impact in compliance with NEPA, BIA must conduct a life cycle assessment of the Project's GHG emissions.

E. Shadow Flicker Impacts

As discussed in Backcountry's December 21, 2018 Scoping Comments on the Campo Wind Project, wind turbines can produce harmful and annoying "shadow flicker." The DEIS states that "shadow flicker can be avoided by using computer programming to shut turbines off during potential shadow flicker times." DEIS at 136. Yet the DEIS fails to provide *any* substantive information about the program or method used, nor does it include the shadow flicker avoidance programming in any mitigation measure. NEPA requires more. 40 C.F.R. § 1502.24.

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[1] Dolan, Stacey L. & Garvin A. Heath, 2012, "Life Cycle Greenhouse Gas Emissions of Utility-Scale Wind Power: Systematic Review and Harmonization," *Journal of Industrial Ecology*, 16(SI) (attached hereto as **Exhibit 11**).

V. Conclusion

For each of the foregoing reasons, the DEIS is deficient and it must be revised and recirculated.

Respectfully submitted,

Stephan C. Volker
Attorney for Backcountry Against Dumps
and Donna Tisdale

SCV:taf

<u>Attachments</u>:

Exhibit 1 – Walker, Bruce, George F. and David M. Hessler, Rob Rand & Paul Schomer, December 24, 2012, "A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin," Public Service Commission of Wisconsin Report #122412-1.

Exhibit 2 – Dwyer, J.F., M.A. Landon, and E.K. Mojica, 2018, "Impact of Renewable Energy Sources on Birds of Prey," in J.H. Sarasola *et al.* (eds.), 2018, *Birds of Prey*, Springer International Publishing AG.

Exhibit 3 – Fernández-Bellon, D., M.W. Wilson, S. Irwin, and J. O'Halloran, 2018, "Effects of Development of Wind Energy and Associated Changes in Land Use on Bird Densities in Upland Areas," *Conservation Biology* 0(0):1-10.

Exhibit 4 – Preston, Kristine L., et al, 2012, "Changing distribution patterns of an endangered butterfly: Linking local extinction patterns and variable habitat relationships," *Biological Conservation* 152:280–290, 289.

Exhibit 5 – Carman, R.A., July 7, 2019, "Review of Campo Wind Project and Boulder Brush Facilities DEIS Noise Analysis," WI #18-063.

Exhibit 6 – Carman, R.A. and M.A. Amato (Wilson Ihrig), March 18, 2019, "Results of Ambient Noise Measurements of the Existing Kumeyaay Wind and Tule Wind Facilities in the Area of Boulevard and Jacumba Hot Springs Pertaining to the Proposed Torrey and Campo Wind Turbine Facilities."

Exhibit 7 – Carlile, S., J.L. Davy, D. Hillman, and K. Burgemeister, 2018, "A Review of the Possible Perceptual and Physiological Effects of Wind Turbine Noise," *Trends in Hearing* 22:1-10.

Exhibit 8 – O'Neal, Robert D., Robert D. Hellweg, Jr., & Richard M. Lampeter, 2011, "Low frequency noise and infrasound from wind turbines," *Noise Control Engineering Journal*, 59(2): 135-157.

Exhibit 9 – Salt, Alec, and James Kaltenbach, 2011, "Infrasound from Wind Turbines Could Affect Humans," *Bulletin of Science, Technology and Society*, 31(4):296-302.

Exhibit 10 – Snyder, S., July 5, 2019, "Campo Wind Draft Environmental Impact Statement (EIS) with Boulder Brush Facilities Draft EIS Review and Opinion," Project No. 0023.004.

Exhibit 11 – Dolan, Stacey L. & Garvin A. Heath, 2012, "Life Cycle Greenhouse Gas Emissions of Utility-Scale Wind Power: Systematic Review and Harmonization," *Journal of Industrial Ecology*, 16(SI).

EXHIBIT 1
to July 8, 2019
Comments

Report Number 122412-1
Issued: December 24, 2012
Revised:

A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin

Prepared Cooperatively By:

Channel Islands Acoustics, Camarillo, CA
Principal: Dr. Bruce Walker

Hessler Associates, Inc., Haymarket, VA
Principals: George F. and David M. Hessler

Rand Acoustics, Brunswick, ME
Principal: Robert Rand

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Principal: Dr. Paul Schomer

1.0_Introduction

Clean Wisconsin is a nonprofit environmental advocacy organization that works to protect Wisconsin's air and water and to promote clean energy. As such, the organization is generally supportive of wind projects. Clean Wisconsin was retained by the Wisconsin Public Service Commission (PSC) to provide an independent review of a proposed wind farm called the Highlands Project to be located in St. Croix County, WI (WI PSC Docket 2535-CE-100). Clean Wisconsin in turn retained Hessler Associates, Inc. (HAI) to provide technical assistance.

During the course of the hearings, attorneys representing groups opposed to the Highlands project, presented witnesses that lived near or within the Shirley Wind project in Brown County, WI. The Shirley wind project is made up of eight Nordex100 wind turbines that is one of the turbine models being considered for the Highlands projects. These witnesses testified that they and their children have suffered severe adverse health effects to the point that they have abandoned their homes at Shirley. They attribute their problems to arrival of the wind turbines. David Hessler, while testifying for Clean Wisconsin, suggested a sound measurement survey be made at the Shirley project to investigate low frequency noise (LFN) and infrasound (0-20 Hz) in particular.

Partial funding was authorized by the PSC to conduct a survey at Shirley and permission for home entry was granted by the three homeowners. The proposed test plan called for the wind farm owner, Duke Power, to cooperate fully in supplying operational data and by turning off the units for short intervals so the true ON/OFF impact of turbine emissions could be documented. Duke Power declined this request due to the cost burden of lost generation, and the homeowners withdrew their permission at the last moment because no invited experts on their behalf were available to attend the survey.

Clean Wisconsin, their consultants and attorneys for other groups all cooperated and persisted and the survey was rescheduled for December 4 thru 7, 2012. Four acoustical consulting firms would cooperate and jointly conduct and/or observe the survey. Channel Islands Acoustics (ChIA) has derived modest income while Hessler Associates has derived significant income from wind turbine development projects. Rand Acoustics is almost exclusively retained by opponents of wind projects. Schomer and Associates have worked about equally for both proponents and opponents of wind turbine projects. However, all of the firms are pro-wind if proper siting limits for noise are considered in the project design.

The measurement survey was conducted on schedule and this report is organized to include four Appendices A thru D where each firm submitted on their own letterhead a report summarizing their findings. Based on this body of work, a consensus is formed where possible to report or opine on the following:

- Measured LFN and infrasound documentation
- Observations of the five investigators on the perception of LFN and infrasound both outside and inside the three residences.
- Observations of the five investigators on any health effects suffered during and after the 3 to 4 day exposure.
- Recommendations with two choices to the PSC for the proposed Highlands project
- Recommendations to the PSC for the existing Shirley project

2.0_Testing Objectives

Bruce Walker employed a custom designed multi-channel data acquisition system to measure sound pressure in the time domain at a sampling rate of 24,000/second where all is collected under the same clock. The system is calibrated accurate from 0.1 Hz thru 10,000 Hz. At each residence, channels were cabled to an outside wind-speed anemometer and a microphone mounted on a ground plane covered with a 3 inch hemispherical wind screen that in turn was covered with an 18 inch diameter and 2 inch thick foam hemispherical dome (foam dome). Other channels inside each residence were in various rooms including basements, living or great rooms, office/study, kitchens and bedrooms. The objective of this set-up was to gather sufficient data for applying advanced signal processing techniques. See Appendix A for a Summary of this testing.

George and David Hessler employed four off-the-shelf type 1 precision sound level meter/frequency analyzers with a rated accuracy of +/- 1 dB from 5 Hz to 10,000 Hz. Two of the meters were used as continuous monitors to record statistical metrics for every 10 minute interval over the 3 day period. One location on property with permission was relatively close (200m) to a wind turbine but remote from the local road network to serve as an indicator of wind turbine load, ON/OFF times and a crude measure of high elevation wind speed. See cover photo. This was to compensate for lack of Duke Power's cooperation. The other logging meter was employed at residence R2, the residence with the closest turbines. The other two meters were used to simultaneously measure outside and inside each residence for a late night and early morning period to assess the spectral data. See Appendix B for a Summary of this testing.

Robert Rand observed measurements and documented neighbor reports and unusual negative health effects including nausea, dizziness and headache. He used a highly accurate seismometer to detect infrasonic pressure modulations from wind turbine to residence. See Appendix C for Rob's Summary.

Paul Schomer used a frequency spectrum analyzer as an oscilloscope wired into Bruce's system to detect in real time any interesting occurrences. Paul mainly circulated around observing results and questioning and suggesting measurement points and techniques. See Appendix D for Paul's Summary.

Measurements were made at three unoccupied residences labeled R1, R2 and R3 on Figure 2.1. The figure shows only the five closest wind turbines and other measurement locations. All in all, the investigators worked very well together and there is no question or dispute whatsoever about measurement systems or technique and competencies of personnel. Of course, conclusions from the data could differ. Mr. M. Hankard, acoustical consultant for the Highland and Shirley projects, accompanied, assisted and observed the investigators on Wednesday, 12/5.

Figure 2.1: *Aerial view showing sound survey locations*

The four firms wish to thank and acknowledge the extraordinary cooperation given to us by the residence owners and various attorneys.

3.0_Investgator Observations

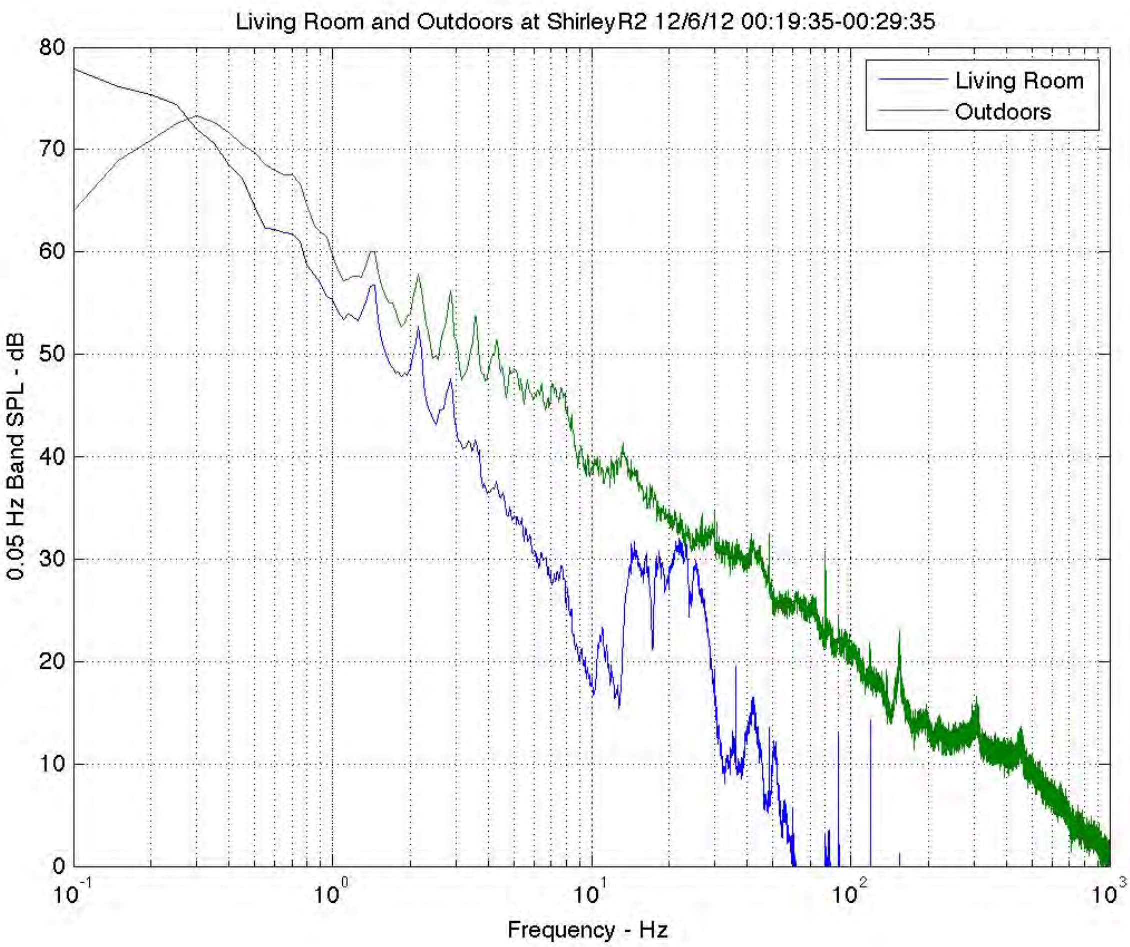
Observations from the five investigators are tabulated below: It should be noted the investigators had a relatively brief exposure compared to 24/7 occupation.

AUDIBILITY OUTSIDE RESIDENCES	
	Observations
Bruce Walker	Could detect wind turbine noise at R1, easily at R2, but not at all at R3
George Hessler	Could detect wind turbine noise at R1, easily at R2, but not at all at R3
David Hessler	Could detect wind turbine noise at R1, easily at R2, but not at all at R3
Robert Rand	Could detect wind turbine noise at all residences
Paul Schomer	Not sure at R1 but could detect wind turbine noise at R2, not at all at R3
AUDIBILITY INSIDE RESIDENCES	
	Observations
Bruce Walker	Could not detect wind turbine noise inside any home
George Hessler	Could not detect wind turbine noise inside any home
David Hessler	Could faintly detect wind turbine noise in residence R2
Robert Rand	Could detect wind turbine noise inside all three homes
Paul Schomer	Could not detect wind turbine noise inside any home
EXPERIENCED HEALTH EFFECTS	
	Observations
Bruce Walker	No effects during or after testing
George Hessler	No effects during or after testing
David Hessler	No effects during or after testing
Robert Rand	Reported ill effects (headache and/or nausea while testing and severe effects for 3+ days after testing
Paul Schomer	No effects during or after testing

4.0_Conclusions

This cooperative effort has made a good start in quantifying low frequency and infrasound from wind turbines.

Unequivocal measurements at the closest residence R2 are detailed herein showing that wind turbine noise is present outside and inside the residence. Any mechanical device has a unique frequency spectrum, and a wind turbine is simply a very very large fan and the blade passing frequency is easily calculated by RPM/60 x the number of blades, and for this case; 14 RPM/60 x 3 = 0.7 Hz. The next six harmonics are 1.4, 2.1, 2.8, 3.5, 4.2 & 4.9 Hz and are clearly evident on the attached graph below. Note also there is higher infrasound and LFN inside the residence in the range of 15 to 30 Hz that is attributable to the natural flexibility of typical home construction walls. This higher frequency reduces in the basement where the propagation path is through the walls plus floor construction but the tones do not reduce appreciably.



Measurements at the other residences R1 and R3 do not show this same result because the increased distance reduced periodic turbine noise closer to the background and/or turbine loads at the time of these measurements resulted in reduced acoustical emission. Future testing should be sufficiently extensive to cover overlapping turbine conditions to determine the decay rate with distance for this ultra low frequency range, or the magnitude of measurable wind turbine noise with distance.

The critical questions are what physical effects do these low frequencies have on residents and what LFN limits, if any, should be imposed on wind turbine projects. The reported response at residence R2 by the wife and their child was extremely adverse while the husband suffered no ill effects whatsoever, illustrating the complexity of the issue. The family moved far away for a solution.

A most interesting study in 1986 by the Navy reveals that physical vibration of pilots in flight simulators induced motion sickness when the vibration frequency was in the range of 0.05 to 0.9 Hz with the maximum (worst) effect being at about 0.2 Hz, not too far from the blade passing frequency of future large wind turbines. If one makes the leap from physical vibration of the body to physical vibration of the media the body is in, it suggests adverse response to wind turbines is an acceleration or vibration problem in the very low frequency region.

The four investigating firms are of the opinion that enough evidence and hypotheses have been given herein to classify LFN and infrasound as a serious issue, possibly affecting the future of the industry. It should be addressed beyond the present practice of showing that wind turbine levels are magnitudes below the threshold of hearing at low frequencies.

5.0_Recommendations

5.1_General

We recommend additional study on an urgent priority basis, specifically:

- A comprehensive literature search far beyond the search performed here under time constraints.
- A retest at Shirley to determine the decay rate of ultra low frequency wind turbine sound with distance with a more portable system for measuring nearly simultaneously at the three homes and at other locations.
- A Threshold of Perception test with participating and non-participating Shirley residents.

5.2_For the Highlands Project

ChIA and Rand do not have detail knowledge of the Highland project and refrain from specific recommendations. They agree in principle to the conclusions offered herein in Section 4.0.

Hessler Associates has summarized their experience with wind turbines to date in a peer-reviewed Journal[1] and have concluded that adverse impact is minimized if a design goal of 40 dBA (long term average) is maintained at all residences, at least at all non-participating residences. To the best of their knowledge, essentially no annoyance complaints and certainly no severe health effect complaints, as reported at Shirley, have been made known to them for *all* projects designed to this goal.

[1] Hessler G., & David, M., "Recommended noise level design goals and limits at residential receptors for wind turbine developments in the United States", Noise Control Engineering Journal, 59(1), Jan-Feb 2011

Schomer and Associates, using an entirely different approach have concluded that a design goal of 39 dBA is adequate to minimize impact, at least for an audible noise impact. In fact, a co-authored paper[2] is planned for an upcoming technical conference in Montreal, Canada.

Although there is no explicit limit for LFN and infrasound in these A-weighted sound levels above, the spectral shape of wind turbines is known and the C-A level difference will be well below the normally accepted difference of 15 to 20 dB. It may come to be that this metric is not adequate for wind turbine work but will be used for the time being.

Based on the above, Hessler Associates recommends approval of the application if the following Noise condition is placed on approval:

> With the Hessler recommendation, the long-term-average (2 week sample) design goal for sound emissions attributable to the array of wind turbines, exclusive of the background ambient, at all non-participating residences shall be 39.5 dBA or less.

Schomer and Associates recommends that the additional testing listed in 5.3 be done at Shirley on a very expedited basis with required support by Duke Energy prior to making a decision on the Highlands project. It is essential to know whether or not some individuals can perceive the wind turbine operation at R1 or R3. With proper resources and support, these studies could be completed by late February or early March. If a decision cannot be postponed, then Schomer and Associates recommends a criterion level of 33.5 dB. The Navy's prediction of the nauseogenic region (Schomer Figure 6 herein) indicates a 6 dB decrease in the criterion level for a doubling of power such as from 1.25 MW to 2.5 MW.

> With the Schomer recommendation, and in the presence of a forced decision, the long-term-average (2 week sample) design goal for sound emissions attributable to the array of wind turbines, exclusive of the background ambient, at all non-participating residences shall be 33.5 dBA or less.

There is one qualifier to this recommendation. The Shirley project is unique to the experience of the two firms in that the Nordex100 turbines are very high rated units (2.5 MW) essentially not included in our past experiences. HAI has completed just one project, ironically named the Highlands project in another state that uses both Nordex 90 and Nordex 100 units in two phases. There is a densely occupied Town located 1700 feet from the closest Nordex 100 turbine. The president and managers of the wind turbine company report "no noise issues at the site".

Imposing a noise limit of less than 45 dBA will increase the buffer distances from turbines to houses or reduce the number of turbines so that the Highlands project will *not* be an exact duplication of the Shirley project. For example, the measured noise level at R2 is approximately 10 dBA higher than the recommendation resulting in a subjective response to audible outside noise as twice as loud. Measured levels at R1 and R3 would comply with the recommendation.

We understand that the recommended goal is lower than the limit of 45 dBA now legislated, and may make the project economically unviable. In this specific case, it seems justified to the two firms to be conservative (one more than the other) to avoid a duplicate project to Shirley at Highlands because there is no technical reason to believe the community response would be different.

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[2] Schomer, P. & Hessler, G., "Criteria for wind-turbine noise immissions", ICA, Montreal, Canada 2013

5.3_For the Shirley Project

The completed testing was extremely helpful and a good start to uncover the cause of such severe adverse impact reported at this site. The issue is complex and relatively new. Such reported adverse response is sparse or non-existent in the peer-reviewed literature. At least one accepted paper at a technical conference[3] has been presented. There are also self-published reports on the internet along with much erroneous data based on outdated early wind turbine experience.

A serious literature search and review is needed and is strongly recommended. Paul Schomer, in the brief amount of time for this project analysis, has uncovered some research that *may* provide a probable cause or direction to study for the reported adverse health effects. We could be close to identifying a documented cause for the reported complaints but it involves much more serious impartial effort.

An important finding on this survey was that the cooperation of the wind farm operator is absolutely essential. Wind turbines must be measured both ON and OFF on request to obtain data under nearly identical wind and power conditions to quantify the wind turbine impact which could not be done due to Duke Power's lack of cooperation.

We strongly recommend additional testing at Shirley. The multi-channel simultaneous data acquisition system is normally deployed within a mini-van and can be used to measure immissions at the three residences under the identical or near identical wind and power conditions. In addition, seismic accelerometer and dedicated ear-simulating microphones can be easily accommodated. And, ON/OFF measurements require the cooperation of the operator.

Since the problem may be devoid of audible noise, we also recommend a test as described by Schomer in Appendix D to develop a "Threshold of Perception" for wind turbine emissions.

Bruce Walker

George F. Hessler Jr.

David M. Hessler

Robert Rand

Paul Schomer

[3] Ambrose, S. E., Rand, R. W., Krogh, C. M., "Falmouth, Massachusetts wind turbine infrasound and low frequency noise measurements", Proceedings of Inter-Noise 2012, New York, NY, August 19-22.

APPENDIX A
by
CHANNEL ISLANDS ACOUSTICS

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Low Frequency Acoustic Measurements at Shirley Wind Park

Bruce Walker, Ph.D., INCE Bd. Cert.

OVERVIEW

Bruce Walker of Channel Islands Acoustics (ChIA) was requested by Hessler Associates to assist in defining low and infrasonic frequency (approximately 0.5 – 100 Hz) sounds at abandoned residences in the environs of Shirley Wind Park near DePere, WI. ChIA has been developing a measurement system that combines extended range microphones and recording equipment with mixed time domain and frequency domain signal processing in an effort to quantify sound levels and waveform properties of very low frequency periodic signals radiated by large wind turbines[i] .

The Shirley Wind park consists of eight Nordex turbines with 85 meter hub height and 100 meter rotor diameter. These turbines are distributed over an approximately six square mile area in Brown County, WI as shown in Figure 1. The turbines are of similar in size to those investigated in Ref. 1.

Figure 1. Environs of Shirley Wind Park, Showing Eight Turbines and Three Abandoned Residences Investigated in the Program

The tests included acoustic measurement at multiple locations inside and outside three abandoned residences, at nominal distances and bearings from the three turbines as shown in Table **1**, and will be described in greater detail in a subsequent section. Test methodology and schedule were constrained to a testing period December 4-7 and inability to park the turbines to establish a reliable background noise baseline.

Table 1. Distances in feet and Bearing in degrees East of North from Turbines to Tested Residences

Receiver	R1		R2		R3	
Source	Distance	Bearing	Distance	Bearing	Distance	Bearing
WTG1	18300	74	15400	53	12250	31
WTG2	18050	78	14800	57	11300	34
WTG3	6270	82	5290	11	8140	322
WTG4	5070	63	6650	353	10330	319
WTG5	3990	93	4330	343	9020	307
WTG6	3303	72	5810	338	10470	309
WTG7	4870	141	2280	286	8360	282
WTG8	5540	127	1280	322	7110	288

ChIA measurements were conducted at residence R1 (Fairview) on the evening of December 4 and the early afternoon of December 5. Measurements were conducted at residence R2 (Glenmore) during late evening and late night December 5/early morning December 6 and mid-afternoon December 6. Measurements were conducted at residence R3 (Schmidt) during late afternoon December 6 and mid-morning December 7. Times of tests are mean wind speeds are shown in Table **3**.

TERMINOLOGY

It is assumed the reader is familiar with commonly encountered acoustical terms and units such as decibel (dB), sound level, sound pressure level, sound power level, spectrum, frequency, hertz (Hz), etc. The following is a brief glossary of terms and units that lay-persons may not be familiar with, but which will be used to describe some of the data analyses in this program.

pascals (Pa) – the standard unit of pressure. The reference sound pressure is 20 microPa. Atmospheric pressure is just over 100,000 Pa. An acoustic signal of 1 Pa rms amplitude has a sound pressure level of 94 dB.

correlation function (CC(τ)) – a time-domain description of the commonality between two signals as a function of the time delay between them. The unit is Pa-squared. The correlation function for a signal and itself is the auto-correlation, and the rms amplitude of the signal is the square-root of the auto-correlation at zero delay. The correlation function between separate signals is the cross-correlation. The peak delay of the cross-correlation time the speed of propagation shows the difference in path length between the two signals if they result from a common source. The **correlation coefficient** is the cross-correlation function divided by the product of the square roots of the auto-correlation at zero delay.

power spectral density function (PSD) – the average of the squared-magnitude of the frequency spectrum of a time-varying signal, divided by the nominal bandwidth (BW in Hz) of the spectral analysis. The unit is Pa-squared per Hz. Narrow band sound pressure levels in this report are computed in dB as 10 log(PSD x BW) + 94.

cross-PSD – the frequency-by-frequency average of the products of the spectra from two signals.

coherence function - a frequency-domain description of the relative commonality between two signals. It is determined as the frequency-by-frequency ratio of the cross-PSD to the product of the square roots of the two PSD's. If a spectral component in two signals results from a common source, the coherence is unity (1) and if the spectral component results from two statistically independent sources, the coherence is zero.

spectrograph – a display of amplitude as color or brightness vs frequency and time.

MEASUREMENT SYSTEM and DATA ACQUISITION

A basic list of the components in the measurement system are shown in Table **2**. Serial numbers and calibration certifications are available on request.

Table 2. Basic Components of ChIA Low-Frequency Acoustic Data Acquisition System

Item	Type	Number
Portable Acoustic Analyzer	B&K 2250	2
Low Frequency Microphone	B&K 4193	6
Microphone Preamp	B&K 2639	4
Signal Conditioning Amp	B&K NEXUS 2690-OS4	1
24 Bit Simultaneous ADC	DT9826-16	1
Laptop Computer	Acer	1
Calibrator	B&K 4231	1
Anemometer	NRG Cup & Resolver	1

As deployed in this program, the 4193 microphones with low-frequency extensions, 2639 preamplifiers and NEXUS signal conditioner were placed in three or four rooms of the residences, while a fifth 4193 and a 2250 analyzer was placed in a standard 3-1/2 inch hemisphere wind ball under an 18 inch foam secondary wind screen on a ground board approximately 50 ft from the residence in the direction of wind turbines. The sixth 4193 and second 2250 were held in reserve and ultimately deployed at R3 on December 7. Full system throughput calibration was run for all channels each day and after each equipment relocation.

Measurement data was collected with simultaneous in 10-minute blocks at sampling rate 24 kHz as shown in the Test Log, Table **3**. The signal conditioning amplifiers were set for range 0.1 Hz to 10 kHz. Amplifier sensitivities were set to allow sound pressures up to 10 Pa (114 dB) to be accepted without system overload. The output of the NRG cup anemometer/resolver was recorded on a seventh channel of the recording system. Acoustic signals, wind speed signals, set-up conditions and microphone location descriptions were stored in Matlab mat files and portions of the recorded signal were displayed for signal quality examination.

Table 3. Summary Test Log

Channel	1	2	3	4	5	6	7	Date	Start Time
Location R1	Study Desk	MBR Bedhead	Kitchen Counter	Outside Wall	Outside Ground Board	No Signal	Wind		
04T182504							2.3	12/4/12	20:25:04
04T184332							2.2	12/4/12	20:43:32
04T191533							3.2	12/4/12	21:15:33
04T192808							2.8	12/4/12	21:28:08
05T102032							1.2	12/5/12	12:20:32
05T110121							1.4	12/5/12	13:10:21
05T112110							1.5	12/5/12	13:21:10
Location R2	Living Room	Upstairs BR	Behind Kitchen	Basement	Outside Ground Board	No Signal	Wind		
05T204657								12/5/12	22:46:57
05T212420								12/5/12	23:24:20
05T213611							2.3	12/5/12	23:36:11
05T221935							3.0	12/6/12	0:19:35
05T231754							3.2	12/6/12	1:17:54
06T001413							3.3	12/6/12	2:14:13
06T120621							2.1	12/6/12	14:06:21
06T122547							1.7	12/6/12	14:25:47
Location R3	Family Room	Upstairs BR	Living Room	Basement	Outside Ground Board	No Signal	Wind		
06T135713							2.8	12/6/12	15:57:13
06T142857							2.4	12/6/12	16:28:57
Location R3	Family Room	Upstairs BR	Living Room	No Signal	Outside Ground Board	Isotron 86 on K Island	Wind		
07T092024							1.1	12/7/12	11:20:24
Location R3	Family Room	Upstairs BR	No Signal	Basement	Outside Ground Board	Living Room 2250	Wind		
07T094616							0.9	12/7/12	11:46:16
07T100232							1.1	12/7/12	12:02:32
	Note Blue = Chevy SUV Front Seat								
	Note Red = Problem Data								
	Note Gray = Channel Not Used								

DATA ANALYSIS

For each ten-minute data block, the following computed values were obtained and stored:

1. For each data channel, the time history of the signal, phaseless band pass filtered from 0.5 to 100 Hz, the time histories of Leq100ms for A, C, Z, G and 0.5-100 Hz bandpass filtering.
2. For each data channel, the 0.1 Hz narrow band and one-third octave frequency spectra covering the range 0.5 to 1,000 Hz, and the coherence function between the outdoor microphone and each indoor microphone.
3. For each data channel, the auto-correlation function and the cross correlation function from the outdoor microphone to each indoor microphone for the delay range -10 to +10 seconds.

It was observed in the time history plots that "high intensity" regions in the indoor and outdoor microphone channels were not necessarily aligned in time, possibly indicating that indoor noise sometimes resulted from sources other than those affecting the outdoor microphone. To study this in additional detail, each 10-minute data block was analyzed in 20-second sub-blocks for narrow-band frequency spectrum, cross-spectrum with the outdoor microphone and coherence with the outdoor microphone.

Following this, the spectrum with the most distinct representation of turbine blade passage pulsation was identified. From the Blade Passage harmonic series noted for this spectrum, waveforms were synthesized assuming two sets of phase relationships. In the first, the harmonics were arranged as sine waves with zero phase. In the second, they were arranged as cosine waves with zero phase. The former produces a composite wave with maximum wavefront slope while the latter produces a composite wave with maximum peak-to-rms ratio (crest factor).

RESULTS EXAMPLES

The test produced a large compendium of testing results, which, it is hoped, can be correlated with turbine operating conditions from data yet to be received. Mean local wind speeds for all blocks are shown (meters per second) in Table **3.** Illustrative examples showing disparities among the three residences are shown in the following graphs. The full set of data is available for review.

Figure **2** shows a sample of raw data collected during windy conditions at Residence R2. Note that apparently wind-driven very low frequency pressure fluctuations are well synchronized and nearly equal in amplitude at four disparate locations within the home.

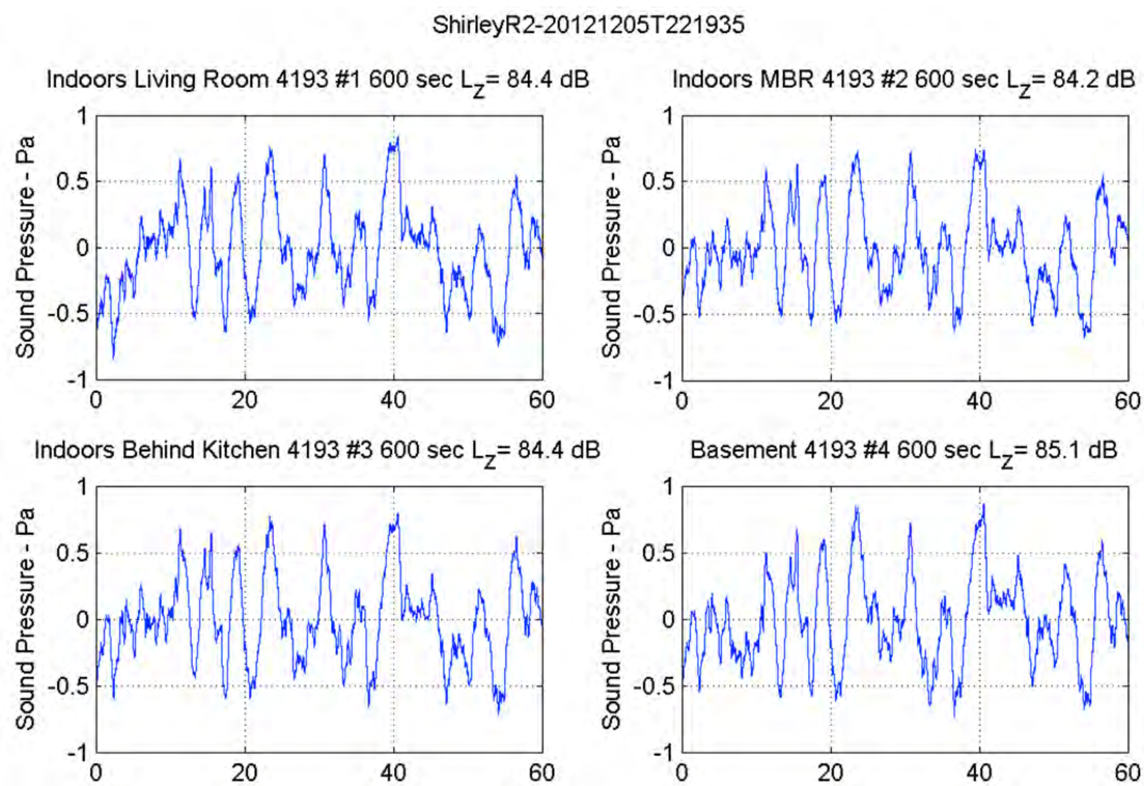

Figure 2. First Minute of Raw Data Collected at R2 On Dec 6 Starting 00:19:35. Note very low frequency fluctuations are nearly equal at four locations.

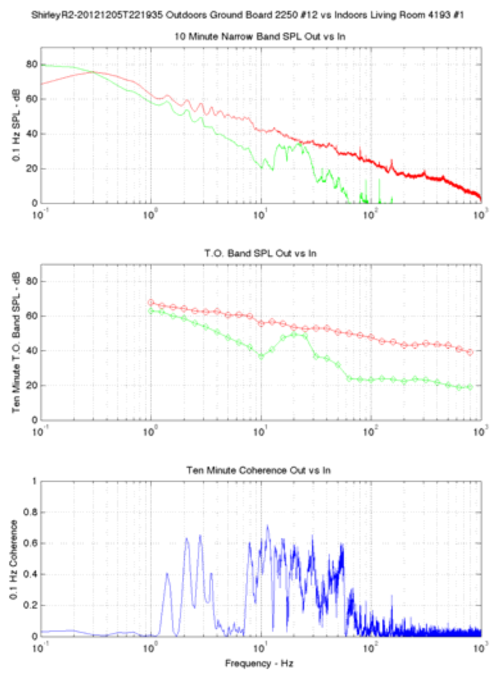

Figure 3. Low Frequency (0.1-1,000 Hz) Spectra and Coherence from Two Rooms in R2 measured 12/6/12 starting 00:19:35 showing differences in detail and well correlated low-order blade-pass harmonics. Red curve is measured outdoors between turbines and home.

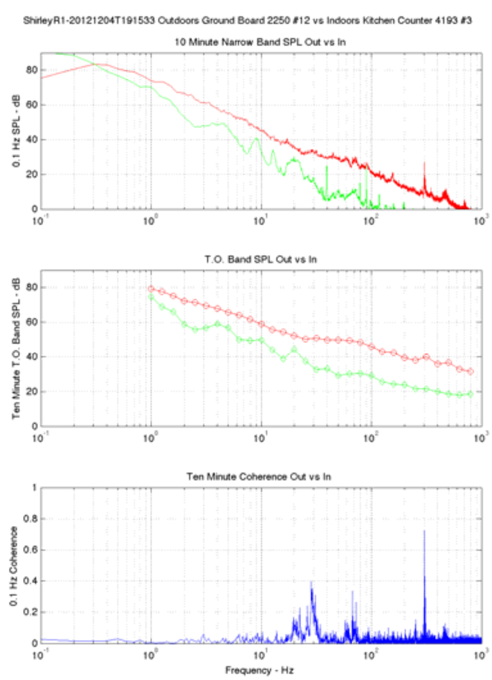

Figure 4. Low Frequency (0.1-1,000 Hz) Spectra and Coherence from Two Rooms in R1 measured 12/4/12 starting 21:15:33 showing differences in detail and poorly correlated low-order blade-pass harmonics. Red curve is measured outdoors between turbines and home.

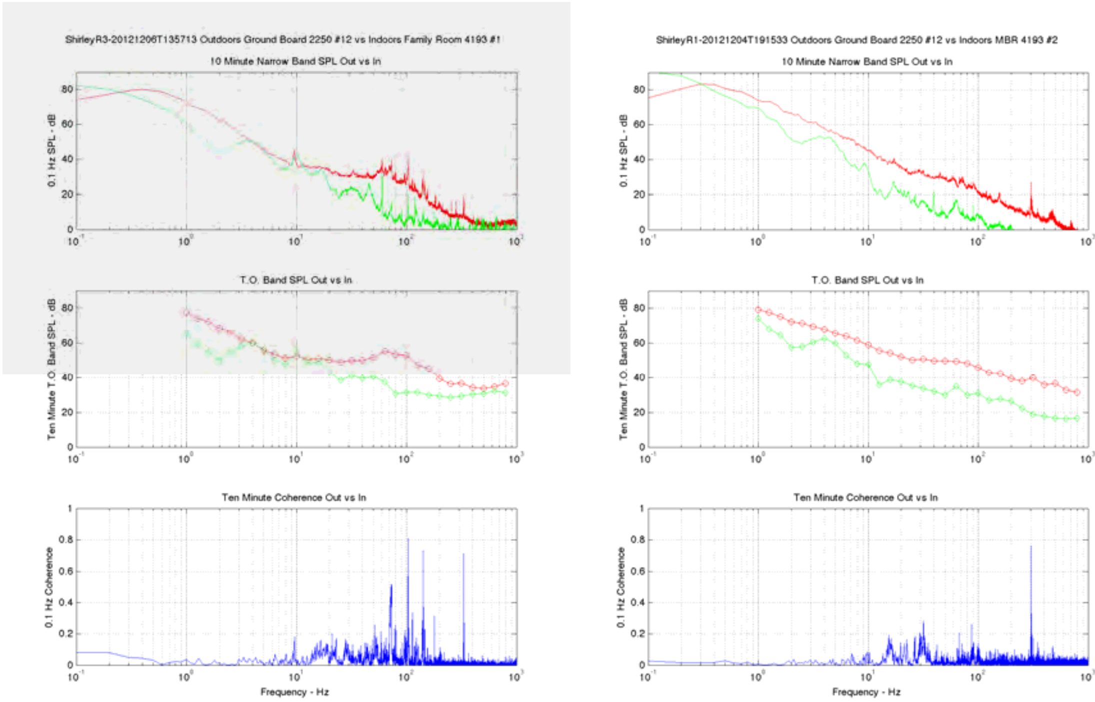

Figure 5. Low Frequency (0.1-1,000 Hz) Spectra and Coherence from Two Rooms in R3 measured 12/6/12 starting 15:57:13 showing differences in detail, poorly correlated low-order blade-pass harmonics and well correlated tones from passing vehicle exhausts. Red curve is measured outdoors between turbines and home.

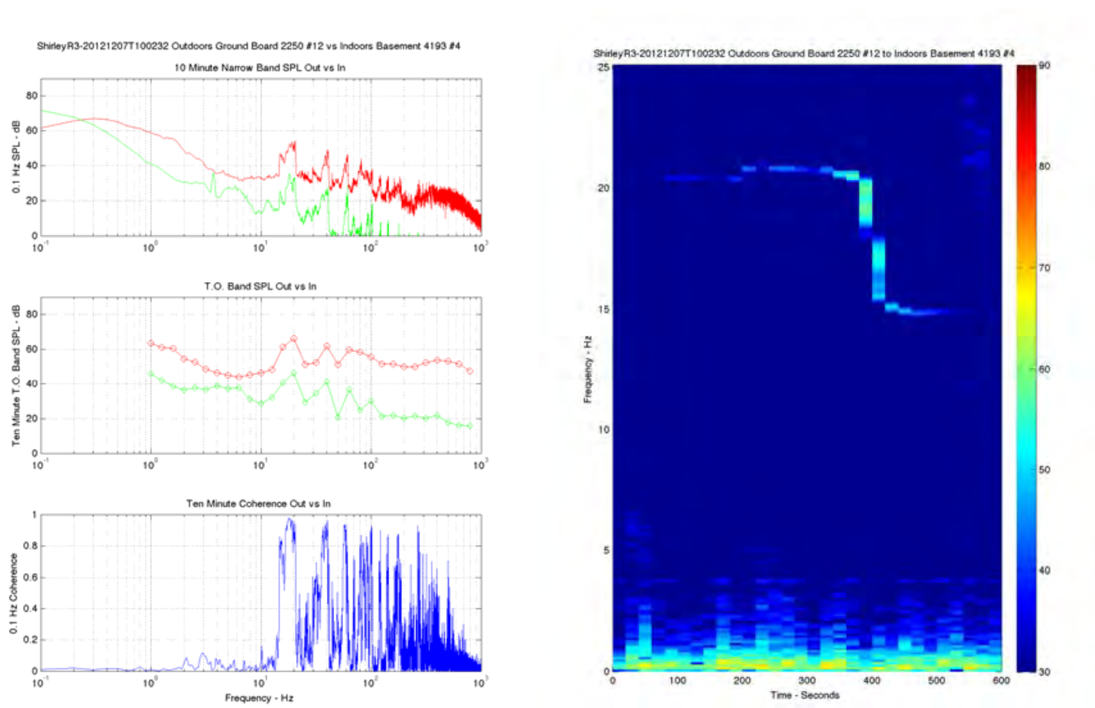

Figure 6. Low Frequency Spectra and Outdoor-Indoor Cross Spectrograph in Basement of R3 with Helicopter flyover. Note Doppler shift of rotor tone from 20.5 Hz on approach to 15 Hz receding. Also note high coherence of the helicopter rotor blade harmonics. Note very low coherence of turbine blade frequencies below 10 Hz, suggesting most of the infrasound is general atmospheric pressure fluctuation and wind force on the residence.

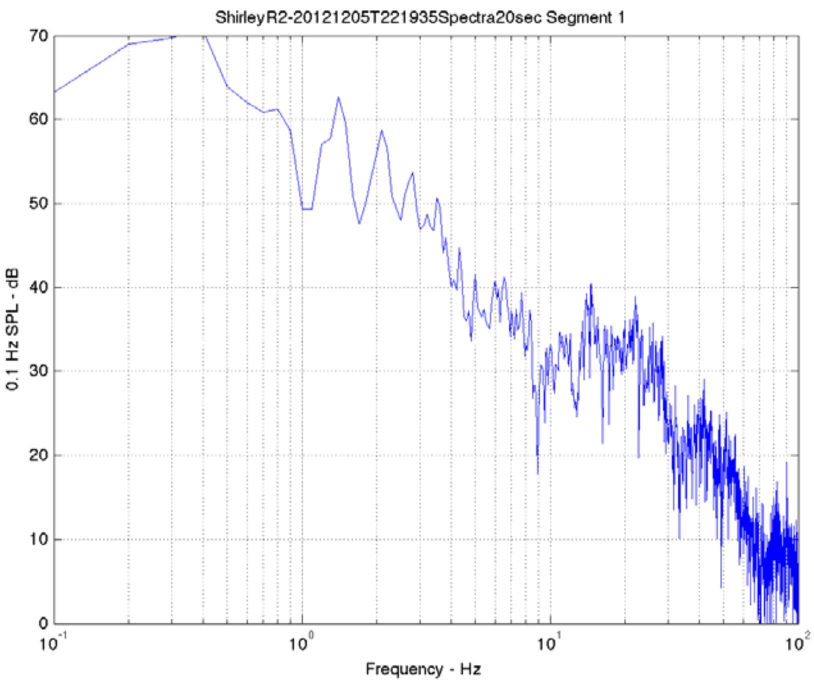

Figure 7. Short (20 sec) duration spectrum with best defined turbine blade harmonics, multiples of 0.7 Hz. Overall SPL of the Blade Pass Signal is 70 dB.

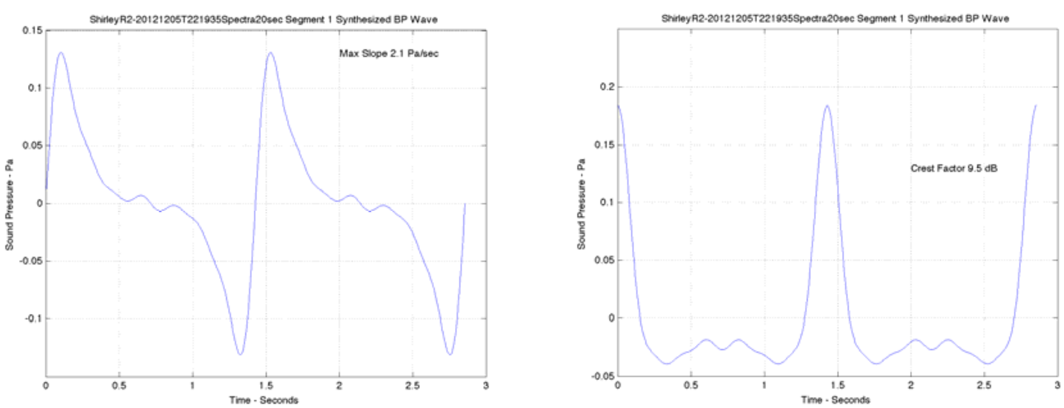

Figure 8. Turbine blade-pass waveforms synthesized from the harmonic series shown in Figure 7. Peak-to-peak SPL of the left-hand, more probable signal is about 82 dB.

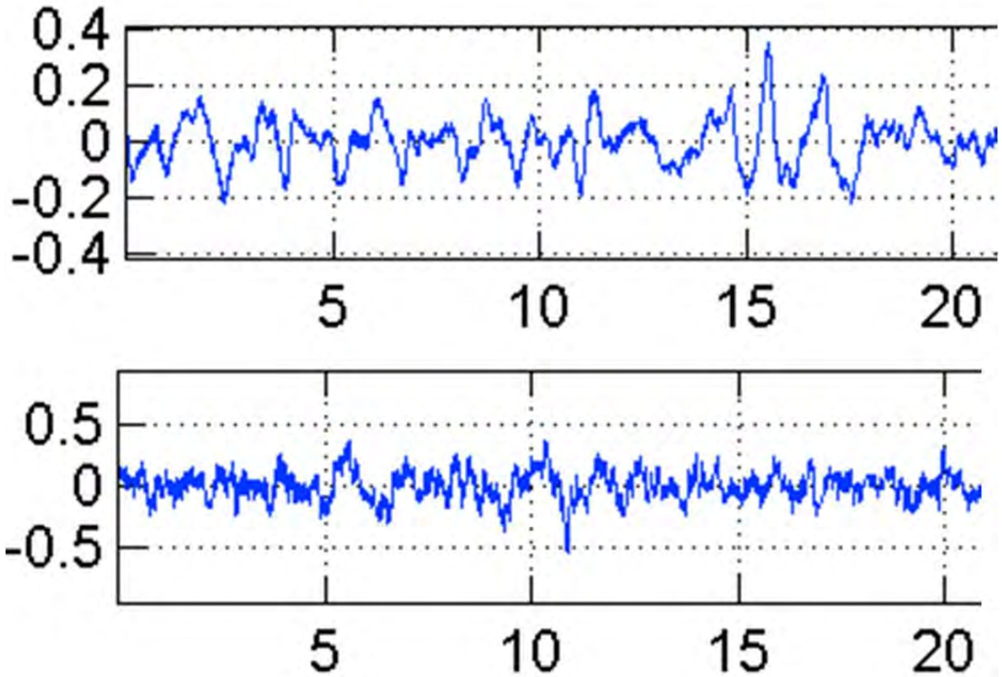

Figure 9. 0.5 Hz Phaseless High-Pass Filtered Waves Indoors (upper) and Outdoors at R2, Corresponding to Spectrum of Figure 7. Note repetitive waves indoors, similar to left-hand synthesized example. Note transient event indoors at 15.5 seconds unrelated to outside noise.

A summary of statistical sound levels for each test is shown in Table **4.** Note that the high frequency noise floor of the low-frequency microphones used indoors limits the A-weighted results to 29-30 dB minimum. The cells marked in red were affected by system overload or other problems and should be discounted. The cells marked in gold are for a seismic accelerometer mounted on the Kitchen island of R3 and are not calibrated except that 94 dB is approximately 1 m/sec^2. The cells marked in teal are taken on the front seat of the Mini-SUV parked outside R2. All others are normal measurements as shown in the Log, Table **3.**

Table 4. Statistical Sound Levels for All 10-minute Tests

Shirley	Weight	LA						LC						LZ						LG						L_0.5-100					
ChIA	Channel	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
R1	L1	36.9	32.3	42.4	54.0	43.6		52.5	49.2	53.0	72.0	62.5		93.7	93.5	93.8	111.9	93.4		67.5	67.1	68.3	87.5	72.4		80.7	79.8	80.1	94.9	90.2	
12/4/12	L10	33.7	30.5	34.6	37.7	42.4		50.7	42.9	46.2	60.0	56.2		89.5	89.1	89.4	94.4	86.1		63.9	63.0	64.1	73.0	66.5		74.7	73.7	73.8	82.4	82.1	
20:43:32	L50	33.2	30.1	30.3	32.3	41.5		48.9	39.8	42.7	48.5	53.9		80.6	80.0	80.5	84.7	75.7		58.6	55.7	58.3	62.0	61.6		66.1	65.2	65.2	71.0	70.9	
20:53:32	L90	32.6	29.8	29.6	31.0	41.0		47.2	37.5	40.0	45.5	52.1		67.7	67.0	67.2	71.3	64.5		53.9	49.7	53.2	55.3	57.3		58.5	56.3	56.5	59.7	62.0	
2.2 mps	Leq	33.9	30.2	32.9	76.2	41.7		49.2	41.2	44.4	94.9	55.1		85.0	84.6	85.0	102.6	82.8		60.4	58.9	60.6	89.4	64.2		70.8	69.8	69.9	98.0	79.2	
R1	L1	36.1	32.6	34.8	66.9	49.6		53.2	51.1	50.8	85.3	68.4		104.1	104.0	104.3	112.9	102.6		77.3	77.2	77.5	92.7	79.2		90.7	89.7	90.0	104.1	97.4	
12/4/12	L10	34.0	31.2	30.7	54.8	45.3		51.2	47.2	47.1	76.3	59.8		98.6	98.5	98.8	107.3	94.0		71.9	71.7	72.1	85.7	71.6		84.1	83.3	83.6	96.7	89.6	
21:15:33	L50	33.5	30.3	29.8	44.7	42.2		49.5	42.7	43.5	64.1	55.8		89.8	89.7	90.0	99.0	84.0		64.1	63.3	64.0	77.6	64.7		75.0	74.3	74.4	87.3	78.7	
21:25:33	L90	33.2	29.9	29.4	41.8	41.4		47.9	39.5	40.6	57.6	53.5		76.4	76.2	76.6	86.2	71.5		57.3	54.1	56.2	69.7	59.6		64.8	63.8	63.9	76.7	67.6	
3.2 mps	Leq	35.9	33.7	34.1	54.0	43.5		50.7	46.4	47.0	73.1	58.6		94.6	94.4	94.7	103.2	90.8		68.2	67.9	68.4	82.3	69.2		80.2	79.4	79.6	93.1	86.0	
R1	L1	34.9	32.4	34.4	64.2	51.9		50.4	48.0	48.2	83.5	66.2		100.6	100.4	100.7	111.5	98.4		73.7	73.6	74.0	91.1	75.6		86.4	85.4	85.7	102.0	94.1	
12/4/12	L10	32.5	30.6	30.4	52.6	43.8		48.7	44.5	44.8	75.1	58.8		95.9	95.7	96.0	106.0	91.3		69.1	69.0	69.3	84.4	68.6		80.7	80.0	80.1	94.8	86.4	
21:28:08	L50	32.2	30.1	29.7	43.2	41.7		47.4	41.0	41.5	62.4	54.7		87.7	87.6	87.8	96.7	80.9		61.6	61.2	61.9	75.8	63.0		72.1	71.5	71.5	85.0	75.5	
21:38:08	L90	32.0	29.8	29.0	40.8	41.0		46.2	38.2	38.4	56.4	52.6		74.1	74.1	74.2	83.6	68.6		53.8	52.3	54.5	67.8	58.3		61.5	61.1	60.8	73.8	64.5	
2.8 mps	Leq	32.7	30.3	30.0	51.9	43.2		47.6	42.0	42.4	71.6	57.1		91.6	91.4	91.7	101.7	87.6		65.0	64.8	65.3	80.8	66.2		76.7	75.9	76.0	91.1	82.8	
R1	L1	36.5	36.8	47.5	56.9	44.4		56.9	57.5	63.4	72.7	59.9		96.6	96.2	96.4	92.9	87.4		71.3	71.4	76.8	73.9	68.8		83.9	83.0	83.4	76.0	82.5	
12/5/12	L10	31.9	31.2	39.1	38.7	41.0		48.4	45.8	50.2	60.9	57.8		90.5	90.1	90.5	85.0	78.9		65.2	64.8	67.0	70.2	66.2		76.8	76.0	76.3	67.5	71.7	
12:30:22	L50	31.3	30.1	30.8	37.4	40.4		46.0	41.5	44.7	58.6	55.8		79.8	79.3	80.1	75.5	68.2		57.8	56.4	60.2	66.5	62.2		65.5	64.7	64.8	64.1	63.0	
12:40:22	L90	31.0	29.7	29.3	36.7	40.0		44.2	38.9	40.9	56.3	53.7		67.2	65.8	66.2	65.8	60.9		52.8	50.6	55.2	62.3	57.8		55.6	54.8	55.6	61.1	59.0	
1.2 mps	Leq	32.1	31.0	37.0	53.4	40.8		47.6	45.8	51.0	70.0	56.1		86.1	85.8	86.2	81.8	75.9		61.7	61.5	65.8	69.4	63.2		73.2	72.3	72.6	71.5	70.4	
R1	L1	46.2	30.8	35.0	41.3	42.1		56.0	45.3	49.1	63.0	60.2		83.5	82.6	83.6	89.6	89.9		66.6	58.2	63.0	73.1	69.6		72.6	69.2	69.4	72.1	84.4	
12/5/12	L10	37.3	30.2	30.7	39.7	41.0		53.5	43.1	46.6	61.3	58.4		79.4	78.2	78.7	81.9	82.9		60.6	55.5	60.3	70.6	67.0		64.7	63.0	62.8	67.9	76.5	
13:01:21	L50	36.3	29.9	29.6	38.7	40.6		52.3	40.9	43.4	59.1	56.5		71.2	69.8	69.9	73.8	72.4		56.6	51.8	56.3	66.8	63.0		59.2	56.4	56.3	64.9	66.4	
13:11:21	L90	35.9	29.7	29.2	38.0	40.2		51.3	38.7	40.5	56.9	54.4		59.8	57.4	57.9	65.3	62.7		52.1	47.7	51.7	62.5	58.5		55.1	49.9	51.1	62.0	60.7	
1.4 mps	Leq	40.3	30.0	30.4	39.0	40.7		53.4	41.3	44.2	59.5	56.7		75.0	73.9	74.4	78.8	79.1		59.4	52.7	57.3	67.7	64.0		62.8	59.7	59.8	65.9	73.2	
R1	L1	42.0	44.9	55.5	47.3	58.3		59.4	58.9	64.6	63.9	65.6		100.7	99.0	99.2	88.8	88.2		76.2	73.0	76.0	72.7	68.8		89.8	87.0	87.4	74.4	82.0	
12/5/12	L10	39.9	33.0	41.0	41.0	42.5		56.4	49.1	52.0	61.5	59.2		91.2	90.1	91.5	83.7	79.3		65.8	64.7	67.5	70.3	66.6		78.7	77.3	77.3	69.0	72.6	
13:21:10	L50	33.1	30.0	29.6	38.4	40.3		49.5	44.6	45.9	59.1	56.3		80.1	79.8	81.4	75.0	65.7		57.5	56.7	59.7	67.0	62.5		66.6	65.7	65.8	65.2	62.7	
13:31:10	L90	32.0	29.7	29.1	37.4	[illegible]		46.4	40.1	41.9	56.8	[illegible]		65.7	65.9	66.7	66.0	[illegible]		52.0	51.3	54.5	63.1	[illegible]		56.6	54.9	55.4	62.2	[illegible]	
1.5 mps	Leq	54.5	34.3	43.4	39.7	67.1		66.7	48.6	53.1	59.6	79.8		89.0	87.0	87.8	79.6	84.3		74.4	62.3	66.5	67.8	86.8		78.9	75.1	75.4	66.7	83.3	
R2	L1	32.3	31.1	28.9	31.0	49.7		52.1	47.0	46.3	45.1	62.1		92.0	91.1	91.2	91.8	91.5		66.8	64.7	64.7	65.0	72.2							
12/5/12	L10	30.1	30.6	28.7	30.4	48.5		49.5	44.6	43.6	42.6	60.3		87.7	87.0	87.1	87.7	83.2		64.1	61.2	61.5	61.3	69.4							
22:46:57	L50	29.7	30.3	28.5	30.1	47.2		45.7	41.9	39.8	39.6	58.4		79.2	78.8	78.8	79.6	74.5		60.0	56.2	56.8	55.0	65.7							
22:56:57	L90	29.5	30.0	28.3	29.8	45.9		41.5	39.4	36.0	37.4	56.6		65.6	64.6	64.9	65.4	66.7		55.2	51.6	51.7	49.0	61.6							
[illegible]	Leq	34.0	30.3	28.5	30.2	47.3		48.5	42.5	40.8	40.4	58.7		83.2	82.6	82.6	83.3	80.2		61.4	57.9	58.2	57.4	66.6							
R2	L1	45.3	31.7	35.6	38.3	54.9		63.2	53.9	51.5	61.0	64.7		102.2	101.6	101.0	100.7	92.4		77.8	75.3	74.7	77.0	73.9		90.8	91.2	90.2	89.7	86.9	
12/5/12	L10	37.0	30.9	30.3	32.2	50.4		53.1	46.7	46.2	48.5	62.3		91.4	91.0	91.1	92.0	85.2		67.7	64.9	65.2	66.4	71.2		77.1	76.9	77.3	78.0	79.6	
23:24:20	L50	30.3	30.5	28.6	30.4	48.8		48.3	43.7	42.1	42.4	60.2		82.4	82.1	82.4	83.3	76.5		62.6	58.9	59.5	59.1	67.5		68.5	68.0	68.8	69.5	72.8	
23:34:20	L90	29.7	30.1	28.3	30.1	47.5		44.2	41.2	38.0	39.3	58.3		69.0	68.6	68.9	70.2	68.7		57.7	53.8	54.0	52.3	63.4		59.7	58.4	59.6	60.0	66.8	
[illegible]	Leq	34.9	30.5	29.4	31.6	58.0		54.3	45.3	44.9	51.5	62.5		89.5	89.2	88.8	89.2	81.8		68.0	63.3	63.5	66.0	68.4		78.6	78.7	77.8	77.5	76.7	
R2	L1	38.8	31.3	31.0	36.8	52.1		55.6	49.4	51.8	53.7	63.0		93.0	93.0	93.1	93.9	90.1		69.1	66.7	68.1	68.0	72.7		80.5	80.6	81.1	81.5	85.0	
12/5/12	L10	32.5	30.7	28.9	31.2	49.2		51.1	45.4	44.8	46.0	61.0		89.0	88.9	89.1	89.7	83.7		65.5	62.9	63.5	63.7	69.9		75.7	75.7	76.2	76.5	78.5	
23:36:11	L50	30.0	30.3	28.5	30.2	47.8		47.0	42.6	40.7	41.5	59.0		81.2	80.9	81.3	81.9	74.7		61.3	57.6	58.1	57.5	66.4		67.7	67.7	68.1	68.5	71.6	
23:46:11	L90	29.6	30.0	28.3	29.9	46.6		42.9	40.1	36.8	38.6	57.2		67.7	67.7	68.1	68.4	67.3		56.6	52.8	52.9	51.3	62.1		59.1	58.3	58.7	59.0	65.5	
2.3 mps	Leq	31.4	30.5	28.8	31.1	48.5		48.6	43.5	43.6	44.5	59.4		84.7	84.5	84.7	85.4	80.0		62.7	59.6	60.6	60.2	67.2		71.6	71.6	72.0	72.5	75.1	
R2	L1	37.5	31.2	30.7	35.4	50.6		53.8	48.6	47.7	49.7	63.3		93.1	92.8	93.1	93.9	93.2		67.9	66.4	66.7	67.3	73.4		79.7	79.7	80.1	80.4	87.0	
12/6/12	L10	32.7	30.7	29.0	31.0	49.3		50.9	46.0	45.0	44.9	61.7		88.9	88.7	88.9	89.6	86.2		65.1	62.9	63.1	63.1	70.8		75.3	75.4	75.7	76.0	80.1	
0:19:35	L50	30.1	30.3	28.6	30.0	47.8		47.1	43.2	41.3	41.5	59.8		80.3	80.1	80.2	81.0	76.7		61.3	57.8	58.3	56.9	67.2		67.9	67.9	68.3	68.6	72.7	
0:29:35	L90	29.7	30.0	28.3	29.8	46.5		43.3	40.5	37.4	38.7	57.9		66.6	66.3	66.6	66.9	68.6		56.7	53.1	53.2	51.2	63.2		59.2	58.8	58.9	59.1	66.6	
3.0 mps	Leq	31.6	30.4	29.0	30.8	48.0		48.4	43.8	42.4	43.0	60.0		84.4	84.2	84.4	85.1	82.4		62.3	59.5	59.9	59.5	68.0		71.2	71.3	71.6	71.9	76.8	
R2	L1	31.8	31.7	41.6	37.9	52.1		57.3	49.9	49.7	52.6	64.1		103.8	98.2	98.5	99.2	95.6		77.4	71.6	71.8	72.7	74.2		91.7	86.2	86.0	86.4	90.0	
12/6/12	L10	30.3	31.0	35.7	31.3	50.1		52.9	46.8	46.7	45.5	62.3		98.4	93.7	93.7	94.6	88.7		72.1	67.2	67.2	68.0	71.4		84.0	79.4	79.4	79.9	82.6	
1:17:54	L50	29.9	30.5	28.9	30.3	48.5		49.1	43.9	43.0	41.8	60.1		89.6	84.7	84.6	85.4	79.0		65.4	60.3	60.6	59.7	67.6		75.6	70.6	70.6	71.2	74.3	
1:27:54	L90	29.6	30.1	28.4	30.0	47.1		45.6	41.2	38.8	39.0	58.2		76.6	71.1	71.0	71.1	69.9		58.9	54.7	54.5	52.2	63.4		67.1	60.6	60.6	60.6	67.6	
3.2 mps	Leq	32.7	33.3	34.4	33.4	48.7		50.9	46.4	45.8	45.7	60.5		94.3	89.2	89.2	90.0	84.9		68.6	63.3	63.5	63.7	68.5		80.6	75.8	75.8	76.2	79.2	
R2	L1	39.7	31.4	32.3	40.8	51.8		56.4	49.2	48.8	57.7	64.2		96.1	95.7	96.1	96.6	97.3		70.4	69.1	69.2	71.2	74.7		83.5	83.7	84.1	84.5	91.9	
12/6/12	L10	32.8	31.0	28.9	31.3	50.7		51.7	47.0	45.5	47.2	62.6		91.2	91.2	91.4	92.1	89.6		67.0	65.0	65.1	66.2	71.6		78.6	78.6	79.0	79.5	83.6	
2:14:13	L50	30.1	30.6	28.5	30.1	49.3		47.8	44.3	41.5	42.0	60.7		83.7	83.6	83.8	84.6	79.7		62.6	59.7	59.8	59.7	67.7		70.9	71.1	71.2	71.7	74.9	
2:24:13	L90	29.8	30.2	28.3	29.8	48.0		43.8	41.6	37.6	38.9	59.0		70.5	70.7	70.4	70.8	70.4		57.7	54.7	54.0	52.7	63.6		61.4	61.0	61.2	61.7	68.0	
3.3 mps	Leq	32.0	30.7	28.9	34.8	49.4		49.3	44.9	42.7	46.9	61.0		87.2	87.1	87.2	88.0	86.2		63.9	61.8	61.9	62.8	68.8		74.7	74.9	75.1	75.5	80.6	
R2	L1	54.9	32.0	44.5	45.6	51.0		76.5	58.2	60.4	78.7	63.2		92.6	91.2	92.4	92.3	89.2		87.9	71.4	74.6	90.5	67.8		87.0	84.1	84.6	87.3	85.7	
12/6/12	L10	44.5	30.4	35.8	35.5	45.8		60.7	45.9	50.2	60.3	57.9		86.0	84.4	84.8	85.3	82.3		71.4	61.2	64.1	72.5	64.3		75.4	72.2	72.9	75.0	77.8	
14:06:21	L50	33.9	29.9	28.9	30.3	42.9		47.0	39.6	40.4	43.8	54.6		77.4	74.8	75.5	76.3	72.1		59.6	53.5	55.5	57.3	60.5		65.7	64.0	64.3	65.6	68.2	
14:16:21	L90	29.4	29.7	28.3	29.9	41.3		40.7	36.7	35.2	37.1	52.7		64.6	61.3	62.5	63.9	62.5		53.8	48.1	49.5	49.3	56.4		56.3	54.1	54.9	55.9	60.4	
2.1 mps	Leq	45.0	30.2	35.3	42.2	47.4		63.1	46.4	50.1	64.5	57.0		83.1	81.8	82.2	82.5	78.7		74.7	60.4	63.7	76.7	62.0		76.2	73.0	74.1	75.0	74.7	
R2	L1	43.5	35.0	35.6	42.8	66.1		66.4	51.7	51.3	69.3	72.2		95.8	95.6	95.2	95.8	95.6		78.6	69.0	69.4	81.9	71.4		81.5	81.0	80.5	81.2	91.0	
12/6/12	L10	36.7	30.8	29.9	35.1	49.5		55.2	44.2	44.7	56.2	59.6		90.0	89.7	89.5	90.1	87.5		68.5	63.6	63.9	69.9	66.5		75.2	73.7	73.9	75.3	81.7	
14:25:47	L50	31.8	30.2	28.7	30.4	46.1		47.5	40.7	40.3	46.2	56.7		81.8	81.5	81.3	82.2	76.9		62.1	56.9	57.9	61.4	62.7		67.9	65.6	66.0	68.0	71.0	
14:35:47	L90	30.1	29.9	28.3	29.9	44.2		42.6	38.1	36.9	40.6	54.9		68.7	67.3	67.3	69.1	66.2		56.7	50.8	51.8	54.7	58.5		59.2	56.1	56.7	59.0	62.7	
1.7 mps	Leq	34.8	30.6	29.5	33.4	53.0		55.0	42.6	42.7	56.5	60.4		86.2	85.9	85.7	86.4	84.2		67.4	60.1	60.6	69.5	64.1		71.7	70.3	70.3	71.7	79.0	
R3	L1	46.6	37.9	41.7		51.8		58.1	58.3	59.0		69.7		98.3	94.9	95.6		98.5		72.3	68.3	73.2		72.5		80.2	81.8	80.9		94.5	
12/6/12	L10	37.4	33.9	34.9		48.6		51.4	52.7	50.9		64.4		90.3	89.7	90.5		91.9		65.9	63.6	65.8		68.1		73.8	74.1	74.0		86.9	
15:57:13	L50	31.2	31.9	30.5		43.9		46.0	48.0	45.5		57.3		81.1	80.6	82.1		82.7		59.7	57.6	59.6		63.7		65.7	65.6	65.9		77.4	
16:07:13	L90	30.1	31.0	29.3		40.1		42.3	45.4	42.0		53.9		67.2	66.7	67.9		71.0		53.8	52.4	53.7		59.3		56.6	56.7	56.3		67.2	
2.8 mps	Leq	40.7	32.6	35.6		45.6		49.3	50.0	49.2		60.7		86.8	86.0	86.8		88.1		63.0	60.5	63.3		65.2		73.2	74.2	73.5		83.5	
R3	L1	47.6	37.0	54.3		50.4		60.5	55.6	64.3		69.4		104.4	104.5	104.4		102.6		80.2	78.2	80.9		80.5		93.6	94.0	92.9		98.7	
12/6/12	L10	39.7	33.1	37.5		47.8		51.1	51.3	50.9		62.5		91.3	91.1	91.4		95.1		66.8	64.9	67.3		70.4		73.2	72.7	73.4		90.9	
16:28:57	L50	32.3	31.5	29.7		44.0		44.2	47.0	43.4		56.7		81.8	81.6	81.9		85.1		58.5	57.5	58.4		63.2		64.1	63.9	64.3		80.8	
16:38:57	L90	30.3	30.8	28.8		40.0		40.5	44.3	40.3		53.0		67.8	67.3	68.2		72.8		52.3	51.4	52.3		58.3		54.5	54.6	54.2		69.0	
2.4 mps	Leq	37.0	32.2	42.1		44.9		54.7	49.8	55.6		59.9		92.1	92.1	92.2		91.7		70.1	66.0	70.5		68.8		80.4	81.1	80.3		87.8	
R3	L1	48.8	34.9	44.4		45.0	51.9	62.7	57.6	60.6		68.1	67.6	98.3	95.3	95.3		85.3	69.9	76.0	69.4	73.1		70.1	72.7	86.8	86.4	85.9		81.1	68.3
12/7/12	L10	38.3	31.8	33.6		40.6	36.6	53.5	50.1	49.8		59.8	52.1	91.8	79.6	80.2		79.0	55.0	68.1	58.7	62.4		65.2	57.2	69.1	65.2	67.9		73.9	53.1
11:20:24	L50	30.9	30.2	29.1		38.0	18.8	43.8	44.7	43.9		53.6	37.3	81.9	70.7	71.3		70.3	41.4	60.3	54.1	56.3		60.9	45.1	58.2	56.4	57.6		64.5	40.5
11:30:24	L90	29.7	29.8	28.6		37.2	15.3	39.6	41.9	40.3		51.2	29.8	66.5	58.2	59.6		60.6	34.1	53.1	49.4	51.1		56.2	37.3	50.7	49.8	50.5		58.1	33.4
1.1 mps	Leq	37.6	30.8	33.6		39.0	41.5	51.7	47.4	49.4		57.4	62.0	87.9	82.1	81.9		75.2	63.7	66.1	57.7	62.3		62.5	62.2	75.6	76.3	75.3		70.4	63.1
R3	L1	36.4	33.9			44.9	37.3	53.7	53.8			65.0	50.4	92.3	80.3			84.7	72.7	67.0	59.4			70.2	64.5	65.0	64.8			80.3	64.6
12/7/12	L10	30.8	31.2			40.1	36.2	45.8	46.6			57.2	47.3	85.9	75.8			77.6	67.5	62.3	56.5			65.1	61.0	60.0	59.5			71.9	59.8
11:46:16	L50	30.0	30.1			37.5	36.0	40.9	43.0			52.5	43.9	73.5	67.8			67.9	59.4	54.2	52.3			60.7	56.3	53.3	52.4			62.4	54.0
11:56:16	L90	29.7	29.8			36.9	35.7	37.8	40.4			49.9	40.9	59.9	55.2			59.2	51.8	49.0	47.6			55.9	50.7	47.7	47.5			56.9	49.0
0.9 mps	Leq	31.4	30.5			38.6	36.0	44.0	44.8			55.0	44.8	81.5	71.6			74.0	63.8	58.1	53.4			62.3	57.8	56.3	55.7			69.0	56.4
R3	L1	36.7	46.8		35.7	71.0	44.1	63.8	74.0	38.7	57.7	81.1	72.7	87.5	83.3		83.9	85.8	79.4	76.8	76.1		69.4	90.4	87.6	69.2	75.8		65.7	84.3	79.1
12/7/12	L10	33.0	37.4		30.6	50.8	37.8	55.0	62.1	38.3	45.9	68.8	59.0	81.0	78.7		79.6	80.1	71.6	62.9	67.3		56.8	77.0	69.5	62.6	66.4		60.4	76.1	65.1
12:02:32	L50	30.1	30.5		29.4	38.2	36.1	43.5	48.2	37.9	35.5	55.5	47.4	73.1	70.9		71.6	70.4	61.9	55.5	56.9		48.7	64.6	59.8	54.9	55.9		52.2	66.1	56.3
12:12:32	L90	29.8	29.9		29.1	36.9	35.8	39.1	41.8	37.4	33.1	50.3	42.2	59.5	59.0		57.4	60.7	54.0	50.0	50.5		41.8	58.0	52.9	48.7	49.6		43.9	58.7	50.7
1.1 mps	Leq	31.2	35.3		30.1	56.5	37.2	52.3	60.2	37.9	44.6	67.4	60.0	77.4	74.4		75.2	76.0	68.0	63.5	65.1		56.4	75.9	73.4	59.2	63.2		56.3	72.7	65.8

CONCLUDING REMARKS

In an effort to determine acoustical conditions that could be linked to apparent intense reaction by some Shirley environs homeowners, simultaneous indoor and outdoor acoustic and local wind speed measurements were conducted sequentially at three disparate locations over a three-day period starting the evening of December 4, 2012. A very large compendium of raw and processed data was obtained, a small fraction of which is presented in this summary.

The apparent and tentative result indicates that at the second residence, located approximately 1,280 ft from the nearest turbine, blade-passage induced infrasound was correlated between outdoor and indoor locations and peak amplitudes of periodic waves composed of blade harmonics 0.7 to 5.6 Hz on the order 76 dB were detected both indoors and outdoors. Well correlated broadband low frequency noise at this nearest residence was also detected, with one-third octave band sound pressure levels approximately 50 dB in the frequency range 16-25 Hz. Both of these sounds are below normal hearing threshold; residents report being intensely affected without audibility.

At the other two residences, located approximately 3,300 and 7,100 ft from the nearest turbine, respectively, high levels of infrasound were detected indoors but the correlation with outdoor acoustic signals was not clear except at the 3,300 ft residence, where the broadband noise in the 20 Hz range was moderately correlated and produce one-third octave band level approximately 40 dB, which is well below normal hearing threshold. At the 7,100 ft residence, outdoor-to-indoor correlation was low except during motor vehicle passages or in particular a helicopter overflight. Again, residents report being intensely affected despite inaudibility and to be aware of turbine operation when the turbines are not visible.

The author is not qualified to make judgments regarding human response to normally subliminal sources of acoustic excitation. A detection test has been proposed by the consortium of investigators and put forth by Dr. Schomer. The author concurs that this is an important step in resolving a difficult issue.

An additional missing element in the program is ability to correlate acoustic test results with turbine operating conditions. Near-turbine acoustic monitors placed by HAI showed significant variability in near-field sound levels for turbines WTG6 and WTG8 over the course of the program, with an indication that turbine noise emissions may have decreased shortly before the team started and increased shortly after the team stopped measuring on some days. Review of turbine SCADA records will show turbine-height wind speeds and directions and turbine power output as well as times when turbine were parked for flicker suppression or other purposes. This will help determine the program for additional measurements and/or if scaling of measured levels would be appropriate.

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[i] B. Walker, Time Domain Analysis of Low Frequency Wind Turbine Noise, Low Frequency Noise 2012, Stratford Upon Avon, UK

APPENDIX B
by
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Appendix B to Report Number 122412-1

1. Introduction

Hessler Associates concentrated on acquiring data to define the low frequency issue at the Shirley site using four Norsonics Model N-140 ANSI Type 1 precision instruments (NOR140). These systems with the standard microphone and preamp are rated at an accuracy of +/- 1 dB from 5 Hz to 20,000 Hz. Two of the systems were used as continuous data loggers and the other two for relevant attended measurements. The systems were also calibrated against the extended frequency range system brought by Channel Islands Acoustics (ChIA).

2. Calibration

Two NOR140 units were set-up in the living room of residence R2 adjacent to the high performance ChIA microphone, which is rated accurate from 0.1 Hz to 20,000 Hz. The results of a 10-minute run between the three systems, along with a photograph of the set-up, are shown below. It is clear from the test that the NOR140 off-the-shelf unit can be used with confidence down to about 2 Hz; significantly better than its 5 Hz rating.

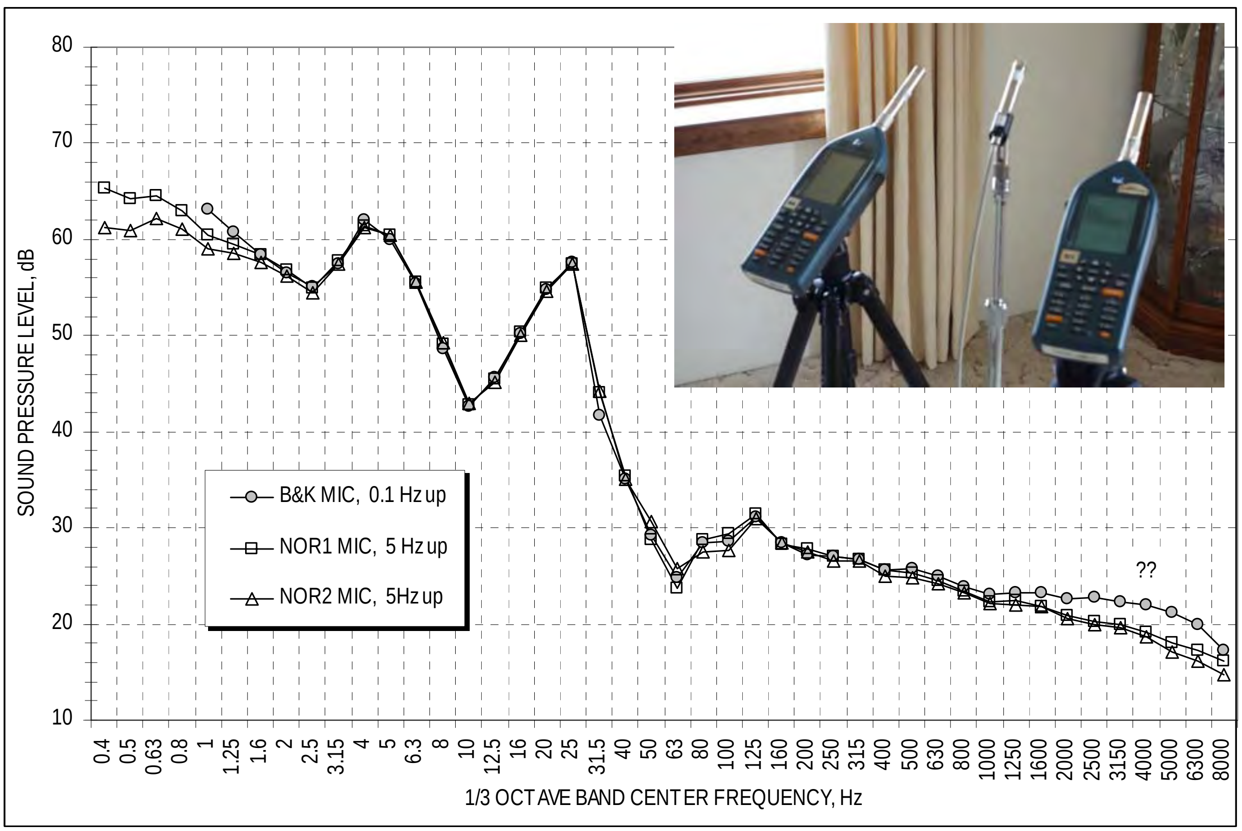

Figure 2.1 *Instrument Calibration Check Relative to High Performance ChIA System*

3. Data Logger

Because Duke Power would not participate in the test, it became necessary to install an automated sound level recorder near Turbine 6 to get a sense of what load that turbine, and presumably the remainder of the project, was operating at - and, indeed, whether the turbines were operating at all. The test position, designated as Monitor 1, is shown in Figure 2.1 in the cover report. A plot for each 10-minute interval in terms of the L50, L90 and Leq statistical metrics is given below.

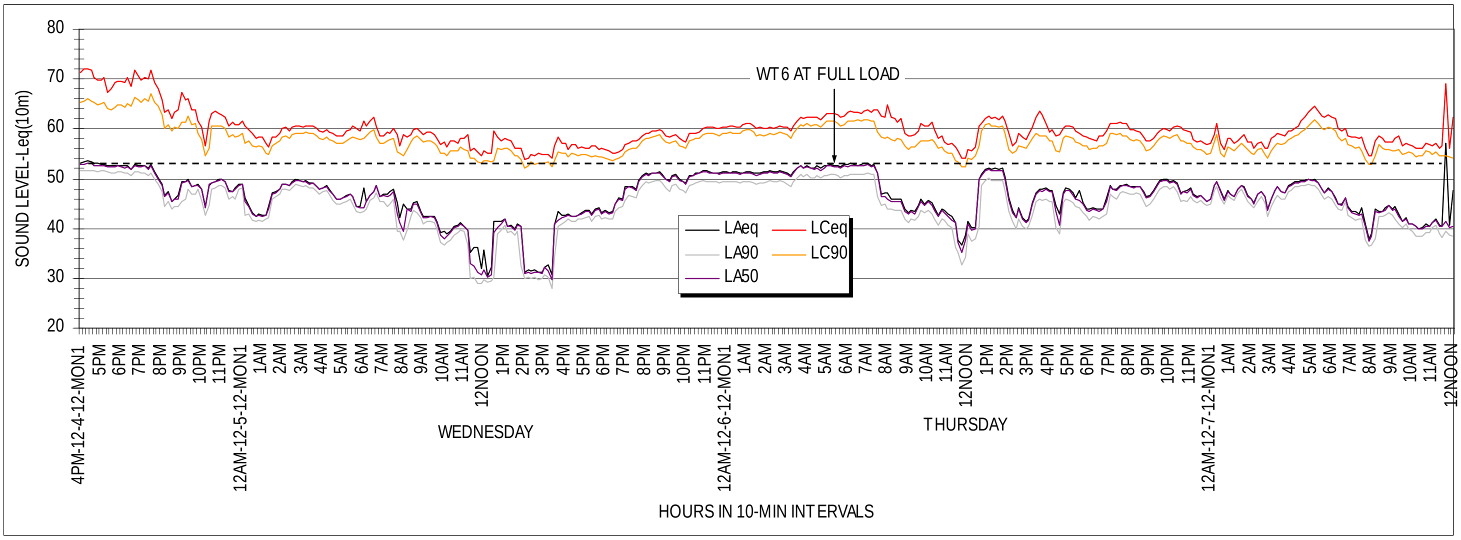

Figure 3.1 *Monitor 1 Results*

Calculations indicate that the turbine is at full power when the sound pressure at the monitor is approximately 53 dBA. In general, the plot shows when the unit was near or at full power and when it was off (e.g. around midday on Wednesday when the sound level dropped to about 31 dBA).

The second long-term logger, Monitor 2, which was located in front of the residence at R2, was not as useful because it was strongly influenced by extraneous, contaminating noise from traffic on Glenmore Road. Nevertheless, the results are given below in Figure 3.2.

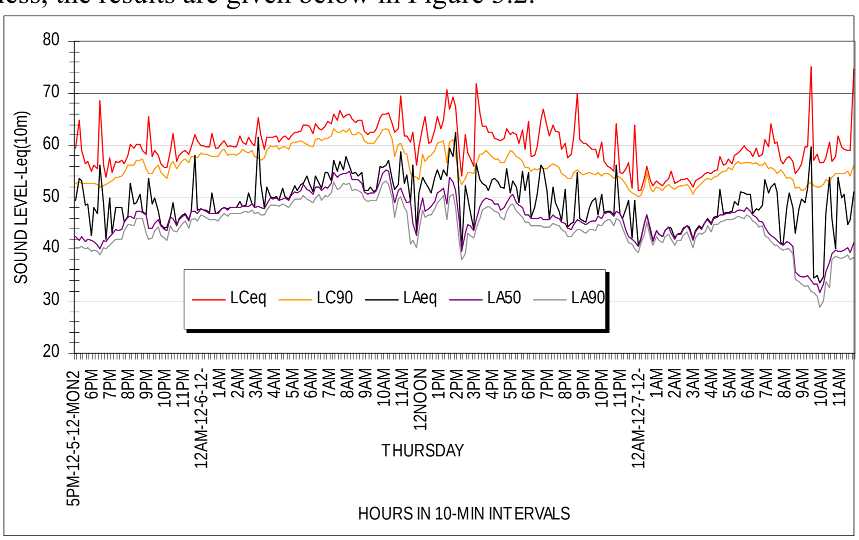

Figure 3.2 *Monitor 2 Results*

4. OUTDOOR/INDOOR Measurements

Measurements of the frequency spectra inside and outside of each of three residences on Wednesday night and early Thursday morning while the turbines were operating near full power are plotted below.

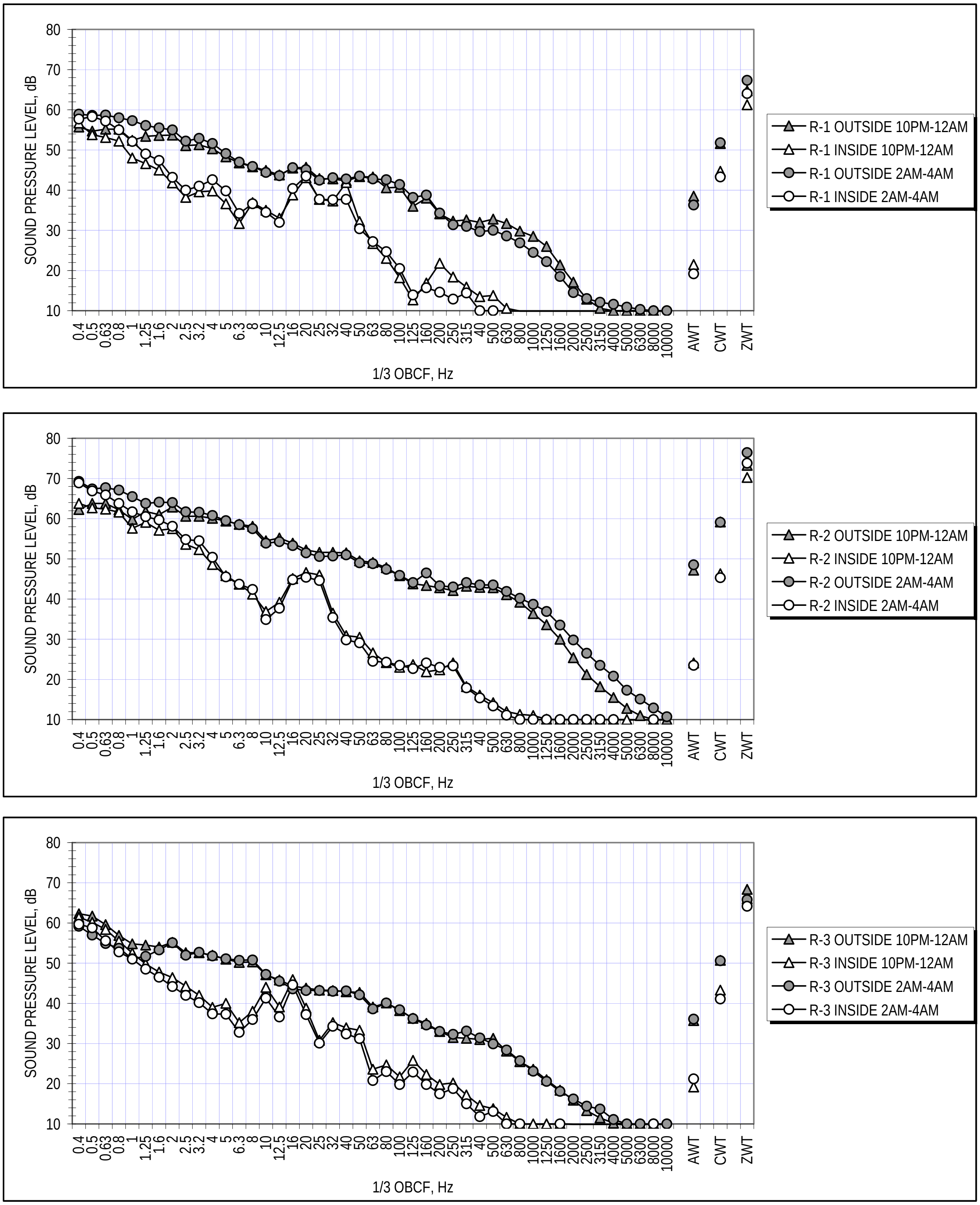

Figure 4.1 *Inside/Outside Sound Levels during Project Operation*

These figures are 10-minute L50 samples made simultaneously outside and inside of the three residences between 10 p.m. and midnight and between 2 and 4 a.m. The measured levels below 1 or 2 Hz may be pseudo noise, or false signal noise from the wind blowing over the microphone, even though the microphone was placed on a reflective ground board under a 7" hemispherical windscreen to minimize this effect. The plotted outdoor levels are the raw measurement results obtained on the reflective ground plane and should be reduced by 3 dB to reflect a standard measurement 1.5 meters above grade. Maximum levels occur at R-2 as one would expect, since it is closest to the turbines and the location where wind turbine noise was most readily audible.

What is significant about these plots is that there is a low frequency region from about 10 to 40 Hz where the noise reduction of each house structure appears to be weakest. This behavior is attributed to the frequency response of each structure, which is known to be in this frequency range. The small differences in the magnitude and frequency of the interior sound levels in this region of the spectrum are largely associated with differences in construction, design, openings, etc. The question is: what is the driving or excitation force in this range? It could be acoustic noise immissions from the wind turbines, normal environmental sources (mostly traffic), the natural response of each structure to varying wind pressure or some combination of these causes. The only sure way to discover the driving force is to turn off the wind turbines for a short period to see if the spectrum changes without the turbines in operation. This type of on/off testing was requested in the first test protocol and these rather inconclusive results make it clear that such an approach is essential to the task of identifying and quantifying the sound emissions specifically from the turbines inside of these homes.

5. ON/OFF Measurements

In the course of taking some supplemental outdoor measurements of the turbine closest to R-2 at least one on/off sample, although outdoors, was obtained through happenstance. After several measurements at a position 269 m WNW of WTG8, with the turbine in operation at some intermediate load in light winds from the north, the unit was unexpectedly shutdown by O&M personnel. Additional measurements were immediately obtained with all variables constant except for turbine operation. Prior to shutdown the rotor was turning at 11 rpm, which equates to a blade passing frequency of 0.55 Hz. The resulting on/off spectra are plotted below in Figure 5.1.

One could conclude that the wind turbine was not producing any low frequency noise since the spectra are essentially equal from 0 to 12.5 Hz; however, despite measuring on a hard surface using a hemispherical windscreen, the low end of both spectra appear to be pseudo, or false-signal noise based on some recent empirical tests of windscreen performance carried out in the Mohave Desert (in support of a new ANSI standard that is being developed for measuring in windy conditions). The objective of this testing was to evaluate measured low frequency sound levels in a moderately windy environment without any actual source of low frequency noise. The on/off measurements of WTG8 show that the levels below about 20 Hz coincide with the sound levels measured in the desert in the presence of a light 1 to 2 m/s wind. Consequently, all that can be concluded is that the low frequency emissions from the turbine were substantially lower in magnitude than the distortion effect produced from a nearly negligible amount of airflow through a 7" windscreen and across the ground-mounted microphone.

The overall reduction in audible sound of 8 dBA is attributable to eliminating the "whoosh" sound, which is clearly seen to occur in the higher frequencies; generally from about 200 to 2000 Hz.

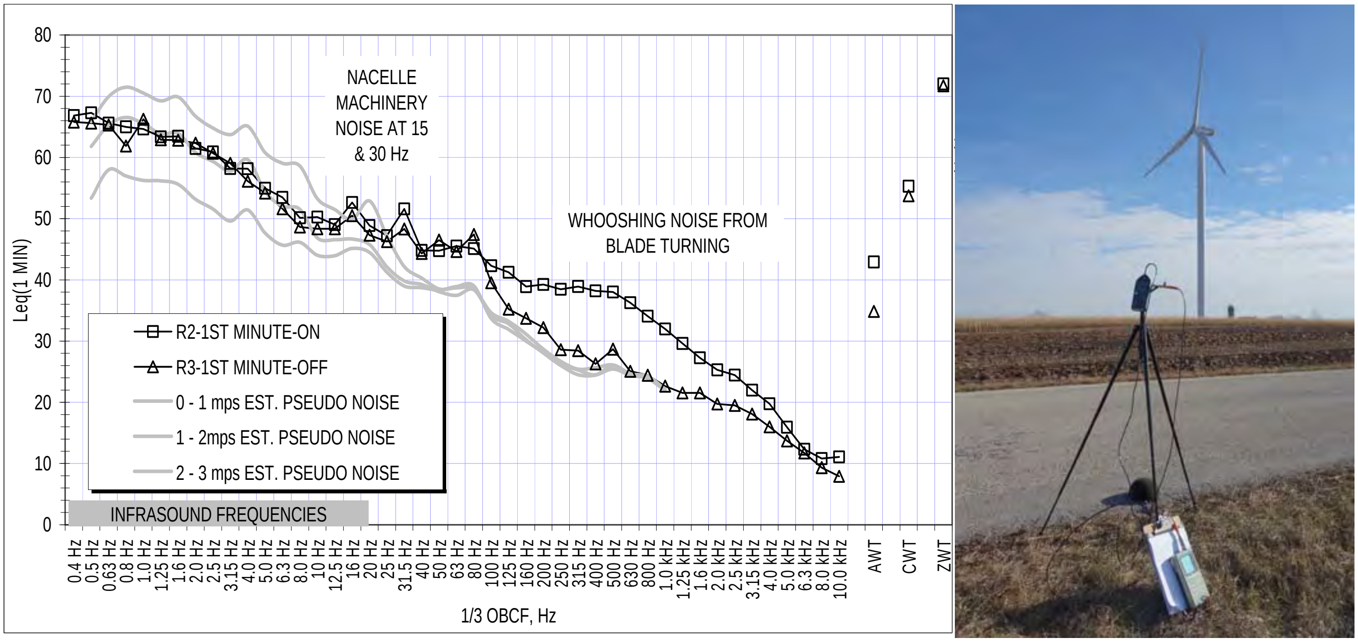

Figure 5.1 *On/Off Sound Levels Outdoors during Project Operation*

6. Proposed Method for Measuring Outdoor LFN in Wind

The experience above with on/off measurements outdoors can be combined with a finding made by Walker and Schomer that LFN inside a dwelling was quite uniform throughout all the rooms in the house, and not, as one might intuitively imagine, in the rooms facing the nearest turbine. This prompted them to measure the sound level inside of a vehicle, an SUV, and compare it to the levels measured inside the residence. It was found that the low frequency levels inside the car were similar to those inside the adjacent dwelling. Since an SUV is a closed, wind-free volume, it follows that the problem of obscuring pseudo could be eliminated with such measurements and accurate narrow band measurement of extreme low frequency sound could be measured inside of a car. The spectrum for a wind turbine shows up as a distinct pattern of peaks beginning at the blade passing frequency (about .5 to 1 Hz for modern wind turbines) with several following harmonic peaks that positively identify wind turbine low-frequency infrasound immissions. The beauty of the system sketched below in Figure 6.1 is that it is mobile and can be used at any public assess near or far from a wind farm.

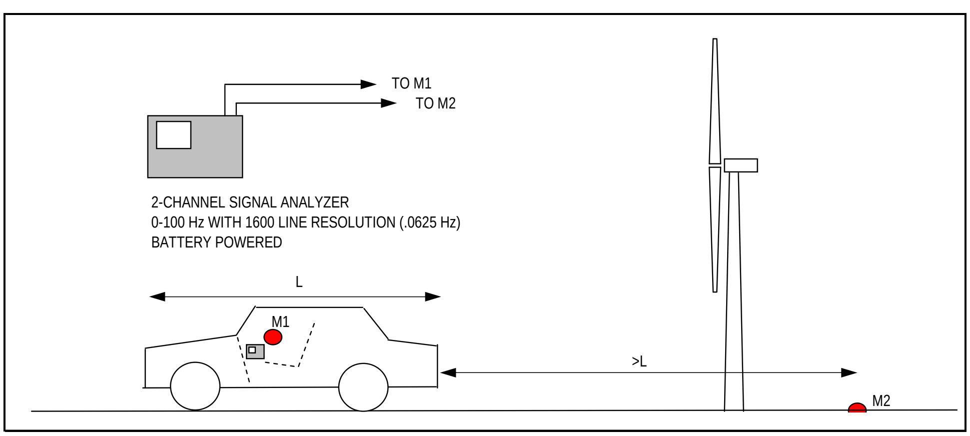

Figure 6.1
Schematic of Alternative, Mobile Measurement Technique for Low Frequency Sound Emissions from Wind Turbines

7. Conclusions

Walker showed unequivocally that low level infrasonic sound emissions from the wind turbines were detectable during near full load operation with specialized instrumentation inside of residence R2 as a series of peaks associated with harmonics of the blade passing frequency. The long-term response of the inhabitants at R2 has been severely adverse for the wife and child while the husband has experienced no ill effects, which illustrates the complexity of the issue. The family moved out of the area to solve the problem.

The industry response to claims of excessive low frequency noise from wind turbines has always been that the levels are so far below the threshold of hearing that they are insignificant. The figure below plots the exterior sound level measured around 2 a.m. on a night at R2 during full load operation compared to the threshold of hearing. In the region of spectrum where the blade passing frequency and its harmonics occur, from about 0.5 to 4 Hz, the levels are so extremely low, even neglecting the very real possibility that these levels are elevated due to self-generated pseudo noise, that one may deduce that these tones will never be audible. What apparently is needed is a new Threshold of Perception.

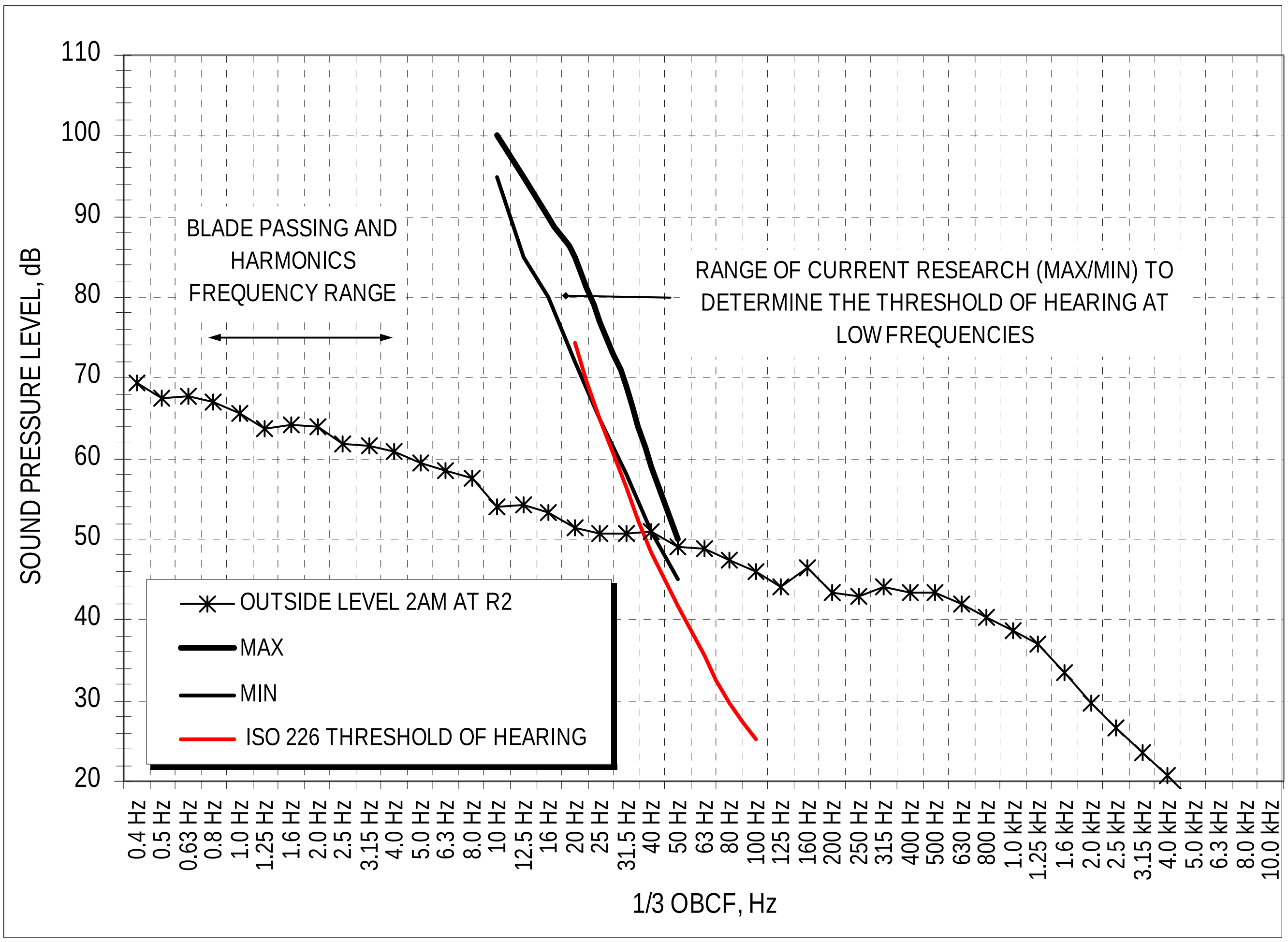

Figure 7.1 *Measured Project Sound Level Compared to Threshold of Hearing*

The study also showed that a wind turbine is indeed a unique source with ultra low frequency energy. The next figure plots the same R2 data above compared to a more commonly recognized low frequency noise source, an open cycle industrial gas turbine complex sited too close to homes. These two sources of electrical energy production, assuming the low end of the wind turbine measurement is actually due to the turbine rather than pseudo noise, have about the same A-weighted and Z-weighted overall sound levels.

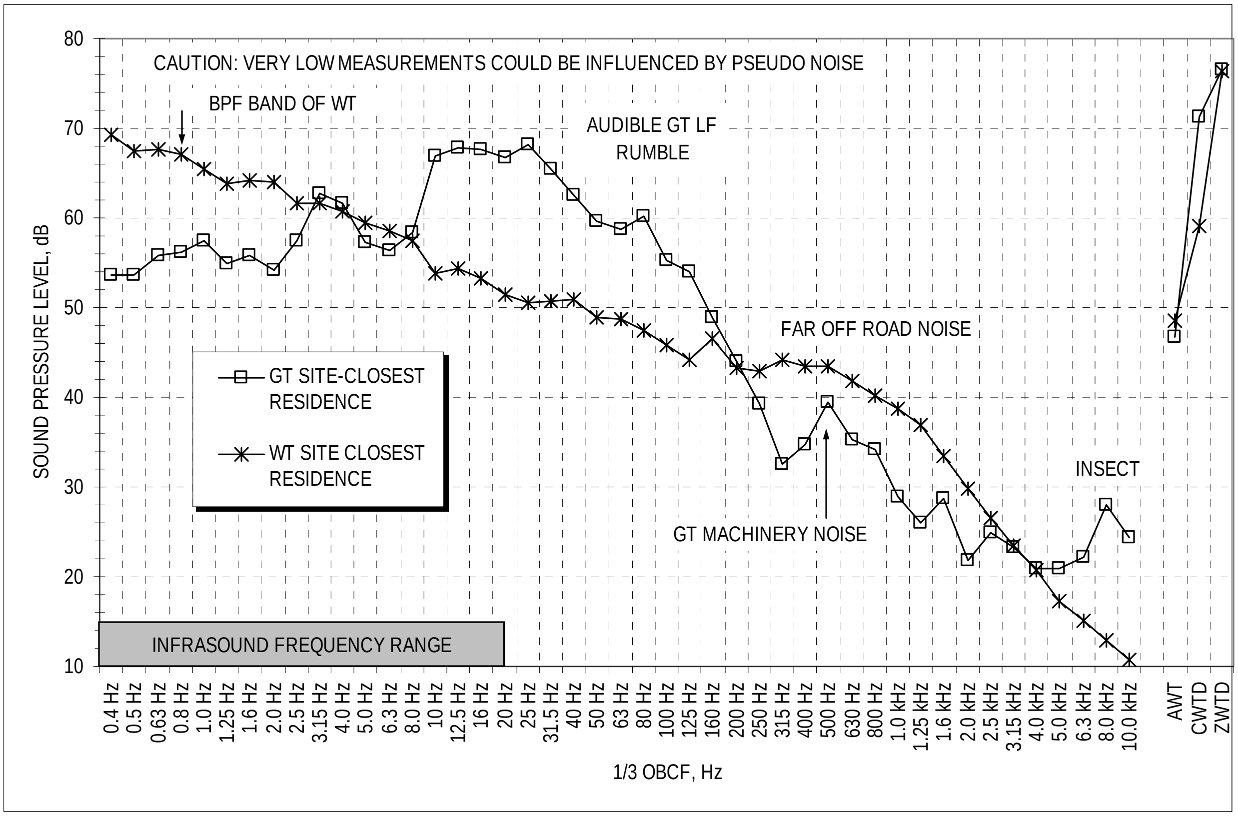

Figure 7.2 *As-Measured Wind Turbine Spectrum Compared to Gas Turbine Sound Level*

The C-weighted sound level is often used as a measure of low frequency noise; most commonly in gas turbine applications. If the C minus A level difference of a source is 15 to 20 dB, further investigation of the source is recommended by some test standards, since that apparent imbalance may be an indicator of excessive low frequency content in the sound. In this instance, the C-A level difference for the wind turbine is only 11 dB compared to 25 dB for the gas turbine, so this metric does not appear to work for wind turbines.

Schomer and Rand contend that the illness that is being reported may be a form of motion sickness associated with the body experiencing motion in approximately the same frequency range as wind turbine blade passing infrasound. However, this conjecture is based on a Navy study in which subjects were physically vibrated in flight simulators at amplitudes that may or may not be comparable to the situation at hand, whereas any such force from a distant wind turbine would need to be conducted through the air. One must make the leap that motion of the body in still air is the same as being still in air containing some level of infrasound. While potentially plausible this hypothesis needs to be verified.

Hessler and Walker have measured overall A-weighted sound levels and levels of infrasound at numerous wind farms that substantially exceed those measured here and to the best of their knowledge there are no reported adverse effects for noise or adverse health issues. It would be informative, in any further study, to survey the reactions of project participants and possibly other neighbors close to turbines, particularly with regard to health effects.

In general, enough was learned by these investigators, all with quite different past experiences, that it can be mutually agreed that infrasound from wind turbines is an important issue that needs to be resolved in a more conclusive manner by appropriate study, as recommended in the cover report.

End of Text

APPENDIX C
by
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December 21, 2012

Investigations of infrasonic and low-frequency noise
Shirley Wind Facility, Wisconsin, December 4-7, 2012

1.0 Introduction

This report presents information on an investigation of infrasonic and low frequency noise performed at the Shirley Wind facility in Wisconsin December 4-7, 2012. The investigation was conducted by acousticians Dr. Bruce Walker, George Hessler, Dr. Paul Schomer, and Robert Rand under a Memorandum of Agreement developed for the investigation by Clean Wisconsin and Forest Voice. Mr. Hessler was accompanied by his son David Hessler. During the investigation, unexpectedly another consultant, Mr. Michael Hankard, visited the team and entered the homes under investigation during testing.

The investigation was conducted using instrumentation provided and employed by the acousticians. Three homes were investigated that had been abandoned by the owners due to negative health effects experienced since the Shirley Wind facility had started up. The health effects were reported to make life unbearable at the homes and had affected work and school performance. It was understood that once relocated far away from the facility, the owners and families recovered their health; yet revisiting the homes and roads near the facility provoked a resurfacing of the adverse health effects. The owners had documented their experiences in affidavits prior to the investigation.

This team functioned very well together with a common goal, and found collectively a new understanding of significant very low frequency wind turbine acoustic components that correlated with operating conditions associated with an intolerable condition for neighbors.

2.0 Methodology

It was generally understood that Dr. Walker would acquire simultaneous multi-channel, wide-bandwidth, high-precision recordings for later analysis. If successful and clear of contamination, those recordings would form the primary database for the investigation. George Hessler would acquire precision sound level meter measurements to correlate with wind turbine operations and for his project requirements. Paul Schomer and Rob Rand would serve as observers and, would also analyze and acquire measurements according to their investigative needs during the test. Measurements by acousticians would be catalogued and made available for later research and analysis. These general understandings were not detailed in the MOU due primarily to time constraints for the unusual, unprecedented collaboration brought together for this investigation.

Having investigated other wind turbine facilities and directly experienced the negative health effects reported by others living near wind turbines [1,2], Mr. Rand focused on acquiring neighbor reports on health impacts during and prior to testing and correlated those to data being acquired. The working assumption borne out by experience is that the human being is the best reporting instrument.

Correlation: When investigating community noise complaints, value can be derived from measurements and analysis primarily when they are highly correlated to neighbor reports. In simple terms: if a recording or analysis is made when the turbines are turning, and the neighbors are present and report feeling intolerable, tolerable, or not a problem, and report such details as headache, nausea, vomiting, dizziness, vertigo, or cloudy thinking, or the absence of health effects, the correlation to the neighbor reports provides very useful information for assessing the utility of those data. Without the neighbor reports, it is difficult to determine the significance of acoustic data. From details given in neighbor reports, the investigators can look for unusual or distinctive acoustic characteristics or differences to clarify what acoustical conditions correspond to the degree of health effects being reported.

Self-reports taken as valid: The team agreed prior to testing that neighbor reports would be useful. They also agreed that neighbor reports are sincere and truthful, not "claims" as often alleged by the wind industry. Neighbors considered and agreed to requests to be available during testing. Mr. Rand also agreed to note his condition during the testing, since unlike the other acousticians he is prone to seasickness and has also proved vulnerable to negative health effects when near large wind turbines.

Due to schedule constraints, Mr. Rand was unable to attend a preliminary meeting with the owners of the three homes during the midday on Tuesday, December 4. However he met with the owners during the evening of December 4 shortly after arriving, and observed and acquired owner health reports and noted his own health over the next three days.

2.1 Equipment

Equipment used by Mr. Rand included:

- Gras 40AN microphone
- Larson Davis Type 902 Preamplifier
- Larson Davis Type 824 Sound Level Meter
- M-Audio MicroTrackII 24-bit line-level audio recorder
- Bruel & Kjaer Type 4230 Acoustic Calibrator
- SoundDevices USBPre audio interface
- Infiltec Model INFRA-20 seismometer (acoustic pressure, 0.1 to 20 Hz)
- SpectraPlus 5.0 acoustic analysis software
- Amaseis helicorder datalogger software

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1 Robert W. Rand, Stephen E. Ambrose, Carmen M. E. Krogh, "Occupational Health and Industrial Wind Turbines: A Case Study", Bulletin of Science Technology Society October 2011 vol. 31 no. 5 359-362.
2 Ambrose, S. E., Rand, R. W., Krogh, C. M., "Falmouth, Massachusetts wind turbine infrasound and low frequency noise measurements", Proceedings of Inter-Noise 2012, New York, NY, August 19-22.

2.2 Protocol

Measurements would be obtained during higher-wind conditions as possible to derive a contrast from low- or no-wind conditions at the three homes under investigation. A "control" home in a quiet location far away from the Shirley Wind facility would be measured to provide background acoustic levels and signatures with no wind turbines nearby. Walker measurements would be observed and discussed and independent analysis performed by the observers as possible during the testing. The first primary goal was to obtain clean precision audio recordings for later analysis. The second primary goal was to obtain neighbor reports and discern acoustic contrast during the field investigations for immediate reporting of significant noise components to concerned parties. Mr. Rand would remain attentive to and report his health state during the testing.

At times during the testing Mr. Rand moved to other locations independently of the Walker system because of easier instrumentation mobility and to reduce noise contamination from activity by the other investigators.

3.0 Data collected

Mr. Rand took notes on health reports during the investigations, conveyed his state to the team during the testing, and compiled notes for later analysis, provided in Table 1. Neighbors were interviewed and they assembled reports for the team's use, listed in Table 2.

Mr. Rand referred primarily to Dr. Walker's acoustic recordings and analysis during testing and analysis. He acquired recordings and infrasonic acoustic pressure data separately for backup and reference.

Weather data were obtained from Wunderground as shown in Table 3.

Note: Although requested prior to the survey and again while at the site, Mr. Hessler made a decision not to acquire acoustic data with the Walker system at a control home far away from the Shirley Wind facility, citing "too many variables."

4.0 Analysis

Analysis focused on health state and, the levels and time-varying waveforms during higher-wind conditions when neighbors reported conditions as intolerable or difficult, versus quieter conditions which neighbors reported as tolerable.

5.0 Results

Results are preliminary. Nausea was experienced and **nauseogenicity** is indicated.

5.1 ***Neighbors report either tolerable or intolerable conditions, with little rating scale in***

between. They said if the turbines are operating, it's intolerable. Mr. Rand observed neighbors unable to stay at the homes at times even under moderate wind conditions during the testing.

5.2 ***Neighbors do not always hear the turbines. The neighbors indicated there is no real difference in wind compass direction on the negative health effects.*** The house could be upwind, downwind or crosswind to the turbine; no difference.

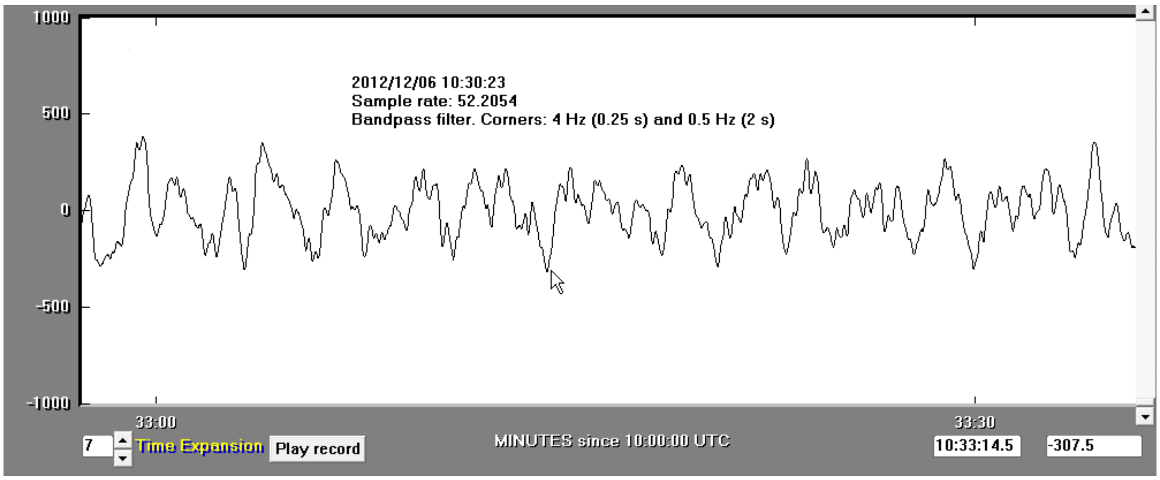
5.3 ***Neighbors retreated to the basement and gained partial relief from symptoms. Tested sound levels are the same everywhere in the home except less in the basement.*** Lower sound levels in the basement matches the neighbor reports to Mr. Rand to the effect that, when the turbines are operating, it's about the same level of difficulty everywhere in the house, except the basement, where they would retreat to gain partial relief, until they either left or abandoned the home to get substantial relief. The neighbors reported that they felt a need to get outside when conditions were intolerable. Their reports are supported by and correlate to the ubiquitous presence of the acoustic energy inside in all locations, except in the basement where it is slightly less. The neighbors take to the basement or if that is not sufficient to gain relief, they leave the home.

5.5 ***Acoustic energy outside was strongly coupled into the home at infrasonic frequencies when turbines operating in design range.*** Neighbors reported feeling worst when turbines are turning compared to light-wind conditions with some or all turbines off when they report using words such as "tolerable". Coherence between outdoor and indoors time-series was high at infrasonic frequencies below 8 Hz when wind turbines operating compared to when wind turbines off or turning slowly in light winds.

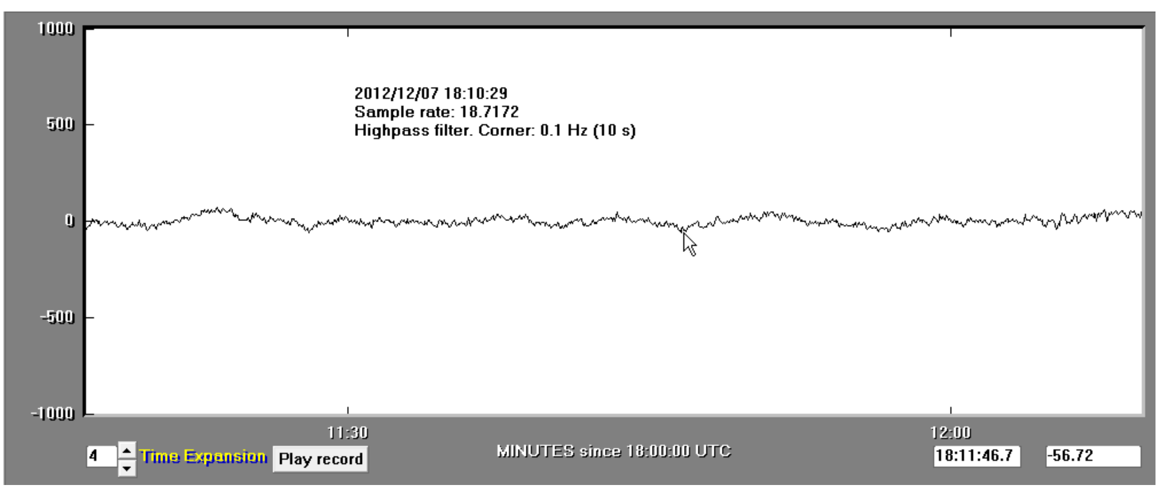
5.6 ***Neighbors reported being highly annoyed by the interior sound. Elevated acoustic energy was observed inside all three homes in the range of 10 to 40 Hz.*** Room, house, wall and floor acoustic modes (resonant frequencies) are found in the 10 to 40 Hz range. The Nordex N100 has in-flow turbulence noise at a peak frequency of 9 to 14 Hz depending on rotational speed, which might be involved in exciting resonant frequencies in walls and floors. More analysis and/or survey work appears needed to determine the extent of the problem. Mr. Rand was able to discern panel excitation in R3 where the owner reported feeling pressure on his ears as he moved toward the southerly wall of the sitting area in the open-area. Two wind turbines operating at a distance were faintly audible in R3 and detectable with ear to wall. Dr. Walker and Mr. Rand discussed the sensation, examined the walls, and made measurements of the home room dimensions for a future check of room modes against acoustic recordings.

5.7 ***Neighbors reported that at a distance of 3-1/2 miles, they could find relief when turbines were operating.*** Outdoor average sound levels at the nearest home R2, a distance of 1100 feet, were measured at approximately 48 dBA. Assuming 6 dB per doubling of distance for the A-weighted sound level, a probable A-weighted sound level at 3-1/2 miles is 48-20log(1100/18480) or, 48-23 or, **25 dBA**. Measured infrasonic unweighted average levels outdoors were approximately 73 dB at 0.3 Hz at 1100 feet. Assuming 3 dB per doubling of distance (cylindrical spreading) [2][3] for infrasonic propagation, a probable average infrasonic level at 3-1/2 miles is 73-10log(1100/18480) or, 73-12 or, **61 dB**. More work is needed to establish what infrasonic levels are consistent with relief for the neighbors.

The sample seismometer graph below shows the time varying waveform inside R2, the closest home at 121206 3:33 am with several turbines turning. Signal is filtered to pass the blade pass frequency and first four harmonics. Peak levels were 0.2 to 0.3 Pa (living room; scale shown approximately in milliPa), about 80 to 83 dB peak.



At R3 on 121207 110pm winds were light and the neighbors described the conditions as "tolerable" with no real problems. The sample seismometer graph below shows the time varying waveform for that period inside R3, the farthest home away in the testing. Peak levels were roughly 0.05 Pa (living room; scale shown approximately in milliPa), or about 50 dB peak. These results are preliminary and roughly similar to Dr. Walker's infrasonic data.



3 H. Møller and C. S. Pedersen: Low-frequency wind-turbine noise from large wind turbines. J. Acoust. Soc. Am. 129 (6), June 2011.

5.7 ***Negative health effects were experienced.*** During testing Mr. Rand experienced again [4] some of the adverse health effects reported by the neighbors. In effect, Mr. Rand "peer-reviewed" the neighbors by staying in two of the homes for extended periods of time overnight to experience what they are reporting. Mr. Rand slept in R1 the night of December 4th to assess the effects on sleep, and worked at R2 much of the second night (to 5:30 am) to assess audibility and effects while awake. Wind turbine sound levels were faintly detectable with interior sound levels in the range of 18-20 dBA. Note: Although he had arrived the previous night feeling good, on awakening on December 5 Mr. Rand felt nauseous (very unusual). To summarize, Mr. Rand encountered unusual negative health effects during the testing period when near the operating wind turbines, including, at various times:

- **Nausea**
- Headache
- Dizziness

Symptoms persisted after the testing for about a week, relieved by rest away from the site. The other investigators do not get seasick and did not report the same negative health effects.

Implications

A nauseogenic factor is present. Naval, aviation and other research has established human sensitivity to motion producing nausea. While mechanism for motion sickness is not well understood, "theories all describe the cause of motion sickness via the same proposition: that the vestibular apparatus within the inner ear provides the brain with information about self motion that does not match the sensations of motion generated by visual or kinesthetic (proprioceptive) systems, or what is expected from previous experience". The range of motion nauseogenicity has been measured at 0.1 to 0.7 Hz and with a maximum nauseogenic potential at 0.2 Hz [5][6] (see Figure 1). The Nordex N100 has a rotational rate of 0.16 to 0.25 Hz and a nominal blade passage rate of 0.5 to 0.7 Hz (three times the rotational rate). A hypothesis is suggested based on the limited, preliminary research correlating acceleration and nauseogenicity: ***Nauseogenicity is present at Shirley due to acceleration on inner ear from modulated, impulsive acoustic pressure at rotation and/or blade passage rates.***

Note: Wind turbines produce periodic acoustic pressure modulations at the rotation rate (per blade) and blade passage rate (per turbine), due to changes in wind speed and turbulence as blades are rotated top to bottom, and as they pass the tower where a pressure blow zone changes local wind speed. Pressure modulations at BPF with strong rates of change were documented by Dr. Walker (see Dr. Walkers report and the main report, conclusions).

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4 Nausea/dizziness/headache (very unusual) experienced at three other wind turbine sites including Falmouth, MA, April 2011 (Vestas V82); Hardscrabble, NY, August, 2012 (Gamesa G90-2MW); Vader Piet, Aruba, October, 2012 (Vestas V90-3MW).

5 Samson C. Stevens and Michael G. Parsons, Effects of Motion at Sea on Crew Performance: A Survey. Marine Technology, Vol. 39, No. 1, January 2002, pp. 29–47.

6 Golding JF, Mueller AG, Gresty MA., A motion sickness maximum around the 0.2 Hz frequency range of horizontal translational oscillation. Aviat Space Environ Med. 2001 Mar;72(3):188-92.

Note: Wind turbines encounter stronger winds at the top of rotation compared to the bottom. As each blade rotates through a full turn (one revolution) the blade is forced, bent, or flexed back by stronger wind load at the top of rotation and then returns to a lesser amount of bending at the bottom of rotation (the bending moment). Flexing occurs at the rotation rate. It's hypothesized that the blade displaces or disturbs a volume of air proportional to bending moment, translating motion into sound pressure at the flexing frequency, just as a loudspeaker moves air by displacement. Blade flexing may also impart a forcing function into the tower then transmitted into the ground, traveling to the house which responds, yielding two paths for acceleration on the inner ear.

Figure 2 shows rotational rates in Hz for various wind turbine models, for the total frequency span of 0.1 to 1 Hz associated with nauseogenicity. As wind turbine MW ratings have increased, the blades have become longer and less stiff with larger bending moments, and the rotational rate has decreased. The operating rpm for the Nordex N100 is 0.16 to 0.25 Hz with blade pass rates at 0.5 to 0.7 Hz.

Under the hypothesis of nausea produced by a periodic forcing acceleration on the inner ear either at rotation or blade pass rates, the Nordex N100 operates in or near the documented range of highest potential for nauseogenicity. Earlier turbine models studied for annoyance (primarily the stall- regulated models shown) have shorter, stiffer blades with smaller bending moments and do not have rotation rates near the peak potential nauseogenic frequencies. Consistent with the hypothesis, a limited review of a previous wind turbine noise study on community effects near smaller wind turbines [3] did not find nausea.

The only range of frequencies capable of creating an identical level throughout an enclosed structure are frequencies with wavelengths significantly larger than the size of the enclosed volume (the house). This points to the lower infrasonic frequency range below 10 Hz. This is consistent with the nauseogenic hypothesis for a driving force near 0.2 Hz and, the highest sound levels which were measured in the range of 0.2-0.4 Hz (see main report) with the wind turbines turning at 9 to 14 rpm (0.16 to 0.25 Hz) with blade pass rates of 0.5 to 0.7 Hz. While the highest sound levels indoors were down near 0.2 Hz, the most strongly coupled acoustic frequencies were the first several multiples of 0.7 Hz.

Shirley neighbors reported sleep interference in affidavits. Sleep deprivation magnifies the occurrence of motion sickness because it interferes with the vestibular system habituation process [4]. Further, many people suffer the misery of motion sickness without vomiting [4].

Conclusions

Nauseogenicity is a factor at Shirley. Acceleration of the inner ear is suggested due to extremely low-frequency pulsations at the rotation and blade pass rates that occur in or near the frequencies of highest potential for nauseogenicity and, are coupled strongly into the homes now abandoned. More research at Shirley is recommended to understand nauseogenicity from wind turbine operations, to properly design and site large industrial wind turbines (over 1 MW) near residential areas to prevent the severe health effects. More work is needed to establish what infrasonic levels are consistent with relief for the neighbors.

Medical research and measurement is urgently needed to be field coordinated along with infrasonic acoustic and vibration testing. The correlations to nauseogenicity at the 2.5MW power rating and size suggest worsening effects as larger, slower-rotating wind turbines are sited near people.

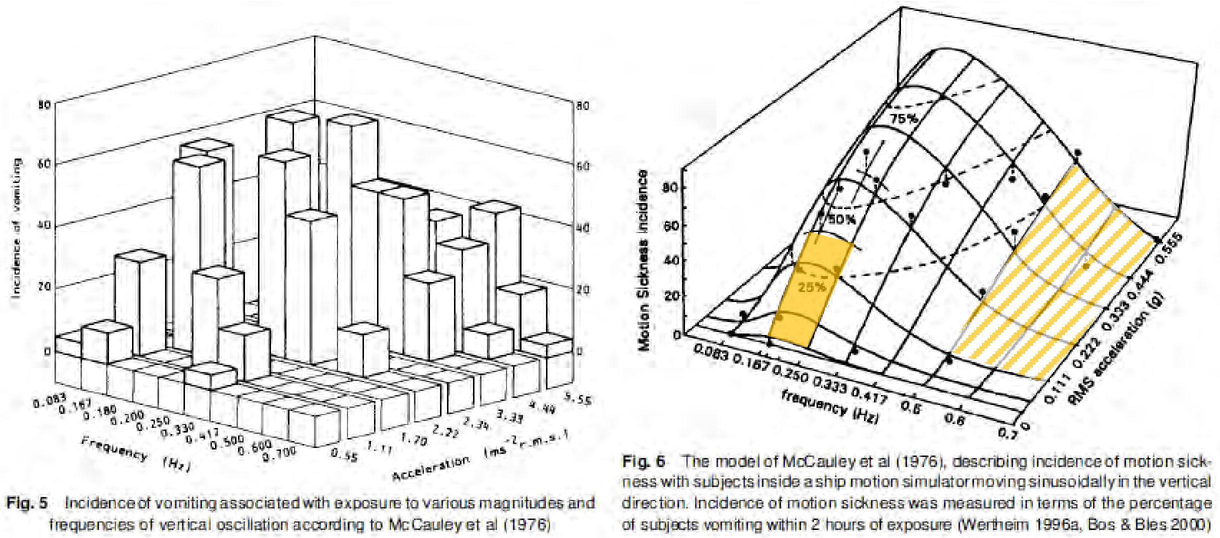


Figure 1. From Stevens et al (2002) Figure 5 showing incidence of vomiting associated with vertical oscillation according to McCauley et al (1976) and modeled. Colored patches postulate association between rotational rate (solid), BPF(striped) and response at Shirley (nausea, did not vomit); acceleration level was not measured.

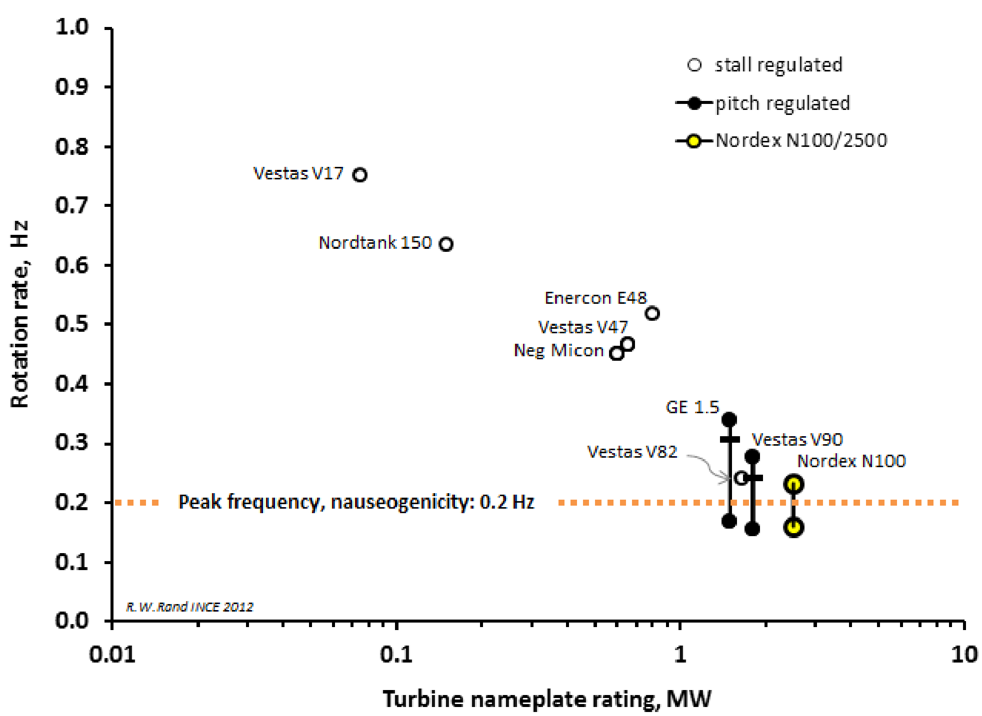
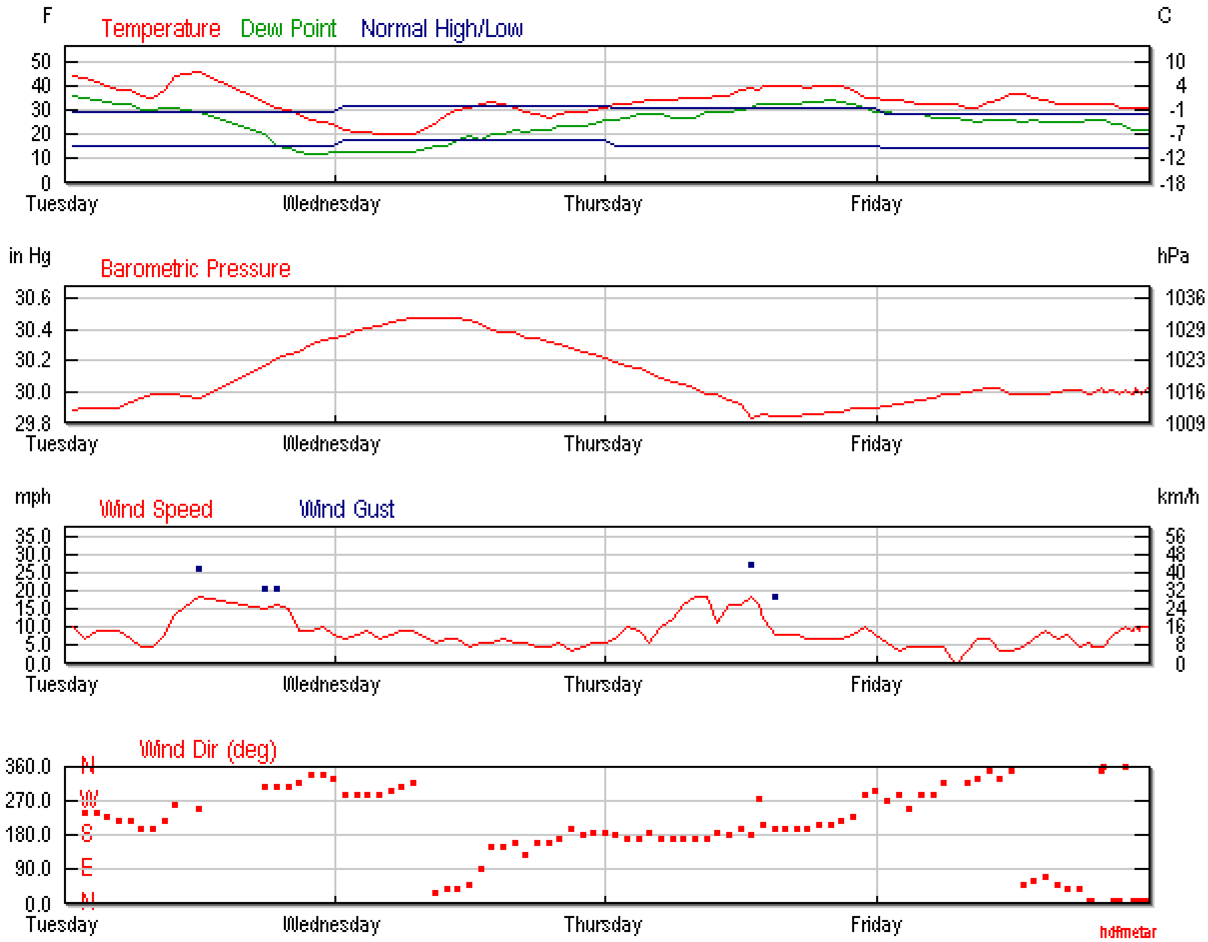


Figure 2. Chart of wind turbine rotation rates (Hz) for various wind turbine models including the Nordex N100. Note nauseogenicity range is 0.1 to 1 Hz with peak potential noted at 0.2 Hz. Note bars on GE 1.5 and Vestas V90 models indicate nominal rotation rate.

Figure 3. Weather conditions during investigations, December 4-7, 2012.



Weather source: KGRB Green Bay, WI. December 4-7, 2012
http://www.wunderground.com/history/airport/KGRB/2012/12/4/CustomHistory.html?dayend=7&monthend=12&yearend=2012&req_city=NA&req_state=NA&req_statename=NA&MR=1

Table 1. Symptom reports logged during investigations.

Date	Time	Location	Condition	Report By
12/4/2012	before 8:15 pm	R1 - Enz	Intolerable (left the home).	Mrs. Enz
12/4/2012	after 8:15 pm	R1 - Enz	Lessened. (sound levels dropped)	Rand Schomer, Rand
12/4/2012	9:30 pm	R2 – Cappelle	Dizzy, tight chest. (No sensation)	Mrs. Cappelle (Mr. Cappelle)
12/5/2012	7 am	R1 – Enz	Slept at R1. Nauseous on awakening (very unusual).	Rand
12/5/2012	11:45 am	R1 – Enz	Feel okay. WTs stopped.	Rand
12/5/2012	12::45 pm	R3 – Ashley	Feel all right. Light winds, only 2 of 8 WTs turning	Rand
12/5/2012	8:38 pm	R2 - Cappelle	Headache, left ear full.	Rand
12/5/2012	9 pm	R1 – Enz Kitchen area	Chest pain (both parties) Left ear pain "Pain of wall echoing off head."	D. Enz, D.Ashley D. Enz D. Ashley
12/5/2012	9:10 pm	R1- Enz Kitchen area	Both ears feel blocked.	Rand
12/5/2012	9:23 pm	R1 – Enz Blue bedroom	Feeling okay. Not comfortable.	Rand D. Enz, D. Ashley
12/5/2012	10:45–11:15 pm	R2 – Cappelle	Felt ill 10:45 pm, felt better around 11:15 pm. Symptoms explained-not WTs.	P. Schomer, Bruce Walker
12/5/2012	11:45 pm	R2 – Cappelle	Feeling okay except pressure in left back of head (very unusual). Stayed listening, judging condition, and observing seismometer until 12/6/12 5:30 am.	Rand
12/6/2012	1:08 pm	R2 – Cappelle	Headache onset, intensified all day (very unusual).	Rand
12/6/2012	2:06 pm	R2 – Cappelle	Pressure in back of head (very unusual, felt only at other wind turbine sites).	Rand
12/6/2012	2:55 pm	R2 – Cappelle	Very dizzy on stairs, almost fell, had to steady with hand, pressure in back of head, strong headache (very unusual).	Rand
12/7/2012	12:02 pm	R3 – Ashley	"very tolerable"; right ear popping and cracking.	D. Ashley
12/9-15/12	after testing	Maine	Dizziness, nausea persist. Eye fatigue. PC work reduced.	Rand

Table 2. Neighbor field notes.

				Enz and Ashley
Name:		Darren Ashley	Location:	Homes
Date	Time	What you were feeling	Wind direction	# turbines on
4-Dec	12-1 pm	Tight chest, slight starting ear pain/pressure	west	4-6
4-Dec	2:30-3:30	Ears burning, more burning as on more turbine starts up	west	4-6
4-Dec	8:45 PM	Ears burning, especially strong sensation as I approached west window in Enz house	west/northwest	6 I think
5-Dec	am	Traveled from Denmark home to Schmidt home, mild ear pain in and outside of home, and while traveling	southeast	on and off
5-Dec	3-4:30 pm	At Schmidt home, in basement, fixing furnace, mild ear pain, very anxious all day into evening.	southeast	6 of 8
5-Dec	9-9:45 pm	pain in middle of my chest at Enz house, could not sit in kitchen against north wall because of head pain/pressure, no strong sensation as I would approach window west windows	south/southeast	6 of 8
6-Dec	12-12:45 am	felt strong presence in cozy room at Schmidt house, better outside not nearly as anxious all day	south/southeast	8
6-Dec	12-12:45 am	I had a tight neck while sitting on couch at Schmidt house, waiting for test	south/southeast	8
6-Dec	11:30 AM	drove thru wind farm, no issues, no pain, no headache	south	ZERO
6-Dec	12:40-12:50 pm	Driving home from Schmidt home thru wind farm I had a splitting headache, which lessoned as got further away.	south	7
6-Dec	4:15 PM	Stood on Glenmore road, close to Shirley road, felt sicker and sicker through my body the longer I stayed	south/southwest	6?
6-Dec	4:25 PM	could feel pressure in cozy room at Schmidt house, not as strong as night before, but still detectable	Southwest	5
6-Dec	4:35 PM	While testing I stepped outside, two turbines at School rd were off, I could immediately feel pressure in my right ear as the two turbines started up, reported this to Rand. At Schmidt home	Southwest	2at School rd and 3 others

Table 2 (continued). Neighbor field notes.

				Enz and Ashley
Name:		Dave Enz	Location:	Homes
4-Dec	8:30 AM	Headache, tight chest, unstable at Enz home	west	4
4-Dec	3:00 PM	blurred vision, tight chest, head pressure at Enz Home	West	4-5
5-Dec	am	head and ear pressure, felt upstairs in Schmidt house from turbines dir	S-SE	1-3
5-Dec	9-10 pm	At Enz home, felt chest pain mostly on left side-it moved toward the center. It felt like my forehead was being pushed into my head, ear pressure, pain queasy stomach.	SE I think	8?
5-Dec	Midnight	At Schmidt house, head pain and ear pressure, both downstairs along east side of house where it was the worst, eyes blurry, upset stomach and unstable	SE	
6-Dec	1:00 AM	we stopped on Highview RD and videoed turbines, loud whooshing and thumping sounds varied a lot as the turbines meshed with each other.	SE	
6-Dec	1:45 AM	while laying in bed, my chest started to quiver, I checked my pulse, it seemed OK. It lasted a few minutes. Eyes are blurry and I am very unstable, I don't feel well yet.	In Denmark away from turbines	
6-Dec	8:00 AM	At Denmark House, away from turbines. Working on computer difficult due to blurry vision/eye strain. Still unstable and nauseated. I don't feel well, hope it will pass soon. Ears are still burning and sore. I don't think I will go among turbines today. I am not sure being a lab rat. Left eye seems out of touch with right eye.	In Denmark away from turbines	

Name:		Rose Enz	Location:	Enz Home
Date	Time	What you were feeling	Wind direction	# turbines on
4-Dec	8:30 AM	My ears started hurting as we retrieved some items out of the house before testing	tails to the house	
4-Dec	8:45 PM	My ears started hurting and then I started side stepping as not walking in a straight line. I had a hard time not tripping over all the wires. I sat down in my rocker chair, kitchen corner for a short time, felt sick to my head and stomach.	tails to the house	

APPENDIX D
by
SCHOMER AND ASSOCIATES, INC.

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December 21, 2012

I) Observations from discussions with residents:

Four of the five researchers; George Hessler, David Hessler, Bruce Walker, and Paul Schomer met with affected residents of Shirley and discussed the problems they had that were precipitated by the wind turbines. This discussion produced several notable points not previously known by this researcher.

1. At most locations where these health problems occurred, the wind turbines were generally not audible. That is, these health problems are devoid of noise problems and concomitant noise annoyance issues. The wind turbines could only be heard distinctly a one of the 3 residences examined, and they could not even be heard indoors at this one residence during high wind conditions.

2. The residents could sense when the turbines turned on and off; this was independent of hearing the turbines.

3. The residents reported "bad spots" in their homes but pointed out that these locations were as likely to be "bad" because of the time they spent at those locations, as because of the "acoustic" (inaudible) environment. The residents certainly did not report large changes from one part of their residences to another.

4. The residents reported little or no change to the effects based on any directional factors. Effects were unchanged by the orientation of the rotor with respect to the house; the house could be upwind, downwind, or crosswind of the source.

5. Residents of the nearest house reported that their baby son, now 2 years old, would wake up 4 times a night screaming. This totally stopped upon their leaving the vicinity of the wind turbines, and he now sleeps 8 hours and awakens happy.

I) Implications of these observations:

1. The fact that these residents largely report wind turbines as inaudible, and the reported effects on a baby seem to rule out the illness being caused by extreme annoyance as some have suggested.

2. The lack of change with orientation of the turbine with respect to the house and the lack of change with position in the house suggest that we are dealing with very low frequencies; frequencies where the wind turbine size is a fraction of the wavelength--about 3 Hz or lower.

II) Observations from results of measurements:

1. These observations are based upon the coherence plots and coherence graphs produced by Bruce Walker. He produced both amplitude, frequency and coherence plots and 10 minute coherence charts showing only amplitude and frequency. While both show the same thing, this analysis concentrates on the latter because the former have only a 30 dB dynamic range. Figures 1 and 2 show the coherence between the outdoor ground plane microphone and 4 indoor spaces at Residence 2: the living room, the master bedroom, behind the kitchen, and in the basement. Figure 3 shows the single valid example of basement measurements at Residence 3. The data from Residence 2 are for optimum wind conditions in terms of the turbine operation. Whereas the data at Residence 3 are for low wind conditions and not necessarily indicative of what would be found were the wind turbines operating at normal power.

2. In Implications (I), it is inferred from the resident observations that the important effects result from very low frequency infrasound, about 3 Hz or lower. We can test the assertion with the data collected at the three residences at Shirley. Only Residence 2 was tested during optimum wind conditions, so that is the primary source of data used herein. Figures 1 and 2 show the coherence

between the outdoor ground plane microphone and the four indoor spaces listed above. First, we examine Figure 1. All of the four spaces exhibit coherence at 0.7 Hz, 1.4 Hz, 2.1 Hz, 2.8 Hz and 3.5 Hz, and in this range there is no coherence indicated except for these five frequencies. The basement continues, with coherence exhibited at 4.2 Hz, 4.9 Hz. 5.6 Hz, 6.3 Hz and 7 Hz. The coherence in the basement drops low from 10-18 Hz and is more or less random and low after 18 Hz. Figure 1b shows the coherence just for the frequency range from 10 Hz to 35 Hz, and essentially this figure exhibits random patterns with no correlation from one room to the next. For example, coherence with the microphone behind the kitchen is high from 10-14 Hz and the master bedroom is high from 12-14 Hz while the other two spaces exhibit low coherence, and again the master bedroom is high 28-35 Hz with the others being low, and the living room is high from 50-58 Hz with the other spaces low; no pattern. In contrast all four spaces are lock step together in their coherence with the outdoor microphone below about 4 Hz. Figure 2, another sample from Residence 2 shows much the same pattern. In this case, 0 .7 Hz, 1.4 Hz, 2.1 Hz clearly are evident for all four spaces. For some reason 2.8 Hz is much reduced for the living room but 3.5 Hz is evident for all four spaces. In terms of the basement a number of other peaks are evident up to about 8 Hz where the basement then falls low until about 18 Hz and is random thereafter. As with Figure 1, there is no pattern to the coherence function above about 8 Hz.

3. Residence 2, and indeed all three residences, exhibit classic wall resonances in about the 10-35 Hz range which are different for each room and exposure, so it is reasonable to suppose that the randomness in the 10-35 Hz region in the above ground rooms is the result of wall resonances. The basement, which has no common wall with the outside, exhibits generally the lowest coherence in the 10-35Hz region. Thus, I conclude that the only wind turbine related data evident in the measurements at Residence 2 are the very low frequencies ranging from the blade passage frequency of 0.7 Hz to up to about 7 Hz. This conclusion is consonant with the residents' reports that the effects were similar from one space to another but a little to somewhat improved in the basement, the effects were independent of the direction of the rotor and generally not related to audible sound.

4. Figure 4 shows the coherence as functions of both time and frequency, and it is clear that the basement shows the greatest coherence below 8Hz of the four spaces and the least coherence above 8Hz. This result further supports the conclusion that it is the very low frequencies that are important.

5. Figure 3 is for Residence 3 which was 7000 feet from the nearest turbine, in contrast to Residence 2 which was only 1100 feet from the nearest turbine. Even here with much reduced amplitude there seems to be several frequencies where the four spaces have peaks together beginning at 0.8 Hz. However, unlike Residence 2, the coherence functions for all four of the space move together from about 15 Hz to 70 Hz. The sound pressure level at the outdoor microphone and at each of the four indoor spaces shows every harmonic from what appears to be the first harmonic at 20 Hz through 200 Hz. To my thinking this was clearly a loud outdoor source with a fundamental frequency of just under 20 Hz. And indeed it was. I called Bruce and he told me it was a helicopter. (I was not present the last day)

6. Figure 5 shows the sound pressure level for first minute of the 10 minutes represented by Figure 1, above. This figure, which is sensitive to the lowest frequencies shows that at these very low frequencies the sound pressure level in all four spaces is quite similar. The small changes from different positions in the house also suggests that the house is small compared to the wavelength so that the insides of the house are acting like a closed cavity with uniform pressure throughout being driven by very low-frequency infrasound.

II) Implications of the measurements:

1. The measurements support the hypothesis developed in (I)that the primary frequencies are very low, in the range of several tenths of a Hertz up to several Hertz. The coherence analysis shows that only the very low frequencies appear throughout the house and are clearly related to the blade

passage frequency of the turbine. As Figure 5 shows, the house is acting like a cavity and indeed at 5 Hz and below, where the wavelength is 200 Ft or greater, the house is small compared to the wavelength.

III) Observations from related literature:

1. We consider a 1987 paper entitled: Motion Sickness Symptoms and Postural Changes Following Flights in Motion-Based Flight Trainers .

This paper was motivated by Navy pilots becoming ill from using flight simulators. The problems encountered by the Navy pilots appear to be somewhat similar to those reported by the Shirley residents. This 1987 paper focused on whether the accelerations in a simulator might cause symptoms similar to those caused by motion sickness or seasickness. Figure 6 (Figure 1 from the reference) shows the advent of motion sickness in relation to frequency, acceleration level and duration of exposure. To develop these data, subjects were exposed to various frequencies, acceleration levels and exposure durations, and the Motion Sickness Incidence (MSI) was developed as the percentage of subjects who vomited. Figure 6 show two delineated regions. The lower region is for an MSI of 10%. The top end of this region is for an exposure duration of 30 minutes and the bottom end is for eight hours of exposure. The upper delineated region has the same duration limits but is for an MSI of 50%. The acceleration levels indicated for the SH3 Sea King Simulator show that the accelerations in the y and z direction went well into the nauseogenic region as defined by the Navy, whereas the P3-C Orion simulator had comparable accelerations in the x direction and lower accelerations in the y and z direction. Not surprisingly pilots' reports of sickness increased dramatically after exposure to the SH3 simulator while exposure to the P3 -C simulator had virtually no effect on reports of sickness.

2. What is important here is the range encompassed by the delineated regions of Figure 6. Essentially, this nauseogenic condition occurs below 1 Hz; above 1Hz it appears that accelerations of 1G would be required for the nauseogenic condition to manifest itself. While the Navy criteria are for acceleration, in Shirley we are dealing with pressures in a closed cavity, the house. Acceleration of the fluid filled semi-circular canal in the ear will manifest itself as force on the canal. The similarity between force on the canal from acceleration and pressure on the canal from being in a closed cavity suggest that the mechanisms and frequencies governing the nauseogenic region are very similar for both pressure and acceleration.

3. As the generated electric power of a wind turbine doubles the sound power doubles and the blade passage frequency decreases by about 1/3 of an octave. The wind turbines at Shirley have a blade passage frequency of about 0.7 Hz. This suggests that a wind turbine producing 1 MW would have a blade passage frequency of about 0.9 Hz, and on Figure 6, a change from 0.7 Hz to 0.9 Hz requires a doubling of the acceleration for the same level of response. Thus, it is very possible that this nauseogenic condition has not appeared frequently heretofore because older wind farms were built with smaller wind turbines. However, the 2 MW, 0.7Hz wind turbines clearly have moved well into the nauseogenic frequency range.

III) Implications from the Navy's Nauseogenic Criteria:

1. This analysis suggests that similar problems to the problems in Shirley can be expected for other wind turbines that have the same or lower fundamental frequency. The Navy criteria suggests that to maintain the same level of health-related effects as have occurred heretofore, the levels of a 2 MW,0.7 Hz wind turbine as experienced in the community must be 6 dB lower than those for 1 MW, 0.9 Hz wind turbine. Moreover, Figure 6 does not bode well for future larger wind turbines if they go even lower in frequency.

IV) Descriptors for Wind Turbine Emissions

1. Currently the wind turbine industry presents only A-weighted octave band data down to 31 Hz. They have stated that the wind turbines do not produce low frequency sound energies. The

measurements at Shirley have clearly shown that low frequency infrasound is clearly present and relevant. A-weighting is totally inadequate and inappropriate for description of this infrasound. In point of fact, the A-weighting, and also the C and Z-weightings for a Type 1 sound level meter have a lower tolerance limit of -4.5 dB in the 16 Hz one-third-octave band, a tolerance of minus infinity in the 12.5 Hz and 10 Hz one-third- octave bands, and are totally undefined below the 10 Hz one-third-octave band. Thus, the International Electro-technical Commission (IEC) standard needs to include both infrasonic measurements and a standard for the instrument by which they are measured.

V) The Tests We Should Perform

1. That the wind turbines make people sick is difficult to prove or disprove. However, the sensing of the turbines turning on or off is testable. Consider the two houses where there is no audible sound. Residents would arrive at the house with the wind turbines running for something like a 2-hour test. Sometime during the first hour, the wind turbines might or might not be turned off. If turned off, it would be the residents task to sense this "turn off" within some reasonable time--say 1 hour. Correct responses (hits) would be sensing a "turn off" when the turbines were turned off, or sensing no change if they were not turned off. Incorrect responses (misses) would be failure to sense a turn off when the turbines were turned off, or "sensing" a turn off when the turbines were not turned off. Similar tests could be done starting with the turbines initially off.

2. It would be necessary to prevent the subjects from seeing the turbines or being influenced by one another. If everyone marked a silent response on their board or into their laptop at the same time; say every 5 minutes, then no one would be able to know another person's responses. Pure chance is 50/50, so a hit rate statistically significantly greater than 50/50, and/or a miss rate statistically significantly less than 50/50 would indicate that the residents were able to sense the wind turbines without the use of sight or sound.

3. Testing would take about 3 to 5 good days; days when the wind was such that the wind turbines were operating at a substantial fraction of full power. Up to 3 tests per day could be done, with 3-4 subjects in each of the two, or possibly 3, houses. Physical measurements would be made of the before and after conditions at each house simultaneously to correlate with the sensing tests. Each subject would be tested up to 5 times. Note: Testing multiple times per day presupposing that the subjects could tolerate such a rigorous testing schedule.

4. The testing would require at least 1 researcher at each house to take the physical measurements and one researcher to supervise the sensing test with one test "proctor" per test room. It would be necessary for the proctor to help the researcher performing the physical measurements during non-test hours with activities like calibration.

5. Conduct of this test clearly requires the assistance and cooperation of Duke Energy. This test can only be done if Duke Energy turns on and off the turbines from full power, as requested and for the length of time requested.

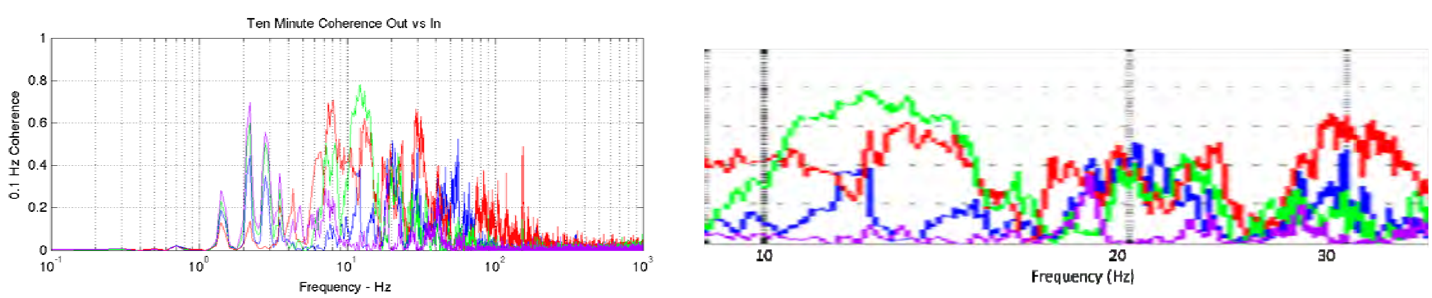


Figure 1a, b: R2-5T212420--coherence with outdoor-ground plane microphone; Living Room-Blue, Master Bed Room- Red, Behind Kitchen- Green, Basement-Purple, b is an expanded view from 9` Hz to 35 Hz

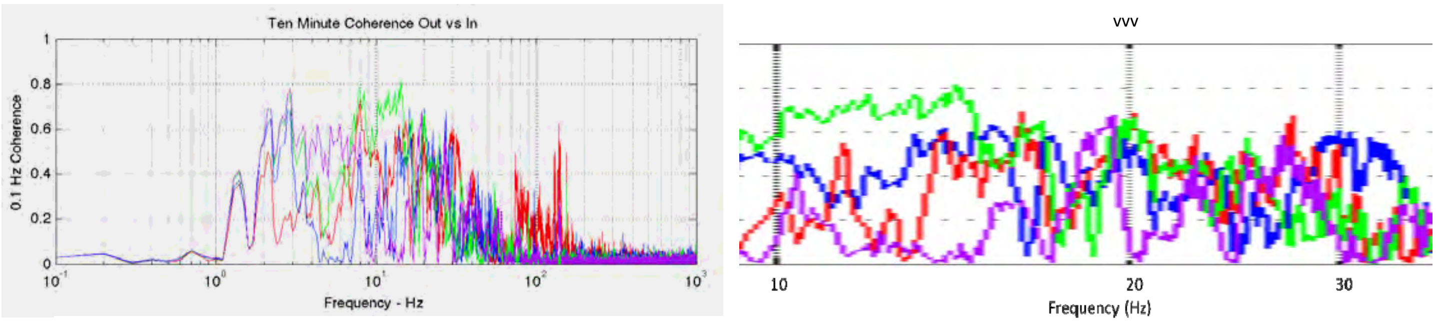


Figure 2a, b: R2-5T204657--coherence with outdoor, ground-plane microphone; Living Room-Blue, Master Bed Room-Red, Behind Kitchen- Green, Basement-Purple, b is an expanded view from 9 Hz to 35 Hz

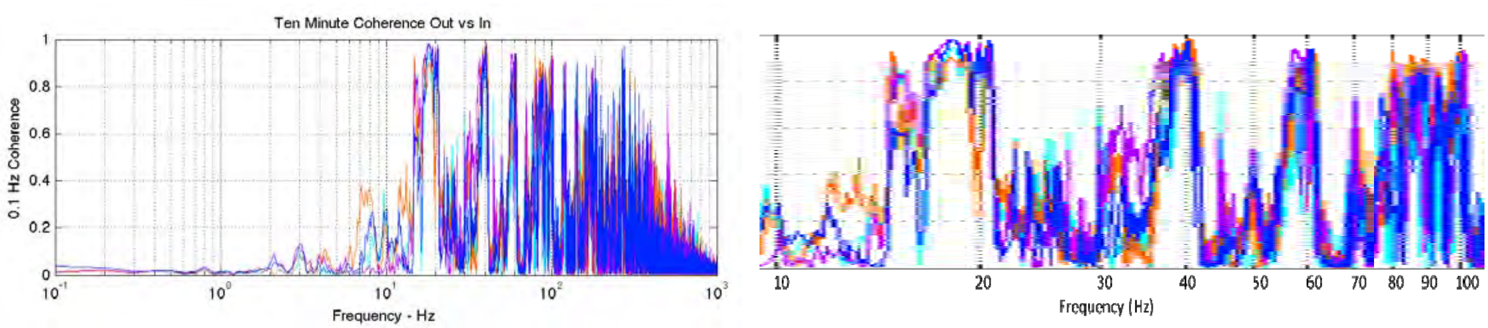
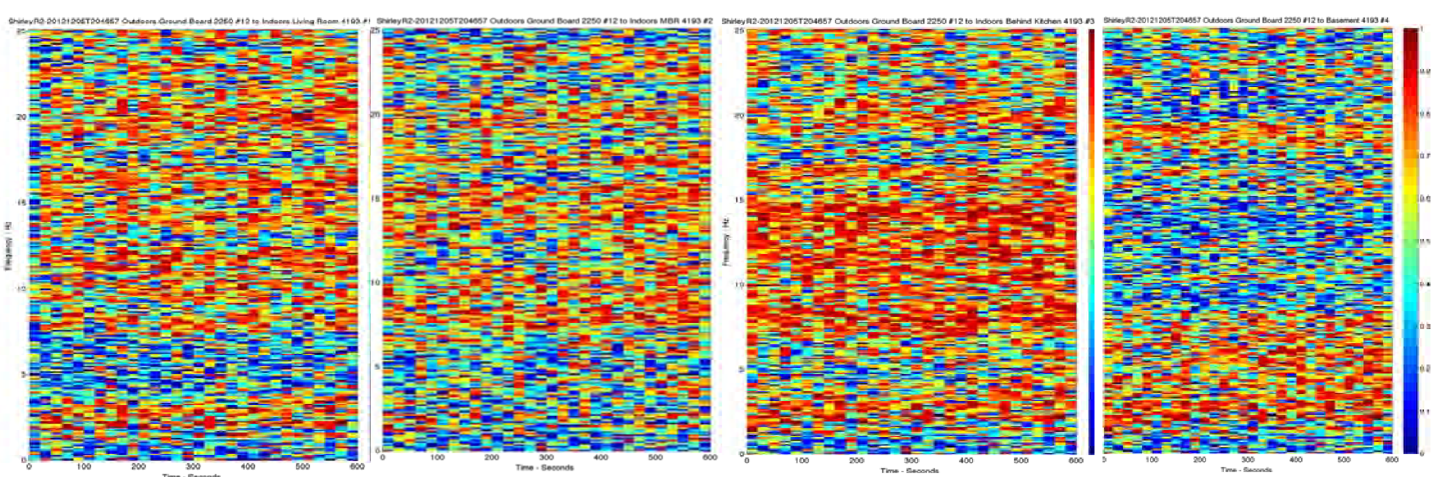


Figure 3a, b: R2-5T204657; Living Room-Blue, Upstairs Bed Room- Orange, Family Room- Turquoise, Basement-Purple, b is an expanded view from 10 Hz to 100 Hz. Note the strong coherence from 20 through at least 80 Hz that resulted from a nearby Helicopter.



4a- Living Room 4b- Master Bed Room 4c- Behind Kitchen 4d- Basement

Figure 4a,b,c,d- Coherence with the outside ground microphone and the four inside microphones in the locations indicated. Note the Basement (4d) which does not have walls coincident with outside shows high coherence at the wind turbine blade passage frequency for several harmonics and almost no coherence above about 8 Hz where the at or above ground walls are resonant.

5

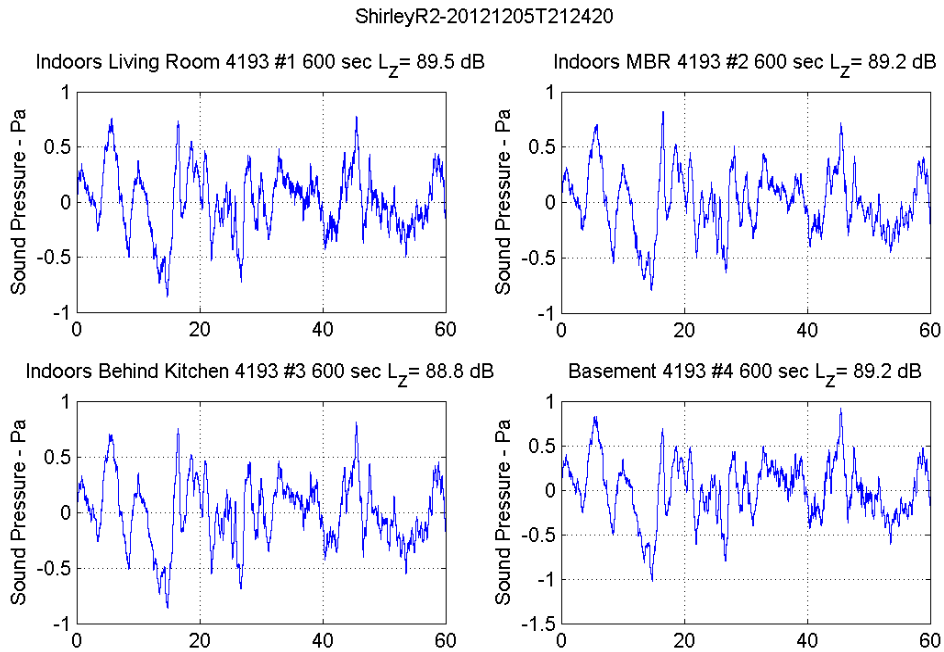


Figure 5- First of the ten minute period of 5T212420. Note that the SPL is very similar for all indoor locations.

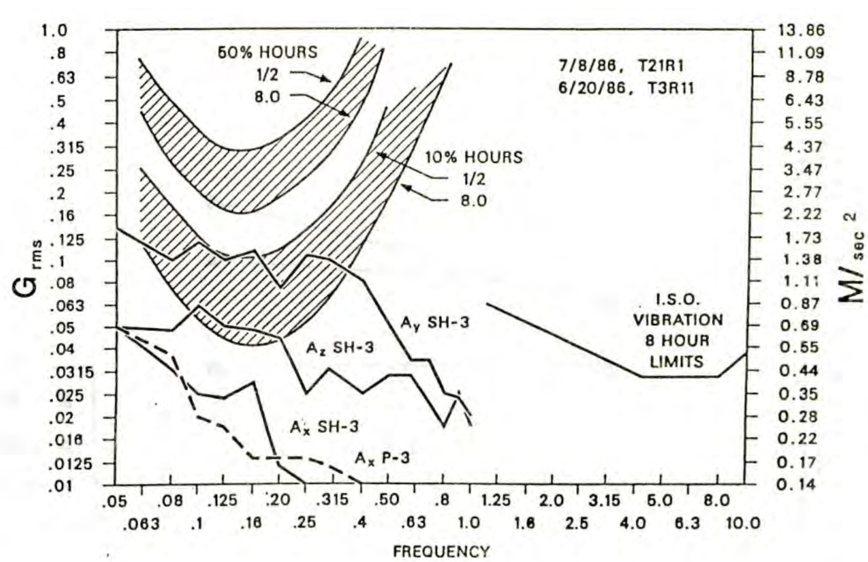


Figure 6. SH3 Sea King Nominal Run vs P-S Orion Nominal A_x

Figure 1 from "Motion Sickness Symptoms and Postural Changes Following Flights in Motion-Based Flight Trainers"

R.S. Kennedy, G.O. Allgood, B.W. Van Hoy, M.G. Lilienthal, **(1987).** " Motion Sickness Symptoms and Postural Changes Following Flights in Motion-Based Flight Trainers," Journal of Low Frequency Noise and Vibration, **6** (4), 147-154.

EXHIBIT 2
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Comments

Impact of Renewable Energy Sources on Birds of Prey

Chapter · July 2018

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Birds of Prey

Biology and conservation in the XXI century

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Contents

Chapter 13
Impact of Renewable Energy Sources on Birds of Prey

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Introduction

Renewable energy, defined as energy generated from natural processes that are replenished over time (Johnson and Stephens 2011), is increasingly important in global energy portfolios. This chapter begins by reviewing reasons for shifting from fossil fuels to renewable energy, including reasons which have nothing to do with environmental concerns but are nevertheless driving advances in the renewable sector. The chapter then focuses on birds of prey, describing actual and potential direct and indirect mortality, habitat loss, avoidance, and displacement resulting from the development and operation of renewable energy facilities. The chapter considers renewable energy facilities themselves, including wind, biofuel, solar, hydro, geothermal, and oceanic energy sources. Transmission connections linking renewable facilities to the existing electric transmission grid are considered, as are potential offsite impacts where the materials used to construct renewable infrastructure are mined and manufactured. The chapter closes with a discussion of mitigation strategies designed to reduce or compensate for negative impacts for birds of prey and a discussion of potential benefits of renewable energy facilities for birds of prey. The latter are important to understand when evaluating the overall balance of costs and benefits of renewable energies on birds of prey.

Knowledge of the connections between global conflicts and international dependencies on fossil fuels is important in understanding how macroeconomic forces independent of environmental concerns drive the advancement of renewable energy technologies. Because "green" initiatives may not in fact be grounded in environmental concerns, but be grounded instead in economics and national interests, potential negative environmental impacts of renewables and their high initial investment costs may carry little weight in the overall discussion, a paradox not readily apparent without consideration of the context of global competition over traditional energy reserves.

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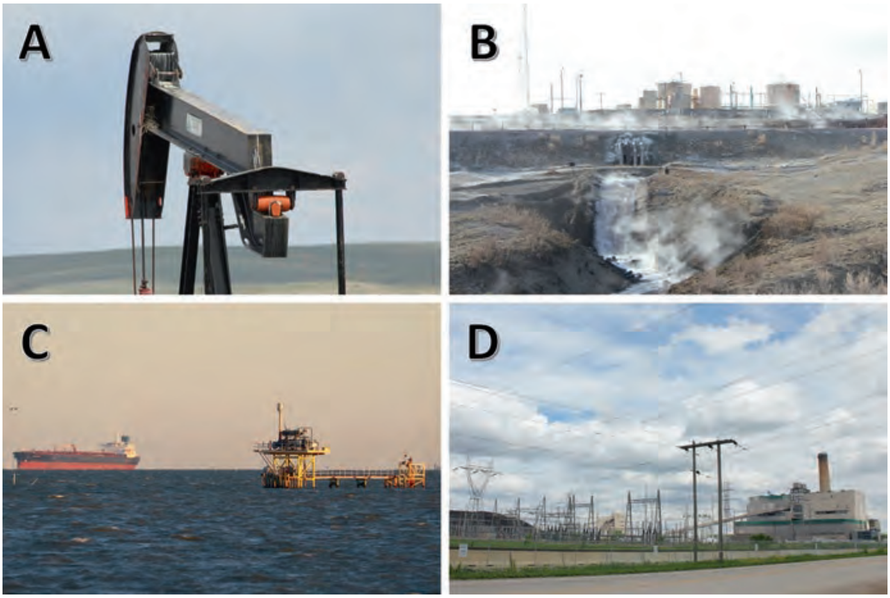

Fig. 13.1 (**a**) A pump designed to extract liquid and gas fossil fuels from terrestrial deposits; note great horned owl (*Bubo virginianus*) nest and whitewash. (**b**) Collection facility for traditional liquid and gas fossil fuels from terrestrial deposits. (**c**) Transport (left) and collection (right) of traditional fossil fuels, (**d**) Traditional coal-burning electricity generation station

Fossil fuels have been the primary energy source for developing and developed nations since the Industrial Revolution of the early 1800s when coal began to be used to power steam-driven machines and energy-intensive metallurgic and chemical processes. Emissions from these machines and processes were recognized almost immediately as harmful, triggering early environmental responses to protect urban air and water. From the late 1800s through the early twenty-first century, fossil fuels remained the primary solution to global energy needs as petroleum and natural gas products made the storage and use of chemical energy more efficient and economical (Fig. 13.1).

The resulting dependence of national and international economies on fossil fuels has created two fundamental problems. The first is a globally ubiquitous reliance on fossil fuels often derived from outside national boundaries. This reliance can place less developed nations with large reserves at the center of conflicts for control of those reserves and can place more developed nations without large reserves at the mercy of nations with reserves. Shifting energy sources from fossil fuels to renewables offers nations the ability to achieve energy independence.

The second fundamental problem created by the global reliance on fossil fuels is the impact of combustion products on the global climate. Greenhouse gases released during combustion of fossil fuels are contributing to global climate changes. Shifting energy sources from fossil fuels to renewables offers nations the ability to achieve energy independence and offers potential environmental benefits. These benefits are not without their own potential costs however, and it is those potential costs, as exerted on birds of prey populations, that are discussed here.

Effects at Renewable Facilities

Potential effects to birds of prey at renewable facilities include direct mortality and indirect effects resulting from habitat loss, avoidance, and displacement. Direct mortality is defined as death occurring as an immediate consequence of an interaction between a bird of prey and a component of renewable infrastructure. For example, a golden eagle (*Aquila chrysaetos*) killed when struck by a rotating wind turbine blade or killed when colliding with the suspended high-voltage wires of a transmission power line connecting a renewable facility to the electric grid. Habitat loss is defined as occurring when the landscape occupied by birds of prey is converted to non-habitat, for example, the displacement of prey species resulting from conversion of hunting habitat to a mirror field for a solar plant or the removal of a nest tree when creating an agricultural monoculture for biofuel production. Avoidance and displacement are similar processes occurring at different scales. Both occur when habitat persists, but is no longer used. Avoidance is defined as a shift in use of specific portions of a renewable facility, not the entire site (Band et al. 2007). Displacement occurs when an entire site is abandoned (Band et al. 2007).

These effects rarely occur in isolation but are instead likely additive, co-occurring with one another and with other anthropogenic and natural agents of mortality. Additive effects can be problematic, even at low rates, because most birds of prey are k-selected species with relatively little annual reproduction and breeding often delayed during multiple years of maturation. Population persistence for many bird of prey species requires individual breeding adults to produce young over an entire lifetime. Mortality of breeding adults can have substantial effects on the population (Bellebaum et al. 2013). For example, at some sites, griffon vultures (*Gyps fulvus*) and red kites (*Milvus milvus*) cannot maintain stable local populations with additive mortality from wind farms (Carrete et al. 2009; Bellebaum et al. 2013).

Wind Resource Areas

Direct effects of wind energy facilities (Fig. 13.2) on birds of prey involve mortality occurring when rotating turbine blades strike birds in flight. Impacts are largely species-specific. Directly affected species are characterized by low-altitude flight when gliding on local winds and on thermal and orographic lifts (Katzner et al. 2012; de Lucas et al. 2008). Because wind turbines are designed and specifically placed to harvest the kinetic energy in some of these same winds, low-altitude flight behaviors largely dictate risk by placing birds of prey and rotating turbine blades

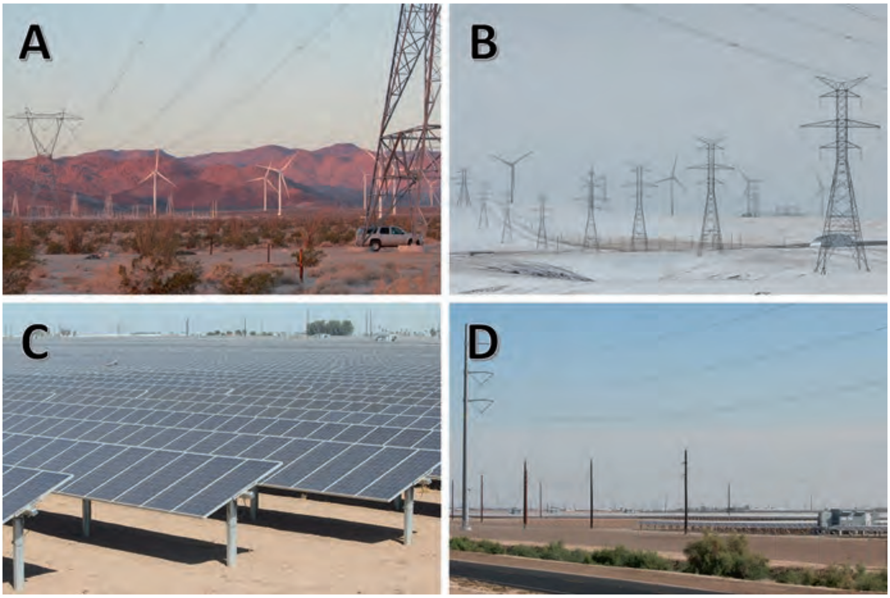

Fig. 13.2 (**a**) A wind resource area in desert habitat; note substation under construction in the background will provide a connection from the wind resource facility to the existing transmission power line network. (**b**) A wind resource area above agricultural fields, potentially facilitating both wind energy and biofuel production. (**c**) Close view of a solar field illustrating the bare and leveled earth (non-habitat) typical of such facilities. (**d**) Wide view of a solar field, illustrating fencing and bare earth designed to limit attractiveness as habitat and illustrating associated distribution and transmission lines

together in the same airspace. Hunting in these airspaces has been hypothesized to hinder the ability of a bird of prey to recognize turbines as a flight hazard (Orloff and Flannery 1992; Smallwood et al. 2009), so species habituated to hunting within wind resource areas can be at higher risk of collision. Collision risk can also increase along flight corridors where large numbers of migrating birds of prey funnel along narrow ridges and coastlines supporting wind energy facilities (Barrios and Rodriguez 2004; Katzner et al. 2012; de Lucas et al. 2012) or where communal roosts occur near wind resource areas (Carrete et al. 2012). Intraspecific and inter-specific interactions during flight also increase risk for collision because birds of prey can be distracted and less likely to recognize flight hazards (Dahl et al. 2013; Smallwood et al. 2009).

Though at least 34 bird of prey species have been documented in collisions with wind turbines, population-level impacts from direct effects are unknown for most species (Beston et al. 2016); only griffon vultures (Carrete et al. 2009), red kites (Bellebaum et al. 2013) and golden eagles (USFWS 2013) are currently known to be at risk of population-level effects from these collisions.

Species-specific behaviors also drive indirect effects of wind resource areas. Species avoiding or displaced by wind resource areas tend not to be affected by direct mortality but may abandon breeding territories (Dahl et al. 2013), shift local space use (Walker et al. 2005), or decrease in local abundance (Garvin et al. 2011; de Lucas et al. 2004). Some species show avoidance behaviors for individual turbine structures by adjusting flight paths to fly between or around turbines (Cabrera-Cruz and Villegas-Patraca 2016; Hull and Muir 2013; de Lucas et al. 2004) or adjust altitude to fly over turbines in their path (Johnston et al. 2014; de Lucas et al. 2004). There is limited evidence of net population loss in birds of prey from avoidance or displacement attributable to wind resource areas, but effects could be important for threatened species when considered with direct effects (Martínez et al. 2010).

Biofuels

Biofuels primarily describe energy resources developed from agriculture and most often describe production by industrial farms focused on extracting the greatest possible crop yields per acre. Yields are maximized by eliminating as many non-producing inclusions as possible and by promoting maximum growth through regular inputs of synthetic chemicals. Eliminating inclusions requires conversion of potential nest groves and bird of prey hunting habitat to cropland. Chemical inputs regularly consist of fertilizers to maximize crop yields, and pesticides, rodenticides, and herbicides, to protect monoculture crops from competing organisms in the environment. Collectively, these processes contribute to agricultural intensification which has been at least partly responsible for declines in farmland bird populations (Campbell et al. 1997; Uden et al. 2015).

Meeting increasing demand for ethanol requires increasing cropland in production, and consequently, the development footprint of biofuels is expected to be one of the fastest growing of all renewable energy sources in the next two decades (Johnson and Stephens 2011). Impacts of biofuel energy production on birds of prey occur primarily due to indirect effects triggered by the loss of breeding and foraging habitats when stands of trees used for nesting and open spaces used for hunting are converted to biofuel monocultures. Indirect effects include habitat loss, decreases in prey abundance, and potential biochemical effects from exposure to toxic chemicals. Direct effects are generally limited to rare occurrences of nestling mortality when nest trees are removed during breeding seasons, though exposure to bioaccumulating chemicals may also have effects that have not yet been identified.

Solar Facilities

Solar energy facilities also have the potential to impact birds of prey. Direct effects most often include electrocution on collection power lines, collisions with mirrors, and thermal trauma in solar flux fields (Kagan et al. 2014; McCrary et al. 1986). Electrocution can occur when a bird of prey simultaneously contacts two differently energized conductors or an energized conductor and a path to ground (APLIC 2006, in this book Chap. 12). Collisions occur when birds apparently mistake reflections of the sky in mirrors as the sky itself and attempt to fly through a mirror, perhaps in pursuit of prey.

Solar flux fields are the areas of concentrated light surrounding the collection tower(s) at thermal solar plants. Mirrors are used at these facilities to concentrate solar energy on a single area where water within a container is heated to produce steam which powers a generator. The air around the collection tower can reach 500–800 °C (McCrary et al. 1986; Diehl et al. 2016). Damage to feathers occurs at 160 °C (Wendelin et al. 2016), so flight through a solar flux field can result in burns to feathers and tissues, causing immediate mortality or limiting or eliminating the ability to fly, depending on individual exposure. Unlike other renewable energy technologies like wind turbines, which are relatively benign when not operational, solar flux fields can be dangerous to birds even when solar flux fields are not focused on collection towers (Wendelin et al. 2016). This can occur because mirrors in standby positions often focus solar energy just above collection towers. Heat in these standby positions can be intense enough to harm birds.

Morbidity and mortality of birds of prey in solar flux fields appear relatively rare, but when cases do occur, taxonomic patterns are emerging. Specifically, falcon (Falconiformes) species may be more susceptible, apparently because falcons are attracted to hunt aerial prey concentrated near collection towers (WEST 2016). Alternatively, in both active and standby positions, warm air rising above collection towers may attract buteos and vultures seeking thermal air currents to power flight, and these birds may inadvertently enter solar flux zones regardless of the presence or absence of potential prey.

Indirect effects of solar energy facilities include habitat loss, displacement, and avoidance (Hernandez et al. 2014). Unlike wind energy facilities where some of these effects might be temporary, with birds returning after construction, solar facilities eliminate habitat from within the facility, creating a flat bare earth-scape unattractive for hunting or nesting by birds of prey. Habitat loss at solar energy facilities is generally greater per megawatt generated than at wind facilities because wind resource areas retain most of the habitat below turbines, whereas solar facilities cover much of the facility in mirror arrays. Birds of prey and other wildlife species also may avoid habitats in and around solar facilities as a result of increased human activity and habitat alteration (DeVault et al. 2014).

Other Renewable Facilities

Other renewable energy sources include geothermal, hydroelectric, and oceanic. There are no substantial direct mortality effects to birds of prey documented for these energy sources. Geothermal power stations use heat energy from within the earth's crust to generate electrical energy. Facility footprints are similar to those of liquid and gas fossil fuel extraction facilities, with impacts to birds of prey limited to indirect effects resulting from disturbance during construction and operation. Roads to extraction wells increase habitat fragmentation (Jones and Pejchar 2013), impacting edge-sensitive species. Geothermal emissions often contain vaporized toxins which, while less than coal burning plants, release toxins into the air including hydrogen sulfide, carbon dioxide, ammonia, methane, and boron, mercury, and other heavy metals (Kagel et al. 2007), so indirect effects could also include reactions to toxic emissions.

Hydroelectric and oceanic renewable energy facilities use the energy of flowing rivers or tides to turn turbines and generate electricity. Hypothetically, aquatic hunters like osprey (*Pandion haliaetus*) could become entrapped in the machinery of hydroelectric or oceanic renewable energy infrastructure, but neither of these potential agents of mortality has yet been documented. This indicates that even if mortality occurs, levels are sufficiently low to preclude population impacts. Indirect effects likely do occur, though are not necessarily negative. Construction of reservoirs to store water for a hydroelectric dam floods and destroys bottomland habitats used as nest sites by some bird of prey species, but this habitat loss may be offset by creation of new reservoirs with far more shoreline hunting and nesting habitat than existed previously.

Effects of Transmission Linkages

Renewable facilities are connected to the existing electric system through construction of new transmission lines (Fig. 13.3), termed connections, interconnections, links, or linkages (hereafter interconnections). These interconnections have the potential to create avian collision and habitat fragmentation concerns well away from, but directly attributable to, renewable energy facilities. Post-construction environmental impacts of renewable energy infrastructure are generally considered only within the footprint of renewable energy facilities, but may not include the associated interconnections even though transmission lines are associated with avian collision mortalities (Bevanger 1998; Loss et al. 2014; Rogers et al. 2014). Because renewable interconnections have not yet been thoroughly studied with respect to potential impact to birds of prey, this section summarizes knowledge of potential impacts of transmission lines in general.

Direct effects of power lines on birds occur through mortality caused by electrocution and collision (Bevanger 1998; Loss et al. 2014). Electrocution is limited mostly to distribution lines (<69 kV) where clearances are minimal and birds can simultaneously contact multiple energized components or energized and grounded components (APLIC 2006, in this book Chap. 12). Transmission clearances designed to prevent electrical energy from arcing across conductors generally include separations greater than birds can bridge with extended wings, though there are exceptions on certain configurations used for lower transmission voltages (69–138 kV). Because electrocution is generally of little concern at the transmission voltages used in renewable energy interconnections, and because detailed

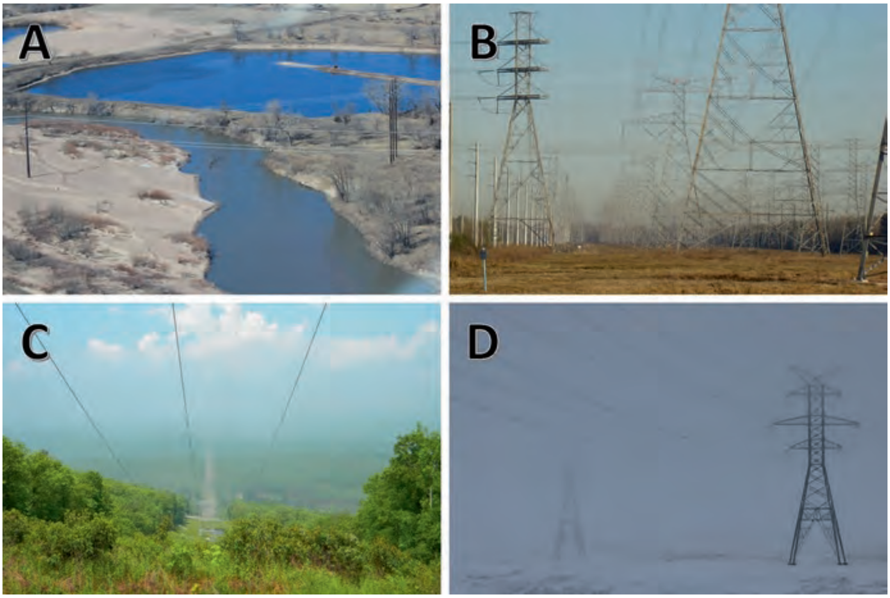

Fig. 13.3 Transmission line issues: (**a**) Transmission line bisecting a water source used by birds as a movement corridor. (**b**) Numerous transmission lines within a transmission corridor. (**c**) Overhead shield wires are less visible than conductors. (**d**) Transmission line partially obscured by fog

discussion of avian electrocution is available elsewhere in this book (in this book Chap. 12), this chapter does not address avian electrocutions.

Avian collision mortality is an ongoing global concern (Sporer et al. 2013; Rioux et al. 2013; Loss et al. 2014), though most research on the topic is not bird-of-prey-specific. Collisions involving transmission lines occur when a flying bird hits suspended wires, most often at night. Transmission lines are typically constructed with relatively thin overhead shield wires at the top and thicker energized conductors below. Birds appear to adjust flight altitudes upward to avoid large-diameter energized wires and then collide with smaller, less visible overhead shield wires (Murphy et al. 2016; Ventana Wildlife Society 2009; Martin and Shaw 2010). Transmission lines do not pose consistent risk. Rather, collision risk varies as a function of avian species and populations in the area of a given line, the surrounding habitat, and the line design (Bevanger and Brøseth 2004; Mojica et al. 2009; Rollan et al. 2010). Among birds, factors affecting collision risk include size, maneuverability, and flocking behavior (Jenkins et al. 2011; APLIC 2012). Transmission lines bisecting daily movement corridors, such as those located between roosting and foraging sites, also have been most associated with avian collisions (Bevanger and Brøseth 2004; APLIC 2012), with risk exacerbated during low-light, fog, and other inclement weather conditions (APLIC 2012; Hüppop and Hilgerloh 2012).

Birds of prey are at relatively low risk for power line collisions in general (SAIC 2000; Rioux et al. 2013), though large raptors with high wing loading and poor in-flight maneuverability like bustard species and condor species are collision prone.

In part, collision risk is low for birds of prey because they tend to fly diurnally during good weather (Ligouri 2005) and appear to detect and avoid transmission lines (Pope et al. 2006; Luzenski et al. 2016). Though risk for birds of prey is low compared to some other avian groups, collisions involving birds of prey do occur (Olendorff and Lehman 1986; Rollan et al. 2010, in this book Chap. 12). For example, California condors (*Gymnogyps californianus*) have collided with power lines (Snyder 2007), the Ventana Wildlife Society (2009) documented collisions by a northern harrier (*Circus cyaneus*) and a white-tailed kite (*Elanus leucurus*), and Mojica et al. (2009) documented multiple carcasses of bird of prey species (bald eagle (*Haliaeetus leucocephalus*), osprey, and owls) under distribution lines. Studies have shown certain African birds of prey are vulnerable to colliding with lines in foraging habitats (Boshoff et al. 2011; Rollan et al. 2010). Peregrine falcons can be at risk because they attain high speeds when pursuing prey near the ground (Olendorff and Lehman 1986). Mañosa and Real (2001) documented both collisions of breeding Bonelli's eagle (*Hieraaetus fasciatus*) and high turnover rates of pairs nesting within 1 km of power lines in Catalonia, Spain. González et al. (2007) documented infrequent collision as a cause of mortality in a study examining 267 records of nonnatural mortality of the Spanish imperial eagle (*Aquila adalberti*).

Indirect effects of transmission lines on birds of prey are not well studied but are likely low following initial disturbance and acclimation during and following construction given the fact that many birds of prey readily nest on or near transmission lines. Transmission lines can create corridors for human incursion into otherwise natural landscapes because maintenance access roads and rights-of-way may be used for recreational activities (hiking, running, mountain biking, cross-country skiing, all-terrain vehicles, etc.). Some bird of prey species respond negatively to recreational human traffic (Steidl and Anthony 1996), but no firm connection has yet been established to confirm widespread impacts with respect to power lines.

Power lines generate strong electromagnetic fields, UV discharges, and acoustic signatures which can affect animal health and behavior (Phernie et al. 2000; Tyler et al. 2014). Recent research suggests that avoidance by reindeer (*Rangifer tarandus*) may be linked to their ability to detect ultraviolet light emitted by transmission lines (Tyler et al. 2014). At least some birds also see in the ultraviolet spectrum (Lind et al. 2014), but the potential implications of this for indirect effects have not been investigated in birds of prey (in this book Chap. 12).

Offsite Effects

Offsite effects are indirect by definition. The natural resources used in constructing renewable infrastructure are typically harvested from areas well beyond the boundaries of renewable project sites. This has the potential to shift some of the environmental costs of renewable energy away from project sites where resources are used, to mine and factory sites where resources are extracted and processed. Consequently, offsite mining should be considered when developing a comprehensive understanding of potential impacts of renewable energy sources on birds of prey.

Effects of mines on birds of prey are site-specific and species-specific. For example, peregrine falcons and gyrfalcons (*Falco rusticolus*) breeding near two diamond mines in Northwest Territories, Canada, showed no difference in nest occupancy or breeding success as a function of distance from mine footprints, despite those footprints expanding during the study (Coulton et al. 2013). In contrast, prairie falcons (*Falco mexicanus*) in New Mexico appeared to avoid an entire mountain range where mining and blasting for various minerals was common but did nest in two adjacent ranges with similar habitats but less mining activity (Bednarz 1984). Mild responses to the vibration and noise associated with mining may derive from the occurrence of such natural events as thunder and landslides (Holthuijzen et al. 1990), with which birds of prey are presumably familiar both individually and over evolutionary time. Across studies, with few exceptions, evidence of disturbance by mining activity seems isolated and in some cases can be offset by relocating birds of prey nests prior to the advance of mine operations (McKee 2007). However, at least some mine sites likely included nesting territories prior to initiation of mining activities. In these cases, productivity from directly affected territories likely was reduced at least while affected individuals sought alternate nest sites. Even these impacts may be minimized, however, with measures specifically designed to support birds of prey populations, for example, through installation during reclamation of permanent structures designed to serve as nest substrates (Harshbarger 1997) and through the use of unreclaimed anthropogenic cliffs used for nesting (Moore et al. 1997). Mines also are associated with environmental pollution. Mining and smelting can lead to increased levels of lead in ospreys and American kestrels (*Falco sparverius*) nesting downstream (Henny et al. 1991, 1994) and in Eurasian eagle owls (*Bubo bubo*; Espin et al. 2014), though to our knowledge, definitive links to survival or productivity specifically related to mine sites have not been established. Though reductions in nesting attempts or productivity appear minimal overall, spills, pollution, and sedimentation from mine sites may have effects that are difficult to link conclusively to evidence of impacts specifically affecting birds of prey.

Though mining does have deleterious ecological consequences, and some examples involving birds of prey can be identified, overall it appears that offsite indirect impacts are either small or difficult to quantify and isolate (Anderson et al. 2008). Regardless of potential effects associated with renewable infrastructure, mined materials would also be necessary for fossil fuel extraction, which renewable energy facilities are designed to replace. That being so, it appears that indirect effects of extractive industries on birds of prey are minimal and offset by equivalent needs across energy sources.

Mitigation

Renewable energy facilities have the potential to bring together ecologically novel combinations of juxtaposed land covers like water bodies in deserts, prominent features like tall perches where none existed naturally, potential risks to wildlife like electrocution and mirror collisions, and potentially, unique combinations of species drawn to these features from their respective native habitats. Consequently, the removal and addition of biotic and abiotic materials at renewable energy facilities may require novel mitigation strategies applied to microclimates and biological communities which may not occur naturally. The rotor-swept zones of wind resource areas and the heated-air zones of solar tower collection areas have no natural analogues and thus no evolutionary context preparing wildlife for the risks encountered in these areas.

It should be incumbent on those creating these new landscapes, to also provide new and effective mitigation. With regard to mitigation of bird of prey mortalities at wind resource areas, innovative techniques are being developed to compensate for mortality at the renewable sites by mitigating the electrocution of birds of prey elsewhere (Fig. 13.4), creating a net benefit overall (USFWS 2013).

Wind energy facilities can also adjust turbine operations to prevent collisions by curtailing operations when birds of prey are flying within the wind resource area, and by increasing minimum operational wind speeds to wind speeds above those within which birds of prey generally choose to fly (USFWS 2013). At solar facilities with collection towers, successful mitigation involves spreading the aim points of mirrors apart to reduce the peak flux value to <4 kW/m^2 when the facility is in standby mode and not actively producing power (Multiagency Avian-Solar Collaborative Working Group 2016). For both wind resource areas and solar facilities, direct and indirect effects may be minimized by siting facilities away from

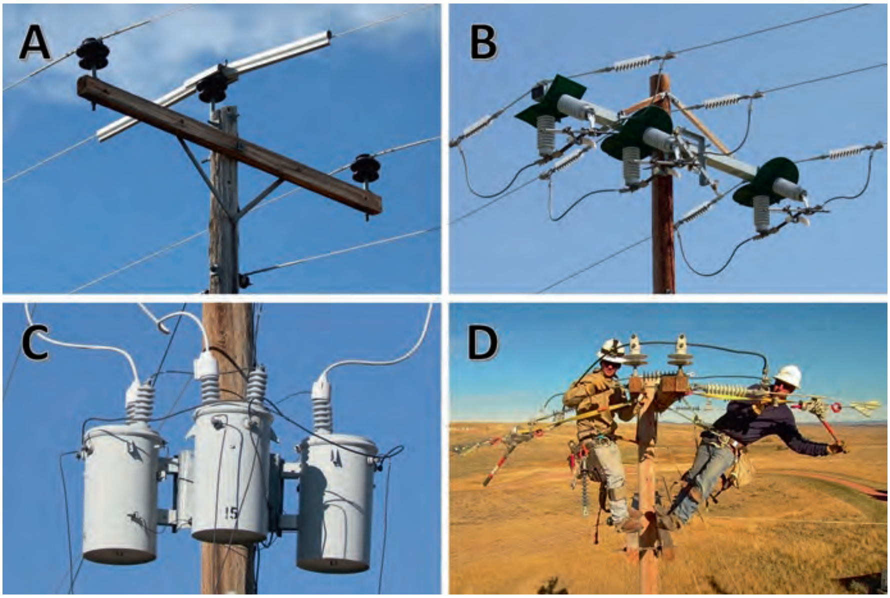

Fig. 13.4 Retrofitted power poles: (**a**) Insulation on center wire. (**b**) Insulation on connecting wires and on switches. (**c**) Insulation on connecting wires and on energized components of equipment. (**d**) Installation of insulation on equipment. (See in this book Chap. 12 for additional technical details on electrocution of birds of prey)

concentrated populations of birds of prey at migration, foraging, or roosting sites. Collisions involving birds of prey and transmission interconnections can be mitigated by marking transmission lines to increase their prominence to approaching birds of prey so lines can be avoided (in this book Chap. 12).

Unlike compensation programs for wind and solar energy, which are still in their infancy, compensation programs for biofuel monocultures are well established within a general framework of minimizing agricultural impacts to natural systems to the extent practical. Mitigation for biofuel monocultures may be achieved through existing mitigation programs, such as the US Department of Agriculture's Conservation Reserve Program which enables farmers to remove environmentally sensitive land from agricultural production in exchange for an annual payment. These types of programs tend to be successful if three obstacles can be overcome. First, because participation is voluntary, individual decisions may be influenced by the value of the payment compared to the value of potential crop yields. This mitigation strategy may lose effectiveness if demands for biofuels, and other crops competing in the market place for the same land, result in crop profits per acre that are greater than payments (Johnson and Stephens 2011). Second, compensation may undermine an individual's sense of responsibility for the land (Ramsdell et al. 2016), potentially resulting in a reduced sense of stewardship over the long term and enabling landowners to justify conversion of natural habitats if compensation programs terminate. Third, compensation programs may not be practical in developing countries lacking the necessary financial or political resources. Despite the potential obstacles involved in compensation-based mitigation programs, these solutions are nevertheless the best currently available, at least in areas like the USA where most arable farmland is privately owned and decisions affecting land use are primarily market driven. Though not necessarily focused on bird of prey concerns, these approaches often result in habitat patches that can contain hunting habitat or potential nest sites, creating focal locations which allow bird of prey populations to persist within areas dominated by agriculture.

Siting new facilities in previously disturbed habitat like nonproductive agricultural fields also can reduce impacts to birds from loss of breeding and foraging habitat (Pearce et al. 2016). Birds of prey can be intentionally displaced from solar projects when nesting sites are destroyed during construction. Burrowing owls (*Athene cunicularia*) have been successfully translocated to new breeding sites away from solar facilities (Multiagency Avian-Solar Collaborative Working Group 2016).

Benefits to Birds of Prey

Birds of prey also can benefit from renewable energy facilities and transmission linkages, primarily through provision of new nesting opportunities (Fig. 13.5) since birds of prey routinely nest on transmission structures. For example, bald eagles and osprey regularly nest on utility structures (Buehler 2000; Poole et al. 2002).

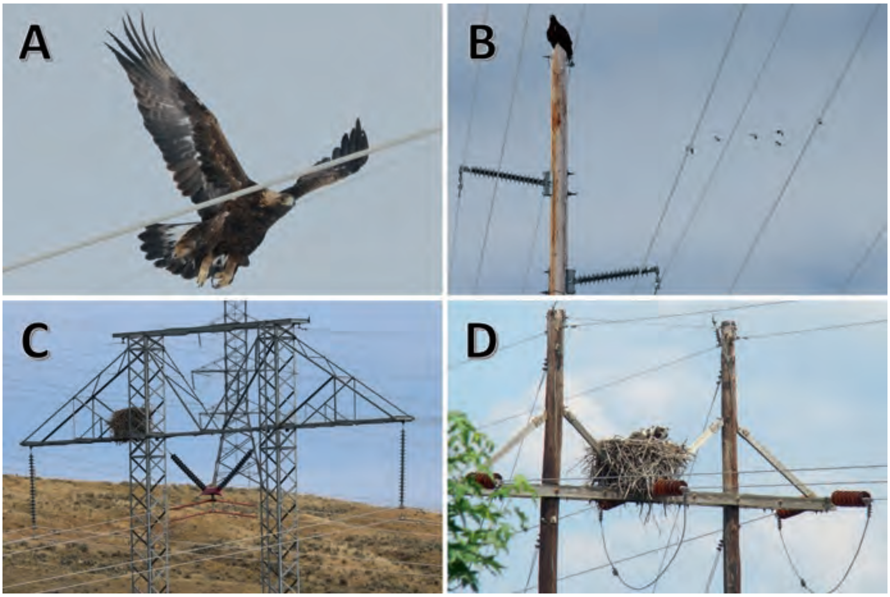

Fig. 13.5 (**a**) A golden eagle (*Aquila chrysaetos*) departing a transmission tower, potentially benefitting through hunting opportunities and, simultaneously, potentially at risk of collision with transmission wires. (**b**) A golden eagle roosting atop a transmission pole. (**c**) A golden eagle nest on a transmission tower. (**d**) An osprey (*Pandion haliaetus*) nest on a transmission H-frame structure

Other species nesting on utility structures include ferruginous hawks (*Buteo regalis*; Gilmer and Wiehe 1977), hobbies (*Falco subbuteo*; Puzović 2008), common kestrels (*Falco tinnunculus*; Krueger 1998), greater kestrels (*Falco rupicoloidesa*; Ledger and Hobbs 1999), martial eagles (*Polemaetus bellicosus*; Jenkins et al. 2013), prairie falcons (Roppe et al. 1989), lanner Falcons (*Falco biarmicus*; Ledger and Hobbs 1999), upland buzzards (*Buteo hemilasius*; Ellis et al. 2009), Swainson's hawks (*Buteo swainsoni*; James 1992), tawny eagles (*Aquila rapax*; Jenkins et al. 2013), black eagles (*Aquila verreauxii*; Jenkins et al. 2013), African hawk eagles (*Hieraaetus fasciatus*; Ledger and Hobbs 1999), and white-backed vultures (*Gyps africanus*, Ledger and Hobbs 1999). Though none of these were on renewable interconnections, the consistency between transmission structures in general and transmission structures supporting renewable interconnections specifically indicates that nesting is likely. Nesting habitat can also be created from mines providing new nest substrates for cliff-nesting birds of prey like peregrine falcons (Moore et al. 1997). Habitat conversion for dams and agriculture can also increase food availability for birds of prey because dams and reservoirs create aquatic habitat and provide abundant year-round food resources for birds of prey including water snakes (Tingay et al. 2010), waterbirds (Mukherjee and Wilske 2006; Mwaura et al. 2002), and stunned or dead fish flowing through dam spillways or turbines (Sánchez-Zapata et al. 2016).

Integrated vegetation management techniques employed in rights-of-way management for renewable energy interconnections can also play an important role in maintaining and improving habitat for wildlife (Ball 2012; Rogers 2016). These activities could create hunting habitat for birds of prey or be used as migration corridors (Denoncour and Olson 1982).

Other indirect benefits may also be important. The fundamental motivators of shifting global economies from fossil fuels to renewable energies are national energy independence and reduction of greenhouse gas emissions. Energy independence is perhaps irrelevant to birds of prey, but reduction of greenhouse gas emissions and global climate change do have substantial potential benefits for birds of prey. Global climate change is associated with increased frequency and intensity of weather events. Late spring and high-intensity weather events can directly impact the productivity and survival of birds of prey. For example, breeding success is negatively correlated with precipitation during nesting in peregrine falcons (Anctil et al. 2014; Burke et al. 2015). Survival of peregrines migrating south from the Artic is negatively correlated with climatic events suggesting the species is vulnerable to weather events along the migration route (Franke et al. 2011). Reduced impacts of climate change in general will likely reduce weather-related impacts on nesting birds of prey.

Conclusions

Ultimately, the large, widely dispersed territories of most birds of prey minimize the population impacts of either direct or indirect effects at most renewable energy facilities, transmission interconnections, or mines. This is because even if a specific territory is affected by a renewable energy facility, through habitat loss, for example, the effect is unlikely to have a population-level effect. There are exceptions however. For example, collisions involving migrating or wintering birds of prey with wind turbines can result in impacts dispersed throughout breeding ranges, and large-scale biofuel monocultures can result in elimination of habitat patches far larger than a single territory. These two areas of renewable energy advancement in particular warrant ongoing consideration, mitigation, and monitoring as renewable energy facilities expand into the habitats of birds of prey.

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EXHIBIT 3
to July 8, 2019
Comments

Conservation Biology

Contributed Paper

Effects of development of wind energy and associated changes in land use on bird densities in upland areas

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Abstract: *Wind energy development is the most recent of many pressures on upland bird communities and their habitats. Studies of birds in relation to wind energy development have focused on effects of direct mortality, but the importance of indirect effects (e.g., displacement, habitat loss) on avian community diversity and stability is increasingly being recognized. We used a control-impact study in combination with a gradient design to assess the effects of wind farms on upland bird densities and on bird species grouped by habitat association (forest and open-habitat species). We conducted 506 point count surveys at 12 wind-farm and 12 control sites in Ireland during 2 breeding seasons (2012 and 2013). Total bird densities were lower at wind farms than at control sites, and the greatest differences occurred close to turbines. Densities of forest species were significantly lower within 100 m of turbines than at greater distances, and this difference was mediated by habitat modifications associated with wind-farm development. In particular, reductions in forest cover adjacent to turbines was linked to the observed decrease in densities of forest species. Open-habitat species' densities were lower at wind farms but were not related to distance from turbines and were negatively related to size of the wind farm. This suggests that, for these species, wind-farm effects may occur at a landscape scale. Our findings indicate that the scale and intensity of the displacement effects of wind farms on upland birds depends on bird species' habitat associations and that the observed effects are mediated by changes in land use associated with wind-farm construction. This highlights the importance of construction effects and siting of turbines, tracks, and other infrastructure in understanding the impacts of wind farms on biodiversity.*

Keywords: bird guilds, displacement, habitat modification, land-use change, uplands, wind farms, wind turbines

Efectos del Desarrollo de la Energía Eólica y los Cambios Asociados al Uso de Suelo sobre las Densidades de Aves en Tierras Altas

Resumen: *El desarrollo de la energía eólica es la más reciente de muchas presiones ejercidas sobre las comunidades de aves de tierras altas y sus hábitats. Los estudios sobre aves en relación con el desarrollo de la energía eólica se han enfocado en los efectos de la mortalidad directa, pero la importancia de los efectos indirectos (p. ej.: desplazamiento, pérdida de hábitat) sobre la diversidad y estabilidad de las comunidades aviares cada vez se reconoce más. Usamos un estudio de control-impacto combinado con un diseño de gradiente para evaluar los efectos de los campos eólicos sobre las densidades de aves de tierras altas y sobre las especies de aves agrupadas por asociación de hábitat (especies de bosque y de hábitat abierto). Realizamos 506 censos de conteo por puntos en 12 sitios de campos eólicos y 12 sitios control en Irlanda durante dos temporadas de reproducción (2012 y 2013). Las densidades de aves totales fueron más bajas en los campos eólicos que en los sitios control, con las diferencias más importantes ocurriendo cerca de las turbinas. Las densidades de las especies de bosque fueron significativamente más bajas a 100 m de las turbinas que a distancias mayores y esta diferencia estuvo mediada por modificaciones asociadas con el desarrollo de campos eólicos. De manera particular, las reducciones en la cobertura de bosque adyacente a las turbinas estuvieron vinculadas con la disminución observada en las densidades de las especies de bosque.*

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Las densidades de las especies de hábitat abierto fueron más bajas en los campos eólicos pero no estuvieron relacionadas con la distancia a las turbinas y tuvieron una relación negativa con el tamaño del campo eólico. Lo anterior sugiere que, para estas especies, los efectos del campo eólico pueden ocurrir a la escala de paisaje. Nuestros hallazgos indican que la escala y la intensidad de los efectos de desplazamiento de los campos eólicos sobre las aves de tierras altas dependen de las asociaciones de hábitat de las especies de aves y que los efectos observados están mediados por cambios en el uso de suelo asociados con la construcción de campos eólicos. Esto remarca la importancia de los efectos de construcción y el sitiado de las turbinas, pistas y demás infraestructura en el entendimiento de los impactos que tienen los campos eólicos sobre la biodiversidad.

Palabras Clave: cambio de uso de suelo, campos eólicos, desplazamiento, gremios de aves, modificación de hábitat, tierras altas, turbinas de viento

摘要: 风能的开发是山地鸟类群落面临的许多压力中最近出现的一种。关于鸟类与风能开发有关的研究主要集中于其直接导致鸟类死亡的影响, 但人们也逐渐认识到其对鸟类群落多样性和稳定性的间接影响 (如被迫迁徙、生境丧失) 的重要性。我们用控制-影响研究, 结合梯度设计, 来评估风电场对山地鸟类密度和按生境相关性分类的鸟类物种 (森林和开放生境的物种) 的影响。我们在 *2012* 年和 *2013* 年的两个繁殖季对爱尔兰 *12* 个风电场和 *12* 个对照位点对 *506* 个样点进行计数调查。结果显示, 风电场的鸟类总密度比对照位点低, 且差异最大的位置在涡轮机附近。在涡轮机附近 *100* 米内森林鸟类的密度显著低于离涡轮机更远的位置, 这一差异受到风电场建设相关生境改造的调控。特别是与观察到的森林鸟类密度下降与涡轮机附近森林覆盖的减少有关。风电场开放生境的物种密度也较低, 但这与距离涡轮机的远近无关, 而与风电场的大小呈负相关。这说明风电场对这些物种的影响可能发生在景观尺度上。我们的结果表明, 风电场导致山地鸟类被迫迁徙的影响尺度和强度取决于物种的生境相关性, 观察到的影响是由风电场建设相关的土地利用变化介导的。这强调了涡轮机、轨道和其它基础设施的施工效应及选址对于理解风电场对生物多样性影响的重要性。 **【翻译: 胡怡思; 审校: 聂永刚】**

关键词: 鸟类同资源种团, 被迫迁徙, 生境改造, 土地利用变化, 山地, 风电场, 风力涡轮机

Introduction

In recent decades, development of wind energy has played a key role in efforts to mitigate climate change by reducing carbon emissions while meeting increasing energy demands. It is expected that by 2050, wind energy will provide 20% of global energy requirements (IPCC 2015). Although widely perceived as one of the most environmentally responsible and affordable energy sources, ongoing increases in development of wind energy have led to concerns about its potential environmental impacts (Leung & Yang 2012; Tabassum et al. 2014; Zwart et al. 2016). Large-scale installations can result in habitat loss and degradation, displacement of wildlife, and direct mortality of birds and bats (Kuvlesky et al. 2007; Pearce-Higgins et al. 2009; Northrup & Wittemyer 2013).

In many parts of the world, onshore wind farms are commonly built in areas with high elevation, sparse human populations, and relatively low levels of management and economic productivity. These areas are attractive for wind-energy development because they typically combine high wind yield with few economically competing land uses (Bright et al. 2008; Schuster et al. 2015). However, these upland areas are often also priority conservation areas with important bird assemblages, including generalists, upland specialists, and migratory birds. In Europe many of these bird species are of conservation concern; thus, their populations are sensitive to wind-farm development and expansion (e.g., Bright et al. 2008; Bonn et al. 2009; Wilson et al. 2017). Upland bird communities have been shaped by human activity, in particular habitat loss and degradation related to agricultural improvement, peat extraction, recreation, air pollution, and climate (Fielding & Haworth 1999; Pearce-Higgins et al. 2008). Because development of wind energy has been incentivized by policies aiming to reduce carbon emissions from energy production, its effects on upland birds can be regarded as an indirect consequence of climate change (Evans & Douglas 2014). The scale of wind-farm development in many upland areas has led to a growing demand for information on its potential impacts on birds to guide sustainable development of the wind energy sector (Katzner et al. 2013; Zwart et al. 2016).

Early studies of the effects of wind farms on birds most commonly assessed direct mortality associated with wind turbines (Leung & Yang 2012; Erickson et al. 2014; Smith & Dwyer 2016). Recently, the scope of studies has broadened to include assessments of secondary effects, such as disturbance and displacement, either through habitat loss or species avoidance of habitat (e.g., Pearce-Higgins et al. 2009; Astiaso Garcia et al. 2015; Shaffer & Buhl 2016). Research has also evaluated the impact of wind farms on a variety of bird breeding indices (e.g., Pearce-Higgins et al. 2012; Sansom et al. 2016; Rasran & Mammen 2017). Reviews on the displacement effect of wind farms on birds indicate that the existence and extent of impacts varies considerably across species, land cover, seasons, and geographic regions (e.g., Pearce-Higgins et al. 2009; Shaffer & Buhl 2016; Smith & Dwyer 2016). Despite this variability, the majority of studies have focused on a small number of endangered or charismatic species with already low abundances (e.g., De Lucas et al. 2008; Smith & Dwyer 2016). Although the displacement of key species can ultimately result in a shift in the structure of avian communities (Tabassum et al. 2014), there have been few publications on the impacts of wind farms at a multispecies scale. Furthermore, few studies take into account the interdependent effects of the presence of wind turbines and habitat modification or address ecosystem-level impacts of wind-energy development. Understanding whether, and to what extent, wind turbines affect bird communities as a whole is an essential step toward understanding the effects of wind farms at an ecosystem scale.

We designed an impact-control study to assess bird densities and changes in land use due to construction at a range of large, modern wind farms and paired control sites. By surveying points at a range of distances from turbines, we simultaneously assessed impact-gradient effects. We sought to compare bird densities between areas with and without a wind farm; determine the effects of distance from wind turbines and age and size of a wind farm on total bird densities; assess whether, and how, observed effects are related to changes to species groups with different habitat associations; and assess potential effects of changes in land use due to wind-farm development on total bird densities. Our study is one of the first to combine surveys of multiple wind farms and control sites with an impact-gradient approach to assess the effects of wind-energy development on upland birds in a multispecies context (review of studies in Shaffer and Buhl [2016]).

Methods

Survey Design

We surveyed 6 wind farms and 6 control sites in 2012 and a further 6 of each in 2013, all in upland habitats across Ireland. Irish uplands are characterized by a mosaic of open habitats (e.g., heath, bog, rough and improved grassland, scrub) and closed habitats (commercial forestry plantation and natural forests). To maximize the detection of effects, we selected large, modern wind farms with at least 8 turbines of similar design covering a broad geographical range (2–8 years since construction; 8–35 turbines with individual outputs of 850–2500 kW [Supporting Information]). For each wind-farm site, a control site was selected within 12 km in an area of similar size, habitat composition, and topography but without wind-farm development. The similarity between wind-farm and control-site habitat composition (preconstruction) was assessed by visual inspection of satellite images and topographical maps. To avoid confounding effects of yearly variations in bird densities, each wind farm and its corresponding control site were surveyed during the same breeding season.

At each wind farm, 27 survey points were selected at increasing distances from the nearest turbine (9 survey points within 100 m of turbines, 6 at 100–400 m, 6 at 400–700 m, and 6 at 700–1000 m). To avoid any confounding effects of multiple turbines, points farther than 100 m from individual turbines were selected only outside of the minimum polygon containing all turbine 100-m buffers. Within each distance band, survey points were selected to represent the range of habitats and human-made structures present within that band. All points were at least 200 m from the nearest neighboring point to avoid multiple detections of individual birds.

For each survey point at a wind farm, a matching survey point with similar habitat characteristics and elevation was selected at the corresponding control site. Our aim was to assess the overall effect of wind-farm development, including the presence of turbines and the effect of changes in land use associated with wind-farm construction. For this reason, habitat composition (percent cover, based on aerial photographs) at control points was matched with that of the survey point at the wind farm prior to construction (habitat types: pre-thicket forest, closed canopy, clearfell, grassland, scrub, peatland, or human altered). This was done with the aid of aerial photographs taken prior to wind-farm construction. All pairs of wind farm and control points were selected to contain the same habitat types in as similar percentage cover as possible (±5%). By matching control-point habitats with those of wind-farm points prior to construction we ensured that land-use and habitat changes due to wind-farm development could be assessed. As a result, we expected that habitat differences would be greatest for points located closest to wind farms, where habitats would be most affected by construction. To account for variation in bird densities due to elevation, control survey points were also selected to match the elevation of their corresponding wind-farm point.

Many upland bird species in Ireland are rare and occur at relatively low abundances. Because this could affect the observed trends in total bird densities, we also carried out an analysis of densities of the most common bird species. Because of the configuration of upland habitats in Ireland, the most common bird species are associated with either forest or open habitats. By analyzing densities of forest birds and open-habitat birds, we were able to study the effects of land-use changes associated with wind farms on bird groups linked to specific habitats.

Bird and Habitat Surveys

Breeding birds were surveyed using the point-count method following Bibby et al. (2000). Surveys were conducted on days without persistent rain or strong wind (<20 km/hour) during the breeding seasons (April to

June) and in the mornings (from 1 hour after dawn until noon). Each point was visited once for 5 minutes, during which time all birds detected by sight or sound within a 100-m radius were recorded and their distance from the observer noted. All data collection was carried out under license issued by the National Parks & Wildlife Service in Ireland in accordance with the Wildlife Act 1976. Flying birds were excluded from the data analysis unless they were actively foraging or singing. Distance estimates were made by experienced observers aided by scaled aerial photos. Because time of day or season can affect bird densities, point-count pairs (wind farm and control) were surveyed in succession. If this was not possible, they were visited within the next 2 days at the same time of day and under similar weather conditions. Distance software version 5.0 (Thomas et al. 2010) was used to derive species densities from field observations. For further details on survey methods and density estimate calculations, see Supporting Information.

Survey-point bird densities were calculated for individual species and summed to calculate total bird densities. Using information on avian ecology and habitat associations in Ireland (Nairn & O'Halloran 2012), we also classified the most commonly occurring species in our study as either forest species or open-habitat species. Forest species included Great Tit (*Parus major*), Coal Tit (*Periparus ater*), Chaffinch (*Fringilla coelebs*), and Goldcrest (*Regulus regulus*). Open-habitat species included Meadow Pipit (*Anthus pratensis*), Skylark (*Alauda arvensis*), and Wheatear (*Oenanthe oenanthe*).

Once the bird survey at each point was completed, habitats within the 100-m survey radius were categorized as pre-thicket forest, closed canopy, clearfell, grassland, scrub, peatland, or human altered (e.g., bare ground, buildings, tracks providing access for forestry operations or wind farms). Percent cover of habitats, point-count elevation, and distance from nearest wind turbine were calculated using ArcGIS 10 software (Environmental Science Research Institute, Redlands, California).

Of the 648 designated point counts, it was not possible to carry out surveys at 71 points due to land-access constraints. To maintain the paired design, their corresponding survey-point pairs were also excluded from analysis. This resulted in analysis of 506 survey points (253 points at wind farms, 253 points at control sites). The final distribution of wind-farm points was 68 within 100 m of the nearest turbine; 70 from 100 to 400 m; 56 from 400 to 700 m; and 59 from 700 to 1000 m.

Data Analyses

To assess how different factors affected bird densities, we used generalized linear mixed models (GLMMs) with a Gaussian distribution and identity link functions (Zuur et al. 2013). We followed a 3-step process to test the effects of wind-energy development on bird densities. First, we built a base model explaining total bird densities (i.e., density of all species combined) based on environmental factors (percent cover of each habitat type and elevation in meters) and retaining only significant variables (model A). We then added a categorical variable with 2 levels (wind farm or control) to this model to test the effect of wind-farm development on total bird densities (model B). Finally, we used a subset of data from wind-farm sites only to test the effects of distance to turbine (meters), age of wind farm (years), and size (number of turbines as a proxy for size) on total bird densities, on forest bird densities, and on open-habitat bird densities (models C). Thus, models A and B included data from all survey points ($n = 506$), whereas model C included data from wind-farm survey points only ($n = 253$). To control for site-specific patterns, we included site as a random factor in all models (factor with 12 levels, 1 for each wind-farm and control-site pair). To control for non-independence of survey-point pairs, pair was included as a random effect nested within site for models A and B. Spearman correlation coefficients were calculated for all variable pairs. All variables included in analyses had values of $|r| < 0.5$.

Preliminary analysis revealed that the effects of wind farms on habitat were greatest closest to wind turbines. Therefore, to further analyze the spatial nature of any effects, we calculated total, forest, and open-habitat bird densities at wind-farm points at increasing distance bands from turbines (0–100 m, 100–400 m, 400–700 m, and 700–1000 m) and compared them with the densities of their matching control points with Wilcoxon signed-rank tests. To detect differences in habitats between matched points that could be attributed to wind-farm development (habitats at control points were matched to those at wind-farm points prior to construction), we performed similar analyses comparing percentage of each habitat type between wind-farm points and their matched control points for each of the distance bands. All statistical analyses were performed using R version 3.4.3 (www.r-project.org). The GLMM analyses were performed with R packages lme4 and nlme.

Results

Fifty-six bird species and 3715 individual birds were recorded. Thirty-six percent of the species recorded ($n = 20$) are of conservation concern in Ireland at present (Colhoun & Cummins 2013). Mean densities across all sites were 2.99 birds/ha, with 0.99 forest birds/ha and 0.47 open-habitat birds/ha. At wind farms, mean densities were 2.80 birds/ha, 0.93 forest birds/ha, and 0.41 open-habitat birds/ha. At control sites, mean densities were 3.19 birds/ha, 1.04 forest birds/ha, and 0.52 open-habitat birds/ha. For a list of species recorded, their conservation statuses, and densities see Supporting Information.

Table 1. Summary of environmental effects on total bird densities at wind-farm and control sites (model A).*

Factor	*Estimate (SE)*	t	p
Intercept	5.677 (0.552)	10.29	<0.001
Closed canopy	0.024 (0.003)	7.08	<0.001
Pre-thicket	0.009 (0.004)	2.46	0.012
Peatland	−0.012 (0.003)	−4.01	<0.001
Elevation	−0.010 (0.001)	−5.74	<0.001

**Predicted total bird densities (birds/ha) at individual point counts (n= 506) at 12 wind farm and 12 control sites modeled as a function of environmental factors (land-cover type and elevation). Point-count pair nested within site was included as a random factor.*

Table 2. Summary of effects of wind-farm development on total bird densities at wind farm and control sites (model B).*

Factor	*Estimate (SE)*	t	p
Intercept	5.822 (0.555)	10.50	<0.001
Closed canopy	0.024 (0.003)	6.84	<0.001
Pre-thicket	0.008 (0.004)	2.25	0.024
Peatland	−0.012 (0.003)	−4.20	<0.001
Elevation	−0.010 (0.002)	−5.62	<0.001
Wind farm present	−0.313 (0.148)	−2.11	0.035

**Predicted bird densities (birds/ha) at individual point counts (n = 506) at 12 wind farm and 12 control sites modeled as a function of different land-cover types (percent), elevation (meters), and presence or absence of wind farms. Point-count pair nested within site was included as a random factor.*

Bird densities at all survey points (wind farm and matching control) were influenced by different habitat covers and elevation (model A, Table 1). However, point counts at wind farm sites showed significantly lower bird densities than point counts at control sites (model B, Table 2).

Tests of characteristics specific to wind farms revealed different effects on total, forest, and open-habitat bird densities (C models, Table 3). Distance to turbine was significantly and positively related to total bird densities, indicating an increase in densities at increasing distances from turbines. Densities of forest birds showed a similar significant positive effect of distance to turbine. However, for open-habitat birds, only size of the wind farm was significant; large wind farms held lower densities of open-habitat birds.

Differences in total bird densities were greatest for paired wind-farm and control points that were closest to wind turbines (Fig. 1a). When assessed by distance bands, these differences were significant between wind-farm points within 100 m of turbines and their paired control points ($z = 1043.5, p < 0.001$) (Fig. 1b) but not for other distance bands. Densities of forest birds were significantly lower at wind-farm points within 100 m of wind turbines than at matching control points ($z = 553.5$, $p = 0.009$) (Fig. 1c) but not for other distance bands. Densities of open-habitat bird species were significantly lower at wind-farm sites than control sites ($z = 2910.0$, $p = 0.008$), but this difference was not significant for any specific distance band (Fig. 1d).

Comparison of habitat composition at wind-farm and control points highlighted significant differences for 3 habitat types attributed to construction effects: human-altered (bare ground, tracks, and buildings), clearfelled forest, and closed canopy forest (Fig. 2). Human-altered habitats occurred more frequently at wind-farm points ($z = 4126.0$, $p < 0.001$) (Fig. 2a); differences were significant up to 700 m from turbines. Likewise, clearfelled forest occurred more frequently at wind-farm points ($z = 492.0$, $p = 0.039$) (Fig. 2b); differences were significant within 100 m from turbines. Closed canopy forest was less abundant at wind-farm points within 100 m of turbines than at their corresponding control points ($z = 636.5, p = 0.020$) (Fig. 2c).

Discussion

Total bird densities were lower at wind-farm sites than at control sites without wind-farm development. Because wind farms were generally located at high elevations, elevation decreased and bird densities increased at points farther from turbines and at matched control points (positive slope of both lines in Fig. 1a). However, bird densities close to wind turbines were lower than at matching control points, and we recorded a higher rate of elevation-related increase at wind-farm than at control sites (lower y-intercept and steeper slope of wind-farm average density represented by the dark grey line in Fig. 1a). This indicates a gradient effect of wind farms on bird densities. Maximum differences in bird densities were recorded between wind-farm points within 100 m of turbines and their corresponding control point pairs (Fig. 1b). These findings are consistent with other studies showing the displacement of birds in areas within a few hundred meters of turbines (Pearce-Higgins et al. 2009; Stevens et al. 2013; Sansom et al. 2016; Shaffer & Buhl 2016). The magnitude of these displacement effects are shown by model estimate values indicating that total bird densities were 0.313 birds/ha (SE 0.148) lower at wind farms than control sites (Table 2). At wind-farm sites, total densities increased by 0.001 birds/ha/m (SE 0.000) (or 1.3 birds/ha/km [SE 0.4]) from a wind turbine (Table 3). Although these values may seem low, in the context of upland bird densities (e.g., mean of 2.99 birds/ha in our study) changes of 0.3–1.3 birds/ha can have important effects at both bird species population and community scales.

Densities of forest species were lower at wind farms than at control sites; distance to turbine significantly explained this observed difference. Specifically, points within 100 m of wind turbines had significantly lower densities of forest species than paired control points. In contrast, densities of open-habitat species were lower

Table 3. Summary of effects of wind-farm development on total, forest, and open-habitat bird densities at wind-farm sites (models C).*

Response variable	*Factor*	*Estimate (SE)*	*z*	*p*
Total species density (birds/ha)	intercept	4.966 (0.988)	5.03	0.002
	closed canopy	0.022 (0.004)	5.31	<0.001
	peatland	−0.015 (0.003)	−4.73	<0.001
	elevation	−0.007 (0.003)	−2.72	0.006
	distance	0.001 (0.000)	3.26	0.001
	age	−0.035 (0.084)	−0.41	0.681
	size	−0.014 (0.012)	−1.14	0.254
Forest species density (birds/ha)	intercept	0.770 (0.201)	3.83	<0.001
	closed canopy	0.018 (0.003)	7.00	<0.001
	peatland	−0.006 (0.002)	−2.94	0.003
	distance	0.001 (0.000)	3.33	0.001
	age	−0.030 (0.030)	−1.01	0.315
	size	−0.005 (0.004)	−1.25	0.213
Open-habitat species density (birds/ha)	intercept	−0.324 (0.272)	−1.19	0.234
	closed canopy	−0.003 (0.002)	−2.03	0.043
	grassland	0.005 (0.001)	3.78	<0.001
	peatland	0.007 (0.001)	5.51	<0.001
	elevation	0.002 (0.001)	2.61	0.009
	distance	0.001 (0.000)	0.91	0.365
	age	0.010 (0.016)	0.55	0.581
	size	−0.007 (0.002)	−3.11	0.002

Predicted total, forest, and open-habitat bird densities (birds/ha) at individual point counts (n = 253) at 12 wind farms modeled as a function of different land-cover types (percent), elevation (meters), distance to turbine (meters), and age (years) and size of wind farm (number of turbines). Site was included as a random factor.

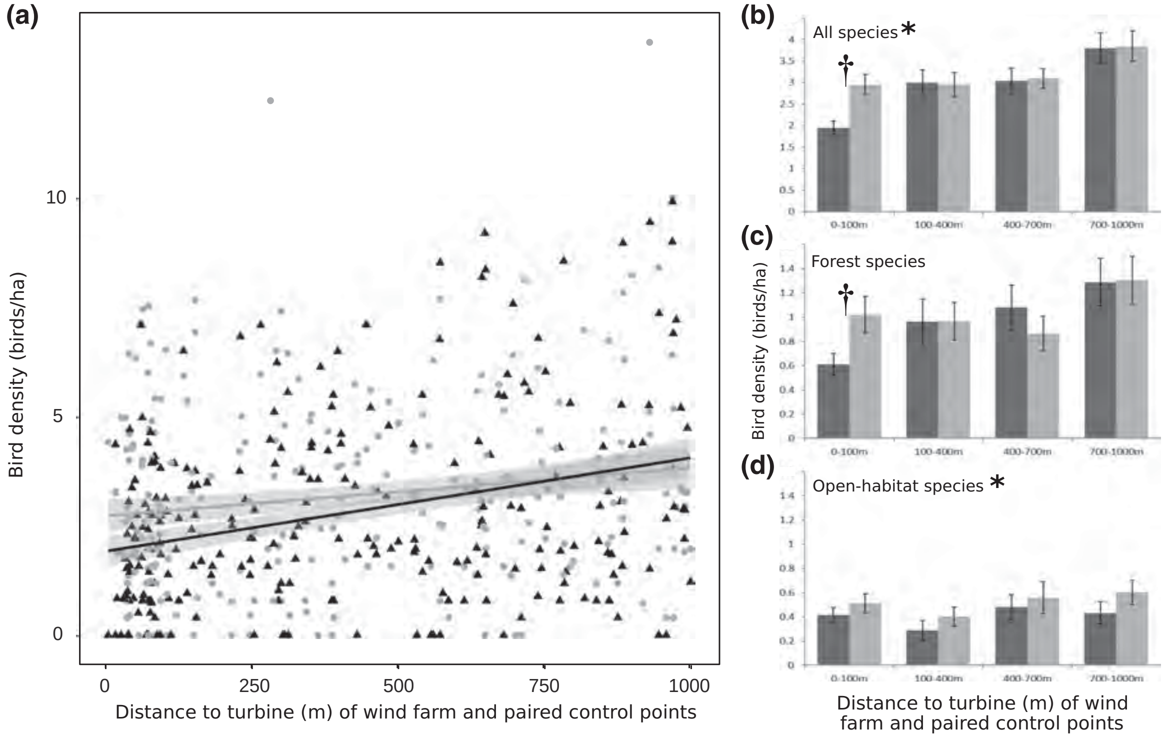

Figure 1. Bird densities recorded at 506 point counts at 12 wind farms (black) and 12 control sites (grey) in 2012 and 2013: (a) total bird densities at wind-farm point counts (triangles) and control point counts (circles) (lines, means; shading, 95% CI); (b) mean (SE) total bird densities in each distance band; (c) mean (SE) densities of forest bird species in each distance band; (d) mean (SE) density of open-habitat bird species in each distance band. Control point values are represented at the distance of their corresponding wind farm point pair (, statistical significance for that group independent of distance; †, statistical significance for that distance band).*

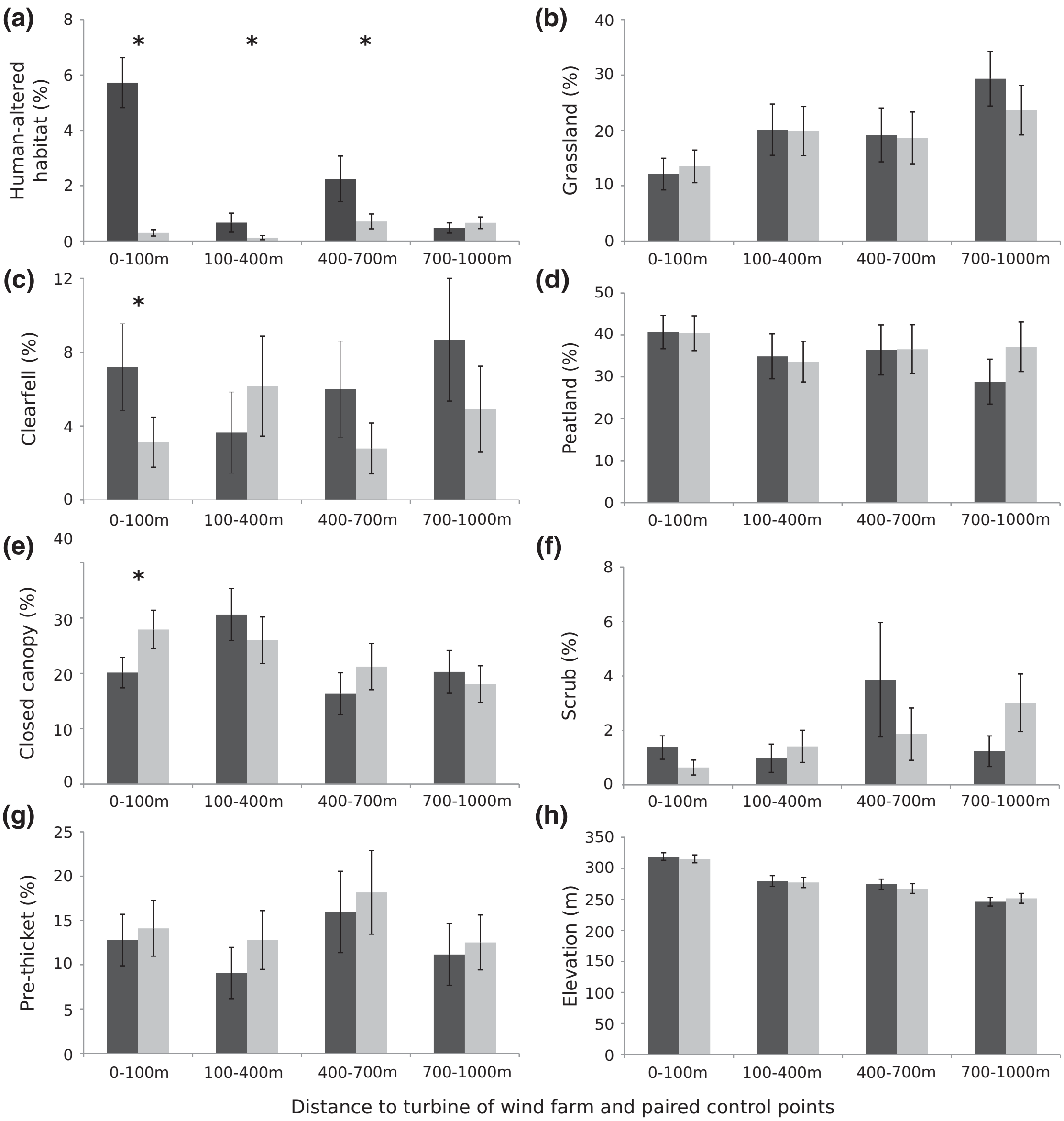

Figure 2. Mean (SE) (a–g) cover of different land-cover types and (h) elevations at wind farms (dark grey) and control sites (light grey) where bird point counts were conducted (, p < 0.05; values on x-axes differ). Control point values are represented at the distance of their corresponding wind-farm point pair.*

at wind farms independent of distance to turbines, although size of the wind farm was negatively related to their densities. These findings indicate a variation in the intensity and scale of the effects of wind-farm development that depends on the ecological association of bird species. Previous research suggests that sensitivity to displacement by wind turbines may be related to species' characteristics, such as their social behavior and habitat use (Stevens et al. 2013; Schuster et al. 2015).

Habitat changes resulting from wind-farm development may help explain the different responses of forest and open-habitat species. Because control survey points were selected to match the habitat and elevation of wind-farm points prior to wind-farm construction (Fig. 2), differences in habitat composition can be attributed to wind-farm construction. Wind-farm points close to turbines had proportionally less closed canopy cover and relatively more clearfell forest and human-altered habitats (bare ground, tracks, and buildings) than did matching control points. Ground clearing and clear felling are often undertaken to make space for wind-farm infrastructure or to maximize wind load (Nayak et al. 2010), whereas access roads increase the area of bare ground. These changes in land use had a net effect of decreasing natural habitat cover at wind farms. In our study, these changes particularly affected closed-canopy habitats, resulted in reductions of habitat for forest bird species, and ultimately led to lower recorded densities. Similar patterns have been observed in response to development of shale gas in forested areas, where changes in land use affect mature forest birds but not birds associated with early successional or disturbed habitats (Farwell et al. 2016). These patterns highlight the importance of planning the precise location of turbines, roads, and other infrastructure in determining which habitats and thus species will be affected by wind-energy development. Presence of wind turbines could also affect bird densities through blade noise, visual disturbance, increased predation risk, or human activity around these structures (Drewitt & Langston 2006; Helldin et al. 2012). Although our findings suggest that changes in land use played an important role, it is possible that these other indirect effects may have contributed to decreased forest bird densities.

Densities of open-habitat birds followed a different pattern from that of forest species. The lack of an apparent gradient in densities at increasing distance from turbines (Fig. 1d) could be explained if either the spatial scale of our study was insufficient (i.e., impact gradients occurred beyond 1000 m from turbines) or if these effects were occurring at a landscape scale. However, typical territory sizes of the open-habitat species are within this scale (Cramp 1988), and for forest species we detected gradient effects within 100 m of turbines. Therefore, it seems unlikely that our study scale was inappropriate, which suggests that for open-habitat birds, effects were operating at a landscape scale. Although there were no differences in extent of open habitat between wind-farm and control survey points (Fig. 2b, d), we did not assess the extent of these habitats in the wider landscape or their quality (e.g., plant species composition, vegetation height). Wind farms are typically located in areas of relatively low value for nature or where access is easy, which may in turn be associated with differences in habitat quality, land use, or habitat management. These, or other differences at a landscape scale that are indirectly linked to presence of wind farms, may play a role in determining bird densities (Lachance et al. 2005). Furthermore, the susceptibility of different species to disturbances (e.g., human activity, movement of turbine blades) may also determine the scale of the effect.

Previous research shows that the extent of wind-farm impacts on bird populations varies considerably across species and regions (Farfán et al. 2009; Pearce-Higgins et al. 2009; Sansom et al. 2016). Where reduced bird abundance at wind farms has been reported, this has generally been confined to areas close to turbines and has not extended into the wider landscape (Leddy et al. 1999; Drewitt & Langston 2006; Pearce-Higgins et al. 2009). Other studies report effects of wind farms specific to certain habitats or to their structure (Hale et al. 2014; Shaffer & Buhl 2016). However, these studies are typically restricted to a small number of species or wind farms, often with limited sample sizes, and efforts to assess impacts on multiple bird species across multiple sites have relied largely on meta-analyses or reviews (Drewitt & Langston 2006; Madders & Whitfield 2006).

Despite the large body of work on best practice for the assessment of effects of wind-energy development on wildlife in general, and birds in particular (Strickland et al. 2007; Astiaso Garcia et al. 2015; Schuster et al. 2015), few studies combine different assessment designs (i.e., before-after, control-impact, impact-gradient approaches) or cover multiple bird species, wind farms, or years (Shaffer & Buhl 2016). Our approach allowed us to compare areas with wind-farm development with control areas of similar environmental characteristics and avoid confounding temporal effects associated with before-after designs (Strickland et al. 2007). By combining this paired control-impact design with an impact-gradient approach, it was possible to evaluate the effects of wind turbine presence and changes in land use while maximizing our ability to detect displacement gradients (NRC 2007). Surveys of breeding birds targeting multiple species allowed detection of nonlethal effects on overall bird densities, as well as of differential effects dependent on species habitat associations.

Ours is one of the first studies to highlight differences in nonlethal effects of wind farms on different bird groups in relation to their ecological association and to demonstrate how the spatial scale of this response may be specific to each group (Pearce-Higgins et al. 2009, 2012). These findings are particularly relevant for planners and policy makers. The differential response of bird guilds reported here suggests that it is possible to locate wind farms and to plan changes in land use in accordance with conservation interests. Depending on regional conservation priorities, it may be possible to locate wind-farm infrastructure such that habitat changes will affect species and habitats of lower conservation concern or even benefit those in need of conservation action. Furthermore, consideration must be given to the ecological role of these habitats and species from a wider ecological perspective. Many of the birds recorded in our study are important prey for key flagship species such as Hen Harrier (*Circus cyaneus*), Merlin (*Falco columbarius*), or Short-eared Owl (*Asio flammeus*), predators that are the focus of considerable conservation effort (Glue 1977; Fernández-Bellon & Lusby 2011; Watson 2013). As such, understanding the effects of wind farms on prey populations and how this may influence these species' foraging habits near wind turbines is essential for their effective management and conservation.

Our study highlights the relevance of assessing the effects of wind farms or other developments on ecological communities or ecosystems as a whole, rather than solely on individual species. Further research into wind-farm impacts on birds should look beyond the effects of turbine presence and take into consideration effects of construction, associated infrastructure, and changes in land use and habitat composition. Similarly, wind-farm planners should consider these potential effects by taking into account not only the precise location of wind turbines, but also that of associated infrastructure (e.g., roads, buildings) and how changes in land use may affect wildlife. Understanding the ways in which land-use changes impact upland ecology is particularly important in the context of continued growth in wind-energy development in combination with other pressures such as afforestation, agricultural intensification, and climate change.

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Supporting Information

Details on site locations (Appendix S1), survey methods and density calculations (Appendix S2), and bird species recorded and their conservation status and densities (Appendix S3) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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Changing distribution patterns of an endangered butterfly: Linking local extinction patterns and variable habitat relationships

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ABSTRACT

Multiple processes are increasingly recognized as being responsible for species' extinctions. We evaluated population extinctions between 1930 and 1998 for the endangered Quino checkerspot (*Euphydryas editha quino*) butterfly relative to agricultural history, human population growth, climate variability, topographical diversity, and wildflower abundance. Overall agricultural land use was calculated for extinct and extant populations based upon cultivation and grazing intensities averaged across five time periods reflecting distinct agricultural practices from 1769 to present. Extinct populations were associated with a history of more intensive agriculture and greater human population growth at time of extinction. A long history of intensive livestock grazing was the strongest agricultural predictor of extinction. Based upon historic vegetation maps, extinct butterfly populations were typically isolated from other known populations by 1930, and in landscapes fragmented by cultivation and development. Precipitation and topographical variability were not important predictors of extinction. Wildflower host plants and nectar sources have declined across the butterfly's range because of invasive plants and habitat loss. The proportion of years considered average or abundant in wildflowers declined significantly during extinction periods. The Quino checkerspot has shifted in distribution from the coast into foothills and mountains. Newly discovered higher elevation populations experience more precipitation and are buffered from drought. Efforts to conserve Quino checkerspot are enhanced by understanding that the butterfly's decline and shifting distribution is a complex multi-scale process related to agricultural history, human population growth, climate variability, and wildflower decline.

1. Introduction

Multiple interacting stressors are driving species to extinction (Brook et al., 2008). Butterflies are especially sensitive to environmental change and accelerating extinction rates are leading to a global decline in butterfly diversity (Forister et al., 2010; Potts et al., 2010; Warren and Bourn, 2010). These declines are associated with urban and agricultural expansion and changing agricultural practices (Maes and Van Dyck, 2001; Stefanescu et al., 2004; Norris et al., 2010; Warren and Bourn, 2010; Fattorini, 2011). Agricultural intensification employing large-scale cultivation and use of pesticides and herbicides is reducing butterfly diversity (Schmitt and Rákosy, 2007; Marini et al., 2009; Ekroos et al., 2010; Warren and Bourn, 2010). Livestock grazing also affects butterfly populations, although the nature of the relationship depends on butterfly life history traits, plant community succession, grazing regimes, and invasive plant dynamics (Swengel, 2001; Pöyry et al., 2005; Schtickzelle et al., 2007; Vogel et al., 2007). In some species, lack of grazing leads to population extinction, whereas in others over-grazing causes extinction. Invasive species are another threat to butterfly populations (Moroń et al., 2009; Potts et al., 2010; Wagner and Van Driesche, 2010).

Climate change may cause future large-scale extinctions and interact with other drivers to accelerate extinction and biodiversity loss (Purvis et al., 2000; Brook et al., 2008). Insects are especially vulnerable to global warming as ambient temperature controls body temperature influencing metabolic reaction rates and life history phenology (Parmesan, 2006; Memmott et al., 2007; Wilson and Maclean, 2011). Precipitation patterns are changing with extremes in precipitation increasing (Easterling et al., 2000; IPCC, 2007; Seager et al., 2007). Increasing climate variability can lead to phenological mismatches between butterflies and host plants

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causing population extinctions (Ehrlich et al., 1980; McLaughlin et al., 2002; Parmesan, 2006; Hegland et al., 2009; Singer and Parmesan, 2010).

To effectively conserve declining species, it is important to understand the multiple processes leading to extinction. The endangered Quino checkerspot butterfly (*Euphydryas editha quino*) provides an opportunity to evaluate the association between population extinction and global change processes, including changing climate and land use. Quino checkerspot is the southernmost subspecies of Edith's checkerspot (*E. editha*), which is broadly distributed throughout western North America. The range of Edith's checkerspot has shifted northward and upwards in elevation, consistent with global warming predictions (Parmesan, 1996). Quino checkerspot populations exhibited the highest extinction rates, as expected for southerly populations in a warming and drying climate. Currently, this butterfly may be undergoing a range shift into higher elevations (USFWS, 2009), consistent with climate change predictions for the species (Parmesan, 1996; Preston et al., 2008). However, local extinctions and changes in historic distribution are also attributed to extensive habitat loss and degradation resulting from urban and agricultural land uses (Mattoni et al., 1997; USFWS, 1997, 2003).

In this paper, we evaluate spatial and temporal patterns of extinction in southern California populations of Quino checkerspot relative to agricultural history, human population growth, climate and topographic variability, and wildflower abundance. We also assess distributional changes and differences in environmental conditions across the United States (US) portion of the subspecies' historic and current range. Insights derived from these analyses will help us understand those environmental conditions under which Quino checkerspot populations may be more resilient or susceptible to global change processes. Such knowledge is important in prioritizing lands for conservation and informing management of this endangered subspecies.

2. Methods

2.1. Study system

Quino checkerspot was formerly distributed throughout cismontane southern California, US and northern Baja California, Mexico. Our southern California study area extends from the Pacific Ocean east through valleys, foothills, and mountains to the desert edge (Fig. 1). Climate, vegetation, and topography vary substantially. This once widespread and abundant butterfly currently occupies open coastal sage scrub and chaparral shrublands with native forbs. In early studies, Quino checkerspot primarily used *Plantago erecta* as a larval host plant with secondary use of *Plantago ovata* (Singer, 1971, 1982; White, 1974). More recently, butterflies have been observed using other host plants, particularly at higher elevation sites. These include *Castilleja exserta*, *Plantago patagonica*, *Antirrhinum coulterianum*, *Collinsia concolor*, and *Cordylanthus rigidus* (Mattoni et al., 1997; Pratt and Pierce, 2008; USFWS, 2003, 2009). Adult Quino checkerspot use multiple nectar sources, including species in the *Cryptantha*, *Eriodictyon*, *Gilia*, *Lasthenia*, *Lomatium*, *Muilla*, and *Plagiobothrys* genera. More than 75% of the butterfly's former range has been converted to agriculture and urban development, prompting listing as a federally-endangered species in 1997 (USFWS, 1997).

Quino checkerspot likely have a complex metapopulation structure with large (20–100 fold) fluctuations over 10–20 year periods (Mattoni et al., 1997; USFWS, 2009). Under certain environmental conditions, Quino checkerspot populations can explode in size and defoliate larval host plants leading to massive dispersal events (Murphy and White, 1984; White and Levin, 1981). Large populations tend to persist in more extensive, diverse habitats, whereas smaller, lower quality habitats are temporarily colonized by butterflies following massive dispersal events and sufficient rainfall for larval host plant growth. Extirpation of large, source populations is likely to lead to long term extinction in an area. In Edith's checkerspot, the annual timing and amount of precipitation drives population fluctuations by determining larval survival; 99% of pre-diapause larvae can die from starvation when host plants senesce after winter rains (Ehrlich et al., 1980).

2.2. Temporal and spatial patterns of the butterfly's distribution

To assess the spatial and temporal distribution of Quino checkerspot occurrences in the study area, we combined current butterfly locations with historic records and mapped observations by decade.

2.3. Environmental databases for modeling

To compare land use and climate differences at extinct and extant Quino checkerspot populations, we developed a database characterizing agricultural history, human population size, and precipitation and topographical variability. These data were derived from many sources and linked spatially to each population (Appendix Table 1). We developed a second environmental dataset using Geographic Information Systems (GISs) software and digital data to calculate variables reflecting current environmental conditions across the historic and present range of Quino checkerspot.

2.3.1. Environmental conditions at extinct and extant butterfly populations

For our analysis of environmental factors associated with extinction, we identified extinct populations and selected comparable extant populations for the purposes of calculating environmental variables during equivalent time periods. Extant populations were undeveloped locations where Quino checkerspot have been recorded since 1998. Extinct populations were those where a butterfly was detected historically (1905–1982) but has not been recorded since 1998. We defined the extinction period as the 20-year window centered on the last recorded butterfly observation. This period corresponds to the 10–20 year cycle in which butterfly populations can fluctuate exponentially and during which environmental conditions likely influence population dynamics leading to extinction (Mattoni et al., 1997; USFWS, 2003, 2009).

We calculated environmental variables during relevant time periods for each extinct population and then selected the closest extant population to calculate environmental variables during the same time periods. If there were no nearby extant populations, we selected an extant population in similar proximity to the coast as the extinct population. The intent was to select extinct and extant populations comparable in environmental conditions so that factors most strongly associated with extinction could be distinguished.

2.3.1.1. Human population. We used the size of the human population near a Quino checkerspot population as a proxy for the relative amount of historic habitat loss to urbanization (Forister et al., 2010). We used 1930 Wieslander Vegetation Type Maps (VTMs) to assess the level of development versus natural habitat in the vicinity of each butterfly population prior to the period of documented population extinctions (Wieslander, 1935; VTM, 2011). We aggregated decadal US Census Bureau human population data for counties, cities, and towns (Forstall, 1995; CSDF, 2000) in the vicinity of Quino checkerspot populations. We defined "vicinity" as a distance of ⩽5 km between the butterfly population and a town or city, which is within Quino checkerspot's dispersal

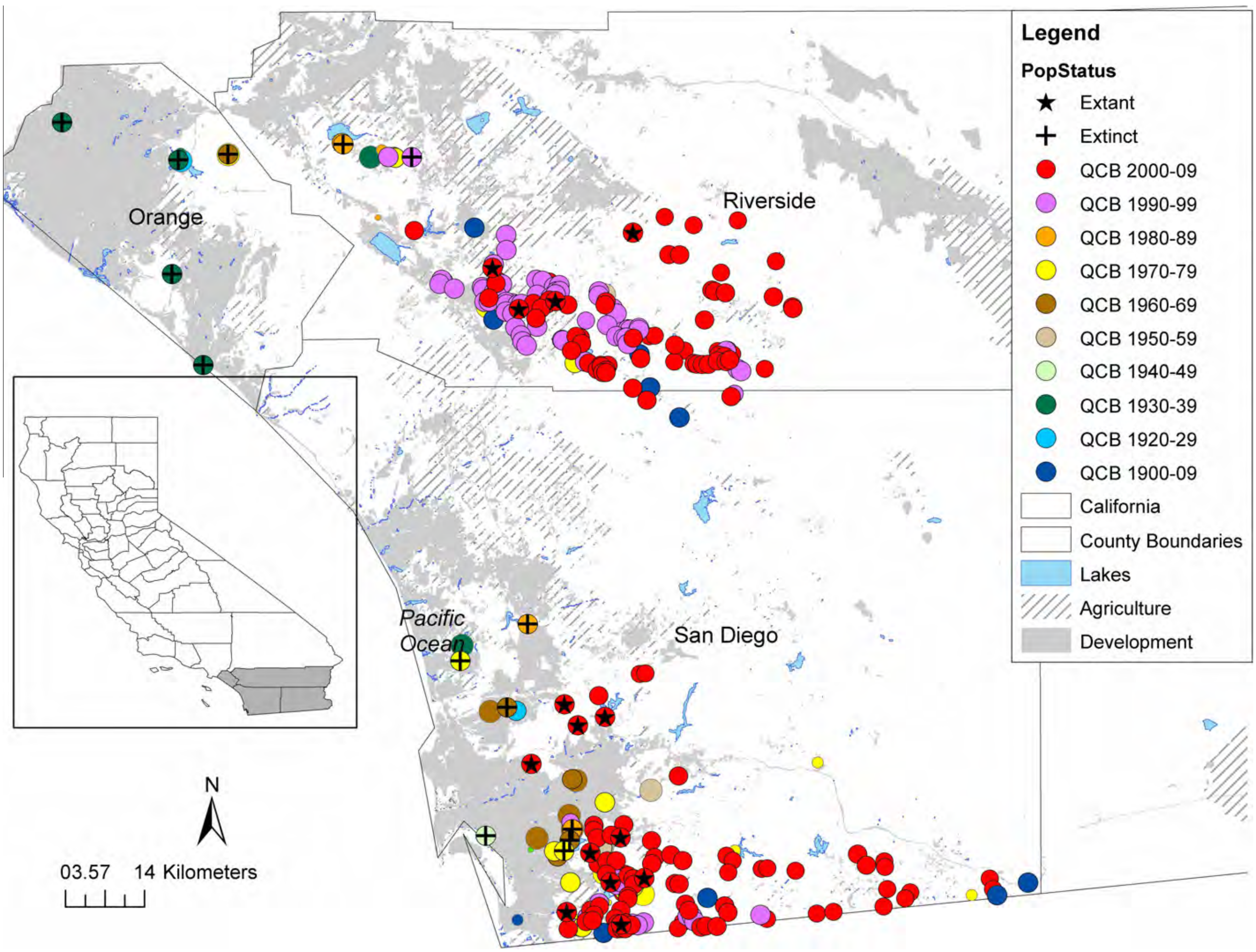

Fig. 1. Quino checkerspot butterfly (QCB) study area and butterfly locations classified by colored circles according to the most recent decade in which an observation was reported. Also shown are locations of extinct (triangle) and extant (circle) populations used in modeling.

capabilities (Harrison, 1989; Parmesan, 1996). We used maps with jurisdictional boundaries (Rand McNally, 2004, 2008) and a GIS layer of cities (ESRI, 2005) to determine towns and cities ⩽5 km from butterfly populations. Growth in human population was calculated as the difference in population density between the decade prior to the last butterfly observation for an extinct population and the decade following that observation. Human population growth was calculated for the same time period for the comparable extant population.

2.3.1.2. Agricultural history. To categorize land use change associated with agricultural practices, a score was developed for each population reflecting the relative intensity of grazing and cultivation over five discrete time periods between 1769 and present. These time periods represent different patterns of agricultural production in this region (Johnston and McCalla, 2004). Agriculture was introduced into California by Spanish missionaries in 1769. During the Spanish Mission/early Mexican (1769–1834) and Mexican rancho (1835–1848) periods, livestock grazing was the predominant form of agriculture. The early California statehood period (1849–1889) is characterized by cattle production, with a switch in the 1870s to sheep production and dry farming of wheat and barley. The agricultural intensification period (1890–1930) includes expansion of dry farming and rapid growth of intensive irrigated crops, such as fruits and vegetables. After 1930, there was further growth of agriculture, although following World War II a population boom converted large areas of farmland to urban/suburban development.

We compiled historical records from many sources (Appendix Table 1) to estimate relative livestock grazing intensities ⩽5 km from extinct and extant Quino checkerspot populations. We used historic Wieslander Vegetation Type Maps (VTMs) to assess spatial patterns of agriculture and natural vegetation near butterfly populations in 1930 (Wieslander, 1935; VTM, 2011). Lands used for livestock grazing were assigned a grazing intensity score based upon categories of livestock stocking rates (number of hectares/head of cattle/horse; Appendix Table 2). Cut-offs for stocking rates within each grazing category were based upon historic livestock grazing intensities in California (Minnich, 2008). Extinct and extant butterfly populations were given numeric scores for each time period based upon average livestock production records or upon typical stocking rates for that area. We used descriptions of historic land use (Appendix Table 1) to identify whether there was significant livestock grazing near populations or whether land was used for farming, urban/suburban development or left undisturbed. We categorized intensity of livestock grazing before 1930 to reflect grazing history before extinction and after 1890 to represent the period before and during extinction episodes. We also quantified grazing for only the decades prior to (1890–1930) and during (post-1930) documented butterfly extinctions.

In a similar manner, we compiled cultivation information from different sources (Appendix Table 1). We scored each extinct and extant population for relative intensity of cultivation during the five time periods (Appendix Table 2). We used historic Wieslander VTMs to categorize the amount of cultivated land ⩽5 km of butterfly populations in 1930, the start of the period of extinctions examined in this study. Cultivation included dry farming (grains) and irrigated crops (orchards, vineyards, vegetables, and hay). We calculated cultivation intensity from 1890 through 1930 to reflect conditions preceding extinctions and after 1930 to characterize extinction episodes.

To quantify overall agricultural land use for each population, we calculated an average score representing combined grazing and cultivation scores across the five time periods.

2.3.1.3. Climate. We obtained weather station records closest to extinct and extant Quino checkerspot populations and calculated climate parameters (WRCC, 2012). Since precipitation and temperature are highly correlated, we focused on precipitation variables, which are important in Edith's checkerspot population dynamics (Ehrlich et al., 1980; McLaughlin et al., 2002). We calculated mean and standard deviation annual rainfall (August 1–July 31) for the entire weather station record and for the 20-year extinction period at each population. Extremely low precipitation years experienced less precipitation than one standard deviation below the mean precipitation for the butterfly population with the lowest average rainfall. Similarly, extremely high precipitation years were those receiving more precipitation than one standard above the mean precipitation of the population with the highest average rainfall. Thresholds defining extreme rainfall years were ⩽140 mm and ⩾566 mm of precipitation.

We summarized precipitation from December to June of the rainfall year, the period of time most relevant to the Quino checkerspot life-cycle. We determined the proportion of extreme rainfall years for the entire weather station record for each population. For each extinct population, we calculated the difference between the proportion of extreme December to June rainfall years for the 20 year extinction window and preceding years of the weather station record. We also calculated this for the comparable extant population during the same time period. To further assess whether extreme precipitation was associated with extinction, we conducted a two sample paired *t*-test with extinct populations testing the null hypothesis that the proportion of extreme precipitation years was higher during the extinction period than in preceding years. We conducted the same analysis for extant populations.

2.3.1.4. Topography. Topography plays a strong role in sister subspecies Bay checkerspot (*E. editha bayensis*) larval development and survival and the timing of adult emergence (Weiss et al., 1988, 1993). We used a vector ruggedness measure (VRM) calculated in GIS to quantify local variation in terrain, this measure is less dependent on slope than other methods (Sappington et al., 2007). Vector analysis is used with a raster-based digital elevation model to decompose each grid cell into x, y, and z components using trigonometry and the slope and aspect of the cell. We calculated terrain ruggedness for a 3 × 3 neighborhood of 90 m cells at each population location.

2.3.1.5. Wildflower abundance. Minnich (2008) compiled newspaper records categorizing annual wildflower abundance for Los Angeles County from 1886 to 2007 and Riverside County from 1918 to 2007. Orange County was originally part of Los Angeles County and was included in the analysis. We had no wildflower records for San Diego County. For each extinct population in Los Angeles, Orange and Riverside counties, we calculated the proportion of years that wildflowers were average or high in abundance during the extinction period. We then calculated the proportion of average and high wildflower years for the period prior to extinction. We used a two sample paired *t*-test to test the null hypothesis that for extinct populations, wildflower abundance was lower during the extinction period than the preceding period.

2.3.2. GIS-based environmental dataset to compare butterfly habitats

For a larger-scale analysis of habitat relationships across the current distribution of Quino checkerspot, we used ARCGIS 9.1 software (ESRI, 2005) to calculate environmental variables from various digital source layers for a 1 km^2 grid across the study area. For each Quino checkerspot location we extracted values for environmental variables at the grid cell encompassing the location. Climate variables included average annual precipitation and minimum January temperature (OSU, 2006). To characterize topography we used a 90-m resolution Digital Elevation Model (USGS, 2006) to calculate median values for elevation, slope, and aspect within a 1 km^2 cell. Land cover variables included percent of coastal sage scrub and chaparral habitats and agricultural and developed lands within 1 km^2, as calculated from a vegetation map for the region (CDF, 2006).

2.4. Modeling methods

2.4.1. Model construction

2.4.1.1. Comparing extinct versus extant populations. We constructed and compared alternative logistic regression models to distinguish between environmental conditions associated with extinct versus extant populations. These models represented different *a priori* hypotheses regarding the importance of land use and climate in association with population extinction. We used an information-theoretic comparative approach to evaluate alternative models (Burnham and Anderson, 2002).

2.4.1.1.1. Butterfly extinctions, agriculture, human population, precipitation and terrain ruggedness. To explore the relationship of local-scale butterfly extinctions and land use change, climate variability, and topographic heterogeneity, we developed models comparing average intensity of agriculture (grazing and cultivation) since 1769 with human population growth, the difference in proportion of extreme precipitation during December through June rainfall years before and during the extinction period, and terrain ruggedness. We created a global model incorporating all four variables and alternative models with land use versus climate/topographic variables and interaction terms. We avoided multicollinearity by examining correlations among pairs of variables and for $r > 0.7$ we retained only one of the independent variables in the model (Tabachnick and Fidell, 1996).

2.4.1.1.2. Butterfly extinctions, grazing, and cultivation intensity over different time periods. We ran a second series of models to explore the association between butterfly population extinction and livestock grazing and crop cultivation during different time periods. We calculated intensity of grazing and cultivation, for the entire period preceding extinction (1769–1930) and several decades prior (1890–1930), during extinction (post-1930), and for the entire history of agriculture from 1769.

2.4.1.2. Environmental conditions across the Quino checkerspot's distribution. To determine if there were environmental differences within the current distribution of Quino checkerspot populations, we characterized environmental attributes for locations where Quino checkerspot populations were historically documented and still persist with areas where populations have only recently been detected. "Established" populations included both historical (<1998) and current locations, whereas "newly discovered" included a distinct region with no spatially explicit location records before 1998. We calculated mean ± standard deviation values for environmental variables. We used the comparative logistic regression modeling approach to evaluate differences in climate, vegetation, and land use at established versus newly discovered locations. As there were more records for established populations, we randomly selected a subset of these records to obtain equivalent sample sizes for modeling.

2.4.2. Model evaluation

To select the best approximating model(s), we used Akaike's information criterion adjusted for small samples (AIC; Burnham and Anderson, 2002). We selected the model with the lowest AIC_c value and calculated a difference in AIC_c (Δ_i) for each model. We computed Akaike weights (ω_i) representing the probability that a model was the best approximating model for the dataset. We also calculated an evidence ratio representing the probability that the model with the highest ω_i was likely to be correct compared to another model. Based upon cumulative Akaike weights, we identified a $\geqslant$95% confidence subset of best approximating models. To evaluate the relative importance of each variable, we calculated model averaged parameter estimates (MAPEs) and cumulative variables weights (CVWs).

3. Results

3.1. Temporal and spatial patterns of the Quino checkerspot's distribution

Quino checkerspot butterflies were historically recorded from the coast to the foothills of southern California (Fig. 1). Between the 1930s and 1970s the butterfly disappeared from most coastal areas. Current populations are distributed in the central and eastern portions of the butterfly's historic range. Most recent observations are clustered in southwestern Riverside County, particularly in the foothills, and in southern San Diego County. The most easterly distributed newly discovered locations in Riverside County were first documented in 1998 and are at higher elevations in the Peninsular Mountains.

3.1.1. Patterns of extinction relative to 1930 land use

Inspection of the VTMs reveals that in 1930 southern California was largely agrarian with human population centers in the major cities of Los Angeles, Riverside, and San Diego. There was extensive cultivation along the coast in northern Orange and San Diego counties and in large interior valleys. Native shrublands along the coast were fragmented by grassland, cultivated fields, and rural residences. Extensive native shrublands, particularly chaparral, were located away from the coast at higher elevations in the Santa Ana Mountains and Peninsular foothills. Only a few areas with large expanses of potential habitat lack historic butterfly observations, such as foothills/mountains in southern Orange County and northern San Diego County. In 1930 only 18% of butterfly populations that later went extinct had shrublands encompassing more than 50% of the area within 5 km of their location, compared with 58% of extant populations. Extinct populations were also more isolated in 1930, with only 9% having a known butterfly population within 5 km compared with 92% of extant populations.

3.2. Environmental conditions at extinct versus extant populations

We classified 14 local Quino checkerspot populations as extinct and selected 14 comparable extant populations within the historically established range (Fig. 1).

3.2.1. Butterfly extinctions, agriculture, human population, and precipitation

In distinguishing between extinct and extant Quino checkerspot populations three candidate models comprised a 97% confidence subset of best approximating models (Table 1). The top-ranked model included average agricultural intensity since 1769 and growth in human population during the extinction period. All three candidate models included these two variables. Difference in proportion of extreme precipitation years during the extinction period, terrain ruggedness, and interaction between agricultural intensity and human population growth did not improve performance of the other two candidate models.

There was a positive relationship between extinction and average agricultural intensity (Fig. 2a; MAPE: 0.10; 90% C.I.: 0.01–0.18). Agricultural intensity was an important predictor of extinction (CVW = 0.99). Extinct populations showed variable levels of human population growth (Fig. 2b), but there was a positive association between human population growth and extinction (MAPE: 0.0001; 95% C.I.: 0.0000–0.0003). Human population growth was as important as agriculture in predicting extinction (CVW of 0.97). Average annual rainfall (Fig. 2c) and minimum January temperature did not differ between extinct and extant populations. The difference in proportion of extreme December to June rainfall years during the 20-year extinction window compared with previous years did not show a trend relative to extinction (Fig. 2d, MAPE: 0.07; 95% C.I.: −0.07 to 0.21). Terrain ruggedness also did not show a trend in association with extinction (Fig. 2e, MAPE: −0.14; 95% C.I.: −0.37 to 0.09). CVWs of 0.42 indicate extreme precipitation and terrain ruggedness were substantially less important than land use in distinguishing between extinct and extant butterfly populations.

There was a subtle difference in extreme precipitation for extinct and extant populations that was detected only with paired sample comparisons. For extinct populations, the proportion of extreme rainfall years was significantly higher during the extinction period (mean ± standard deviation: 0.10 ± 0.06) compared with the prior period (0.06 ± 0.06; Paired two-sample t test, $t = 2.49$, $p = 0.01$). Similarly, for extant populations extreme rainfall was greater in the extinction period (0.13 ± 0.06) compared with the prior period (0.08 ± 0.05; Paired two-sample t test, $t = 2.50$, $p = 0.01$).

3.2.2. Butterfly extinctions, grazing, and cultivation

Three models comprised a 98% confidence subset of models relating livestock grazing and cultivation intensities over different time periods to butterfly extinction (Appendix Table 3). Average grazing intensity from 1769 to 1930 was the most important predictor of extinction. The best approximating model with a weight of 0.75 included only pre-1930 grazing, which had a positive association with extinction (Fig. 2f; MAPE: 1.36; 95% C.I.: 0.14–2.58; CVW = 0.98).

The second ranked model included pre-1930 grazing and post-1930 cultivation ($\Delta_i = 2.74$; $\omega_i = 0.19$; $\omega_i/\omega_1 = 3.9$), while the third ranked model included these two variables and an interaction term ($\Delta_i = 5.66$; $\omega_i = 0.05$; $\omega_i/\omega_1 = 13.8$). Post-1930 cultivation intensity showed no trend in relation to extinction (Fig. 2g; MAPE: 0.01; 95% C.I.: −0.13 to 0.15; CVW = 0.24). Other measures of grazing and cultivation were unimportant predictors of extinction.

3.2.3. Butterfly extinctions and wildflower abundance

Based upon newspaper accounts (Minnich, 2008), thirteen extinct Quino checkerspot populations in Los Angeles, Orange, and Riverside Counties had significantly fewer average or high abundance wildflower years (mean ± standard deviation: 0.18 ± 0.16; Paired two-sample t-test, $t = -5.795$, $p = <.0001$) during the extinction period than prior to extinction (0.51 ± 0.16). Between 1886 and 1918, 73% of years with records in Los Angeles County were classified as average or high abundance wildflower years. However,

Table 1
Performance of logistic regression models[a] in distinguishing between extinct and extant populations of Quino checkerspot relative to human population, precipitation extremes, terrain ruggedness and cumulative agricultural land use scores from first European settlement to present. *K* represents the number of model parameters, Δ_i is the difference in AIC_c values for each model relative to the model with the lowest AIC_c, ω_i is the model weight, and ω_i/ω_1 is the evidence ratio.

Model parameters	*K*	Δ_i	ω_i	ω_i/ω_1
Agriculture and human population	**4**	**0.000**	**0.444**	
Agriculture, human population, terrain ruggedness and December–June extreme precipitation	**6**	**0.147**	**0.413**	**1.1**
Agriculture, human population and interaction	**5**	**2.796**	**0.110**	**4.0**
Agriculture	3	6.353	0.019	23.9
Terrain ruggedness	4	8.256	0.007	61.7
Human population	3	9.614	0.004	123.3
Terrain ruggedness and December–June extreme precipitation	5	10.508	0.002	191.4
Terrain ruggedness, December–June extreme precipitation and interaction	5	13.09	0.001	191.4
December–January extreme precipitation	3	13.686	0.001	888.0

[a] Models highlighted in bold form 96% confidence subset of best approximating models. Variables are defined in the methods.

between 1918 and 2007, only 9% of years were average with no high abundance years. This trend in declining wildflower populations proceeded inland with increasing low abundance years beginning in the 1940s in Riverside County. However, wildflower fields have persisted in areas of western Riverside County with high abundances recorded as late as 1952 and average abundances as late as 2003. Populations remaining extant during the period of wildflower decline are located in eastern portions of the butterfly's range where wildflowers have remained more abundant.

3.3. Environmental variation across the historic and current range

In characterizing differences in environmental attributes across the historic range of Quino checkerspot, the butterfly's current distribution is shifted toward higher elevations (Fig. 3a). This is caused by the extinction of low elevation coastal populations and occurrence of newly discovered populations in the Peninsular Mountains. These latter populations receive substantially more rainfall than extinct or established populations (Fig. 3b). The proportion of extreme rainfall years calculated from long-term weather station records varies by region and tends to be lower for newly discovered populations (Fig. 3c). Average minimum January Temperature between 1970 and 2000 was much lower for newly discovered populations (Fig. 3d). There was little difference in the amount of current urban and agricultural development for established populations (Fig. 3e and f). Newly discovered populations occur in landscapes with more chaparral and less coastal sage scrub (Fig. 3g and h).

3.3.1. Environmental conditions at established versus newly discovered populations

Three logistic regression models formed a 95% confidence subset in distinguishing between established and newly discovered populations and all three models included climate variables (Table 2). The single most important predictor was annual rainfall with a CVW of 1.0; annual rainfall was lower at established populations (MAPE: −0.11; 95% C.I.: −0.18 to −0.03). The proportion of extreme rainfall years at weather stations near populations did not show a trend (MAPE: 2.70; 95% C.I.: −25.75 to 31.16; CVW = 0.35). Minimum January temperature was highly correlated with precipitation ($r = -0.96$, $p < .0001$) and was not used in modeling. Land use and vegetation variables showed no trends in distinguishing between established and newly discovered populations and CVWs were less than 0.10.

4. Discussion

4.1. Environmental conditions at extinct versus extant populations

Quino checkerspot population extinctions in southern California were most strongly associated with agricultural intensity from 1769 to present and to human population growth during the extinction period. By the early 1930s agriculture and rural development had led to extensive habitat loss and fragmentation. Climate played a subtle and localized role; it was not an important predictor of extinction, although extinct populations had significantly more extreme rainfall years during the extinction period. Climate variability may have exacerbated the effects of habitat loss and degradation on Quino checkerspot population dynamics. An interaction between habitat loss, degradation, and climate variability contributed to Bay checkerspot population extinctions where extreme precipitation was associated with large population fluctuations (Ehrlich et al., 1980; McLaughlin et al., 2002). Habitat loss and degradation resulted in the inability of butterflies to recolonize isolated habitat patches after populations were extirpated as a result of climate variability.

Many Quino checkerspot populations in southern California likely disappeared prior to the extinction events examined in this study (Mattoni et al., 1997). The Wieslander VTMs indicate that by 1930 populations that went extinct over the next six decades occurred in relatively isolated natural habitats fragmented by agriculture. Temporal and spatial patterns of Quino checkerspot population extinctions mirror trends in agricultural intensity and human population growth. Thus, land use practices may have directly caused butterfly extinctions through habitat destruction as well as indirectly through loss of resilience. Fragmented habitats with butterfly extinction following stochastic events (e.g., fire, flood, drought) would likely remain unoccupied because of isolation from other butterfly populations.

4.1.1. Butterfly extinctions, grazing, invasive plants, and declining wildflowers

Quino checkerspot population extinctions were associated with a longer, more intensive history of grazing. Those areas with the longest history of grazing and highest livestock stocking rates comprised the best pasture (Minnich, 2008) and were where butterflies initially went extinct. Other studies have also documented relationships between livestock grazing, quantified at relatively coarse scales, and landscape-scale patterns of butterfly diversity, abundance, population dynamics, and extinction (Hoyle and James, 2005; Pöyry et al., 2005; Saarinen and Jantunen, 2005).

The causal relationship between livestock grazing and Quino checkerspot population extinction is unknown. Grazing can cause direct mortality of immobile larvae and pupae through trampling (Weiss, 1999; Swengel, 2001; Schtickzelle et al., 2007). Grazing can indirectly affect butterflies by reducing the richness and abundance of native larval host and nectar plants and by altering vegetation structure and microclimate, thereby impacting thermoregulatory environments for developing larvae (Swengel, 2001; Hoyle and James, 2005; Saarinen and Jantunen, 2005; Schtickzelle et al., 2007). It is conceivable that over-grazing led to Quino checkerspot population extinctions in the 1800s when stocking rates

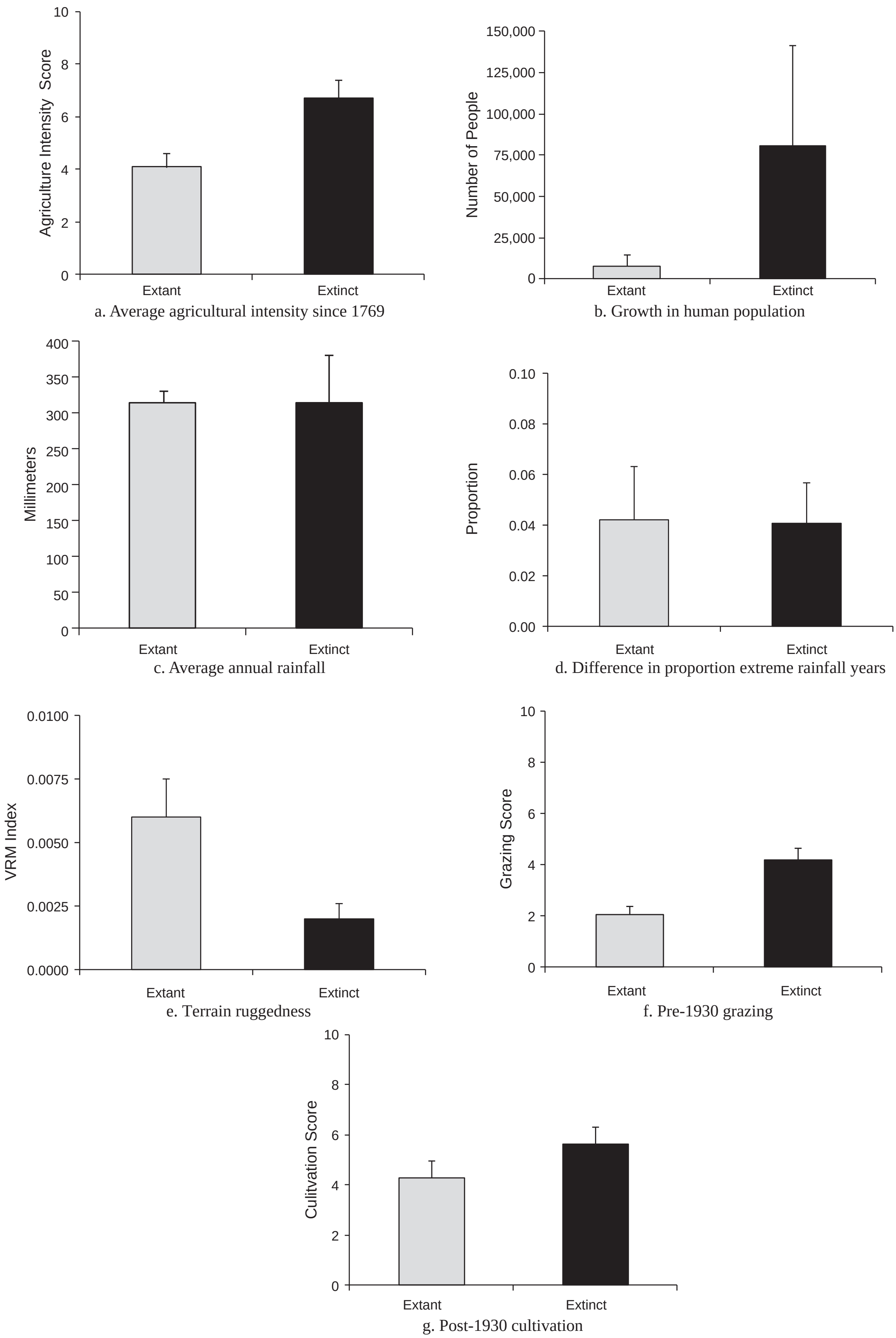

Fig. 2. Environmental attributes at 14 extinct and 14 extant Quino checkerspot populations.

were at their highest and that populations remaining in the 1930s were remnants of a previously more abundant distribution.

Based upon descriptions of Spanish Explorers, missionaries, and early settlers, the best pasture lands supported diverse and

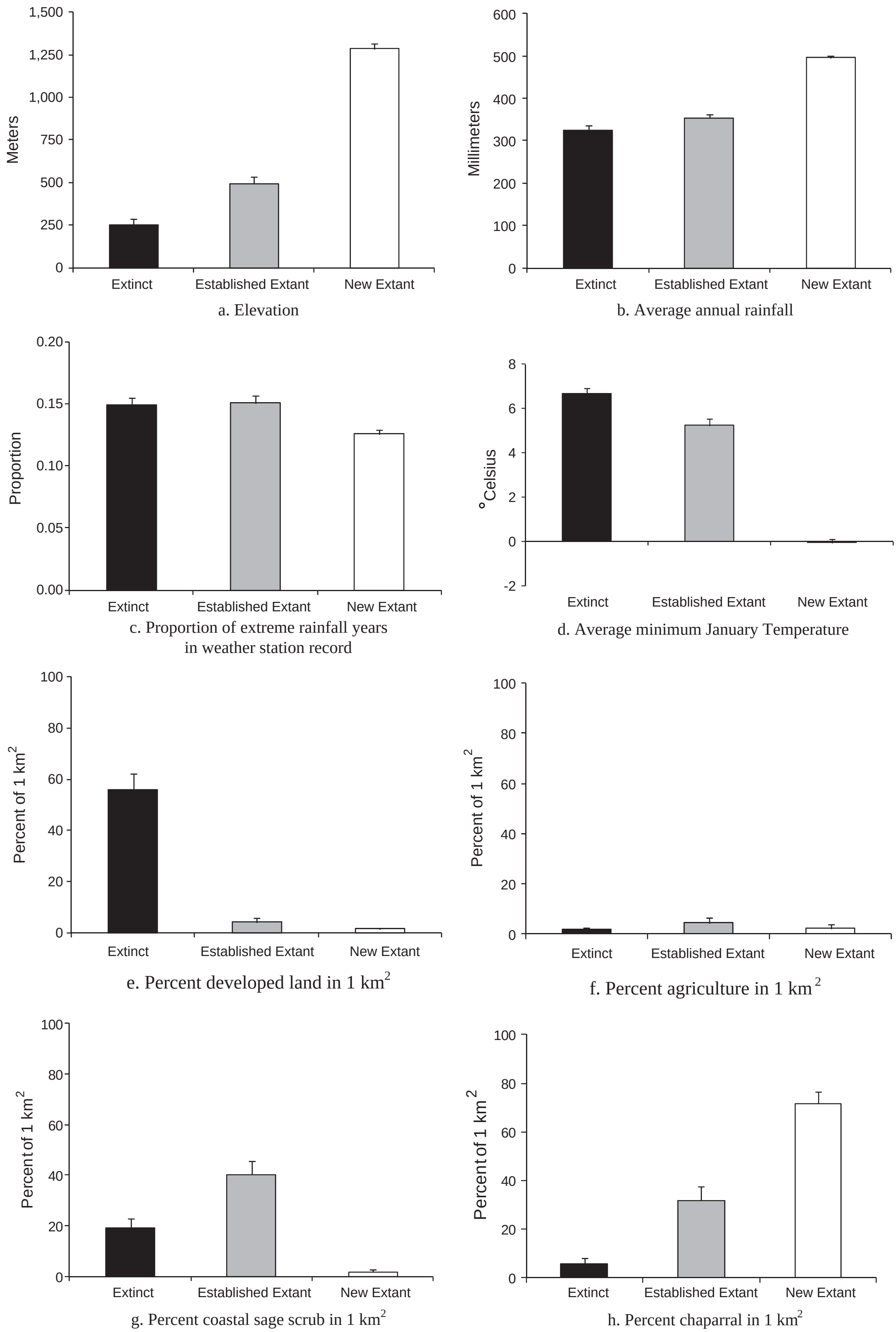

Fig. 3. Environmental attributes at regions currently occupied by Quino checkerspot compared with regions where the butterfly is extinct. "Extinct" indicates areas with no butterfly records since 1998, "established extant" indicates currently occupied areas where the butterfly was historically documented, and "new extant" indicates areas with no location records prior to 1998.

Table 2
Performance of logistic regression models[a] in distinguishing between newly discovered and established extant Quino checkerspot populations relative to current land use (percent agriculture and development in 1 km^2) and natural (climate, percent vegetation in 1 km^2) environmental factors. K represents the number of model parameters, Δ_i is the difference in AIC$_c$ values for each model relative to the model with the lowest AIC$_c$, ω_i is the model weight, and ω_i/ω_1 is the evidence ratio.

Model type	Model parameters	K	Δ_i	ω_i	ω_i/ω_1
Climate	**Annual rainfall**	**3**	**0.000**	**0.654**	
Climate	**Annual rainfall, proportion extreme rainfall**	**4**	**2.044**	**0.235**	**2.8**
Climate and land use	**Annual rainfall, proportion extreme rainfall, % agriculture, % development**	**6**	**4.638**	**0.064**	**10.2**
Climate and vegetation	Annual rainfall, proportion extreme rainfall, % chaparral, % coastal sage scrub	6	5.834	0.035	18.5
Climate, vegetation and land use	Annual rainfall, proportion extreme rainfall, % chaparral, % coastal sage scrub, % agriculture, % development	8	8.257	0.011	62.3
Vegetation	% Coastal sage scrub	3	48.451	0.000	6540000000.0
Vegetation	% Chaparral, % coastal	4	50.514	0.000	>6540000000.0
Vegetation and land use	% Chaparral, % coastal sage scrub, % agriculture, % development	6	54.084	0.000	>6540000000.0
Vegetation	% Chaparral	3	71.341	0.000	>6540000000.0
Climate	Proportion extreme rainfall	3	81.394	0.000	>6540000000.0
Land use	% Development	3	90.508	0.000	>6540000000.0
Land use	% Agriculture	3	92.007	0.000	>6540000000.0
Land use	% Agriculture, % development	4	92.027	0.000	>6540000000.0

[a] Models highlighted in bold form 95% confidence subset of best approximating models. Variables are defined in the methods.

abundant wildflower communities. These areas were also where exotic Mediterranean plants were first introduced and established (Mattoni et al., 1997; Minnich, 2008). Open forb lands with patches of shrubs are characteristic of high quality Quino checkerspot habitat. As late as the early 1900s, primary host and nectar plants for this butterfly were still common. However, southern California wildflowers started a precipitous decline in abundance around 1920 (Minnich, 2008). The trend in decreasing wildflower abundance began at the coast and spread inland, although in some years wildflowers are still average abundance in Riverside County, especially in areas with poor soils. The pattern and timing of wildflower decline corresponds with patterns of Quino checkerspot population extinctions.

Invasive annual grasses in combination with urban development and agricultural expansion contributed to the collapse of extensive native wildflower fields (Minnich, 2008). A suite of Mediterranean annual grasses first invaded coastal areas in the late 1800s, became well established by the 1930s, and then expanded into inland valleys (Wieslander, 1935; Minnich, 2008). This wave of invaders included red brome (*Bromus rubens*), ripgut brome (*Bromus diandrus*), and slender wild oat (*Avena barbata*). The rapid decline of Quino checkerspot in the 20th century is likely caused in part by invasive plants and the collapse of native wildflower fields. Invasive grasses reduce the abundance of native larval host and nectar plants and bare ground available for optimal larval development (Weiss, 1999; Osborne and Redak, 2000). Invasive annual grasses have also contributed to population extinctions in other Edith's checkerspot subspecies (Weiss, 1999; Severns and Warren, 2008).

Intensive grazing can facilitate invasion of exotic plants and likely played a role in the spread and dominance of exotic grasses in California's native plant communities (Leiva et al., 1997; Weiss, 1999; Hayes and Holl, 2003; Seabloom et al., 2003; HilleRisLambers et al., 2010). Although livestock grazing may have contributed to the spread of invasive grasses and forbs, it can also be used to control these species and aid in the return of native species. Butterfly species, including the Bay checkerspot, have benefited from low intensity, managed grazing that reduces exotic grass cover and increases nectar and larval host plant cover (Weiss, 1999; Pöyry et al., 2005; Vogel et al., 2007; Thomas et al., 2010). Intensity and duration of livestock grazing, in relation to other factors determines the magnitude and type of impact grazing has on butterfly populations.

4.1.2. Extinction and cultivation intensity

Cultivation intensity and crop types varied across the study area. There was no clear association between cultivation intensity and extinction. Cultivation was localized and of low intensity from 1769 until the late 1800s. By 1930, the most intensively cultivated areas were coastal plains and river valleys with access to water for irrigating crops. Inland areas were used for dry farming barley and wheat. Extinct Quino checkerspot populations were located near irrigated orchards and crops, whereas extant populations near cultivation tended to be in dry farming regions.

4.1.3. Extinction and human population growth

Human population growth was associated with extinction; although, there was considerable variability. A number of extinctions occurred when the surrounding human population was relatively small. Human population was used as an indicator of urbanization driving habitat loss and fragmentation; we assumed that the larger the population the greater the area impacted by urban activities. This measure is an approximation of impacts and does not provide an actual overlay of converted land relative to butterfly populations. It also underestimates the impact of rural and semi-rural development. It is clear that urban development has fundamentally changed the southern California landscape and areas in which butterfly populations have gone extinct in Orange and San Diego counties currently support substantially higher levels of development compared with extant populations.

4.2. Historic distribution or range shift in response to changing climate?

Parmesan (1996) documented a northward and upward elevation shift in the overall range of Edith's checkerspot associated with changing climate. While habitat degradation and isolation could increase extinction rates, these factors were not thought to contribute to the latitudinal range shift in Edith's checkerspot. Quino checkerspot has not demonstrated a northward shift; rather, extant populations are occurring at higher elevations as predicted by climate change modeling (Parmesan, 1996; Preston et al., 2008). Quino checkerspot populations may have historically occurred, but were unrecorded, at higher elevations along their eastern range margin. High elevation populations are not unprecedented, as populations of Edith's checkerspot occur in the Sierra Nevada and San Bernardino Mountains (Thomas et al., 1996; Mattoni et al., 1997).

Alternatively, newly discovered populations may represent a range shift in response to changing climate, as these high elevation areas are buffered against drought compared with established areas within the historic distribution. Future climate projections for southern California predict temperatures will increase;

precipitation may decrease and is expected to be more variable, with longer, more severe droughts and more intense floods (Seager et al., 2007). The eastern edge of Quino checkerspot's range supports large and robust butterfly populations, abundant and diverse larval host plants and nectar sources, and relatively low levels of development and intensive agriculture. These areas may provide climate refugia that Quino checkerspot will require under future predicted scenarios of climate change (Preston et al., 2008).

5. Conclusion

Local-scale extinctions of Quino checkerspot butterfly populations in southern California were related to agricultural history, human population growth, and wildflower decline. The association of extreme precipitation with extinction was outweighed by the effects of land use. Butterfly population extinctions coincided with spatial and temporal patterns of habitat loss, high intensity grazing, invasion by exotic annual grasses, and wildflower decline. At a larger scale, differences within the distribution of extant Quino checkerspot populations were best predicted by climate variables. Higher elevation populations are buffered from drought. To develop conservation plans and management actions that result in successful long-term conservation of Quino checkerspot, it is important to recognize that multiple stressors operating at different scales influence population dynamics and changes in the butterfly's distribution.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biocon.2012.03.011.

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EXHIBIT 5
to July 8, 2019
Comments

WI #18-063

July 7, 2019

Donna Tisdale
Backcountry Against Dumps
PO Box 1275
Boulevard, California 91905

Subject: Review of Campo Wind Project and Boulder Brush Facilities DEIS Noise Analysis

Dear Donna Tisdale,

As requested, below please find our review of the environmental noise analysis[1] for the Campo Wind DEIS[2] prepared by Dudek for the Campo Wind Project with Boulder Brush Facilities (Project).

Reviewer Qualifications:

This review was led by Dr. Richard A. Carman. Dr. Carman has been an acoustical consultant with Wilson Ihrig for 33 years and is now semi-retired since 2017. His acoustical consulting work has included both large and small environmental studies to evaluate noise and vibration impacts on local communities. He has been the noise and vibration consultant on numerous EIR and EIS projects and is very familiar with establishing noise criteria, assessment of impacts and their mitigation. He has also consulted on many projects on the acoustical evaluation and design of building interiors and the noise control for indoor and outdoor mechanical equipment. He is the primary author on numerous articles on noise and acoustics as well as noise conference presentations. He was the Principal Investigator on two large research studies[3,4] conducted under the auspices of the National Academy of Sciences, Engineering and Medicine – Transportation Research Board. He received his Ph.D. in

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[1] DRAFT Acoustical Analysis Report for the Campo Wind Project and Boulder Brush Facilities, prepared by Dudek for the Bureau of Indian Affairs, May 2019.

[2] DRAFT Environmental Impact Statement for the Campo Wind Project with Boulder Brush Facilities, prepared by Dudek for the Bureau of Indian Affairs, May 2019.

[3] NHCRP Research Report 25-25/Task 72, Current Practices to Address Construction Vibration and Potential Effects on Historic Buildings Adjacent to Transportation Projects, sponsored by the AASHTO Committee on Environment and Sustainability, September 2012.

[4] ACRP Research Report 175, Improving Speech Intelligibility of Airport Terminal Public Address Systems, sponsored by the Federal Aviation Administration, 2017.

mechanical engineering from U.C. Berkeley and is a licensed Mechanical Engineer in the State of California.

1 Summary:

We conclude that the noise analysis is deficient for the following reasons:

1. The DEIS preparer relied on three federal documents and two San Diego County ordinances for regulatory criteria and neglected to address other relevant government criteria.
2. The analysis fails to recognize a limitation of the preparer's noise logging instrumentation, which was used to measure and characterize the existing ambient noise in the Project area. The instrument used has an internal "noise floor" that prevents it from measuring noise levels less than 30 dBA. Noise levels in many locations in the Project area are less than this throughout the day, in particular those away from local roadways. Noise levels less than 30 dBA have been documented in measurements by others. The consequence is an overstatement of the existing ambient noise resulting in an incorrect assessment of the impact of Project noise.
3. The analysis fails to address the substantial increase in ambient noise that would occur in the operational phase of the Project resulting in a significant impact to Noise Sensitive Local Uses (NSLUs). Federal guidelines[5] ,which Dudek used to assess Project construction noise, were not used to assess Project impacts that would be caused by increases in ambient noise caused by the Project in the operational phase. Application of these federal guidelines indicate a substantial increase in noise resulting in a significant impact.
4. The analysis fails to adequately address the effects of low frequency noise on NSLUs.
5. The analysis fails to adequately address the effects on NSLUs of "amplitude modulation" associated with low frequency wind turbine noise.
6. The analysis fails to adequately address the effects of infrasound on NSLUs.
7. The DEIS noise analysis relies on the computer program CadnaA to predict noise generated by Project wind turbines. Although CadnaA was not intended to be applied to prediction of noise generated by large wind turbines due to inherent limitations in the modeling methodology, the DEIS claims to overcome these limitations by introducing a factor of conservatism recommended by a wind turbine acoustics report[6]. In spite of this claimed conservatism, the DEIS understates noise impacts.

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[5] FTA (Federal Transit Administration), Transit Noise and Vibration Impact Assessment, May 2006.
[6] RSG (Resource Systems Group, Inc.), Massachusetts Study on Wind Turbine Acoustics, Report 2.18.2016, 2016.

2 Regulatory Setting

Dudek relied on three federal guidelines[7,8,9] and two San Diego County noise ordinances[10,11] to establish significance criteria for Project generated noise. When assessing operational noise impacts to NSLUs on private land the analysis relies on San Diego County noise ordinances No. 9962 and No. 10262. County ordinance No. 9962 sets absolute limits on A-weighted noise based on the time of day (i.e., 50 dBA for daytime and 45 dBA for nighttime). County ordinance No. 10262 sets a limit on C-weighted noise relative to the A-weighted ambient noise.

The Project DEIS uses FTA guidelines to establish significance criteria for construction noise and vibration impact assessment. However, the DEIS ignores FTA criteria for operational noise. The FTA construction noise and vibration criteria recommend limiting daytime noise for residential land use to 80 dBA energy-averaged over an 8-hour period (L_{eq}(8hr)). The Project DEIS uses an FTA vibration criterion of 0.2 inches per second (ips) PPV to limit damage to "non-engineered structures." Although this is generally accepted practice, this criterion does not ensure no damage will occur to residential structures. The 0.2 ips PPV criterion is generally viewed as a "structural damage" criterion. Damage to plaster walls and drywall can occur at lower levels of vibration.

The Project DEIS noise analysis uses the U.S. Bureau of Land Management (BLM) noise criterion for rural land (RU) to assess noise impacts to the local population residing on the Campo Indian reservation. While the primary purpose of this review pertains to impacts to NSLUs on private land, we would comment that the BLM noise criterion relies on criteria in the 1974 EPA document. The EPA criteria is commonly referred to as "absolute" (i.e., levels not to be exceeded) noise criteria. We include the following quote from the 1974 EPA guidelines:

> *Not all of the scientific work that is required for basing such levels of environmental noise on precise objective factors has been completed. Some investigations are currently underway, and the need for others has been identified.*

More recent criteria reflect contemporary thinking on noise impacts as expressed in the current FTA guidelines, which combine absolute criteria and "relative" (i.e., change in level) criteria. Relative noise criteria accounts for the impact due to increases in ambient noise that are caused by new (i.e., Project) noise sources. The FTA criteria for operational noise impacts are discussed below.

2.1 San Diego County Noise Criteria

San Diego County noise ordinance 9962 limits exterior noise in rural areas (zoned RU) to a one-hour average of 50 dBA during daytime hours (7 a.m. to 10 p.m.) and 45 dBA during nighttime hours (10

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[7] U.S. Department of the Interior Bureau of Land Management, Final Programmatic Environmental Impact Statement on Wind Energy Development on BLM-Administered Land in the Western United States, June 2005.
[8] EPA (U.S. Environmental Protection Agency), Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety, prepared by the U.S. Environmental Protection Agency Office of Noise Abatement and Control, 550/9-74-004, March 1974.
[9] FTA (Federal Transit Administration), Transit Noise and Vibration Impact Assessment, May 2006.
[10] San Diego County, Ordinance No. 9962 (N.S.), An Ordinance Amending Title 3, Division 6, Chapter 4 of the San Diego County Code of Regulatory Ordinances Relating to Noise Control and Abatement.
[11] San Diego Count y, Ordinance No. 10262 (N.S.), An Ordinance Amending the San Diego County Zoning Ordinance Related to Large Wind Turbines

p.m. to 7 a.m.). San Diego County noise ordinance No. 10262 imposes a limit on low-frequency noise from wind turbines as measured using C-weighting.

Ordinance 10262 defines the Residual Background Sound Criterion ($RBSCL_{90}$) as the Background Sound Level measured relative to A-weighting (LA_{90}) plus 5 dBA. Ordinance 10262 further requires preparation of an acoustical study to demonstrate compliance with Section 36.401 of Ordinance 9962 and that the C-weighted sound level from each large wind turbine does not exceed the $RBSCL_{90}$ criterion by more than 20 dB at the property line of the lot on which the large wind turbine is located.

2.2 EPA Criteria

The EPA 1974 criteria, which are incorporated in the BLM criteria, have been discussed above. For rural land use with NSLUs, the BLM absolute criterion is a limit of L_{dn} 55 dBA, which the DEIS applies to residential land on the reservation.

The EPA in a review[12] of the DEIS for the Shu'luuk Wind Project commented that health impacts were not discussed and referenced the World Health Organization[13] recommendation that "where noise is continuous, the equivalent sound pressure level should not exceed 30 dBA indoors if negative effects on sleep are to be avoided." The EPA review letter further states that "when the noise is composed of a large proportion of low-frequency sounds, a still lower guideline is recommended, because low-frequency noise can disturb rest and sleep even at low sound pressure levels." The DEIS for the Campo Wind Project with Boulder Brush Facilities does not address this concern of the EPA.

The DEIS fails to address the EPA concern for potential impacts on sleep due to wind turbine noise that contains substantial continuous low-frequency components.

2.3 Federal Noise Criteria Ignored in the DEIS

The FTA guidelines for operational noise impact assessment recognize that changes in ambient noise can adversely affect local populations. This is particularly important in rural areas (such as the Project area) where a very low ambient noise environment exists, and Project noise would result in a substantial increase over existing ambient noise. FTA criteria for project operational impacts are based on the principle that the absolute noise level alone is insufficient to assess impact and that an increase in noise generated by a project can cause significant impacts depending on the existing ambient level and the amount of increase. The FTA criteria incorporate both the existing ambient noise and the increase in noise. The reasoning behind the FTA criteria for low ambient conditions can be found in Appendix B of the FTA guidelines. Figure 1 illustrates FTA criteria for determining the level of impact as a function of the increase in ambient noise.

Much of the land surrounding the Project can be characterized as "Category 2" (i.e., residential land where nighttime sensitivity is a factor). The noise metric L_{dn} (day-night level also denoted as DNL) is the noise metric used for Category 2 land. Where the existing ambient noise is L_{dn} 40 dBA or less, the threshold for Moderate Impact is 10 dBA and for Severe Impact it is 15 dBA. Using County noise

[12] EPA, review letter dated 4 March 2013 for the DEIS, Shu'luuk Wind Project, Campo Indian Reservation, San Diego County, California (CEQ #201300001).
[13] See http://www.who.int/docstore/peh/noise/Comnoise-4.pdf p. 58.

ordinance No. 9662 alone to assess impacts to NSLUs would in some cases allow increases of 15 dBA and greater.

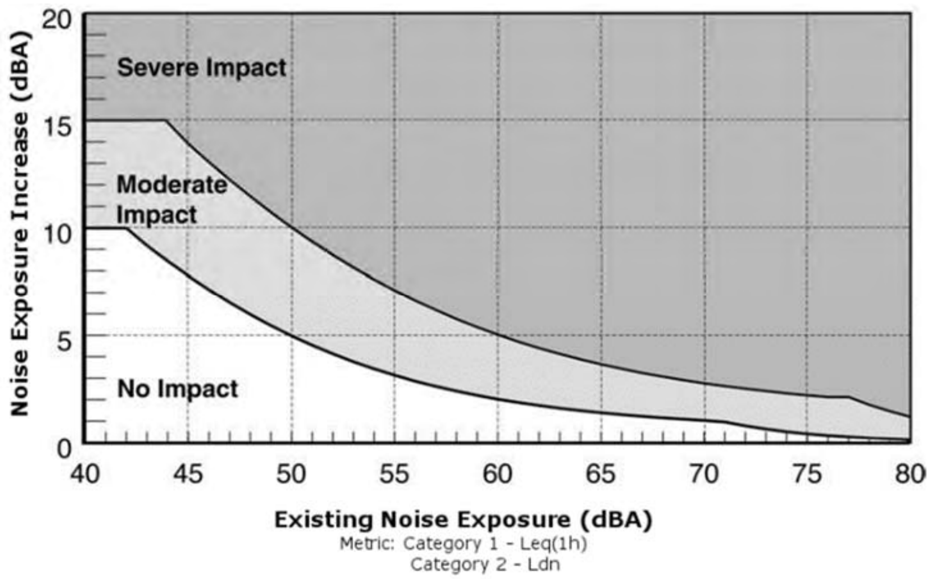

Figure 1 - FTA Operational Noise Impact Criteria

The County ordinance No. 9662 allows hourly average levels up to 50 dBA during daytime hours (7 a.m. to 10 p.m.) and 45 dBA during nighttime hours (10 p.m. to 7 a.m.). The equivalent L_{dn} based on these hourly daytime and nighttime limits is 52 dBA. We note that the BLM criteria document[14] indicates that an L_{dn} of 35 dBA can be expected in a typical rural environment. Consequently, if for example the existing L_{dn} is 37 dBA, then applying only the County noise limit would result in a Severe Impact (i.e., cause a 15 dBA increase) using the FTA relative criteria. Since the DEIS fails to accurately characterize the existing ambient as discussed in Section 3 below this is a real possibility.

A similar problem arises when using the absolute noise criterion for rural land of 55 L_{dn} as recommended in the BLM guidelines, which rely on the 1974 EPA document. For example, if the existing L_{dn} is 37, applying only this absolute criterion would allow an 18 dBA increase, which would be a Severe Impact according to the FTA guidelines.

The DEIS fails to consider the potential noise impacts from significant increases in ambient noise as addressed by the FTA guidelines.

3 Existing Conditions

In preparing the DEIS, Dudek conducted ambient noise measurements to characterize the existing ambient noise condition at thirteen (13) locations on the Campo Indian Reservation, some at or near

[14] U.S. Department of the Interior Bureau of Land Management, Final Programmatic Environmental Impact Statement on Wind Energy Development on BLM-Administered Land in the Western United States, June 2005.

the reservation boundary. These measurements were limited to one twenty-four-hour (24) period at each location. The instrument used by Dudek to measure the ambient noise was a Piccolo II, Type 2 sound level meter and data logger. The manufacturer's published, specification data indicates the Piccolo II instrument is only capable of measuring sound levels equal to or greater than 30 dBA (i.e., the noise floor of the instrument).

Furthermore, since the instrument used by Dudek to measure ambient noise is a Type 2 sound level meter its accuracy is limited to ±2 dBA. In such low background noise environments, it is necessary to use a Type 1 sound level meter with an appropriate microphone, which has a lower noise floor (capable of measuring down to 20 dBA or lower). A Type 1 sound level meter has an accuracy of ±1 dBA.

The DEIS does not mention what type or size microphone windscreen was used or in fact if one was. Microphone windscreens are typically spherical and constructed from open-cell, porous foam. Commercially available windscreens range in size from 2.5 to 7 inches in diameter. In conducting outdoor sound measurements in low ambient noise and potential high wind conditions, a larger windscreen is imperative to minimize artificial wind noise and ensure the accuracy of measured data.

The consequence of using a smaller windscreen (e.g., 3 inch diameter) is that there is a greater likelihood that artifacts are introduced into the measured data due to noise created by air turbulence acting on the microphone. These effects can become substantial as wind speed increase. The end result is higher levels of reported noise than actually exist.

Previous measurements[15] in the area have documented levels less than 30 dBA. Measurements conducted at two locations (one which is in close proximity to LT-1 in the DEIS) between 15:00 and 16:00 indicated an L_{eq} (5-minute duration) of 25 and 29 dBA respectively. It is reasonable to assume that at night (i.e., 10 p.m. to 7 a.m.) the ambient noise levels are lower than this at this and other similar locations remote from roadways, but close to NSLUs. In 2018 Wilson Ihrig measured a background noise level of 25 dBA at a location close to LT-1 at approximately 16:45.

The data for LT-1 in the Campo Wind Project DEIS indicates a minimum level (L_{min}) of 33.6 dBA for all nighttime hours Curiously the Leq for two of those hours is greater than the Lmin, which is physically impossible. Furthermore, the statistical level noise data (i.e., L_n or the noise level exceeded n% of the time) between 3 and 4 a.m. are all the same (e.g., L_1 and L_{99} are both 35 dBA).

A close review of the data for LT-12 indicates a serious problem. We note that the statistical noise level L_1 (the level exceeded 1% of the time) is less than the L_5 (the level exceeded 5% of the time) for all hours of the day and the L_5 is less than the L_{10} (the level exceeded 10% of the time) from 10 a.m. until 7 p.m., both of which are impossible. A noise level that is exceeded for a longer time period cannot be greater than the level exceeded for a shorter time period (i.e., the shorter the time interval the greater the noise level). This calls into question the reliability of the instrumentation.

These are clear indications that the instrumentation used is unable to accurately measure the ambient noise when it is less than 30 dBA (i.e., the "noise floor" for the Type 2 sound level meter used). The combination of the 30 dBA noise floor of the sound level meter and the inaccuracy of the

[15] DEIS, Campo Solid Waste Management Project, Campo Indian Reservation, San Diego County, California, prepared for U.S. Department of Interior, Bureau of Indian Affairs, February 1992.

Type 2 (±2 dBA) renders the data at lower sound levels presented in the DEIS inaccurate and unreliable.

We note that the ambient data for each location were only measured for one, 24-hour period. It is customary to measure for at least two or three days to ensure the data presented are representative and not anomalous, in particular in such low background conditions where one loud noise event can skew the L_{eq}.

The DEIS fails to accurately characterize the existing ambient noise conditions as a result of the limitations of the noise measuring instrument(s) used and the inadequacy of measuring for only one 24-hour period.

4 Impacts

4.1 Noise Impact Predications Based on the Computer Program CadnaA

The predicted Project noise levels for wind turbines are based on the acoustical computer program CadnaA. CadnaA incorporates the outdoor sound propagation models (i.e., formulas) contained in ISO 9613-2[16]. ISO 9613-2 has inherent limitations that preclude using these formulas to accurately predict wind turbine noise. Those limitations include source height and wind speed. ISO 9613-2 is intended to be used for cases where the wind speed does not exceed 5 meters/second (measured at a height of 3 to 11 meters above the ground), the noise source and receiver heights are not too dissimilar, and the source height is less than 30 meters.

The DEIS states that "wind turbines were treated as point sources located at hub height (110 meters or 361 feet) relative to grade, and receptors were assumed to be 5 feet above grade. The stated accuracy of the ISO 9613-2 formulas for a mean height of the source and receiver of between 5 meters and 30 meters is ±3 dB. There is no stated accuracy in ISO 9613-2 for source heights greater than 30 meters. It is reasonable to believe that it would be greater than 3 dB. The proposed wind turbine hub heights are 116 meters or 86 meters greater than the specified range of applicability of ISO 9613-2 formulas.

ISO 9613-2 does not include the effects of sound refraction due to temperature or wind gradients, both of which can increase sound levels. Consequently, CadnaA does not include these effects. CadnaA would not appear to be appropriate for use in accurately predicting noise from large wind turbines.

The DEIS states that the limitations inherent in CadnaA (i.e., those of ICO 9613-2) are addressed by incorporating a "conservative factor" (i.e., +2 dB) as recommended by the RSG study[17]. The RSG study indicates that this 2 dB "penalty" resulted in the "greatest precision for receivers at 330 meters downwind" (i.e., at 1,072 feet). There is no mention in the RSG study of the accuracy of predications using ISO 9613-2 at other distances or other directions (e.g., upwind or crosswind). We note that it is difficult to evaluate the RSG study's applicability to the Project and its wind turbines.

[16] International Standards Organization, ISO 9613-2, Acoustics – Attenuation of sound during propagation outdoors – Part 2: General method of calculation, 1996.
[17] RSG, Massachusetts Study on Wind Turbine Acoustics, Report 2.18.2016, 2016.

The RSG study mentions that the wind turbines in the study were 1.5 MW and larger, but it does not specify the highest rated capacity or the range of turbine capacities. The Project wind turbines will have a rated capacity of 4.2 MW. Obviously, there is a big difference between 1.5 MW and 4.2 MW. Consequently, we question the applicability of the RSG study conclusions to the Project with regard to conservative factors that were added to the DEIS predictions.

The DEIS fails to accurately predict Project noise levels by using a computer program based on formulas that have specified limitations and have not been validated for wind turbine noise prediction for wind turbines of the size to be constructed for the Project.

4.2 Problems with the Manufacturer's Noise Data

The noise data supplied by the manufacturer is in terms of measured, sound power. Sound power is measured across the sound spectrum of importance. Based on our personal experience, it is difficult to accurately measure sound power for mechanical sources even under ideal conditions. In general, the larger the size of the noise source (machine) the more difficult it is to measure sound power accurately. Accurate sound power measurements can only be made by measuring sound radiated in all directions from a noise source.

There are methods (e.g., acoustic beamforming) that can be applied to measure sound power of large noise sources in-situ. However, no supporting documentation has been supplied in the DEIS to properly evaluate the manner in which the manufacturer's sound power data was measured and thus its accuracy. Consequently, we question the accuracy of the manufacturer's sound power measurements, particularly at lower frequencies.

Except for turbine blade noise, the main source of wind turbine noise is the generator. Unless very sophisticated means were used, it is unlikely that manufacturer's sound power measurements were made for a fully operating wind turbine given that the hub height is 116 meters. We can only surmise that the sound power measurements may have been made with the generator on the ground. At higher frequencies this may not be as much of an issue, but the wavelength of lower frequency (e.g., less than 125 Hz) sound is much longer than at higher frequencies (e.g., 1,000 Hz). For example, the wavelength of sound at 31.5 Hz is 35 feet. Accurately measuring sound power with the source on the ground of sound with a 35 foot wavelength poses a challenging if not insurmountable problem.

Typically, mechanical noise sources are directional in nature, which means that noise is not emitted uniformly in all directions. It would appear from the reported data in Appendix B of the DEIS noise analysis report that the wind turbine was modeled as an omni-directional noise source (i.e., noise is emitted uniformly in all directions). We see no evidence that the CadnaA model used in the DEIS noise analysis accounts for directionality. It is doubtful that the data pertaining to the directionality of wind turbine noise is available from the manufacturer; otherwise it would have been incorporated.

The DEIS does indicated how the manufacturer measured noise emission data for the planned wind turbines. Consequently, it is not possible to evaluate whether or not there are inherent limitations of the turbine manufacturer's data as they pertain to noise emission from the Project's turbines.

4.3 A-weighted, Project Noise Impacts

The inability of the sound level meter used by Dudek to measure low ambient noise (i.e., less than 30 dBA) means that nighttime levels reported at several locations are inaccurate and higher than actual. This is a problem in that the calculation of L_{dn} adds 10 dB to nighttime levels to account for the increased sensitivity to noise affecting sleep. Consequently, measured nighttime levels that are higher than actual due to instrumentation limitations mean that the reported L_{dn} values in the DEIS are greater than actual. We note that the lowest existing ambient L_{dn} reported in the DEIS is 43.5 dBA (LT-9).

The overstating of ambient noise in combination with ignoring the potential for substantial increases in ambient noise due to the Project minimizes the actual impact from Project noise. For example, nighttime levels at DEIS location LT-10, are indicated as being approximately 31 dBA (L_{50}). Actual levels in fact could be 5 to 6 dBA lower (i.e., 25 to 26 dBA). This means that if wind turbine noise is only limited to 45 dBA at night, the ambient noise could increase by up to 20 dBA. Using the FTA criteria, a 20 dBA increase would be a Severe Impact and thus a significant impact under NEPA.

The DEIS minimizes the Project noise impacts by using inaccurate ambient noise data while applying only the County noise ordinance criteria and ignoring substantial increases in ambient noise caused by the Project.

4.4 Low Frequency Noise Impacts

Low frequency noise impacts were evaluated in the DEIS using the County's noise ordinance No.10262 and the $RBSLC_{90}$. The DEIS uses the CadnaA program to predict low frequency noise. As discussed above in Section 4.1, the CadnaA program has explicit limitations that preclude its use for predicting large wind turbine noise. This is particularly true with regard to low frequency noise. At lower frequencies the noise emitted by wind turbines can in certain circumstances be more directional even than at higher frequencies.

For example, Kim, et. al.[18] have developed a noise prediction model for amplitude modulation from large WTs. As discussed below amplitude modulation is associated with low frequency noise. The noise model developed by Kim, et. al. predicts that the overall sound pressure level is highly directional. In the case of amplitude modulation, the model predicts noise levels that are greatest on-axis (in the direction of the turbine rotor, which is also the direction that the wind is blowing) and that the amount (or depth) of modulation is greatest in the plane of the turbine blades (perpendicular to the rotor). In other words, low frequency noise from large wind turbines can be anything but omni-directional.

The DEIS not only uses CadnaA, with the program's inherent limitations, to model low frequency noise, it also treats noise emission at all frequencies (in particular at low frequencies) to be omni-directional. Consequently, the DEIS low frequency predictions are inaccurate.

[18] Lee, Seunghoon, H. Kim, Kyutae Kim, and Soogab Lee, Perception of amplitude-modulated noise from wind turbines, 17th International Congress on Sound and Vibration, Cairo, 18-22 July 2010.

4.5 Noise Impacts Due to Amplitude Modulation

Amplitude modulation is the rhythmic fluctuation in noise level. Pilot studies[19] have been conducted in a laboratory setting to investigate the effect of wind turbine noise on sleep disturbance. The study reported that "findings indicated that amplitude modulation strength, spectral frequency and the presence of strong beats might be of particular importance for adverse sleep effects."

Measurements[20] conducted in the Project area demonstrate that the existing wind turbines generate amplitude modulated noise. Figure 2 illustrates amplitude modulation measured at a distance of 4,400 feet from the closest wind turbine at Tule Wind with peak-to-peak variation ranging from 4 to 9 dBA. These measurements demonstrate the presence of "excessive amplitude modulation" (peak-to-peak variation of 4 dBA or more) as defined by Cooper[21] or "enhanced amplitude modulation" (variation of 6 dBA) as characterized by Oerlemans[22].

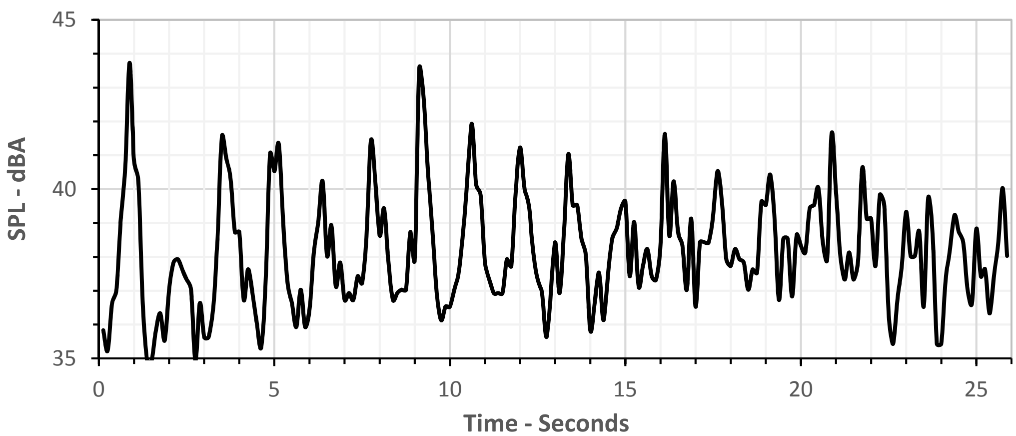

Figure 2 - Example of Amplitude Modulation

The DEIS addresses the impact of amplitude modulation by citing a study by RSG[23] that seems to minimizes the severity of this phenomenon contrary to the evidence in Figure 2 above. Whereas the RSG study cited notes that modulations depths are rarely above 4 dB, the measurement at 4,400 feet from a Tule wind turbine indicates modulation depths up to 9 dB or *excessive* modulation under either Cooper's or Oerlemans' definition.

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[19] Morsing, J.A., M.G. Smith, M. Ögren, P. Thorsson, E. Pederson, J. Forssén, and K.P. Waye, Wind Turbine Noise and Sleep: Pilot Studies on the Influence of Noise Characteristics, International Journal of Environmental Research and Public Health, **15**(2573), 2018.

[20] Wilson Ihrig, Results of Ambient Noise Measurements of the Existing Kumeyaay Wind and Tule Wind Facilities in the Area of Boulevard and Jacumba Hot Springs Pertaining to the Proposed Torrey and Campo Wind Turbine Facilities, report for Backcountry Against Dumps, 18 March 2019.

[21] Cooper, S., Hiding wind farm noise in ambient measurements – Noise floor, wind direction and frequency limitations, 5th International Conference on Wind Turbine Noise, Denver, 28-30 August 2013.

[22] Oerlemans, S., An explanation of enhanced amplitude modulation of wind turbine noise, report for the National Aerospace Laboratory, July 2011.

[23] RSG, Massachusetts Study on Wind Turbine Acoustics, Report 2.18.2016, 2016.

Furthermore, the DEIS attempts to address amplitude modulation by adding 2 dB to the source levels in the CadnaA model. The only effect this has is to increase the predicated A-weighted noise levels. This fails to address the actual impact of amplitude modulation in two ways. First it ignores the fact that A-weighted noise impacts, which the County noise ordinance addresses, are a short range issue. Amplitude modulation is not a short range issue and occurs up to long distances (e.g., 4,400 feet) from wind turbines. Consequently, amplitude modulation cannot be evaluated by applying the County noise ordinance criteria. Secondly the DEIS approach to assessing amplitude modulation impact misses the point altogether. The salient feature of amplitude modulation impact is the depth of the variation (i.e., peak-to-peak range) of the noise level and not the noise level itself. CadnaA cannot be used to predict amplitude modulation.

The DEIS fails in the assessment of Project noise to accurately address amplitude modulation noise and its potential for sleep disturbance.

4.6 Noise Impacts Due to Infrasound

Infrasound (very low frequency sound, i.e., lower than 20 Hz) from large wind turbines has been clearly documented[24,25,26]. Infrasound from large wind turbines is characterized by its tonal nature and a spectrum that consists of sharp peaks at the "blade passage frequency" f_o (typically 1 Hz and lower) and the harmonics of the blade passage frequency (i.e., $2f_o$, $3f_o$, $4f_o$, etc.).

An example shown in Figure 3 illustrates infrasound spectra of existing wind turbines measured in the vicinity of the Project under low wind conditions. It should be noted that infrasound tends to increase with wind speed. The infrasound spectrum in Figure *3* is a classic example of noise produced by a machine with blades (e.g., helicopter).

Previous measurements[27,28] in the vicinity of the Project documented the existence of infrasound generated by the four existing wind farms in the area (Kumeyaay, Tule, Ocotillo, and Energia Sierra Juarez). The noise levels shown in Figure 4 illustrate the magnitude of infrasound and low frequency noise measured at 4,400 feet from the closest wind turbine at Tule Wind. Please note that the frequency scale in Figure 3 is "logarithmic" whereas the frequency scale in Figure 4 is "linear." The reason for doing this is to more clearly highlight the tonal nature of infrasound including the harmonics of the blade passage frequency as illustrated in Figure 3. It should also be noted that the magnitude of harmonics can often be greater than the blade passage frequency and higher wind speeds generally create higher levels of noise.

An often stated misconception is that measurements of wind turbine infrasound might be affected by microseisms (small earthquakes). This ignores the fact that small earthquakes occur randomly and

[24] Channel Islands Acoustics, et. al., A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin, Report No. 122412-1, December 24, 2012.
[25] Epsilon Associates, A Study of Low Frequency and Infrasound from Wind Turbines, July 2009.
[26] Ambrose, S. and R. Rand, The Bruce McPherson Infrasound and Low Frequency Noise Study, 14 December 2011.
[27] Wilson Ihrig, Kumeyaay and Ocotillo Wind Turbine Facilities Noise Measurements, report submitted to Stephan C. Volker, Esq., 25 February 2014.
[28] Wilson Ihrig, Results of Ambient Noise Measurements of the Existing Kumeyaay Wind and Tule Wind Facilities in the Area of Boulevard and Jacumba Hot Springs Pertaining to the Proposed Torrey and Campo Wind Turbine Facilities, report for Backcountry Against Dumps, 18 March 2019.

typically last for only a few seconds. The spectral data in Figure 3 and Figure 4 were obtained from recorded samples that lasted for several minutes. The analytical methodology used to obtain these data minimizes any effects of very short term events that are random in nature. This misconception also ignores the fact that any sound generated by small earthquakes would be very low in magnitude (i.e., the ground is generally a poor radiator of sound). Furthermore, ground radiated sound from small earthquakes would produce a “broadband” spectrum and not one that is tonal in nature.

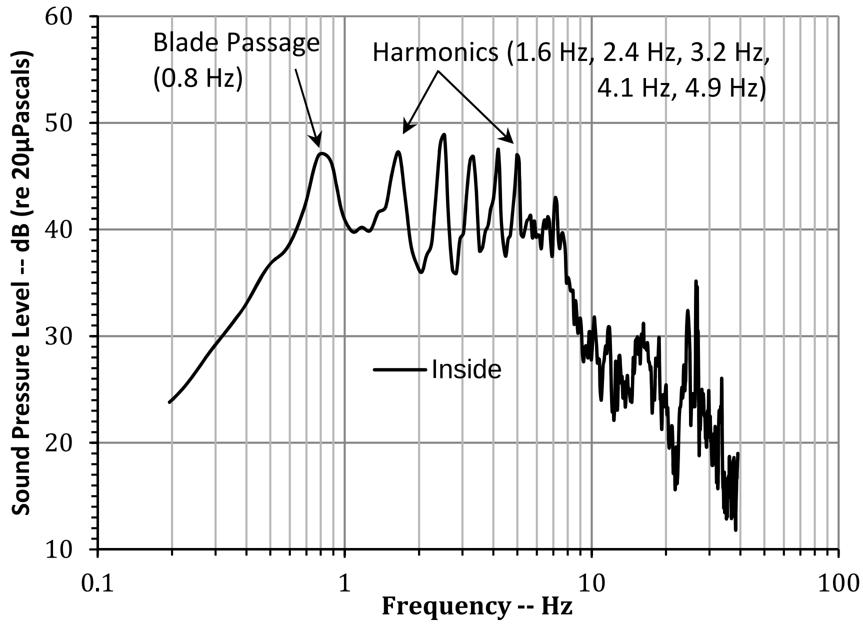

Figure 3 - Example of Infrasound Measured in the Vicinity of the Project

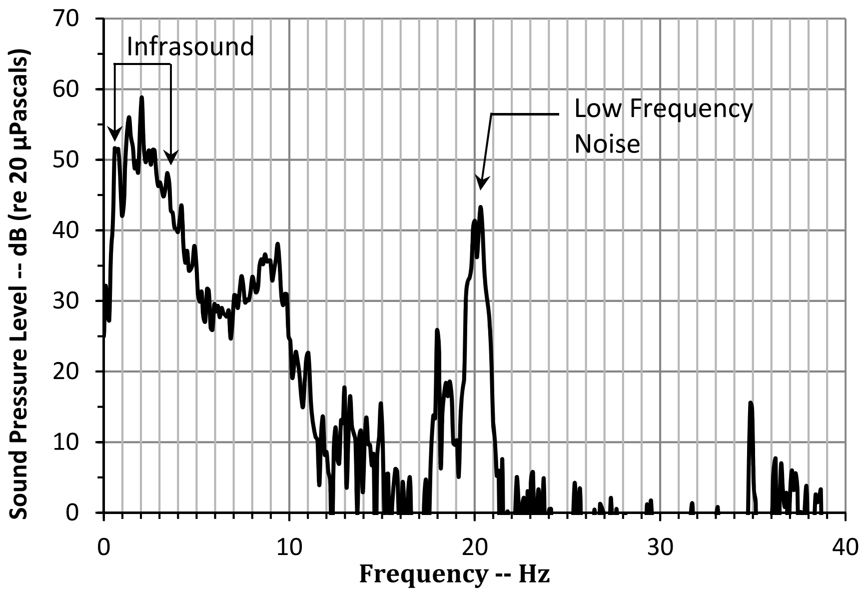

Figure 4 - Infrasound and Low Frequency Noise Measured at 4,400 feet from a Wind Turbine

The research work of Salt and Lichtenhan.[29] has made a clear case for the perception of infrasound and low frequency noise (ILFN) below the threshold of hearing as defined by ISO 389-7. ISO 289-7 is related to the response of the ear's inner hair cells (IHC). Salt has demonstrated that it is possible for the ear's outer hair cells (OHC) to respond to ILFN at sound pressure levels that are much lower than the IHC threshold. Salt and Kaltenbach[30] have reported that ILFN levels commonly generated by wind turbines can cause physiologic changes in the ear. The DEIS neglects the research into the effects of infrasound on humans and defers to the RSG study which relies solely on an argument of audibility. The research indicates that humans could be negatively impacted at sound levels significantly below the threshold of audibility.

The DEIS fails to adequately assess infrasound and its potential for physiologic impacts on the local population especially with regard to sleep disturbance.

Please feel free to contact me with any questions on this information.

Sincerely,

Richard A. Carman, Ph.D., P.E.
Principal Emeritus
Wilson Ihrig & Associates

[29] Salt, A. and J. Lichtenhan, Perception based protection from low frequency sounds may not be enough, Internoise 2012, August 2012.
[30] Salt, A. and J. A. Kaltenbach, Infrasound from Wind Turbines Could Affect Humans, Bulletin of Science, Technology and Society, **31**(4), pp. 296-302, 12 September 2011.

EXHIBIT 6
to July 8, 2019
Comments

RESULTS OF AMBIENT NOISE MEASUREMENTS

OF THE EXISTING KUMEYAAY WIND AND TULE WIND FACILITIES

IN THE AREA OF BOULEVARD AND JACUMBA HOT SPRINGS

PERTAINING TO THE PROPOSED TORREY AND CAMPO WIND TURBINE FACILITIES

18 March 2019

Submitted to:

Donna Tisdale

Backcountry Against Dumps

Submitted by:

Richard A. Carman, Ph.D., P.E.

Michael A. Amato

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EXECUTIVE SUMMARY

Two wind turbine (WT) farms, Torrey Wind, with thirty (30) WTs, and Campo Wind with sixty (60) WTs are proposed for construction in the Boulevard, California area. Noise recordings were obtained between November 13 and November 17, 2018 in the area of Boulevard and Jacumba Hot Springs. The purpose of the recordings was to measure and document the existing infrasound and low frequency noise (ILFN) generated by the existing wind turbines in the area. Another purpose of the measurements was to document the existing C-weighted noise levels at several locations on the boundaries of the Torrey and Campo wind farm projects. During the noise recordings, amplitude modulated (AM) noise was observed in the field. Analysis of the noise recordings indicated the existence of AM noise generated by the WTs.

There are currently two WT farms in the Boulevard area: Kumeyaay with twenty-five (25) WTs and Tule with fifty-seven (57) WTs. To the east is the Ocotillo wind farm with one hundred and twelve (112) WTs, which are about 11 miles between the closest recording location and wind turbine. To the southeast in Mexico is the Energia Sierra Juarez (ESJ) wind farm with forty-seven (47) WTs, which are about 7 miles between the closest recording location and wind turbine.

In 2013 noise measurements were conducted in the Boulevard and Ocotillo areas. At that time only the Kumeyaay and Ocotillo wind farms existed. The 2014 Wilson Ihrig (WI) report[1] documents the results of the 2013 measurements. The current report and the 2014 WI report conclusively document the presence of WT generated infrasound (IS) as measured at residential and other locations up to 8 miles from the wind turbines at the Kumeyaay and Tule facilities. Analysis of the current noise recordings also indicates excessive amplitude modulated noise generated by the existing WTs.

It is clear from the measured noise data obtained for the Kumeyaay and Tule and other wind turbine facilities in the area that there is significant wind turbine-generated ILFN. This was to be expected as it has been documented by others such as in the Falmouth noise study[2], the Shirley Wind Turbine study[3], and by Epsilon Associates.[4] And indeed the measured ILFN levels near Kumeyaay and Tule wind turbine facilities are similar to those measured in previous studies after accounting for the proximity of the measurements to a wind turbine and the total number of the wind turbines in the facility.

Both the Falmouth and Shirley wind turbine noise studies were conducted to investigate whether and at what levels the subject wind turbines (the turbines in Falmouth,

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[1] Kumeyaay and Ocotillo Wind Turbine Facilities, Noise Measurements, report by Wilson Ihrig submitted to Stephen C. Volker, Esq., 28 February 2014.

[2] Ambrose, S. and R. Rand, The Bruce McPherson Infrasound and Low Frequency Noise Study, 14 December 2011.

[3] Channel Islands Acoustics, et al, A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin, Report No. 122412-1, December 24, 2012.

[4] Epsilon Associates, A Study of Low Frequency and Infrasound from Wind Turbines, July 2009.

Massachusetts, and those in the Shirley Wind Project in Brown County, Wisconsin) produce ILFN, and whether that ILFN was contributing to the significant health and other impacts reported by nearby residences. In some cases, the impacts were so severe that residents abandoned their homes. Both studies found high levels of wind turbine-generated ILFN at numerous nearby residences that correlated with residents' reported impacts.

Human health impacts from wind turbines had been reported previously in several countries with large wind facilities in proximity to residences. But these impacts were often attributed to certain individuals' aversion to the presence of a large industrial facility constructed in what was previously a quiet rural setting. Scientific understanding has developed significantly since then.

Research and investigations into human response to ILFN seem to provide strong evidence of a cause and effect relationship. The work of Salt, et al.[5] has made a clear case for perception of ILFN below the threshold of hearing as defined by ISO 389-7 which is related to the response of the ear's inner hair cells (IHC). Salt has demonstrated that it is possible for the ears' outer hair cells (OHC) to respond to ILFN at sound pressure levels that are much lower than the IHC threshold. Salt has reported that ILFN levels commonly generated by wind turbines can cause physiologic changes in the ear.[6] Salt and Kaltenbach "estimated that sound levels of 60 dBG will stimulate the OHC of the human ear."[7]

Furthermore, Matsumoto et al.[8] have demonstrated in a laboratory setting that humans can perceive ILFN at sound pressure levels below the IHC threshold when the noise is a complex spectrum (i.e. contains multiple frequency components). From this laboratory research it was clearly demonstrated that humans can sense sound pressure levels, although not through the normal hearing mechanism, that are from 10 to 45 decibels (dB) less than the OHC threshold in the ILFN range. In fact, the Matsumoto thresholds clearly follow the OHC threshold down to the frequency below which the two diverge. The Matsumoto thresholds are lower than the OHC thresholds at frequencies below the point at which they diverge.

The studies cited above, and more recent studies demonstrate that wind turbines (specifically wind turbine-generated ILFN) have the potential to not only annoy humans, but harm them physiologically. For example, an extensive literature review by Carlile, et al.[9] presents data and discusses findings from numerous sources that document the existence

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[5] Alec Salt, and J. Lichtenhan, Perception based protection from low-frequency sounds may not be enough, Internoise 2012, August 2012.

[6] Alec Salt, and J .A. Kaltenbach, "Infrasound from Wind Turbines Could Affect Humans," Bulletin of Science, Technology and Society, 31(4), pp.296-302, September 12, 2011.

[7] Ibid., p. 300, "As discussed below, G-weighting (with values expressed in dBG) is one metric that is used to quantify environmental noise levels. While it is a more accurate measure of ILFN than most other metrics, G-weighting still de-emphasizes infrasound."

[8] Yasunao Matsumoto, et al., An investigation of the perception thresholds of band-limited low frequency noises; influence of bandwith, published in The Effects of Low-Frequency Noise and Vibration on People, Multi-Science Publishing Co. Ltd.

[9] Carlile, Simon, John L. Davy, David Hillman and Kym Burgermeister, A review of the possible perceptual and physiological effects of wind turbine noise, Trends in Hearing, v.22, Jan-Dec 2018.

and sources of ILFN from large wind turbines and the potential physiological effects on humans resulting from wind turbine ILFN. In discussing human reaction to WT ILFN, Carlile, et al. highlight that "a further mechanism considered by Salt and Hullar[10] is the increased fluid coupling of vestibular cells to sound input produced by changes in the input impedance of the vestibular system in conditions such as superior canal dehiscence (SCD), which can result in sound induced dizziness or vertigo, nausea, and nystagmus (Tullio phenomena)." This is relevant since many who tell of adverse effects of WT ILFN report that dizziness or vertigo is one of the effects they feel.

The data presented herein represent the conditions of measurement during the study and do not necessarily represent maximum noise conditions produced by the Kumeyaay, Tule, Ocotillo and Energia Sierra Juarez facilities. Higher wind speeds generally produce higher noise levels and particularly higher ILFN. This was clearly demonstrated in the Ocotillo data from 2013 when comparing the daytime and nighttime levels.

INTRODUCTION

As requested, WI performed noise measurements in November 2018 in the areas of the proposed Torrey and Campo wind farms, the existing Kumeyaay wind farm, located on the Campo Indian Reservation, and the existing Tule wind farm, located on Bureau of Land Management (BLM) land. In 2013 WI conducted similar noise measurements in the Boulevard area and in the vicinity of the Ocotillo Wind Energy Facility located near Ocotillo, California. The results of those measurements are contained in Appendix D.

The purpose of the current measurements is to determine whether, and at what levels and under what conditions, the Kumeyaay and Tule wind turbines generate ILFN[11], and how far the ILFN is propagated. A subsidiary goal was to accurately show the pressure fluctuations in the sound, to allow an accurate and robust analysis of the human health and other environmental impacts of the ILFN generated. Another goal was to document the existing ambient (C-weighted) noise levels at the boundaries of the proposed Torrey and Campo wind farms.

Between November 13 and November 16, 2018, WI recorded noise samples at numerous residential and proposed wind farm project boundary locations. The wind turbines at the Tule wind farm were operating the entire time during which we conducted our noise recordings. Some but not all the WTs at the Kumeyaay wind farm were operating during this time. On the morning of November 17, the wind turbines at Kumeyaay Wind and Tule Wind that were observable from the last measurement location were not operating. However, on review of the spectral data, it appears that some WTs, most likely on the northern end at Tule Wind were operating. Through a spectral analysis of the noise recordings, we obtained sound

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[10] Salt, A. N., T.E. Hullar, Responses of the ear to low frequency sounds, infrasound and wind turbines, Hearing Research, 16 June 2010.

[11] Infrasound is defined as sound at frequencies less than 20 Hz. The focus of this report is frequencies less than 40 Hz, which includes low frequency sound as well.

pressure level data demonstrative of wind turbine-generated ILFN. In this report, we present and analyze the study results.

WIND TURBINE DETAILS

Kumeyaay Wind Farm

Kumeyaay Wind is owned by Kumeyaay Wind LLC (part of Leeward Renewable Energy LLC) and managed by Kumeyaay Holdings LLC, on 45 acres of land on the Campo Indian Reservation in southeastern San Diego County.[12] The nearest community outside of the tribal land is Boulevard, California. Currently there are twenty-five (25) wind turbines operating at this facility. The wind turbines are located on a north-south ridge (Tecate Divide) at elevations ranging from 4,200 to 4,600 feet. The turbines started generating power in December 2005.

Kumeyaay Wind's turbines are Gamesa model G87X-2.0, with a rated power of 2.0 megawatts (MW). According to the manufacturer's published data, the G87X-2.0 has a hub height (height of the nacelle, which houses the gearbox, transmission and generator) that can vary from 217 to 325 feet depending on site conditions. The manufacturer also represents that the turbine has a rotor diameter of 283 feet, with three 138-foot-long, adjustable pitch blades. According to Councilman Miskwish the hub height of the Kumeyaay Wind turbines is typically 228 feet, and the blades are 145 feet long. Figure 1 shows some of the wind turbines at Kumeyaay Wind as seen from the Morgan residence.

The G87-2.0 model has a reported cut-in wind speed of 8.9 mph and achieves its rated (max) power generation at about 31 mph. The operational speed of the turbines is reported by the manufacturer to be in the range of 9 to 19 revolutions per minute (rpm) depending on wind conditions.

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[12] "Kumeyaay Wind Energy Project," PowerPoint presentation by Councilman Michael Connolly Miskwish, Campo Kumeyaay Nation, November 30, 2008., *available here:* http://www.lawseminars.com/materials/08TRIBDC/tribdc%20m%2017%20Connolly%20A.pdf

Figure 1 Gamesa Wind G87-2.0 Turbines at Kumeyaay Wind 1.7 Miles from Morgan Res.

Tule Wind Farm

The Tule Wind facility is owned and operated by Avangrid Renewables, on 12,360 acres of public land located in southeastern San Diego County and managed by the United States Bureau of Land Management (BLM). Tule Wind currently has fifty-seven (57) operating wind turbines. The wind turbines are located on a ridge line adjacent to the community of Boulevard, California, at elevations ranging from approximately 3,880 to 4,550 feet above sea level. The Tule WTs are GE model 2.3-107 ESS, with a rated power of 2.3 MW. Figure 2 shows some of WTs at Tule Wind as seen from the Chase residence. Figure 1 shows Tule WTs as seen from the Guy residence.

Figure 2 GE 2.3-107 ESS Wind Turbines at Tule Wind 1.4 Miles from Chase Residence

Figure 3 GE 2.3-107 ESS Wind Turbines at Tule Wind 4,300 Feet from Guy Residence

According to the manufacturer's published data, the 2.3-107 ESS model has a nominal hub height of 260 feet depending on site conditions, with a turbine rotor diameter of 348 feet and three 174-foot-long blades. The 2.3-107 ESS has a manufacturer-reported cut-in wind speed of 6.6 mph and achieves its rated power at wind speeds in the range of 16 to 24 mph. The manufacturer stated range of operational rpm is 5 to 14.9 rpm depending on wind conditions.

Torrey Wind and Campo Wind Farm Projects

Two wind turbine (WT) farms, Torrey Wind, with thirty (30) WTs, and Campo Wind with sixty (60) WTs are proposed for construction in the Boulevard area. The developer of both projects is Terra Gen. The proposed Torrey Wind will install 4.2 MW WTs on private land. The proposed Campo project will install 4.2 MW WTs on reservation land. Torrey Wind will also construct a collector substation, a 230-kV/500-kV substation/switchyard, which will be shared by Campo Wind and an operations and maintenance building. The zones for WT sites for Torrey Wind have been identified[13]. A map of Torrey Wind is contained in Appendix E. A map of Campo Wind is contained in Appendix F.

MEASUREMENT LOCATIONS

Kumeyaay and Tule Wind Area Residences

Both indoor and outdoor noise recordings were made at fifteen (15) residences in the Boulevard area near the Kumeyaay Wind and Tule Wind turbines and in Jacumba Hot Springs. Table 1 lists the addresses of the residences at which the measurements were taken, along with the dates and times of the recordings. The area residences where measurements were obtained are located at distances of from 4,430 feet to 8.02 miles from the nearest wind turbine at either Kumeyaay Wind or Tule Wind. A map showing the Kumeyaay and Tule wind area measurement locations is provided in Appendix A. Some of the residents wished to remain anonymous and are identified as such.

Table 1 Addresses of Residences for Measurements

Resident/Owner	Address	Distance to Closest Wind Turbine	Date	Recording Start Time[1]
J.&T. Morrison	2920 Ribbonwood Road, Boulevard	1.46 miles	Nov.13	9:54
W.&H. Skains	2810 Ribbonwood Road, Boulevard	1.65 miles	Nov.13	10:56
K.&T. Daubach	39954 Ribbonwood Road, Boulevard	2.9 miles	Nov.13	11:58
R.&P. Guy	2975 Ribbonwood Road, Boulevard	4,430 feet	Nov.13	14:43

[13] Plot Plan - Torrey Wind, San Diego County, PDS2018-MUP-18-014-PDS-PLN, 21 June 2018.

B.&B. Chase	2948 Ribbonwood Road, Boulevard	1.40 miles	Nov.14	9:33
Anonymous Residence 1	--	1.49 miles	Nov.14	11:07
Anonymous Residence 2	--	1.50 miles	Nov.14	13:30
M.&S. Morgan	2912 Ribbonwood Road, Boulevard	1.58 miles	Nov.14	15:16
J.&S. McKernan	37131 Hwy. 94, Boulevard	4.72 miles	Nov. 14	16:45
Anonymous Residence 3	--	2.91 miles	Nov.15	9:34
M.&L. Ostrander	43477 Old Hwy 80, Jacumba Hot Springs	8.02 miles	Nov.15	10:33
A.&T. DeGroot	2693 Paso Alto Court, Boulevard	4,970 feet	Nov.15	11:46
R.&B. Blaisdell	2941 La Posta Circle East, Pine Valley	3.87 miles	Nov.15	14:41
D.&E. Tisdale	1250 Tierra Real Ln, Boulevard	5.70 miles	Nov.15	15:36
M. Strand	2235 Tierra Heights Road, Boulevard	2.24 miles	Nov.17	8:57

[1] Recordings were nominally 15 to 20 minutes long

Torrey and Campo Wind Project Boundary

To document the existing ambient, C-weighted noise levels near the proposed Torrey Wind and Campo Wind projects, we obtained noise recordings at locations near the proposed boundary lines of the two projects. Table 2 indicates the Torrey Wind project boundary ambient measurement locations, the distances to the closest existing wind turbine, dates, and times of the recordings. Table 3 indicates the Campo Wind project boundary ambient measurement locations, the distances to the closest wind turbine, dates, and times of the recordings. A map showing the Torrey Wind and Campo Wind project boundary measurement locations is provided in Figure A-2.

Table 2 Torrey Project Boundary - Ambient Measurements

Location	Dist. to Closest Existing Wind Turbine (mi)	Date	Recording Start Time[1]
Torrey PL1	1.43	Nov. 14	10:15
Torrey PL2	1.52	Nov. 14	12:10

[1] Recordings were nominally 15 to 20 minutes long

Table 3 Campo Project Boundary - Ambient Measurements

Location	Dist. to Closest Existing Wind Turbine (mi)	Date	Recording End Time[1]
Campo PL1	7.73	Nov. 16	10:45
Campo PL2	0.98	Nov. 16	12:16
Campo PL3	2.68	Nov. 16	14:07
Campo PL4	5.30	Nov. 15	16:41

[1] Recordings were nominally 15 to 20 minutes long

NOISE RECORDING METHODOLOGY

WI conducted similar noise measurements in 2013. The way sound recordings were made are described in detail in the 2014 WI report, which is included as Appendix D. For a discussion of the sound recording instrumentation refer to Appendix D. To record noise samples in 2018, WI used a RION DA21 digital recorder, which provides a linear frequency response (i.e., ±0.1% or less) to a lower frequency limit of essentially 0.1 Hz when used in the "AC mode" (which we did). Twenty-minute (nominal) noise recordings were made at each location. At the residence locations recordings were made simultaneously both indoors and outdoors at using two different microphones. This same approach was also used in the Shirley Wind Farm study[14]. All measurement data reported herein are based on an analysis of the noise recordings played back in the WIA laboratory in Emeryville, California.

[14] Channel Islands Acoustics, et al, A Coop erative Measurement Survey and Analys is of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin, Report No. 122412-1, December 24, 2012.

Measurements at Residences

For measurements conducted at the residences, a microphone was set up inside each residence mounted on a tripod at 4.5 feet above the floor, typically in the middle of the room. The indoor recordings were made in the living room (mostly), dining room or bedroom of the residences. Indoors, the microphone was oriented vertically and covered with a 3-inch-diameter wind screen.

Figure 4 shows the microphone and windscreen mounted on a tripod inside one of the residences.

A second microphone was set up outside of each residence. Following IEC Standard 61400-11, the outside microphone was rested horizontally (i.e., flush mounted) on a ½-inch-thick plywood "ground board" that is 1 meter in diameter. The microphone was oriented in the direction of the nearest visible wind turbine and the ground board was placed in a flat location between the residence and the wind turbines. For a discussion of details of microphone and windscreens used refer to Appendix D. Figure 4 shows the indoor microphone on a tripod. Figure 5 shows the outdoor microphone, secondary windscreen, and ground board outside one of the residences. Inside and outside noise signals were recorded simultaneously to allow for correlation of interior and exterior sound levels during subsequent analysis.

Figure 4 Microphone Inside Residence

Figure 5 Microphone Outside Residence

Proposed Torrey Wind and Campo Wind Project Boundary Ambient Measurements

Two B&K 4193 microphones were used to obtain ambient noise measurements at locations adjacent to the Torrey and Campo project boundaries. The microphones were powered by a B&K Type-5935 power supply and amplifier, with the signals recorded on a RION DA21 recorder. The same type of windscreen and ground board configuration (i.e., primary and secondary windscreen) used for the residential recordings, were also used for the project boundary ambient measurements.

NOISE MEASUREMENT BACKGROUND

Purpose of Measurements

The primary purpose of making the wind turbine noise measurements in 2018, which are reported herein was to determine whether, and at what levels and under what conditions, the Kumeyaay Wind, Tule Wind and Ocotillo Wind WTs generate ILFN, and how far the ILFN is propagated. In light of increasing evidence in the literature that ILFN can affect and harm humans[15,16,17,18,19], along with numerous complaints of health impacts from Boulevard residents[20] since the wind turbines near their respective residences began operating, we had a subsidiary goal to obtain measurements that accurately show the pressure fluctuations in the sound, so as to allow an accurate and robust analysis of the human health and environmental impacts of the ILFN generated.

Another purpose of the current measurements was to document the existing C-weighted, ambient noise levels at several locations on the boundaries of the two proposed wind turbine facilities, Torrey Wind and Campo Wind.

Noise Measurements in Presence of Wind

For a discussion of the effects of local wind on noise measurements and the analysis procedures WI used to minimize wind effects on the measurement refer to Appendix D.

WIND TURBINE OPERATION DURING MEASUREMENTS

Video recordings were made several times during the study period to document the operation of the wind turbines. Using the video recordings, we determined both the rotational speed of the wind turbine rotor (Ω in rpm) and the so-called "blade passage frequency" (f_0, also referred to as "blade passing frequency" or BPF), which is calculated in cycles per second, where $f_0 = N \times \Omega / 60$, and N is the number of blades. For a three-bladed rotor ($N = 3$) the blade passage frequency is given by the equation:

$$f_0 = \frac{\Omega}{20}.$$

Associated with the blade passage frequency are harmonics, which are integer multiples of the blade passage frequency. In this study, we typically observed at least five discrete harmonics in the measurement data. This pattern was also observed in the Shirley Wind Farm study.

The harmonic frequencies are given by:

$$f_n = (n+1) \times f_0 \, , where \; n \geq 1 \, .$$

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[15] Salt, A. N., T.E. Hullar, Responses of the ear to low frequency sounds, infrasound and wind turbines, Hearing Research, 16 June 2010.

[16] Salt, A.N., J.T. Lichtenhan, Reponses of the Inner Ear to Infrasound, Fourth International Meeting on Wind Turbine Noise, Rome, Italy, April 2011.

[17] Salt, A.N., J.A. Kaltenbach, Infrasound from Wind Turbines Could Affect Humans, Bulletin of Science, Technology & Society, 31, 296-302, 2011.

[18] Salt, A.N., J.T. Lichtenhan, Perception-based protection from low-frequency sounds may not be enough, Inter-Noise 2012, New York, New York, August 2012.

[19] Lichtenhan, J.T., A.N. Salt, Amplitude Modulation of Audible Sounds by Non-Audible Sounds: Understanding the Effects of Wind-Turbine Noise, Proceedings of JASA, 2013.

[20] San Diego Reader, Volume 42, Number 34, August 22, 2013.

For example, if Ω = 17 rpm, then f_0 = 0.85 Hz and the frequencies of the first six harmonics (n = 1 through 6) are: 1.7, 2.6, 3.4, 4.3, 5.1 and 6.0 Hz.

Table 4 summarizes a representative selection of the wind turbine speeds observed during the recordings. The average rotational speed for Tule WTs was approximately 14 rpm and for Kumeyaay WTs it was approximately 16 rpm.

Table 4 Rotational Speeds Observed for Nearest Visible Wind Turbines

Facility	Date	Location[1]	Time	Speed (rpm)	BPF (Hz)
Tule Wind (GE Turbines – rated speed of 5.0 to 14.9 rpm)	November 13	Morrison	10:59	14.5	0.72
		Guy	14:37	14.1	0.70
			16:03	14.4	0.72
	November 14	Chase	9:42	13.9	0.69
			10:15	13.9	0.69
Kumeyaay Wind (Gamesa Turbines – rated speed of 9 to 19 rpm)	November 13	Guy	15:25	16.6	0.83
	November 14	Chase	10:17	15.8	0.79

[1] Locations refer to where video was recorded
[2] Based on observed rotor speeds during recording

Most WTs at Kumeyaay were observed to be operating from the start of recording on 11/13 through the last recording on 11/16. Approximately seven (7) Kumeyaay WT located approximately in the center of the array of WTs were not operating for all or most of this time period. On the morning of 11/17 it was observed that the WTs at Kumeyaay were not operating during the time the last recording was being made.

Visual observation indicated essentially all the WTs at Tule were operating 11/13 through 11/16. On the morning of 11/17 it was observed that the WTs at Tule that were visible from the last measurement location were not operating during the time the last recording was being made. However, the noise measurement data from that morning would indicate that some of the Tule WTs were operating. It is possible that only a few WTs at the northern of Tule Wind were operating, which the noise data seems to indicate.

As far as could be discerned by visual observation the WTs at Energia Sierra Juarez were not operating on the morning of 11/17 during the last recording. Information concerning operation of WTs at Ocotillo indicated that on the morning of 11/17 WTs there started operating at 7:54 am, which was just before the start of the last recording.

METEOROLOGICAL DATA

Weather Underground[21] is a source for local weather data including wind speed and direction, temperature, precipitation, and atmospheric pressure. The closest weather monitoring station to Boulevard is approximately 12 miles away in Campo. Weather Underground data are archived by Meso West[22] from which we obtained meteorological data for the days of noise recordings. The hourly wind speeds are plotted in Appendix B for the days of measurement (November 13 through 17).

On the 13th and 14th wind speeds ranged from 15 to a high of 45 mph. Starting on the morning of the 15th wind speeds decreased. From the 13th through 6am on the 15th the wind was primarily out of the northeast at times varying from NNE to ENE. Wind speeds decreased on the 15th through the morning of the 17th with the wind direction primarily continuing from the NE.

METHOD OF ANALYSIS OF RECORDED DATA

The 15 to 20-minute recordings were subsequently analyzed in the WIA laboratory with a Larson Davis type-2900 2-channel FFT analyzer. We first viewed each recorded sample in digital strip chart format to visually locate periods of lower local wind gusts to minimize low-frequency wind pressure transient effects on the data. We set the FFT analyzer for 40-Hz bandwidth, with 400-line and 0.1-Hz resolution. We used linear averaging. A Hanning window was used during a one- to two-minute, low-wind period to obtain an "energy average" with maximum sampling overlap. We stored the results for each sample, including autospectra, coherence, and coherent output power for both channels of data at the residential locations (i.e., indoors and outdoors). We also obtained autospectra for the reference locations.

Autospectra and Coherent Output Power

One of the strengths of our indoor-outdoor sampling procedure is that it made possible the use of what is called the "coherent output power" to minimize the effect of the low-frequency wind pressure transients caused by local wind gusts. For a discussion of coherent output power and its applicability to ILFN noise measurements refer to the WI 2014 report in Appendix D.

Sound Level Correction Due to Use of Ground Board

For a discussion of why it is not necessary to make a correction to ILFN noise measurement data when using a ground board refer to the WI 2014 report in Appendix D.

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[21] https://wunderground.com

[22] https://mesowest.utah.edu/

NOISE MEASUREMENT RESULTS

Plots of coherent output power are provided in Appendix C. Before reviewing the spectral data from 2018, it is instructive to first re-examine the spectra measured in 2013 at the Live Oak Springs Resort when there was wind at the Kumeyaay turbines (determined from observing the closest turbine rotating at the time), but virtually no local wind at the recording microphone. This 2013 measurement clearly demonstrates and establishes the validity of noise measurement results using coherent output power.

ILFN Data from 2013 -- Live Oak Springs Resort Measurements

Plots of the coherent output power spectra measured inside residences are provided in Figures C-1 and C-2. Live Oak Springs Resort is somewhat sheltered from wind but has a direct line of sight to the closest Kumeyaay wind turbine 5,950 feet away. Looking at Figure C-1, it is evident in the coherent output spectrum for both indoor and outdoor measurements that the discrete frequencies predominating in the infrasound range correspond to the blade passage frequency of the nearest wind turbine (0.8 Hz) and its first five harmonics (1.6, 2.4, 3.2, 4.1 and 4.9 Hz). A blade passage frequency of 0.8 Hz corresponds to a rotational speed of 16 rpm. We note that the indoor levels at these frequencies are slightly higher than the outdoor levels, an indication of possible amplification associated with the building structure.

Figure C-2 presents the coherence of the indoor to outdoor signals. At the blade passage frequency (0.8 Hz) and in the range of 1.6 to 5 Hz (including the first five blade passage frequency harmonics of 1.6, 2.4, 3.2, 4.1 and 4.9 Hz), the coherence is 0.75 or greater, indicating a strong correlation between indoor and outdoor sound levels.

A high coherence indicates that two signals are strongly correlated and contain the same frequency content. This is what one would expect from a large rotating mechanical device such as a wind turbine that produces a steady, tonal (periodic) sound, whereas the effects of wind are random in time and space for signals from two different microphones, one of which is indoors. Thus, there will in general be a low coherence associated with the wind and its effects on the two different signals averaged over time. The correlation of the wind effects in the indoor and outdoor signals should be weak for the random effects of the wind. Averaging the total microphone signal over time and weighting the result by the coherence results in a diminished contribution from the wind, because of the low coherence of the wind effects.

Inside the guest cabin at Live Oak Springs Resort, sound pressure levels in the infrasound range measured between 45 and 49 dB. The outside sound pressure levels were somewhat lower in the ILFN range, seeming to indicate an amplification occurring from outside to inside, which became even more pronounced in the range of 5 to 8 Hz.

ILFN Data from 2018 Residential Measurements

There were two wind turbine facilities in 2013 and are now there are four wind turbine facilities with a combined total of two hundred and forty-one (241) WTs within 11 miles of the residences at which recordings were made in 2018. Each of the current WT facilities has an array of WTs made by a different manufacturer or installed with a different WT model. Consequently, the WTs at each facility have different rotational speeds.

It is not possible to simultaneously observe all the WTs at the four facilities and the rotational speeds of individual WTs vary over time depending on local wind conditions. Furthermore, the WTs at Kumeyaay Wind and Tule Wind operate at rotational speeds that are not too dissimilar (i.e., about 14 and 16 rpm respectively). These factors make linkage of ILFN at certain frequencies with a specific wind turbine facility somewhat more challenging than in 2013.

It should be clear from the discussion above that well-defined spectral peaks at frequencies less than 10 Hz are generally mechanically generated infrasound (IS), and at frequencies less 5 Hz the IS is obviously generated by WTs. We note that in general for large, industrial wind turbines the highest operational speed is 20 rpm, which corresponds to a BPF of 1.0 Hz. Consequently, peaks below 1.0 Hz are clearly BPFs of various WTs, and peaks that are multiples of a BPF between the frequencies of 1.0 Hz and 10 Hz are harmonics of BPF, although harmonics that appear in the spectral data are typically limited to about 5 Hz.

The turbine rotational speeds observed in 2018 for Tule Wind and Kumeyaay Wind (about 14 and 16 rpm respectively) correspond to BPFs of 0.7 and 0.8 Hz respectively. In the 2013 measurements, the Kumeyaay WTs were observed to operate at a rotational speed ranging from 16.3 to 17.3 rpm or slightly higher than observed in 2018.

In 2013, the Ocotillo wind turbines were observed to have a wide range of rotational speeds varying from 6.5 to 16.2 rpm. This wide range seemed to be related to the local wind conditions, which varied significantly over the period measurements were made. Using this information on WT rotational speeds, we can identify which WTs in 2018 are mostly like associated with the spectral peaks in the 2018 data plots.

Plots of the coherent output power spectra measured inside residences are provided in Figures C-3 through C-17. It is apparent from the data plots for the fifteen residences that there are reoccurring spectral peaks at specific frequencies at frequencies less than 5 Hz. Although not all the peaks occur for all the residences, where they are present, they are present regardless of time of day or location, which is a clear indication of IS generated by WTs.

Infrasound Data for Residences

Table 5 lists the frequencies of the infrasound (IS) peaks present in the spectral plots for each of the fifteen residences and the WTs that generate the IS. The peaks indicated correspond to turbine blade rotational speeds of 7.8, 9.8, 11.7, 13.7 and 17.6 rpm respectively. The observed rotational speeds of turbines in Kumeyaay Wind and Tule Wind indicated in Table 4 above, represent a snapshot in time of a couple of WTs. They are not meant to be representative of all to the WTs in a wind farm nor are they representative of speeds over many hours since wind conditions change. WTs in a wind farm tend to operate at the same rotational speed at any given time. However, it should be expected there will be some variation in speed of any two WTs, especially where there are many WTs spread out over some distance.

As indicated in the column headers in Table 5, certain BPF frequencies are identified with either Kumeyaay Wind (KWT), Tule Wind (TWT) or Ocotillo Wind (OWT). Since Ocotillo WTs (OWT) operate over a wide range of speeds and specifically less than 10 rpm, we can conclude that the first two frequencies (0.39 and 0.49 Hz) are most likely generated by Ocotillo WTs as well as the third frequency (0.59 Hz). Kumeyaay WTs (KWT) and Tule WTs (TWT) have been observed to operate over a much narrower range of speeds. The next highest BPF (0.68 Hz) is associated with Tule Wind IS. The highest BPF (0.88 Hz) is associated with Kumeyaay Wind since it is the closest frequency to the observed BPF shown in Table 4.

Other than to determine if they were operating (i.e., turbine blades could be seen to be rotating), visual observation of rotational speeds of ESJ WTs was difficult given the distance even at the closest residence (Ostrander) to ESJ and when there was intervening terrain between the residence measurement location and ESJ. Although clear evidence of ESJ IS was not indicated in the measured spectral data, under other wind conditions ESJ IS may impact the residences included in this study.

Table 5 IS Spectral Peaks Corresponding to WT BPFs

		BPF range				
		Peak (Hz)				
Date	Residence	OWT	OWT	OWT	TWT	KWT
13-Nov	Morrison					0.88
	Skains		0.49		0.68	
	Daubach	0.39			0.68	
	Guy				0.68	0.88
14-Nov	Chase	0.39				
	Anon Res 1[1]					
	Anon Res 2			0.59		
	Morgan	0.39		0.59		
	McKernan	0.39			0.68	0.88
15-Nov	Anon Res 3		0.49			
	Ostrander				0.68	
	DeGroot		0.49		0.68	0.88
	Blaisdell	0.39				0.88
	Tisdale	0.39				
17-Nov	Strand	0.39			0.68	0.88

[1] No BPF peak present, but several harmonics are (e.g., 1.46 Hz and higher)

It might be asked why all the BPF peaks don't occur at all the locations measured if the WTs are operating. The answer is that the distance from the measurement location to a set of WTs, the orientation of WT blades to that location, the possible shielding provided by the intervening terrain, and atmospheric conditions can affect the sound pressure level at a location. There may also be some cancellation of IS at certain frequencies emitted by different wind turbines due to some or all these factors.

Once peaks associated with BPFs are identified it is possible to identify peaks corresponding to their harmonics (i.e., peaks at frequencies which are integer multiples of the BPF). Any peak that corresponds to a rotational speed greater than 20 rpm (i.e., 1.0 Hz) is clearly a harmonic of one of the BPFs, since the highest rotational speed of the WTs in the area (including Ocotillo and Energia Sierra Juarez) is 19 rpm. Table 6 lists the more prominent harmonic peaks observed in the spectral plots up to a frequency of 1.6 Hz. It is not uncommon for harmonics to be present and BPF peaks missing in the spectrum. Harmonic peaks also tend to be more pronounced than BPF peaks.

Table 6 IS Spectral Peaks Corresponding to Harmonics of WT BPFs

Nov. Date	Residence	Harmonic Range Peak (Hz)								
		OWT[1]	OWT[2]	OWT[3]	OWT[4]	OWT[5]	TWT[6]	OWT[7]	OWT[8]	TWT[9]
13	Morrison							1.46		
	Skains		0.98				1.37		1.56	
	Daubach		0.98				1.37			
	Guy							1.46		2.15
14	Chase		0.98		1.17			1.46		
	Anon 1	0.78					1.37			2.15
	Anon 2			1.07						
	Morgan	0.78	0.98					1.46		2.15
	McKernan					1.27				2.15
15	Anon 3	0.78		1.07		1.27		1.46		2.15
	Ostrander				1.17					
	DeGroot			1.07		1.27				2.15
	Blaisdell			1.07			1.37			
	Tisdale	0.78	0.98				1.37			2.15
17	Strand			1.07			1.37			

[1] 1st harmonic of 0.39 Hz (7.8 rpm)
[2] 1st harmonic of 0.49 Hz (9.8 rpm)
[3] 2nd harmonic of 0.39 Hz (7.8 rpm) or 1st harmonic of 0.59 Hz (11.8 rpm)
[4] 1st harmonic of 0.54 Hz (10.8 rpm)
[5] 1st harmonic of 0.64 Hz (12.8 rpm)
[6] 1st harmonic of 0.68 Hz (13.6 rpm)
[7] 2nd harmonic of 0.49 Hz (9.8 rpm)
[8] 3rd harmonic of 0.39 Hz (7.8 rpm)
9 2nd harmonic of 0.72 Hz (14.4 rpm)

The peaks at 2.15 Hz are identified as the 2nd harmonic of a BPF of 0.72 Hz or 14.4 rpm even though this BPF doesn't appear in the spectra. Since the observed rotational speed of the Tule WTs was on average 14, we can associate these peaks with Tule WTs.

Table 7 lists each of the residential measurement locations, along with their distance from the nearest wind turbine, the highest measured indoor sound pressure levels, and the frequency of those peak sound pressure levels of ILFN and whether it corresponds to a BPF or harmonic.

We note that during the measurement on the morning of 11/17, Ocotillo was starting to operate. The peak at 0.39 Hz corresponds to an Ocotillo WT BPF, whereas the peak at 0.68 Hz corresponds to a Tule WT BPF. It is most likely that a few WTs at Tule were operating during the measurements, even though the Tule WTs we could see from our last measurement location were not operating. The sound pressure level at 0.68 Hz measured at Strand is 35 dB, which would, given the distance to the Strand residence, be expected if only a few Tule WTs on the northern end of the facility were operating.

The peaks at 0.98 Hz are identified as 1st harmonics corresponding to a BPF of 0.49 or 9.8 rpm. From the 2014 report this was identified with Ocotillo WTs. It was also observed in 2013 as noted above that not all Ocotillo WTs operate at the same rotational speed at the same time. The operational speed of individual WTs depends on their location and the local wind conditions, which may vary. Consequently, the highest IS level of 66 dB measured in 2018 is most likely generated by Ocotillo Wind WTs.

Table 7 Summary of Wind Turbine IS Inside Residences

Residence	Distance[1]	Highest Sound Pressure Spectrum Level Indoors[2,3]	Peak Frequency (Hz)	Rotor Rotational Component
Morrison	11 miles	62	0.78	1st Harmonic OWT
Skains	11 miles	63	0.98	1st Harmonic OWT
Daubach	12 miles	63	0.98	1st Harmonic OWT
Guy	4,430 feet	59	2.15	2nd Harmonic TWT
Chase	11 miles	66	0.98	1st Harmonic OWT
Anon Res 1	1.7 miles	52	2.15	2nd Harmonic TWT
Anon Res 2	1.5 miles	48	2.15	2nd Harmonic TWT
Morgan	1.6 miles	53	2.15	2nd Harmonic TWT
McKernan	4.7 miles	49	0.88	BPF KWT
Anon Res 3	11 miles	47	0.78	1st Harmonic OWT

Ostrander	8.0 miles	50	0.68	BPF TWT
DeGroot	4,970 feet	61	0.88	BPF KWT
Blaisdell	3.87 miles	63	0.88	BPF KWT
Tisdale	16 miles	49	0.98	1st Harmonic OWT
Strand	6.4 miles[4]	35	0.68	BPF TWT

[1] Distance to the closest wind turbine in WT farm associated with highest spectral peak

[2] Decibels (re: 20 μPa)

[3] All data are coherent output power sound levels

[4] Estimate

In summary, putting aside the measurement on 11/17, the sound pressure level of the dominant peaks of the infrasound measured in 2018 were in the range of 47 to 66 dB. On the 17th the levels measured at Strand residence were considerably lower (i.e., 35 dB), because no Kumeyaay WTs were operating and only a few of the most distant Tule Wind WTs along with a few Ocotillo WTs were likely operating. It is important to note again that the measured levels of IS only represent the wind conditions which existed at the time of the recordings. Higher wind speeds exist at times and typically generate higher levels of IS.

Low Frequency Noise Data for Residences

Several residents stated that they are bothered most noticeably in the evening and night by a low frequency rumble that is generated by the WTs. Some of the residents describe the noise they hear as being like noise from jets flying overhead that never land. One property owner reported losing two tenants to the disturbance from turbine noise. We note that all our 2018 measurements were conducted during the day. LFN may not be as pronounced in the measured spectra as it would be at night.

Low frequency noise occurs in the range of 20 to 100 Hz. We see examples of LFN in the spectra from both 2013 and 2018. There is a substantial peak at 27 Hz in the LOSR cabin measurements from 2013 in Figure C-1 in Appendix C. There were also other peaks in the spectra from 2013, that can be seen in Appendix C. For example, at one on the Kumeyaay Wind reference measurement locations in 2013, there was a substantial peak at 34 Hz. At the Guy residence in 2018, we see in Figure C-18 a very substantial peak at 20.4 Hz.

Amplitude Modulation Noise Levels for Tule Wind

While WI was making recordings, several of the residents commented on what they characterized as a "whooshing" sound from the WTs that bothered them. Wilson Ihrig noticed this sound at several of the measurement locations in the Ribbonwood Road area. It was most pronounced at the Guy residence, the closest measurement to the Tule WTs. An analysis of the Guy residence recording clearly indicates amplitude modulation (AM).

The phenomenon of AM has been identified and documented by others [e.g., 23,24,25] in the past although all do not use the same descriptive labels. Stigwood, et. al, discuss two types of amplitude modulation, "lashing" and "thumping", where the former is centered around 125 Hz and the latter around 315 Hz. Others have referred to AM as a "swishing" sound. Regardless of the onomatopoetic label used, AM is the fluctuation of sound, in this case air flow turbulence noise generated at the WT blades' trailing edge[25], modulated (changing sound level) at the frequency of the BPF.

Cooper defines "excessive modulation" as a peak-to-peak variation of 4 (dBA) or more and that such situation would require a 5-dBA penalty to the measured level. Oerlemans indicates the AM from one blade may be up to 5 dB, but that the effective sound level variation will be much smaller because of the summation of the noise from three (3) blades. Oerlemans defines what he calls "enhanced amplitude modulation," which are swish amplitudes that vary by more than that predicted by a standard swish model (i.e., 6 dB).

Kim, et.al.[26] have developed a noise prediction model for amplitude modulation from large WTs. The authors' noise model predicts that the overall sound pressure level is greatest on-axis (in the direction of the turbine rotor, which is the direction that the wind is blowing) and that the amount (or depth) of modulation is greatest in the plane of the turbine blades (perpendicular to the rotor). Their prediction is that the modulation depth is by from 1 to 3 dB greater in a stable atmosphere, which can have a greater wind gradient than in an unstable atmosphere. From their prediction model, Kim et.al. conclude that amplitude modulated, wind turbine noise can be perceived up to 1 mile away, which implies residents living up to this distance and possibly further may feel annoyance due to the perception of amplitude modulation.

We analyzed a sample of recorded noise from the Guy locations. Figure C-18 shows the 1/3-octave filtered levels (dB) of the same sample. Although there is AM at 160, 200 and 250 Hz, the strongest AM is at 200 Hz. At 200 Hz the AM ranges from 8 to 11 dB. If we consider the A-wtd level variation as shown in Figure C-19, ranges from 3 to 9 dBA with the typical variation of from 5 to 6 dBA. Consequently, under either definition (Cooper or Oerlemans) of the amount of AM, the measured level at the Guy residence would be considered excessive.

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[23] Stigwood, M., S. Large, and Duncan Stigwood, Audible amplitude modulation – results of field measurements and investigations compared to phyco-acoustical assessment and theoretical research, 5th International Conference on Wind Turbine Noise, Denver, 28-30 August 2013.

[24] Cooper, S., Hiding wind farm noise in ambient measurements – Noise floor, wind direction and frequency limitations, 5th International Conference on Wind Turbine Noise, Denver, 28-30 August 2013.

[25] Oerlemans, S., An explanation of enhanced amplitude modulation of wind turbine noise, report for the National Aerospace Laboratory, July 2011.

[26] Lee, Seunghoon, H. Kim, Kyutae Kim, and Soogab Lee, Perception of amplitude-modulated noise from wind turbines, 17th International Congress on Sound and Vibration, Cairo, 18-22 July 2010.

Ambient Noise Data for Torrey and Campo Project Boundaries

The Use Permit for Torrey Wind is contingent on the project complying with a San Diego County Zoning Ordinance related to large wind turbines[27]. The ordinance states: "the C-weighted sound level from each large wind turbine while operating does not exceed the Residual Background Sound Criterion for Wind Energy Facilities by more than 20 decibels as both sound levels are measured at the lot line on which the turbine is located."

The residual background sound level (L_{90}) is defined as "the sound level exceeded for 90 percent of the total measurement period as described in the current edition of Quantities and Procedures for Description and Measurement of the Environmental Sound by the American National Standards Institution. When C-weighted, the L_{90} is denoted L_{C90}.

Recorded samples of ambient noise were analyzed to obtain C-weighted levels. Table 8 list the measured, L_{C90} noise levels.

Table 8 Torrey and Campo Project Boundary, C-weighted Ambient Noise Levels

Location	Nearest Address	L_{C90} (dBC)
Torrey PL1	2948 Ribbonwood Rd	51.4
Torrey PL2	Anon. Residence 2	51.2
Campo PL1	35876 Shockey Trail (one car)	48.2
Campo PL1	35876 Shockey Trail (no cars)	43.7
Campo PL2	Near 37573 Old Hwy 80	46.0
Campo PL3	Hwy 94 at Shasta Way	38.6
Campo PL4	1250 Tierra Hts.	40.6

DISCUSSION OF RESULTS

It is clear from the measured noise data obtained that there is significant wind turbine-generated IS and there are approximately 240 wind turbines in the area at the Kumeyaay, Tule, Ocotillo and Energia Sierra Juarez facilities. This was to be expected as it has been documented by others such as in the Falmouth noise study, the Shirley Wind Turbine study, and by Epsilon Associates.[28] And indeed the measured ILFN levels near Kumeyaay and Tule wind turbine facilities are similar to those measured in previous studies after accounting for the proximity of the measurements to a wind turbine and the total number of the wind turbines in the facility.

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[27] Subsection 6952.c.5.f(b) of the San Diego Zoning Ordinance.

[28] Epsilon Associates, A Study of Low Frequency and Infrasound from Wind Turbines, July 2009.

Both the Falmouth and Shirley wind turbine noise studies were conducted to investigate whether and at what levels the subject wind turbines (the turbines in Falmouth, Massachusetts, and those in the Shirley Wind Project in Brown County, Wisconsin) produce IS, and whether that IS was contributing to the significant health and other impacts reported by nearby residences. In some cases, the impacts were so severe that residents abandoned their homes. Both studies found high levels of wind turbine-generated IS at numerous nearby residences that correlated with residents' reported impacts.

In 2017 a Superior Court Judge in a case[29] involving noise generated by WTs in Falmouth Massachusetts found for the defendants "that the operation of the town's wind turbines and the consequent sound emissions constitute a substantial and unreasonable interference with the Funfars' enjoyment of their property and constitute a nuisance." Brown County Board of Health (Falmouth, Massachusetts) approved a motion[30] that stated: *"To declare the Industrial Wind Turbines at Shirley Wind project in the town of Glenmore, Brown County, WI, a human health hazard for all people (residents, workers, visitors, and sensitive passersby) who are exposed to infrasound/low-frequency noise and other emissions potentially harmful to human health"*.

Human health impacts from wind turbines had been reported previously in several countries with large wind facilities in proximity to residences. But these impacts were often attributed to certain individuals' aversion to the presence of a large industrial facility constructed in what was previously a quiet rural setting. Scientific understanding has developed significantly since then demonstrating the potential for annoyance and physiological effects of ILFN from WTs.

The data presented herein represent the conditions of measurement during the study and do not necessarily represent maximum noise conditions produced by the Kumeyaay, Tule, Ocotillo and Energia Sierra Juarez facilities. Higher wind speeds generally produce higher overall noise levels and higher levels of IS.

POTENTIAL EFFECTS OF TULE WIND AND CAMPO WIND PROJECTS

Both Torrey Wind and Campo Wind if implemented would install larger wind turbines (i.e., 4.2 MW) than those in Kumeyaay Wind (2.0 MW) and Tule Wind (2.3 MW). As Moller and Pedersen[31] have demonstrated, larger wind turbines are expected to produce higher levels of LFN than wind turbines in the 2.0 MW range. The authors also show that it should be expected that the LFN will shift down in frequency with larger WTs.

The Torrey Wind WT sites have already been designed. A map of Torrey Wind is contained in Appendix E. The zones for WT sites for Campo Wind are indicated in the map in Appendix F. Some of the proposed sites for WTs at Torrey Wind and the zones for WT sites will be

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[29] Town of Falmouth (Plaintiff) v. Falmouth Zoning Board of Appeals and Matthew McNamara, Patricia Johnson, Kenneth Forman, Edwin Zylinski, David Haddad and Mark Cool as members of the Falmouth Zoning Board of Appeals and Barry Funfar and Diane Funfar (Defendants), 20 June 2017.

[30] Proceedings of the Brown County Board of Health Meeting, Tuesday, October 12, 2014.

[31] Moller, H. and Christian Sejer Pedersen, Low-frequency noise from large wind turbines, Journal of the Acoustical Society of America, p.3727-3744, **129**(6), June 2011.

much closer than the existing Tule Wind and Kumeyaay Wind WTs to the Guy, Chase, Morrison and Morgan residences as well as other residences in the area. Although actual WT sites have not yet been proposed for Campo it is conceivable that they will be much closer to residences than the Kumeyaay WTs. An example of this is the DeGroot residence and a neighboring residence that could be only hundreds of feet from a Campo WT site.

The Morrisons are considering moving out at great expense due to the current health problems that he and his wife say they are suffering that they attribute to operation of the Kumeyaay Wind and Tule Wind WTs. Tule Wind seems to bother them the most. Other residents indicated they suffer from negative impacts due to ILFN, which effects are greater at night. This phenomenon of increased nighttime effects has been documented in other studies[32,33,34].

NOISE METRICS FOR MEASURING ILFN

There are several noise metrics which are used to quantify environmental noise levels. The most common metric is A-weighting (A-wt). The A-wt curve is shown in Figure 6. The A-wt metric is intended to approximate the loudness sensitivity of the human ear for common environmental sounds in the range of 20 to 20,000 Hz. A-wt at 1 Hz is -149 dB. Hence a noise limit based on A-wt would not be appropriate to address ILFN, a major component of which is infrasound below 20 Hz.

A noise metric sometimes used when there is low frequency noise is the C-weighting (C-wt). While the C-wt metric does attempt to address low frequency noise better than A-wt, it would also not be appropriate for quantifying infrasound, since it still strongly de-emphasizes sound at frequencies below 20 Hz as shown in in Figure 6. C-wt at 1 Hz is -52.5 dB.

One noise metric recently used to quantify ILFN is G-weighting (G-wt). The G-wt measure has been used in Europe. G-wt would certainly be a more representative measure of ILFN than either the A- wt or the C- wt metrics, but as shown in Figure 6 it too de-emphasizes the very low frequency infrasound by -40 dB at 1 Hz.

32 Leventhall G, Pelmear P, Benton S. A review of published research on low frequency noise and its effects. London: Report for Department for Environment, Food and Rural Affairs; 2003.

33 Bakker RH, Pedersen E, van den Berg GP, Stewart R, Lok W, Bouma J. Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress. Sci Total Environ. 2012; 425:42–51.

34 Pedersen E. Health aspects associated with wind turbine noise-results from three field studies. Noise Control Eng. J. 2011; 59:47–53.

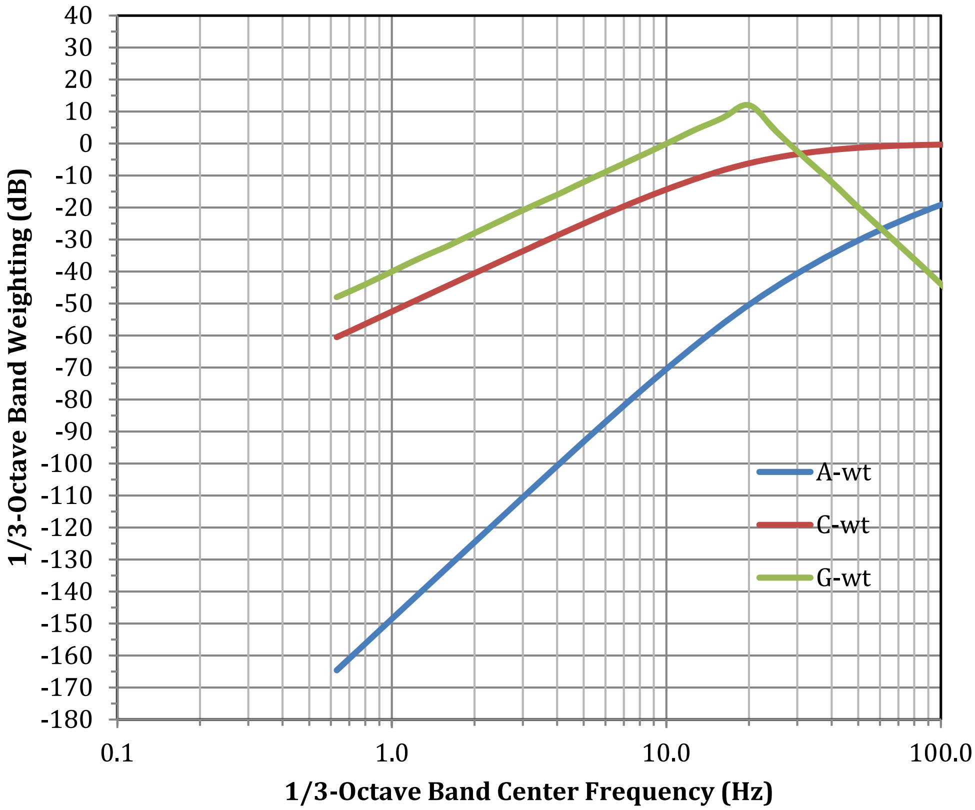


Figure 6 A, C and G Spectral Weighting Curves

CONCLUSIONS

The results of this study conclusively demonstrate that both the Kumeyaay Wind and Tule Wind facilities' wind turbines generate infrasound at residential locations up to 8 miles away based on the current measurements. Ocotillo Wind infrasound from wind turbines 11 to 12 miles away from Boulevard and Jacumba Hot Springs were measured at levels as high as 66 dB. The current data indicates that there is also significant low frequency noise in the range of 20 to 34 Hz. The measurement results also show excessive amplitude modulation of wind turbine noise. Although Energia Sierra Juarez Wind turbine-generated IS was not detected in the current measurements, under different wind conditions (wind direction and speed), high levels of infrasound from those wind turbines could impact the residences in the current study.

TERMINOLOGY

- Autospectrum: The autospectrum is the narrow band, energy average sound pressure level spectrum (in dB) measured for a specific time interval.
- Amplitude modulation: periodic fluctuation of audible noise.
- Coherence: The spectral coherence is a statistic that can be used to examine the relation between two signals or data sets. It is commonly used to estimate the power transfer between input and output of a linear system. If the signals are ergodic, and the system function linear, it can be used to estimate the causality between the input and output.
- Cross-spectrum: In time series analysis, the cross-spectrum is used as part of a frequency domain analysis of the cross correlation or cross covariance between two time series.
- Cycles per second: A unit of frequency, same as hertz (Hz).
- Decibel (dB): A unit of level which denotes the ratio between two quantities that are proportional to power; the number of decibels is 10 times the logarithm (to the base 10) of this ratio. For sound, the reference sound pressure is 20 micro-Pascals.
- FFT (fast Fourier transform): An algorithm to compute the discrete Fourier transform and its inverse. A Fourier transform converts time to frequency and vice versa; an FFT rapidly computes such transformations.
- ILFN: Infrasound and low frequency noise.
- IS: Infrasound at frequencies lower than 20 Hz.
- LFN: Low frequency noise at frequencies between 20 and 100 Hz.
- Noise level: The sound pressure energy measured in decibels.

APPENDIX A – 2018 NOISE MEASUREMENT LOCATIONS

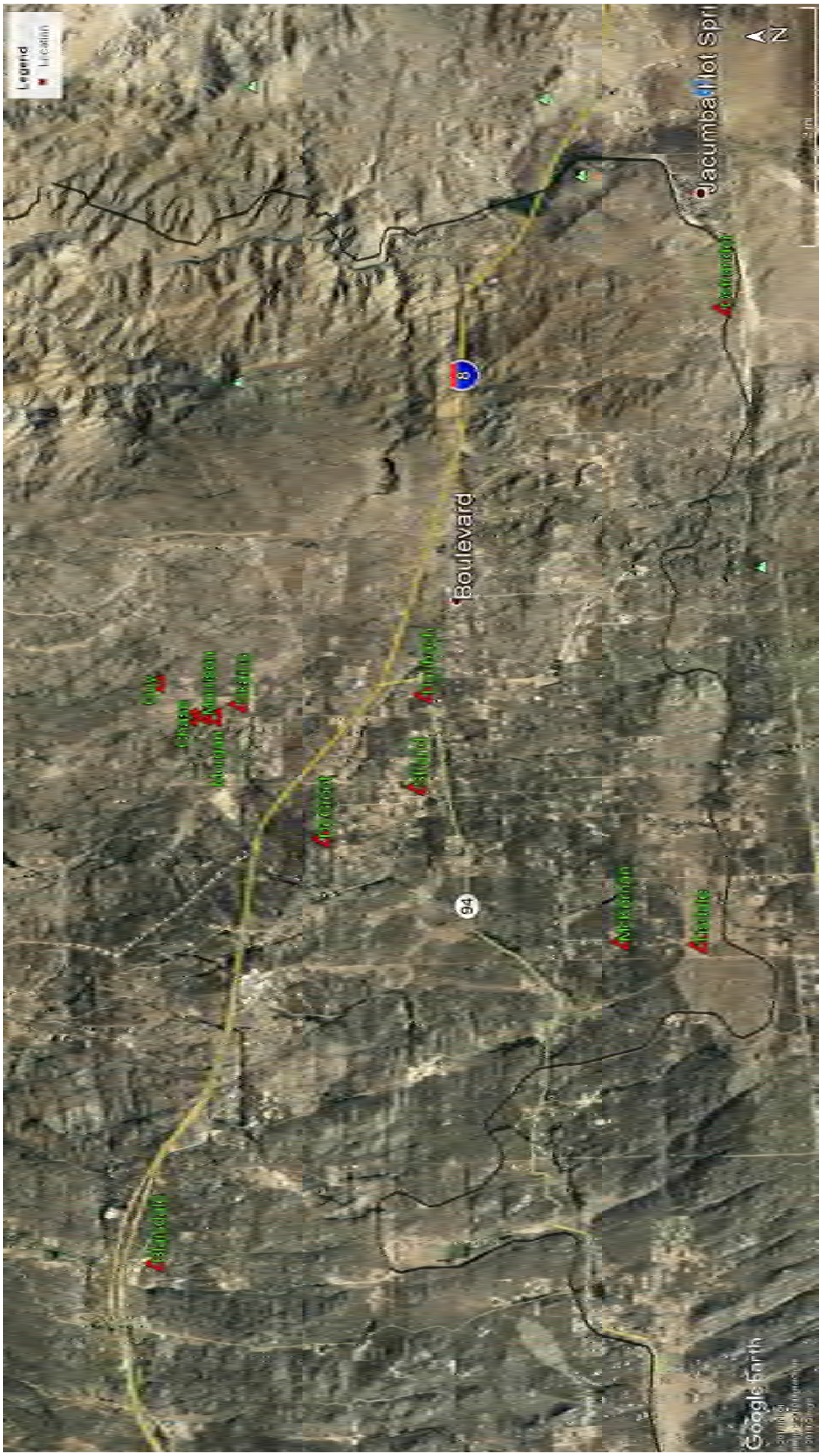


Figure A - 1 Residential Measurement Locations

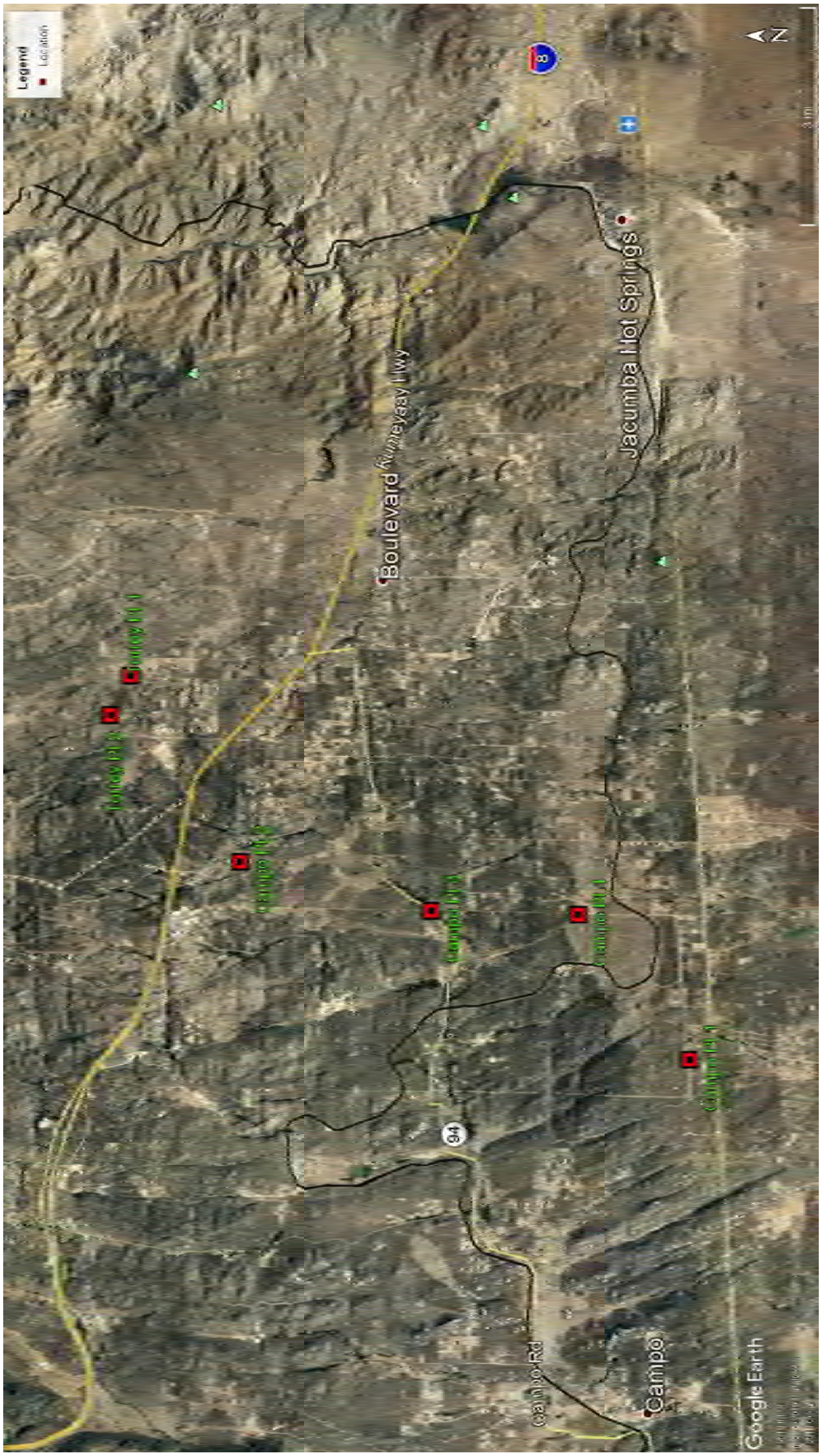


Figure A - 2 Torrey Wind and Campo Wind Boundary, Ambient Noise Measurement Locs

APPENDIX B – METEOROLOGICAL DATA

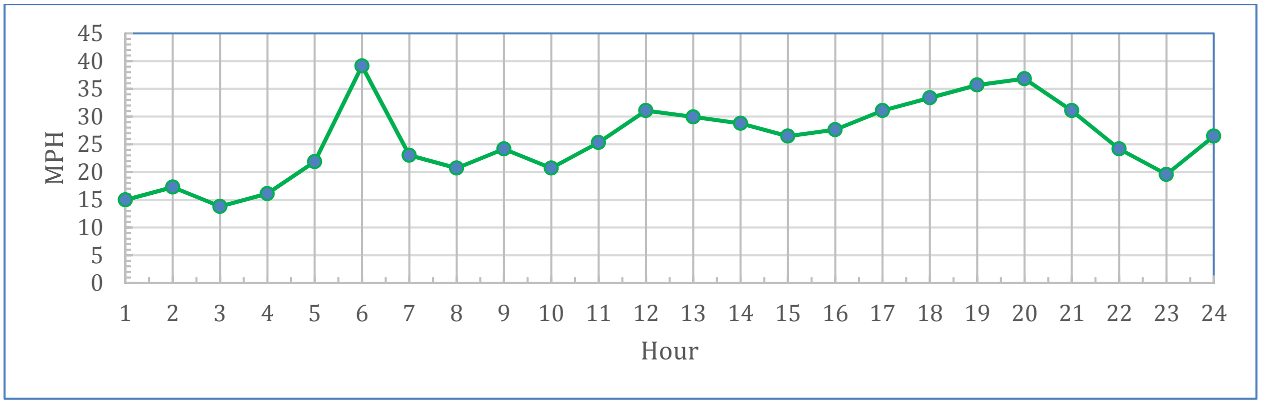


Figure B - 1 Wind Speed for Boulevard Area 11/13/18

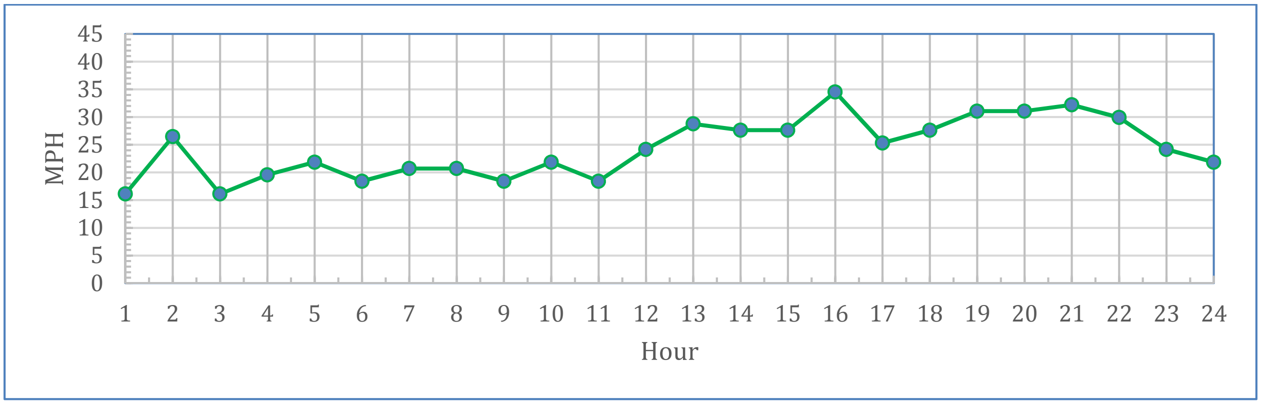


Figure B - 2 Wind Speed for Boulevard Area 11/14/18

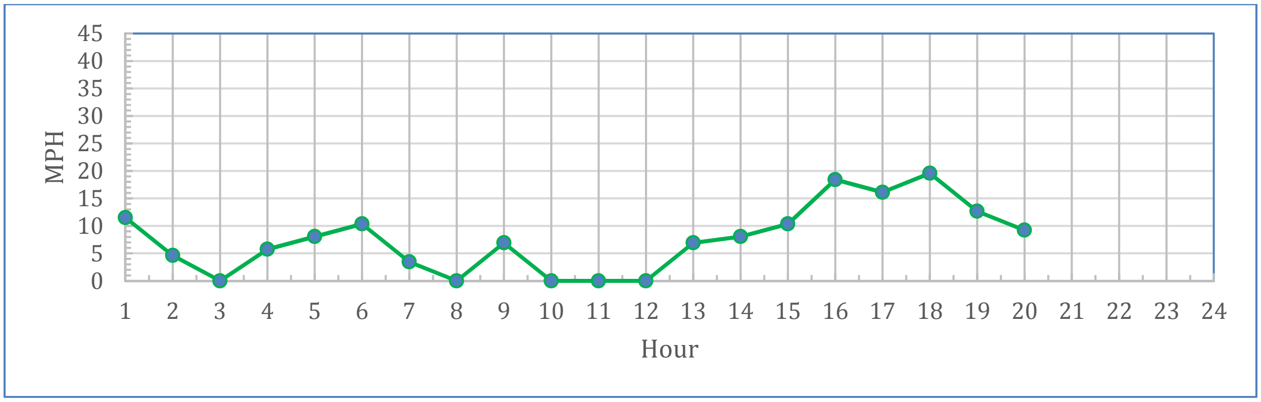


Figure B - 3 Wind Speed for Boulevard Area 11/15/18

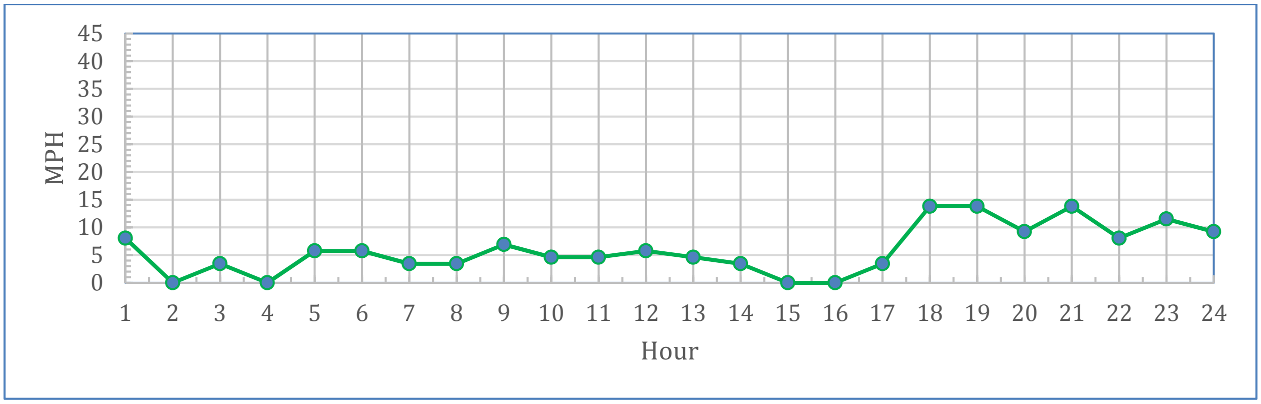


Figure B - 4 Wind Speed for Boulevard Area 11/16/18

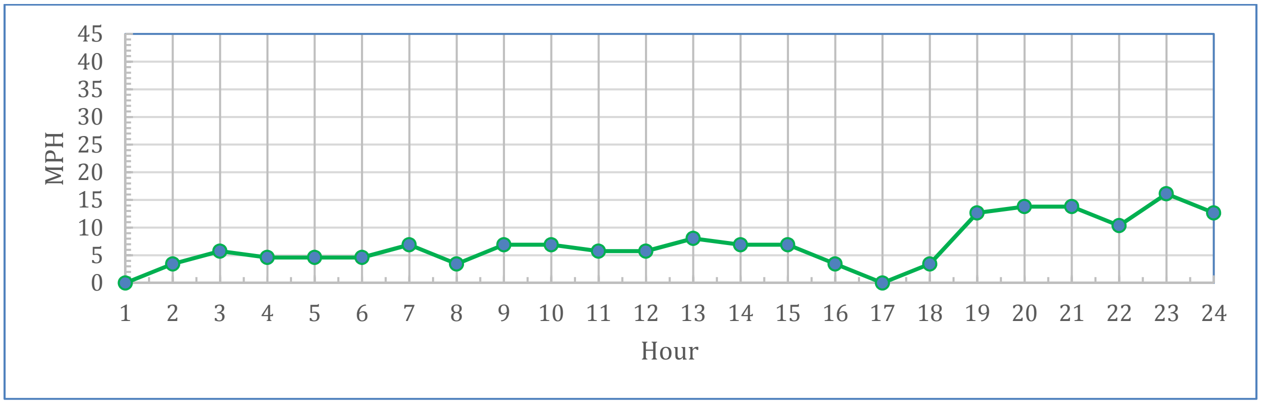


Figure B - 5 Wind Speed for Boulevard Area 11/17/18

APPENDIX C – 2018 NOISE MEAUREMENT DATA

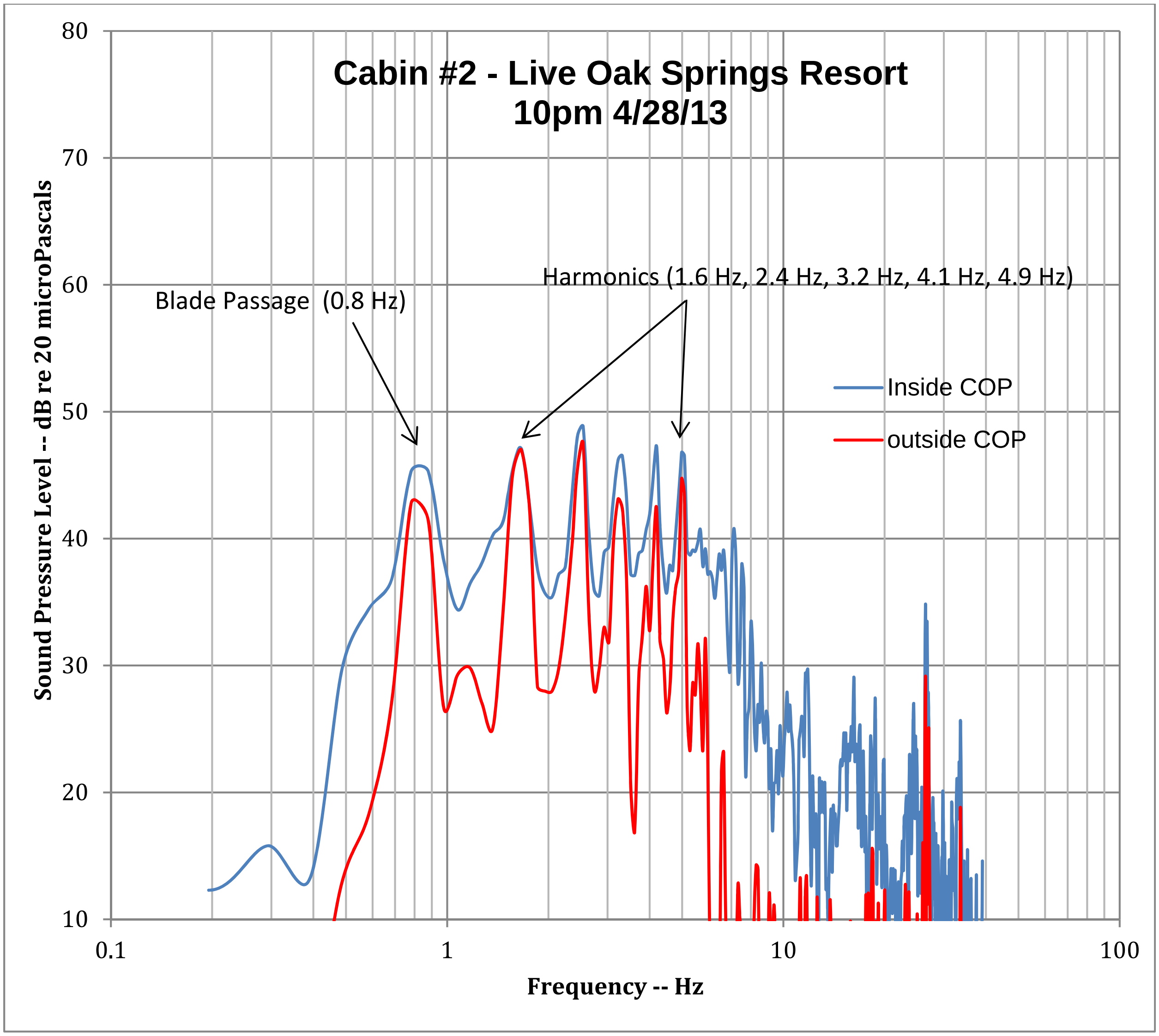


Figure C - 1 Cabin #2 at Live Oak Springs Resort – Coherent Output Power

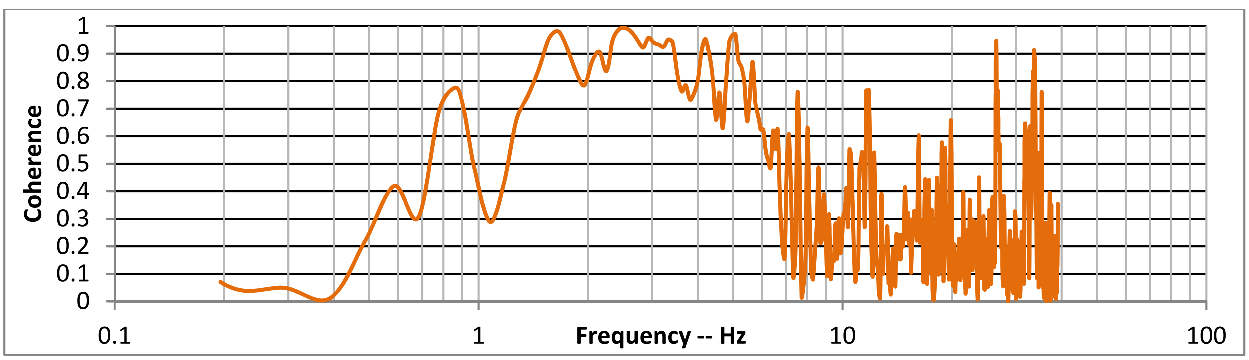


Figure C - 2 Cabin #2 at Live Oak Springs Resort – Coherence

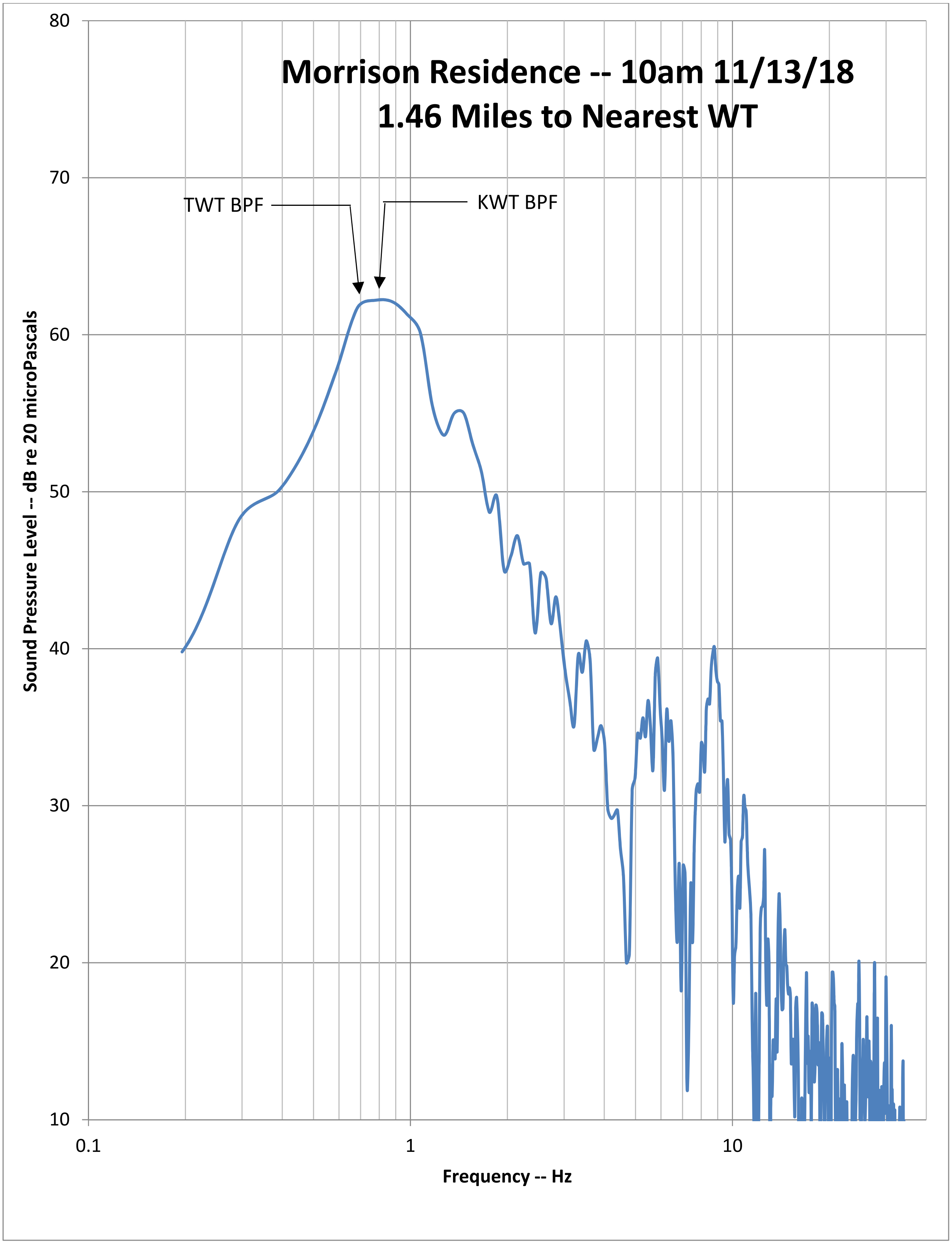


Figure C - 3 Morrison Residence

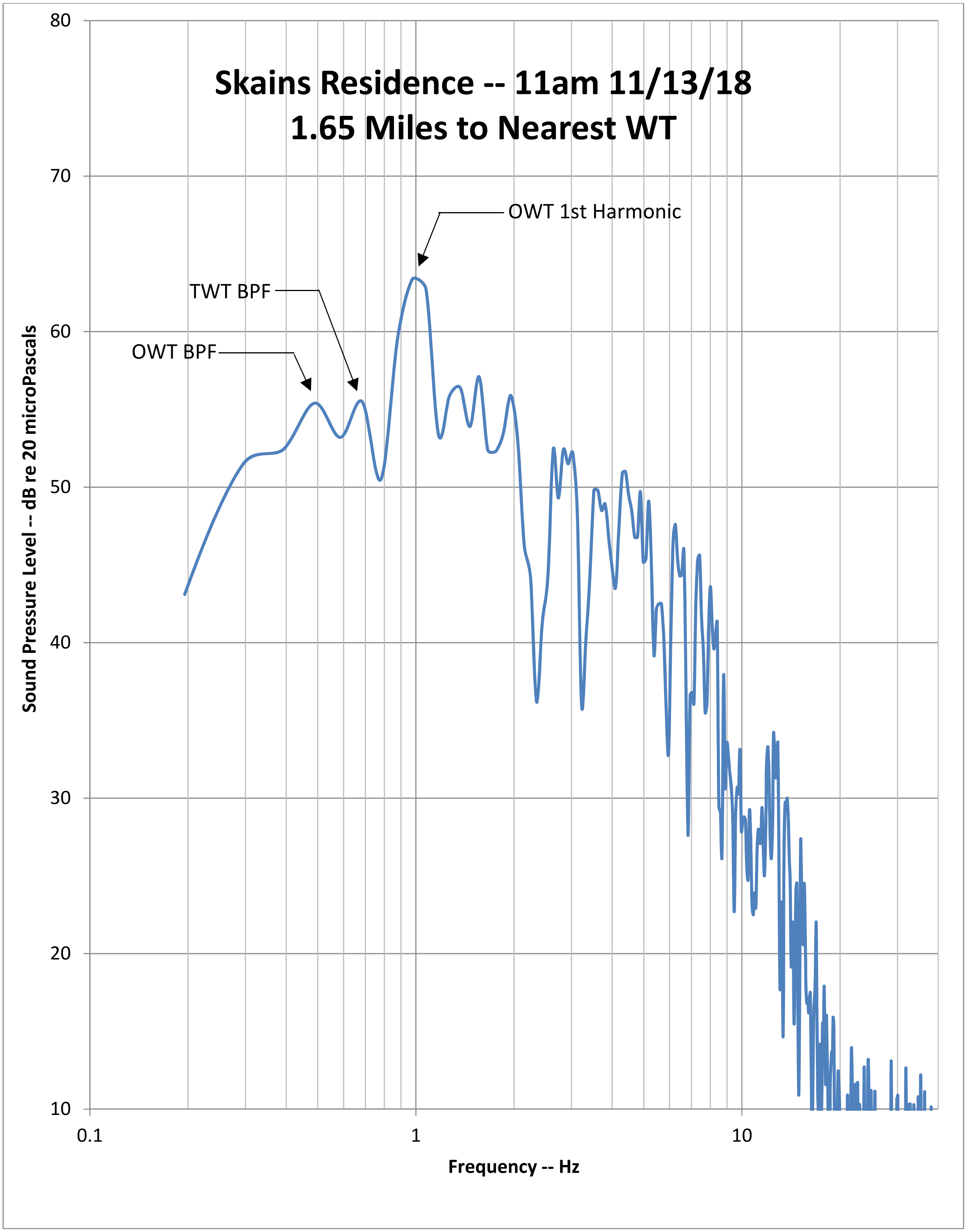


Figure C - 4 Skains Residence

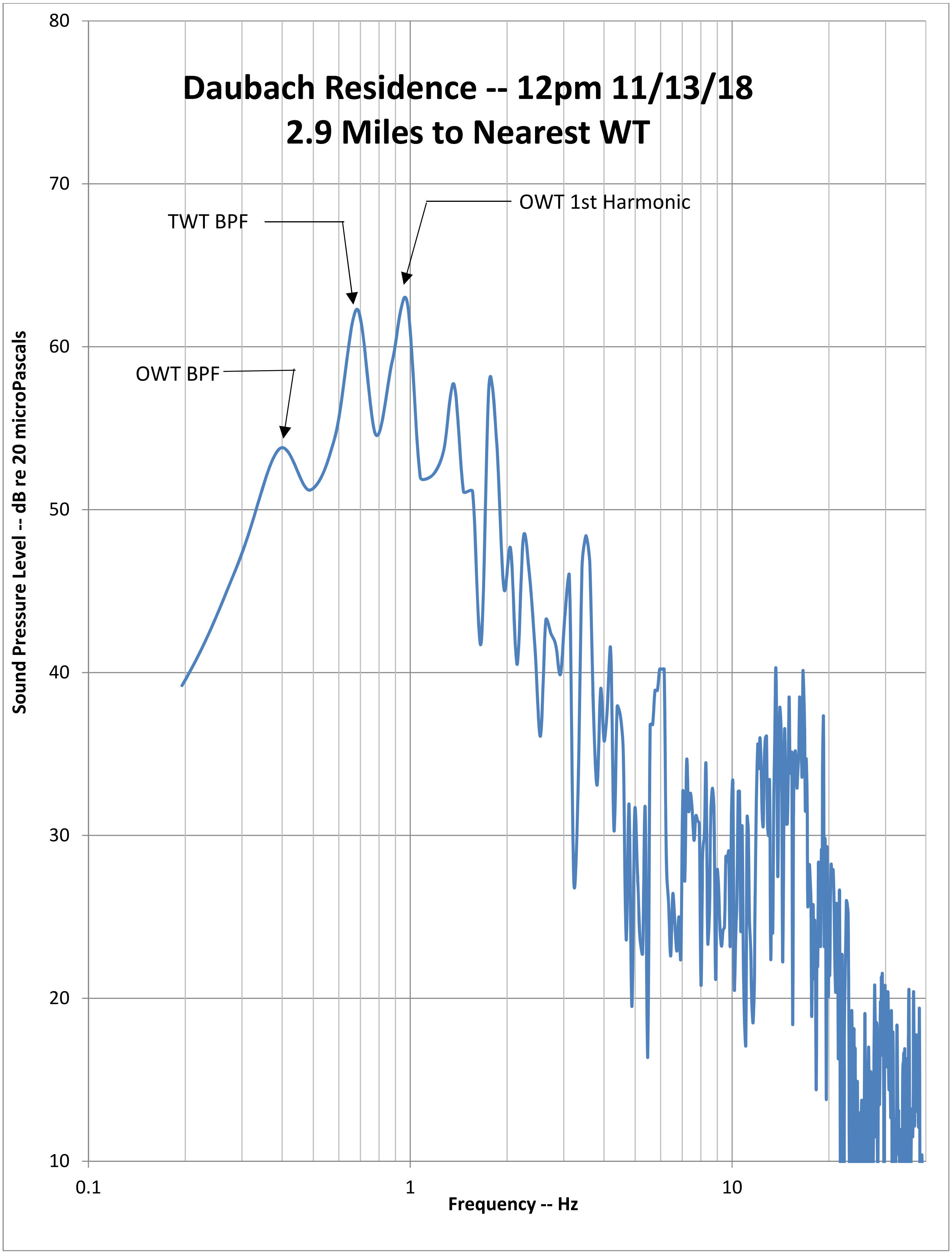


Figure C - 5 Daubach Residence

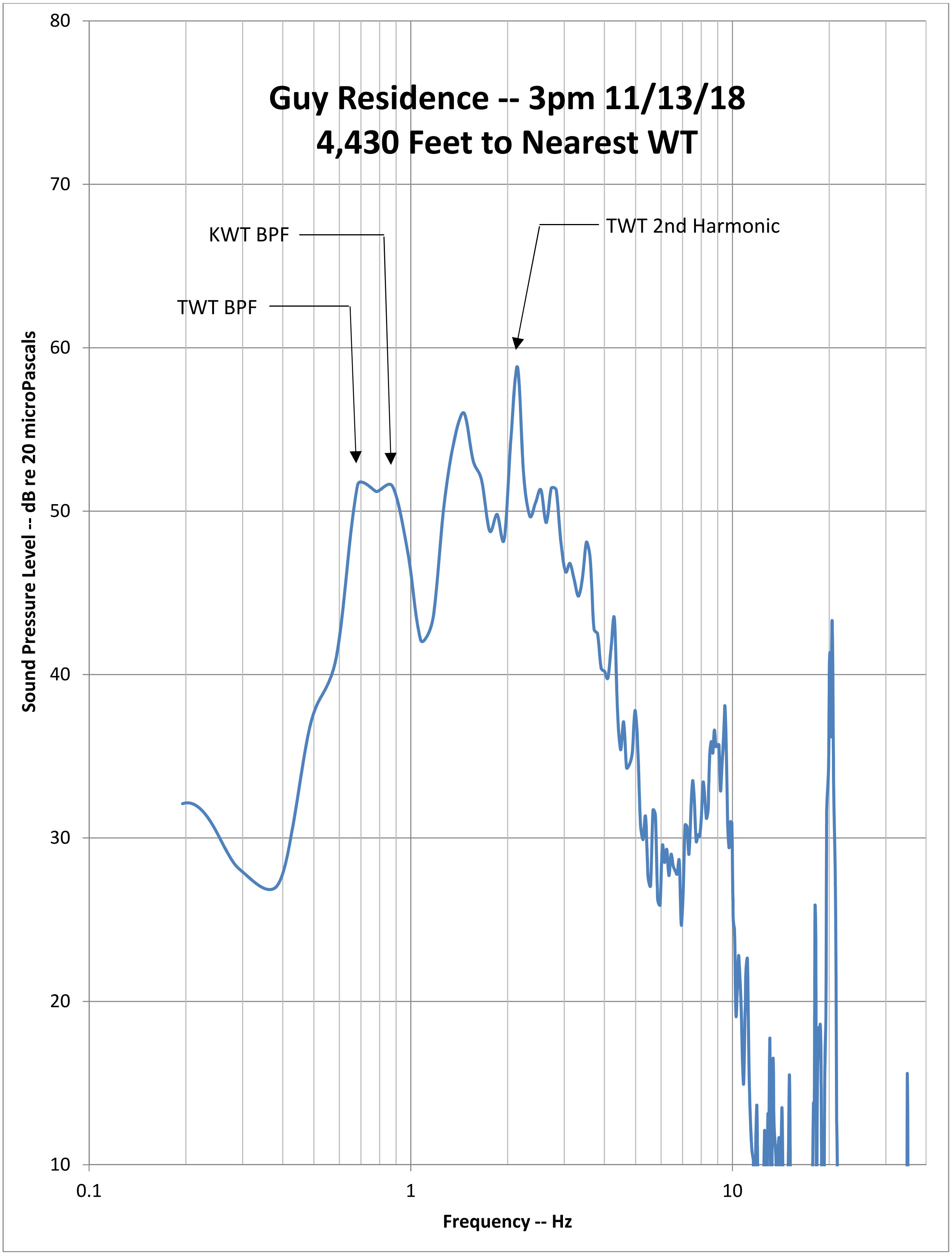


Figure C - 6 Guy Residence

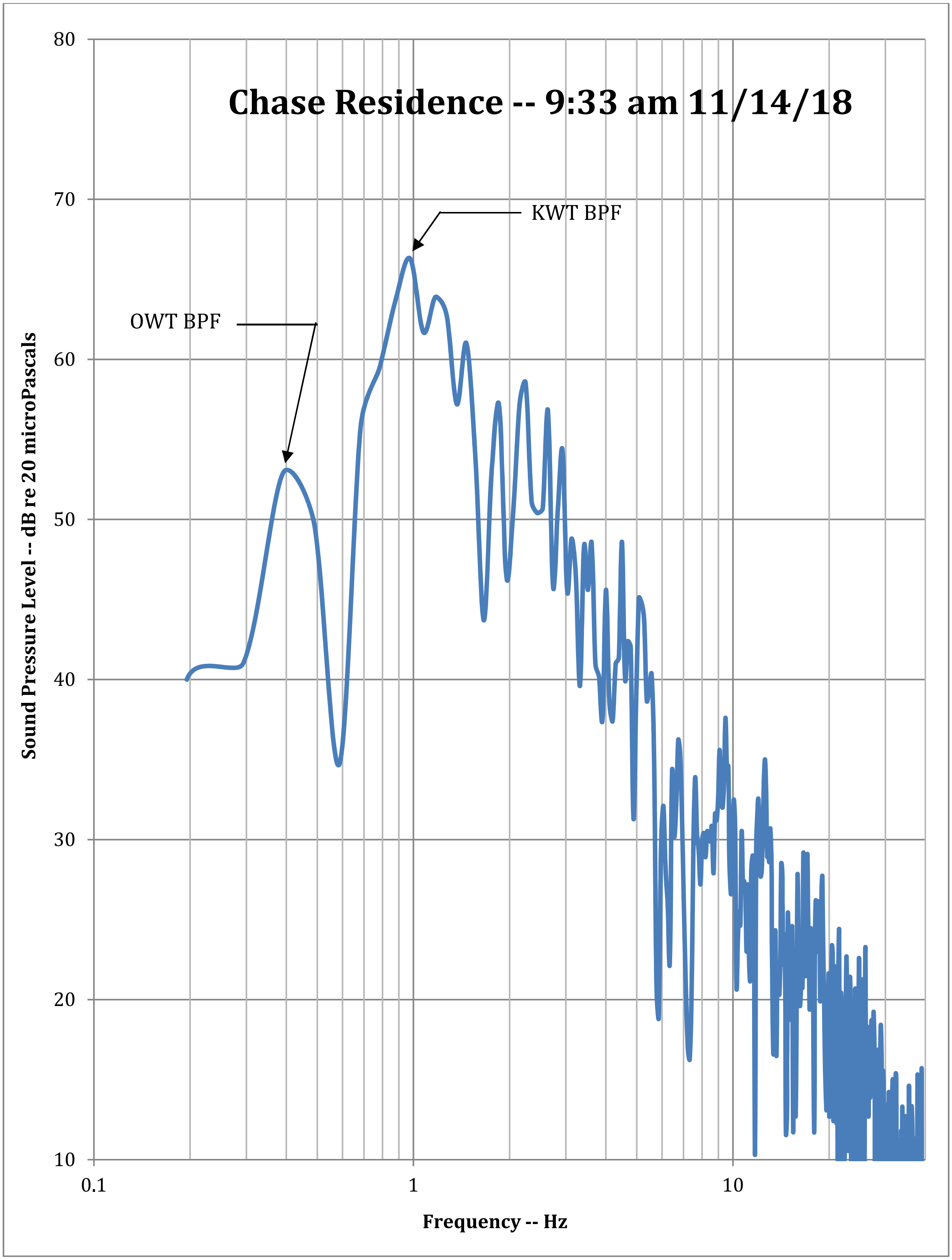


Figure C - 7 Chase Residence

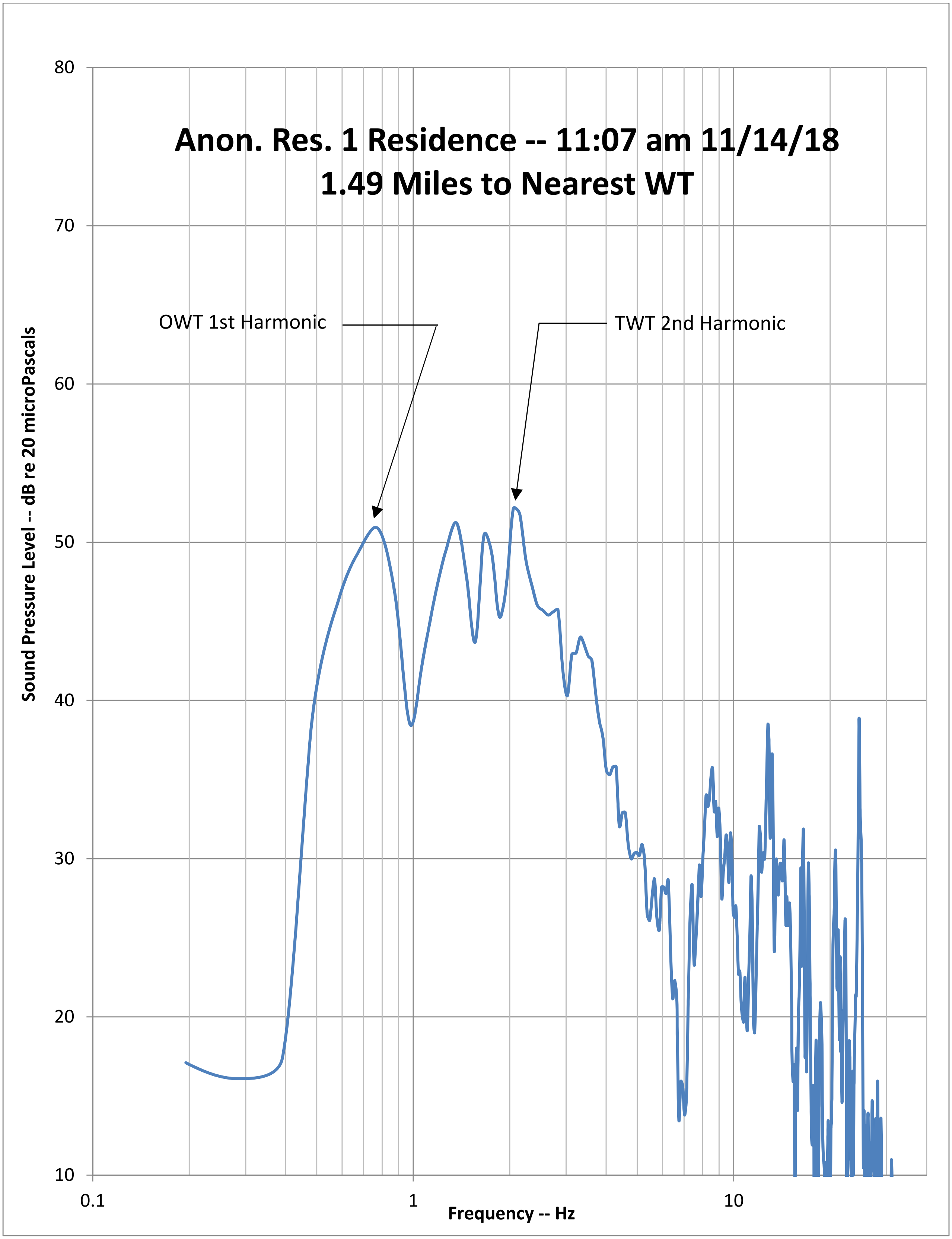


Figure C - 8 Anonymous Residence 1

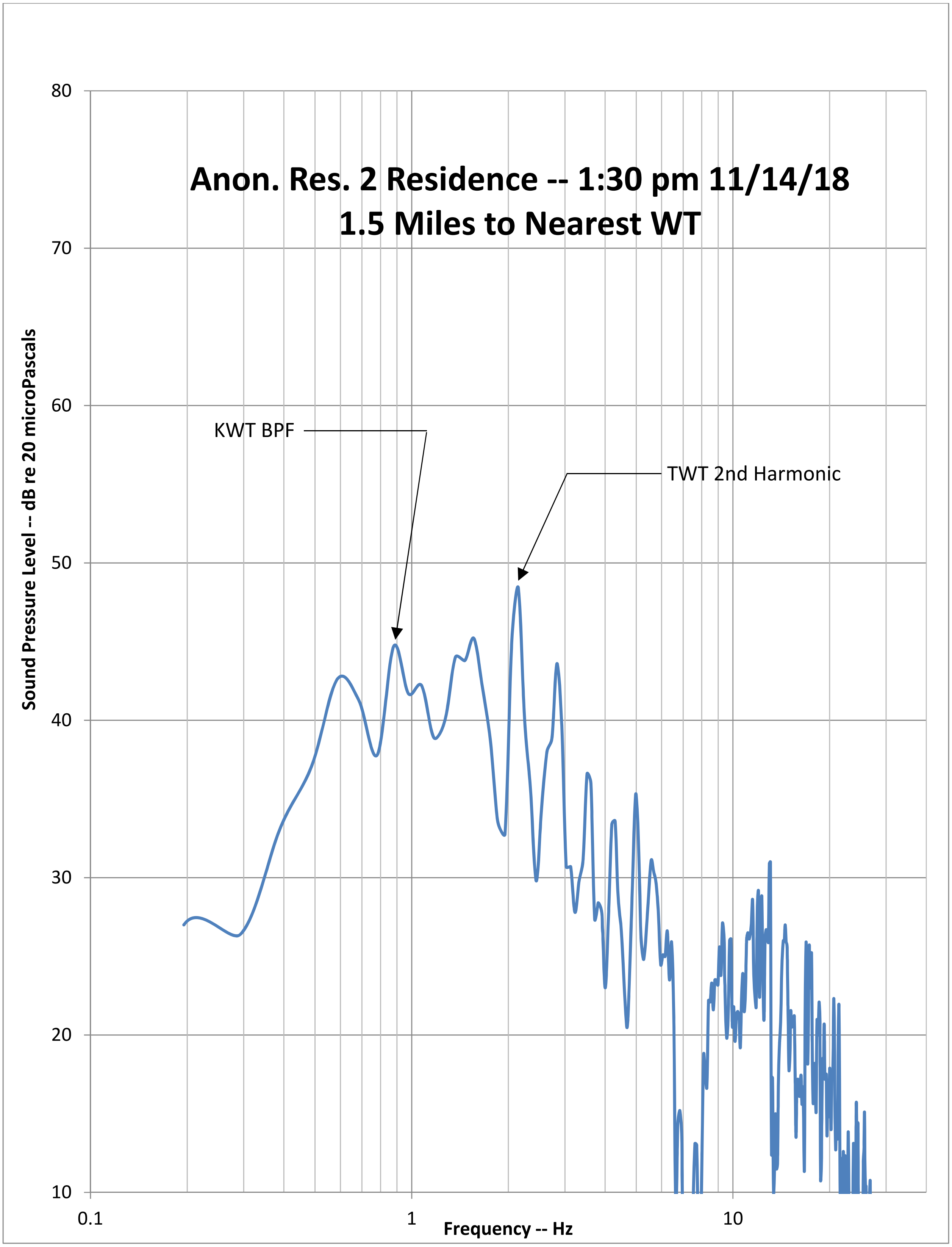


Figure C - 9 Anonymous Residence 2

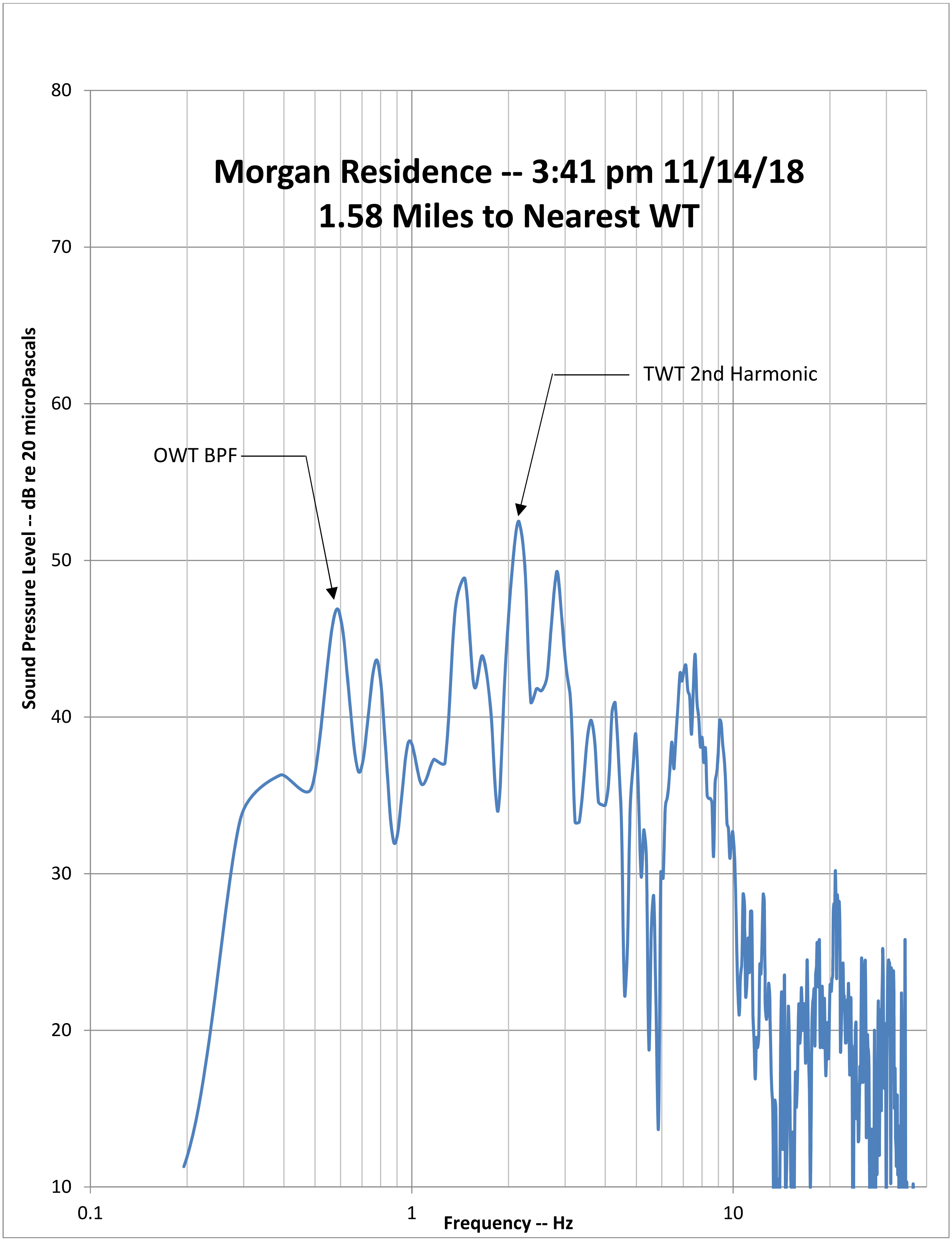


Figure C - 10 Morgan Residence

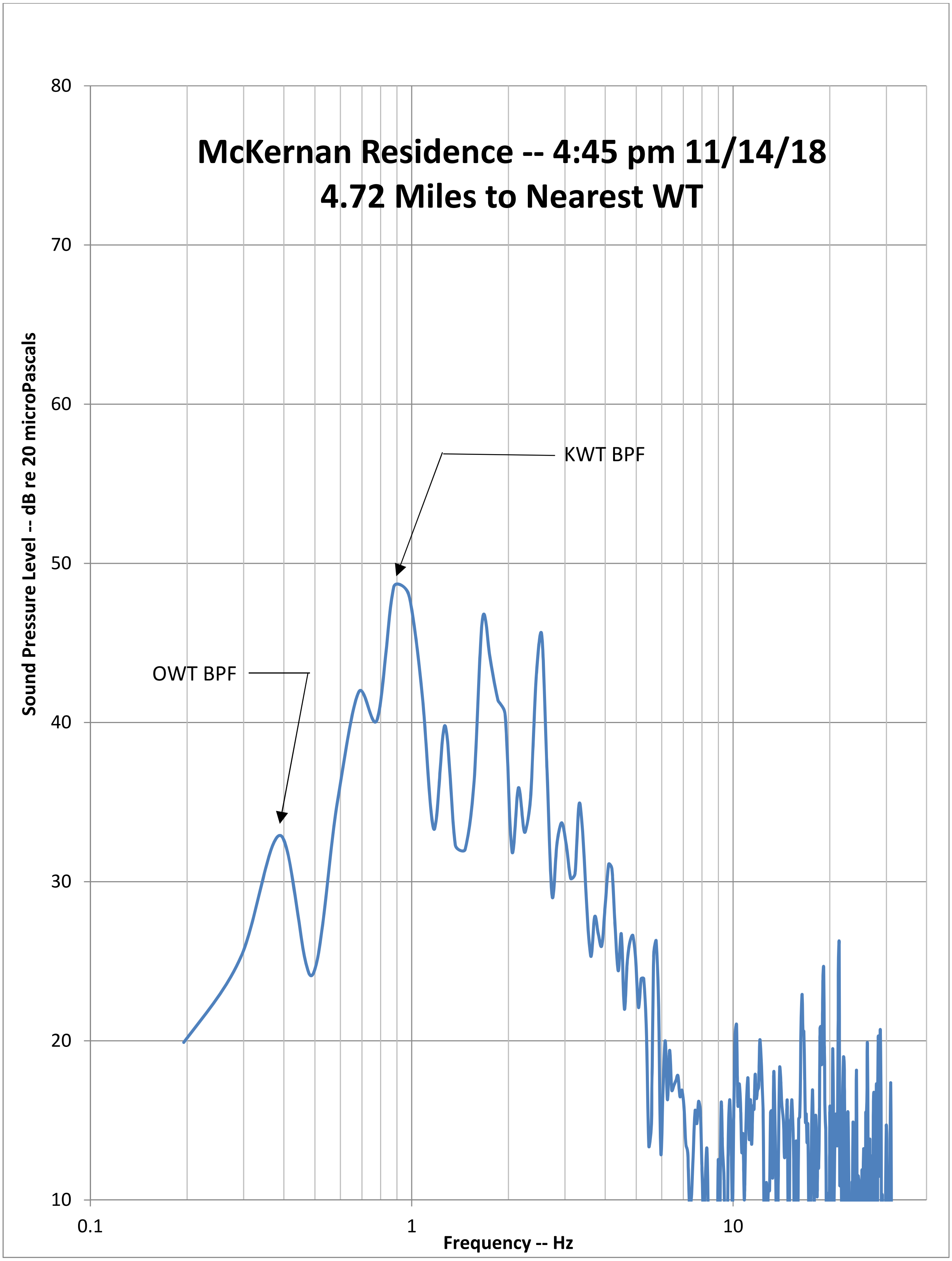


Figure C - 11 McKernan Residence

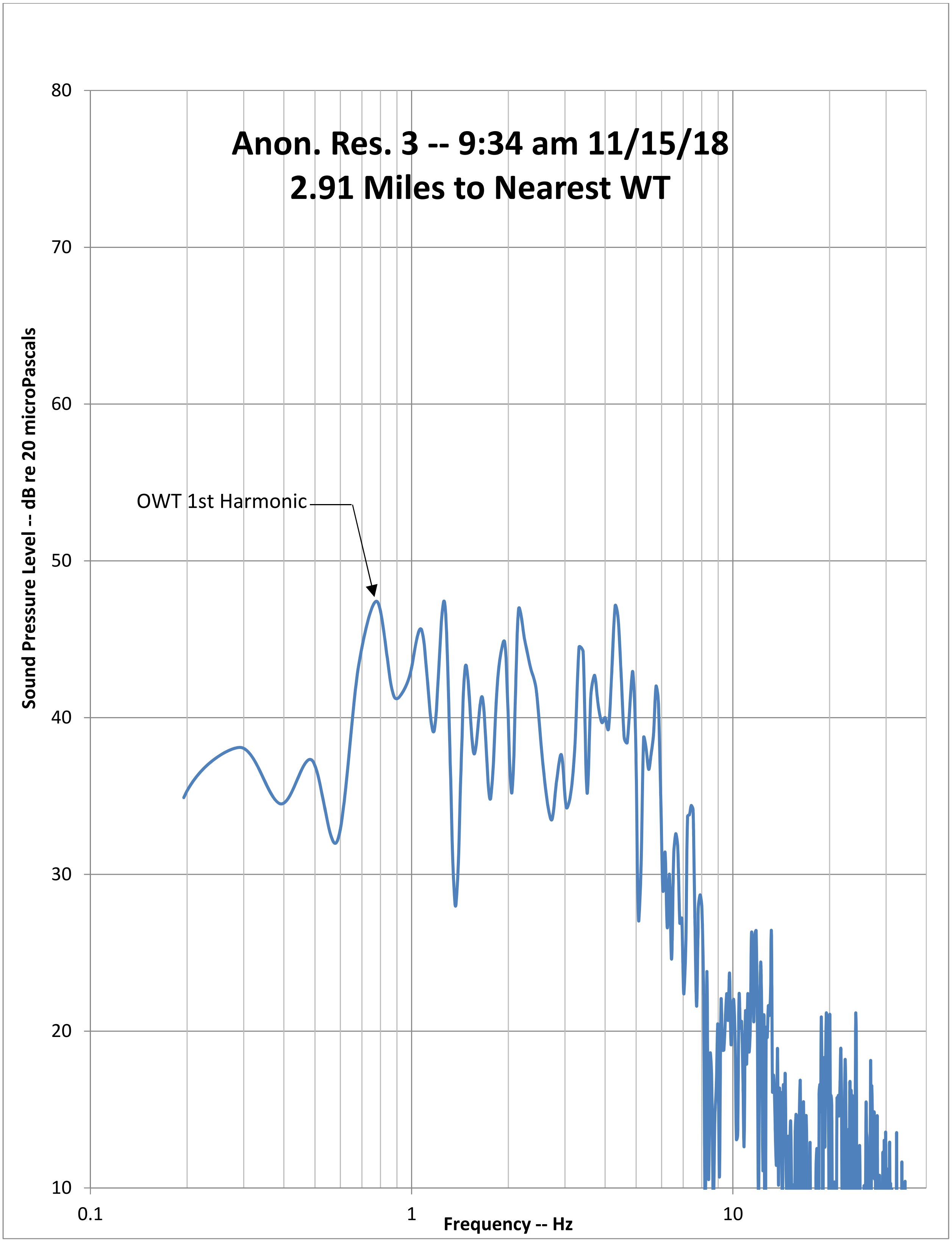


Figure C - 12 Anonymous Residence 3

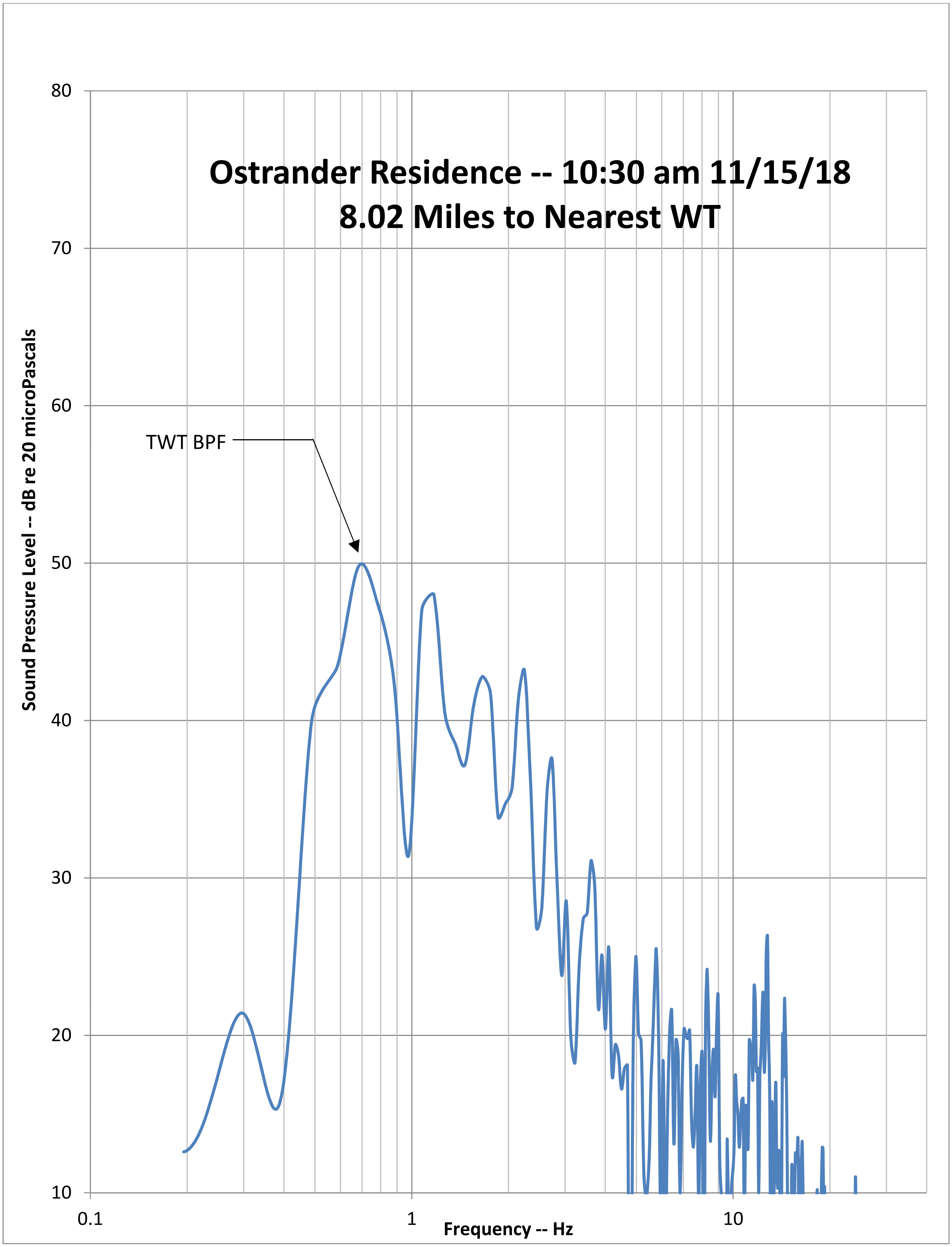


Figure C - 13 Ostrander Residence

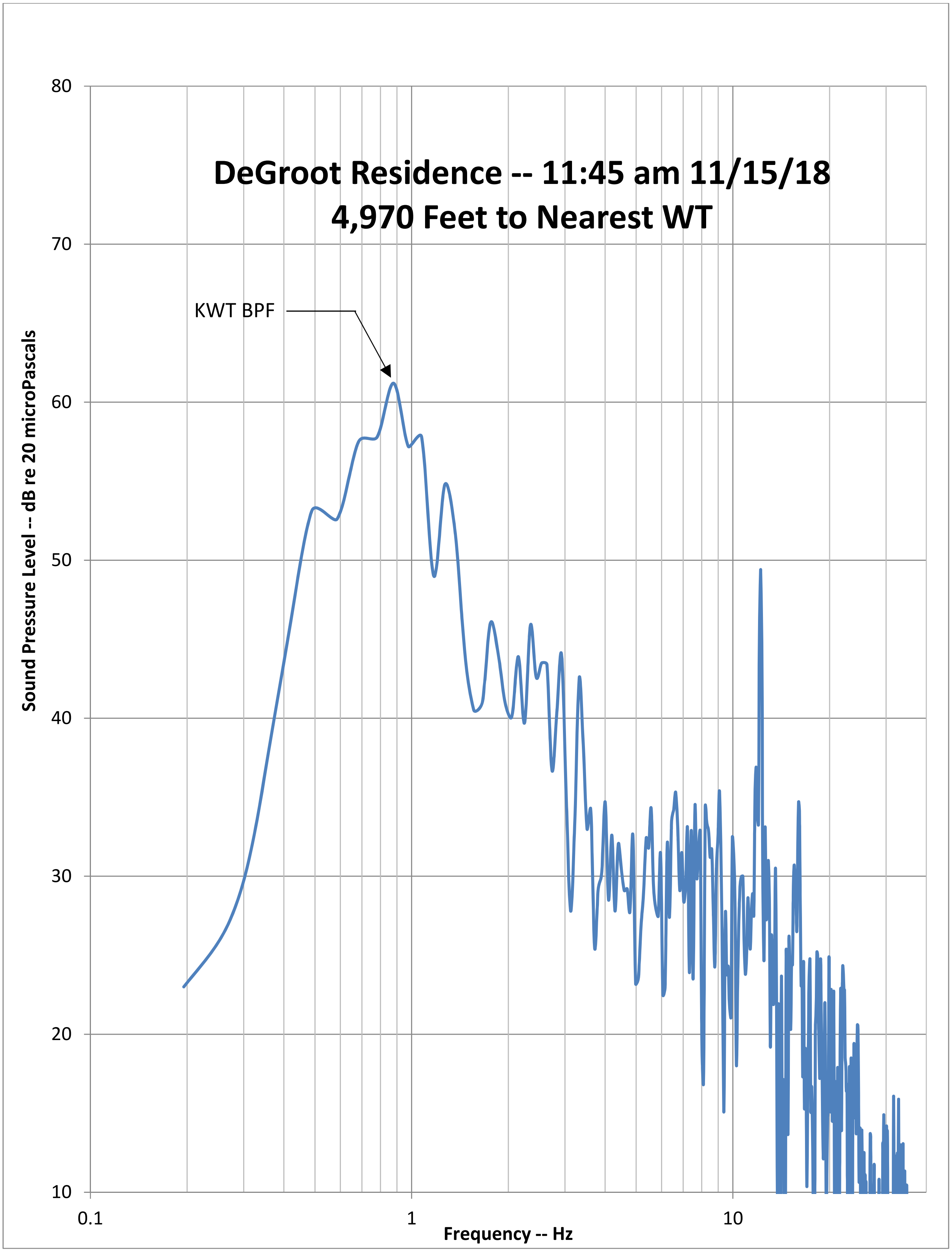


Figure C - 14 DeGroot Residence

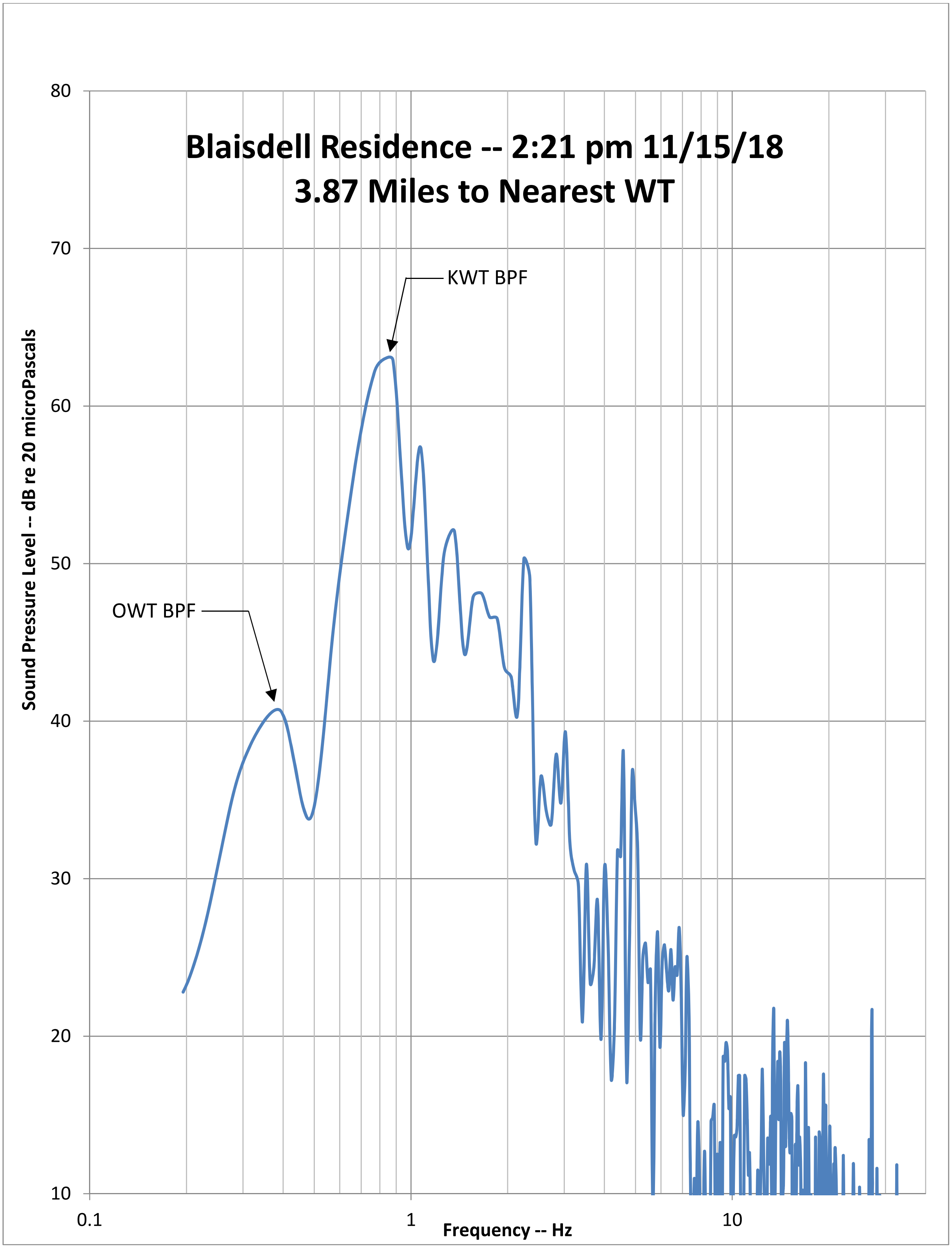


Figure C - 15 Blaisdell Residence

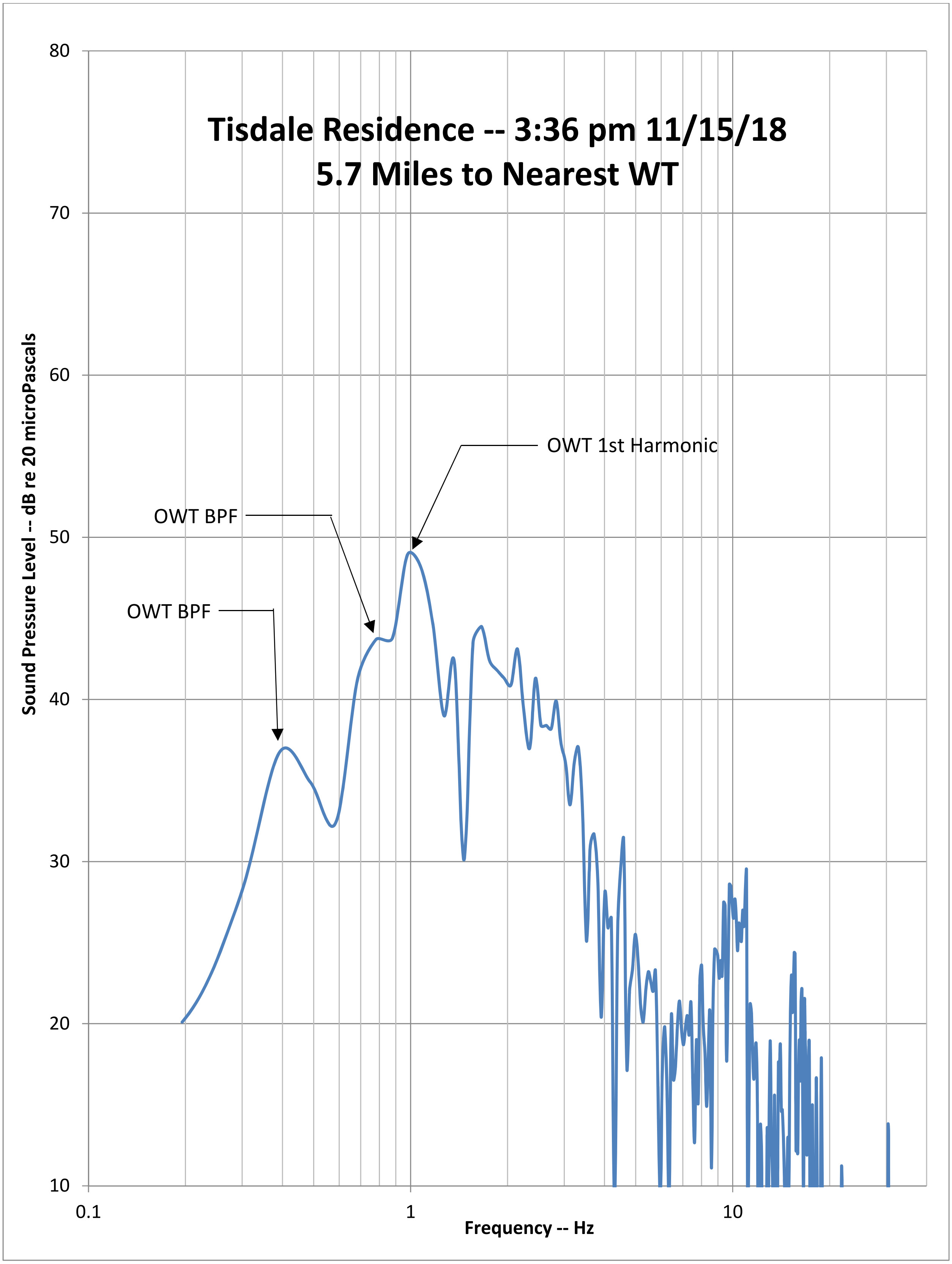


Figure C - 16 Tisdale Residence

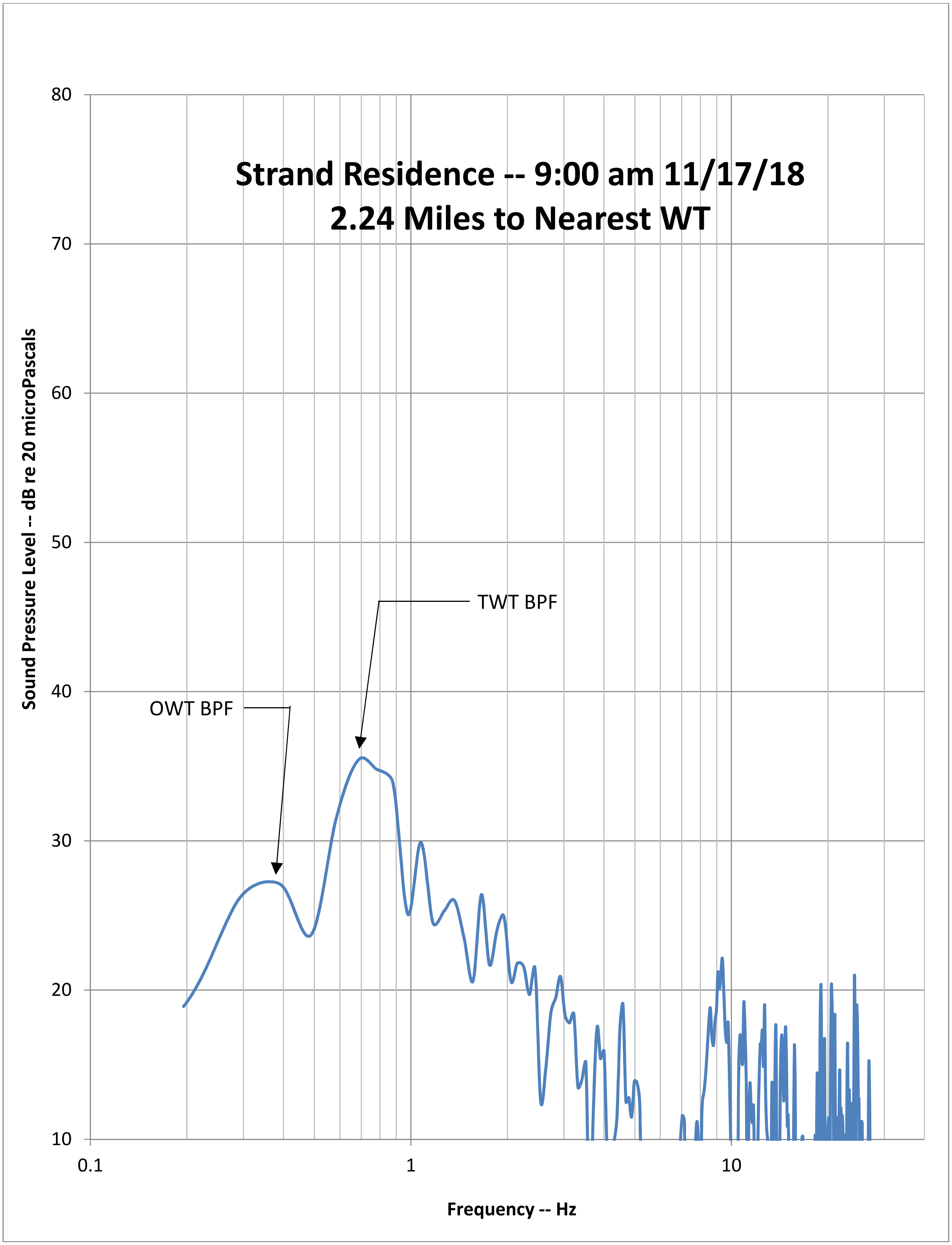


Figure C - 17 Strand Residence

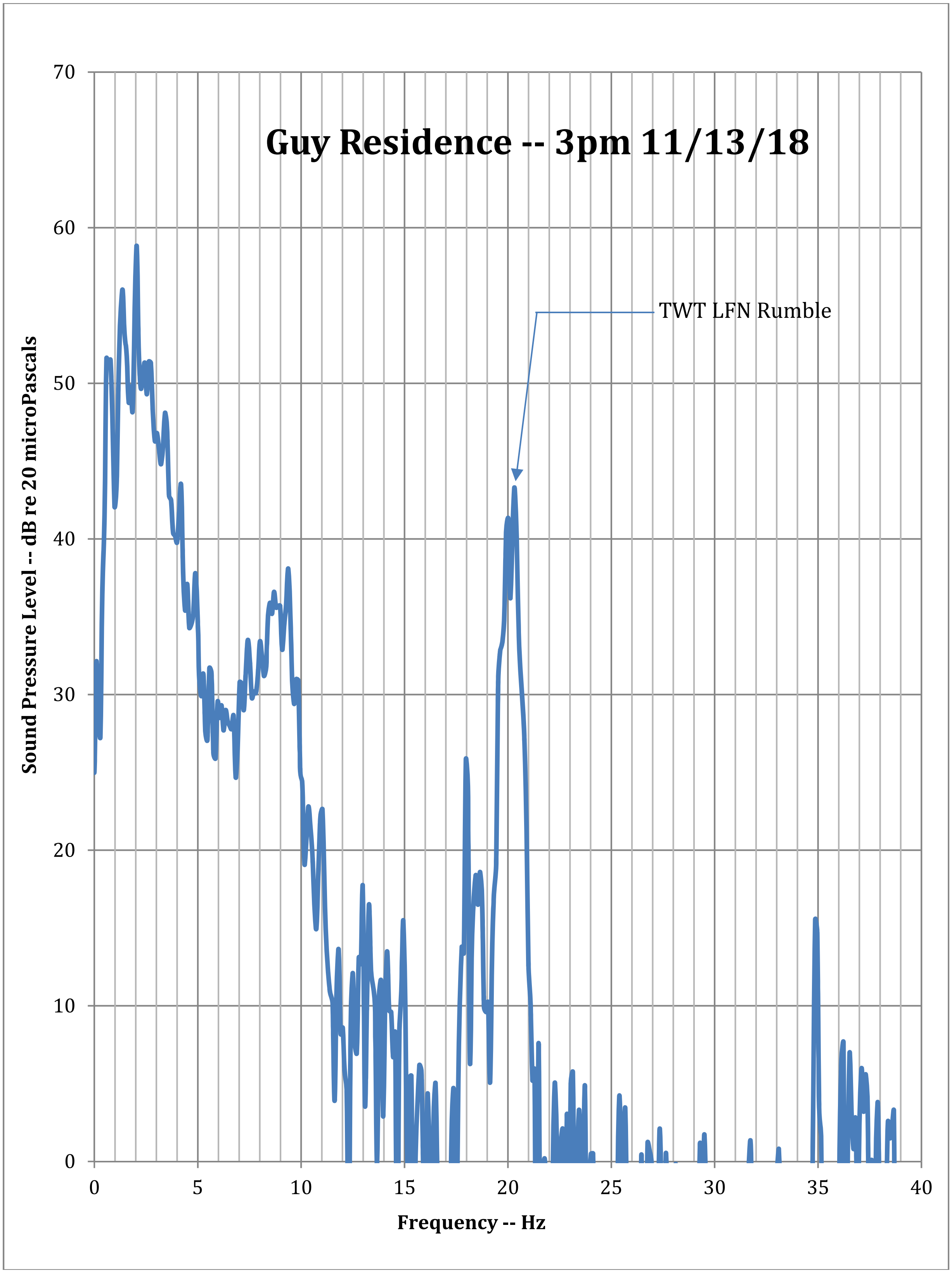
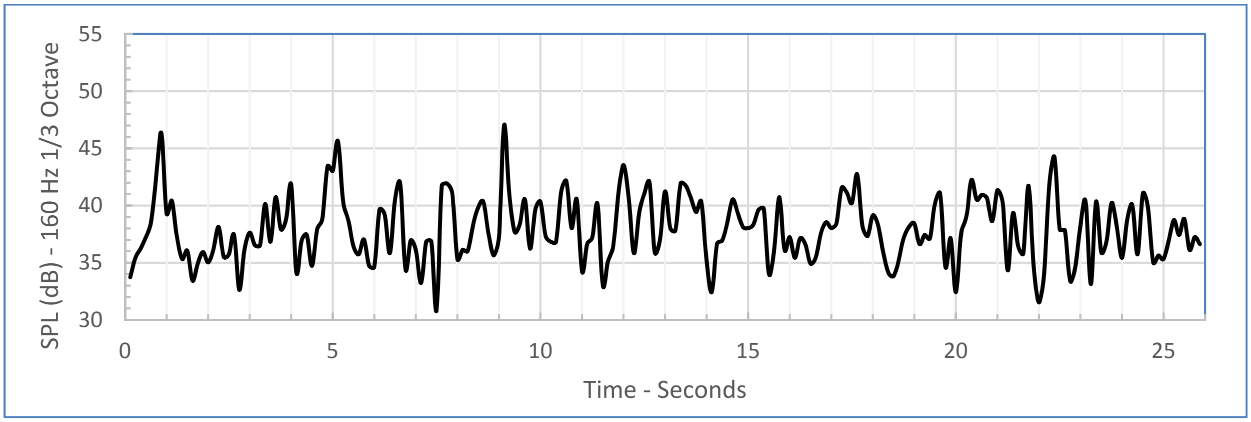
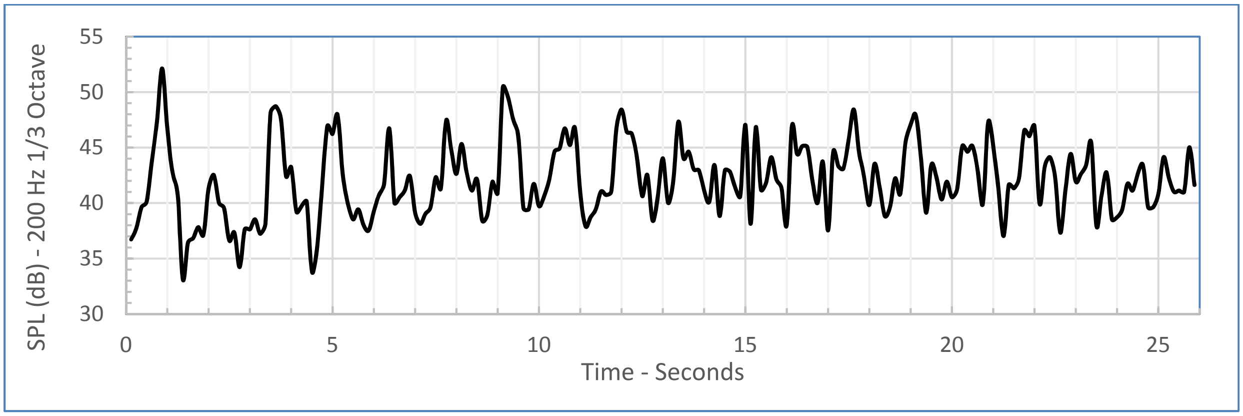


Figure C - 18 LFN at Guy Residence





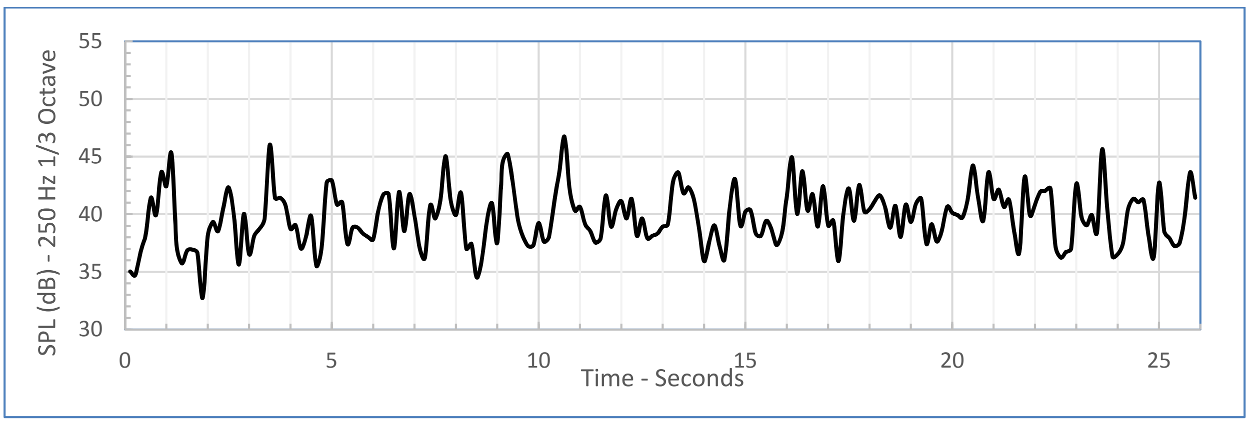


Figure C - 19 Frequency Filtered Samples of Amplitude Modulated WT Noise (Guy Res.)

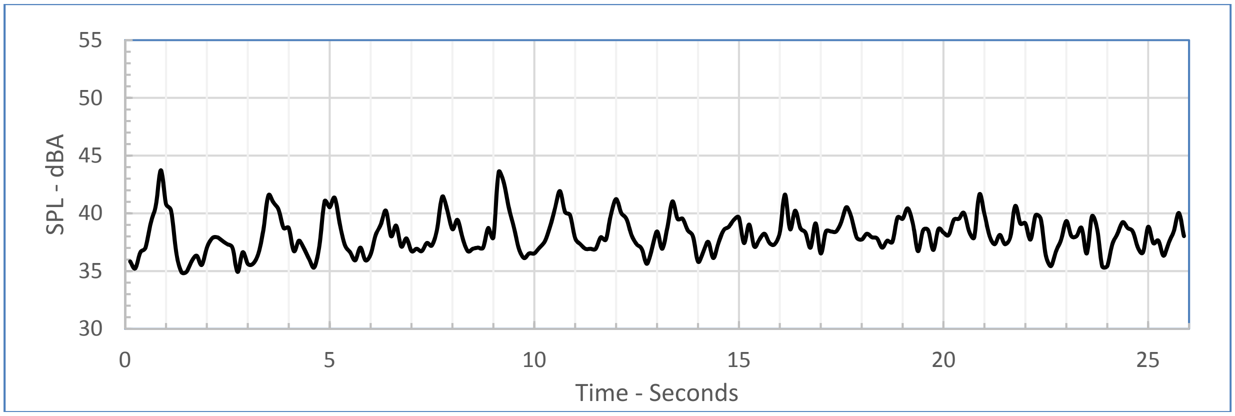


Figure C - 20 A-wtd Sample of Amplitude Modulated WT Noise (Guy Res.)

APPENDIX D – 2014 WILSON IHRIG REPORT

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KUMEYAAY AND OCOTILLO WIND TURBINE FACILITIES

NOISE MEASUREMENTS

28 February 2014

Submitted to:

Stephan C. Volker, Esq.

Law Offices of Stephan C. Volker

Submitted by:

Richard A. Carman, Ph.D., P.E.

Michael A. Amato

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EXECUTIVE SUMMARY

Noise measurements were obtained for wind turbines (WTs) at the Kumeyaay Wind Farm (Kumeyaay Wind) and Ocotillo Wind Energy Facility (Ocotillo Wind or OWEF) between April 28 and April 30, 2013. This report conclusively documents the presence of infrasound and low frequency noise (ILFN) generated by the two facilities' wind turbines at residential and other locations up to 6 miles from the wind turbines.

It is clear from the measured noise data obtained from Kumeyaay and Ocotillo facilities that there is significant wind turbine-generated ILFN. This was to be expected as it has been documented by others such as in the McPherson noise study, the Shirley Wind Turbine study, and by Epsilon Associates.[1] And indeed the measured ILFN levels near Kumeyaay and Ocotillo wind turbine facilities are similar to those measured in previous studies after accounting for the proximity of the measurements to a wind turbine and the total number of the wind turbines in the facility.

Both the McPherson and Shirley wind turbine noise studies were conducted to investigate whether and at what levels the subject wind turbines (the turbines in Falmouth, Massachusetts, and those in the Shirley Wind Project in Brown County, Wisconsin) produce ILFN, and whether that ILFN was contributing to the significant health and other impacts reported by nearby residences. In some cases, the impacts were so severe that residents abandoned their homes. Both studies found high levels of wind turbine-generated ILFN at numerous nearby residences that correlated with residents' reported impacts.

Human health impacts from wind turbines had been reported previously in several countries with large wind facilities in proximity to residences. But these impacts were often attributed to certain individuals' aversion to the presence of a large industrial facility constructed in what was previously a quiet rural setting. Scientific understanding has developed significantly since then.

Recent research and investigations into human response to ILFN seem to provide strong evidence of a cause and effect relationship. In particular the work of Salt, et al.[2] has made a clear case for perception of ILFN below the threshold of hearing as defined by ISO 389-7 which is related to the response of the ear's inner hair cells (IHC). Salt has demonstrated that it is possible for the ears' outer hair cells (OHC) to respond to ILFN at sound pressure levels that are much lower than the IHC threshold. Salt has reported that ILFN levels (levels commonly generated by wind turbines nearby residences) can cause physiologic changes in the ear.[3] Salt and Kaltenbach "estimated that sound levels of 60 dBG will stimulate the OHC of the human ear."[4]

---

[1] Epsilon Associates, A Study of Low Frequency and Infrasound from Wind Turbines, July 2009.

[2] Alec Salt, and J. Lichtenhan, Perception based protection from low-frequency sounds may not be enough, Internoise 2012, August 2012.

[3] Alec Salt, and J.A. Kaltenbach, "Infrasound from Wind Turbines Could Affect Humans," Bulletin of Science, Technology and Society, 31(4), pp.296-302, September 12, 2011.

[4] Ibid., p. 300, "As discussed below, G-weighting (with values expressed in dBG) is one metric that is used to quantify environmental noise levels. While it is a more accurate measure of ILFN than most other metrics, G-weighting still de-emphasizes infrasound."

Furthermore, Matsumoto et al.[5] have demonstrated in a laboratory setting that humans can perceive ILFN at sound pressure levels below the IHC threshold when the noise is a complex spectrum (i.e. contains multiple frequency components). From this laboratory research it was clearly demonstrated that humans can perceive sound pressure levels that are from 10 to 45 decibels (dB) less than the OHC threshold in the ILFN range. In fact, the Matsumoto thresholds clearly follow the OHC threshold down to the frequency below which the two diverge. The Matsumoto thresholds are lower than the OHC thresholds at frequencies below the point at which they diverge.

These studies and more recent studies demonstrate that wind turbines (specifically wind turbine-generated ILFN) have the potential to not only annoy humans, but harm them physiologically.

The data presented herein represent the conditions of measurement during the study and do not necessarily represent maximum noise conditions produced by the Kumeyaay and Ocotillo facilities. Higher wind speeds generally produce higher noise levels in particular higher ILFN. This is clearly demonstrated in the Ocotillo data when comparing the daytime and nighttime levels.

INTRODUCTION

As requested, Wilson, Ihrig & Associates (WIA) performed noise measurements in the vicinity of the Kumeyaay Wind Farm, located on the Campo Indian Reservation near Boulevard, California. We also took similar measurements in the vicinity of the Ocotillo Wind Energy Facility located near Ocotillo, California. The purpose of the measurements was to determine whether, and at what levels and under what conditions, the Kumeyaay Wind and Ocotillo Wind turbines generate ILFN[6], and how far the ILFN is propagated. A subsidiary goal was to accurately show the pressure fluctuations in the sound, so as to allow an accurate and robust analysis of the human health and other environmental impacts of the ILFN generated.

Between April 28 and April 30, 2013, we recorded noise samples at numerous residential and reference locations near each wind turbine facility. The wind turbines at both facilities were operating the entire time during which we took our noise measurements. Although it would have been our preference to also measure ambient noise conditions with all wind turbines taken out of operation, turbine operation was out of our control. In any event, even without measurements of the ambient noise sans wind turbines, we successfully measured and isolated wind turbine-generated noise.

Through a spectral analysis of the noise recordings, we obtained sound pressure level data demonstrative of the wind turbine-generated ILFN. In this report, we discuss the manner in which the data were obtained and present and analyze the study results.

---

[5] Yasunao Matsumoto, et al, An investigation of the perception thresholds of band-limited low frequency noises; influence of bandwith, published in The Effects of Low-Frequency Noise and Vibration on People, Multi-Science Publishing Co. Ltd.

[6] Infrasound is defined as sound at frequencies less than 20 Hz. The focus of this report is frequencies less than 40 Hz, which includes low frequency sound as well.

WIND TURBINE DETAILS

Kumeyaay Wind Farm

Kumeyaay Wind is owned by Infigen Energy of Australia and operated by Bluarc Management of Texas, on 45 acres of land on the Campo Indian Reservation in southeastern San Diego County.[7] The nearest community outside of the tribal land is Boulevard, California. Currently there are 25 wind turbines operating at this facility. The wind turbines are located on a north-south ridge (Tecate Divide) at elevations ranging from 4,200 to 4,600 feet. The turbines started generating power in December 2005.

Kumeyaay Wind's turbines are Gamesa model G87X-2.0, with a rated power of 2.0 megawatts (MW). According to the manufacturer's published data, the G87X-2.0 has a hub height (height of the nacelle, which houses the gearbox, transmission and generator) that can vary from 217 to 325 feet depending on site conditions. The manufacturer also represents that the turbine has a rotor diameter of 283 feet, with three 138-foot-long, adjustable pitch blades. According to Councilman Miskwish the hub height of the Kumeyaay Wind turbines is typically 228 feet, and the blades are 145 feet long. Figure 1 shows some of the wind turbines.

The G87-2.0 model has a reported cut-in wind speed of 8.9 mph (5 mph according to former Campo tribal Councilman Miskwish, a.k.a. Michael Connolly) and achieves its rated (max) power generation at about 31 mph. The operational speed of the turbines is reported by the manufacturer to be in the range of 9 to 19 revolutions per minute (rpm) depending on wind conditions.

Figure 1 Wind Turbines at Kumeyaay Wind

---

[7] "Kumeyaay Wind Energy Project," PowerPoint presentation by Councilman Michael Connolly Miskwish, Campo Kumeyaay Nation, November 30, 2008., *available here:* http://www.certredearth.com/pdfs/Presentations/2007/KumeyaayWindEnergyProjectCampoKumeyaayNation.pdf

Ocotillo Wind Energy Facility

The Ocotillo Wind facility is owned and operated by Pattern Energy, on 10,200 acres of federal land located in southwestern Imperial County and managed by the United States Bureau of Land Management (BLM). Ocotillo Wind currently has 112 operating wind turbines. The wind turbines are located on the desert floor adjacent to the community of Ocotillo, California, at elevations ranging from approximately 300 to 1,400 feet above sea level. The Ocotillo Wind turbines are Siemens model SWT-2.3-108, with a rated power of 2.3 MW. Figure 2 shows some of Ocotillo Wind's turbines.

According to the manufacturer's published data, the SWT-2.3-108 model has a nominal hub height of 260 feet depending on site conditions, with a turbine rotor diameter of 351 feet and three 172-foot-long blades. The SWT-2.3-108 has a manufacturer-reported cut-in wind speed between 6.6 and 8.9 mph and achieves its rated power at wind speeds between 24 and 27 mph. The operational speed of the turbines reported by the manufacturer is in the range of 6 to 16 rpm depending on wind conditions.

Figure 2 Wind Turbines at Ocotillo Wind

MEASUREMENT LOCATIONS

Kumeyaay Wind-Area Residences

Both indoor and outdoor noise recordings were made at six residences in the Boulevard area near the Kumeyaay Wind turbines.

Table 1 lists the addresses of the residences at which the measurements were taken, along with the dates and times of the recordings. A map showing the Kumeyaay Wind-area measurement locations is provided in Appendix A.

Table 1 Addresses of Residences Used in Kumeyaay Measurements

Resident/Owner	Address	Distance to Closest Wind Turbine	Date	Recording Start Time	Recording End Time[1]
D. Elliott	Off of Crestwood, Campo Indian Reservation	2,960 feet	April 28	16:02	16:22
			April 30	11:00	11:20
G. Thompson	33 Blackwood Road, Manzanita Indian Reservation	2,880 feet	April 28	18:47	19:07
R. Elliott	25 Crestwood Road, Manzanita Indian Reservation	4,330 feet	April 28	17:30	17:50
D. Bonfiglio	40123 Ribbonwood Road, Boulevard	2.9 miles	April 29	9:15	9:35
K. Oppenheimer	39544 Clements Street, Boulevard	1.6 miles	April 30	15:11	15:31
M. Morgan	2912 Ribbonwood Road, Boulevard	1.7 miles	April 30	16:15	16:35
D. Tisdale	Morning Star Ranch, San Diego Co.	5.7 miles	April 30	13:45	14:05

[1] Recordings were nominally 20 minutes long

The Kumeyaay Wind-area residences at which we took measurements are located at distances of 2,880 feet to 5.7 miles from the nearest wind turbine at Kumeyaay Wind Farm. Additional recordings were made at two reference locations, which were closer to the wind turbines than the residential locations, as shown below in Table 2.

A recording was also obtained at the Tisdale ranch located 5.7 miles from the nearest wind turbine (see Table 1 above). The purpose of this recording was primarily to document existing ambient conditions; however, even at that great distance, analysis of the data indicates the presence of noise generated by the existing turbines.

A recording was also made at one of the guest cabins at the Live Oak Springs Resort. The purpose of this latter measurement was to obtain noise recordings in a condition with essentially no "local wind." By no local wind, it is meant that the wind at the microphone was either very light or non-existent even though there was wind at the wind turbine level, which was confirmed by observing the closest wind turbine rotating, thus providing a sample of wind turbine noise that was minimally affected by wind on the microphone. This latter recording was made at 10:10 pm on April 28. Cabin #2 at Live Oak Springs Resort is 5,950 feet from the nearest wind turbine.

Kumeyaay Reference Noise Measurements

To more fully document wind turbine-generated noise levels and spectra, we took noise measurements at locations closer to the subject wind turbines than the residences used in this study. Two reference locations were used near Kumeyaay Wind. Table 2 indicates the locations, distances to the closest wind turbine, dates and times of the reference recordings.

Table 2 Reference Locations for Kumeyaay Wind

Location	Distance to Closest Wind Turbine (feet)	Date	Recording Start Time	Recording End Time[1]
Kumeyaay (K-R1)	2,040	April 28	15:58	16:18
Kumeyaay (K-R2)	930	April 30	11:00	11:20

[1] Recordings were nominally 20 minutes long

The recording on April 28 at 10:00 pm at Live Oak Springs Resort (K-LOSR) also serves as a reference measurement.

Ocotillo Wind-Area Residences

Recordings were made at three Ocotillo residences near the Ocotillo Wind turbines. Table 3 lists the addresses of the residences at which the measurements were taken, along with the dates and times of recordings. A map showing the Ocotillo Wind-area measurement locations is provided in Appendix A.

Table 3 Addresses of Residences Used in Ocotillo Measurements

Resident/Owner	Address	Distance to Closest Wind Turbine	Date	Recording Start Time	Recording End Time[1]
J. Pelly	1362 Shell Canyon Road, Imperial County	3,220 feet	April 29	11:22	11:42
				20:00	20:20
P. Ewing	98 Imperial Highway, Ocotillo	3,590 feet	April 29	12:32	12:52
				21:00	21:20

D. Tucker	1164 Seminole Avenue, Ocotillo	1.2 miles	April 29	13:42	14:02
				22:20	22:40

[1] Recordings were nominally 20 minutes long

The Ocotillo Wind-area residences at which we took measurements are located at distances of 3,220 feet to 1.2 miles from the closest wind turbine at Ocotillo Wind. We also made measurements at three reference locations closer to the wind turbines, as shown in Table 4 below.

Ocotillo Reference Noise Measurements

We used three reference locations near Ocotillo Wind. Table 4 lists the locations, distance to the closest wind turbine, dates and times of the reference recordings.

Table 4 Reference Locations for Ocotillo

Location	Distance to Closest Wind Turbine (feet)	Date	Recording Start Time	Recording End Time[1]
Ocotillo (O-R1)	1,540	April 29	11:19	11:39
			20:00	20:20
Ocotillo (O-R2)	1,470	April 29	13:44	14:04
			21:30	21:50
Ocotillo (O-R3)	2,100	April 29	22:08	22:28

[1] Recordings were nominally 20 minutes long

NOISE RECORDING METHODOLOGY

We made all of the noise recordings with Brüel and Kjaer (B&K) type-4193, ½-inch, pressure-field microphones, which are specifically designed for infrasound measurement and provide a linear response from 0.07 cycles per second (Hz) to 20,000 Hz. A B&K type-UC-0211 adapter was used to couple the microphones to a B&K type-2639 preamplifier, providing a linear frequency response down to 0.1 Hz for the microphone/adaptor/preamplifier system. All recordings were calibrated with B&K type-4230 calibrators, which are checked and adjusted with NIST traceable accuracy with a B&K type-4220 pistonphone in the WIA laboratory in Emeryville, California.

We recorded all the noise samples with a TEAC LX10, 16-channel digital recorder, which provides a linear frequency response (i.e., ±0.1% or less) to a lower frequency limit of essentially 0.1 Hz when used in the "AC mode" (which we did). Twenty minute (nominal) noise recordings were made at each location. Using two different microphones, recordings were made simultaneously both indoors and outdoors at each subject residence. This same approach was also used in the Shirley Wind Farm study[8].

Using a third microphone and another recorder (SONY PCM D-50 digital recorder), recordings were made at reference locations closer to the wind turbines while the residential recordings were in progress. The frequency response of this third system is linear down to a frequency of 1.4 Hz, being limited by the SONY recorder.

For several of the residential and reference locations, recordings were repeated at a different time and/or date. All measurement data reported herein are based on an analysis of the noise recordings played back in the WIA laboratory.

Residence Location Measurements

For measurements conducted at the residences, a microphone was set up inside each residence mounted on a tripod at 4.5 feet above the floor, typically in the middle of the room. The indoor recordings were made in either the living room (mostly) or dining room of the residences. Indoors, the microphone was oriented vertically and covered with a 7-inch-diameter wind screen. Figure 3 shows the microphone and windscreen mounted on a tripod inside one of the residences.

A second microphone was set up outside of each residence. Following IEC Standard 61400-11, the outside microphone was rested horizontally (i.e., flush mounted) on a ½-inch-thick plywood "ground board" that is 1 meter in diameter. The microphone was oriented in the direction of the nearest visible wind turbine and the ground board was placed in a flat location between the residence and the wind turbines.

Also following IEC 61400-11, wind effects on the outdoor microphone were reduced using both a hemispherical 7-inch-diameter primary windscreen placed directly over the microphone, and a hemispherical 20-inch-diameter secondary windscreen placed over the primary windscreen and mounted on the ground board. The microphone and primary windscreen were placed under the center of the secondary windscreen.

The primary windscreen was cut from a spherical, ACO-Pacific foam windscreen with a density of 80 pores per inch (ppi). The secondary windscreen was constructed by WIA using a wire frame covered with ½ inch open wire mesh. A one-inch-thick layer of open cell foam with a density of 30 ppi was attached to the wire mesh. Figure 4 shows the outdoor microphone, secondary windscreen, and ground board outside one of the residences.

Both microphones used at the residences were powered by B&K type-2804 power supplies, with signals amplified by a WIA type-228 multi-channel measurement amplifier, and recorded on a TEAC LX10 16-channel digital data recorder. Inside and outside noise signals were recorded simultaneously to allow for correlation of interior and exterior sound levels during analysis.

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[8] Channel Islands Acoustics, et al, A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin, Report No. 122412-1, December 24, 2012.

Figure 3 Microphone Inside Residence

Figure 4 Microphone Outside Residence

Reference Location Measurements

A third B&K 4193 microphone was used to obtain simultaneous reference measurements at locations closer to the wind turbines during each of the residential measurements. This third microphone was powered by a B&K type-5935 power supply and amplifier, with the signal recorded on a Sony type PCM D-50 recorder. The same windscreen and ground board configuration (i.e., primary and secondary windscreen) used for the residential recordings, was also used for the reference locations. Reference measurements were obtained at different locations at each of the two facilities. Figure 5 shows the microphone, ground board and secondary windscreen at one of the reference measurement locations in Ocotillo.

Figure 5 Reference Location O-R2 with Microphone, Ground Board and Windscreen

NOISE MEASUREMENT BACKGROUND

Purpose of Measurements

The primary purpose of making the wind turbine noise measurements reported herein was to determine whether, and at what levels and under what conditions, the Kumeyaay Wind and Ocotillo Wind turbines generate ILFN, and how far the ILFN is propagated. In light of increasing evidence in the literature that ILFN can affect and harm humans[9] [10] [11] [12] [13], along with numerous complaints of health impacts from both Boulevard- and Ocotillo-area residents[14] since the wind turbines near their respective residences began operating, we had a subsidiary goal to obtain measurements that accurately show the pressure fluctuations in the sound, so as to allow an accurate and robust analysis of the human health and environmental impacts of the ILFN generated.

Noise Measurements in Presence of Wind

Some atmospheric pressure fluctuations are oscillatory in nature, whereas others are not. An example of a non-oscillatory pressure fluctuation is a change in barometric pressure; a change that occurs over a much longer time scale (e.g., hours) than the fluctuations being measured in this study. Wind and, in particular, gusts of wind cause another form of non-oscillatory pressure fluctuation, though it occurs on a much shorter time scale (e.g., fraction of a second). Local wind can cause a pressure change affecting the human ear similar to the pressure change that occurs in an airplane as it ascends or descends during takeoff and landing, but this pressure change is not sound.

Sound, in contrast to non-oscillatory fluctuations, consists of regular oscillatory pressure fluctuations in the air due to traveling waves. Sound waves can propagate over long distances depending on many factors. In the case of noise generated by machinery, the pressure fluctuations can be highly periodic in nature (i.e., regular oscillations). Sound that is characterized by discrete frequencies is referred to as being tonal. Although wind can generate sound due to turbulence around objects (e.g., trees, buildings), this sound is generally random in nature, lacks periodicity and is usually not in the infrasound range of frequencies.

However, the sound measurements we were interested in for this study (i.e. periodic wind turbine-generated ILFN) can be greatly impacted by non-oscillatory pressure fluctuations and extraneous noise caused by, for example, wind turbulence due to steady wind and particularly during gusts. The microphones we used in these measurements are highly sensitive instruments, with pressure sensor diaphragms that will respond to any rapid enough pressure change in the air regardless of the cause. To minimize the artificial (i.e. unrelated to the noise source being measured) noise or "pseudo sound" caused by wind gusts and other pressure fluctuations not associated with the wind turbine-generated noise itself, we employed special procedures. The

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[9] Salt, A.N., T.E. Hullar, Responses of the ear to low frequency sounds, infrasound and wind turbines, Hearing Research, 16 June 2010.

[10] Salt, A.N., J.T. Lichtenhan, Reponses of the Inner Ear to Infrasound, Fourth International Meeting on Wind Turbine Noise, Rome, Italy, April 2011.

[11] Salt, A.N., J.A. Kaltenbach, Infrasound from Wind Turbines Could Affect Humans, Bulletin of Science, Technology & Society, 31, 296-302, 2011.

[12] Salt, A.N., J.T. Lichtenhan, Perception-based protection from low-frequency sounds may not be enough, Inter-Noise 2012, New York, New York, August 2012.

[13] Lichtenhan, J.T., A.N. Salt, Amplitude Modulation of Audible Sounds by Non-Audible Sounds: Understanding the Effects of Wind-Turbine Noise, Proceedings of JASA, 2013.

[14] San Diego Reader, Volume 42, Number 34, August 22, 2013.

main sources of artificial noise and the procedures we used to minimize its impact are discussed more fully below.

Artificial Noise due to Turbulence at the Microphone

One source of artificial noise caused by wind on the microphone – and the most commonly encountered artificial noise source in outdoor noise measurements – is the turbulence caused by wind blowing over the microphone. To minimize this effect of wind when conducting environmental noise measurements outdoors, it is standard practice to use a windscreen,[15] the size of which is usually selected based on the magnitude of the wind encountered. The higher the wind speed generally the larger the windscreen required to minimize artificial noise caused by air turbulence at the microphone.

The windscreen used must be porous enough so as not to significantly diminish the pressure fluctuations associated with the noise being measured, which is to say that the wind screen must be acoustically transparent. As indicated above, the measurements reported herein followed procedures on windscreen design and usage as recommended by IEC 64100-11.

Artificial Noise due to Air Gusts

There is another – and more problematic – source of artificial wind-based noise. This one is caused by non-oscillatory pressure fluctuations associated with wind gusts as well as the pressure associated with the air flow in a steady wind. Air gusts can have an effect on a microphone signal in two ways. Outdoors, the microphone diaphragm will respond to the direct change in pressure associated with air flow; whereas indoors, the microphone will respond to the indirect change in pressure associated with wind and particularly gusts of wind that pressurize the interior of the building. These wind effects induce artificial noise that appears in the electrical signal generated by the microphone that is in the ILFN frequency range. This pseudo noise can, in turn, affect the spectral analysis of the recorded data. This form of pseudo noise (i.e., pressure changes due to air flow) is not substantially reduced by the use of a windscreen or even multiple windscreens generally regardless of their size.

Here, as discussed more fully in the Method of Analysis of Recorded Data section below, we analyzed the sound recordings in this study using a fast Fourier transform (FFT) technique to resolve low frequency and infrasound data. The primary range of interest in these measurements was in frequencies between 0.1 and 40 Hz. An FFT analysis produces a constant bandwidth (B). A 400-line FFT was used in the analysis, which means the bandwidth was B = 0.1 Hz. This allows resolution of frequency components to fractions of one Hz.

When using a very narrow bandwidth (e.g., 0.1 Hz), the time required for filtering is long in order to obtain the frequency resolution. The FFT analysis time T required for a specific bandwith B is given by: $T = 1/B$. For a 0.1 Hz bandwidth the time required is 10 sec. At this time scale, the effects of air pressure changes due to air movement tend to linger in the filtering process as discussed in the Method of Analysis of Recorded Data section below.

[15] ANSI S12.9-2013/Part 3, Quantities and Procedures for Description and Measurement of Environmental Sound, Part 3: Short-Term Measurements with an Observer Present, American National Standards Institute, 2013.

To reduce the wind gust-induced artificial noise that manifests in the data with such long filtering times, both physical means during recording and analytical post-recording methods can be employed to minimize this artificial noise. The most effective pre-measurement technique is to dig a hole in the ground and put the microphone into it.[16] If two pits and microphones are used, then a cross-spectral analysis is also possible. In this study, however, it was impractical and, in some cases, impossible to dig microphone pits at the 15 total measurement locations. We thus relied on post-measurement analytical methods to filter out the pseudo noise as much as possible.

Each of the two most effective analytical techniques takes advantage of the fact that wind turbines and other large rotating machinery with blades (e.g., building ventilation fans and helicopters) produce very regular, oscillatory pressure fluctuations that are highly deterministic,[17] whereas pressure changes due to air movement associated with local wind gusts are essentially random in nature. The sound produced by wind turbines is tonal in nature, meaning that it has a spectrum with discrete frequencies that, in this case, are interrelated (i.e., harmonics of the blade passage frequency). This difference between the random wind noise and the wind turbine noise provides a means to minimize the latter in the signal processing of the recorded data. It has been posited that it is the tonal nature of wind turbine infrasound that may have some influence on residents in the vicinity of large wind turbines[18].

The artificial noise associated with pressure changes at the microphone due to local wind gusts can be minimized in two ways when analyzing the recorded signal. The first technique is to average the noise measurements over a longer time period. This tends to reduce the effect of pseudo noise associated with random air pressure transients during wind gusts, but does not affect the very regular, periodic pressure fluctuations generated by wind turbines.

When averaging over time is not sufficient, a second technique can be used to further minimize the effect of random pressure fluctuations associated with local wind. This second technique uses "coherent output power," a cross-spectral process. Both time averaging and coherent output power are discussed below under the method of analysis of recorded data.

WIND TURBINE OPERATION DURING MEASUREMENTS

Video recordings were made several times during the study period to document the operation of the wind turbines. Using the video recordings, we determined both the rotational speed of the wind turbine rotors (Ω in rpm) and the so-called "blade passage frequency" (f_0, also referred to as "blade passing frequency" or BPF), which is calculated in cycles per second, where $f_0 = N \times \Omega /60$, and N is the number of blades. For a three-bladed rotor ($N = 3$) the blade passage frequency is given by the equation:

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[16] Betke, L. and H. Remmers, Messung and Bewertung von tieffrequentem Schall, Proceedings of DAGA 1998 (in German)

[17] Johnson, Wayne, Helicopter Theory, Dover Publications, New York, 1980.

[18] Hessler, G., P. Schomer, Criteria for Wind-turbine Noise Immissions, Proceedings of the Meetings on Acoustics ICA 2013, Montreal, 2-7 June 2013, Acoustical Society of America, Vol. 19, 040152 (2013).

$$f_0 = \frac{\Omega}{20} .$$

Associated with the blade passage frequency are harmonics, which are integer multiples of the blade passage frequency. In this study, we typically observed at least five discrete harmonics in the measurement data. This pattern was also observed in the aforementioned Shirley Wind Farm study.

The harmonic frequencies are given by:

$$f_n = (n+1) \times f_0 , where\ n \geq 1 .$$

For example, if Ω = 17 rpm, then f_0 = 0.85 Hz and the frequencies of the first six harmonics (n = 1 through 6) are: 1.7, 2.6, 3.4, 4.3, 5.1 and 6.0 Hz.

Table 5 summarizes a selection of the wind turbine speeds observed during the recordings. We note that the turbine speed of 16.2 rpm observed in Ocotillo at 19:51 on April 29 is the maximum rated speed for the Siemens SWT-2.3-108.

Table 5 Rotational Speeds Observed for Nearest Wind Turbines

Facility	**Date**	**Location**[1]	**Time**	**Speed (rpm)**	**BPF (Hz)**
Kumeyaay Wind (Gamesa Turbines – rated speed of 9 to 19 rpm)	April 28	D. Elliott	14:14	17.3	0.87
			15:05	17.1	0.86
			16:29	16.8	0.84
			16:30	16.3	0.81
		R. Elliott	17:28	16.7	0.83
		Thompson	19:32	17.2	0.86
Kumeyaay Wind (Gamesa Turbines – rated speed of 9 to 19 rpm)	April 29	Bonfiglio	9.37	12.2	0.61

Ocotillo Wind (Siemens Turbines – rated speed of 6 to 16 rpm)	April 29	O-R1	11:26	9.8	0.49
			11:29	7.4	0.37
			11:32	6.5	0.32
		O-R2	12:40	13.3	0.67
			13:54	15.0	0.75
			14:02	12.5	0.63
		O-R1	19:51	16.2	0.81
Kumeyaay Wind (Gamesa Turbines – rated speed of 9 to 19 rpm)	April 30	D. Elliott	10:33	15.6	0.78
		K-R2	11:22	16.7	0.83
			11:24	13.6	0.68
		Tisdale	13:45	14 to 16.6[2]	0.7 to 0.83[2]
		Oppenheimer	14:50	16.7	0.83
			15:17	17.1	0.86
			15:27	16.7	0.83
		Morgan	16:12	17.1	0.86
			16:18	16.2	0.81
			16:28	17.1	0.86

[1] Locations refer to where video was recorded

[2] Based on observed rotor speeds before and after recording

METEOROLOGICAL DATA

Weather Underground provides publicly available weather data for the two measurement areas (Boulevard and Ocotillo) on its website (wunderground.com). Among other things, this data includes wind speed, wind direction, temperature, and pressure. Weather Underground reports that it measures the meteorological conditions for Boulevard and Ocotillo at respective elevations of 4,113 feet and 694 feet above sea level. The relevant Weather Underground weather data for the Boulevard and Ocotillo areas is provided in Appendix B and summarized below.

Meteorological Data for the Kumeyaay Wind-Area Noise Measurements

We obtained noise measurements in the vicinity of the Kumeyaay Wind turbines on two different days. We took measurements on April 28, 2013, in the mid-afternoon to early evening. On April 30, we took measurements from mid-morning to mid-afternoon.

April 28, 2013

The Weather Underground data for this date show wind from the northwest in the morning, shifting to the west in the afternoon when the noise recordings were made. Average wind speeds between 1pm and 7pm were approximately 15 mph, with some gusts reaching 25 mph.

April 29, 2013

The Weather Underground data for this date show that wind speeds were considerably lower than on April 28, typically averaging between 5 and 8 mph, with some gusts reaching 10 mph. The wind direction between 9 am and 10 am, when the lone Kumeyaay Wind-area noise recording on this date was made, was from west south west.

April 30, 2013

The Weather Underground data for this date show that the wind direction in the morning was from the west, with average wind speeds that were 5 mph or less during the second recording at Mr. Elliott's residence. In the afternoon, during recordings at the Oppenheimer, Morgan and Tisdale residences, the wind was from the southwest, with average wind speeds between 10 and 17 mph and gusts up to 25 mph.

Meteorological Data for the Ocotillo Wind-Area Noise Measurements

We took noise measurements only on April 29, 2013, for the Ocotillo Wind Energy Facility. We took measurements from mid-morning to mid-afternoon, and then again from early evening to late evening.

April 29, 2013

The Weather Underground data for this date show that between 11am and 2 pm the wind direction was from the southwest with average wind speeds between 10 and 15 mph, with gusts from 15 to 20 mph. In the evening, the wind was also from the southwest, but was much stronger, with average wind speeds between 15 and 25 mph and gusts up to 35 mph.

METHOD OF ANALYSIS OF RECORDED DATA

We analyzed the 20 minute (nominal) recordings in the WIA laboratory with a Larson Davis type-2900 2-channel FFT analyzer. We first viewed each recorded sample in digital strip chart format to visually locate periods of lower local wind gusts to minimize low-frequency wind pressure transient effects on the data. We set the FFT analyzer for 40-Hz bandwidth, with 400-line and 0.1-Hz resolution. We used linear averaging. A Hanning window was used during a one- to two-minute, low-wind period to obtain an "energy average" with maximum sampling overlap. We stored the results for each sample, including autospectra, coherence, and coherent output power for both channels of data at the residential locations (i.e., indoors and outdoors). We also obtained autospectra for the reference locations.

Autospectra and Coherent Output Power

One of the strengths of our indoor-outdoor sampling design is that it made possible the use of what is called the "coherent output power" to filter out of the data the effect of the low-frequency wind pressure transients caused by local wind gusts. If two closely correlated signals are available (such as we have here, with the indoor and outdoor measurements for each residential study location), it is possible to use the coherent output power to reduce the effects of uncorrelated or weakly correlated phenomenon associated with wind gusts.

Coherent output power is based on use of the coherence between two signals to weight the spectra of one of the signals based on coherent frequency components common to the two simultaneously recorded signals. Where, as here, the wind turbine-generated noise remains at fairly consistent frequencies over the recording periods, the effects on the recorded signal of the essentially random, non-oscillatory pressure fluctuations caused by wind gusts should be reduced using this analysis procedure. The result is sometimes referred to as the coherent output spectrum.[19] For an example of previous studies that have used coherent output power to obtain wind turbine noise spectra, see Kelley, et al. (1985).[20]

In discussing coherent output power we use standard signal processing terminology. Obviously, all of the terms are functions of frequency.

For two signals (signal 1 and signal 2), the coherent output power for signal 2 (i.e., G_2) is defined as:

$$G_2 = {\gamma_{12}}^2 G_{22}\ .$$

The term ${\gamma_{12}}^2$ is the coherence (also referred to as spectral coherence) between the two signals and the term $G_{22}$is the autospectral density of the second signal. The value of the coherence lies in the range of $0 \leq {\gamma_{12}}^2 \leq 1$. A value of ${\gamma_{12}}^2 = 1$ indicates there is a one-to-one correlation between the two signals, which could only occur within an ideal system. In practice, ${\gamma_{12}}^2$ will generally be less than 1.

The coherence is defined as:

$${\gamma_{12}}^2 = \frac{|G_{12}|^2}{G_{11} G_{22}}$$

The term autospectral density used here has the same meaning as sound pressure level spectrum, the units of which are dB (re: 20 µPa). The term G_{11} is the autospectral density of the first signal.

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[19] Bendat, J. and A. Piersol, Random Data – Analysis and Measurement Procedures, 2nd Edition, John Wiley & Sons, 1986.

[20] Kelley, N.D., et al., Acoustic Noise Associated with the MOD-1 Wind Turbine: Its Source, Impact and Control, SERI/TR-635-1166 report prepared for U.S. Department of Energy, Solar Energy Research Institute, February 1985.

The term G_{12} is the cross-spectral density between the two signals, and the term $|G_{12}|^2$ is the square of the magnitude of the cross-spectral density.

For two recorded signals, it is possible to determine the coherence of the first with respect to the second (γ_{12}) and switch the two and determine the coherence of the second with respect to the first (γ_{21}). Consequently it is possible to obtain an inside coherent output power spectrum and an outdoor coherent output power spectrum. The measurement data presented herein indicate when the data are the autospectra, and when they are determined from the coherent output power. Where coherence data are presented, it is the coherence of the indoor signal with respect to that of the outdoor signal.

Sound Level Corrections Due to Use of Ground Board

Placing an outdoor microphone on a ground board, as was done in this study, results in higher sound pressure levels (up to 3 dB greater) for frequencies in the range of 50 to 20,000 Hz when compared to those measured at 4.5 to 5.5 feet above the ground, a standard height used to make environmental noise measurements as indicated in ANSI S12.9-2013/Part 3. Consequently corrections to the sound level data at frequencies greater than 50 Hz obtained using a ground board would be required.

However, for frequencies less than 50 Hz, the sound pressure level at the ground surface is essentially the same as that at a height of 5 feet. This is because a microphone on a tripod 5 feet above the ground is at a height less than one-fourth the wavelength of the sound at this frequency (i.e., $0.25\ \times \lambda_{50\,Hz} = 0.25 \times \frac{1{,}100}{50} =\ 5.5\,feet$) and there is little difference at frequencies less than 50 Hz between the sound field at ground level and the sound field at 5 feet above the ground. This fact has been confirmed by other measurements[21].

Because the data presented herein are in the ILFN range with frequencies less than 40 Hz, no corrections to the sound level data are necessary, even though the measurements were made with a ground board.

NOISE MEASUREMENT RESULTS

Noise Data for Kumeyaay Wind

The noise spectra data from the Kumeyaay Wind-area measurements are provided in Appendix C. The turbine blade passage frequencies – in the range of 0.7 to 0.9 Hz (see Table 5) – and their harmonics up to 5 Hz are evident in the sound spectra from both recording days. Indeed, they align almost exactly with the predominant spectral peaks. This is a very strong indication that the wind turbines produced the ILFN at those frequencies.

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[21] Hansen, K., Z. Branko, C. Hansen, Evaluation of Secondary Windshield Designs for Outdoor Measurements of Low Frequency Noise and Infrasound, 5th International Conference on Wind Turbine Noise, Denver, 28-30 August 2013.

Data for Live Oak Springs Resort, Cabin #2 (K-LOSR)

It is instructive to first examine the spectra obtained at the Live Oak Springs Resort where there was virtually no local wind during the recording even though there was wind at the turbines as determined from observing the closest turbine rotating at the time. Live Oak Springs Resort is somewhat sheltered from wind, but has a direct line of sight to the closest wind turbine at a distance of 5,950 feet.

Looking at Figure C-1, it is evident in the autospectra for both indoor and outdoor measurements that the discrete frequencies predominating in the infrasound range correspond to the blade passage frequency of the nearest wind turbine (0.8 Hz) and its first five harmonics (1.6, 2.4, 3.2, 4.1 and 4.9 Hz). A blade passage frequency of 0.8 Hz corresponds to a rotational speed of 16 rpm. We note that the indoor levels at these frequencies are slightly higher than the outdoor levels, an indication of possible amplification associated with the building structure.

Figure C-2 presents the two coherent output power spectra and the coherence of the indoor to outdoor signals. At the blade passage frequency (0.8 Hz) and in the range of 1.6 to 5 Hz (including the first five blade passage frequency harmonics of 1.6, 2.4, 3.2, 4.1 and 4.9 Hz), the coherence is 0.75 or greater, indicating a strong correlation between indoor and outdoor sound levels.

A high coherence indicates that two signals are strongly correlated and contain the same frequency content. This is exactly what one would expect from a large rotating mechanical device such as a wind turbine that produces a steady, tonal (periodic) sound, whereas the effects of wind are very random in particular concerning signals from two different microphones, one of which is indoors. Hence, the correlation of the wind effects in the indoor and outdoor signals should be weak for the random effects of the wind. Thus there will be a low coherence associated with the wind and its effects on the two different signals. Averaging the total microphone signal over time and weighting the result by the coherence results in a diminished contribution from the wind, because of the low coherence of the wind effects.

Figure C-3 compares the autospectrum with the coherent output spectrum for the indoors measurement at Live Oak Springs Resort. It shows a very close match over the frequency range of 0.8 to 5 Hz at the discrete frequencies associated with the wind turbine ILFN.

Inside the guest cabin at Live Oak Springs Resort, sound pressure levels in the infrasound range measured between 45 and 49 dB. The outside sound pressure levels were somewhat lower in the ILFN range, seeming to indicate an amplification occurring from outside to inside, which became even more pronounced in the range of 5 to 8 Hz. There is also a strong peak at 26.4 Hz, which may be caused by an "amplitude modulation" similar to that identified in the Falmouth wind turbine study[22]. The coherence at this frequency is 0.95. Amplitude modulation occurs when a low frequency signal causes the level of a higher frequency signal to fluctuate. This fluctuation occurs at the frequency of the lower frequency signal. This has been the subject of many complaints concerning wind turbine noise[23] [24].

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[22] Ambrose, S. and R. Rand, The Bruce McPherson Infrasound and Low Frequency Noise Study, 14 December 2011.

[23] Gabriel, J., S. Vogl, T. Neumann, Amplitude Modulation and Complaints about Wind Turbine Noise, 5th International Conference on Wind Turbine Noise, Denver, 28-30 August 2013.

The ILFN levels at Live Oak Springs Resort's guest Cabin #2 would have been even greater if the cabin were closer to the nearest Kumeyaay Wind turbine than it is – 1.1 miles, or 5,950 feet. The ILFN levels would have also been greater under different wind conditions. According to the Weather Underground report for Boulevard, at the time we measured the noise at the guest cabin – starting at 10:10 pm on April 28 – the wind was blowing from the west with an average speed of approximately 7 mph and gusts up to 12 mph, which is at the lower end of the operating conditions for the Gamesa wind turbines. Because the closest wind turbine is north-northeast of the cabin, the cabin was crosswind and somewhat upwind of the turbine and thus receiving lower levels of turbine-generated noise than locations downwind of the turbines.

Data for Dave Elliott's Residence

Like the Live Oak Springs Resort guest cabin measurements, the April 30 (11 am) measurements at Dave Elliott's residence show pronounced peaks in the autospectra at frequencies corresponding to the blade passage frequency of the nearest wind turbine (0.78 Hz) and the first five harmonics. The inside level at 0.78 Hz was 54 dB. In this case, as displayed in Figure C-4, the sound levels were slightly higher inside than outside at 1.6 and 2.4 Hz. Above 3 Hz the inside levels were lower than outside. The maximum inside sound level of 59 dB occurred at 1.6 Hz (the first harmonic of the blade passage frequency).

Data for Ginger Thompson's Residence

As shown in the autospectrum in Figure C-5, the April 28 (6:50 pm) measurements at Ginger Thompson's residence demonstrate a similar discrete frequency pattern between 0 and 5.2 Hz that corresponds to the blade passage frequency of the nearest turbine (0.80 Hz) and the first three associated harmonics (1.6, 2.4, and 3.2 Hz), which corresponds to a rotational speed of 16.0 rpm. The lowest frequency peak in the spectrum occurs somewhat lower (i.e., at 0.78 Hz) than the blade passage frequency; a phenomenon seen in some of the other measurement data.

As also seen at Mr. Elliott's residence and at most other study sites, the measured ILFN levels at Ms. Thompson's residence were amplified indoors, with the inside levels higher than outside levels throughout the frequency range. The maximum inside sound level of 60 dB occurred at just below the blade passage frequency of 0.80 Hz.

Data for Rowena Elliott's Residence

In the April 28 (5:30 pm) measurement data from Rowena Elliott's residence, shown in Figure C-6, the autospectra peaks corresponding to WT infrasound from Kumeyaay protrude above the general wind noise spectrum. The inside coherent output power spectrum is also plotted in Figure C-6 with most of the same peaks that appear in the autospectrum. Also present in the spectrum is a peak at 1.0 Hz, which does not correspond to any of the harmonics of the BPF observed in Kumeyaay at that time. We suspect that this infrasound is coming from the wind turbines at Ocotillo Wind, which are 15 to 20 miles away. This peak would correspond to a BPF

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[24] Stigwood, M., S. Large, D. Stigwood, Audible Amplitude Modulation – Results of Field Measurements and Investigations Compared to Psycho-acoustical Assessment and Theoretical Research, 5th International Conference on Wind Turbine Noise, Denver, 28-30 August 2013.

of 0.5 Hz, which would be consistent with the somewhat slower rotational speeds for the WTs in Ocotillo. Detecting WT infrasound from 15 to 20 miles away is not surprising. Metelka[25] for example has measured WT infrasound at a distance of 77 miles from its source. The maximum inside sound level of 53 dB occurred at 1.6 Hz, the first harmonic of the Kumeyaay BPF (0.8 Hz).

Data for Kenny Oppenheimer's Residence

As with the data for the previously discussed measurement locations, the April 30 (3:11 pm) measurement data for Kenny Oppenheimer's residence, shown in Figure C- 7, reveal sound pressure level peaks at the blade passage frequency of the nearest wind turbine (0.9 Hz) and its first three harmonics (1.8, 2.7 and 3.6 Hz). There is also a strong peak both indoors and outdoors at 13.6 Hz whose source, in contrast to the wind turbine-generated ILFN peaks at the blade passage frequency and its first three harmonics, we have been unable to identify. In this case, however, the outside sound levels were much greater than those inside the residence. The highest outside sound level was 57 dB and occurred at the blade passage frequency of 0.9 Hz. By contrast, the highest indoor sound level in the coherent output power spectrum was 44 dB, also at 0.9 Hz.

We have estimated the WT infrasound inside at 0.9 Hz to be approximately 51 dB using the coherent output power spectrum level and correcting for the coherence at that frequency. This seems to indicate that the residence is attenuating the wind turbine infrasound more substantially than at some of the other residences investigated, which could be due to a much more tightly sealed building envelope and/or a more substantial exterior wall construction. This effect was also evident in the data for one of the Ocotillo residences.

As a result of this disparity, the coherence of the indoor and outdoor ILFN signals is not as great as with closer measurement locations, including the Live Oak Springs Resort guest cabin and the residences of Mr. Elliott, Ms. Thompson and Ms. Elliott. Nonetheless, the coherence of the two signals at the blade passage frequency and its first three harmonics is still relatively strong, at 0.5 or greater. This evinces a definite correlation between outdoor and indoor sound levels even at great distance from the wind turbine noise source. Also evident in the data is a peak at 13.7 Hz. The may be caused by amplitude modulation.

Data from Marie Morgan's Residence

The April 30 (4:20 pm) measurement data from Marie Morgan's residence, including the inside and outside coherent output power spectra, are shown in Figure C-8. Like the data measured at the residences of Mr. Elliott, and Ms. Thompson, the data at Ms. Morgan's residence show higher levels of ILFN indoors than outdoors.

And like the data measured at Ms. Elliott's residences, there appear to be multiple – in this case three – different BPFs in the data. The lowest BPF, similar to the data measured at Ms. Elliott's residence, appears to be infrasound coming from Ocotillo Wind (i.e., BPF1 of 0.39 Hz). Above that frequency there are two BPF which are associated with Kumeyaay WTs. Note that not all

[25] Metelka, A., Narrowband low frequency pressure and vibration inside homes in the proximity to wind farms, presentation at the 166th Meeting: Acoustical Society of America, San Francisco, 4 December 2013.

Kumeyaay WTs could be observed, and it is possible that some could be operating at a speed of 14 rpm and others at a speed of 18 rpm. The two BPF are at 0.68 Hz (BPF2) and 0.88 Hz (BPF3). A peak indoor level of 58 dB at the first harmonic of BPF 3 (1.7 Hz) was measured

In any event, the Morgan residence data demonstrate that under the right weather and topographical conditions, large wind turbines like those used at Kumeyaay Wind can produce high levels of ILFN inside buildings even miles away.

Data from Don Bonfiglio's Residence

As with the other Kumeyaay Wind-area study sites, the measurement data for Don Bonfiglio's residence, shown in Figure C- 9, display sound level peaks at the blade passage frequency of the nearest wind turbine (0.61 Hz) and the first three associated harmonics (1.2, 1.8 and 2.4 Hz). The sound levels, both indoors and outdoors, at these frequencies are in the range of 30 to 42 dB. The maximum inside level is 42 dB at 1.2 Hz (the frequency of the first harmonic of the blade passage frequency – BPF2).

While the coherence between the indoor and outdoor measurements is less than 0.5 at the blade passage frequency and associated harmonics, it is not surprising given the distance to the nearest wind turbine (2.9 miles, which is a greater distance than at any other Kumeyaay Wind-area study site except the Tisdale residence). Propagation effects (e.g., intervening terrain, atmospheric conditions) and interactions between infrasound from different wind turbines result in a more complex sound field at infrasound frequency as the distance increases. The wavelength of sound at 1 Hz is approximately 1,100 feet. At 2.9 miles the site is approximately 14 wavelengths from the sources of infrasound. Hence it is normal to witness declining coherence with increased distance due to this complexity. Also evident in the spectral data is a BPF peak at 0.39 Hz, which is most likely infrasound from Ocotillo Wind. There is also a harmonic at 0.78 Hz associated with the BPF.

Data from Donna Tisdale's Residence

The farthest (from a Kumeyaay Wind turbine) measurements we took were at the residence of Donna Tisdale, which is 5.7 miles from the nearest wind turbine. Yet even at that great distance, the data show as indicated in Figure C-10 peaks at the blade passage frequency (BPF2) of the nearest turbine (0.7 Hz) at Kumeyaay and its associated harmonics, albeit at lower sound pressure levels than observed at the closer study sites. The maximum measured indoor ILFN sound level was 43 dB at 0.7 Hz (the blade passage frequency). There is also a lower BPF at 0.39 Hz, which is most likely infrasound from Ocotillo Wind.

As similarly observed at the Bonfiglio residence, the coherence between the indoor and outdoor measurements at the Tisdale residence is mostly less than 0.5 for frequencies below 10 Hz. As indicated above, given the distance from the Tisdale residence to the nearest wind turbine (5.6 miles), this is not surprising. The Tisdale ranch is approximately 27 wavelengths from the wind turbines. The turbines are not visible from the ranch, because of intervening terrain. However the turbines are visible from some higher elevations of the ranch property.

Data from the Reference Sites

In contrast to the data for the Kumeyaay Wind-area residential measurement sites, the frequency and sound level data we present in the autospectra in Figures C-11 and C-12 for the two reference locations shows the autospectra values rather than the coherent output power. Because there was no option for making indoor sound measurements near the reference locations, we only used a single microphone to take measurements and thus did not measure a coherence or coherent output power. At both reference locations (K-R1 and K-R2), the data show clear sound level peaks at the blade passage frequency of the nearest turbine and the associated harmonics in the 0 to 5 Hz range. At K-R1, the sound levels of the peaks ranged from 53 dB to 60 dB (at the blade passage frequency, 0.84 Hz). At K-R2, which at 930 feet away was the measurement site closest to the Kumeyaay Wind turbines, the sound levels were even greater, between 60 dB and 70 dB for the spectral peaks below 3 Hz.

Tabulated Data

Table 6 lists the Kumeyaay Wind-area residential measurement locations, along with their distance from the nearest wind turbine, the highest measured indoor sound pressure levels, and the frequency of those peak sound pressure levels.

Table 6 Summary of Wind Turbine Noise for Kumeyaay Inside Residences

Residence	**Distance[1]**	**Highest Sound Pressure Spectrum Level Indoors[2,3,4]**	**Frequency (Hz) of Peak Spectrum Level**	**Rotor Rotational Component**
D. Elliott	2,960 feet	59 dB	1.6	1st harmonic
G. Thompson	2,880 feet	60 dB	0.8	BPF
R. Elliott	4,330 feet	53 dB	1.6	1st harmonic
K-LOSR	1.1 miles	48 dB	2.4	2nd harmonic
K. Oppenheimer	1.6 miles	51 dB	0.9	BPF
M. Morgan	1.7 miles	58 dB	1.7	1st harmonic
D. Bonfiglio	2.9 miles	42 dB	1.1	1st harmonic
D. Tisdale	5.7 miles	43 dB	1.4	1st harmonic

[1] Distance from closest wind turbine

[2] Decibels (re: 20 µPa)

[3] All but Live Oak Spring Resort, D. Elliott and G. Thompson data are coherent output power levels

[4] Oppenheimer data are estimated from coherent output power and correction for coherence

We note that while the Morgan residence data appears anomalous when compared with the trend of sound pressure levels as a function of distance from the wind turbines, it is not. Instead, the Morgan residence data demonstrates that under the right weather and topographical conditions, large wind turbines like those used at Kumeyaay Wind can produce high levels of ILFN inside buildings even miles away. It appears that one factor that contributed to the higher infrasound levels at the Morgan residence is the fact that this house was located downwind of multiple turbines, whereas the other residences except for Mr. Elliott's were either upwind of the turbines and/or had a more obscured line-of-sight to the full array of turbines compared to the Morgan's.

Noise Data for Ocotillo Wind

The noise spectra for the Ocotillo Wind-area measurements are displayed in Figures C-13 through C-21 in Appendix C. Table 7, below, summarizes much of the relevant data for the residential measurements.

In contrast to the relatively consistent wind conditions in the Kumeyaay Wind area throughout the measurement periods, the wind at the Ocotillo Wind Energy Facility varied greatly across the measurement periods. During the first recordings on the morning of April 29, the wind was generally light and the turbine blades were rotating slowly (less than 10 rpm). In the afternoon, however, the wind picked up considerably and the rotational speed of the turbine blades increased (e.g. 13 rpm). And later that night, when we took our last measurements, the wind speed had increased even more, causing the turbine blades to rotate even faster (i.e., 16 rpm observed at 7:51 pm just before dark). Between the first measurements in the morning and the last measurements at night, the turbines' average blade passage frequency increased from 0.5 Hz to 0.8 Hz.

The Ocotillo recordings were analyzed several different ways using cross-correlation, longer averaging times and 1/3-octave band filtering among other methods, without significantly changing the results. For the Ocotillo data, the coherence between the indoor and outdoor signals is low (i.e., less than 0.5). This, along with the spectral data, indicates a complex sound field with more than one BPF present, rather than a classical spectrum of tonal components including just one BPF and its harmonics. Note that it was only possible to observe a handful of turbines at a time out of the 112 turbines at Ocotillo Wind. Consequently, the BPF indicated in Table 5 for the Ocotillo recordings represent the BPF of the turbine or turbines closest to the reference location measurements and not the BPF for turbines in the entire facility.[26]

One possible explanation for low coherence is that Ocotillo Wind has so many turbines spread out over such a large area (with accompanying differences in wind speed and direction at each turbine), the ILFN produced by the turbines at Ocotillo has a greater probability of being less strongly synchronized as it is at Kumeyaay, for example, where the turbines are arrayed in a line on a ridge and experience a much more uniform wind configuration (i.e., speed and direction). At Ocotillo, it is much more likely that the wind turbines rotate at different speeds from one another. Thus where a residence or other receptor is exposed to ILFN from more than one

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[26] After dark (approximately 8 pm) on 30 April 2013 it was not possible to observe the rotational speed of turbines at Ocotillo Wind. However, it was possible to deduce the rotational speed of the turbines from the measured data.

turbine, which will usually be the case with most Ocotillo-area locations, it will experience a complex sound field with varying tonal components derived not only from the different turbines directly, but also possibly from the interaction of tonal components from a multitude of turbines.

Another possible factor contributing to the lower coherence between outdoor and indoor sound levels at Ocotillo could be that the residential structures alter the frequency of the WT noise just enough as the sound energy passes through them that the sound indoors is at a slightly different frequency than the sound outdoors. Although this effect is not as apparent in the Kumeyaay data, it is possible that the distributed pattern of the Ocotillo wind turbines makes it more apparent here.

Data for the Residential Sites

As evidenced by the data in Table 7 and by comparing the coherent output power spectra from the morning and night measurements at the Pelley residence (Figures C-13 and C-14), as well as the afternoon and night measurements at the Ewing residence (Figures C-15 and C-16), the ILFN sounds pressure level increased substantially as the wind speed picked up and the blade passage frequency of the turbines increased. This indicates not only that the Ocotillo Wind turbines produced much of the measured ILFN, but that the turbines can create very high ILFN sounds levels even at substantial distance. The Tucker residence data are shown in Figures C-17 and C-18.

Looking specifically at the Pelly residence data for the daytime measurement (Figure C-14) it would appear that there are two blade passage frequencies present (0.5 and 0.6 Hz). This is not surprising considering the distribution of turbines over a large area where different turbines see different wind conditions. The spectral peaks above the blade passage frequencies are consistent with this assessment. The two blade passage frequencies indicate corresponding rotational speeds of 10 and 12 rpm.

Two distinct blade passage frequencies (0.68 and 0.88 Hz) are also evident from the nighttime measurements at the Pelley residence. These blade passage frequencies are indicative of rotation speeds of 13.6 and 17.6 rpm respectively. Although the higher rotational speed is slightly above the reported, operational speed range (6 to 16 rpm) for the Siemens turbines, there is no other source for the infrasound in this area. Note that the outdoor coherent output power spectrum is omitted for clarity in Figure C-14.

The spectra from the Ewing residence likewise indicate two different blade passage frequencies during both the day and night. In Figure C-15 we see the same frequency of the second BPF of 0.88 Hz in the daytime data, confirming that in fact this is infrasound from the Ocotillo WTs. The nighttime data at the Ewing residence as shown in Figure C-16 indicates two BPF also (0.39 and 0.49 Hz) and their associated harmonics.

The data for the Tucker residence similarly contain two BPF during the day (0.6 and 0.8 Hz) and two in the nighttime (0.39 and 0.68 Hz), with the lower BPF reflected in the data at the Ewing residence at night.

Whereas the Pelly residence data indicates an amplification of sound level between inside and outside, the data for other two residences indicate the opposite. Apparently the Ewing residence is more tightly sealed. It also seemed to be of a more substantial construction. The Tucker residence data also shows a reduction from outside to inside. An explanation for this effect could be the shielding provided by neighboring structures, which are more closely spaced than at the Pelly residence. The Tucker residence may also be more tightly sealed.

That the Ocotillo Wind turbines generated much of the ILFN measured at the Pelley and Ewing residences is strongly supported by the fact that the recorded data for both residences show sound level peaks at the turbine blade passage frequencies and many of the associated harmonics. The reference location measurement data also demonstrate this pattern, although not as clearly.

Data for the Reference Sites

At reference location 1 for the Ocotillo Wind-area measurements (O-R1), the nighttime ILFN levels were quite high, with multiple peaks above 60 dB including at frequencies that correspond to many of the harmonics of the blade passage frequency of the nearest wind turbine. The overall peak sound level of 74 dB occurred at the blade passage frequency (0.8 Hz). At O-R2, which at 1,470 feet away was the measurement site closest to the Ocotillo Wind turbines, the peak sound level of 78 dB was even greater, and also occurred at the blade passage frequency of 0.8 Hz. Similarly, at O-R3, which was adjacent to the Ocotillo substation, the peak sound level was 77 dB and occurred at the blade passage frequency of 0.8 Hz. These data are shown in Figures C-19 through C-21.

Tabulated Data

Table 7 lists the Ocotillo Wind-area residential measurement locations, along with their distance from the nearest wind turbine, the highest measured indoor sound pressure levels, and the frequency of those peak sound pressure levels. As expected given higher wind speeds at night, nighttime, indoor noise levels range from 15 to 27 dB higher than those measured during the day.

Table 7 Summary of Wind Turbine Noise for Ocotillo Inside Residences

Residence	**Distance[1]**	**Time of Day**	**Highest Sound Pressure Spectrum Level Indoors[2,3]**	**Frequency (Hz) of Spectrum Peak Level**	**Rotor Rotational Component**
Pelley	3,220 feet	Day	42 dB	0.6	BPF2
			49 dB	1.0	1st of BPF1
		Night	67 dB	0.68	BPF1
			69 dB	0.88	BPF2
Ewing	3,590 feet	Day	48 dB	0.59	BPF1
			51 dB	0.88	BPF2
		Night	42 dB	0.39	BPF1

			59 dB	0.78	1st of BPF2
Tucker	1.2 miles	Day	42 dB	0.6	BPF1
			48 dB	0.8	BPF2
		Night	66 dB	0.68	BPF2
			69 dB	1.37	1st of BPF2

[1] Distance from closest wind turbine

[2] Decibels (re: 20 μPa)

[3] All are coherent output power spectrum levels

DISCUSSION OF RESULTS

It is clear from the measured noise data obtained from Kumeyaay and Ocotillo facilities that there is significant wind turbine-generated ILFN. This was to be expected as it has been documented by others such as in the McPherson noise study, the Shirley Wind Turbine study, and by Epsilon Associates.[27] And indeed the measured ILFN levels near Kumeyaay and Ocotillo wind turbine facilities are similar to those measured in previous studies after accounting for the proximity of the measurements to a wind turbine and the total number of the wind turbines in the facility.

Both the McPherson and Shirley wind turbine noise studies were conducted to investigate whether and at what levels the subject wind turbines (the turbines in Falmouth, Massachusetts, and those in the Shirley Wind Project in Brown County, Wisconsin) produce ILFN, and whether that ILFN was contributing to the significant health and other impacts reported by nearby residences. In some cases, the impacts were so severe that residents abandoned their homes. Both studies found high levels of wind turbine-generated ILFN at numerous nearby residences that correlated with residents' reported impacts.

Human health impacts from wind turbines had been reported previously in several countries with large wind facilities in proximity to residences. But these impacts were often attributed to certain individuals' aversion to the presence of a large industrial facility constructed in what was previously a quiet rural setting. Scientific understanding has developed significantly since then.

Recent research and investigations into human response to ILFN have been conducted and seem to provide strong evidence of a cause and effect relationship. In particular the work of Salt, et al.[28] has made a clear case for perception of ILFN below the threshold of hearing as defined by ISO 389-7 which is related to the response of the ear's inner hair cells (IHC). Salt has demonstrated that it is possible for the ears' outer hair cells (OHC) to respond to ILFN at sound

[27] Epsilon Associates, A Study of Low Frequency and Infrasound from Wind Turbines, July 2009.

[28] Alec Salt, and J. Lichtenhan, Perception based protection from low-frequency sounds may not be enough, Internoise 2012, August 2012.

pressure levels that are much lower than the IHC threshold. Salt has reported that ILFN levels (levels commonly generated by wind turbines nearby residences) can cause physiologic changes in the ear.[29] Salt and Kaltenbach "estimated that sound levels of 60 dBG will stimulate the OHC of the human ear."[30]

Furthermore, Matsumoto et al.[31] have demonstrated in a laboratory setting that humans can perceive ILFN at sound pressure levels below the IHC threshold when the noise is a complex spectrum (i.e. contains multiple frequency components). From this laboratory research it was clearly demonstrated that humans can perceive sound pressure levels that are from 10 to 45 decibels (dB) less than the OHC threshold in the ILFN range. In fact, the Matsumoto thresholds clearly follow the OHC threshold down to the frequency below which the two diverge. The Matsumoto thresholds are lower than the OHC thresholds at frequencies below the point at which they diverge.

These studies and more recent studies demonstrate that wind turbines (specifically wind turbine-generated ILFN) have the potential to not only annoy humans, but harm them physiologically.

The data presented herein represent the conditions of measurement during the study and do not necessarily represent maximum noise conditions produced by the Kumeyaay and Ocotillo facilities. Higher wind speeds generally produce higher noise levels in particular higher ILFN. This is clearly demonstrated in the Ocotillo data when comparing the daytime and nighttime levels.

NOISE METRICS FOR MEASURING ILFN

There are several noise metrics which are used to quantify environmental noise levels. The most common metric is A-weighting (A-wt). The A-wt curve is shown in Figure 6. The A-wt metric is intended to approximate the loudness sensitive of the human ear for common environmental sounds in the range of 20 to 20,000 Hz. A-wt at 1 Hz is -149 dB. Hence a noise limit based on A-wt would not be appropriate to address ILFN, a major component of which is sound below 20 Hz.

A noise metric sometimes used when there is low frequency noise is the C-weighting (C-wt). While the C-wt metric does attempt to address low frequency noise better than A-wt, it would also not be appropriate for quantifying infrasound, since it still strongly de-emphasizes sound at frequencies below 20 Hz as shown in Figure 6. C-wt at 1 Hz is -52.5 dB.

One noise metric recently used to quantify ILFN is G-weighting (G-wt). The G-wt measure has been used in Europe. G-wt would certainly be a more representative measure of ILFN than

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[29] Alec Salt, and J.A. Kaltenbach, "Infrasound from Wind Turbines Could Affect Humans," Bulletin of Science, Technology and Society, 31(4), pp.296-302, September 12, 2011.

[30] Ibid., p. 300, "As discussed below, G-weighting (with values expressed in dBG) is one metric that is used to quantify environmental noise levels. While it is a more accurate measure of ILFN than most other metrics, G-weighting still de-emphasizes infrasound."

[31] Yasunao Matsumoto, et al, An investigation of the perception thresholds of band-limited low frequency noises; influence of bandwith, published in The Effects of Low-Frequency Noise and Vibration on People, Multi-Science Publishing Co. Ltd.

either the A- wt or the C- wt metrics, but as shown in Figure 6 it too de-emphasizes the very low frequency infrasound by -40 dB at 1 Hz.

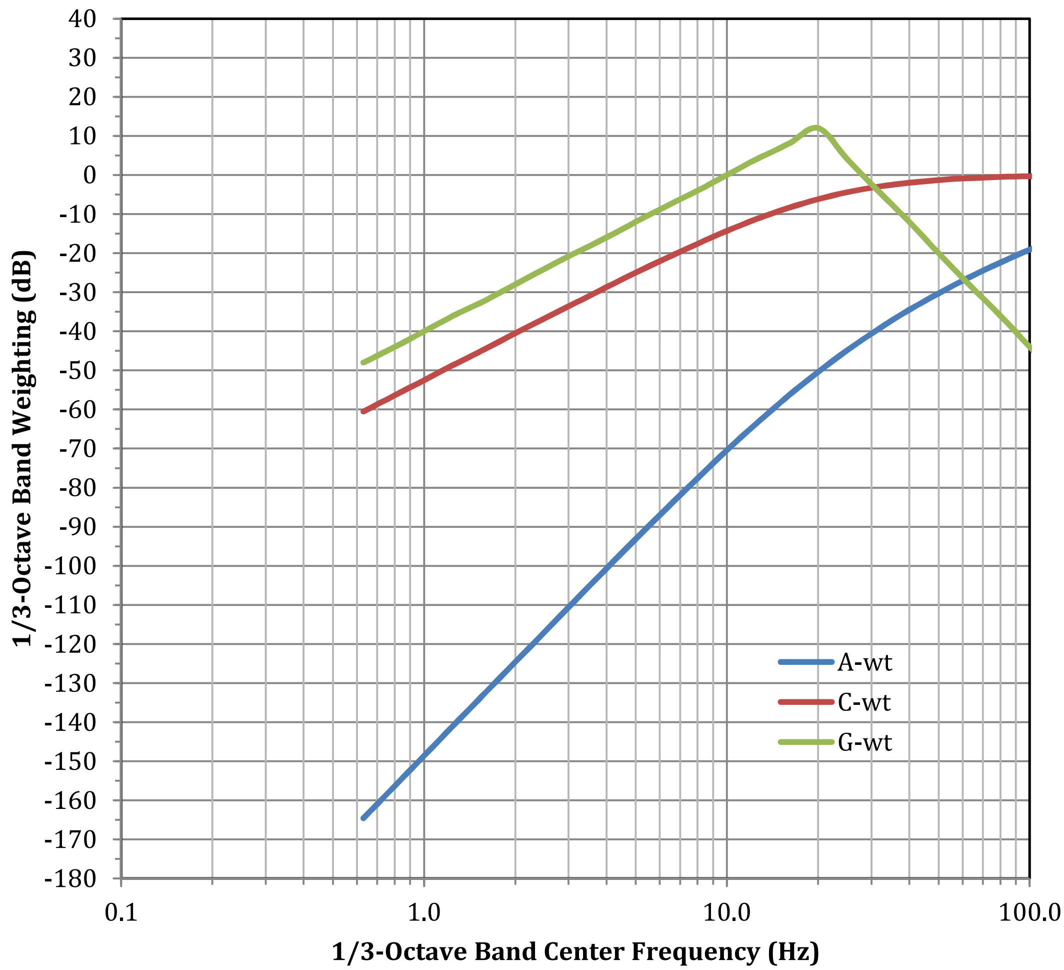


Figure 6 A, C and G Spectral Weighting Curves

CONCLUSION

The results of this study conclusively demonstrate that both the Kumeyaay and Ocotillo facilities' wind turbines generate ILFN at residential and other locations up to 15 miles away.

TERMINOLOGY

- Autospectrum: The autospectrum is the narrow band, energy average sound pressure level spectrum (in dB) measured for a specific time interval.
- Coherence: The spectral coherence is a statistic that can be used to examine the relation between two signals or data sets. It is commonly used to estimate the power transfer between input and output of a linear system. If the signals are ergodic, and the system function linear, it can be used to estimate the causality between the input and output.
- Cross-spectrum: In time series analysis, the cross-spectrum is used as part of a frequency domain analysis of the cross correlation or cross covariance between two time series.
- Cycles per second: A unit of frequency, same as hertz (Hz).
- Decibel (dB): A unit of level which denotes the ratio between two quantities that are proportional to power; the number of decibels is 10 times the logarithm (to the base 10) of this ratio. For sound, the reference sound pressure is 20 micro-Pascals.
- FFT (fast Fourier transform): An algorithm to compute the discrete Fourier transform and its inverse. A Fourier transform converts time to frequency and vice versa; an FFT rapidly computes such transformations.
- ILFN: Infrasound and low frequency noise.
- Infrasound: Sound at frequencies lower than 20 Hz.
- Low frequency noise: Noise at frequencies between 20 and 200 Hz.
- Noise level: The sound pressure energy measured in decibels.

APPENDIX A – MEASUREMENT LOCATIONS

Figure A - 1 Kumeyaay Measurement Locations

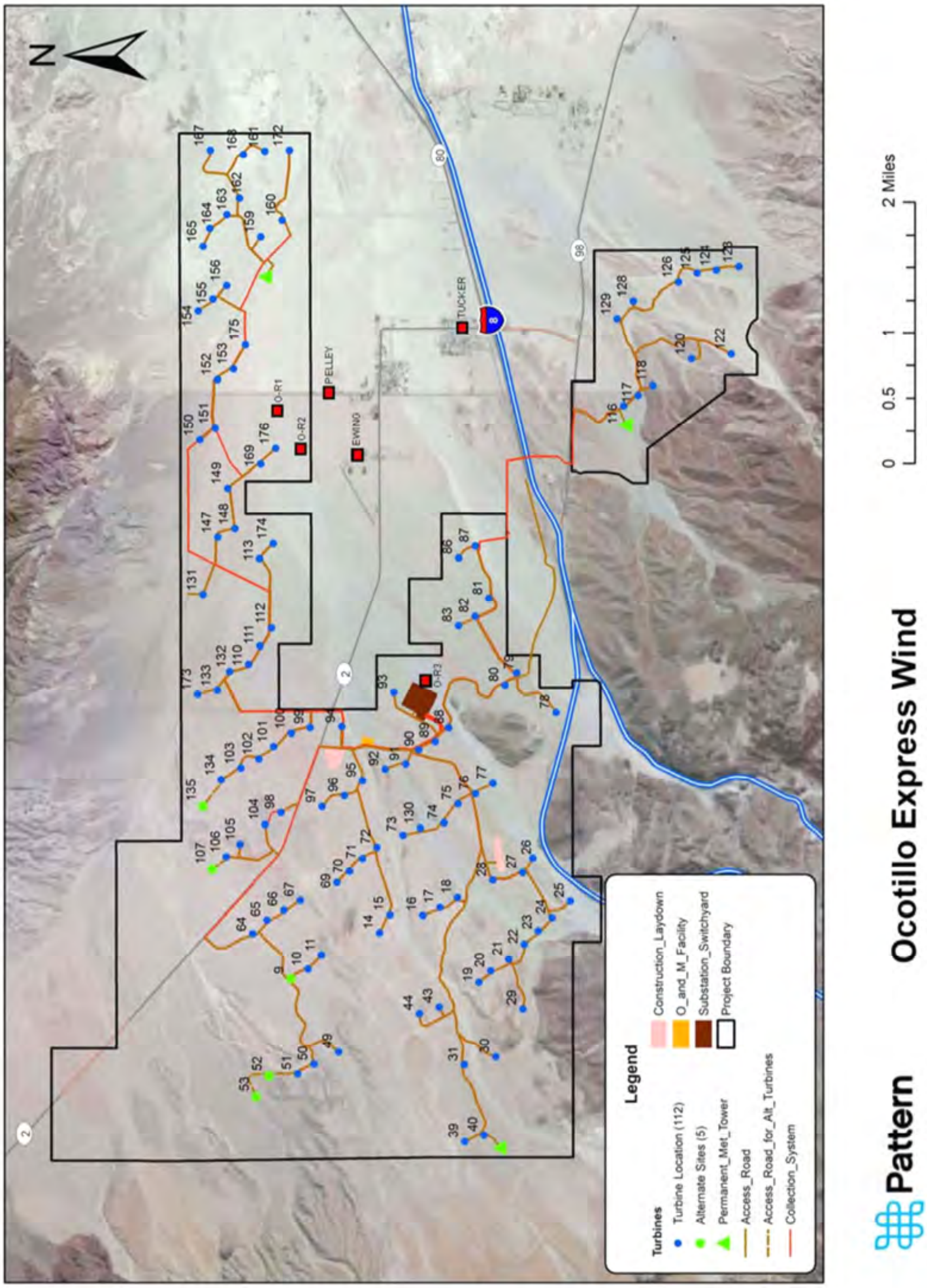


Figure A - 2 Ocotillo Measurement Locations

APPENDIX B – METEOROLOGICAL DATA

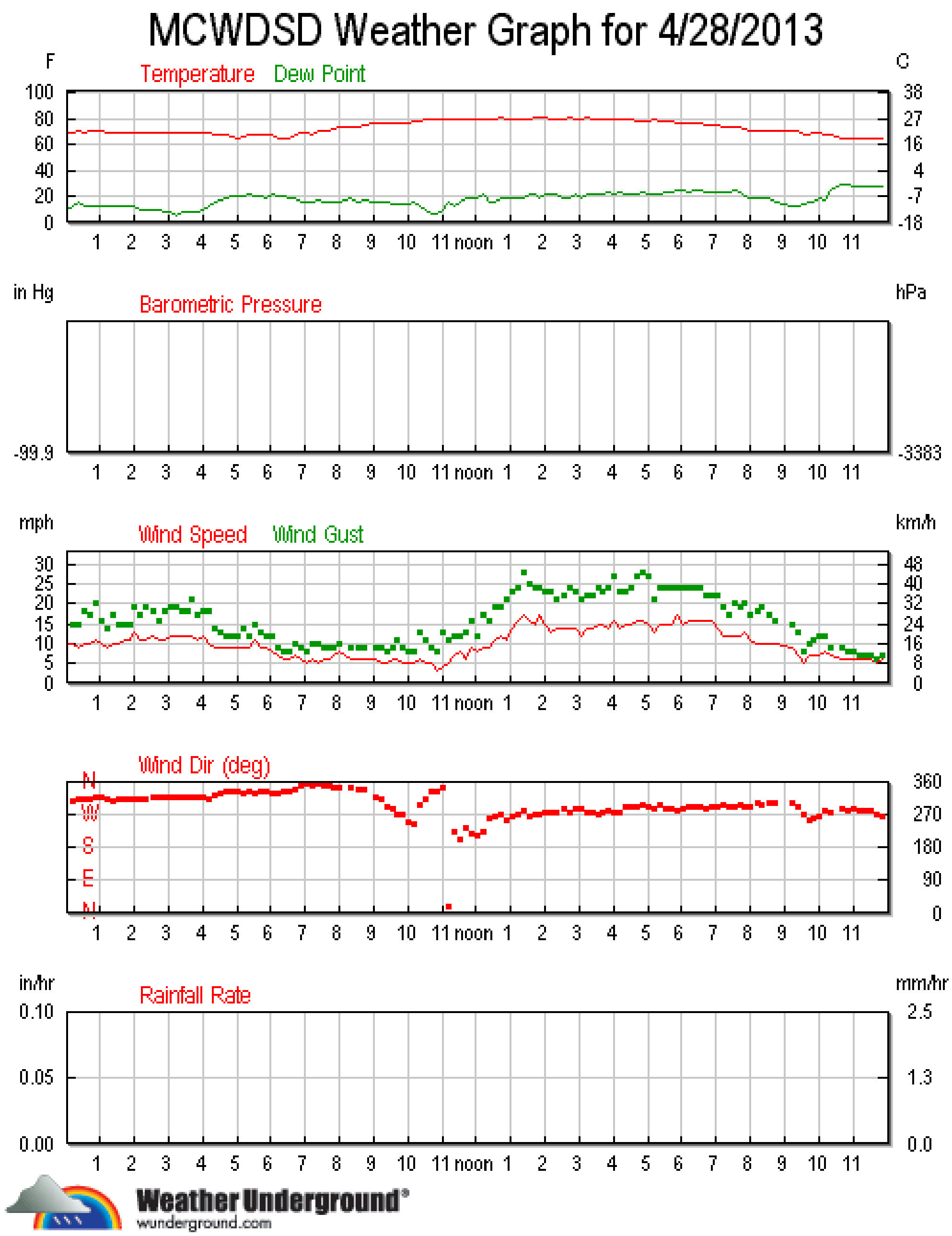


Figure B - 1 Weather Data for Kumeyaay 28 April 2013

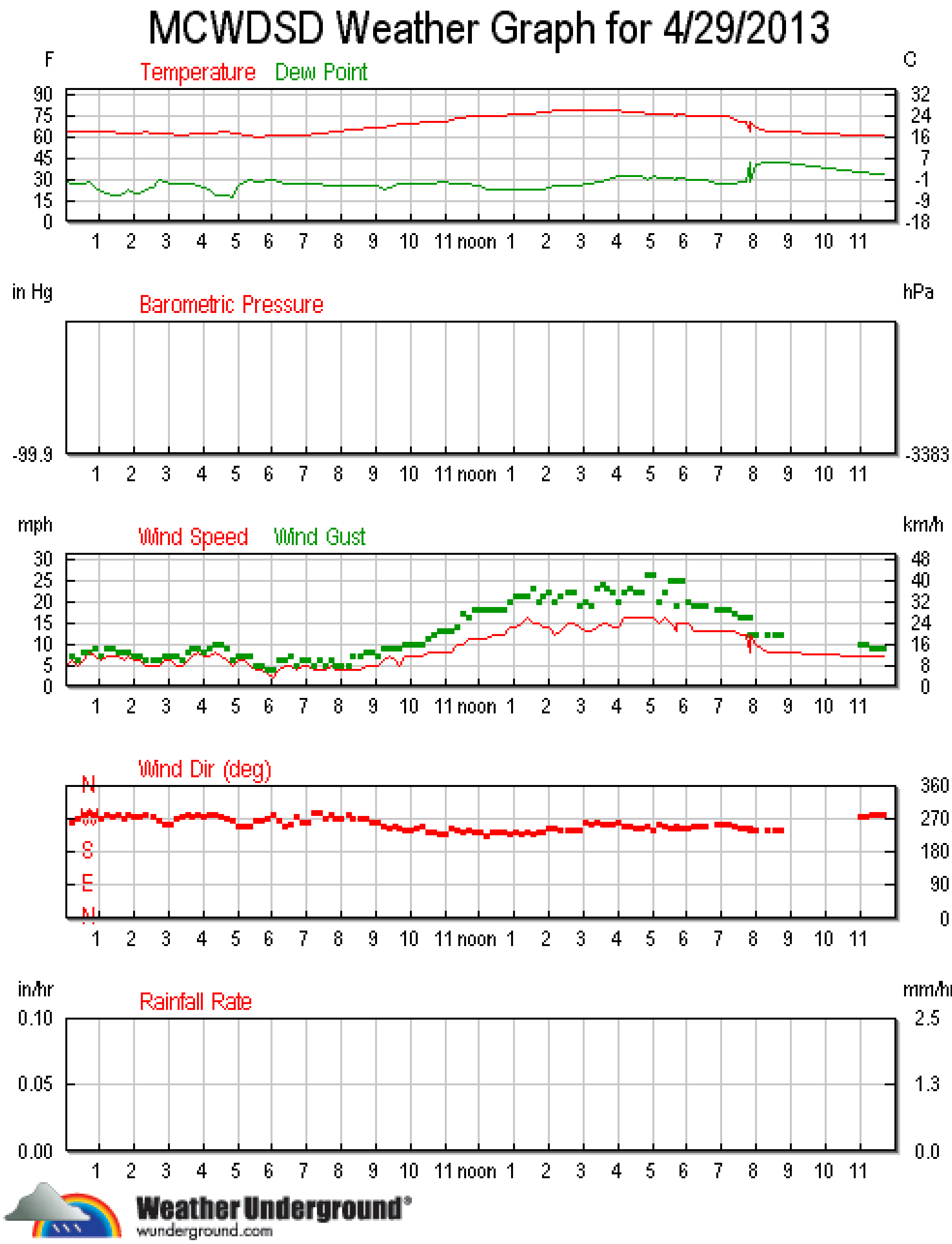


Figure B - 2 Weather Data for Kumeyaay April 29 2013

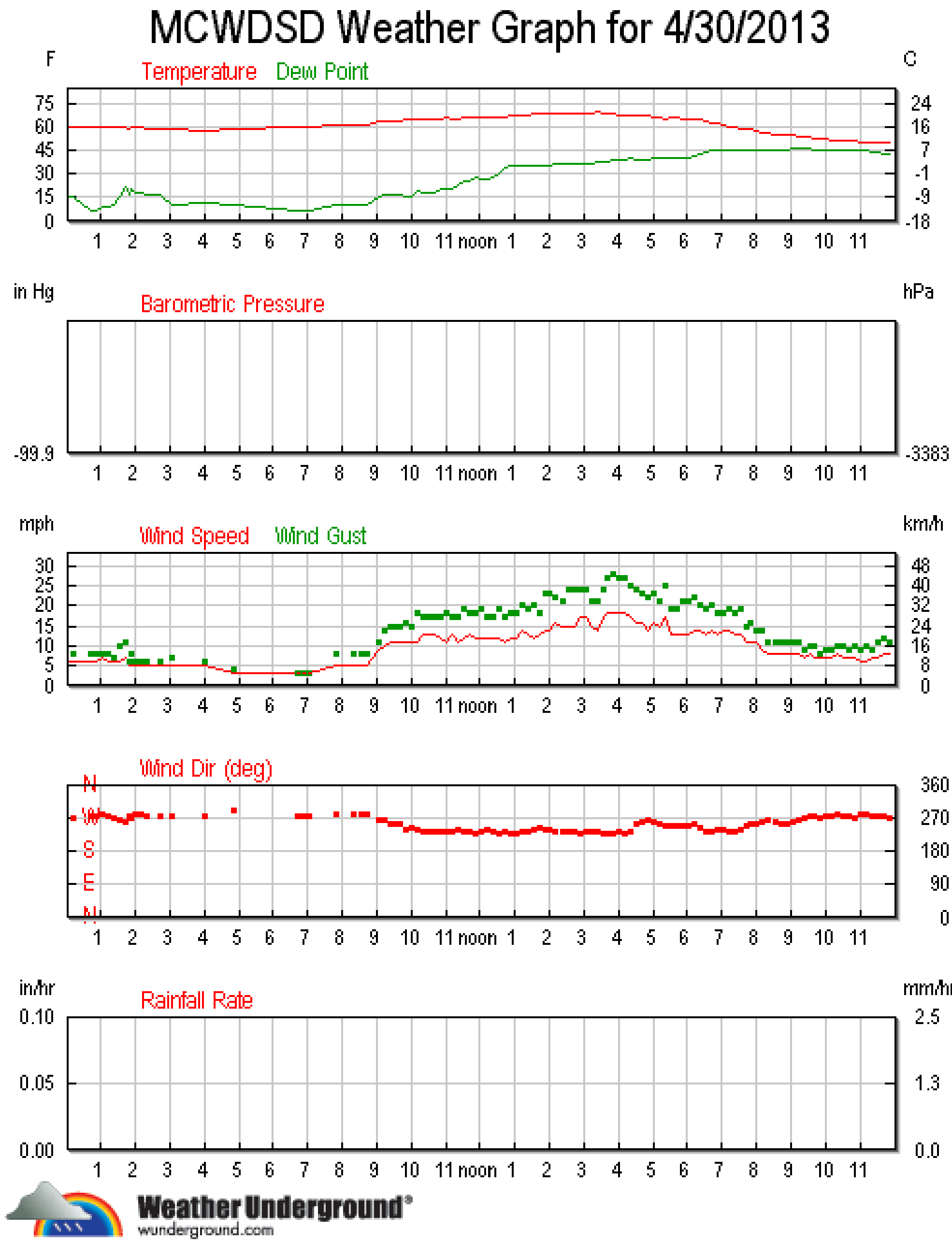


Figure B - 3 Weather Data for Kumeyaay 30 April 2013

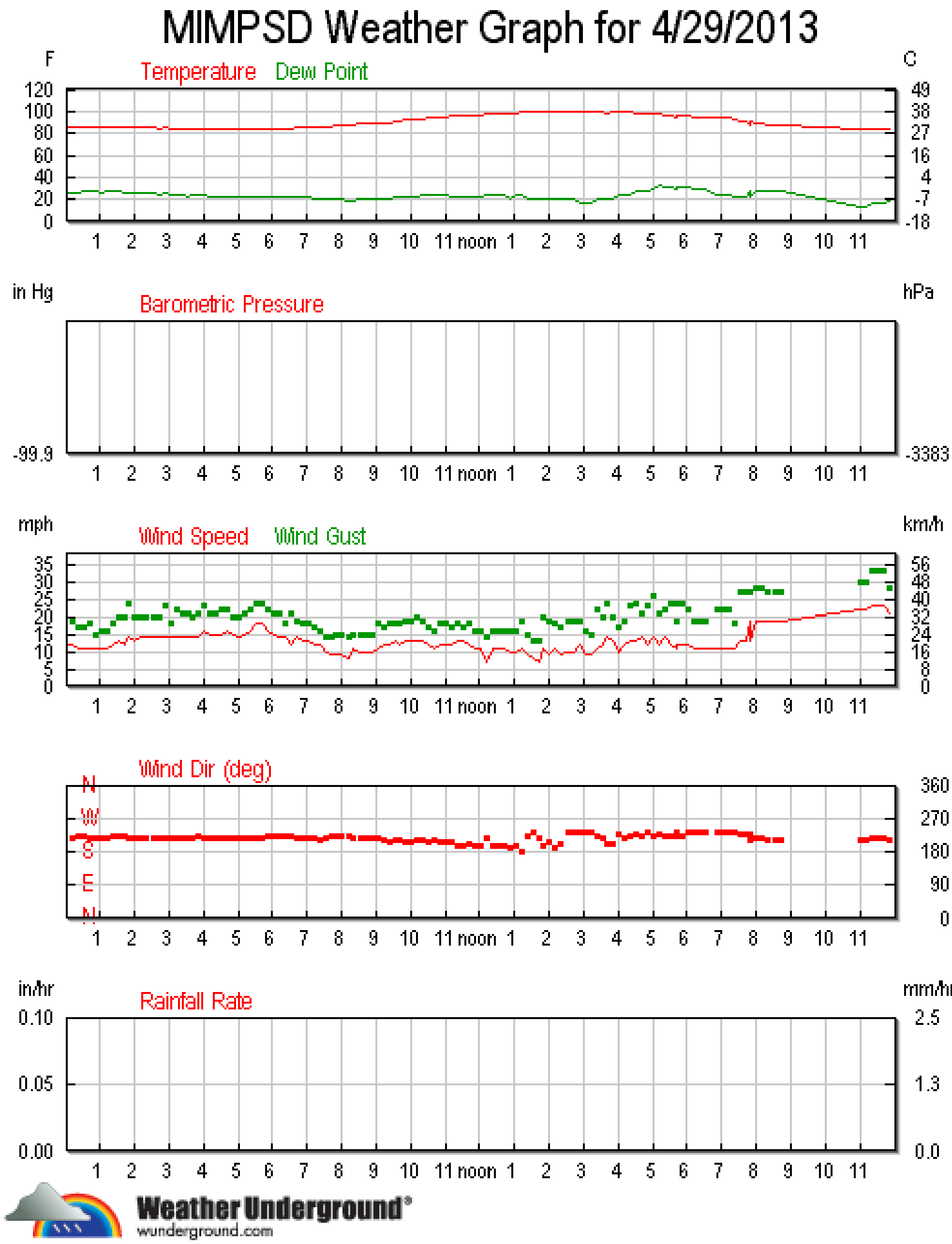


Figure B - 4 Weather Data for Ocotillo 29 April 2013

APPENDIX C – NOISE DATA

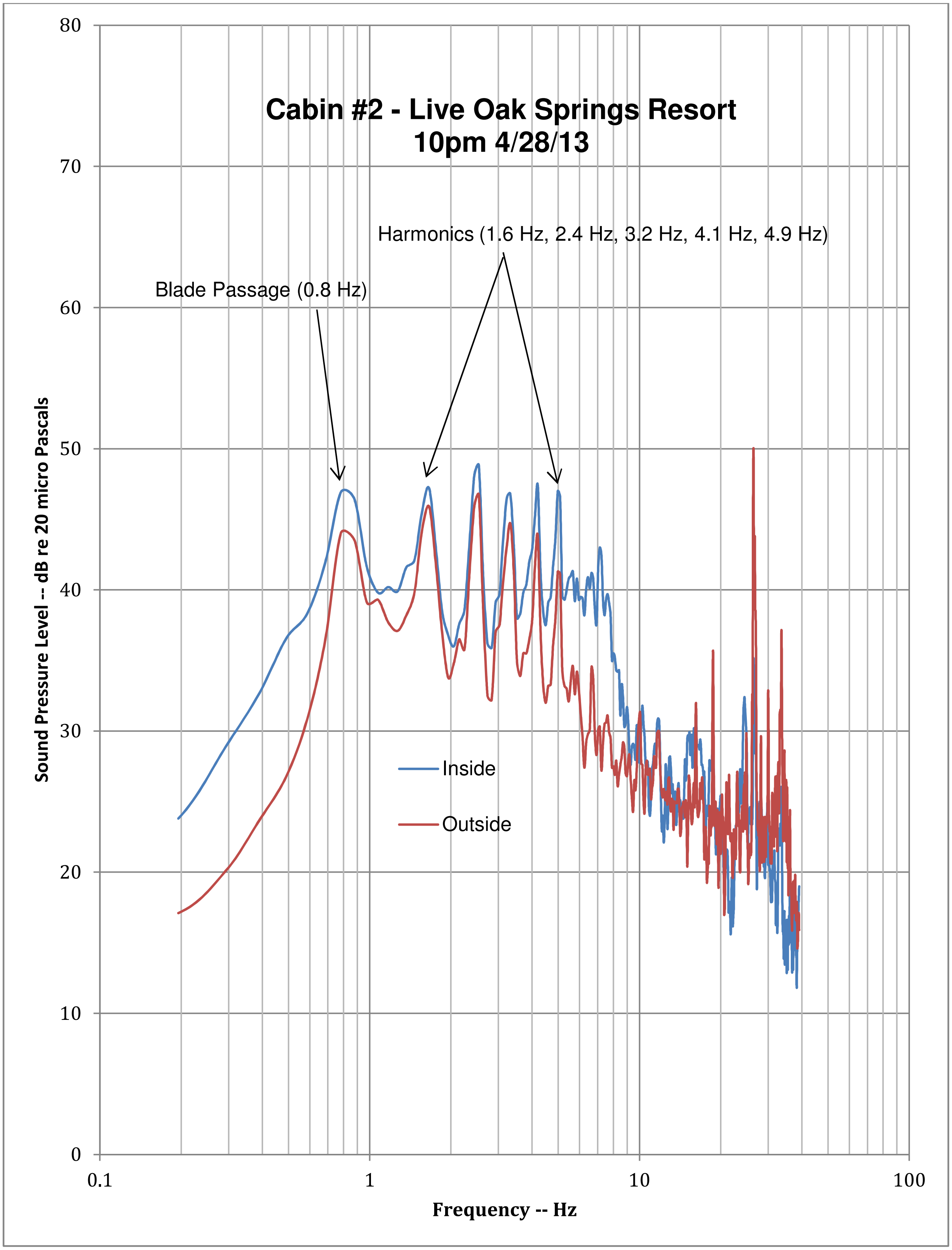
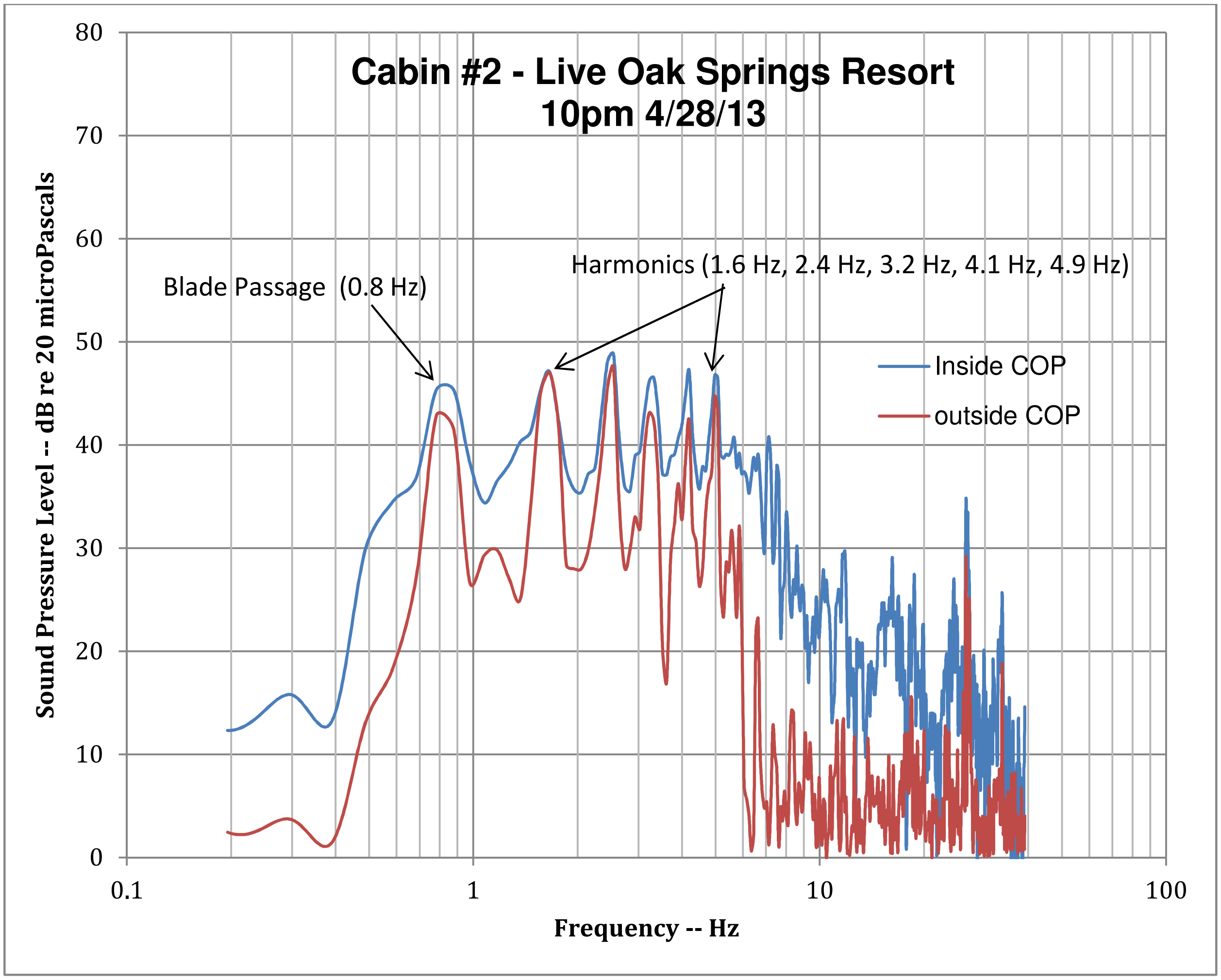


Figure C - 1 Live Oak Springs Resort – Cabin #2 – Autospectra



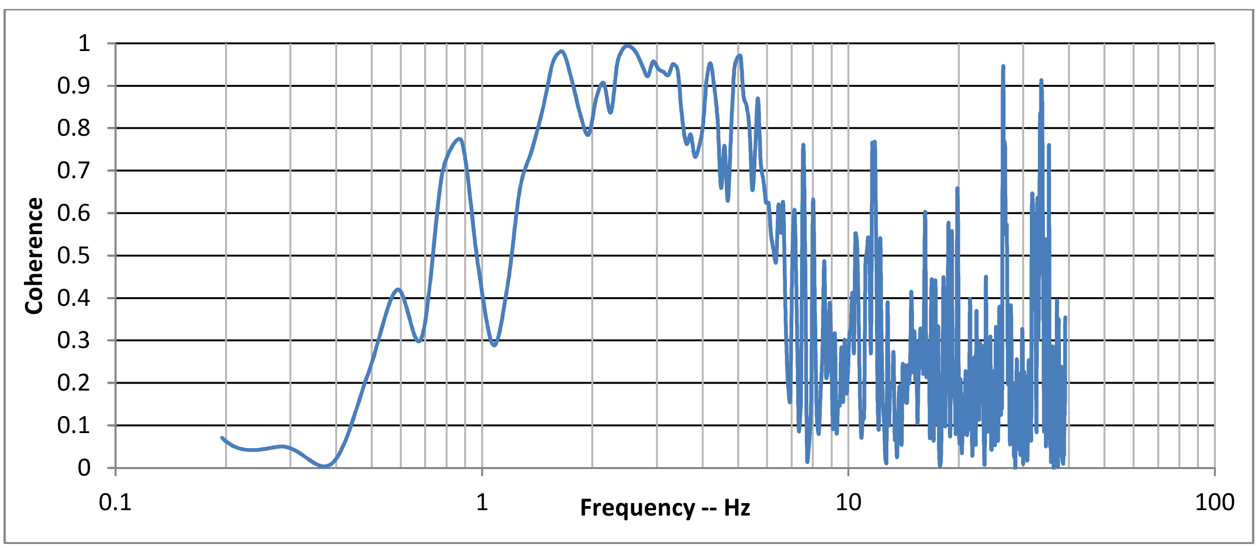


Figure C - 2 Live Oak Springs Resort – Cabin #2 – Coherent Output Power

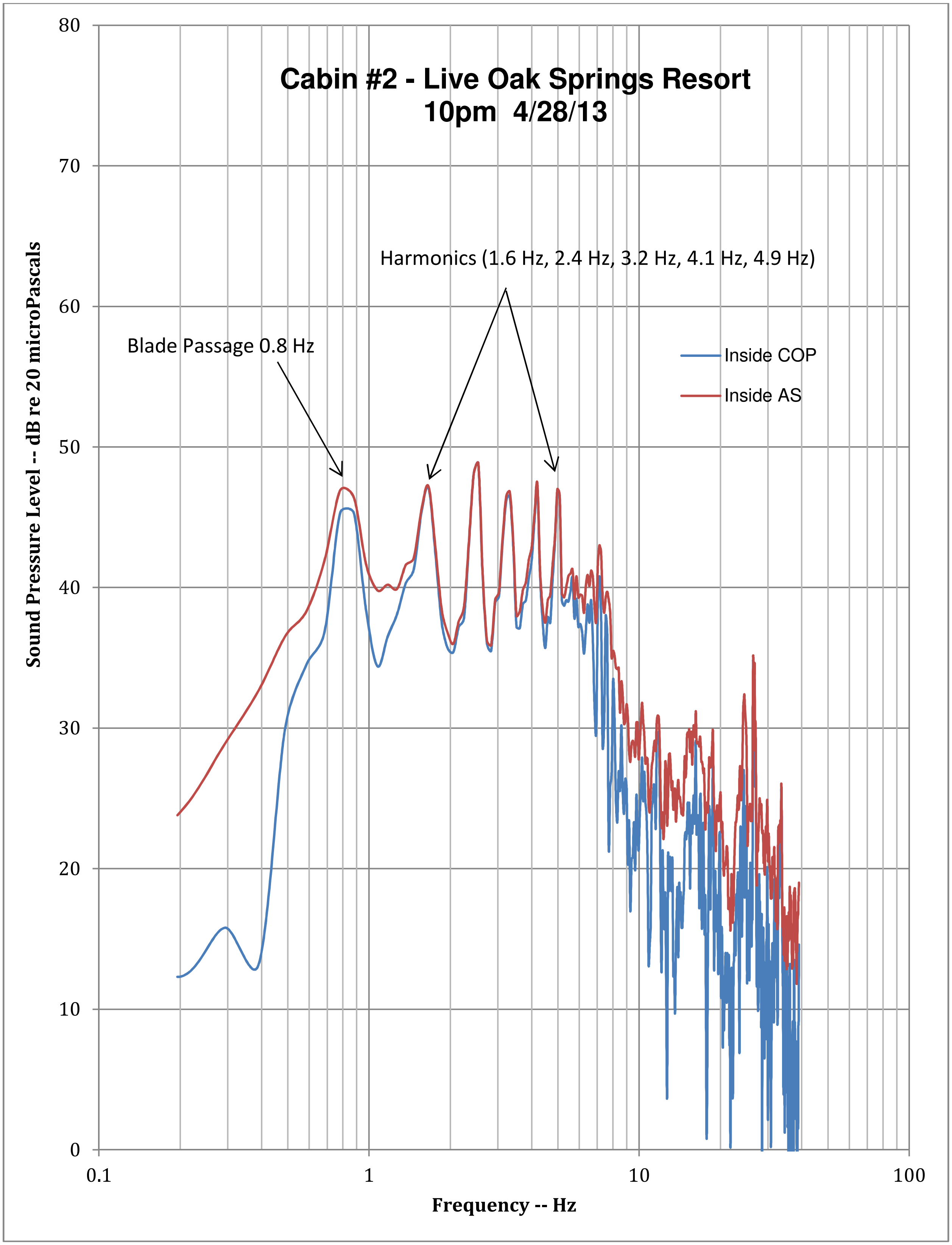


Figure C - 3 Live Oak Springs Resort – Cabin #2 – Comparison of Autospctrum and COP

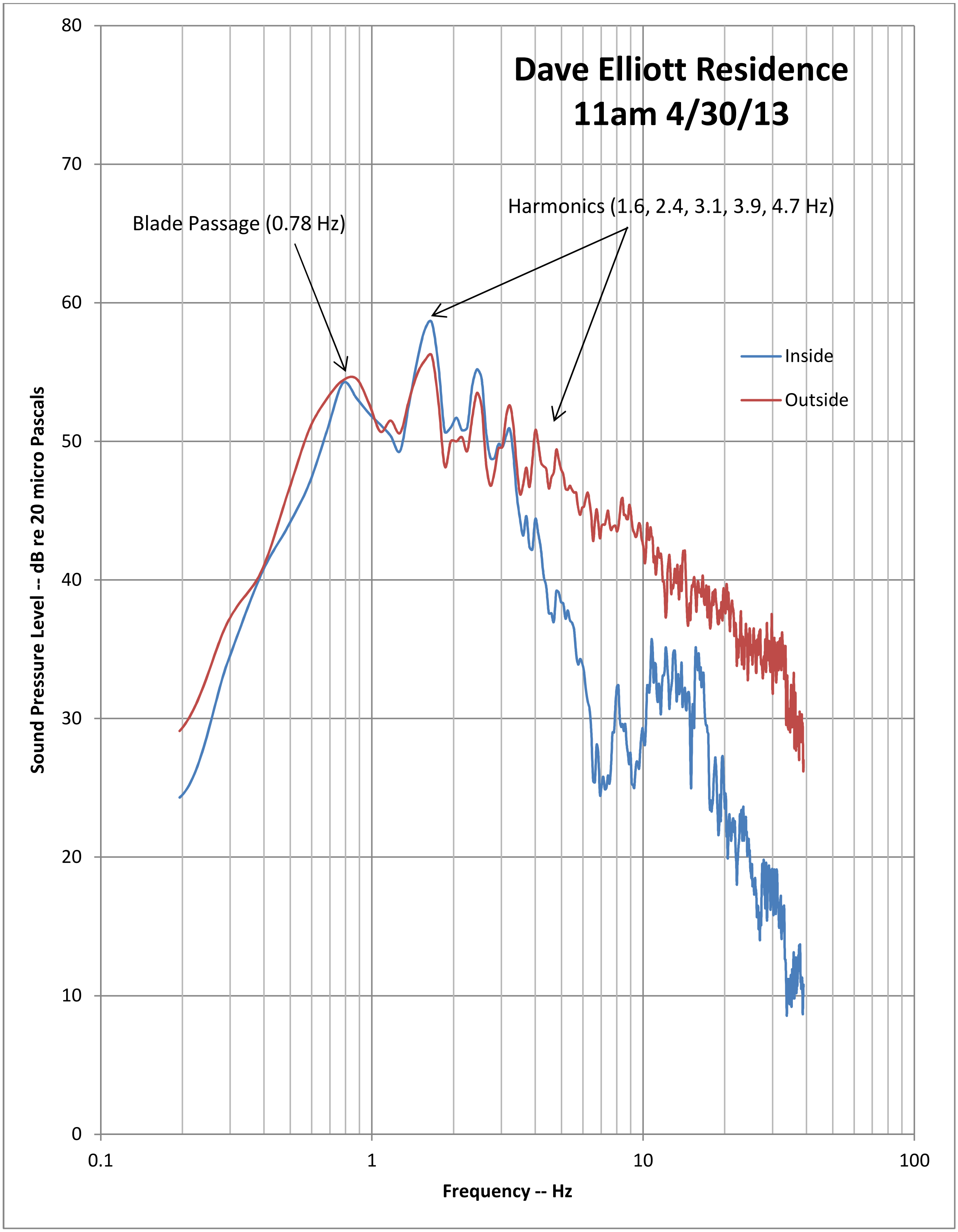


Figure C - 4 Dave Elliott Residence Autospectra

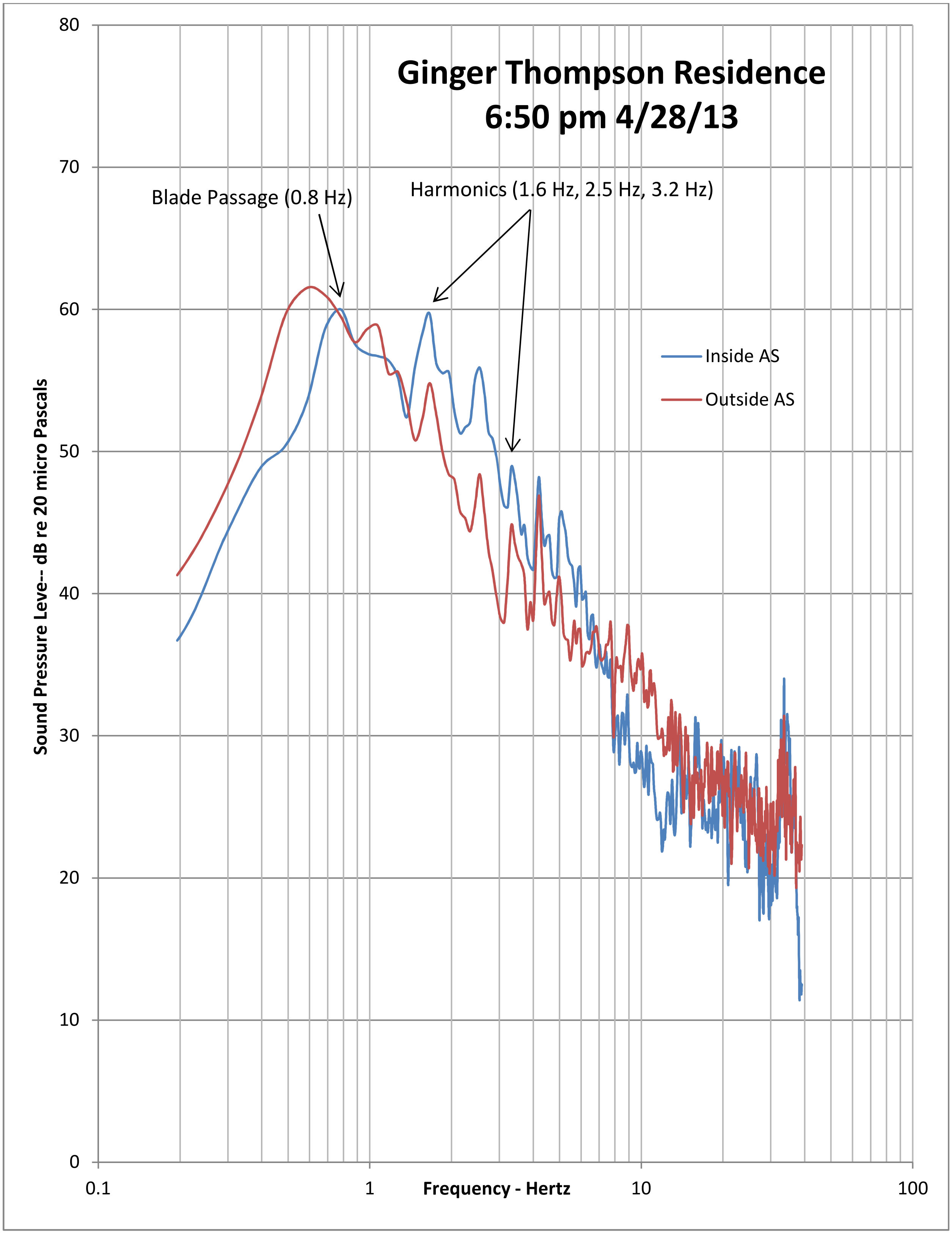


Figure C - 5 Ginger Thompson Residence Autospectra

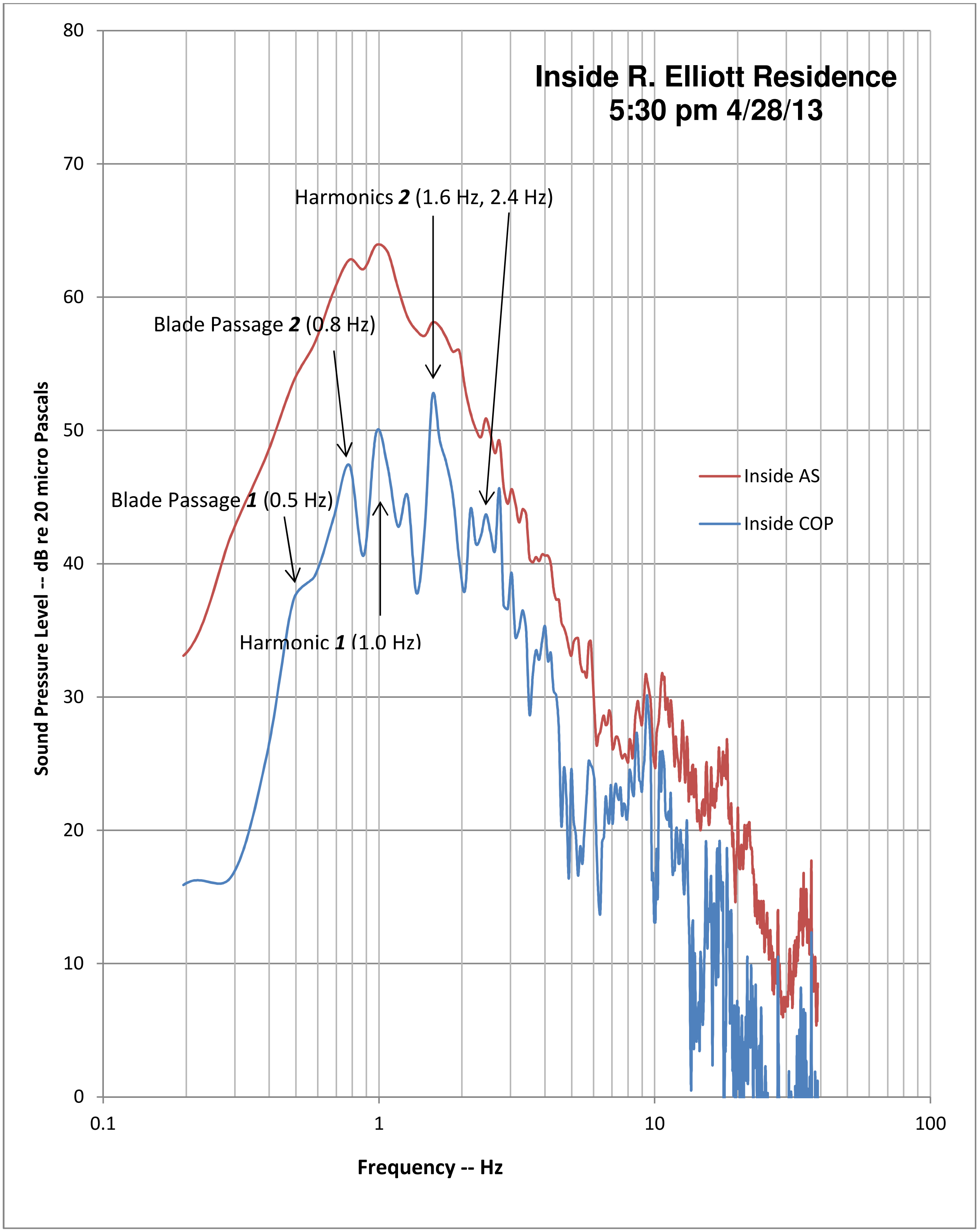


Figure C - 6 R. Elliott Residence Comparison of Autospectrum and Coherent Output Power

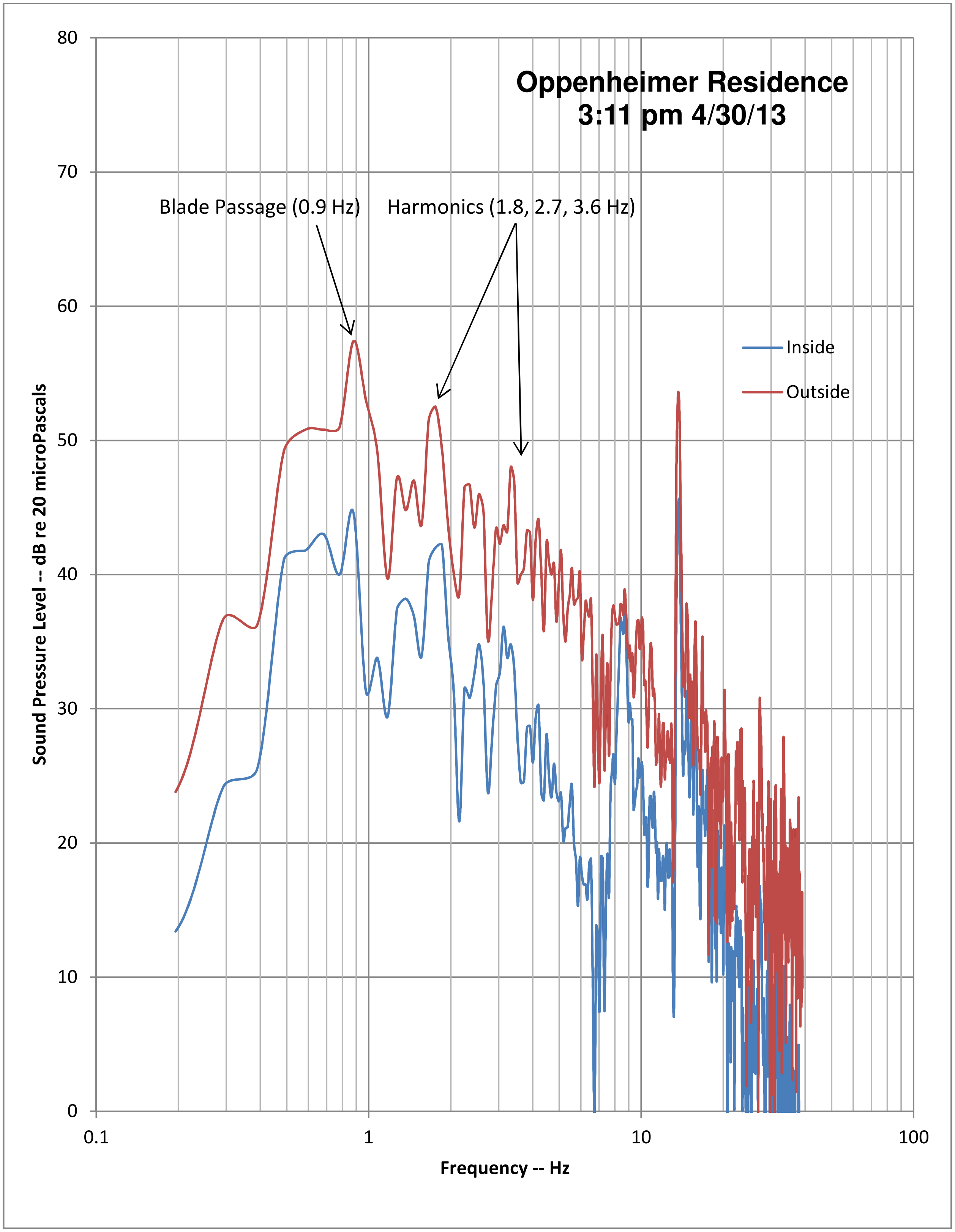


Figure C - 7 Ken Oppenheimer Residence during Day – Coherent Output Power

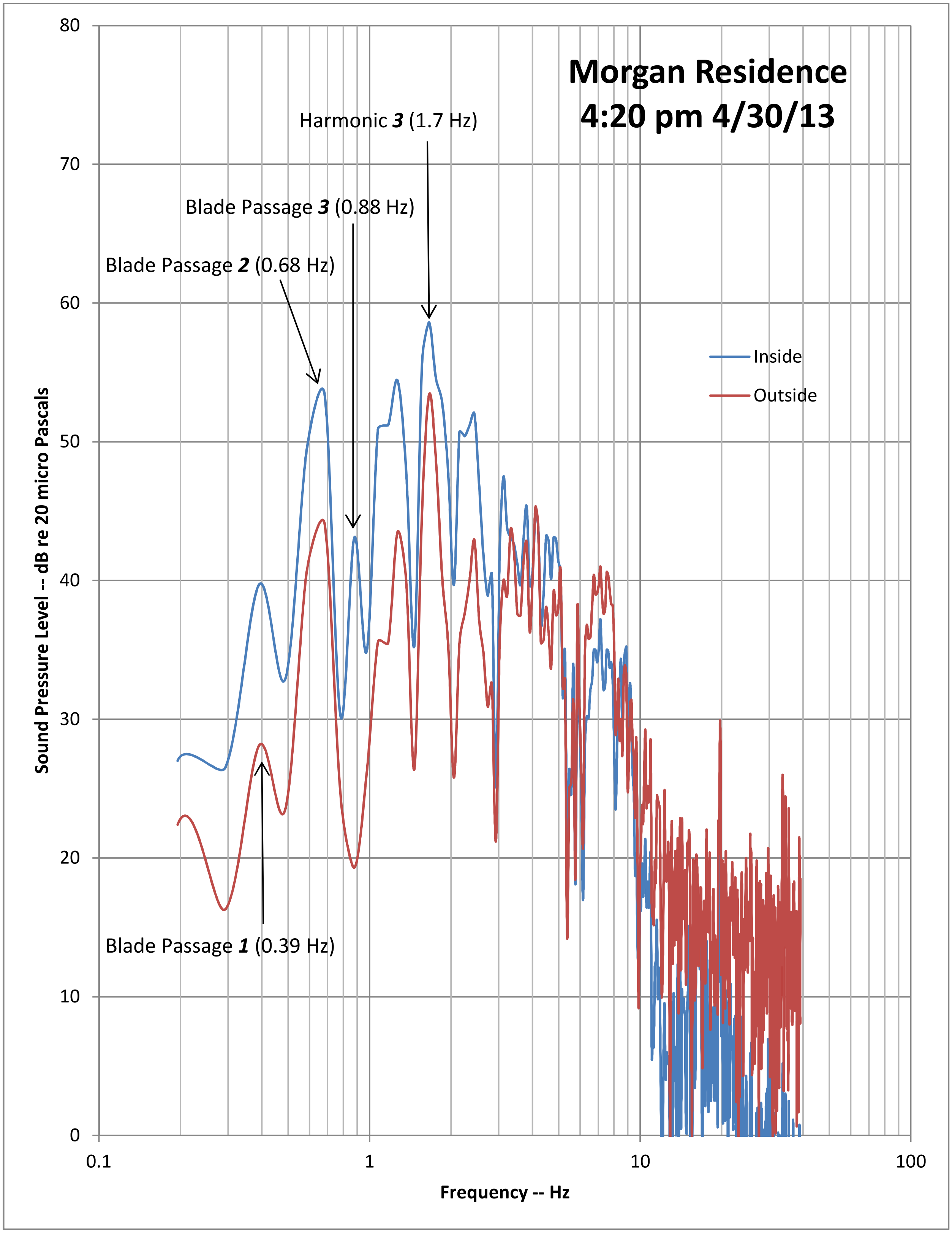


Figure C - 8 Marie Morgan Residence during Day – Coherent Output Power

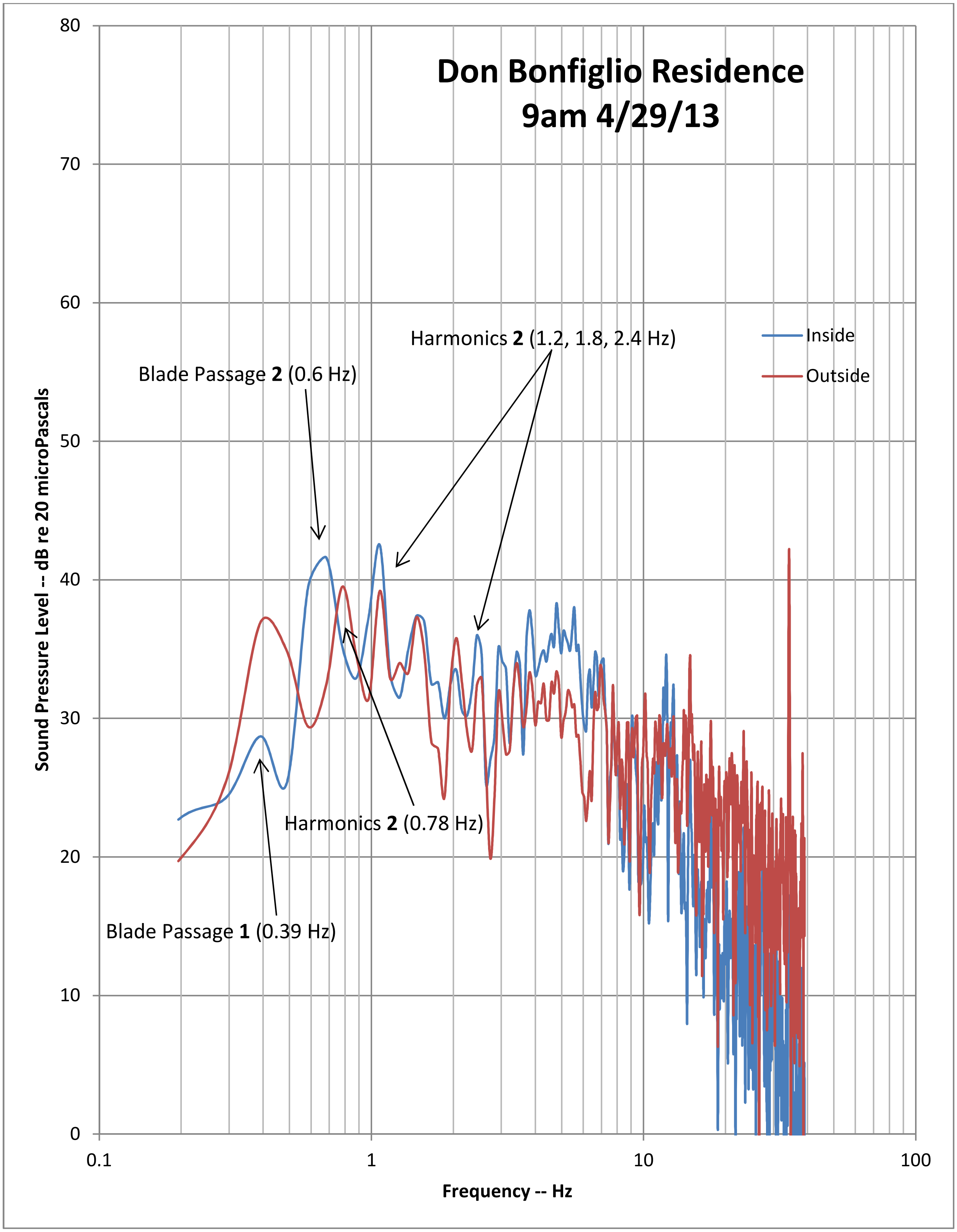


Figure C - 9 Don Bonfiglio Residence during Day – Coherent Output Power

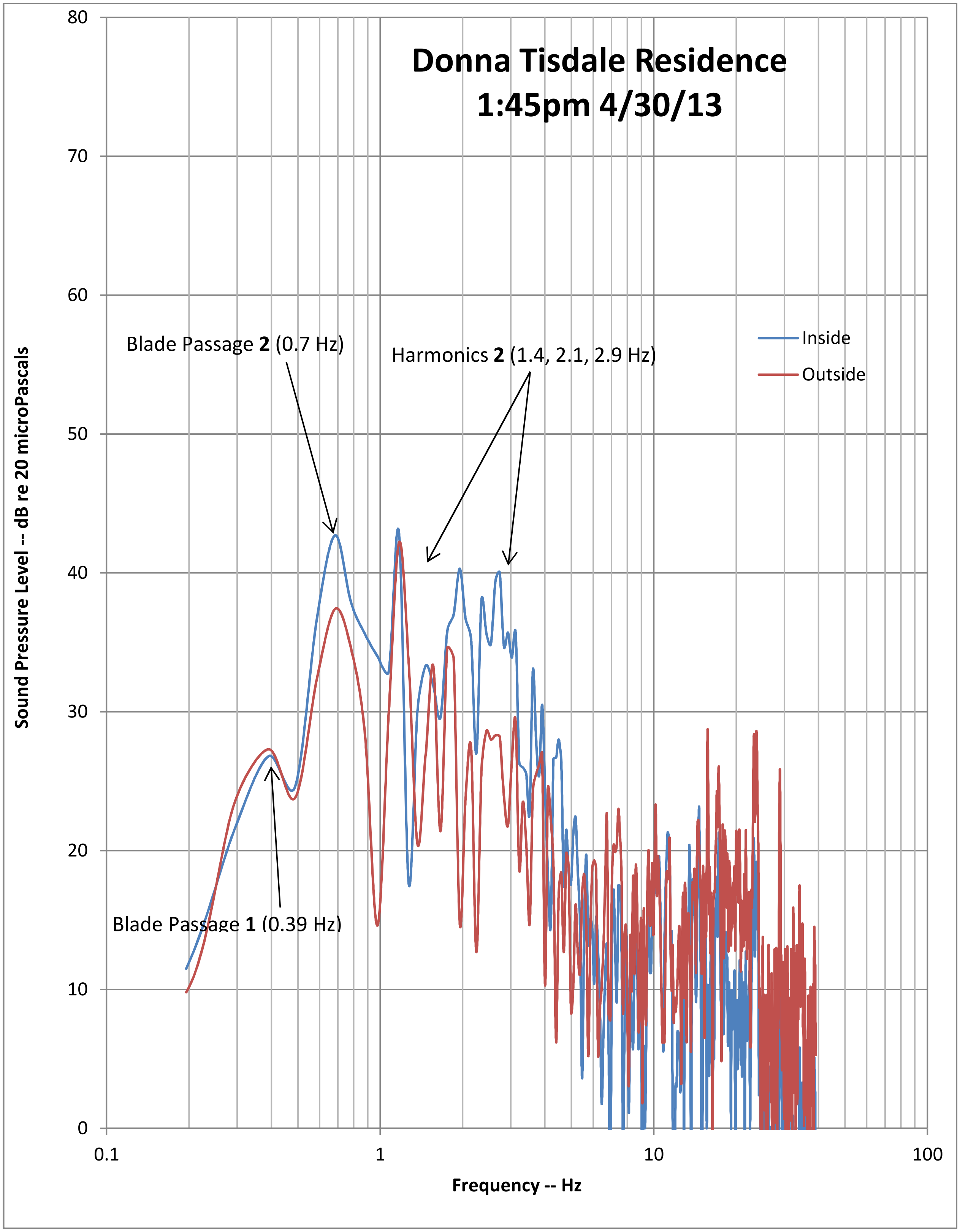


Figure C - 10 Donna Tisdale Residence during Day – Coherent Output Power

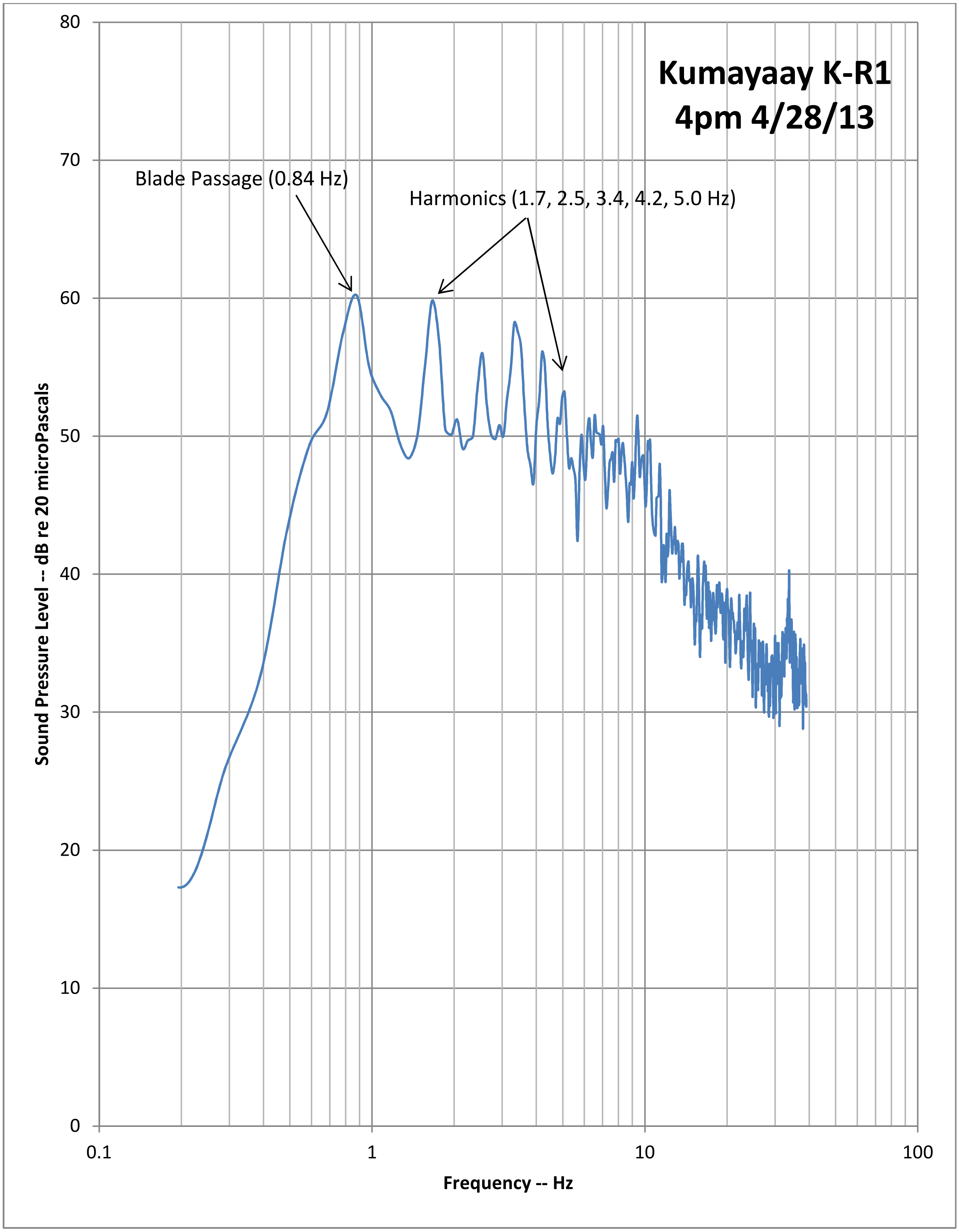


Figure C - 11 Kumeyaay Reference Location 1

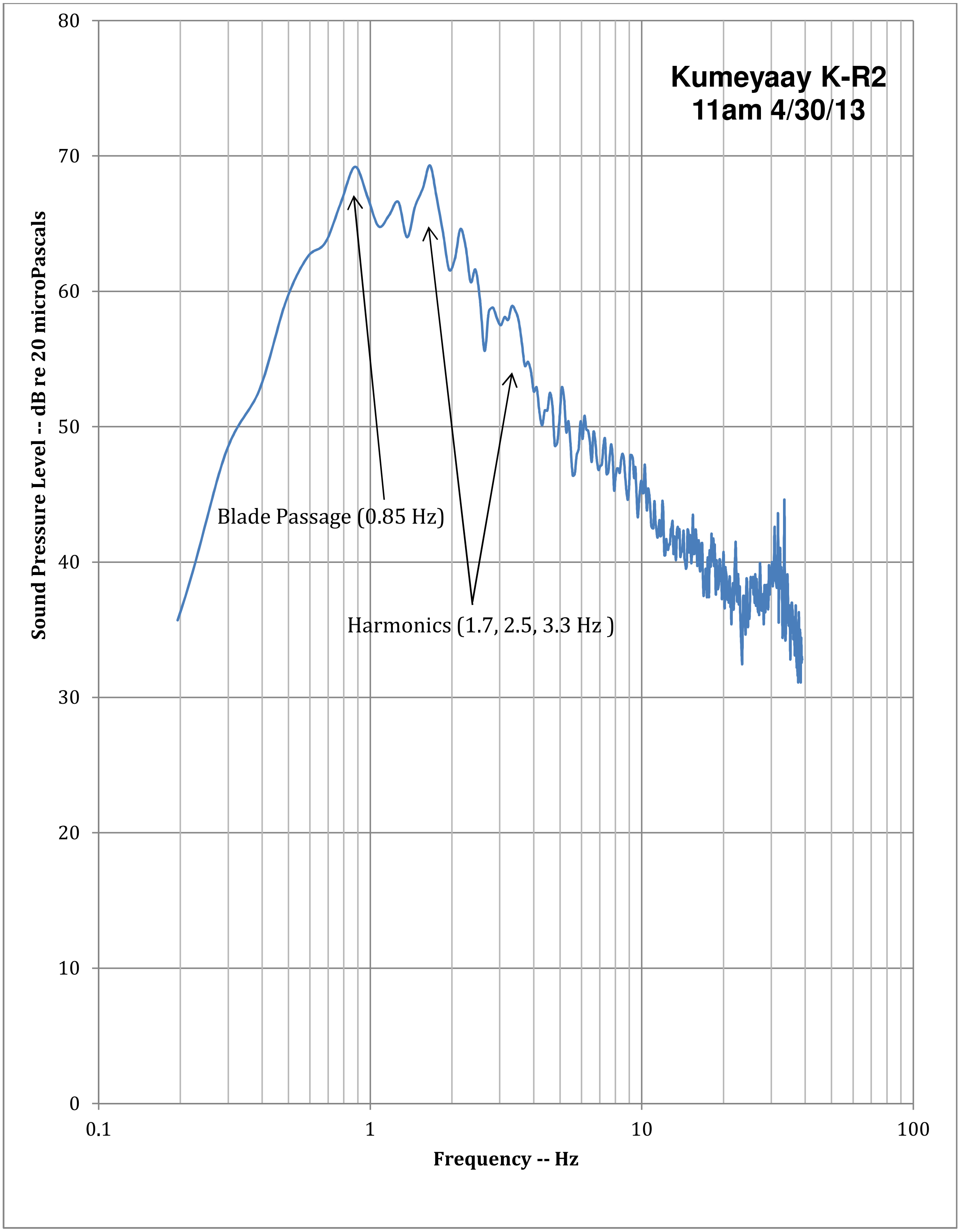


Figure C - 12 Kumeyaay Reference Location 2

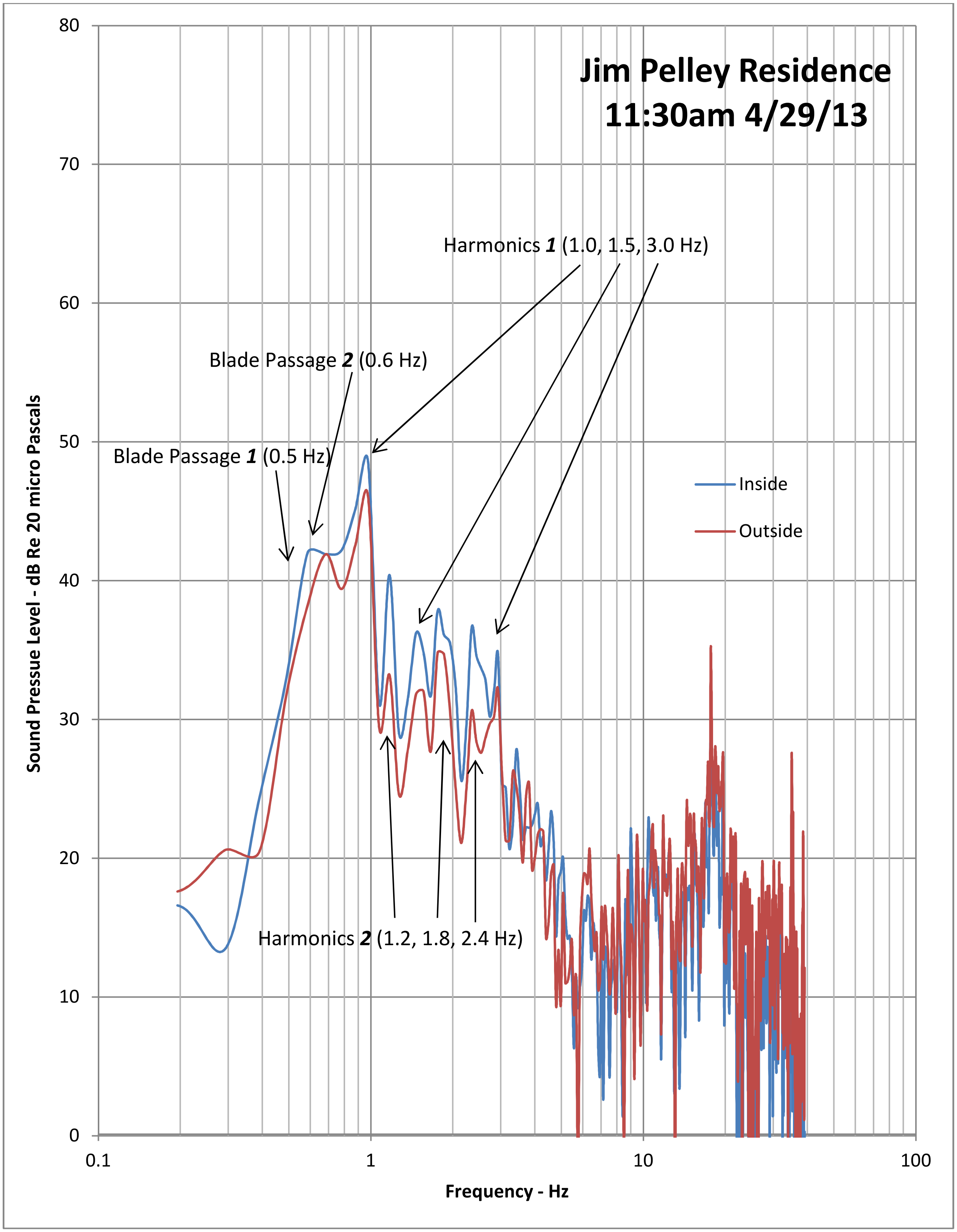


Figure C - 13 Jim Pelly Residence during Day – Coherent Output Power

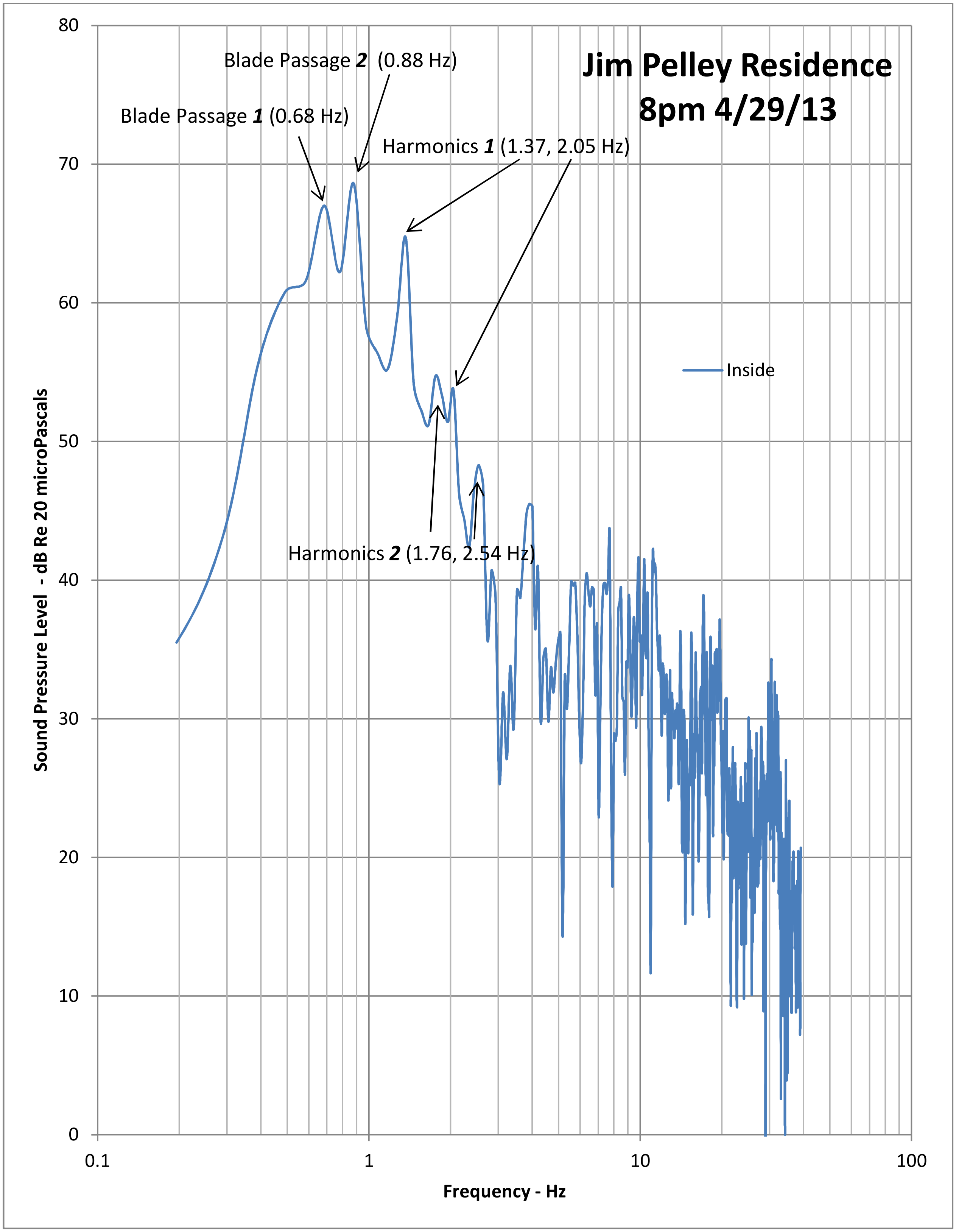


Figure C - 14 Jim Pelly Residence at Night – Coherent Output Power

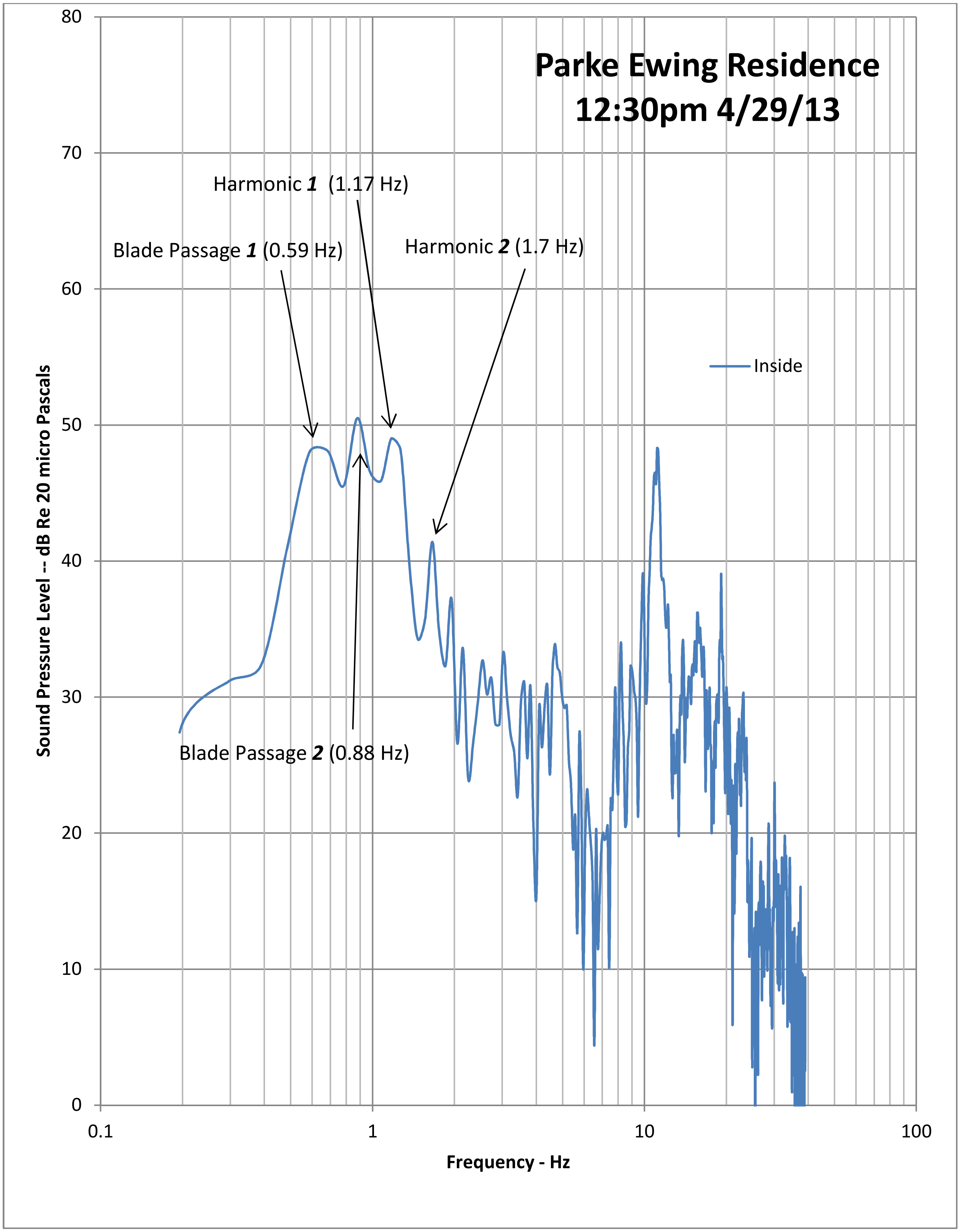


Figure C - 15 Parke Ewing Residence during Day – Coherent Output Power

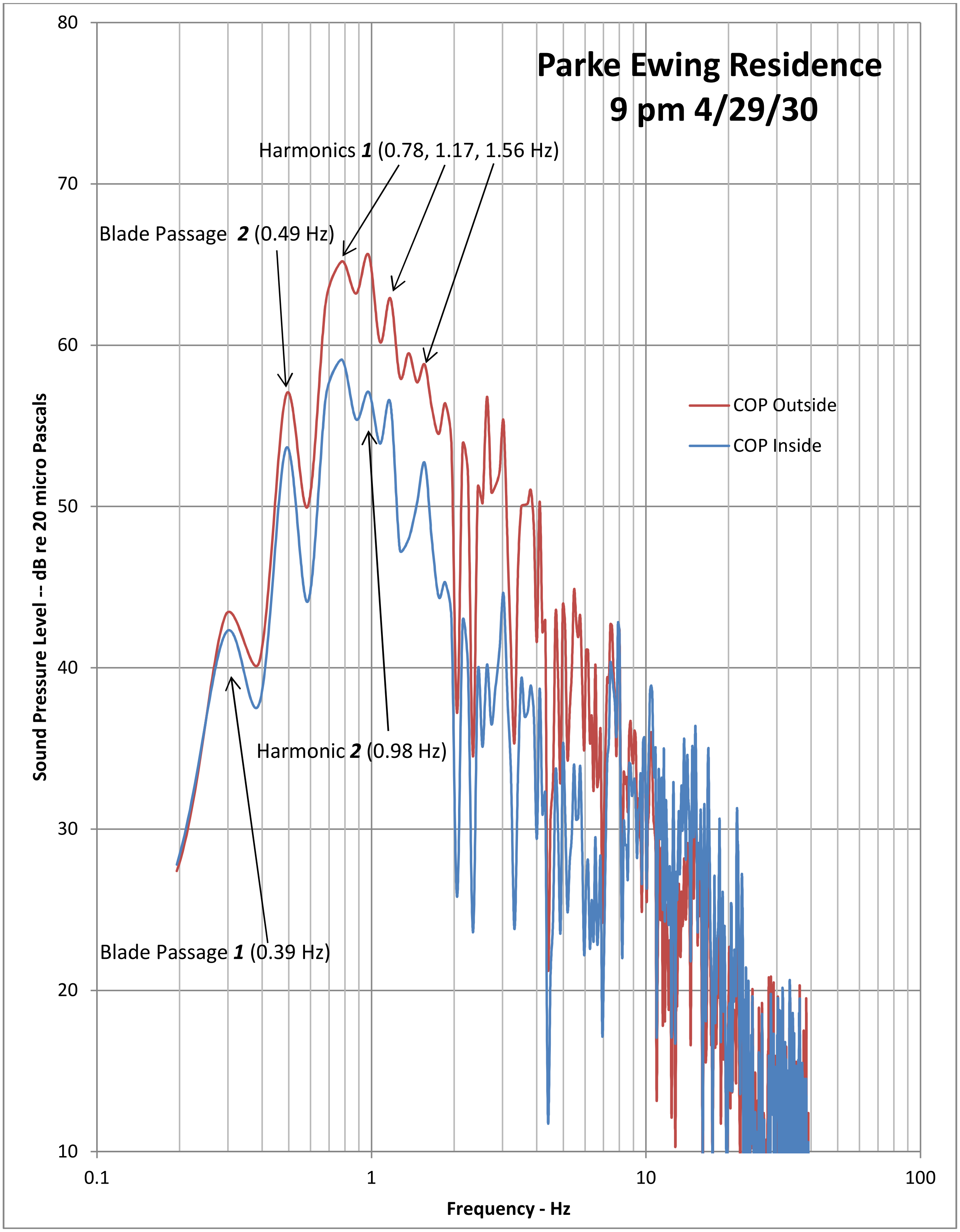


Figure C - 16 Parke Ewing Residence at Night – Coherent Output Power

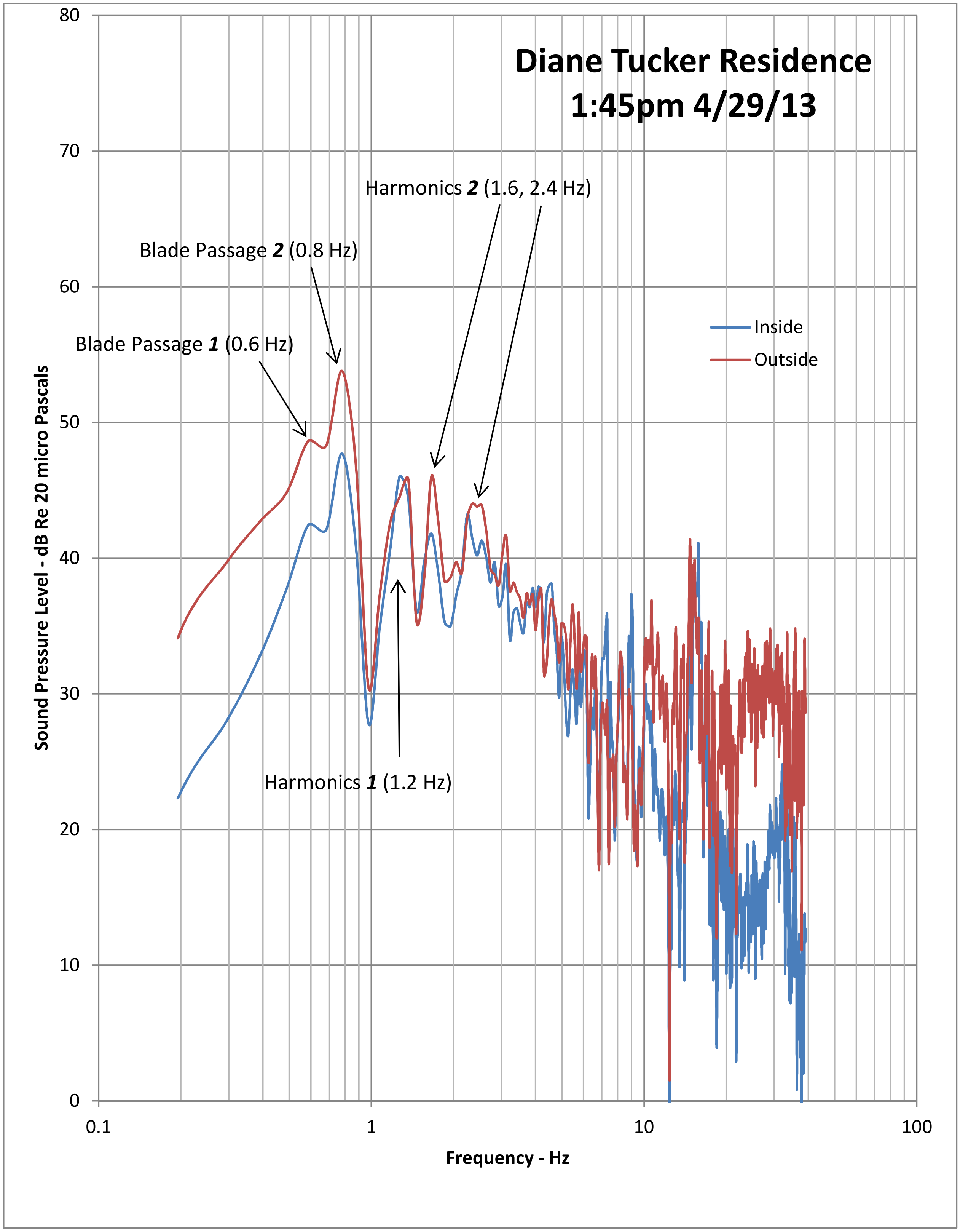


Figure C - 17 Diane Tucker Residence at Day – Coherent Output Power

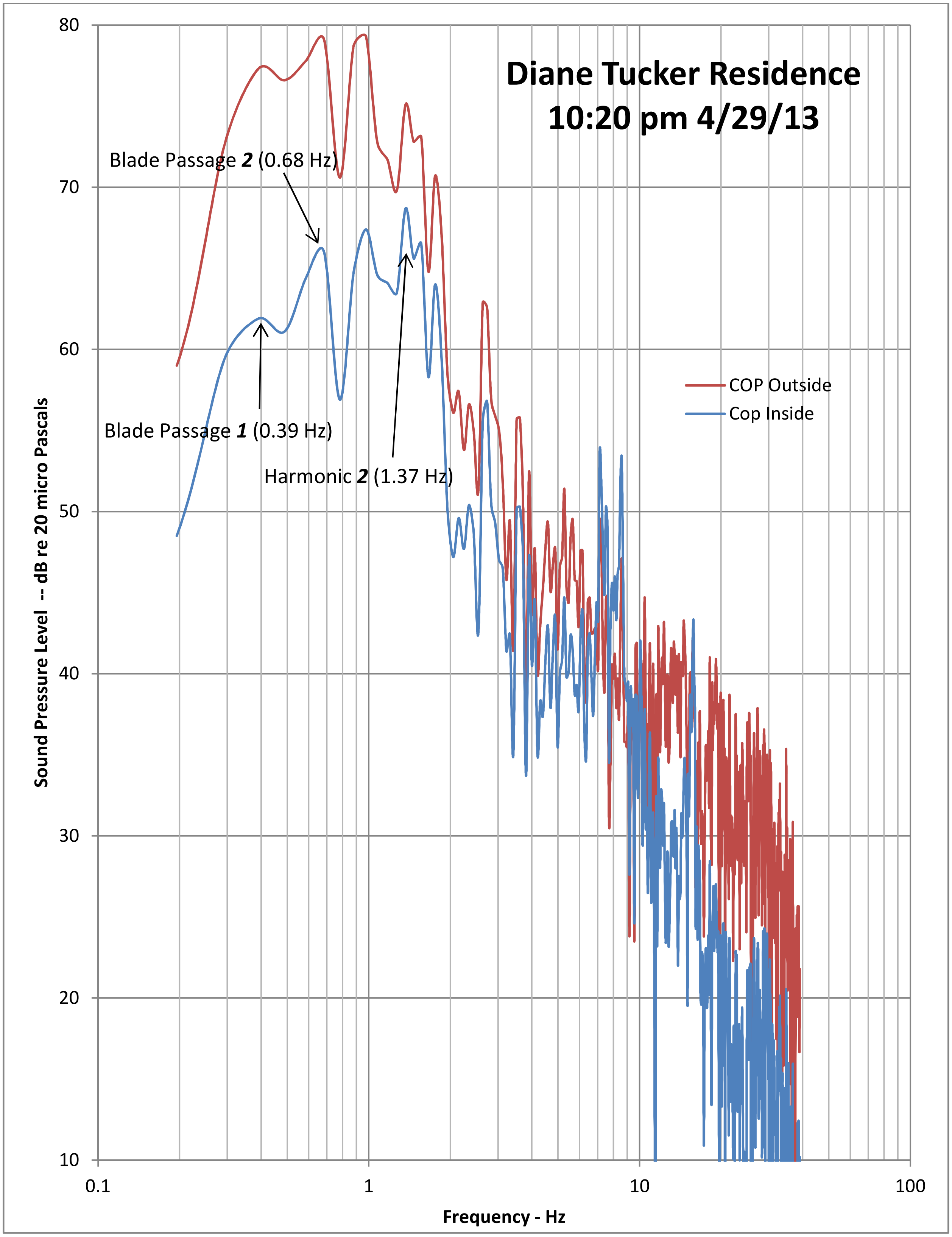


Figure C - 18 Diane Tucker Residence at Night – Coherent Output Power

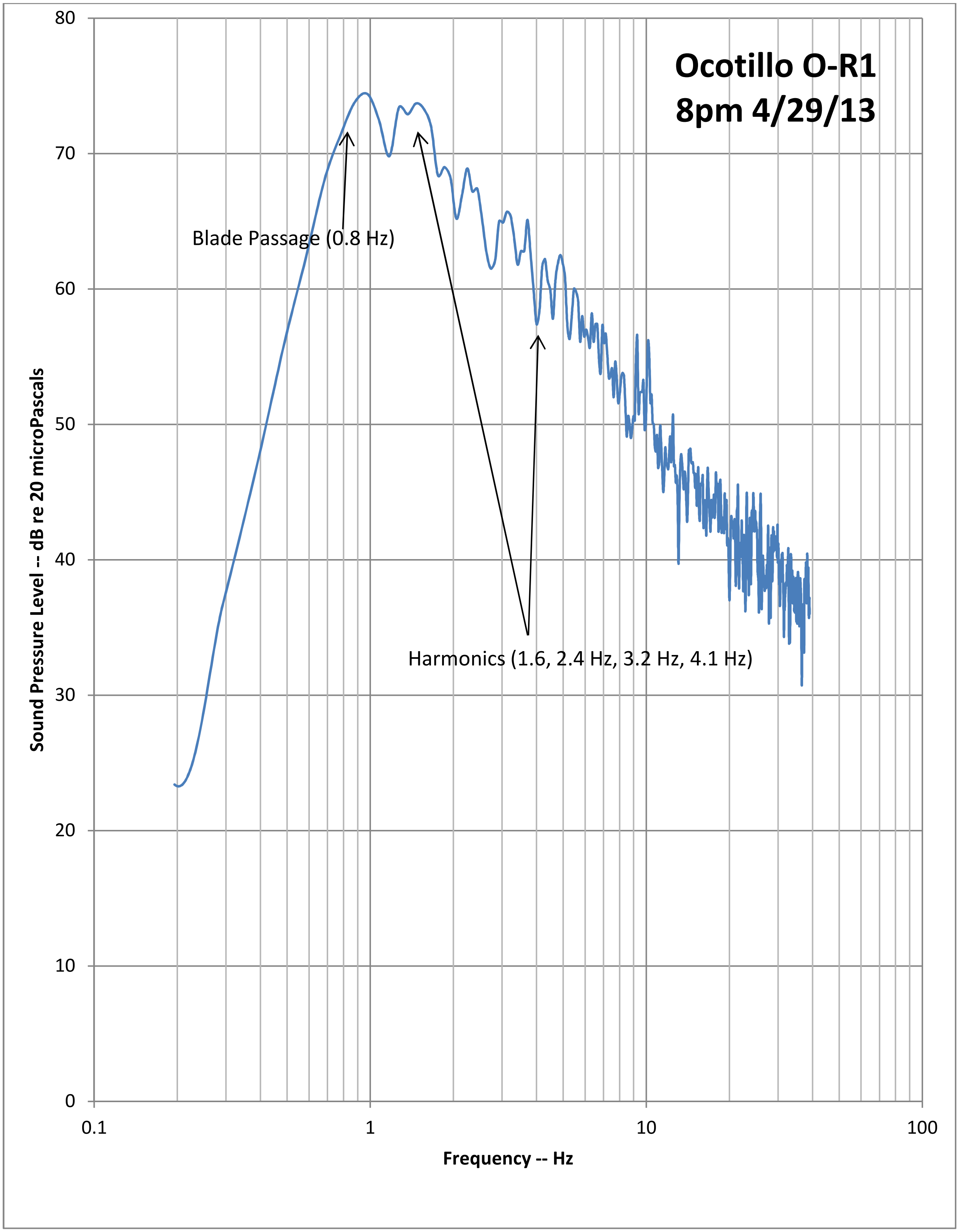


Figure C - 19 Ocotillo Reference Location 1 at Night

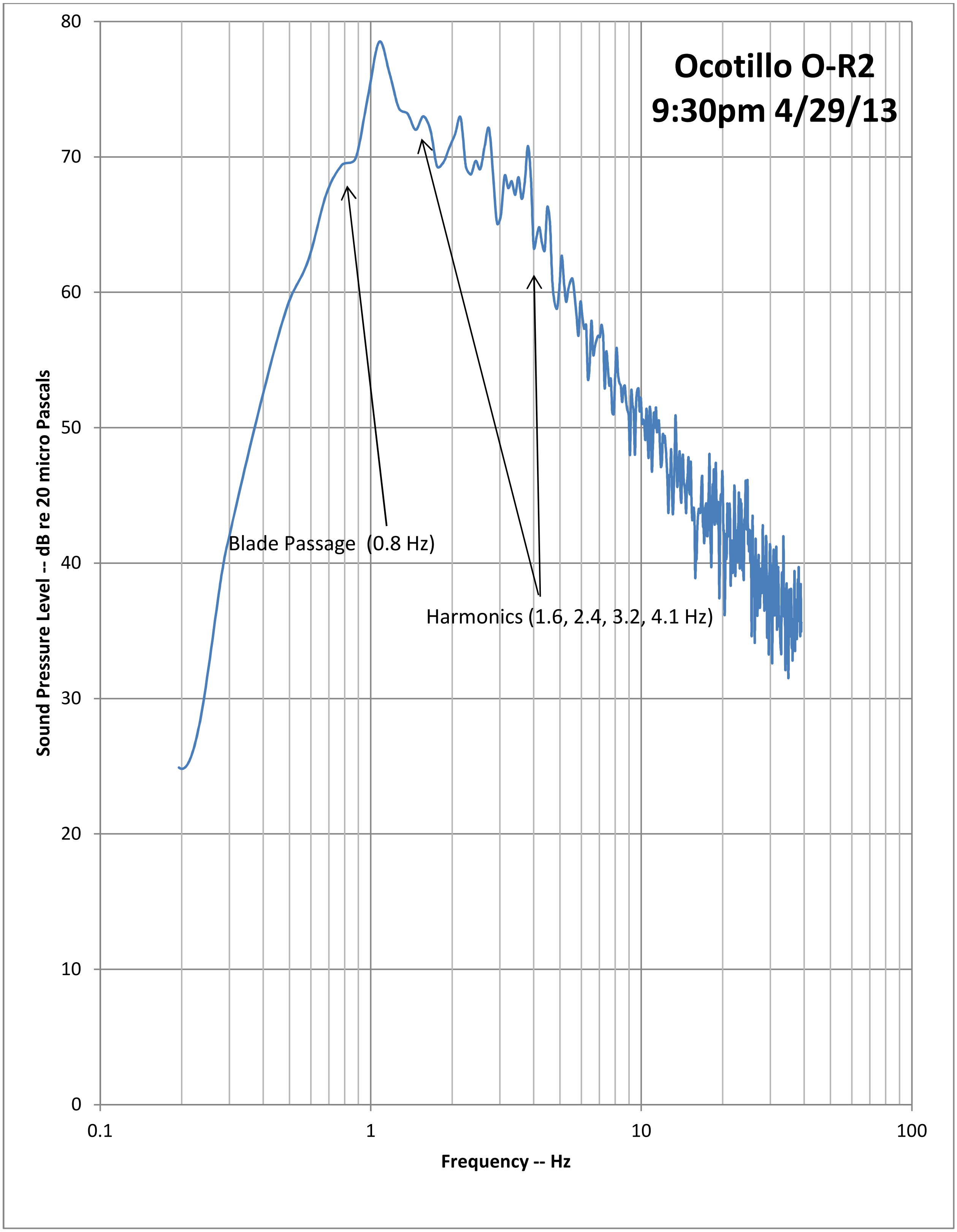


Figure C - 20 Ocotillo Reference Location 2 at Night

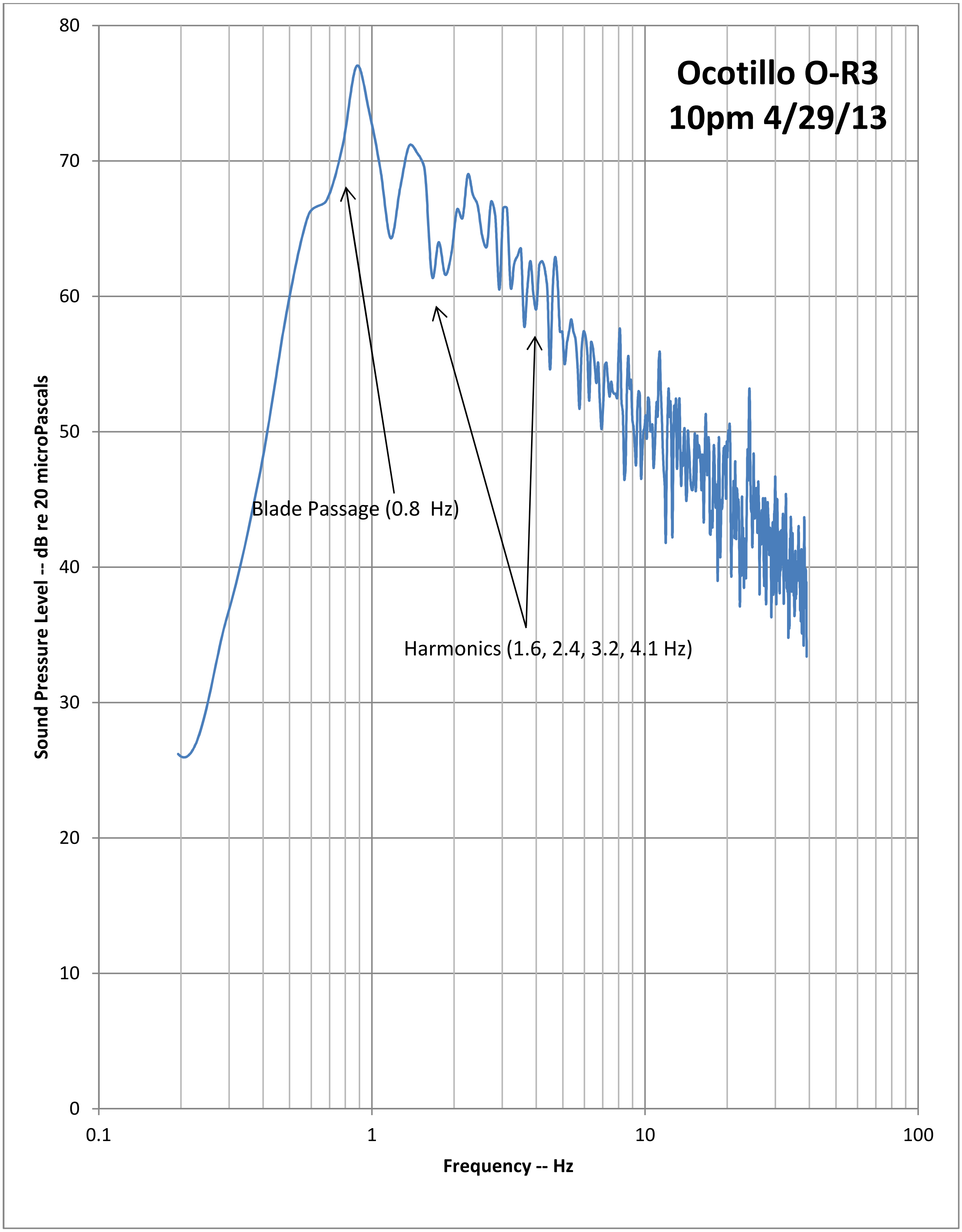
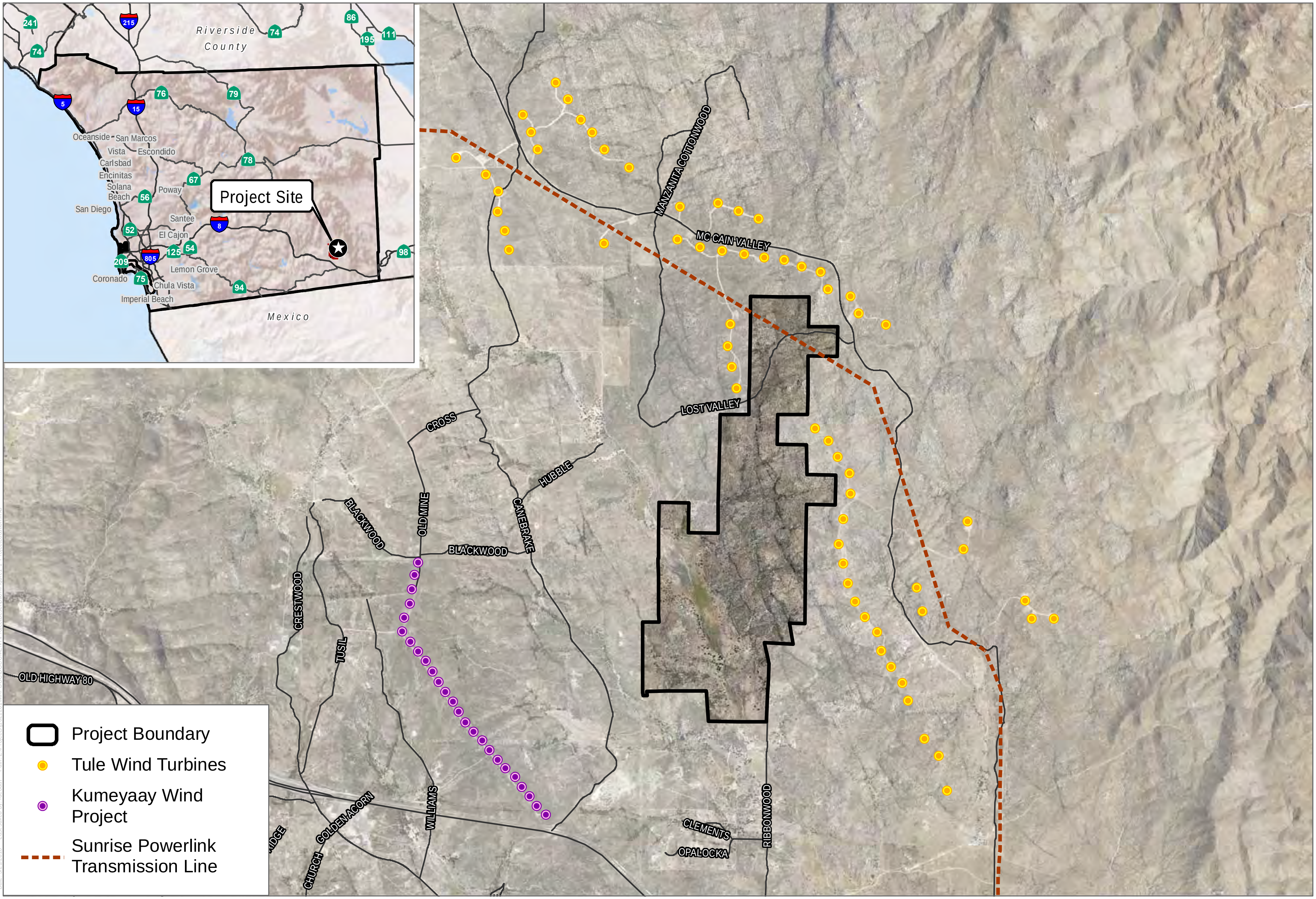


Figure C - 21 Ocotillo Reference Location 3 at Night

APPENDIX E – TORREY WIND MAP



SOURCE: SANGIS 2017

DUDEK

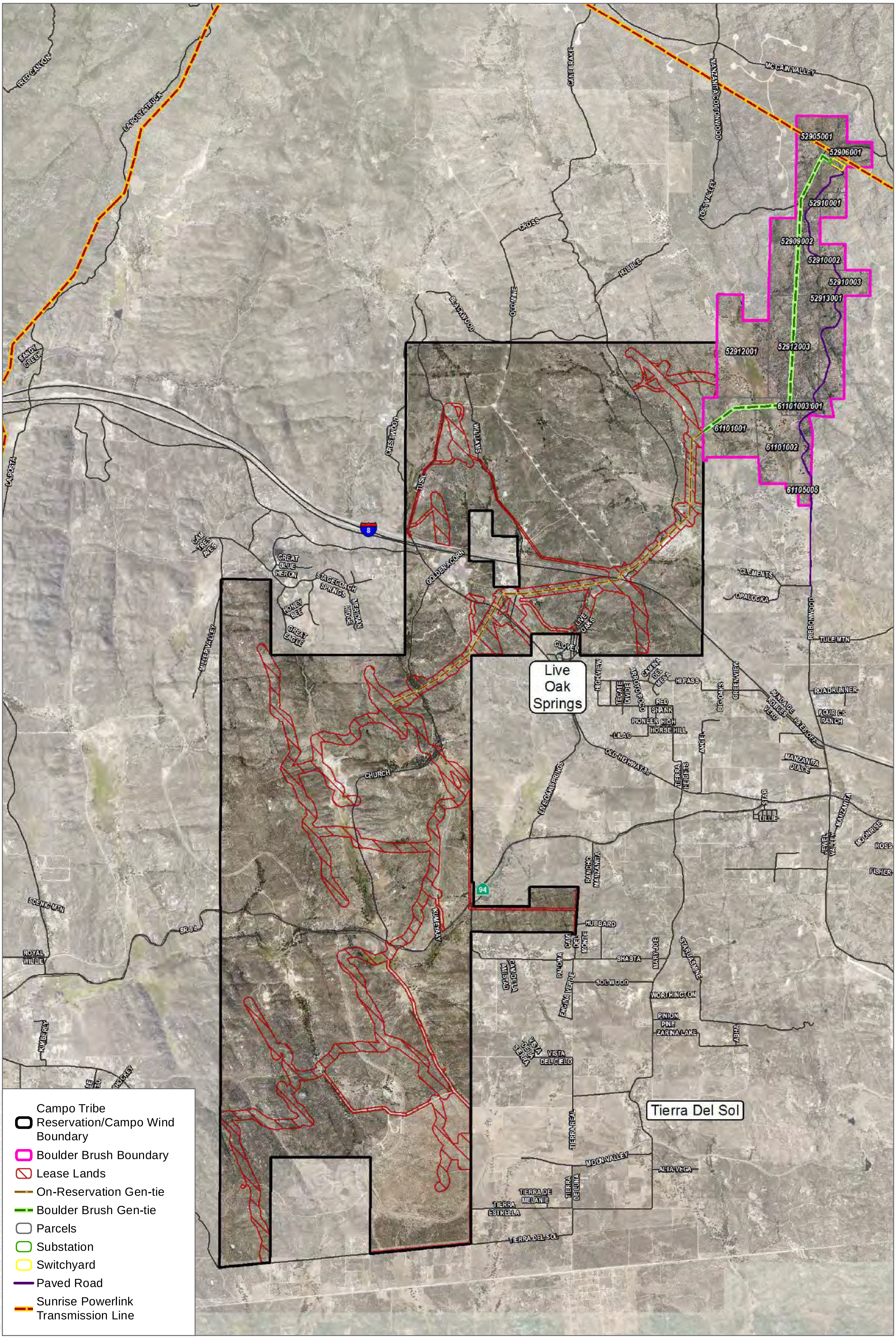
0 2,950 5,900 Feet

FIGURE 1-1

Project Location

Torrey Wind Project

APPENDIX F – CAMPO WIND MAP



SOURCE: SANGIS 2017

DUDEK

FIGURE 1

Project Location Map

Campo Wind and Boulder Brush Facilities

EXHIBIT 7
to July 8, 2019
Comments

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A Review of the Possible Perceptual and Physiological Effects of Wind Turbine Noise

Simon Carlile[1,2], John L. Davy[3,4], David Hillman[5], and Kym Burgemeister[6]

Abstract

This review considers the nature of the sound generated by wind turbines focusing on the low-frequency sound (LF) and infrasound (IS) to understand the usefulness of the sound measures where people work and sleep. A second focus concerns the evidence for mechanisms of physiological transduction of LF/IS or the evidence for somatic effects of LF/IS. While the current evidence does not conclusively demonstrate transduction, it does present a strong prima facia case. There are substantial outstanding questions relating to the measurement and propagation of LF and IS and its encoding by the central nervous system relevant to possible perceptual and physiological effects. A range of possible research areas are identified.

Keywords

auditory transduction, infrasound, low-frequency sound, wind turbine noise

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Introduction

In recent years, there has been growing debate about the effects of wind turbine noise (WTN) on human health. A number of reviews have recently been published (e.g., Knopper et al., 2014; McCunney et al., 2014; Schmidt & Klokker, 2014; Van Kamp & Van Den Berg, 2017), some under the auspice of different government bodies in Australia (National Health and Medical Research Council, 2015), Canada (Council of Canadian Academies, 2015), and France (Lepoutre et al., 2017), with some appearing in the indexed scientific literature (most recently the Health Canada study; D. Michaud, 2015; D. S. Michaud et al., 2016a, 2016b; D. S. Michaud, Keith, et al., 2016). Many of these studies have adopted an epidemiological approach including various meta-analyses of the existing research reports concerning the health effects of WTN. By contrast, the popular press portrays a largely polarized picture where the discourse often appears less informed and more opinionated than scientifically based.

There are clearly complex factors surrounding complaints about WTs that, apart from the health and safety concerns, include financial and other material factors and potential interactions with individuals' perceptions of devices themselves, including their appearance and the sounds they make. These factors are all potential contributors to the annoyance produced by WTs. Many of these concerns—sometimes referred to as nocebo effects—have been recently reviewed in the literature (Chapman & Crichton, 2017; C. H. Hansen, Doolan, & Hansen, 2017). There seems, however, to have been little discussion (or systematic review) of potential perceptual and physiological effects of WTN at the level of the individual. This provides the principal motivation for this review. This review does not consider the important question of whether WTN affects human health, given the reviews and debates referred to earlier, but focuses on two important foundational issues. The first section reviews recent research examining the nature of the sound generated by WTs with a particular focus on the low-frequency sound (LF) and infrasound

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(IS), together with the mechanisms of its generation, propagation, and measures of human exposure. The objective of this first part is to understand the accuracy and usefulness of measures of this sound pressure at locations where people work and sleep. The second issue for focus concerns whether there are plausible mechanisms of transduction of LF/IS or evidence for somatic effects of LF/IS. This is an important question as a key link in any argument attempting to relate WTN exposure to ill health is the extent to which that sound can have a somatic influence. In closing, some of the existing peer-reviewed research examining the perceptual effects of exposure to LF and IS in the laboratory setting is reviewed.

This review has been confined largely to the scientific literature represented by the relevant peer-reviewed articles in indexed journals.

WTN, LF, and IS

There are a range of potential sound generators produced by WTs which include mechanical generators (gearboxes, electrical generators, cooling systems, etc., in the WT nacelle) as well as interactions between the moving blades and the air, particularly where there are variations in flow, angle of incidence, and pressure.

Sound produced by rotating blades on modern upwind WTs (where the rotor is on the front of the nacelle when viewed from the direction that the wind is coming) results in part from an interaction between the airflow disturbed by the rotating blade interacting with the supporting tower (e.g., Jung, Cheung, Cheong, & Shin, 2008; Sugimoto, Koyama, Kurihara, & Watanabe, 2008; reviewed in detail Van den Berg, 2006; Zajamšek, Hansen, Doolan, & Hansen, 2016). The sound generated by this mechanism is tonal in nature with a fundamental frequency at the blade passing frequency (BPF) and a series of six or so harmonics (Figure 1; for further details, see Schomer, Erdreich, Pamidighantam, & Boyle, 2015, their Figures 2 and 3). The fundamental frequency is dependent on the rate of rotation and number of blades and for a modern WT, the sound energy produced by this mechanism is generally well below 20 Hz.

Other sources of sound include the aerodynamic noise generated by air flow across and leaving the trailing edge of the blades (trailing edge noise) and mechanical noise from the nacelle equipment. By contrast with BPF noise, the aerodynamic noise from the blades is broadband with a low-pass roll-off (~5 dB per octave > 1 kHz; Figure 2; Oerlemans, Sijtsma, & López, 2007, their Figures 5, 9, and 11). The center frequency (500–750 Hz, A-weighted) is related to the size and power generation capacity of the turbine with a downward shift of around 1/3 octave comparing 2.3 to 3.6 MW turbines to <2 MW turbines accompanied by a relative increase in the proportion of energy at low frequencies for larger turbines (Moller & Pedersen, 2011).

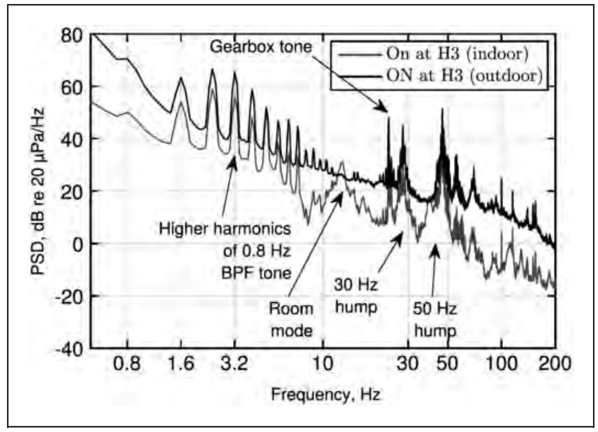

Figure 1. Comparison of indoor and outdoor spectral density recorded at an unoccupied dwelling approximately 3 km from a wind turbine. BPF = blade passing frequency; PSD = power spectral density.
Source: Reproduced with permission from Zajamsek et al. (2016), Figure 4.

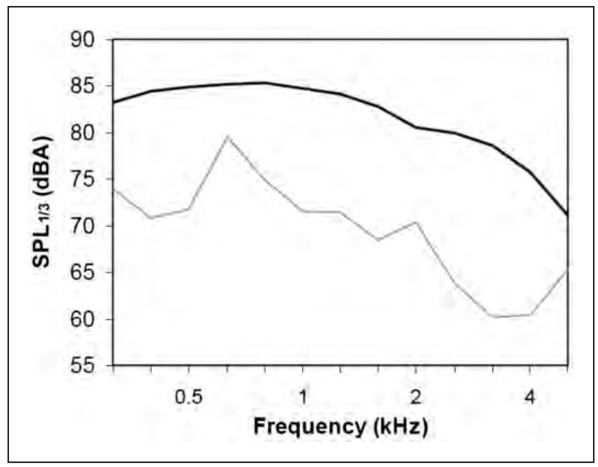

Figure 2. A-weighted average spectra of hub noise (thin line) and blade noise (thick line) recorded from a three-bladed pitch–controlled GAMESA G58 wind turbine (rotor diameter 58 m) using an acoustic array of 148 Panasonic WM-61 microphones 58 m upwind from the turbine.
Source: Reproduced with permission from Oerlemans et al. (2007).

In summary, from both a theoretical and an empirical standpoint, there is ample evidence demonstrating that a component of the sound energy produced by a WT is in the low and infrasonic frequency range. There are three other characteristics of LF that are relevant to understanding the measurements of sounds produced by WTs.

First, both modeling and measurement data have shown that the atmospheric boundary layer which extends from ground level to between 100 to thousands

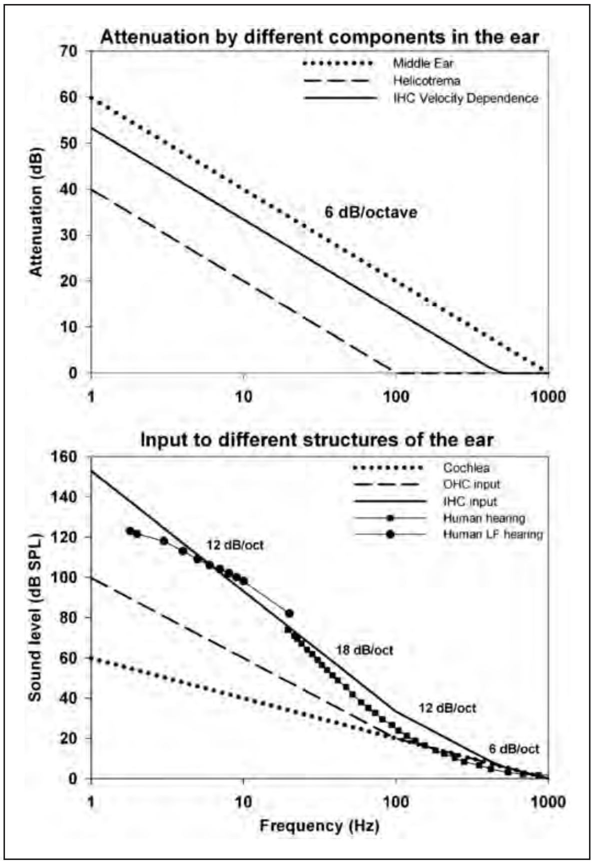

Figure 3. Upper panel: Estimated properties of high-pass filters associated with cochlear signal processing (based on Cheatham & Dallos, 2001). The curves show the low-frequency attenuation provided by the middle ear (6 dB/octave below 1000 Hz), the helicotrema (6 dB/octave below 100 Hz), and by the fluid coupling of the IHC resulting in the IHC dependence on stimulus velocity (6 dB/octave below 470 Hz). Lower panel: Combination of the three processes in the upper panel into threshold curves demonstrating: input to the cochlea (dotted) as a result of middle ear attenuation, input to the IHC as a result of additional filtering by the helicotrema, and input to the IHC as a result of their velocity dependence. Shown for comparison is the sensitivity of human hearing in the audible range (ISO226, 2003) and the sensitivity of humans to infrasound (Moller & Pedersen, 2004). The summed filter functions account for the steep (18 dB/octave) decrease in sensitivity below 100 Hz. OHC = outer hair cells; IHC = inner hair cells; LF = low-frequency sound.
Source: Reproduced with permission from Salt and Hullar (2010), Figure 3.

of meters can act as a low-frequency wave guide under a variety of common meteorological conditions (for review, see Marcillo, Arrowsmith, Blom, & Jones, 2015). With a stable boundary layer, which is common at night, LF radiation occurs as cylindrical waves and follows a two-dimensional decay model (−3 dB per doubling of distance) when measured downwind of a source (Zorumski & Willshire, 1989) in contrast to a three-dimensional decay model for higher frequency audible sound. Under such conditions, therefore, LF and IS levels decay more slowly with distance when compared with higher frequencies. Consistent with this, propagation of sound at the BPF from a 60-turbine wind farm has been recently measured using particularly sensitive equipment as far as 90 km from the source (Marcillo et al., 2015).

Second, IS and LF have wavelengths comparable with the dimensions of building structures such as homes which also allows for resonant interactions with those structures. Recent high-resolution data recorded inside and outside dwellings demonstrate such building cavity resonance in the 10 - to 20-Hz range (Pedersen, Møller, & Waye, 2007; Schomer et al., 2015; Zajamšek et al., 2016) along with other building resonances over a 2- to 80-Hz range. Third, sound attenuation provided by building walls is much less at low frequencies compared with higher frequency sounds (K. L. Hansen, Hansen, & Zajamšek, 2015; Thorsson et al., 2018) and very irregular because of the building resonances. These two observations indicate that exterior measures of LF and IS pressure are not necessarily good predictors of interior sound pressures as these are dependent on the particular characteristics of the structure.

Accurate measures of the sound pressure levels of LF and IS around WTs is complicated because of the very long wavelengths of sound at such low frequencies, and the high susceptibility of measurement microphones to atmospheric turbulence (i.e., wind noise). Special strategies such as very high performance wind-shields (Dauchez, Hayot, & Denis, 2016; K. Hansen, Zajamsek, & Hansen, 2014; Turnbull, Turner, & Walsh, 2012; Zajamšek et al., 2016) and the use of microphone arrays with sophisticated signal processing (Walker, 2013) are needed. There is a complex relationship between the wind speed and angle of incidence, atmospheric conditions, terrain, distance to the source and the number and distribution of sources, and the measurement of LF and IS (for an excellent review, see Van den Berg, 2006). External measures are complicated by wind noise and other interactions with the measuring instrument. The greater majority of measurements are external (rather than internal where the greatest disability is reported) and use A weighting which effectively filters out LF and IS frequencies. Even lower pass weightings (e.g., C weighting) exclude crucial low frequencies particularly at the BPF and first few harmonics. Measures made external to dwellings are not necessarily good predictors of dwelling interior pressures where people spend the majority of their time (particularly sleeping). In turn, internal measurements are also complicated, and often avoided by acousticians because of the influence of the room modes and occupational sources of noise, such as refrigerators and other household equipment. That there is a wide range of reported levels of LF and IS in and around wind farms should not be surprising, given the diversity of relevant factors (e.g., cf. Jung et al., 2008; Schomer et al., 2015; Sugimoto et al., 2008; Van den Berg, 2006). Given some of the physiological work reviewed later (particularly that relating to hydrops and basilar membrane biasing), use of a dosimetry approach to LF and IS exposure may prove a more appropriate measure for determining human exposure although this would require the development of new equipment and measurement techniques.

Sound Pressure Weighting Scales and WTN

The abovementioned considerations indicate that a complete understanding of sound energy emitted by WTs requires careful measurement and modeling approaches that are sensitive to the full range of possible sound frequencies. While the current practice of measuring and analyzing WTN using an A-weighted correction offers convenience and practicality, it will necessarily filter out much of the LF energy actually emitted by a WT. This approach appears to be motivated by practical measurement considerations and the assumption that, from the point of view of human perception, the auditory system sensitivity to sound level (loudness perception) is nonlinear and rolls off very sharply for frequencies below 1 kHz reaching −50 dB by 20 Hz (Keith et al., 2016; Yokoyama, Sakamoto, & Tachibana, 2014). These authors also argued that the A-weighted sound level of a wind farm is highly correlated with the sound levels of the LF and IS, and so A-weighted measures could act as a proxy for LF and IS levels. This supposition is, however, based on 1/3 octave C-weighted measures extending only to 16 Hz which is well above the BPF and it is not consistent with some recent data (e.g., Hansen, Walker, Zajamsek, & Hansen, 2015; Schomer et al., 2015). As reviewed earlier, there are also complicating factors relating to the potential difference in the propagation of IS and LF compared with the middle to high frequencies to which humans are sensitive. This suggests that, even if A-weighted measures are correlated with the total WT energy at a particular point in space, this may not provide an adequate indication of the relative sound levels at other distances from the source (see also Moller & Pedersen, 2011).

There is clearly a need for more research and development of methods to accurately measure and assess the level of exposure of individuals to LF and IS particularly in the built environment where individuals live and sleep. To be clear, in the first instance, this work needs to focus on the collection of high-quality scientific data to provide insights into the mechanisms and processes in play. While this may subsequently have implications for methods of making acoustic measurements in the field, the emphasis first needs to be on collecting high-quality scientific data to address the questions of sound propagation and human exposure.

Perceptual Sensitivity

Perceptual sensitivity to LF and IS has been studied for more than 80 years (reviewed in Moller & Pedersen, 2004), and although there is no international standard, the experimental data are in good agreement. Threshold rises sharply from 80 dB (SPL) at 20 Hz to around 124 dB SPL at 2 Hz and the perceptual effects also include vibration and the sensation of pressure at the ear drums. Consistent with these data, Yokoyama et al. (2014) showed that listeners were insensitive to resynthesized WTN in the laboratory at levels up to 56 dBA.

For a variety of biomechanical and other physiological reasons, the cochlea is known to be a highly nonlinear transducer. Given the relatively high sound levels required to achieve perceptual response to IS, the question arises as to whether this represents neural transduction at the fundamental frequency or sensitivity to nonlinear distortion products produced on the basilar membrane. While mechanisms of transduction are considered in more detail later, recent functional magnetic resonance imaging (fMRI) data (Dommes et al., 2009; Weichenberger et al., 2015) show auditory cortical activation to a 12-Hz tone at thresholds that are broadly consistent with those reviewed by Moller and Pederson (2004). This indicates that, regardless of whether IS is transduced as a fundamental or as a consequence of nonlinear distortion products, it does lead to activation of the auditory cortex providing a primary neural representation of these acoustic stimuli.

A more recent fMRI study (Weichenberger et al., 2017) took a different analytical approach using a regional homogeneity resting mode analysis and a relatively prolonged (200 s) 12-Hz stimulus. They report that subliminal sound levels (2 dB below measured threshold) also activated brain regions known to be involved in autonomic and emotional processing: In particular, the anterior cingulate cortex and amygdala—the latter is believed to be involved with stress and anxiety-related psychiatric disorders. The amygdala is also part of the nonleminiscal auditory pathway that mediates subcortical processing and has input to the reticular activating system, a key component regulating arousal and sleep (for discussion, see Weichenberger et al., 2017). This latter observation provides some explanation as to how subliminal IS stimulation could lead to arousal and potentially mediate sleep disturbances reported by some individuals.

Related to the question of individual differences, Moller and Pedersen (2004) make the observation that the dynamic range of the auditory system decreases significantly at low frequencies, demonstrated in the extreme compression of the equal loudness contours at 2 Hz (20–80 phon from 130 to 140 dB). This indicates that even small changes in pressure can result in very large changes in loudness perception. Likewise, small variations in threshold between individuals could produce significant differences in perceived loudness for the same pressure level stimulus. This would also result in differences in suprathreshold levels which, when taken in the context of the recent report of Weichenberger et al., could in turn explain some of the individual differences in reported physiological effects of WTN. A simple test of this prediction would be to measure the IS thresholds of individuals reporting physiological effects of exposure to WTN compared with those who report no effects under the same exposure conditions. If this proved to be discriminatory, then simple IS threshold measures would provide an indicator of likely susceptibility to WTN. Such measurements could involve perceptual impressions (Kuehler, Fedtke, & Hensel, 2015) or objective assessments such as fMRI (Weichenberger et al., 2017) or magnetoencephalogy (Bauer et al., 2013).

Physiological Transduction of LF and IS

Before considering the evidence for potential sensory or other transduction of LF and IS, it is useful to contextualize this discussion. As indicated in the Introduction section, a critical component in any argument attempting to link the sound level output from WTs (or any mechanical device) to ill health is the extent to which sound energy is able to influence the human body perceptually or somatically. If there is no influence, then it would be difficult to argue that reported health effects could be induced by sound or vibration. For instance, people in urban environments are exposed daily to significant qualities of low-level microwave radiation in the form of communications transmissions (radio, TV, cellular network, etc.) without any known effects of ill health (Valberg, Van Deventer, & Repacholi, 2007). This would likely be a consequence of the fact that, at these levels of exposure, microwave radiation is not an effective stimulus perceptually or somatically for the human body. By contrast, there is much debate and opinion as to whether the human nervous system is sensitive to the infrasonic and LF that is emitted by WTs. There are, unfortunately, very few peer-reviewed publications that consider the potential physiological mechanisms that might underlie sensory transduction of LF and IS. There is a much wider range of opinion pieces on the topic presented in a variety of formats (popular science magazines, newspaper articles, and self-published monographs and newsletters). Subsequently, we will consider principally reports or reviews in peer-reviewed scientific publications.

In a review in *Hearing Research*, Salt and Hullar (2010) outline a number of possible mechanisms by which the LF and IS could influence the function of the inner ear and lead to neural stimulation that may or may not be perceived as sound. These authors describe how, under normal physiological circumstances, the inner ear is remarkably insensitive to LF and IS. This results from the need to mechanically tune the sensory apparatus to sounds of greatest biological interest (in this case, from 100 Hz to a few kilohertz which is the range of human communication and of the inadvertent sounds of movement of predator or prey). Consequently, the anatomical structures of the cochlea would suffer significant damage in response to large mechanical displacements that would result from stimulation by even relatively low pressure LFs (for sounds of constant pressure, particle displacement is inversely proportional to frequency at +6 dB per octave).

There are three principal mechanisms providing this protective attenuation (see Figure 3; Salt & Hullar, 2010; for a very detailed review, see Dallos, 2012). First, the band-pass characteristics of the middle ear are roughly centered on 1 kHz and attenuate frequencies below that at 6 dB/octave. For a constant pressure, this inversely matches the increase in particle displacement so that for frequencies below 1 kHz, movement of the stapes and the amplitude of displacement input to the cochlea is constant. Second, low-frequency stimulation of the cochlea is reduced by the shunting of perilymph fluid between the chambers of the scala tympani and scala vestibuli through the helicotrema resulting in 6 dB/octave attenuation for frequencies less than 100 Hz. Third, the auditory transduction receptors, the inner hair cells (IHC) are sensitive to fluid velocity in the cochlea which results in a further attenuation of 6 dB octave below about 470 Hz. These three mechanisms add linearly to reduce stimulation of the IHC by 18 dB/octave between 100 Hz and 20 Hz.

Salt and Hullar (2010) make the important observation that as the outer hair cells (OHC) are sensitive to displacement (i.e., they are mechanically coupled and not fluid coupled to the tectorial membrane) which is constant for low frequencies, so even under physiologically normal conditions, at these low frequencies they should be stimulated at lower sound levels than the IHC. This prediction is borne out by the thresholds of endolymphatic potentials in the guinea pig cochlea to 5-Hz stimuli which represent strial current gated by OHC activity (Salt, Lichtenhan, Gill, & Hartsock, 2013). In contrast to the original estimates of OHC threshold (∼40 dB lower than IHC at 5 Hz; Salt & Hullar, 2010), gain calculations in the later work suggest that the human apical cochlea could be similarly activated at around 55 dB to 65 dB SPL (corresponding to −38 to −28 dBA). This surprisingly high level of sensitivity of

OHCs to LF (when compared with IHC activation and perceptual threshold) is strongly supported by recent work examining the spontaneous otoacoustic emissions in humans (Drexl, Krause, Gürkov, & Wiegrebe, 2016; see also Drexl, Otto, et al., 2016; Jeanson, Wiegrebe, Gürkov, Krause, & Drexl, 2017; Kugler et al., 2014). It has been known for quite some time using human distortion product otoacoustic emissions (e.g., Hensel, Scholz, Hurttig, Mrowinski, & Janssen, 2007) as well as in vivo animal data (Patuzzi, Sellick, & Johnstone, 1984) that LF and IS do affect cochlear processing and that the cochlea aqueduct does pass IS frequencies into the inner ear (Traboulsi & Avan, 2007). The perceptual and other downstream consequences, however, are still not well studied. The more recent focus on the modulation of OHC activity is likely to provide important insights as to the physiological effects of IS and LF on cochlear processing. While the sensory role of OHCs are currently not well understood, they do carry sensory information via Type-II afferent fibers into the brain and probably play a role in signaling the off-set bias (and therefore operating point) of the basilar membrane and therefore also affect IHC transduction.

Before considering the effects of possible dysfunction of this system, it is worth summarizing the implications mentioned earlier. The healthy human ear significantly attenuates low-frequency input to the IHCs below around 100 Hz (~18 dB/octave). It is likely that at very low frequencies (<20 Hz), the OHCs are responding to stimuli at levels well below those producing activation of the IHCs. It is acoustic stimulation of the IHC which is the effective perceptual stimulus for hearing. Nonetheless, OHCs also have a sensory (afferent) input to the brain, although their stimulation is unlikely to lead to auditory perception per se. What is critical to emphasize at this juncture is that although the mechanisms outlined by Salt and Hullar (2010) are plausible and based on a large body of well-founded research, they do not by themselves constitute a demonstration of direct transduction of LF and IS by the inner ear. The effects of LF on OHC activity, however, could modulate transduction by the IHC, and such affects would likely be perceptible.

These data do provide, however, a strong prima facia case for neural transduction of LF and IS that needs to be properly examined at a functional and perceptual level in both animal and human models. Some critics of Salt and Hullar (2010) have argued that the level of LF and IS required to stimulate the OHCs is much greater than that recorded near wind farms. Given, however, the range of technical issues in making such acoustic measurements and the diversity of reported levels reviewed earlier, this claim is similarly limited by the available acoustic data. Furthermore, the recent work examining the guinea pig endocochlear potential (Salt et al., 2013) and human otoacoustic emissions (e.g., Drexl, Otto, et al., 2016; Kugler et al., 2014) indicate even greater levels of sensitivity of OHCs to LF when compared with the perceptual threshold mediated by IHC activity than first predicted. This suggests the need for a review of such conclusions.

Salt and Hullar (2010) also review the consequences of some pathologic conditions of the inner ear in terms of the potential to increase sensitivity to LF and IS. For instance, blockage or increased resistance of the helicotrema by a condition such as endolymphatic hydrops will reduce fluid shunting and reduce the attenuation for frequencies <100 Hz by up to 6 dB. Acute endolymphatic hydrops can be induced by exposure to low frequencies, although the relationship is complex and suggests that a dosimetry approach to exposure could be most informative. Hydrops would also lead to changes in the operating point of the basilar membrane resulting in a variety of changes in IHC sensory transduction including increased distortion. A further mechanism considered by Salt and Hullar is the increased fluid coupling of vestibular cells to sound input produced by changes in the input impedance of the vestibular system in conditions such as superior canal dehiscence (SCD), which can result in sound induced dizziness or vertigo, nausea, and nystagmus (Tullio phenomena).

Schomer et al. (2015) also examine potential physiological mechanisms that could mediate effects of LF and IS. They draw a link between the nauseogenic effects of low-frequency vestibular stimulation in seasickness and the potential vestibular stimulation by IS under normal listening conditions (as opposed to pathologic conditions of SCD). Using data collected by the U.S. Navy on nauseogenic effectiveness of low-frequency vestibular stimulation produced by whole body motion, they found significant overlap between the most effective nauseogenic frequencies and BPF of modern and larger WTs. Using a first-order model, they also demonstrate a better than order of magnitude equivalence between the force applied to the otoconia in the vestibular apparatus produced by whole body motion of 0.7 Hz at 5 m/s^2 peak and by IS of 0.7 Hz at 54 dB (SPL). Building on previous anatomical work (Uzun-Coruhlu, Curthoys, & Jones, 2007), Schomer et al. argue that pressure normal to the surface of the macular in the inner ear will provide an effective stimulus to the vestibular hair cells in the same way as the sheer motion between the otoconial membrane produced during linear acceleration of the head. While a plausible explanation, it is important to recognize that this suggestion is highly speculative and no data have yet been provided to support this latter assertion. Leventhall (2015) has also questioned this model although not in a peer-reviewed forum. Of note, however, the comparison with seasickness does add to the argument that a dosimetric approach to exposure may be more appropriate than measures of peak or root-mean-square sound pressure.

Perceptual Effects of Laboratory Exposure to LF and IS

A number of laboratory studies have directly exposed human listeners to IS and LF (e.g., Crichton, Dodd, Schmid, Gamble, & Petrie, 2014; Tonin, Brett, & Colagiuri, 2016) either directly recorded from WT (e.g., Yokoyama et al., 2014) or synthesized to reproduce key elements of these recordings (e.g., Tonin et al., 2016). A range of exposure symptoms have been reported but no systematic or significant effects of IS and LF have been demonstrated.

In general, sample sizes have been relatively small (e.g., $n = 2$, Hansen, Walker, et al., 2015; $n = 72$, Tonin et al., 2016) with studies likely to be statistically under powered (see Supplementary Material). Exposure times have been in the order of minutes to a few 10 s of minutes with a diversity of presentation levels above and below the IS/LF levels reported in the field.

Some free field stimulus playback systems have failed to deliver sound at the BPF and low-order harmonics frequencies (Yokoyama et al., 2014) while others have used headphone playback (Tonin et al., 2016). Many studies have not been blinded or double blinded, while others have been specifically designed to examine the effects of demand characteristics by manipulating expectancy (e.g., Crichton et al., 2014; Tonin et al., 2016). The latter studies have demonstrated, unsurprisingly, that manipulation of expectancy regarding the physiological effects of WT IS and LF has a moderate effect on the number and strength of symptoms reported by subjects regardless of the noise exposure conditions. Interestingly, Tonin et al. (2016) also report in their double-blind study that the presence of IS increased concern about health effects of WTN-expressed postexposure although subjects reported not hearing the IS stimulus.

In summary, there appears a prima facia case for the existence of sensory transduction of LF and IS and its representation in the nervous system. While a number of plausible mechanisms have been proposed, the actual mechanism of transduction has yet to be demonstrated. There are some laboratory-based studies examining the exposure to either recorded or simulated WTN, but the current data regarding potential perceptual or physiological are inconclusive.

General Summary and Conclusions

Although not an exhaustive survey of this literature, this review indicates that there are questions relating to the measurement and propagation of LF and IS and its encoding by the central nervous system (e.g., Dommes et al., 2009; Weichenberger et al., 2017) that are relevant to the possible perceptual and physiological effects of WTN but for which we do not have a good scientific understanding. There is much contention and opinion in these areas that, from a scientific perspective, are not well founded in the data, simply because there are little data available that effectively address these issues. This justifies a clear call to action for resources and support to promote high-quality scientific research in these areas.

Some of the research questions that arise from this review include the need for the following:

1. A more complete characterization and modeling of the sound generated by individual WTs and the large aggregations that comprise the modern windfarm. Such research needs to consider the spectrum from the BPF to its higher harmonics and incorporate the different propagation models that apply to different frequency ranges along with the effects of terrain, atmospheric conditions, and other potential modifiers of the sound.
2. The development of a more complete understanding of the interactions between WTN and the built structures in which people live and sleep. Such research needs to consider the different modes of excitation including substrate vibration, cavity resonances (including Helmholtz resonance and the interconnection of rooms), and differential building material sound insulation. New methods need to be developed for accurately and effectively measuring acute and chronic exposure (dosimetry) and for managing wind and other interference in the measurements.
3. Structural and aeronautic engineering research to discover ways to minimize the BPF generation and other potentially annoying sound sources.
4. Research to directly examine the effects of IS on the cochlea and vestibular apparatus. Although different theories have been advanced as to how IS and LF might be transduced and excite the central nervous system, there are little direct data demonstrating whether and how this occurs.
5. Research to better understand the neural connectivity of the putative transducers in the inner ear and an understanding of the consequences of their possible activation by IS and LF, notwithstanding the recent brain imaging data demonstrating differential activation of different brain structures (including the auditory cortex) by IS.
6. Research to better characterize the physiology of individuals who report susceptibility to WTN with a focus on whether these individuals represent a statistical tail of a normally distributed population or display other dysfunction or pathology that mediates susceptibility (e.g., SCD or lymphatic hydrops). In particular, an examination is required of the

hypothesis that small individual differences in threshold sensitivity to IS could underlie the differential activation of the anterior cingulate cortex and amygdala at subliminal sound levels.

This is not intended to be an exhaustive list of possible research areas. A research initiative to encourage and develop a very wide diversity of proposals is warranted as it is from the depth, capacity, and ingenuity of the researchers that work in these areas that the insights and the most effective research questions will come.

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Low frequency noise and infrasound from wind turbines

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A common issue raised with wind energy developers and operators of utility-scale wind turbines is whether the operation of their wind turbines may create unacceptable levels of low frequency noise and infrasound. In order to answer this question, one of the major wind energy developers commissioned a scientific study of their wind turbine fleet. The study consisted of three parts: 1) a world-wide literature search to determine unbiased guidelines and standards used to evaluate low frequency sound and infrasound, 2) a field study to measure wind turbine noise outside and within nearby residences, and 3) a comparison of the field results to the guidelines and standards. Wind turbines from two different manufacturers were measured at an operating wind farm under controlled conditions with the results compared to established guidelines and standards. This paper presents the results of the low frequency noise and infrasound study. Since the purpose of this paper is to report on low frequency and infrasound emissions, potential annoyance from other aspects of wind turbine operation were not considered, and must be evaluated separately.

Primary subject classification: 14.5.4; Secondary subject classification: 21.8.1

1 INTRODUCTION

Early down-wind wind turbines in the US created low frequency noise; however current up-wind wind turbines generate considerably less low frequency noise. Epsilon Associates, Inc. ("Epsilon") was retained by NextEra Energy Resources, LLC ("NextEra"), formerly FPL Energy, to investigate whether the operation of their wind turbines may create unacceptable levels of low frequency noise and infrasound. This question has often been posed to NextEra, and other wind energy developers and operators of utility-scale wind turbines. NextEra is one of the world's largest generators of wind power with approximately 7,600 net megawatts (MW) in operation as of July 2010.

The project was divided into three tasks: 1) literature search, 2) field measurement program, and 3) comparison to criteria. Epsilon conducted an extensive literature search of the technical and scientific literature on the effects of low-frequency noise and infrasound and existing criteria in order to evaluate low-frequency noise and infrasound from wind turbines. After completion of the literature search and selection of criteria, a field measurement program was developed to measure wind turbine noise to compare to the selected criteria.

The frequency range 20–20,000 Hz is commonly described as the range of "*audible*" noise. The frequency range of low frequency sound is generally from 20 Hertz (Hz) to 200 Hz, and the range below 20 Hz is often described as "*infrasound*". However, audibility extends to frequencies below 20 Hz.

Low frequency sound has several definitions. American National Standards ANSI/ASA S12.2[1] and ANSI S12.9 Part 4[2] have provisions for evaluating low frequency noise, and these special treatments apply only to sounds in the octave bands with 16, 31.5, and 63-Hz mid-band frequencies. For these reasons, in this paper on wind turbine noise, we use the term "low frequency noise" to include 12.5 Hz–200 Hz with emphasis on the 16 Hz, 31 Hz and 63 Hz octave bands with a frequency range of 11 Hz to 89 Hz.

International Electrotechnical Commission (IEC) standard 60050-801:1994[3] defines "*infrasound*" as "Acoustic oscillations whose frequency is below the low frequency limit of audible sound (about 16 Hz)." This definition is *incorrect* since sound remains audible at frequencies well below 16 Hz provided that the sound level is sufficiently high. In this paper we define infrasound to be below 20 Hz, which is the limit for the standardized threshold of hearing. Since there is no sharp

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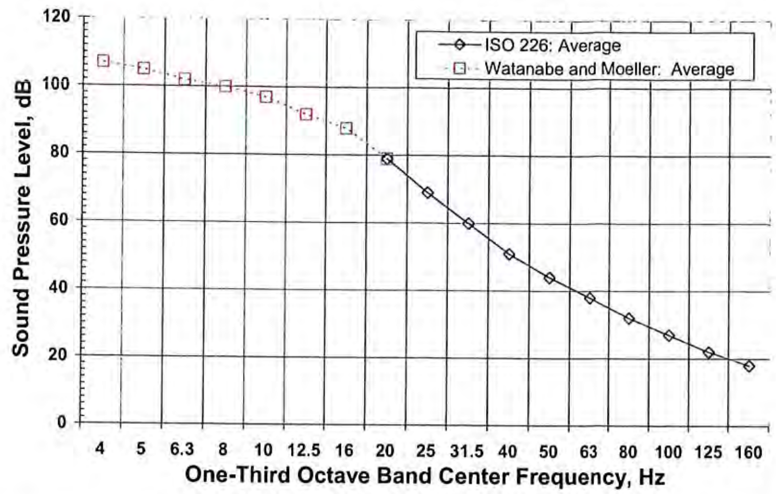

Fig. 1—Low frequency average threshold of hearing from ISO 226[6] and Watanabe and Moeller[7].

change in hearing at 20 Hz, the division into "low-frequency sound" and "infrasound" should only be considered "practical and conventional."

2 EFFECTS AND CRITERIA OF LOW FREQUENCY SOUND AND INFRASOUND

We performed an extensive world-wide literature search of over 100 scientific papers, technical reports and summary reports on low frequency sound and infrasound—hearing, effects, measurement, and criteria. Leventhall[4] presents an excellent and comprehensive study on low frequency noise from all sources and its effects. The Leventhall report also presents criteria in place at that time, which does not include some of the more recently developed ANSI/ASA standards on outdoor environmental noise and indoor sounds.

The United States government does not have specific criteria for low frequency noise. The US Environmental Protection Agency (EPA) has guidelines for the protection of public health with an adequate margin of safety in terms of annual average A-weighted day-night average sound level (L_{dn}), but there are no corrections or adjustments for low frequency noise. The US Department of Transportation (DOT) has A-weighted sound pressure level criteria for highway projects and airports, but these do not have adjustments for low frequency noise. The following sections describe the low frequency and infrasound criteria to which wind turbine sounds are compared in later sections.

2.1 Threshold of Hearing and Audibility

Moeller and Pedersen[5] present an excellent summary on human perception of sound at frequencies below 200 Hz. The ear is the primary organ for sensing infrasound. Hearing becomes gradually less sensitive for decreasing frequencies. But, humans with a normal hearing organ can perceive infrasound at least down to a few hertz if the sound level is sufficiently high.

The threshold of hearing is standardized for frequencies down to 20 Hz[6]. Based on extensive research and data, Moeller and Pedersen propose normal hearing thresholds for frequencies below 20 Hz; however, their proposed threshold is higher than that obtained by Watanabe and Moeller[7]. To be conservative, we have used the data from Watanabe and Moeller[7] for the region below 20 Hz. (See Fig. 1.) Moeller and Pedersen[5] suggest that the curve for low frequency thresholds for normal hearing is "probably correct within a few decibels, at least in most of the frequency range."

The hearing thresholds show considerable variability from individual to individual with a standard deviation among subjects of about 5 dB independent of frequency between 3 Hz and 1000 Hz with a slight increase at 20–50 Hz. This implies that the audibility threshold for 97.5% of the population is greater than the values in Fig. 1 minus 10 dB and for 84% of the population is greater than the values in Fig. 1 minus 5 dB. Moeller and Pedersen suggest that the "pure-tone threshold can with a reasonable approximation be used as a guideline for the thresholds also for [low frequency] non-sinusoidal sounds"[5]; ISO 226 has thresholds for frequencies at and above 20 Hz and approximately equates the thresholds and equal loudness contours for non-sinusoidal sounds to those in the standard for sinusoidal sounds[6].

As frequency decreases below 20 Hz, if the noise source is tonal, the tonal sensation ceases. Below 20 Hz tones are perceived as discontinuous. Below 10 Hz it is possible to perceive the single cycles of a tone, and the perception changes into a sensation of pressure at the ears.

Below 100 Hz, the dynamic range of the auditory system decreases with decreasing frequency, and the compressed dynamic range has an effect on equal loudness contours: a slight change in sound level can change the perceived loudness from barely audible to loud. This combined with the large variation in individual hearing may mean that a low frequency sound that is inaudible to some may be audible to others, and may be relatively loud to some of those for whom it is audible. Loudness for low frequency sounds grows considerably faster above threshold than for sounds at higher frequencies[5].

Non-auditory perception of low frequency and infrasound occurs only at levels above the auditory threshold. In the frequency range of 4–25 Hz and at "*levels* 20–25 dB *above [auditory] threshold it is possible to feel vibrations* in various parts of the body, e.g., the lumbar, buttock, thigh and calf regions. A feeling of pressure may occur in the upper part of the chest and the throat region" [emphasis added][5].

2.2 ANSI S12.9-Parts 4 and 5—Evaluating Outdoor Environmental Sound

American National Standard ANSI/ASA S12.9-2007/Part 5[8] has an informative annex which provides guidance for designation of land uses compatible with existing or predicted annual average adjusted day-night average outdoor sound level (DNL). Ranges of the DNL are outlined, within which a specific region of compatibility may be drawn. These ranges take into consideration the noise reduction in sound level from outside to inside buildings as commonly constructed in that locality and living habits there. There are adjustments to day-night average sound level to account for the presence of low frequency noise, and the adjustments are described in ANSI S12.9 Part 4, which use a sum of the sound pressure levels in octave bands with center frequencies of 16, 31 and 63 Hz.

ANSI S12.9/Part 4 identifies two thresholds: annoyance is minimal when the 16, 31.5 and 63 Hz octave band sound pressure levels are each less than 65 dB and there are no rapid fluctuations of the low frequency sounds. The second threshold is for increased annoyance which begins when rattles occur, which begins at L_{LF} 70–75 dB. L_{LF} is 10 times the logarithm of the ratio of time-mean square sound pressure in the 16, 31.5, and 63-Hz octave bands divided by the square of the reference sound pressure.

The adjustment procedure for low frequency noise to the average annual A-weighted sound pressure level in ANSI S12.9/Part 4 uses a different and more complicated metric and procedure (Equation D.1) than those used for evaluating low frequency noise in rooms contained in ANSI/ASA S12.2. (See Sec. 2.3). Since we are evaluating low frequency noise and not A-weighted sound levels, we do not recommend using the procedure for adjusting A-weighted levels. Instead we recommend using the following two guidelines from ANSI S12.9/Part 4: a sound pressure level of 65 dB in each of the 16-, 31.5-, and 63 Hz octave bands as an indicator of minimal annoyance, and 70–75 dB for the summation of the sound pressure levels from these three bands as an indicator of possible increased annoyance from rattles.

2.3 ANSI/ASA S12.2—Evaluating Room Noise

ANSI/ASA S12.2-2008[1] discusses criteria for evaluating room noise, and has two separate provisions for evaluating low frequency noise: (1) the potential to cause perceptible vibration and rattles, and (2) meeting low frequency portions of room criteria curves. Since the ANSI S12.2 criteria are for indoor sounds, in order to determine equivalent outdoor criteria for comparison to outdoor measurements, data from Sutherland[9] and Hubbard and Shephard[10] were used to determine typical noise reductions from outdoor to indoor with windows open. (The Appendix of this paper describes the noise reductions used to determine equivalent outdoor criteria to indoor criteria.) Table A1 presents octave band noise reductions applied in this evaluation along with the average low frequency octave band noise reductions from outdoor to indoors from Refs. 9 and 10 for open and closed windows. Table A2 presents the one-third octave band noise reductions applied in the analysis that were determined in the same manner using data from the same references.

Vibration and Rattles: Outdoor low frequency sounds of sufficient amplitude can cause building walls to vibrate and windows to rattle. Homes have low values of transmission loss at low frequencies, and low frequency noise of sufficient amplitude may be audible within homes. Window rattles are not low frequency noise, but may be caused by low frequency noise. ANSI/ASA S12.2 presents limiting levels at low frequencies for assessing (a) the probability of *clearly* perceptible acoustically induced vibration and rattles in lightweight wall and ceiling constructions, and (b) the probability of *moderately* perceptible acoustically induced vibration in similar constructions. The limiting sound pressure levels in the octave bands with center frequencies of 16, 31.5 and 63 Hz are presented in Table 1.

Applying the outdoor to indoor attenuations for wind turbine sources with windows open given in the last row of Table A1 to the ANSI/ASA S12.2 indoor sound pressure levels in Table 1 yields the equivalent

Table A1—Average low frequency octave band home noise reductions from outdoor to indoors in dB (from Ref. 9 and 10).

Noise Source	Window condition	Octave Band Center Frequency 16 Hz	31.5 Hz	63 Hz	125 Hz
Average aircraft and traffic sources	Closed windows	16	15	18	20
Average aircraft and traffic sources	Open windows	(11)*	(10)*	12	11
Average Wind Turbine	Closed windows	8	11	14	18
Average Wind Turbine	Open windows	(3)*+	(6)*+	9+	9+

* No data are available for windows open below 63 Hz octave band. The values for 16 Hz and 31 Hz were obtained by subtracting the difference between the levels for 63 Hz closed and open conditions to the 16 and 31 Hz closed values.
+ Used in this paper to determine equivalent outdoor criteria from indoor criteria in Tables 2 and 4

outdoor sound pressure levels that are consistent with the indoor criteria and are presented in Table 2.

Room Criteria Curves: ANSI/ASA S12.2 has three primary methods for evaluating the suitability of noise within rooms: a survey method—A-weighted sound levels, an engineering method—noise criteria (NC) curves, and a method for evaluating low-frequency fluctuating noise using room noise criteria (RNC) curves. ANSI/ASA S12.2 states "The RNC method should be used to determine noise ratings when the noise from HVAC systems at low frequencies is loud and is suspected of containing sizeable *fluctuations or surging*." [emphasis added] The NC curves are appropriate to evaluate low frequency noise from wind turbines in homes since wind turbine noise does not have significant fluctuating low frequency noise sufficient to warrant using RNC curves and since A-weighted sound levels do not adequately determine

Table A2—Average low frequency one-third octave band noise reduction in dB for homes from outdoor to indoors.

Condition	One-Third Octave Band Center Frequency, Hz 10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
Open Window*	2	2	3	4	4.5	5	7	8	9	9	9	9	9
Average Closed Window with wind turbines[10] **	8	7	8	8	8	11	13	14	15	12	18	18	18

* Used to determine equivalent outdoor levels as shown in Table 7.
** Used to determine equivalent outdoor levels as shown in Table 9.

Table 1—ANSI/ASA S12.2 measured interior sound pressure levels for perceptible vibration and rattle in lightweight wall and ceiling structures.[1]

Condition	Octave-band center frequency (Hz) 16	31.5	63
Clearly perceptible vibration and rattles likely	75 dB	75 dB	80 dB
Moderately perceptible vibration and rattles likely	65 dB	65 dB	70 dB

Table 2—Equivalent outdoor sound pressure levels to the ANSI/ASA S12.2 indoor sound pressure levels for perceptible vibration and rattle in lightweight wall and ceiling structures for wind turbines.

Condition	Octave-band center frequency (Hz) 16	31.5	63
Clearly perceptible vibration and rattles likely	78 dB	81 dB	89 dB
Moderately perceptible vibration and rattles likely	68 dB	71 dB	79 dB

if there are low frequency problems. [ANSI/ASA S12.2, Sec. 5.3 gives procedures for determining if there are large fluctuations of low frequency noise.]

Annex C.2 of ANSI/ASA S12.2 contains recommended room criteria curves for bedrooms, which are the rooms in homes with the most stringent criteria: NC and RNC criteria curve between 25 and 30. The recommended NC and RNC criteria for schools and private rooms in hospitals are the same. The values of the sound pressure levels in the 16–125 Hz octave bands for NC curves 25 and 30 are shown in Table 3. Applying the outdoor to indoor attenuations for wind turbine sources with windows open given in the last row of Table A1 to the ANSI/ASA S12.2 indoor sound pressure levels for NC-25 and NC-30 in Table 3 yields the equivalent outdoor sound pressure levels that are consistent with the indoor criteria and are presented in Table 4.

ANSI/ASA S12.2 also presents a method to determine if the levels below 500 Hz octave band are too high in relation to the levels in the mid-frequencies which could create a condition of "spectrum imbalance". The method for this evaluation is:

- Calculate the speech interference level (SIL) for the measured spectrum. [SIL is the arithmetic average of the sound pressure levels in the 500, 1000, 2000 and 4000 Hz octave bands.] Select the NC curve equal to the SIL value with a symbol NC(SIL).
- Plot the measured spectra and the NC curve equal to the SIL value on the same graph and determine the differences between the two curves in the octave bands below 500 Hz.
- Estimate the likelihood that the excess low-frequency levels will annoy occupants of the space using Table 5.

Table 3—ANSI/ASA S12.2 low frequency octave band sound pressure levels for noise criteria curves NC-25 and NC-30. [Table 1 from Ref. 1].

NC Criteria	Octave-band-center frequency, Hz 16	31.5	63	125
NC-25	80	65	54	44
NC-30	81	68	57	48

2.4 Other Criteria

2.4.1 World Health Organization (WHO)

No specific low frequency noise criteria are proposed by the WHO. The Guidelines for Community Noise report[11] mentions that if the difference between

Table 4—Equivalent outdoor sound pressure levels to the ANSI/ASA S12.2 low frequency octave band sound pressure levels for noise criteria curves NC-25 and NC-30. [Table 1 from Ref. 1].

NC Criteria	Octave-band-center frequency, Hz 16	31.5	63	125
NC-25 equivalent outdoor	83	71	63	53
NC-30 equivalent outdoor	84	74	66	57

Table 5—Measured sound pressure level deviations from an NC (SIL) curve that may lead to serious complaints[1].

Octave-band frequency, Hz=>	Measured Spectrum—NC(SIL), dB 31.5	63	125	250
Possible serious dissatisfaction	*	6–9	6–9	6–9
Likely serious dissatisfaction	*	>9	>9	>9

* Insufficient data available to evaluate

Table 6—DEFRA proposed criteria[13] for the assessment of low frequency noise disturbance: Indoor L_{eq} one-third sound pressure levels for non-steady and steady low frequency sounds.

	One-Third Octave Band Center Frequency, Hz												
Location	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
Non-Steady L_{eq}, dB	92	87	83	74	64	56	49	43	42	40	38	36	34
Steady L_{eq}, dB	97	92	88	79	69	61	54	48	47	45	43	41	39

the C-weighted sound level and A-weighted sound level is greater than 10 decibels, then a frequency analysis should be performed to determine if there is a low frequency issue. A document prepared for the World Health Organization states that "there is no reliable evidence that infrasounds below the hearing threshold produce physiological or psychological effects. Infrasounds slightly above detection threshold may cause perceptual effects but these are of the same character as for 'normal' sounds. Reactions caused by extremely intense levels of infrasound can resemble those of mild stress reaction and may include bizarre auditory sensations, describable as pulsation and flutter"[12].

2.4.2 The UK Department for Environment, Food, and Rural Affairs (DEFRA)

The report prepared by the University of Salford for the UK Department for Environment, Food, and Rural Affairs (DEFRA) on low frequency noise proposed one-third octave band sound pressure level L_{eq} criteria and procedures for assessing low frequency noise[13]. The guidelines are based on complaints of disturbance from low frequency sounds and are intended to be used by Environmental Health Officers.

Existing low frequency noise criteria from several countries were reviewed and experiences with low frequencies complaints were considered in developing the proposed guidelines. The criteria are "based on 5 dB below the ISO 226 average threshold of audibility for steady [low frequency] sounds." However, the DEFRA criteria are at 5 dB lower than ISO 226 only at 20–31.5 Hz; at higher frequencies the criteria are equal to the Swedish criteria which are higher levels than ISO 226 less 5 dB. For frequencies lower than 20 Hz, DEFRA uses the thresholds from Ref. 7 less 5 dB.

The DEFRA criteria are based on measurements in an unoccupied room, and it was noted by a practicing consultant that measurements should be made with windows closed[14]. However, we conservatively used windows open conditions for our assessment to determine equivalent outdoor criteria since the DEFRA measurement procedure does not explicitly state measurements are with windows closed. If the low frequency sound is "steady" then the criteria may be relaxed by 5 dB. A low frequency noise is considered steady if either $L_{10}-L_{90} < 5$ dB or the rate of change of sound pressure level (Fast time weighting) is less than 10 dB per second in the third octave band which exceeds the criteria by the greatest margin.

Applying indoor to outdoor one-third octave band transfer functions for open windows (as presented in Table A2 from analysis of data in Refs. 9 and 10) yields *equivalent* one-third octave band sound pressure level proposed DEFRA criteria for outdoor sound levels. Table 6 presents the indoor DEFRA proposed criteria for non-steady and steady low-frequency sounds. Table

Table 7—Equivalent outdoor L_{eq} one-third sound pressure levels for non-steady and steady sounds to the DEFRA indoor criteria[13] for the assessment of low frequency noise disturbance.

	One-Third Octave Band Center Frequency, Hz												
Location	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
Non-Steady Equivalent outdoor * L_{eq}, dB	94	89	86	78	68.5	61	56	51	51	49	47	45	43
Steady Equivalent Outdoor* L_{eq},	99	94	91	83	73.5	66	61	56	56	54	52	50	48

* With windows open

Table 8—Japan Ministry of Environment Guidance for evaluating complaints of low frequency noise: Reference one-third octave band sound pressure level values for complaints of rattling.

Location	One-Third Octave Band Center Frequency, Hz										
	5	6.3	8	10	12.5	16	20	25	31.5	40	50
Outdoor L_{eq}, dB	70*	71*	72*	73	75	77	80	83	87	93	99

* The reference values are several dB lower than the supporting data contained in Ref. 15. At 5 Hz, window rattles started at about 74 dB in one study and 79 dB in another; at 6.3 Hz, rattles started at 74 dB in the first study and at 78 dB in the second; and at 8 Hz, window rattle started at 74 dB in the first study and 77 dB in the second study.

7 presents the DEFRA equivalent outdoor criteria for non-steady and steady low frequency sounds.

2.4.3 Japan Ministry of Environment

The Japan Ministry of Environment has published a handbook to deal with low frequency noise problems and has established reference values for guidance in dealing with complaints of rattling windows and doors and complaints of "mental and physical discomfort"[15]. It was noted that traditional Japanese houses have relatively light-weight and sensitive windows and partitions[16].

Table 8 presents the Japanese reference outdoor one-third octave band sound pressure level values for guidance in dealing with complaints of rattling from environmental sounds from 5 Hz to 50 Hz. From 10 Hz to 50 Hz the guidance levels are equal to the observed threshold of rattles from two studies with a total of 78 samples. However, for the bands centered at 5, 6.3 and 8 Hz, the reference values are several dB lower than the supporting data contained in these two studies[15]. At 5 Hz, the lowest observed window rattle was at 74 dB in one study and 79 dB in another; at 6.3 Hz, rattles started at 74 dB in the first study and at 78 dB in the second; and at 8 Hz, window rattle started at 74 dB in the first study and 77 dB in the second study. Thus the reference values at 5, 6.3 and 8 Hz in Table 8 are conservative in comparison to the other values by 4, 3, and 2 dB respectively.

Table 9 presents the Japanese reference one-third octave band sound pressure level values for guidance in dealing with complaints of mental and physical discomfort from environmental sounds when evaluated indoors. Evaluation measurements are to be performed with windows closed to the outside. The values in Table 9 are less stringent than the DEFRA values in Table 6 for non-steady sounds but more stringent than the DEFRA values for steady sounds in some one-third octave bands. In order to obtain equivalent outdoor sound levels, the average noise reduction from wind turbine noise with windows closed from Ref. 10 was applied to the Japan reference values. Table 9 presents the Japanese indoor reference values, the noise reductions for windows closed[10] and the equivalent outdoor reference values. These equivalent outdoor values are less stringent than the equivalent outdoor DEFRA values in Table 7 for both non-steady sounds and steady sounds except for the 80 Hz band in which the Japanese level is 1 dB more stringent than the DEFRA level for steady sounds.

2.4.4 C-weighted minus A-weighted ($L_{pC}-L_{pA}$)

Leventhall[4] and others indicate that the difference in C-weighted and A-weighted sound pressure levels can be a predictor of annoyance. Leventhall states that if ($L_{pC}-L_{pA}$) is greater than 20 dB there is "a potential for a low frequency noise problem." He further states that ($L_{pC}-L_{pA}$) cannot be a predictor of annoyance but is a simple indicator that further analysis may be needed. This is due in part to the fact that the low frequency noise may be inaudible even if ($L_{pC}-L_{pA}$) is greater than 20 dB.

3 LITERATURE REVIEW

The authors performed an extensive literature search of over 100 scientific papers, technical reports and summary reports on low frequency sound and infrasound—hearing, effects, measurement, and criteria. The following paragraphs briefly summarize the findings from some of these papers and reports.

3.1 Leventhall

Leventhall[4] presents an excellent study on low frequency noise from all sources and its effects. The report presents criteria in place at that time and includes data relating cause and effects. Leventhall[17] reviewed data and allegations on alleged problems from low frequency noise and infrasound from wind turbines, and concluded the following: "It has been shown that there is insignificant infrasound from wind turbines and that there is normally little low frequency noise." "Turbulent air inflow conditions cause enhanced levels of low frequency noise, which may be disturbing, but the overriding noise from wind turbines is the fluctuating audible swish, mistakenly referred to

Table 9—Japan Ministry of Environment Guidance for evaluating complaints of low frequency noise: Reference one-third octave band sound pressure level values for complaints of mental and physical discomfort.

	One-Third Octave Band Center Frequency, Hz									
Location	10	12.5	16	20	25	31.5	40	50	63	80
Indoor L_{eq}, dB	92	88	83	76	70	64	57	52	47	41
Noise Reduction*, dB	8	7	8	8	8	11	13	14	15	12
Equivalent Outdoor L_{eq}, dB	100	95	91	84	78	75	70	66	62	53

* from Hubbard[10] windows closed condition

as "infrasound" or "low frequency noise". "Infrasound from wind turbines is below the audible threshold and of no consequence". Other studies have shown that wind turbine generated infrasound levels are below threshold of perception and threshold of feeling and body reaction.

3.2 DELTA

The Danish Energy Authority project on "low frequency noise from large wind turbines" comprises a series of investigations in the effort to give increased knowledge on low frequency noise from wind turbines[18]. One of the conclusions of the study is that wind turbines do not emit audible infrasound, with levels that are "far below the hearing threshold." Audible low frequency sound may occur both indoors and outdoors, "but the levels in general are close to the hearing and/or masking level." "In general the noise in the critical band up to 100 Hz is below both thresholds". The final report notes that for road traffic noise (in the vicinity of roads) the low frequency noise levels are higher [than wind turbine] both indoors and outdoors.

3.3 Hayes McKenzie Partnership

Hayes McKenzie Partnership Ltd performed a study for the UK Department of Trade & Industry (DTI) to investigate complaints of low frequency noise that came from three of the five farms with complaints out of 126 wind farms in the UK[14]. The study concluded that:

- Infrasound associated with modern wind turbines is not a source which will result in noise levels that are audible or which may be injurious to the health of a wind farm neighbor.
- Low frequency noise was measureable on a few occasions, but below DEFRA criteria. Wind turbine noise may result in indoor noise levels within a home that is just above the threshold of audibility; however, it was lower than that of local road traffic noise.
- The common cause of the complaints was not associated with low frequency noise but the occasional audible modulation of aerodynamic noise, especially at night.
- The UK Department of Trade and Industry, which is now the UK Department for Business Enterprise and Regulatory Reform (BERR), summarized the Hayes McKenzie report: "The report concluded that there is no evidence of health effects arising from infrasound or low frequency noise generated by wind turbines."[19].

3.4 Howe

Howe performed extensive studies on wind turbines and infrasound and concluded that infrasound was not an issue for modern wind turbine installations—"while infrasound can be generated by wind turbines, it is concluded that infrasound is not of concern to the health of residences located nearby."[20]. Since then Gastmeier and Howe[21] investigated an additional situation involving the alleged "perception of infrasound by individual." In this additional case, the measured indoor infrasound was at least 30 dB below the audibility threshold given by Ref. 7 as presented in Fig. 1.

3.5 Branco

Branco and other Portuguese researchers have studied possible physiological affects associated with high amplitude low frequency noise and have labeled these alleged effects as "Vibroacoustic Disease" (VAD)[22]. "Vibroacoustic disease (VAD) is a whole-body, systemic pathology, characterized by the abnormal proliferation of extra-cellular matrices, and caused by excessive exposure to low frequency noise."

Hayes[23,24] concluded that levels from wind farms are not likely to cause VAD after comparing noise levels from alleged VAD cases to noise levels from wind turbines in homes of complainers. Noise levels in aircraft in which VAD has been hypothesized are considerably higher than wind turbine noise levels. Hayes also concluded that it is "unlikely that symptoms will result through induced internal vibration from incident wind farm noise."[23]. Other studies have found no VAD indicators in environmental sound that have been alleged by VAD proponents[25].

3.6 French National Academy of Medicine

In 2006, the French National Academy of Medicine recommended[26] "*as a precaution* construction should be suspended for wind turbines with a capacity exceeding 2.5 MW located within 1500 m of homes." [emphasis added] However, this precaution is not because of definitive health issues but because:

- Sound levels one km from some wind turbine installations "occasionally exceed allowable limits" for France (note that the allowable limits are long term averages).
- French prediction tools for assessment did not take into account sound levels created with wind speeds greater than 5 m/s.
- Wind turbine noise has been compared to aircraft noise (even though the sound levels of wind turbine noise are significantly lower), and exposure to high level aircraft noise "involves neurobiological reactions associated with an increased frequency of hypertension and cardiovascular illness. Unfortunately, no such study has been done near wind turbines."[27].

In March 2008, the French Agency for Environmental and Occupational Health Safety (AFSSET) published a report on "the health impacts of noise generated by wind turbines", commissioned by the Ministries of Health and Environment in June 2006 following the report of the French National Academy of Medicine in March 2006[28]. The AFSSET study recommends that one does not define a fixed minimum distance between wind farms and homes, but rather to model the acoustic impact of the project on a case-by-case basis. One of the conclusions of the AFSSET report is: "The analysis of available data shows: The absence of identified direct health consequences concerning the auditory effects or specific effects usually associated with exposure to low frequencies at high level." ("L'analyse des données disponibles met en évidence: L'absence de conséquences sanitaires directes recensées en ce qui concerne les effets auditifs, ou les effets spécifiques généralement attachés à l'exposition à des basses fréquences à niveau élevé.").

4 FIELD PROGRAM

Two types of utility-scale wind turbines were studied for this field program. These two turbines are among the most commonly used in the NextEra fleet: General Electric (GE) 1.5sle (1.5 MW), and Siemens SWT-2.3-93 (2.3 MW).

Sound levels for these wind turbine generators (WTGs) vary as a function of wind speed from cut-in wind speed to maximum sound level. Cut-in wind speed for the GE 1.5sle wind turbine is 3.5 m/s while the Siemens wind turbine has a cut-in wind speed of 4 m/s. Maximum reference sound power levels for the GE 1.5sle and Siemens 2.3-93 are approximately 104 dB and 105 dB respectively as provided by the manufacturer. These sound power levels are reached at electrical output levels of approximately 924 kW and 1767 kW for the GE and Siemens units, respectively. Under higher wind speeds, the sound levels from the wind turbines do not increase although electrical power output does continue to increase up to the rated power of each wind turbine (1500 kW and 2300 kW respectively).

Each wind turbine manufacturer has an uncertainty factor "K" of 2 dB to guarantee the turbine's sound power level. (K accounts for both measurement variations and production variation[29].) The results presented later in this paper include sound power values which have added the manufacturer's K value to the reference values, that is, 2 dB above the expected reference levels for the measured wind conditions and power output.

Real-world data were collected from operating wind turbines to compare to the low frequency noise guidelines and criteria discussed previously in Sec. 2. These data sets consisted of outdoor measurements at various reference distances, and concurrent indoor/outdoor measurements at residences within the wind farm.

NextEra provided access to the Horse Hollow Wind Farm in Taylor and Nolan Counties, Texas in November 2008 to collect data on the GE 1.5sle and Siemens SWT-2.3-93 wind turbines. The portion of the wind farm used for testing is relatively flat with no significant terrain. The land around the wind turbines is rural and primarily used for agriculture and cattle grazing. The siting of the sound level measurement locations was chosen to minimize local noise sources except the wind turbines and the wind itself. Hub height for these wind turbines is 80 meters above ground level (AGL).

Two of the authors collected sound level and wind speed data over the course of one week under a variety of operational conditions. Weather conditions were dry the entire week with ground level winds ranging from calm to 12.5 m/s (28 mph) over a 1-minute average. In order to minimize confounding factors, the data collection tried to focus on periods of maximum sound levels from the wind turbines (moderate to high hub height winds) and light to moderate ground level winds.

Ground level (2 meters AGL) wind speed and direction were measured continuously at one representative location. Wind speeds near hub height were also measured continuously using the permanent meteorological towers maintained by the wind farm.

A series of simultaneous interior and exterior sound level measurements were made at four houses owned by participating landowners within the wind farm. Two sets were made of the GE WTGs, and two sets were made of the Siemens WTGs. Data were collected with both windows open and windows closed. Due to the necessity of coordinating with the homeowners in advance, and reasonable restrictions on time of day to enter their homes, the interior/exterior measurement data sets do not always represent ideal conditions. However, enough data were collected to compare to the criteria and draw conclusions on low frequency noise.

Sound level measurements were also made simultaneously at two reference distances from a string of wind turbines under a variety of wind conditions. Using the manufacturer's sound power level data, calculations of the sound pressure levels as a function of distance in flat terrain were made to aid in deciding where to collect data in the field. Based on this analysis, two distances from the nearest wind turbine were selected—305 meters (1,000 feet) and 457 meters (1,500 feet)—and were then used where possible during the field program. Distances much larger than 457 meters (1,500 feet) were not practical since an adjacent turbine string could then be closer and affect the measurements, or would put the measurements beyond the boundaries of the wind farm property owners. Brief background sound level measurements were conducted several times during the program whereby the Horse Hollow Wind Farm operators were able to shutdown the nearby WTGs for a brief (20 minutes) period. This was done in real time using cell phone communication.

All the sound level measurements described above were attended. One series of unattended overnight measurements was made at two locations for approximately 15 hours to capture a larger data set. One measurement was set up approximately 305 meters (1,000 feet) from a GE 1.5sle WTG and the other was set up approximately 305 meters (1,000 feet) from a Siemens WTG. The location was chosen based on the current wind direction forecast so that the sound level equipment would be downwind for the majority of the monitoring period. By doing this, the program was able to capture periods of strong hub-height winds and moderate to low ground-level winds.

All sound levels were measured using two Norsonic Model Nor140 precision sound analyzers, equipped with a Norsonic-1209 Type 1 Preamplifier, a Norsonic-1225 half-inch microphone and a 7-inch Aco-Pacific untreated foam windscreen Model WS7. The instrumentation meets the "Type 1—Precision" requirements set forth in American National Standards Institute (ANSI) S1.4 for acoustical measuring devices[30]. The microphone was tripod-mounted at a height of 1.5 meters (five feet) above ground. The measurements included simultaneous collection of broadband (A-weighted) and one-third-octave band data (3.15 hertz to 20,000 hertz bands). Sound level data were primarily logged in 10-minute intervals to be consistent with the wind farm's Supervisory Control And Data Acquisition (SCADA) system which provides electrical power output (kW) in 10-minute increments. A few sound level measurements were logged using 20-minute intervals for use in determining home transmission loss values. The meters were calibrated and certified as accurate to standards set by the National Institute of Standards and Technology. These calibrations were conducted by an independent laboratory within the past 12 months. Ground level wind speed and direction were measured with a HOBO H21-002 micro weather station (Onset Computer Corporation). The wind data were sampled every three seconds and logged every one minute.

5 RESULTS AND COMPARISON TO CRITERIA

Results from the field program are organized by wind turbine type. For each wind turbine type, results are presented per location type (outdoor or indoor) with respect to applicable criteria. Results are presented for 305 meters (1,000) feet from the nearest wind turbine. Data were also collected at 457 meters (1,500 feet) from the nearest wind turbine which showed lower sound levels. Therefore, wind turbines that met the criteria at 305 meters also met it at 457 meters. Data were collected under both high turbine output and moderate turbine output conditions (defined as sound power levels 2 or 3 dB less than the maximum sound power levels), and low ground-level wind speeds. The sound level data under the moderate conditions were equivalent to or lower than the high turbine output scenarios, thus confirming the conclusions from the high output cases. None of the operational sound level data were corrected for background noise. A-weighted sound power levels presented in this section (used to describe turbine operation) were estimated from the actual measured power output (kW) of the wind turbines and the sound power levels as a function of wind speed plus an uncertainty factor K of 2 dB.

Outdoor measurements are compared to criteria for audibility, for UK DEFRA disturbance using equivalent outdoor levels, for rattle and annoyance criteria as

Table 10—Summary of operational parameters—Siemens SWT-2.3-93 (Outdoor).

Parameter	Sample #34	Sample #39
Distance to nearest WTG	305 meters	305 meters
Time of day	22:00-22:10	22:50-23:00
WTG power output	1,847 kW	1,608 kW
A-weighted sound power level*	107 dB	106.8 dB
Measured wind speed @ 2 m	3.3 m/s	3.4 m/s
L_{Aeq}	49.4 dB	49.6 dB
L_{A90}	48.4 dB	48.6 dB
L_{Ceq}	63.5 dB	63.2 dB

* Includes K, uncertainty factor of 2 dB

contained in ANSI S12.9/Part 4, for evaluating complaints of rattling using Japan Ministry of Environment guidance, and for perceptible vibration using equivalent outdoor levels from ANSI/ASA S12.2. Indoor measurements are compared to criteria for audibility, for UK DEFRA disturbance, for evaluating complaints of mental and physical discomfort using Japan Ministry of Environment guidance, and for suitability of bedrooms, hospitals and schools and perceptible vibration from ANSI/ASA S12.2.

5.1 Siemens SWT-2.3-93

5.1.1 Outdoor measurements—Siemens SWT-2.3-93

Sound levels during six 10-minute periods of high wind turbine output and relatively low ground wind speed (which minimized effects of wind noise) were measured outdoors approximately 305 meters (1,000 feet) from the closest Siemens WTG. This site was actually part of a string of 15 WTGs, four of which were within 610 meters (2,000 feet) of the monitoring location. Representative sound level data from two 10-minute periods are presented herein and include contributions from all wind turbines as measured by the recording equipment. One data set is representative of time periods with low frequency sound level values near the maximum measured and the other data set is representative of the mean. The standard deviations for the low frequency one-third octave band levels for the six measurement periods were between 0.2–0.7 dB. The key operational and meteorological parameters during these two measurement periods are listed in Table 10.

Figure 2 plots the one-third octave band sound levels (L_{eq}) for both samples of high output conditions. The results show that infrasound is inaudible to even the most sensitive people 305 meters (1,000 feet) from these wind turbines (more than 20 dB below the median thresholds of hearing). Low frequency sound above 40 Hz may be audible depending on background sound levels.

Figure 3 plots the one-third octave band sound levels (L_{eq}) for both samples of high output conditions. The low frequency sound was "steady" according to DEFRA procedures, and the results show that all outdoor equivalent DEFRA disturbance criteria are met.

Figure 4 compares the one-third octave band sound levels (L_{eq}) for both samples of high output conditions to the Japan Ministry of Environment levels for evaluating complaints on rattle. The rattle criteria is met at all frequencies except at 5 Hz where the mean value is 1 dB (standard deviation of 0.4 dB) higher than the Japanese evaluation value. When one considers that the 5 Hz sound level is 3 dB lower than the observed threshold of rattle, one concludes that the Japanese criteria are met.

The measured outdoor sound levels also meet the outdoor equivalent Japan Ministry of Environment

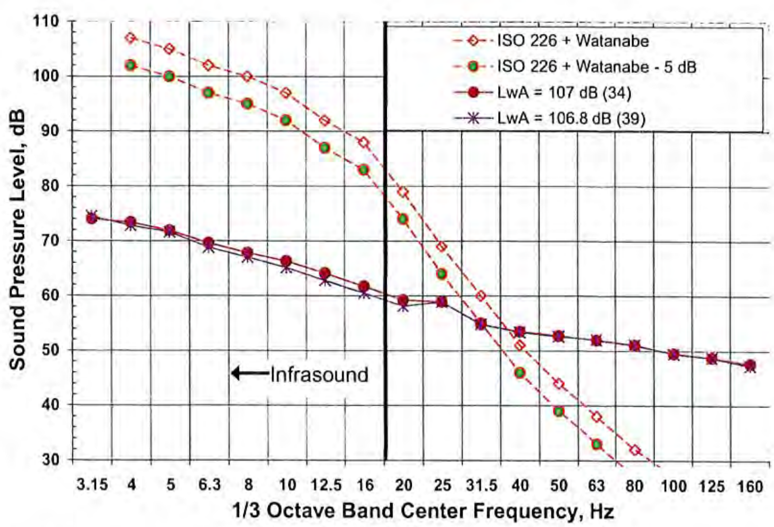

Fig. 2—Siemens SWT-2.3-93 wind turbine outdoor sound levels at 305 meters compared to audibility criteria.

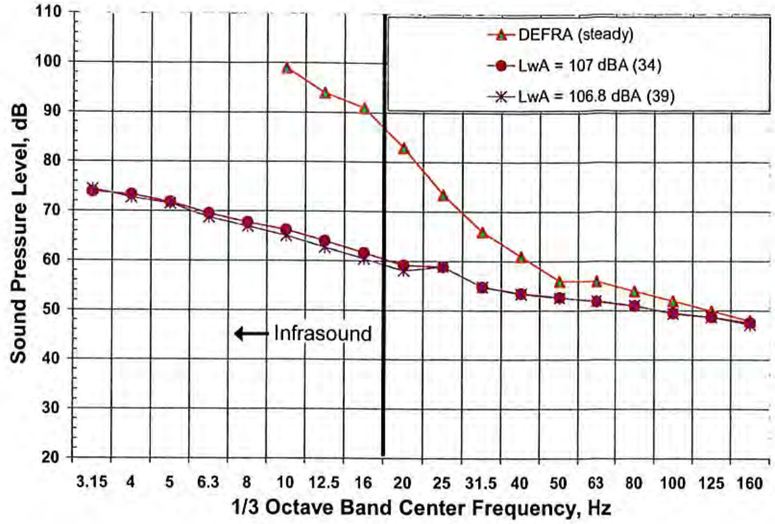

Fig. 3—Siemens SWT-2.3-93 wind turbine outdoor sound levels at 305 meters compared to outdoor equivalent DEFRA criteria.

criteria for evaluating complaints of mental and physical discomfort. This comparison is not presented in a figure since these criteria are generally less stringent than the DEFRA criteria.

Figure 5 plots the 16, 31.5, 63, and 125 Hz octave band sound levels (L_{eq}) for both samples of high output conditions. The results show that all outdoor equivalent ANSI/ASA S12.2 perceptible vibration criteria are met. In addition, the results show that all outdoor equivalent ANSI/ASA S12.2 low frequency NC-25 and NC-30 criteria for bedrooms are met. The low frequency sound levels are below the ANSI S12.9 Part 4 thresholds for the beginning of rattles (16, 31.5, 63 Hz total less than 70 dB). The 31.5 and 63 Hz sound levels are below the level of 65 dB identified for minimal annoyance in ANSI S12.9 Part 4, and the 16 Hz sound level is within 1.5 dB of this level, which is an insignificant increase since the levels were not rapidly fluctuating.

5.1.2 Indoor measurements—Siemens SWT-2.3-93

Simultaneous outdoor and indoor measurements were made at two residences at different locations within the wind farm to determine indoor audibility of low frequency noise from Siemens WTGs. In each house a 10-minute measurement was made in a room facing the wind turbines with a window both open and closed. Results from the testing at one of the homes are not presented due to the very high ground level winds

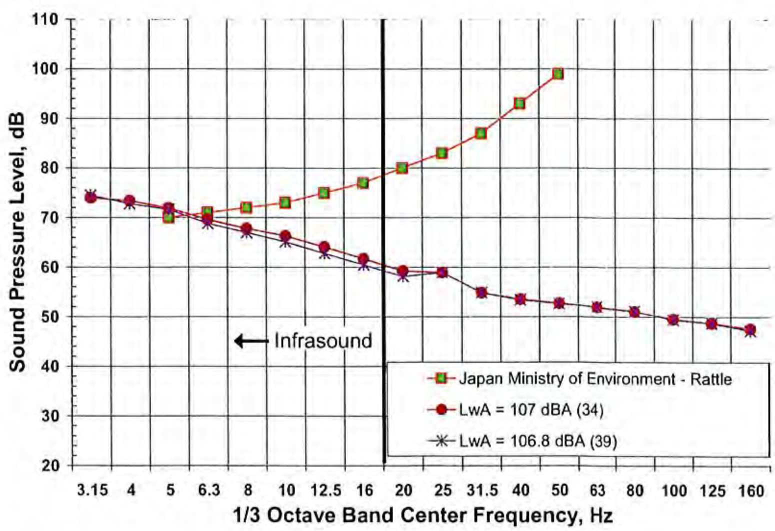

Fig. 4—Siemens SWT-2.3-93 wind turbine outdoor sound levels at 305 meters compared to Japan Ministry of Environment rattle criteria.

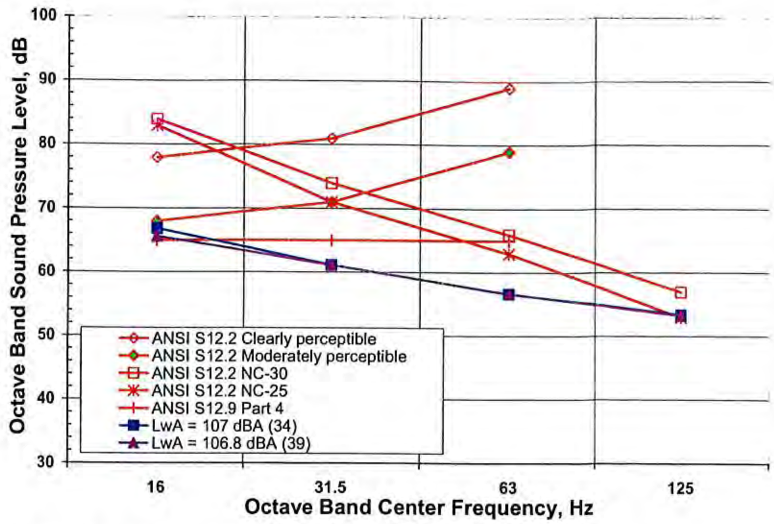

Fig. 5—Siemens SWT-2.3-93 wind turbine outdoor sound levels at 305 meters compared to ANSI criteria.

(~ 9 m/s) which dominated the sound environment. The remaining residence is designated Home "A" and was approximately 323 meters (1,060 feet) from the closest Siemens WTG. The home was near a string of multiple WTGs, four of which were within 610 meters (2,000 feet) of the house. The sound level data presented herein include contributions from all wind turbines as measured by the recording equipment. The key operational and meteorological parameters during these measurements are listed in Table 11.

The room in Home "A" where interior measurements were made had the following characteristics: approximately 3.6 meters wide (12 feet) by 4.9 meters long (16 feet), no furniture, carpeted flooring, two relatively new double-hung windows (no storm windows), sheetrock interior walls, and clapboard exterior walls. The sound level meter was located in the center of the room.

Figure 6 plots the indoor one-third octave band sound levels (L_{eq}) for Home "A". The results show that infrasound is inaudible to even the most sensitive people approximately 1,000 feet from these wind turbines with

Table 11—Summary of operational parameters—Siemens SWT-2.3-93 (Indoor).

Parameter	Home "A" (closed/open)
Distance to nearest WTG	323 meters
Time of day	07:39-07:49/07:51-08:01
WTG power output	1,884 kW/1564 kW
A-weighted sound power level*	107 dB/106.7 dB
Measured wind speed @ 2 m	3.2 m/s/3.7 m/s
L_{Aeq}	33.8 dB/38.1 dB
L_{A90}	28.1 dB/36.8 dB
L_{Ceq}	54.7 dB/57.1 dB

* Includes K, uncertainty factor of 2 dB

the windows open or closed (more than 20 dB below the median thresholds of hearing). Low frequency sound at or above 50 Hz may be audible depending on background sound levels.

Figure 7 plots the indoor one-third octave band sound levels (L_{eq}) for Home "A". The low frequency sound was "steady" according to DEFRA procedures under the window open condition, and the results show that all indoor DEFRA disturbance criteria are met.

Although not shown in Fig. 7, the one-third octave band levels meet the Japan Ministry of Environment criteria for evaluating complaints of mental and physical discomfort since in the frequency range of the Japan criteria both samples meet the more stringent DEFRA criteria for "non-steady" sounds, which is more stringent than the Japan criteria.

Figure 8 plots the indoor 16 Hz to 125 Hz octave band sound levels (L_{eq}) for Home "A". The results show the ANSI/ASA S12.2 low frequency criteria for perceptible vibration were easily met for both windows open and closed scenarios. The ANSI/ASA S12.2 low frequency NC-25 and NC-30 criteria for bedrooms, classrooms and hospitals were met, the spectrum was balanced, and the criteria for moderately perceptible vibrations in lightweight walls and ceilings were also met.

5.2 GE 1.5sle

5.2.1 Outdoor measurements—GE 1.5sle

Sound level data during twelve 10-minute periods of high wind turbine output and relatively low ground wind speed (which minimized effects of wind noise) were measured outdoors approximately 305 meters (1,000 feet) from the closest GE 1.5sle WTG. This site was actually part of a string of more than 30 WTGs, four of which were within 610 meters (2,000 feet) of the

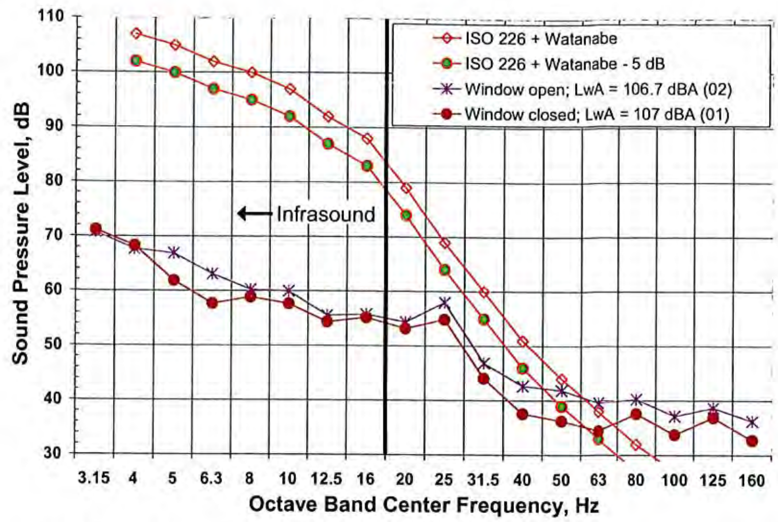

Fig. 6—Siemens SWT-2.3-93 wind turbine indoor sound levels at 323 meters compared to audibility criteria (Home "A").

monitoring location. Representative sound level data from two 10-minute periods are presented herein and include contributions from all wind turbines as measured by the recording equipment. One data set is representative of time periods with low frequency sound level values near the maximum and the other data set is representative of the mean. The standard deviations for the low frequency one-third octave band levels for the twelve measurement periods were between 0.3–1.9 dB with the largest variation in the 10–16 Hz bands and the lowest at 160 Hz. The key operational and meteorological parameters for these two measurement periods are listed in Table 12.

Figure 9 plots the one-third octave band sound levels (L_{eq}) for both samples of high output conditions. The results show that infrasound is inaudible to even the most sensitive people 305 meters (1,000 feet) from these wind turbines (more than 20 dB below the median thresholds of hearing). Low frequency sound at and above 31.5–40 Hz may be audible depending on background sound levels.

Figure 10 plots the one-third octave band sound levels (L_{eq}) for both samples of high output conditions. The low frequency sound was "steady" according to DEFRA procedures, and the results show the low frequency sound meet or are within 1 dB of outdoor equivalent DEFRA disturbance criteria.

Figure 11 compares the one-third octave band sound levels (L_{eq}) for both samples of high output conditions to the Japan Ministry of Environment levels for evaluating complaints on rattle. The rattle criteria is met at all

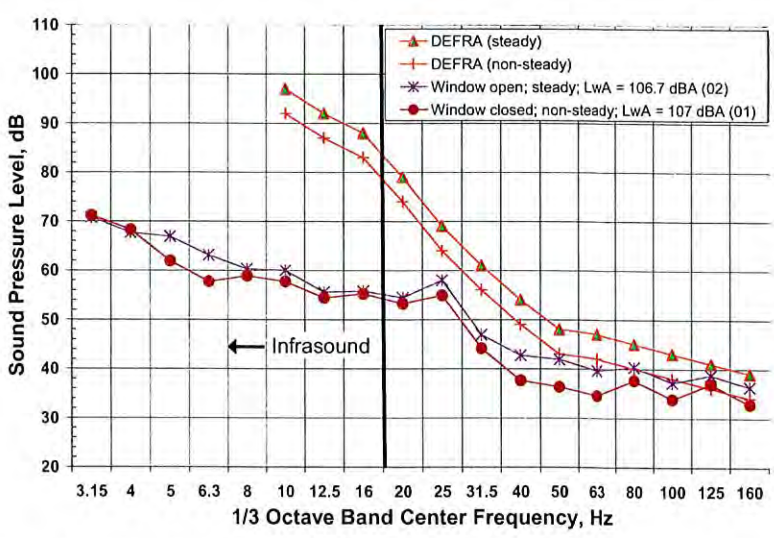

Fig. 7—Siemens SWT-2.3-93 wind turbine indoor sound levels at 323 meters compared to DEFRA criteria (Home "A").

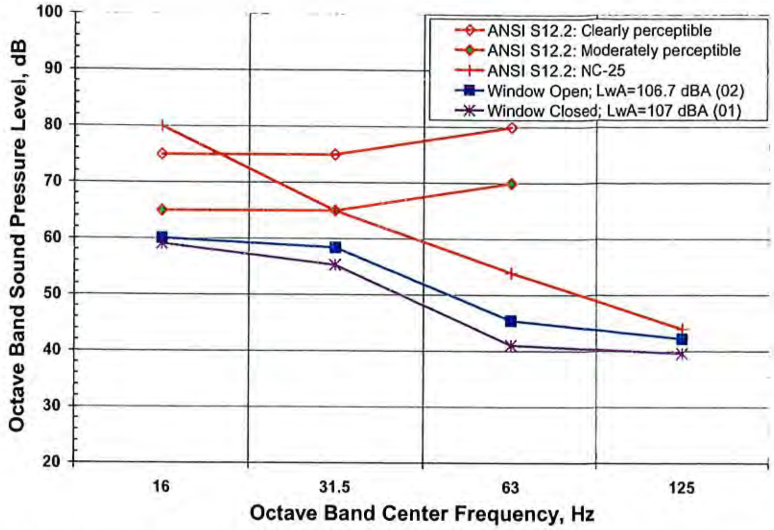

Fig. 8—Siemens SWT-2.3-93 wind turbine indoor sound levels at 323 meters compared to ANSI 12.2 criteria for perceptible vibrations and NC-25 (Home "A").

frequencies; at 5 Hz the mean value is 70 dB (standard deviation=0.9 dB), while the two presented measurements are approximately 1 dB higher, an insignificant increase. When one considers that the 5 Hz sound level is 3 dB lower than the observed threshold of rattle, one concludes that the Japanese criteria are met.

Table 12—Summary of operational parameters—GE 1.5sle (Outdoor).

Parameter	Sample #46	Sample #51
Distance to nearest WTG	305 meters	305 meters
Time of day	23:10-23:20	00:00-00:10
WTG power output	1,293 kW	1,109 kW
A-weighted sound power level*	106 dB	106 dB
Measured wind speed @ 2 m	4.1 m/s	3.3 m/s
L_{Aeq}	50.2 dB	50.7 dB
L_{A90}	49.2 dB	49.7 dB
L_{Ceq}	62.5 dB	62.8 dB

* Includes K, uncertainty factor of 2 dB

The measured outdoor sound levels also meet the outdoor equivalent Japan Ministry of Environment criteria for evaluating complaints of mental and physical discomfort. This comparison is not presented in a figure since these criteria are generally less stringent than the DEFRA criteria.

Figure 12 plots the 16, 31.5, 63 and 125 Hz octave band sound levels (L_{eq}) for both samples of high output conditions. The results show that all outdoor equivalent ANSI/ASA S12.2 perceptible vibration criteria are met. The results show that all outdoor equivalent ANSI/ASA S12.2 low frequency NC-25 and NC-30 criteria for

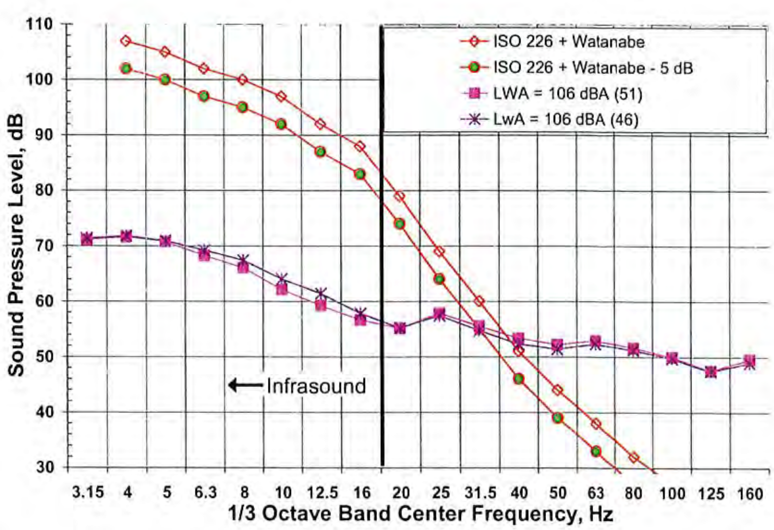

Fig. 9—GE 1.5sle wind turbine outdoor sound levels at 305 meters compared to audibility criteria.

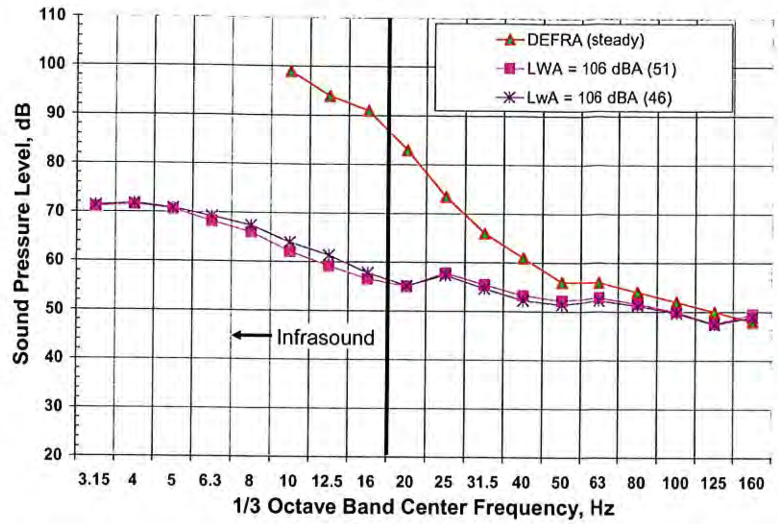

Fig. 10—GE 1.5sle wind turbine outdoor sound levels at 305 meters compared to outdoor equivalent DEFRA criteria.

bedrooms are met. The low frequency sound levels are below the ANSI S12.9 Part 4 thresholds for the beginning of rattles (16, 31.5, 63 Hz total less than 70 dB). The 16, 31.5, 63 Hz sound levels are below the level of 65 dB identified for minimal annoyance in ANSI S12.9 Part 4.

5.2.2 Indoor measurements—GE 1.5sle

Simultaneous outdoor and indoor measurements were made at two residences at different locations within the wind farm to determine indoor audibility of low frequency noise from GE 1.5sle WTGs. In each house, measurements were made in a room facing the wind turbines, and were made with a window both open and closed. These residences are designated Homes "B" and "C" and were approximately 305 meters (1,000 feet) from the closest GE WTG. Operational conditions were maximum turbine noise and high ground winds at Home "B", and within 1.5 dB of maximum turbine noise and high ground level winds at Home "C". Home "B" was near a string of multiple WTGs, four of which were within 610 meters (2,000 feet) of the house, while Home "C" was at the end of a string of WTGs, two of which were within 610 meters of the house. The sound level data presented herein include contributions from all wind turbines as measured by the recording equipment. The key operational and meteorological parameters during these measurements are listed in Table 13.

The room in Home "B" where interior measurements were made had the following characteristics:

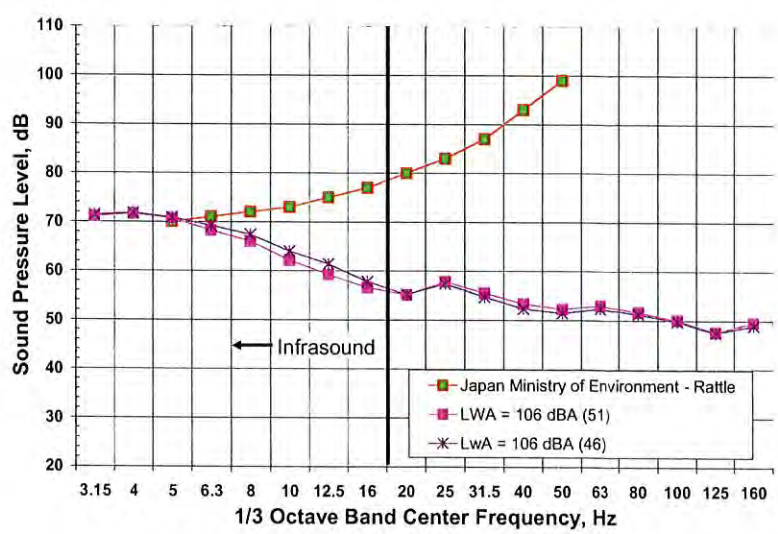

Fig. 11—GE 1.5sle wind turbine outdoor sound levels at 305 meters compared to Japan Ministry of Environment rattle criteria.

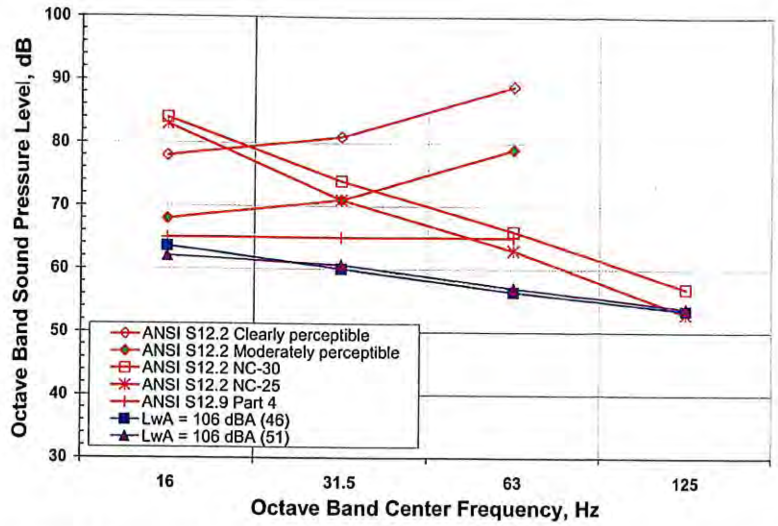

Fig. 12—GE 1.5sle wind turbine outdoor sound levels at 305 meters compared to ANSI criteria.

approximately 3.0 meters wide (10 feet) by 3.6 meters long (12 feet), bedroom furniture, carpeted flooring, two relatively new double-hung windows (no storm windows), paneling on the interior walls, and bricked exterior walls. The sound level meter was located just off-center in the room. The room in Home "C" where interior measurements were made had the following characteristics: approximately 2.4 meters wide (8 feet) by 3.6 meters long (12 feet), bathroom fixtures, linoleum flooring, one old casement window (no storm window), paneling on the interior walls, and wooden exterior walls. The sound level meter was located in the center of the room.

Figure 13 plots the indoor one-third octave band sound levels (L_{eq}) for Home "B", and Fig. 14 plots the indoor one-third octave band sound levels for Home "C". The results show that infrasound is inaudible to even the most sensitive people at around 305 meters (1,000 feet) from these wind turbines with the windows open or closed (more than 20 dB below the median thresholds of hearing). Low frequency sound at and above 63 Hz may be audible depending on background sound levels.

Figure 15 plots the indoor one-third octave band sound levels (L_{eq}) for Home "B", and Fig. 16 plots the indoor one-third octave band sound levels (L_{eq}) for Home "C". The results show the DEFRA disturbance criteria were met for steady and non-steady low frequency sounds.

Although not shown in Figs. 15 and 16, the one-third octave band levels meet the Japan Ministry of Environment criteria for evaluating complaints of mental and physical discomfort since both samples meet the more stringent DEFRA criteria for "non-steady" sounds, which is more stringent than the Japan criteria.

Figure 17 plots the indoor 16 Hz to 125 Hz octave band sound levels (L_{eq}) for Home "B", and Fig. 18 plots the indoor 16 Hz to 125 Hz octave band sound levels (L_{eq}) for Home "C". The results show the ANSI/ASA S12.2 low frequency criteria for perceptible vibration were met for both windows open and closed scenarios. The ANSI/ASA S12.2 low frequency NC-25 and NC-30 criteria for bedrooms, classrooms and hospitals were met,

Table 13—Summary of operational parameters—GE 1.5sle (Indoor).

Parameter	Home "B" (closed/open)	Home "C" (closed/open)
Distance to nearest WTG	290 meters	312 meters
Time of day	09:29-09:39/09:40-09:50	11:49-11:59/12:00-12:10
WTG power output	1,017 kW/896 kW	651 kW/632 kW
A-weighted sound power level	106 dB/105.8 dB	104.7 dB/104.6 dB
Measured wind speed @ 2 m	6.2 m/s/6.8 m/s	6.4 m/s/5.9 m/s
L_{Aeq}	27.1 dB/36.0 dB	33.6 dB/39.8 dB
L_{A90}	23.5 dB/33.7 dB	27.6 dB/34.2 dB
L_{Ceq}	47.1 dB/54.4 dB	50.6 dB/55.1 dB

* Includes K, uncertainty factor of 2 dB

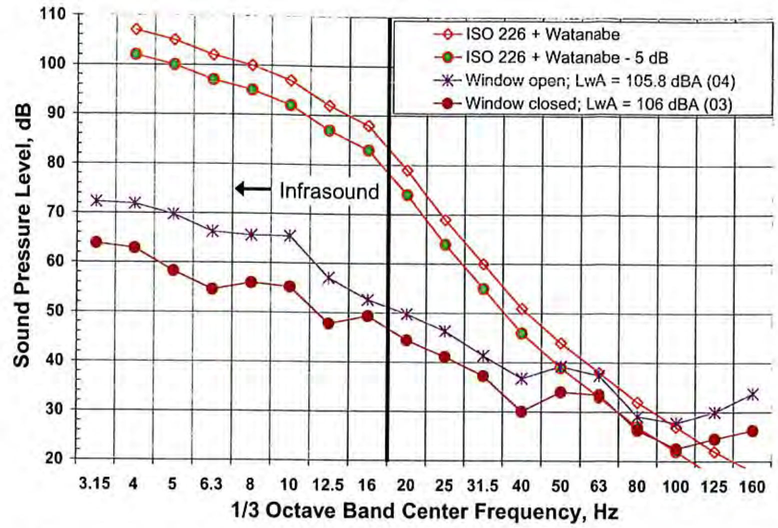

Fig. 13—GE 1.5sle wind turbine indoor sound levels at 290 meters compared to audibility criteria (Home "B").

the spectrum was balanced, and the criteria for moderately perceptible vibrations in light-weight walls and ceilings were also met.

5.3 Noise Reduction from Outdoor to Indoor

Simultaneous outdoor and indoor measurements made at the three residences within the Horse Hollow Wind Farm discussed above, were used to determine noise reductions of the homes for comparison to that used in the determination of equivalent outdoor criteria for indoor criteria, such as ANSI/ASA S12.2 and DEFRA. Indoor measurements were made with windows open and closed. Tables 11 and 13 list the conditions of measurement for these houses.

Figures 19 and 20 present the measured one-third octave band noise reduction for the three homes with windows closed and open, respectively. Also presented in these same figures are the one-third octave noise reductions discussed in the Appendix of this paper to obtain equivalent outdoor criteria for the indoor DEFRA criteria as well as the equivalent outdoor criteria for the Japanese mental and physical discomfort indoor criteria. It can be seen that for the window closed condition in Fig. 19, the measured noise reductions for all houses were greater than that used in our analysis for determining the equivalent outdoor criteria for the Japanese mental and physical discomfort indoor criteria. For the open window case in Fig. 20, which

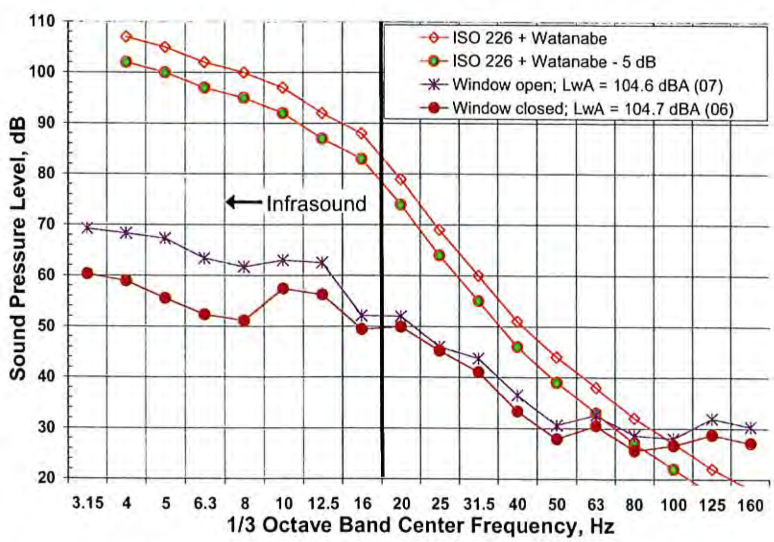

Fig. 14—GE 1.5sle wind turbine indoor sound levels at 312 meters compared to audibility criteria (Home "C").

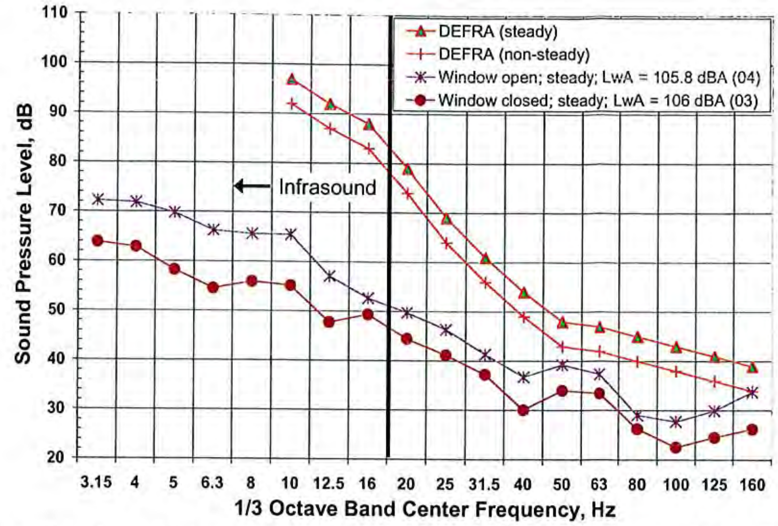

Fig. 15—GE 1.5sle wind turbine indoor sound levels at 290 meters compared to DEFRA criteria (Home "B").

was used in our analysis for obtaining the equivalent outdoor DEFRA criteria, the average of the three homes has a greater noise reduction than assumed in the Appendix and all houses at all frequencies have higher values with one minor exception. Only Home "A" at 25 Hz had a lower noise reduction (3 dB), and this difference is not critical since the measured indoor sounds at 25 Hz at each of these home was significantly lower than the indoor DEFRA criteria and the indoor Japanese criteria. Furthermore, the outdoor measurements for both Siemens and GE wind turbines at 305 meters (1,000 feet) under high output/high noise levels met the equivalent outdoor DEFRA criteria at 25 Hz.

Table 14 presents the measured octave band noise reduction for the three homes with windows closed and open, respectively. Also presented in Table 14 are the octave band noise reductions used in Table 2 of this paper to obtain equivalent outdoor criteria for the indoor ANSI/ASA S12.2 criteria for perceptible vibration and for NC-25 and NC-30. It can be seen that for the window closed condition, the measured noise reductions for all houses were greater than that used in our analysis. For the open window case, the average of the three homes has a greater noise reduction than the values from Table A1, and all houses at all frequencies have higher values with one minor exception. Only Home "A" at 31 Hz (which contains the 25 Hz one-third octave band) had a lower noise reduction (3 dB), and this difference is not critical since the measured indoor sounds at 31 Hz at each of these homes was significantly lower than the indoor ANSI/ASA S12.2 criteria. Furthermore, the outdoor measurements for both Siemens and GE wind

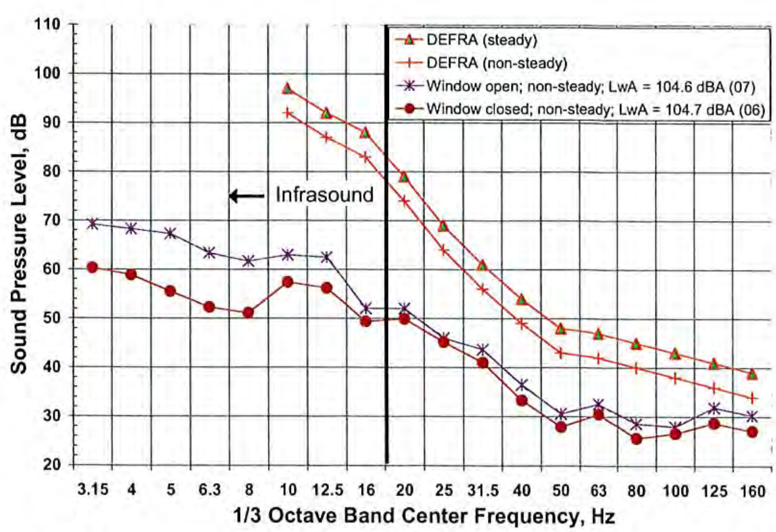

Fig. 16—GE 1.5sle wind turbine indoor sound levels at 312 meters compared to DEFRA criteria (Home "C").

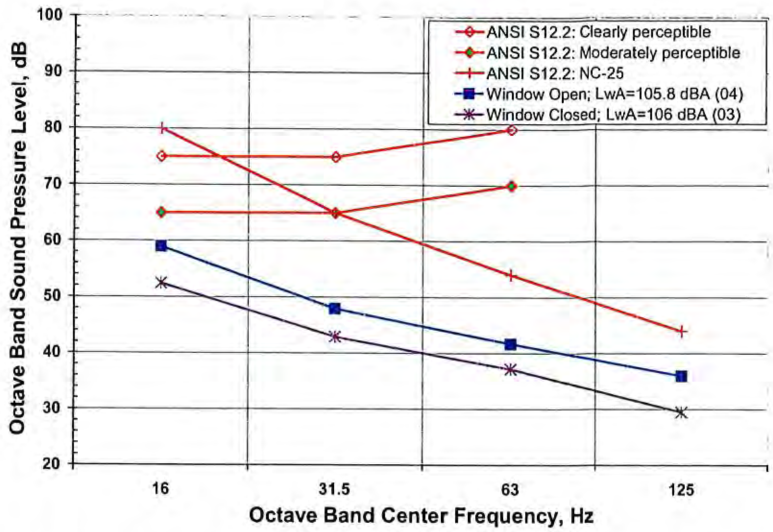

Fig. 17—GE 1.5sle wind turbine indoor sound levels at 290 meters compared to ANSI 12.2 criteria for perceptible vibrations and NC-25 (Home "B").

turbines at 305 meters (1,000 feet) under high output/ high noise levels met the equivalent outdoor ANSI/ASA S12.2 criteria at 31 Hz.

6 CONCLUSION

Sound levels from Siemens SWT 2.93-93 and GE 1.5sle wind turbines under maximum noise conditions at a distance more than 305 meters (1,000 feet) from the nearest residence meet the low frequency and infrasound standards and criteria published by several independent agencies and organizations. At this distance the wind farms:

- meet ANSI/ASA S12.2 indoor levels for low frequency sound for bedrooms, classrooms and hospitals;
- meet ANSI/ASA S12.2 indoor levels for moderately perceptible vibrations in light-weight walls and ceilings;
- meet ANSI/ASA S12.2 criteria for balanced spectrum from low frequency sounds;
- meet ANSI S12.9/Part 4 thresholds for annoyance from low frequency sound and beginning of rattles;
- meet UK DEFRA disturbance based guidelines for low frequency sound;
- meet Japan Ministry of Environment Guidance for evaluating complaints of rattling from low frequency noise;
- meet Japan Ministry of Environment Guidance for evaluating complaints of mental and physi-

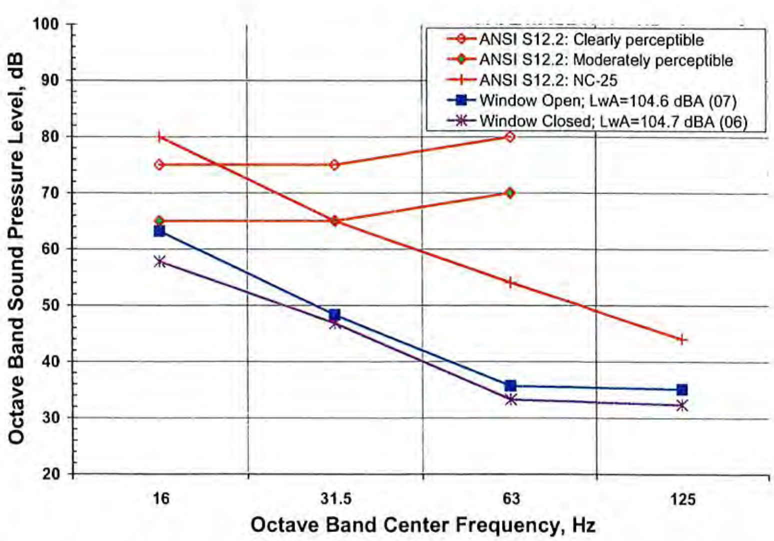

Fig. 18—GE 1.5sle wind turbine indoor sound levels at 312 meters compared to ANSI 12.2 criteria for perceptible vibrations and NC-25 (Home "C").

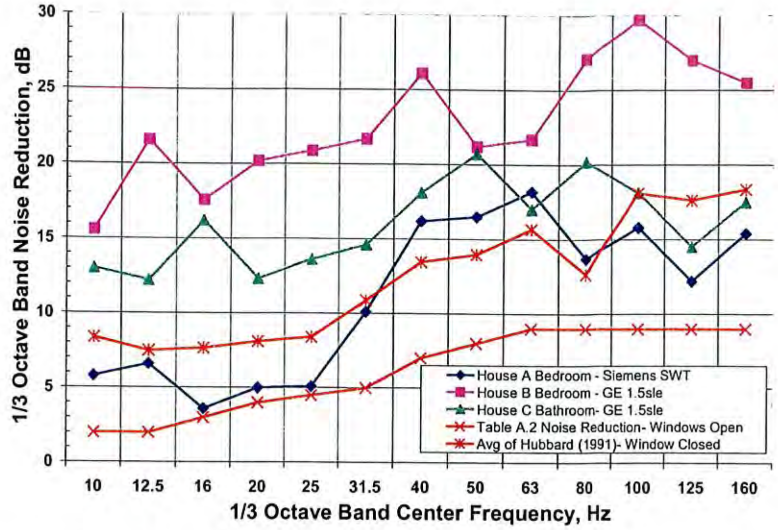

Fig. 19—One-third octave band interior noise reduction—Windows closed.

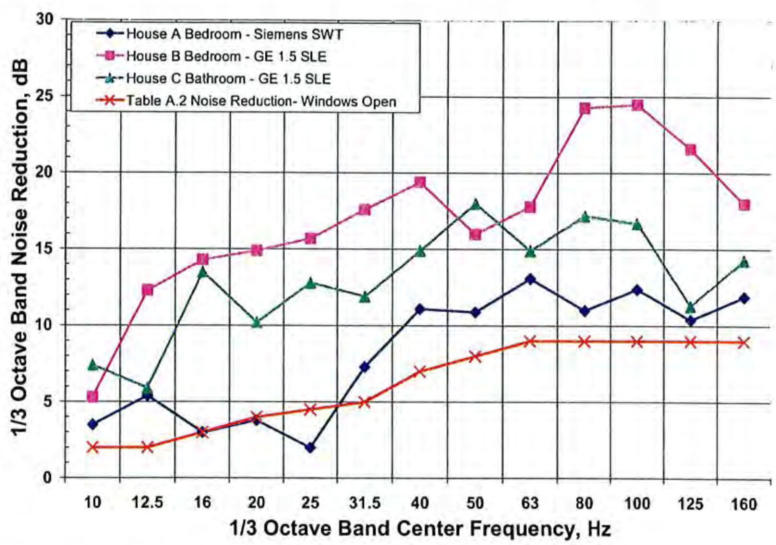

Fig. 20—One-third octave band interior noise reduction—Windows open.

cal discomfort from low frequency noise;

- have no audible infrasound to the most sensitive listeners; and
- might have slightly audible low frequency noise at frequencies at 50 Hz and above depending on other sources of low frequency noises in homes, such as refrigerators or external traffic or airplanes.

In accordance with the above findings, and in conjunction with our extensive literature search of

Table 14—Summary of octave band noise reduction—Interior measurements.

Home	Wind Turbine	Windows	16 Hz	31.5 Hz	63 Hz	125 Hz
A	Siemens SWT-2-3-93	Closed	5	6	16	14
A	Siemens SWT-2-3-93	Open	4	3	12	12
B	GE 1.5sle	Closed	20	22	22	27
B	GE 1.5sle	Open	13	17	18	21
C	GE 1.5sle	Closed	13	14	19	17
C	GE 1.5sle	Open	8	13	17	14
	Table A1 Noise Reduction	Open	3	6	9	9

scientific papers and reports, there should be no adverse public health effects from infrasound or low frequency noise at distances greater than 305 meters (1,000 feet) from the wind turbine types measured: GE 1.5sle and Siemens SWT 2.3-93.

7 ACKNOWLEDGMENTS

Acknowledgement is made to NextEra Energy Resources, LLC ("NextEra"), formerly FPL Energy, for providing financial support for the study, allowing access to the wind farm, and supplying critical operational data. Epsilon determined all means, methods, and the testing protocol without interference or direction from NextEra. No limitations were placed on Epsilon by NextEra with respect to the testing protocol or upon the analysis methods; the conclusions are those of the authors.

8 APPENDIX: HOME NOISE REDUCTION USED TO DETERMINE EQUIVALENT OUTDOOR SOUND PRESSURE LEVEL CRITERIA BASED ON INDOOR CRITERIA

Since indoor measurements are not always possible, for comparison to outdoor sound levels the indoor criteria from ANSI/ASA S12.2 should be adjusted. Outdoor to indoor low frequency noise reductions have been reported by Sutherland for aircraft and highway noise for open and closed windows[9] and by Hubbard and Shepherd for aircraft and wind turbine noise for closed windows[10]. Table A1 presents the average low frequency octave band noise reductions from outdoor to indoors from these two papers for open and closed windows. Sutherland only reported values down to 63 Hz; whereas Hubbard and Shepherd presented values to less than 10 Hz. The closed window conditions of Ref. 10 were used to estimate noise reductions less than 63 Hz by applying the difference between values for open and closed windows from Ref. 9 data at 63 Hz. It should be noted that the attenuation for wind turbines in Ref. 10 is based on only three homes at two different wind farms, whereas the traffic and aircraft data are for many homes. The wind turbine open window values were determined from the wind turbine closed window values by subtracting the difference in values between windows closed and open obtained by Ref. 9.

To be conservative, we use the open window case instead of closed windows except for the adjustments to the Japanese guideline which specifically called for closed windows. To be further conservative, we use the wind turbine noise reduction data in Ref. 10 (adjusted to open windows). However, it should be noted that it is possible for some homes to have some slight amplification at low frequencies with windows open due to possible room resonances.

The average one-third octave band noise reductions used to determine equivalent outdoor one-third octave band criteria were determined in a similar manner. The first row of Table A2 and Fig. 20 present the average one-third octave band noise reductions values for *windows open* that were used to determine the equivalent outdoor one-third octave band criteria levels in Table 7 from the indoor criteria. The second row of Table A2 and Fig. 19 presents the one-third octave band noise reductions for windows closed determined by Ref. 10 for homes exposed to wind turbine sounds—these higher closed window noise reduction values were only used to determine equivalent outdoor levels for determining the equivalent Japanese guidance one-third octave band sound pressure level values for dealing with complaints of mental and physical discomfort from environmental sounds.

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EXHIBIT 9
to July 8, 2019
Comments

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Infrasound From Wind Turbines Could Affect Humans

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Infrasound From Wind Turbines Could Affect Humans

Alec N. Salt[1] and James A. Kaltenbach[2]

Abstract

Wind turbines generate low-frequency sounds that affect the ear. The ear is superficially similar to a microphone, converting mechanical sound waves into electrical signals, but does this by complex physiologic processes. Serious misconceptions about low-frequency sound and the ear have resulted from a failure to consider in detail how the ear works. Although the cells that provide hearing are insensitive to infrasound, other sensory cells in the ear are much more sensitive, which can be demonstrated by electrical recordings. Responses to infrasound reach the brain through pathways that do not involve conscious hearing but instead may produce sensations of fullness, pressure or tinnitus, or have no sensation. Activation of subconscious pathways by infrasound could disturb sleep. Based on our current knowledge of how the ear works, it is quite possible that low-frequency sounds at the levels generated by wind turbines could affect those living nearby.

Keywords

cochlea, hair cells, A-weighting, wind turbine, Type II auditory afferent fibers

Wind Turbines Generate Infrasound

The sounds generated by wind turbines vary widely, depending on many factors such as the design, size, rotor speed, generator loading, and different environmental conditions such as wind speed and turbulence (e.g., Jakobsen, 2005). Under some conditions, such as with a low wind speed and low generator loading, the sounds generated appear to be benign and are difficult to detect above other environmental sounds (Sonus, 2010).

But in many situations, the sound can contain a substantial low-frequency infrasound component. One study (Van den Berg, 2006) reported wind turbine sounds measured in front of a home 750 m from the nearest turbine of the Rhede wind farm consisting of Enercon E-66 1.8 MW turbines, 98 m hub height, and 35 m blade length. A second study (Jung & Cheung, 2008) reported sounds measured 148 to 296 m from a 1.5 MW turbine, 62 m hub height, 36 m blade length. In both these studies, which are among the few publications that report full-spectrum sound measurements of wind turbines, the sound spectrum was dominated by frequencies below 10 Hz, with levels of over 90 dB SPL near 1 Hz.

The infrasound component of wind turbine noise is demonstrated in recordings of the sound in a home with GE 1.5 MW wind turbines 1,500 ft downwind as shown in Figure 1. This 20-second recording was made with a microphone capable of recording low-frequency components. The sound level over the recording period, from which this excerpt was taken, varied from 28 to 43 dBA. The audible and inaudible (infrasound) components of the sound are demonstrated by filtering the waveform above 20 Hz (left) or below 20 Hz (right). In the audible, high-pass filtered waveform, the periodic "swoosh" of the blade is apparent to a varying degree with time. It is apparent from the low-pass filtered waveform that the largest peaks in the original recording represent inaudible infrasound. Even though the amplitude of the infrasound waveform is substantially larger than that of the audible component, this waveform is inaudible when played by a computer's sound system. This is because conventional speakers are not capable of generating such low frequencies and even if they could, those frequencies are typically inaudible to all but the most sensitive unless played at very high levels. It was also notable in the recordings that the periods of high infrasound level do not coincide with those times when the audible component is high.

This shows that it is impossible to judge the level of infrasound present based on the audible component of the sound. Just because the audible component is loud does not mean that high levels of infrasound are present. These measurements show that wind turbine sounds recorded inside a home can contain a prominent infrasound component.

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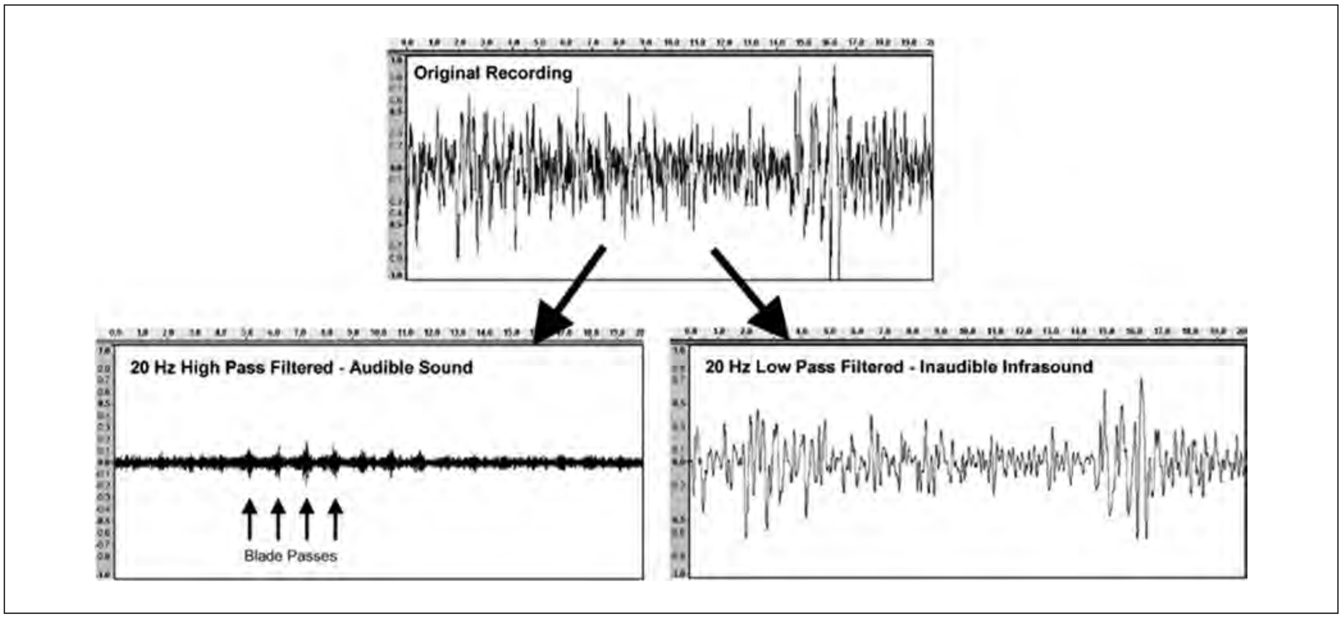

Figure 1. *Upper Panel:* Full-spectrum recording of sound from a wind turbine recorded for 20 seconds in a home with the wind turbine 1,500 ft downwind (digital recording kindly provided by Richard James). *Lower Left Panel:* Result of high-pass filtering the waveform at 20 Hz, showing the sound that is heard, including the sounds of blade passes. *Lower Right Panel:* Result of low-pass filtering the waveform at 20 Hz, showing the infrasound component of the sound

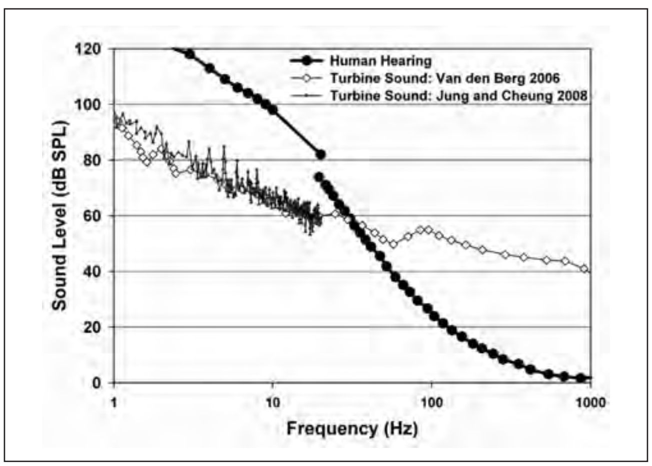

Figure 2. Wide band spectra of wind turbine sounds (Jung & Cheung, 2008; Van den Berg, 2006) compared with the sensitivity of human hearing (International Organization for Standardization, 2003, above 20 Hz; Møller & Pederson, 2004, below 20 Hz). The levels of sounds above 30 Hz are above the audibility curve and would be heard. Below 30 Hz, levels are below the audibility curve so these components would not be heard

Wind Turbine Infrasound Is Typically Inaudible

Hearing is very insensitive to low-frequency sounds, including those generated by wind turbines. Figure 2 shows examples of wind turbine sound spectra compared with the sensitivity of human hearing. In this example, the turbine sound components above approximately 30 Hz are above threshold and therefore audible. The sounds below 30 Hz, even though they are of higher level, are below the threshold of audibility and therefore may not be heard. Based on this comparison, for years it has been assumed that the infrasound from wind turbines is not significant to humans. Leventhall (2006) concluded that "infrasound from wind turbines is below the audible threshold and of no consequence." (p.34) Leventhall (2007) further stated that "if you cannot hear a sound you cannot perceive it in other ways and it does not affect you." (p.135)

Renewable UK (2011), the website of the British Wind Energy Association, quotes Dr. Leventhall as stating, "I can state quite categorically that there is no significant infrasound from current designs of wind turbines." Thus, the fact that hearing is insensitive to infrasound is used to exclude the possibility that the infrasound can have any influence on humans. This has been known for many years in the form of the statement, "What you can't hear can't affect you." The problem with this concept is that the sensitivity of "hearing" is assumed to equate with sensitivity of "the ear." So if you cannot hear a sound then it is assumed that the sound is insufficient to stimulate the ear. Our present knowledge of the physiology of the ear suggests that this logic is incorrect.

The Ear Is Sensitive to Wind Turbine Infrasound

The sensory cells responsible for hearing are contained in a structure in the cochlea (the auditory portion of the inner ear) called the organ of Corti. This organ runs the entire length of the cochlear spiral and contains two types of sensory cells, which have completely different properties. There is one row

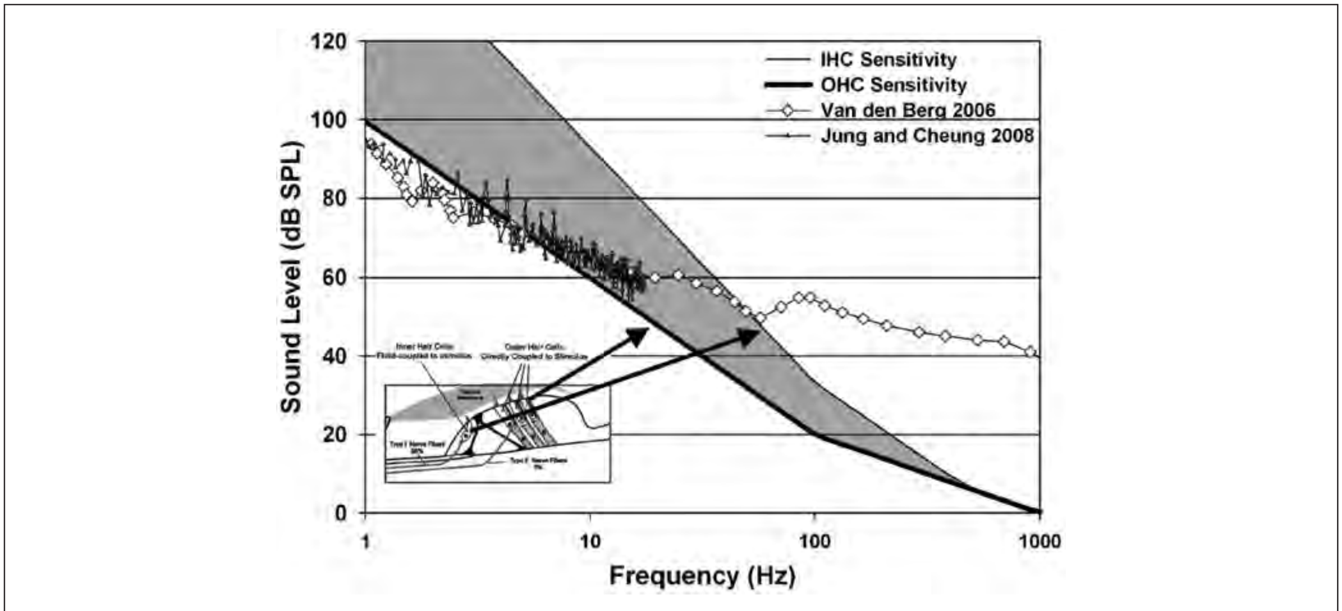

Figure 3. The thin line shows the estimated sensitivity of inner hair cells (IHC) as a function of frequency, which is comparable with the human audibility curve shown in Figure 2 and which is consistent with hearing being mediated by the IHC (based on Cheatham & Dallos, 2001). The thick line shows the estimated sensitivity of the outer hair cells (OHC), which are substantially more sensitive than the IHC. Sound components of the overlaid wind turbine spectra within the shaded region (approximately 5 to 50 Hz) are too low to stimulate the IHC and cannot therefore be heard but are of sufficient level to stimulate the OHC. The inset shows a cross section of the sensory organ of the cochlea (the organ of Corti) showing the locations of the IHC and OHC

of sensory inner hair cells (IHC) and three rows of outer hair cells (OHC) as shown schematically in the inset to Figure 3. For both IHC and OHC, sound-induced deflections of the cell's sensory hairs provide stimulation and elicit electrical responses. Each IHC is innervated by multiple nerve fibers that transmit information to the brain, and it is widelyaccepted that hearing occurs through the IHC. The rapidly declining sensitivity of hearing at lower frequencies (Figure 2) is accounted for by three processes that selectively reduce low-frequency sensitivity (Cheatham & Dallos, 2001), specifically the properties of middle ear mechanics, from pressure shunting through the cochlear helicotrema and from "fluid coupling" of the inner hair cell stereocilia to the stimulus (reviewed in detail by Salt & Hullar, 2010).

The combined effect of these processes, quantified by Cheatham and Dallos (2001), are shown as the "IHC sensitivity" curve in Figure 3. The last component attenuating low frequencies, the so-called fluid coupling of input, arises because the sensory hairs of the IHC do not contact the overlying gelatinous tectorial membrane but are located in the fluid space below the membrane.

As a result, measurements from the IHC show that they do not respond to sound-induced displacements of the structure but instead their amplitude and phase characteristics are consistent with them responding to the velocity of the stimulus. As stimulus frequency is lowered, the longer cycles result in lower stimulus velocity, so the effective stimulus falls by 6 dB/octave. This accounts for the known insensitivity of the IHC to low-frequency stimuli. For low frequencies, the calculated sensitivity of IHC (Figure 3) compares well with measures of hearing sensitivity (Figure 2), supporting the view that hearing is mediated by the IHC.

The problem, however, arises from the more numerous OHC of the sensory organ of Corti of the ear. Anatomic studies show that the sensory hairs of the OHC are embedded in the overlying tectorial membrane, and electrical measurements from these cells show their responses depend on the displacement rather than the velocity of the structure. As a result, their responses do not decline to the same degree as IHC as frequency is lowered.

Their calculated sensitivity is shown as the "OHC sensitivity" curve in Figure 3. It is important to note that the difference between IHC and OHC responses has nothing to do with frequency-dependent effects of the middle ear or of the helicotrema (the other two of the three components mentioned above). For example, any attenuation of low-frequency stimuli provided by the helicotrema will equally affect both the IHC and the OHC. So the difference in sensitivity shown in Figure 3 arises purely from the difference in how the sensory hairs of the IHC and OHC are coupled to the overlying tectorial membrane.

The important consequence of this physiological difference between the IHC and the OHC is that the OHC are stimulated at much lower levels than the IHC. In Figure 3, the portion of the wind turbine sound spectrum within the shaded region represents frequencies and levels that are too low to be heard, but which are suficient to stimulate the OHC of the ear.

This is not confined to infrasonic frequencies (below 20 Hz), but in this example includes sounds over the range from 5 to 50 Hz. It is apparent that the concept that "sounds you can't hear cannot affect you" cannot be correct because it does not recognize these well-documented physiologic properties of the sensory cells of the inner ear.

Stimulation of OHC at inaudible, low levels can have potentially numerous consequences. In animals, cochlear microphonics demonstrating the responses of the OHC can be recorded to infrasonic frequencies (5 Hz) at levels as low as 40 dB SPL (Salt & Lichtenhan, in press). The OHCs are innervated by Type II nerve fibers that constitute 5% to 10% of the auditory nerve fibers, which connect the hair cells to the brainstem. The other 90% to 95% come from the IHCs. Both Type I (from IHC) and Type II (from OHC) nerve fibers terminate in the cochlear nucleus of the brainstem, but the anatomical connections of the two systems increasingly appear to be quite different. Type I fibers terminate on the main output neurons of the cochlear nucleus. For example, in the dorsal part of the cochlear nucleus, Type I fibers connect with fusiform cells, which directly process information received from the ear and then deliver it to higher levels of the auditory pathway. In contrast, Type II fibers terminate in the granule cell regions of the cochlear nucleus (Brown, Berglund, Kiang, & Ryugo, 1988). Some granule cells receive direct input from Type II fibers (Berglund & Brown, 1994). This is potentially significant because the granule cells provide a major source of input to nearby cells, whose function is inhibitory to the fusiform cells that are processing heard sounds. If Type II fibers excite granule cells, their ultimate effect would be to diminish responses of fusiform cells to sound. Evidence is mounting that loss of or even just overstimulation of OHCs may lead to major disturbances in the balance of excitatory and inhibitory influences in the dorsal cochlear nucleus. One product of this disturbance is the emergence of hyperactivity, which is widely believed to contribute to the perception of phantom sounds or tinnitus (Kaltenbach et al., 2002; Kaltenbach & Godfrey, 2008). The granule cell system also connects to numerous auditory and nonauditory centers of the brain (Shore, 2005). Some of these centers are directly involved in audition, but others serve functions as diverse as attentional control, arousal, startle, the sense of balance, and the monitoring of head and ear position (Godfrey et al., 1997).

Functions that have been attributed to the dorsal cochlear nucleus thus include sound localization, cancellation of self-generated noise, orienting the head and ears to sound sources, and attentional gating (Kaltenbach, 2006; Oertel & Young, 2004). Thus, any input from OHCs to the circuitry of the dorsal cochlear nucleus could influence functions at several levels.

A-Weighted Wind Turbine Sound Measurements

Measurements of sound levels generated by wind turbines presented by the wind industry are almost exclusively A-weighted and expressed as dBA. When measured in this manner, the sound levels near turbines are typically in the range of 30 to 50 dBA, making wind turbine sounds,

> about the same level as noise from a flowing stream about 50-100 meters away or the noise of leaves rustling in a gentle breeze. This is similar to the sound level inside a typical living room with a gas fire switched on, or the reading room of a library or in an unoccupied, quiet, air-conditioned office. (Renewable UK, 2011)

On the basis of such measurements, we would expect wind turbines to be very quiet machines that would be unlikely to disturb anyone to a significant degree. In contrast, the human perception of wind turbine noise is considerably different. Pedersen and Persson-Waye (2004) reported that for many other types of noise (road traffic, aircraft, railway), the level required to cause annoyance in 30% of people was over 70 dBA, whereas wind turbine noise caused annoyance of 30% of people at a far lower level, at around 40 dBA. This major discrepancy is probably a consequence of A-weighting the wind turbine sound measurements, thereby excluding the low-frequency components that contribute to annoyance. A-weighting corrects sound measurements according to human hearing sensitivity (based on the 40 phon sensitivity curve). The result is that low-frequency sound components are dramatically deemphasized in the measurement, based on the rationale that these components are less easily heard by humans. An example showing the effect of A-weighting the turbine sound spectrum data of Van den Berg (2006) is shown in Figure 4. The low-frequency components of the original spectrum, which resulted in a peak level of 93 dB SPL at 1 Hz, are removed by A-weighting, leaving a spectrum with a peak level of 42 dBA near 1 kHz. A-weighting is perfectly acceptable if hearing the sound is the important factor. A problem arises though when A-weighted measurements or spectra are used to assess whether the wind turbine sound affects the ear. We have shown above that some components of the inner ear, specifically the OHC, are far more sensitive to low-frequency sounds than is hearing. Therefore, A-weighted sounds do not give a valid representation of whether wind turbine noise affects the ear or other aspects of human physiology mediated by the OHC and unrelated to hearing. From Figure 3, we know that sound frequencies down to 3 to 4 Hz may be stimulating the OHC, yet the A-weighted spectrum in Figure 4 cuts off all components below approximately 14 Hz. For this reason, the determination of whether wind turbine sounds affect people simply cannot be made based on A-weighted sound measurements. A-weighted measurements are inappropriate for this purpose and give a misleading representation of whether the sound affects the ear.

Alternatives to A-weighting are the use of full-spectrum (unweighted), C-weighted, or G-weighted measurements. G-weighted measurements use a weighting curve based on the human audibility curve below 20 Hz and a steep cutoff above 20 Hz so that the normal audible range of frequencies is deemphasized. Although the shape of this function is arbitrary

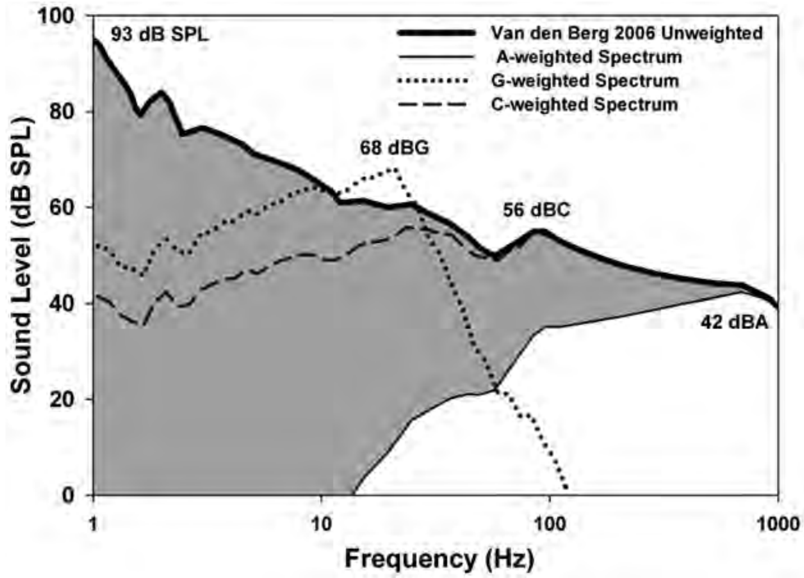

Figure 4. Low-frequency components of wind turbine sound spectrum (below 1 kHz) before and after A-weighting. The original spectrum was taken from Van den Berg (2006). The shaded area represents the degree of alteration of the spectrum by A-weighting. A weighting (i.e., adjusting the spectrum according to the sensitivity of human hearing) has the effect of ignoring the fact that low-frequency sounds can stimulate the OHC at levels that are not heard. Representing this sound as 42 dBA, based on the peak of the spectrum, ignores the possibility that low-frequency components down to frequencies as low as 5 Hz (from Figure 3) are stimulating the OHC. Also shown are the spectra after G-weighting (dotted) and C-weighting (dashed) for comparison

when hearing is not the primary issue, it does give a measure of the infrasound content of the sound that is independent of higher frequency, audible components, as shown in Figure 4. By applying the function to the normal human hearing sensitivity curve, it can be shown that sounds of approximately 95 dBG will be heard by humans, which agrees with observations by Van den Berg (2006). Similarly, by G-weighting the OHC sensitivity function in Figure 3, it can be estimated that sound levels of 60 dBG will stimulate the OHC of the human ear. In a survey of infrasound levels produced by wind turbines measured in dBG (Jakobsen, 2005), upwind turbines typically generated infrasound of 60 to 70 dBG, although levels above and below this range were observed in this and other studies. From Jakobsen's G-weighted measurements, we conclude that the level of infrasound produced by wind turbines is of too low a level to be heard, but in most cases is sufficient to cause stimulation of the OHC of the human ear. C-weighting also provides more representation of low-frequency sound components but still arbitrarily de-emphasizes infrasound components.

Is the Infrasound From Wind Turbines Harmful to Humans Living Nearby?

Our present understanding of inner ear physiology and of the nature of wind turbine sounds demonstrates that low-level infrasound produced by wind turbines is transduced by the OHC of the ear and this information is transmitted to the cochlear nucleus of the brain via Type II afferent fibers. We therefore conclude that dismissive statements such as "there is no significant infrasound from current designs of wind turbines" are undoubtedly false. The fact that infrasound-dependent information, at levels that are not consciously heard, is present at the level of the brainstem provides a scientific basis for the possibility that such sounds can have influence on people. The possibility that low-frequency components of the sound could contribute both to high annoyance levels and possibly to other problems that people report as a result of exposure to wind turbine noise cannot therefore be dismissed out of hand.

Nevertheless, the issue of whether wind turbine sounds can cause harm is more complex. In contrast to other sounds, such as loud sounds, which are harmful and damage the internal structure of the inner ear, there is no evidence that low-level infrasound causes this type of direct damage to the ear. So infrasound from wind turbines is unlikely to be harmful in the same way as high-level audible sounds.

The critical issue is that if the sound is detected, then can it have other detrimental effects on a person to a degree that constitutes harm? A major complicating factor in considering this issue is the typical exposure duration. Individuals living near wind turbines may be exposed to the turbine's sounds for prolonged periods, 24 hours a day, 7 days a week for weeks, possibly extending to years, although the sound level will vary over time with varying wind conditions. Although there have been many studies of infrasound on humans, these have typically involved higher levels for limited periods (typically of up to 24 hours). In a search of the literature, no studies were found that have come close to replicating the long-term exposures to low-level infrasound experienced by those living near wind turbines. So, to date, there are no published studies showing that such prolonged exposures do not harm humans. On the other hand, there are now numerous reports (e.g., Pierpont, 2009; Punch, James, & Pabst, 2010), discussed extensively in this journal, that are highly suggestive that individuals living near wind turbines are made ill, with a plethora of symptoms that commonly include chronic sleep disturbance. The fact that such reports are being dismissed on the grounds that the level of infrasound produced by wind turbines is at too low a level to be heard appears to totally ignore the known physiology of the ear. Pathways from the OHC to the brain exist by which infrasound that cannot be heard could influence function. So, in contrast, from our perspective, there is ample evidence to support the view that infrasound could affect people, and which justifies the need for more detailed scientific studies of the problem. Thus, it is possible that people's health could suffer when turbines are placed too close to their homes and this becomes more probable if sleep is disturbed by the infrasound. Understanding these phenomena may be important to deal with other sources of low-frequency noise and may establish why some individuals are more sensitive than others. A better understanding may also allow effective procedures to be implemented to mitigate the problem.

We can conclude that based on well-documented knowledge of the physiology of the ear and its connections to the brain, it is scientifically possible that infrasound from wind turbines could affect people living nearby.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Bios

Alec N. Salt received his PhD from the University of Birmingham, UK, in 1977 and has been actively involved in research into the physiology of the ear for over 35 years.

James A. Kaltenbach received his PhD from the University of Pennsylvania in 1984. He specializes in the neurobiology of hearing disorders and is currently the Director of Otology Research at the Cleveland Clinic.

EXHIBIT 10
to July 8, 2019
Comments

July 5, 2019
Project No. 0023.004

Backcountry Against Dumps
c/o Donna Tisdale
PO Box 1275
Boulevard, CA 91905-0375

Subject: Campo Wind Draft Environmental Impact Statement (EIS) with Boulder Brush Facilities
Draft EIS Review and Opinion

Dear Ms. Tisdale,

We are pleased to present this report to Backcountry Against Dumps that provides an independent, technical review of relevant groundwater portions of the Campo Wind Draft EIS, prepared by Dudek, for the Campo Wind Project with Boulder Brush Facilities (project). Scott Snyder is a California Professional Geologist and Certified Hydrogeologist with 25 years of experience in hydrogeology, 18 of which have been in San Diego County.

PURPOSE

The purpose of this report is to provide opinions on the following: whether or not the groundwater technical work (Groundwater Resource Evaluation – Appendix F of the Draft EIS) was conducted in accordance with County of San Diego guidelines (standards to which Dudek stated they would compare their work); if the hydrogeologic work meets the standard of care for the industry; and if the protections proposed for the groundwater users surrounding the project site are adequate.

This report addresses the following:

1. Whether the reports follow the standard of care in San Diego County for such investigations (the County has no jurisdiction on this project, which is on Tribal land; however, Dudek has indicated they used the County guidelines for significance thresholds and the guidance in order to compare this project to others in the County),

2. Whether the investigations were conducted in a competent manner,

3. Whether the report's conclusions are consistent with the results of the investigations,

4. Whether the proposed protections are adequate for groundwater users near the site, and

5. Whether the conclusions of the report are considered within the context of the entire project.

DOCUMENTS REVIEWED

We reviewed the following documents found on the Bureau of Indian Affairs website for Campo Wind (www.campowind.com):

- Draft EIS Section 1 – Introduction
- Draft EIS Section 2 – Project Description and Alternatives
- Draft EIS Section 3.2 – Affected Environment and Areas Not Further Discussed, Water Resources
- Draft EIS Section 4.2 – Environmental Consequences, Water Resources
- Draft EIS Appendix B – Project Description Details
- Draft EIS Appendix C – Regulatory Settings
- Draft EIS Appendix D – Environmental Resources Section Tables and Graphs
- Draft EIS Appendix E – EIS Figures
- Draft EIS Appendix F – Groundwater Resource Evaluation (GRE)
- Draft EIS Appendix P – Mitigation Measures

Other reports that were reviewed in whole or in part include:

- Groundwater Resources Investigation Report, Tierra Del Sol Solar Farm Project (Dudek)
- Study Area Photolineament Map, Proposed Campo Landfill (Dames & Moore)
- Draft EIS, Campo Solid Waste Management Project (SAIC)
- East County Substation Amended Construction Water Supply Plan (BETA/SDG&E)
- East County Substation Construction Water Use Report, November 1 to 30, 2013 (SDG&E)

PROJECT LOCATION AND DESCRIPTION, AND PROJECTED WATER USE

The proposed project would be a wind farm on the Campo Reservation located in the east county San Diego mountains. The Campo Reservation lies among several unincorporated communities of San Diego County including Boulevard, Campo, Live Oak Springs, and Clover Flat. All of the communities in the east county mountains are fully reliant on groundwater for their water supply through either privately owned wells or community water systems that derive their water from groundwater sources. There are no imported water supplies to this region.

The Campo Wind project would be located on 2,200 acres of the approximately 16,000 acres of reservation land. Additionally, the Boulder Brush Facilities (a transmission and storage facility) would be constructed on approximately 500 acres of privately held land under lease that is adjacent to, and would be connected to, the wind farm project. The project as proposed would include the construction of up to 60 wind turbines and associated infrastructure including roads, meteorological towers, an operations and maintenance facility, and transmission lines.

DEMAND/PROJECT PLAN

The projected water demand from the project is 173 acre feet (AF), or 56,370,000 gallons, over a 14-month construction period. For the wind farm portion of the project, 123 AF will be required, with approximately 36 AF of water for concrete mixing and 87 AF for dust suppression. For the Boulder Brush Facility Project, the projected water demand is 50 AF, with 15 AF for concrete mixing and 35 AF for dust suppression.

During the first 3 months of construction (peak construction), it is estimated that the project will use 250,000 gallons per day (gpd, 0.76 AF per day) or 173 gallons per minute (gpm) over a 24-hour period (the rate would be higher if work days are less than 24 hours per day). During the remaining 11 months of construction it is estimated that the project will use 120,000 to 150,000 gpd (0.37 to 0.46 AF per day) or 84 to 105 gpm over a 24-hour period (the rate would be higher if work days are less than 24 hours per day).

The project proposes to use water from three sources: the on-reservation "South Well Field" consisting of four groundwater supply wells (presumably PD-1 though PD-4, though this is not stated in the EIS) on the Campo Reservation; the Jacumba Community Services District (JCSD); and Padre Dam Municipal Water District (PDMWD). The proportion of water expected to be supplied to the project from these three sources is not provided in the Draft EIS.

EXISTING GROUNDWATER DEMAND

The existing groundwater demand in the basin was tabulated in the GRE at 185.4 AF per year (AFY). The basin is estimated to hold approximately 3,000 AF, some of which is not available for withdrawal due to physical constraints. The GRE reports that current demand on the basin is 6% of the groundwater in storage. However, there are several assumptions that are liberal in nature, which likely underestimate the actual or potential groundwater consumption. These are discussed in more detail below.

<u>Residential Wells</u>

For the existing water demand (Section 3.4) the groundwater withdrawal rate for a residential property was assumed to be 0.5 AFY, equivalent to 0.31 gpm or 446 gpd. While this may be water use for a typical American family on a standard-sized lot, this consumption rate for residents of the project area is grossly underestimated for some of the land owners, and at the very least places an undue burden and restriction on residents. The size of the properties for many residents in the area can exceed 10 acres and some own 100 acres or more. In addition, many residents have livestock or landscaping which both place an additional demand on groundwater resources. Residential properties can use up to 20,000 gpd without being considered a water intensive use (i.e., without special permission from the County), and this is not factored into the storage calculations. As a conservative approach, the 50% reduction in storage analysis which reflects potential conditions should consider the maximum permitted withdrawal by residences, or 22.4 AFY per property.

While many of the residents of the area choose to conserve water as much as possible, they are permitted to use such quantities; as mentioned, it is entirely likely that many do use much more than 450 gpd for their large properties.

<u>Golden Acorn Casino</u>

As the Golden Acorn Casino is also owned by the reservation who will provide groundwater for the Campo Wind Project, annual groundwater use data should be provided to aid in a more accurate calculation of the existing water demand. The groundwater use for the casino (owned by the Campo Indians) was not provided for this GRE; instead Dudek had to rely on estimated use of 23.4 AFY, as provided in the proposed project report.

<u>Live Oak Springs Water Company</u>

According to the GRE, Live Oak Springs Water Company (LOSWC) has a total of 97 connections. It also states that in 2011 (more recent data was not used), 14.5 AF of groundwater was used. While these data may be accurate for 2011, the data are 8 years out-of-date, and more recent data should be provided for the GRE. The 14.5 AFY does not represent a worst-case scenario of water use within the water company. The connections could use far more water in the future should landowners change their land use and thus water consumption. At a minimum, the calculations should conservatively use 0.5 AFY per connection if this is the number that was used for the private wells on residential property (although, as discussed above, this number is not considered a maximum allowable use).

In addition to the demand on the LOSWC for domestic and commercial uses of groundwater, Live Oak Springs has also provided groundwater for retail sale for several projects in the area similar to this project. Dudek should evaluate current and future projects that are planned and make an assumption of groundwater that might be sold on the retail market and add those estimates to the total water demand for LOSWC and the basin.

GROUNDWATER QUANTITY IMPACT ANALYSIS

Dudek conducted a groundwater quantity impact analysis (Section 4) in the GRE. The results of this analysis were compared to significance criteria contained in the County of San Diego regulation “County Groundwater Ordinance and Guidelines for Determining Significance and Report Format Content Requirements: Groundwater Resources.” Two primary thresholds were used to evaluate the impact of the project on groundwater resources:

- A soil moisture balance or equivalent analysis using a minimum of 30 years of precipitation data must show that groundwater in storage is not reduced to a level of 50% or less.
- After a 5-year projection of drawdown, water levels in off-site wells must not be decreased more than 20 feet.

These criteria and other indications of possible impact to local groundwater resources and users are further described below.

Well Depths

The depths of the production wells are not given in the EIS; however, their depths may be of concern during groundwater extraction. The average depth of wells in the area is 350 feet and the median depth is 300 feet. There is a reasonable concern that a deep well or wells, while perhaps not reducing groundwater in storage to less than 50%, could reduce the overall groundwater levels below the depths of shallower private residential wells. Even in the short term, this could negatively affect the private well users’ use of groundwater, which is their only source of water.

50% Reduction in Storage Calculations

For the 50% reduction in storage calculations for the GRE, a groundwater withdrawal rate for residential properties of 0.5 AFY was assumed, equivalent to 0.31 gpm or 446 gpd. While this may be water use for a typical American family on a standard-sized lot, this extraction rate for residents of the project area is grossly underestimated for some of the land owners, and at the very least places an undue burden and restriction on residents. The size of the properties for many residents in the area can exceed 10 acres and some own 100 acres or more. In addition, many residents have livestock or landscaping which both place an additional demand on the water resources. Residential properties can use up to 20,000 gpd without being considered a water intensive use (i.e., without special permission from the County), and this is not factored into the storage calculations. As a conservative approach, the 50% reduction in storage analysis which reflects potential conditions should consider the maximum permitted withdrawal by residences, or 22.4 AFY per property. While many of the residents of the area choose to conserve water as much as possible, they are permitted to use such quantities; as mentioned, it is entirely likely that they do use much more than 450 gpd (0.5 AFY).

According to the GRE, LOSWC has a total of 97 connections. It also states that in 2011 (more recent data was not given), 14.5 AF of groundwater was used. While this data may be accurate, it does not represent a worst case scenario of water use within the water company. The connections could use far more water in the future should landowners change their land use and thus water consumption. At a minimum, the calculations should conservatively use 0.5 AF per connection if this is the number used for the private wells on residential property.

In addition to the demand on the LOSWC for domestic and commercial uses of groundwater, Live Oak Springs has also provided groundwater for retail sale for several projects in the area similar to this project. Dudek should evaluate current and future projects that are planned and make an assumption of groundwater that might be sold on the retail market and add those estimates to the total water demand for LOSWC.

As the Golden Acorn Casino is also owned by the reservation who will provide groundwater for the Campo Wind Project, annual groundwater use data should be provided to aid in a more accurate calculation of the existing water demand. The data for the casino used in the analysis was 23.4 AFY, based on a 2008 project water use study.

Groundwater Levels in Off-Site Wells

The second of the two significant impact tests according to County of San Diego Guidelines is that residual drawdown in off-site wells after 5 years must not exceed 20 feet. The nearest well to the well field is reported to be 4,500 feet. Therefore, the drawdown in this well was estimated in order to evaluate the County criterion.

A significant omission in the report was the variable Q (pumping rate) which was not presented or discussed, so the validity of the calculations using Q cannot be independently verified for all three calculated scenarios (Tierra Del Sol [TDS], Border Patrol Well 2, and Border Patrol Well 3). It is not known if Q was used from each pumping test that was analyzed (and whether that is a reasonable rate for the on-site wells) or if Q was used from rates at the well field that were developed during the ECO Substation project.

Transmissivity (T) for the equation in Section 4.2 is presented in gallons per day per foot, whereas the transmissivity for each pumping scenario is presented as ft^2 per day. At a minimum the transmissivities in Table 4-2 should be presented in units that are consistent with the equation used.

For the TDS well scenario, an estimate of Storativity (S) was presented as 0.001 since S could not be calculated for the TDS project. The calculation resulted in a residual drawdown of 19 feet after 5 years, one foot below the criterion of 20 feet. The arbitrary nature of the storativity value selection must be re-evaluated. Given that the transmissivity for the TDS well was 75 percent lower than the transmissivities for the Border Patrol wells, it seems appropriate to select a storativity value that is also proportionately lower than the Border Patrol wells (i.e., 0.00012 to 0.00019). However, we calculated the 5-year drawdown under the TDS well scenario at the nearest off-site well using the two storativity values from the Border Patrol wells (0.00074 and 0.00048) and the resulting drawdown values were 21.89 and 26.25 feet, respectively. Using the storage value (S) used by Dudek in their own calculation of groundwater in storage in the basin (0.0005), the drawdown after 5 years at the nearest off-site well under the TDS well scenario is 25.84 feet.

No discussion was presented as to the comparability of the well tests conducted at TDS, or Border Patrol Wells 2 and 3 to the wells at the southern well field on the reservation. No details regarding well depths, well diameters, geologic conditions, or pumping rates for the three off-site well tests versus the on-site wells' production during the SDG&E ECO Substation project were given. Therefore, it is impossible to know if the calculations provided in Section 4.2 accurately reflect the conditions that would result from actual pumping tests of the product wells at the southern well field.

Groundwater levels in off-site wells (Section 4.2) should be monitored during constant rate pumping tests at the southern well field to assess potential impacts. However, in the absence of pumping test data, the Section 4.2 estimates of residual drawdown in the nearest off-site well should be recalculated.

Groundwater Use and Water Levels During ECO Substation Project

The SDG&E ECO Substation project obtained groundwater from the southern well field on the reservation from July to November 2013. During the project, SDG&E extracted more than 36.4 AF, or 9.1 AF per month. This project proposes to use 22.8 AF per month for 3 months and 11.1 to 13.8 AF per month for 11 months, both of which exceed the amount of water extracted during the ECO Substation project. Since the amount and timing of water use from each of the three potential water purveyors is not known at this time, it should be conservatively assumed that all of the water would come from the reservation wells. Groundwater testing should be conducted based on this assumption. If the water use from the reservation is known, then the wells should be tested based on the known planned extraction rates.

Dudek stated that groundwater levels in the four production wells PD-1 through PD-4 did not fall more than 110 feet during pumping for the ECO Substation project, and referred to Appendix A of the GRE as evidence of this statement. However, in reviewing the hydrographs for the four wells, it is evident the groundwater fell in these wells much further than 110 feet. In fact, wells PD-1 through PD-4 water levels dropped a maximum of 202, 145, 165, and 165 feet, respectively, or 32 to 83% more than reported in the GRE. It is not entirely clear how this error occurred except that the groundwater levels dropped below the transducers in the wells and thus it appeared that only 110 feet of water decline occurred; however, the manual readings clearly indicate a greater decline. Since the total depths of the wells were not provided in the GRE, how close to the bottom of the well or the pump intake the water levels dropped to is not known, which could indicate whether the wells had been pumped to their maximum capacity.

Neighbors reported that their water levels were substantially lower during this time and that after the pumping occurred in 2013 during the ECO Substation project, four large oak trees on one adjacent neighbor's property died, presumably due to lack of available shallow groundwater.

ITEMS NOT ADDRESSED

These items were either omitted from the report and should be included, or were stated as a goal of the investigations and were not discussed.

Comparison to Local Projects

In Section 2, Study Methodology, Dudek stated that the GRE would use the County's significance thresholds to "clearly investigate groundwater impacts from Project groundwater use." However, Dudek did not investigate the groundwater conditions at the site or surrounding area. There appears to be no evidence that any investigation was conducted that included actual testing of the groundwater wells in the southern well field. No information was provided that discusses the sustainable groundwater pumping rates of the proposed production wells, or the effect their pumping may have on the wells of other local groundwater users, specifically, private wells. Instead what was presented in the GRE report was water level data from the SDG&E ECO Substation project from 2013 that did not provide groundwater pumping rates or duration, or any off-site impacts to groundwater wells in the area during pumping.

Also provided were assumptions and projections on how the south well field supply wells would perform and affect local resources using hydrogeologic data from wells that are several miles from the project site for which there was incomplete data (discharge rate), liberal assumptions were made (storativity value), and no basis for the pumping rate used in the calculations (the pumping rate also was not stated). Those liberal assumptions led to a conclusion that the County significance criteria would not be exceeded. A calculation of this criterion by Snyder Geologic using data that Dudek presented elsewhere in the report (a storativity of 0.0005 instead of 0.001) led to the conclusion that in fact the 5-year, 20-foot residual drawdown criterion would be exceeded at the nearest off-site private well.

Dudek also stated in Section 2 that their investigation would "allow for comparison of impacts between this Project and other projects within the County." No such comparisons were made to recent local projects including ECO Substation, Tule Wind, or Soitec Solar.

SUMMARY/RECOMMENDATIONS

Based on the review of the GRE, we make the following recommendations:

- We recommend that this report be used to provide the decision makers with information regarding the lack of appropriate groundwater data to make an informed decision as to whether groundwater extraction from the reservation's southern well field would have a significant impact to groundwater resources in the basin and a detrimental impact on private wells in the area.
- Specifically, this report should be used to provide the project proponent with specific recommendations for further investigation of the southern well field itself, analysis of available data, and re-analysis of the data presented in this report using more conservative assumptions, or no assumptions wherever actual data can be collected.

The following section provides more detail with respect to data gaps that need to be addressed.

SIGNIFICANT DATA GAPS

There are several significant data gaps that should be addressed, or re-analysis of data that should occur, to better analyze the impact on groundwater supplies from the proposed project.

- The identification and location of wells is not provided on any map anywhere in the EIS document, nor are the well details (total depth, geologic conditions, yield) provided. There is no information regarding the safe pumping capacity for any of the wells that would be used for water production. Constant rate pumping tests with a minimum 72-hour duration should be conducted on any of the water supply wells that are proposed to supply water to the project. These tests will determine the safe yield for each well and will allow monitoring of water levels in nearby residential wells for potential impacts.
- The soil moisture balance calculations (Section 4.1.1) and groundwater in storage (Section 4.1.2 and a San Diego County significant impact criterion) should be recalculated using average rainfall data rather than rainfall data from the one weather station that is furthest of all five stations from the well field and is 1,000 feet lower in elevation. The rainfall amount should be calculated either by averaging all five stations (14.9 inches), or by omitting the highest and lowest rainfall amount stations and averaging the three remaining rainfall stations (15.6 inches).

  Groundwater in storage calculations (related to the 50% reduction in storage analysis significance criterion) should be reanalyzed using the maximum permitted groundwater use per residence/private well of 22.4 AFY.
- The second of the two significant impact tests, according to County of San Diego Guidelines, is residual drawdown in off-site wells after 5 years must not exceed 20 feet. The nearest well to the well field is reported to be 4,500 feet. Therefore, the drawdown in this well was estimated in order to evaluate the County criterion.

A significant omission in the report was the variable Q (pumping rate) which was not presented or discussed, so the validity of the calculations using Q cannot be independently verified for all three calculated scenarios. It is not known if Q was used from each pumping test that was analyzed (and whether that is a reasonable rate for the on-site wells) or if Q was used from rates at the well field that were developed during the ECO Substation project.

Transmissivity (T) for the equation in Section 4.2 is presented in gallons per day per foot, whereas the transmissivity for each pumping scenario is presented as ft^2 per day. At a minimum the transmissivities in Table 4-2 should be presented in units that are consistent with the equation used.

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No discussion was presented as to the comparability of the well tests conducted at TDS, or Border Patrol wells 2 and 3 to the wells at the southern well field on the reservation. No details regarding well depths, well diameters, geologic conditions, or pumping rates for the three off-site well tests versus the on-site well production during the SDG&E ECO Substation project were given. Therefore, it is impossible to know if the calculations provided in Section 4.2 accurately reflect the conditions that would result from actual pumping tests of the product wells at the southern well field.

- The effects of pumping on the basin and on water levels in nearby residential wells use estimates of aquifer parameters from unacceptable proxies to actual groundwater pumping tests. It is our opinion that the standard of care is not being met by using estimates of storativity and using transmissivities from other wells in other locations many miles from the project site to evaluate if there will be unacceptable off-site impacts. When these estimates were used, the result was within 5% of the acceptable limit. This is an unacceptable margin for error given the broad assumptions that are being made. Our recalculations indicated the 20-foot drawdown limit would be exceeded.

- No groundwater protections were proposed as part of this project because the GRE stated there would be no groundwater impact. Given the data provided and assumptions made in this report, it is premature to make such a statement. Until actual groundwater investigations can be undertaken and more conservative assumptions can be made with regard to groundwater in storage and off-site impacts, it should be assumed that the project will have negative, unacceptable, and avoidable impacts. Along with the investigation and re-analysis of data, groundwater protections including well extraction rate caps and intensive off-site well monitoring should be included in any approval for the project, if it were to move forward. These protections would be necessary to ensure that nearby private well owners would continue to have sufficient groundwater resources to meet their consumptive needs, as the basin is their only resource for a water supply.

These changes and additional analyses will provide substantially more protection for the groundwater dependent communities in the area of the project. Some of the changes and reanalysis will also further clarify the use of groundwater during the project.

Respectfully submitted,
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EXHIBIT 11
to July 8, 2019
Comments

Life Cycle Greenhouse Gas Emissions of Utility-Scale Wind Power

Systematic Review and Harmonization

Stacey L. Dolan and Garvin A. Heath

Keywords:

greenhouse gas emissions
industrial ecology
life cycle assessment
meta-analysis
renewable energy
wind energy

Supporting information is available on the *JIE* Web site

Summary

A systematic review and harmonization of life cycle assessment (LCA) literature of utility-scale wind power systems was performed to determine the causes of and, where possible, reduce variability in estimates of life cycle greenhouse gas (GHG) emissions. Screening of approximately 240 LCAs of onshore and offshore systems yielded 72 references meeting minimum thresholds for quality, transparency, and relevance. Of those, 49 references provided 126 estimates of life cycle GHG emissions.

Published estimates ranged from 1.7 to 81 grams CO_2-equivalent per kilowatt-hour (g CO_2-eq/kWh), with median and interquartile range (IQR) both at 12 g CO_2-eq/kWh. After adjusting the published estimates to use consistent gross system boundaries and values for several important system parameters, the total range was reduced by 47% to 3.0 to 45 g CO_2-eq/kWh and the IQR was reduced by 14% to 10 g CO_2-eq/kWh, while the median remained relatively constant (11 g CO_2-eq/kWh). Harmonization of capacity factor resulted in the largest reduction in variability in life cycle GHG emission estimates.

This study concludes that the large number of previously published life cycle GHG emission estimates of wind power systems and their tight distribution suggest that new process-based LCAs of similar wind turbine technologies are unlikely to differ greatly. However, additional consequential LCAs would enhance the understanding of true life cycle GHG emissions of wind power (e.g., changes to other generators' operations when wind electricity is added to the grid), although even those are unlikely to fundamentally change the comparison of wind to other electricity generation sources.

Introduction

Electricity generation accounted for approximately 40% of energy-related carbon dioxide (CO_2) emissions in the United States in 2008 (EIA 2009). Interest in technologies powered by renewable energy sources such as the wind and sun has grown partly because of the potential to reduce greenhouse gas (GHG) emissions from the power sector. However, due to GHG emissions produced during equipment manufacture, transportation, on-site construction, maintenance, and decommissioning, wind and solar technologies are not GHG emission-free. Life cycle assessment (LCA) is particularly well suited for comparing conventional power generation systems to renewables because it accounts for GHG emissions across the full life cycle of each technology, and therefore helps to inform decision makers of the attributable environmental impacts of energy technologies.

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Hundreds of LCAs have been published on various solitary wind turbines and wind farms over the past several decades, as well as two articles reviewing the wind power LCA literature (Lenzen and Munksgaard 2002; Varun et al. 2009) and one meta-analysis, which focuses on energy return on investment (Kubiszewski et al. 2010). Lenzen and Munksgaard (2002) investigated the effects capacity factor, lifetime, power rating, method, scope, country of manufacture, and vintage have on energy and CO_2 emission intensities of 72 previously published analyses of wind turbines taken from 32 LCAs. They also performed a multivariate regression normalizing the capacity factor to 25% and lifetime to 20 years, resulting in a decrease in the range of energy intensities from almost two orders of magnitude to one.

In contrast, objectives of the present meta-analysis include identifying, explaining, and, where possible, reducing variability in estimates of life cycle GHG emissions through a meta-analytical process called "harmonization." The purpose of this analysis and its umbrella project, the LCA Harmonization Project, which examines other electricity generation technologies such as coal and natural gas, is to inform decision making and future analyses that rely on such estimates. (Articles from the LCA Harmonization Project appearing in this special issue on meta-analysis of LCAs perform similar analysis on crystalline silicon photovoltaic [Hsu et al. 2012], thin film photovoltaic [Kim et al. 2012], coal [Whitaker et al. 2012], concentrating solar power [Burkhardt et al. 2012], and nuclear [Warner and Heath 2012].)[1]

Variability exists in estimates of life cycle GHG emissions even between studies performed on the same technology. Differences can be attributed to several factors, including specifics of the particular model, configuration and operating conditions of the system studied, methodological decisions and assumptions made by those conducting the study, variability in data sources, and LCA approach (e.g., consequential or attributional, process chain or economic input-output). To better understand the extent to which some of these sources of variability affect the overall results of a study, the present research systematically reviews previously published wind power LCAs and harmonizes their GHG emission estimates by establishing more consistent methods and assumptions, including characteristics of system performance, system boundaries, and global warming potentials (GWPs) of the individual GHG species.

Methods

An exhaustive literature search of the English-language literature was performed to compile a database of published wind LCAs. Studies were initially screened out if they did not meet the following criteria: published as a scholarly journal article, trade journal article greater than three published pages in length, conference proceeding greater than five double-spaced pages in length, books or chapters, theses, dissertations, or reports; were published after 1980; were written in English; and evaluated electricity as an end product. This preliminary screen reduced the number of references from 237 to 175. The database was structured to record certain defining characteristics of each study, such as whether it is an empirical or theoretical study. Specific study information extracted included publication year, reference type, onshore or offshore technology, vertical- or horizontal-axis turbines, utility-scale or distributed generation, manufacturer, tower type, publication date, which GHG species were inventoried, and vintage of the GWPs used. Several quantitative system parameters were also recorded, such as capacity, capacity factor, lifetime, and lifetime power output.

An LCA's system boundary is the choice of the researcher, so there may be considerable differences in scope across studies. To allow for comparison of studies in a common framework, our research defines the wind power life cycle as comprising three generalized life cycle phases illustrated in figure 1 and described below:

One-time upstream emissions, which includes emissions resulting from raw materials extraction, materials manufacturing, component manufacturing, transportation from the manufacturing facility to the construction site, and on-site construction.

Ongoing emissions during the turbine's operating phase, which includes emissions from maintenance activities such as replacement of worn parts and lubricating oils, and transportation to and from the turbines during servicing.

One-time downstream emissions, which includes emissions resulting from turbine and site decommissioning, disassembly, transportation to the waste site, and ultimate disposal and/or recycling of the turbines and other site materials.

Transmission and distribution (T&D) of electricity is sometimes included within the scope of LCAs, either through accounting for construction of the infrastructure or the loss of generated electricity in delivery to the consumer, or both.

Screening of the Literature

After the preliminary screen, a quality screen consistent with the general principles of the umbrella LCA Harmonization Project was applied to each estimate of life cycle GHG emissions, as many references produced more than one estimate because they evaluated multiple scenarios. Although a reference wasn't necessarily eliminated if only one of its estimates was screened out, most screening criteria applied to the reference as a whole; the results of screening are therefore reported at the level of the reference.

The pool of references was reduced from 175 to 72 upon applying the following minimum screening criteria:

1. LCA method:
    a. Employed a currently accepted LCA method (e.g., following guideline 14040 from the International Organization for Standardization [ISO 2006a, 2006b]).
    b. Included the upstream life cycle stage, as this stage is known to be the largest contributor to total GHG emissions for wind power systems.

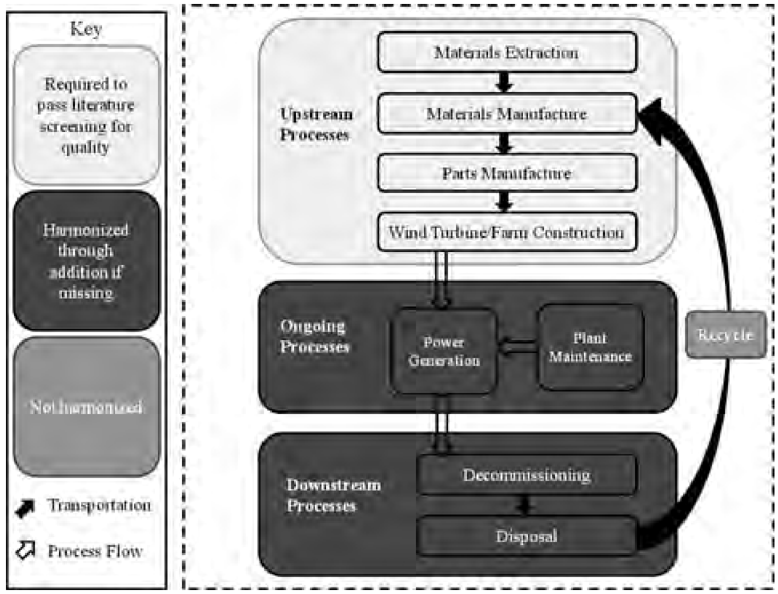

Figure 1 Process flow diagram illustrating the life cycle stages of wind power systems. Inclusion of at least one or more upstream life cycle stage was required for passing the screening process. Transportation between life cycle stages was not harmonized.

2. Transparency and completeness of reporting:
   a. Reported a reasonably descriptive method (e.g., scope and boundaries of study) and set of assumptions (e.g., capacity factor, system lifetime, recycling in end-of-life scenario).
   b. Cited primary or secondary data sources used for the analysis.
   c. Described, numerically where possible, characteristics of the wind power system studied (e.g., turbine model, capacity, site description or location, wind class, single turbine, or wind farm).
   d. Reported the name of software or database, if used, (e.g., SimaPro, Ecoinvent) as well as input parameters for the modeling (e.g., a material requirements list).
3. Relevance of the evaluated technology to modern, utility-scale wind power systems:
   a. Excluded wooden, steel, and aluminum rotor blades.
   b. Excluded non-three-bladed turbines.
   c. Excluded vertical-axis turbines.
   d. Excluded turbines with a rated capacity of less than 150 kilowatts (kW).

All estimates passing the above screening criteria were categorized as onshore, offshore, or a mix of the two, and are listed in table 1 along with important characteristics of the study and technology evaluated.

Harmonization Process

For the LCA Harmonization Project as a whole, two levels of harmonization were devised. The more resource-intensive level was envisioned as a process similar to that employed by Farrell and colleagues (2006) to harmonize the results of LCAs of ethanol. In that process, a subset of the available literature estimates of life cycle GHG emissions was carefully disaggregated. This process produced a detailed meta-model based on factors such as adjusted parameter estimates, realigned system boundaries within each life cycle phase, and a review of all data sources. A less-intensive and therefore grosser approach is more appropriate for the harmonization of a large set of literature estimates of life cycle GHG emissions. The less-intensive approach was chosen as the appropriate level of harmonization for wind power LCAs. The decision-making process for the level of harmonization is discussed in the supporting information available on the Journal's Web site.

This less-intensive harmonization process was performed by proportional adjustment of the published estimates of life cycle GHG emissions in grams CO_2-equivalent per kilowatt-hour (g CO_2-eq/kWh) to consistent values of two influential performance characteristics (capacity factor, system lifetime) and then, by addition or subtraction, to a consistent system boundary at the level of major life cycle stage.[2] GWPs were also harmonized where possible.

In keeping with the less-intensive harmonization approach, estimates were not audited for accuracy; published GHG emission estimates were taken at face value and converted to consistent units prior to being harmonized. Additionally, no exogenous assumptions were employed; if a reference did not report the information required for harmonization or conversion to the common functional unit, no assumptions were made. In those cases, that particular step of harmonization was not applied to that specific published GHG emission estimate, or the estimate wasn't included for harmonization, respectively. For instance, several estimates reported on a damages basis (e.g.,

Table 1 Studies and technologies that passed the screening criteria and produced an estimate of life cycle greenhouse gas (GHG) emissions, including key harmonization parameters

Author	*Year*	*Technology type*	*Turbine capacity (MW)*	*Lifetime (years)*	*Capacity factor (%)*	*Wind farm name, location*	*Study type*	*Notes*
Ardente et al.	2008	Onshore	0.66	20	19%	Italy (Sicily)	Empirical	
Berry et al.	1998	Onshore	0.3	—	31%	Penryddlan and Llidiartywaun, Wales	Empirical	
Chataignere and Le Boulch	2003	Onshore	0.6	20	29%		Theoretical	(1) Vestas 600 kW turbine
Chataignere and Le Boulch	2003	Onshore	2.5	20	34%		Theoretical	(1) Nordex 2.5 MW turbine
Chataignere and Le Boulch	2003	Offshore	2.5	20	46%		Theoretical	(50) Nordex 2.5 MW turbines, cassion
Chataignere and Le Boulch	2003	Offshore	2.5	20	46%		Theoretical	(100) Nordex 2.5 MW turbines
Chataignere and Le Boulch	2003	Offshore	2.5	20	46%		Theoretical	(50) Nordex 2.5 MW turbines, monopile
Chataignere and Le Boulch	2003	Onshore	1.5	20	29%		Theoretical	(1) Enercon 1.5 MW turbine
Crawford	2009	Onshore	3	20	33%		Theoretical	
Crawford	2009	Onshore	0.85	20	34%		Theoretical	
Dolan	2007	Offshore	1.8	20	30%	U.S. (Florida)	Theoretical	
Dones et al.	2005	Onshore	0.8	20/40	20%	Germany	Empirical	Turbine parts assume different lifetimes
Dones et al.	2005	Offshore	2	20	30%	Middelgrunden, Germany	Empirical	
Dones et al.	2007	Onshore	0.8	20/40	20%	Europe	Empirical	Turbine parts assume different lifetimes
Dones et al.	2007	Offshore	2	20	30%	Europe	Empirical	
Dones et al.	2007	Onshore	0.8	20/40	14%	Mont Crosin, Switzerland	Empirical	Turbine parts assume different lifetimes
DONG Energy	2008	Offshore	2	20	46%	Horns Rev, North Sea	Empirical	
Enel SpA	2004	Onshore	0.66	20	18%	Sclafani Bagni, Italy	Empirical	
European Commission	1995	Onshore	0.4	20	30%	Delabole, Penryddlan and Llidiartywaun, UK	Empirical	
Frischknecht	1998	Onshore	0.15	20	9.0%	Switzerland	Empirical	
Hartmann	1997	Onshore	1	20	19%		Theoretical	Process chain analysis
Hartmann	1997	Onshore	1	20	19%		Theoretical	EIO analysis
Hondo	2005	Onshore	0.4	50	20%	Japan	Theoretical	
Hondo	2005	Onshore	0.4	30	20%	Japan	Theoretical	
Hondo	2005	Onshore	0.3	50	20%	Japan	Theoretical	
Hondo	2005	Onshore	0.4	20	20%	Japan	Theoretical	
Hondo	2005	Onshore	0.3	30	20%	Japan	Theoretical	
Hondo	2005	Onshore	0.3	20	20%	Japan	Theoretical	
Hondo	2005	Onshore	0.4	10	20%	Japan	Theoretical	

(*Continued*)

Table 1 *(Continued)*

Author	*Year*	*Technology type*	*Turbine capacity (MW)*	*Lifetime (years)*	*Capacity factor (%)*	*Wind farm name, location*	*Study type*	*Notes*
Hondo	2005	Onshore	0.3	10	20%	Japan	Theoretical	
Jacobson	2009	Onshore	5	30	43%		Theoretical	
Jacobson	2009	Onshore	5	20	43%		Theoretical	
Jacobson	2009	Onshore	5	30	29%		Theoretical	
Jacobson	2009	Onshore	5	20	29%		Theoretical	
Jungbluth et al.	2005	Onshore	0.8	20/40	20%	Europe	Theoretical	Turbine parts assume different lifetimes
Jungbluth et al.	2005	Offshore	2	20	30%	Middelgrunden, Baltic Sea	Theoretical	
Khan et al.	2005	Onshore	0.5	20	—	Canada (Newfoundland)	Theoretical	
Krewitt et al.	1997	Onshore	0.25	20	25%	Northfriesland, Germany	Empirical	1990 technology vintage
Kuemmel and Sørensen[a]	1997	Mix	1.3	25	29%	Denmark	Theoretical	
Kuemmel and Sørensen	1997	Onshore	0.4	20	23%	Denmark	Theoretical	
Lee and Tzeng[b]	2008	Onshore	0.6–1.75	20	33%	Mailiao, Jhongtun and Chunfong, Taiwan	Empirical	
Lenzen and Wachsmann	2004	Onshore	0.6	20	68%	Manufactured and operated in Brazil	Theoretical	Recycled steel, coastal, 44 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	71%	Manufactured and operated in Brazil	Theoretical	Recycled steel, coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	55%	Manufactured and operated in Brazil	Theoretical	Recycled steel, near-coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	68%	Manufactured and operated in Brazil	Theoretical	Coastal, 44 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	71%	Manufactured and operated in Brazil	Theoretical	Coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	55%	Manufactured and operated in Brazil	Theoretical	Near-coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	42%	Manufactured and operated in Brazil	Theoretical	Recycled steel, inland, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	46%	Manufactured and operated in Brazil	Theoretical	Recycled steel, inland 65 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	42%	Manufactured and operated in Brazil	Theoretical	Inland, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	46%	Manufactured and operated in Brazil	Theoretical	Inland, 65 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	68%	Manufactured in Brazil and Germany, operated in Brazil	Theoretical	Coastal, 44 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	71%	Manufactured in Brazil and Germany, operated in Brazil	Theoretical	Coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	55%	Manufactured in Brazil and Germany, operated in Brazil	Theoretical	Near-coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	46%	Manufactured in Brazil and Germany, operated in Brazil	Theoretical	Inland, 65 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	42%	Manufactured in Brazil and Germany, operated in Brazil	Theoretical	Inland, 55 m hub height

(Continued)

Table 1 *(Continued)*

Author	Year	Technology type	Turbine capacity (MW)	Lifetime (years)	Capacity factor (%)	Wind farm name, location	Study type	Notes
Lenzen and Wachsmann	2004	Onshore	0.6	20	68%	Manufactured in Germany, operated in Brazil	Theoretical	Coastal, 44 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	71%	Manufactured in Germany, operated in Brazil	Theoretical	Coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	55%	Manufactured in Germany, operated in Brazil	Theoretical	Near-coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	46%	Manufactured in Germany, operated in Brazil	Theoretical	Inland, 65 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	42%	Manufactured in Germany, operated in Brazil	Theoretical	Inland, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	25%	Manufactured and operated in Germany	Theoretical	Coastal, 44 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	26%	Manufactured and operated in Germany	Theoretical	Coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	20%	Manufactured and operated in Germany	Theoretical	Near-coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	17%	Manufactured and operated in Germany	Theoretical	Inland, 65 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	15%	Manufactured and operated in Germany	Theoretical	Inland, 55 m hub height
Liberman and LaPuma[c]	2003	Onshore	0.75–1.3	Various	—	U.S. (Arkansas)	Empirical	
Martínez et al.	2009	Onshore	2	20	23%	Munilla, Spain	Empirical	
Martínez et al.	2009	Onshore	2	20	23%	Munilla, Spain	Empirical	
Martínez et al.	2009	Onshore	2	20	23%	Munilla, Spain	Empirical	
McCulloch et al.	2000	Onshore	0.6	25	20%		Theoretical	
Nadal	1995	Onshore	0.225	20	20%		Theoretical	
Pacca and Horvath	2002	Onshore	0.6	20	24%		Theoretical	
Pacca	2003	Onshore	0.6	40	24%	U.S. (Southern Utah)	Theoretical	
Pacca	2003	Onshore	0.6	30	24%	U.S. (Southern Utah)	Theoretical	
Pacca	2003	Onshore	0.6	20	24%	U.S. (Southern Utah)	Theoretical	
Pacca	2003	Onshore	0.6	10	24%	U.S. (Southern Utah)	Theoretical	
Pehnt	2006	Offshore	2.5	—	—	Germany	Theoretical	2010 technology vintage
Pehnt	2006	Onshore	1.5	—	—	Germany	Theoretical	2010 technology vintage
Pehnt et al.	2008	Offshore	5	—	—	North Sea	Theoretical	
Proops et al.	1996	Onshore	6.6	20	29%	UK	Theoretical	Used 1989 EIO tables
Proops et al.	1996	Onshore	6.6	20	29%	UK	Theoretical	Used 1989 EIO tables
Proops et al.	1996	Onshore	6.6	20	29%	UK	Theoretical	Used 1989 EIO tables
Rule et al.	2009	Onshore	1.65	100	39%	Te Apiti, New Zealand	Empirical	
Rydh et al.	2004	Onshore	0.225	30	26%	Gronhogen, Sweden	Empirical	End-of-life scenario: renovation
Rydh et al.	2004	Onshore	2	20	35%	Gronhogen, Sweden	Empirical	End-of-life scenario: replacement
Rydh et al.	2004	Onshore	0.225	20	26%	Gronhogen, Sweden	Empirical	End-of-life scenario: relocation

(*Continued*)

Table 1 *(Continued)*

Author	*Year*	*Technology type*	*Turbine capacity (MW)*	*Lifetime (years)*	*Capacity factor (%)*	*Wind farm name, location*	*Study type*	*Notes*
Rydh et al.	2004	Onshore	0.225	20	26%	Gronhogen, Sweden	Empirical	End-of-life scenario: recycling
Schleisner	2000	Onshore	0.5	20	25%	Tuno Knob, Denmark	Empirical	
Schleisner	2000	Offshore	0.5	20	29%	Fjaldene, Denmark	Empirical	
SECDA	1994	Onshore	0.3	40	24%	Canada (Saskatchewan)	Theoretical	
Spitzley and Keoleian	2004	Onshore	0.5	30	36%	Western U.S.	Theoretical	Ridge site, class 6 winds
Spitzley and Keoleian	2004	Onshore	0.5	30	26%	Western U.S.	Theoretical	Plains site, class 4 winds
Tremeac and Meunier	2009	Onshore	4.5	20	30%	Southern France	Theoretical	Transport by train
Tremeac and Meunier	2009	Onshore	4.5	20	30%	Southern France	Theoretical	Transport by truck
Tremeac and Meunier	2009	Onshore	4.5	20	30%	Southern France	Theoretical	Doubling transport distance
Uchiyama	1996	Onshore	0.4		20%	Japan	Theoretical	Micon 400/100 kW two-speed turbine
Uchiyama	1996	Onshore	0.3		20%	Japan	Theoretical	Mitsubishi 300 kW turbine
van de Vate	1996	Onshore	0.3	20	23%		Theoretical	
Vattenfall[d]	2003	Onshore	0.225–1.75	25	21%	Various wind farms, Sweden	Empirical	
Vattenfall[e]	2010	Mix	0.6–3	20	29%	Denmark, UK, Poland, Sweden, Germany	Empirical	Does not include T&D grid
Vattenfall[e]	2010	Mix	0.6–3	20	29%	Denmark, UK, Poland, Sweden, Germany	Empirical	Includes T&D grid
Vestas Wind Systems	2006a	Onshore	1.65	20	41%		Theoretical	
Vestas Wind Systems	2006b	Onshore	3	20	54%		Theoretical	
Vestas Wind Systems	2006b	Offshore	3	20	54%		Theoretical	
Voorspools et al.	2000	Onshore	0.6	20	34%	Belgium (coastal)	Theoretical	EIO analysis
Voorspools et al.[f]	2000	Onshore	0.15–1.5	20	34%	Belgium (coastal)	Theoretical	Process chain analysis
Voorspools et al.	2000	Onshore	0.6	20	11%	Belgium (inland)	Theoretical	EIO analysis
Voorspools et al.[f]	2000	Onshore	0.15–1.5	20	11%	Belgium (inland)	Theoretical	Process chain analysis
Waters et al.	1997	Onshore	0.15	25	23%	Baix Ebre, Spain	Empirical	
WEC	2004	Onshore	0.23	—	35%	Greece	Theoretical	
WEC	2004	Onshore	0.6	—	23%	Finland	Theoretical	
WEC	2004	Onshore	0.6	—	21%	Australia	Theoretical	
WEC	2004	Onshore	0.5	—	25%	Denmark	Theoretical	
WEC	2004	Offshore	0.5	—	29%	Denmark	Theoretical	
Weinzettel et al.	2009	Deep offshore	5	20	53%		Theoretical	With end-of-life scenario
Weinzettel et al.	2009	Deep offshore	5	20	53%		Theoretical	Without end-of-life scenario
Weinzettel et al.	2009	Offshore	2	20	30%		Theoretical	Ecoinvent database process
White	2006	Onshore	0.3425	25	26%	Buffalo Ridge, U.S. (SW Minnesota)	Empirical	Update to 1998 publication estimate
White	2006	Onshore	0.75	30	29%	Buffalo Ridge, U.S. (SW Minnesota)	Empirical	Update to 1998 publication estimate
White	2006	Onshore	0.6	20	20%	Glenmore, U.S. (Wisconsin)	Empirical	Update to 1998 publication estimate

(Continued)

Table 1 *(Continued)*

Author	*Year*	*Technology type*	*Turbine capacity (MW)*	*Lifetime (years)*	*Capacity factor (%)*	*Wind farm name, location*	*Study type*	*Notes*
White and Kulcinski	1998	Onshore	0.75	30	35%	Buffalo Ridge, U.S. (SW Minnesota)	Empirical	Zond Z-46 turbines
White and Kulcinski	1998	Onshore	0.3425	25	24%	Buffalo Ridge, U.S. (SW Minnesota)	Empirical	Kenetech KVS-33 turbines
White and Kulcinski	1998	Onshore	0.6	20	31%	Glenmore, U.S. (Wisconsin)	Empirical	Tacke 600e turbines
White and Kulcinski	2000	Onshore	0.3425	25	24%	Buffalo Ridge, U.S. (SW Minnesota)	Empirical	Update to 1998 publication estimate
Wibberly	2001	Onshore	0.6	30	21%	Crookwell, Australia	Empirical	

Notes: One meter (m, SI) ≈ 3.28 feet (ft); MW = megawatts; kW = kilowatts.
[a]This data point represents a mix of 1 megawatt (MW) onshore and 3 MW offshore turbines. Therefore a mean capacity of 2 MW listed here was assumed for plotting in figure 2. Because the proportion of onshore to offshore turbines in the mix is unknown, this estimate could not be harmonized by capacity factor.
[b]This data point represents a mix of (4) 660 kilowatt (kW), (4) 600 kW, and (2) 1.75 MW turbines. Therefore the average was assumed for plotting purposes in figure 2. A weighted average was also used for capacity factor to allow harmonization by this parameter.
[c]This data point represents a mix of various turbines for which only the capacity range of 750 kW to 1.3 MW was reported; therefore a mean capacity of 1.025 MW was assumed to include this data point in the scatter plots in figure 2.
[d]The capacity listed represents a weighted average of (1) 225 kW, (2) 500 kW, (7) 600 kW, and (1) 1.75 MW turbines. The capacity factor also represents a weighted average based on the reported power outputs of the 11 turbines.
[e]The capacity listed represents a weighted average of the mix of (7) 600 kW, (4) 850 kW, (10) 1.5 MW, (63) 2.0 MW, (50) 2.3 MW, and (30) 3 MW turbines. The capacity factor is also an average weighted by the reported capacity factors of the groups of turbines.
[f]This data point represents a range of turbine capacities for which only the endpoints of the range were given. Therefore the mean of the endpoints was assumed as the capacity to include this point in the scatter plots in figure 2.

milliperson-equivalents/kWh) could not be back-calculated to the common functional unit and thus were not retained. Only nonduplicative estimates were included; however, any estimate that adapted previous work in a way that resulted in an estimate different from the original was accepted. Only the latest publication from authors who published the exact same estimates in multiple papers was retained for further analysis. Finally, GHG emission estimates had to be reported numerically (not just graphically) for inclusion.

Harmonization Parameters

Life cycle GHG emission estimates for wind power systems are calculated as follows:

$$\frac{CO_2 + \left(CH_4 * 25\frac{\text{g } CO_2-\text{eq}}{\text{g } CH_4}\right) + \left(N_2O * 298\frac{\text{g } CO_2-\text{eq}}{N_2O}\right)}{\textit{Capacity factor} * 8760\frac{\text{hours}}{\text{year}} * \textit{Lifetime} * \textit{Nameplate capacity}}.$$

This equation allows for clear identification of the potential magnitude for adjustment that each of the harmonization parameters has in the life cycle GHG emission estimates. The numerator represents the total emissions over the life cycle, while the denominator represents the lifetime power output of the system. The GWP harmonization step adjusts two of the values in the summation in the numerator; however, the CO_2 portion of the emission estimates remains unchanged. Both the capacity factor and system lifetime harmonization steps scale the denominator in its entirety, and therefore have a larger potential than GWP harmonization to adjust the life cycle GHG emission estimates. The system boundary harmonization step adds additional emissions onto the numerator to account for life cycle stages that were not included in the scope of the original analysis. Thus this harmonization step has a potential for adjustment of the life cycle GHG emission estimates similar to that of the GWP harmonization step.

Statistical Assessment

Central tendency and variability in life cycle GHG emission estimates passing our screens are described using several statistical metrics. The key statistical metric chosen to characterize central tendency is the median value. The arithmetic mean is also reported but, due to the slight positive skew of the dataset, the median is preferred. Variability is discussed mainly in terms of interquartile range (IQR = 75th percentile − 25th percentile), which represents the spread of the middle 50% of estimates. Total range is also a key metric for expressing variability, as IQR only summarizes variability in the central half of the estimates. Standard deviation, as well as minimum and maximum values, is also reported. For each harmonization step, changes in central tendency and variability are compared with published estimates to describe the impact of the harmonization step. Decreases in measures of variability indicate effective harmonization in terms of a tightened IQR or range of life cycle GHG emissions from the evaluated technology.

These statistics are meant to summarize the current state of LCA literature of utility-scale wind power technologies. Although the studies and estimates that we selected were reasonably large in number and high quality, the available studies might not cover all possible cases of manufacture, deployment, or use. Thus the range exhibited in this article may not represent the true minimum, maximum, or central tendency for wind power GHG emissions, the current state of the technology as deployed or anticipated, or the inclusivity of all relevant contributions with regard to the depth and breadth across the supply chain. For example, the difference in results generated using process chain compared to hybrid economic input-output methods indicates that system boundary truncations can have significant impacts (Suh et al. 2004). In this respect, the upper end of the range exhibited in this article may be closer to the true life cycle GHG emissions than those estimates at the lower end.

The distribution of our results also cannot be considered a distribution of likelihood for actual life cycle GHG emissions for current or future applications of the technology. The precision and range of results are improved with the large sample size evaluated here, but sample limitations impact the accuracy of the results compared to the "true" life cycle GHG emission range and central tendency of wind power under all potential conditions. Confidence in the results for onshore wind is higher than for offshore owing to the larger sample size.

Finally, the impact on variability reduction of harmonizing a particular parameter is an indicator of the influence that parameter exerts on life cycle GHG emissions for wind, but is not a formal sensitivity analysis.

Harmonization of Global Warming Potentials

Per the screening criteria, the pool of articles ranged in publication year from 1980 to 2010, with several updates to GWPs published by the Intergovernmental Panel on Climate Change (IPCC) during this time. Therefore, because various GWPs were utilized in the literature, wherever mass emissions of individual GHGs were reported the GHG emission estimates were updated to reflect the most recent 100-year time horizon GWPs published by the IPCC (Forster et al. 2007) of 25 g CO_2-eq/g methane (CH_4) and 298 g CO_2-eq/g nitrous oxide (N_2O).

Harmonization of Operating Lifetime

Life cycle GHG emission estimates were also harmonized by assumed operating lifetime of the wind turbine and its components. Reported lifetimes ranged from 10 to 100 years, 20 years being the most commonly cited. Since 20 years is also a common design life for modern turbines (Vestas Wind Systems 2006a, 2006b), all GHG emission estimates were harmonized to a 20-year life span by proportionally scaling the lifetime power output while holding the life cycle emissions estimate constant. This assumes that emissions resulting from maintenance are not changed when a different lifetime is assumed. Operational maintenance, however, was the life cycle stage with the least coverage in the literature, and because its emissions are small relative to the other life cycle stages, any errors resulting from this assumption are likely small in magnitude. Several publications (Dones et al. 2005, 2007; Jungbluth et al. 2005; Rule et al. 2009) assumed lifetimes longer than 20 years and included a certain amount of parts replacement after the 20-year point, but did not separately report the emissions resulting from the refurbishing process. These estimates could not be harmonized by lifetime because the emissions from parts replacement could not be subtracted out. It is worth noting that different wind turbines or farms will have different lifetimes in practice. These depend on various factors—the length of the operating contract with the utility company, the lease on the land where the turbine is sited, parts failure and replacement with new turbines instead of repowering—and it is the nature of LCAs to be context specific. However, harmonization of assumed lifetime was nonetheless performed to demonstrate the effect that system lifetime has on wind power's life cycle GHG emissions, and to assess the degree to which harmonizing by this parameter tightens the range of estimates.

Harmonization of Capacity Factor

For wind power, capacity factor is the ratio of actual electricity generated to the maximum potential electricity generation (nameplate capacity multiplied by 8,760 hours per year). For a given wind resource, turbines operating at a higher capacity factor produce more electrical output than those with lower capacity factors by operating for longer periods of time over the course of the year.

In practice, different wind farms will operate at different capacity factors for several reasons, for instance, the specific wind conditions experienced at the site and the frequency and duration of maintenance. However, the purpose of harmonizing the GHG emission estimates is not to suggest that all LCAs of wind turbines or farms should assume a consistent nominal capacity factor, but to observe how large a role differences in assumed capacity factor play in the variability of published GHG emission estimates. The mean assumed capacity factor for onshore turbines in the pool of literature passing the quality and relevance screens was, after rounding, 30%, while the mean assumed capacity factor for offshore wind turbines was 40%. The latest survey of deployed turbines (Wiser and Bolinger 2010) suggests that the capacity-weighted average in 2009 is very close to these literature averages. Therefore GHG emission estimates that assumed alternative capacity factors were adjusted to these values. Modern turbines deployed in high wind class zones can reach 35% for onshore turbines and 45% for offshore turbines. In 2008, capacity-weighted average capacity factors for onshore wind reached 34%, owing to 2008 being a better wind resource year and having less curtailment than 2009. An additional contributing factor to the reduction in average capacity factor from 2008 to 2009 is the recent trend of wind installations in lower-quality wind resource areas because of transmission and other siting constraints (Wiser and Bolinger 2010). The effect of the higher capacity factor benchmarks on life cycle GHG emission estimates is provided in the supporting information on the Web.

Harmonization of System Boundary

The quality screen required that studies include an estimate for upstream GHG emissions because wind turbine operation has no direct combustion emissions. To improve consistency and reduce sources of variability, the median estimate of GHG emissions for operational or downstream life cycle phases from studies that included those phases were added to studies whose scope did not include one or both of those phases. When testing the effect of harmonization by system boundary independently, the median was calculated using published GHG emission estimates; when performed cumulatively with the other harmonization steps, the GHG emission estimates for studies that included these life cycle phases were harmonized by the other parameters first, and then the median of those harmonized estimates (per phase) was calculated. The rationale for employing these methods is further described in the supporting information on the Web.

Cumulative Harmonization of All Parameters

The last harmonization step was to harmonize by GWP, lifetime, capacity factor, and system boundary consecutively. As some harmonization steps may counteract previous ones, this represents the final results of the complete harmonization process.

Results

Summary of the Published Literature

The 126 estimates from 49 studies of wind power life cycle GHG emissions display a median of 12 g CO_2-eq/kWh, IQR of 12 g CO_2-eq/kWh, and a range of 79 g CO_2-eq/kWh. The IQR shows that the central 50% of the estimates lie within only 12 g CO_2-eq/kWh of each other, which is a relatively tight range when compared to the magnitude of other power technologies such as coal, for which life cycle GHG emission estimates are on the scale of 1,000 g CO_2-eq/kWh (Whitaker et al. 2012).

While the onshore studies are far greater in number than the offshore studies and have a larger total range of values, the IQR for the onshore group is only 13 g CO_2-eq/kWh, ranging from 7.3 to 20 g CO_2-eq/kWh. The published offshore studies are even tighter, with a smaller total range, and the central 50% of estimates within less than 5 g CO_2-eq/kWh of each other, lying in the range of 9.4 to 14 g CO_2-eq/kWh.

Cumulative installed wind capacity in the United States gradually grew from nearly zero in the early 1980s to roughly 3,000 megawatts (MW) by the year 2000, followed by exponential growth over the past decade to more than 35,000 MW in 2009.[3] The average turbine size in 1999 was 0.71 MW and the average price of wind energy was $65/megawatt-hour (MWh) expressed in 2009 U.S. dollars.[4] In 2009 the average turbine size had more than doubled to 1.74 MW while the average price had reduced to $45/MWh (Wiser and Bolinger 2010). These trends suggest that considerable learning has taken place in the industry. One might expect the increasing scale and industrial learning to reduce materials usage, which could reduce embodied GHG emissions. Figure 2 explores these potential trends, but neither is found, suggesting that with regard to GHG emissions, wind power has been stable over time and scale. This constancy may not remain into the future, but given the already low life cycle GHG emissions, even if relative reductions were to be achieved, they might not appreciably affect the magnitude.

Harmonization Results

The harmonization process was performed in a stepwise fashion, illustrated in figures 3 and 4 for onshore and offshore wind, respectively. In both figures, frame (a) displays the published estimates and frames (b) through (e) display the results of applying each harmonization step independently. Frame (f) is the final result of harmonizing by all factors cumulatively. Estimates are displayed in an ordinal ranking (from lowest to highest) that remains constant through all frames such that the effect of harmonization can be seen in the vertical translation of a given point. If a point remains in the same position after a given step, either the value of the harmonization parameter in the publication was already the same as the benchmark value chosen for harmonization, or the value for the harmonization parameter was not reported so harmonization of the estimate could not be performed.

Table 2 reports summary statistics for the onshore, offshore, and total pool of estimates passing the screens for each harmonization step. Life cycle GHG emission estimates that could not be harmonized in any given harmonization step due to missing data remain unchanged in the harmonization plots and the calculation of summary statistics from published values so that all of the summary statistics for each harmonization step are based on the same number of estimates ($n = 126$ for all values, $n = 107$ for onshore, and $n = 16$ for offshore). The three life cycle GHG emission estimates that were reported for an aggregated mix of both onshore and offshore technologies (Kuemmel and Sørensen 1997; Vattenfall 2010) were included in the harmonization process and the summary statistics for all technology types only. The individual GHG emission estimates from each publication for each harmonization step are also reported numerically in table S3 of the supporting information on the Web.

Harmonization of Global Warming Potentials

Only six estimates were harmonized in this step because most references do not report both the GWPs used and mass emissions of individual GHGs. All adjustments were less than 1 g CO_2-eq/kWh, resulting in an insignificant (less than 1%) change in variability and central tendency as a result of this harmonization step (figures 3b and 4b).

Harmonization of System Lifetime

Of the 126 estimates evaluated, 107 report system lifetimes; 80 were already at the benchmark value selected for harmonization, that is, 20 years. Therefore the effect of this harmonization step was relatively small, with a 2% increase in the median value, an 11% increase in the IQR, and a less than 1% reduction in total range (figures 3c and 4c).

Harmonization of Capacity Factor

Of the 126 GHG emission estimates in the pool, 118 report capacity factors. Because the assumed capacity factors of the literature vary considerably more than the assumed lifetimes, harmonizing by capacity factor reduced variability significantly

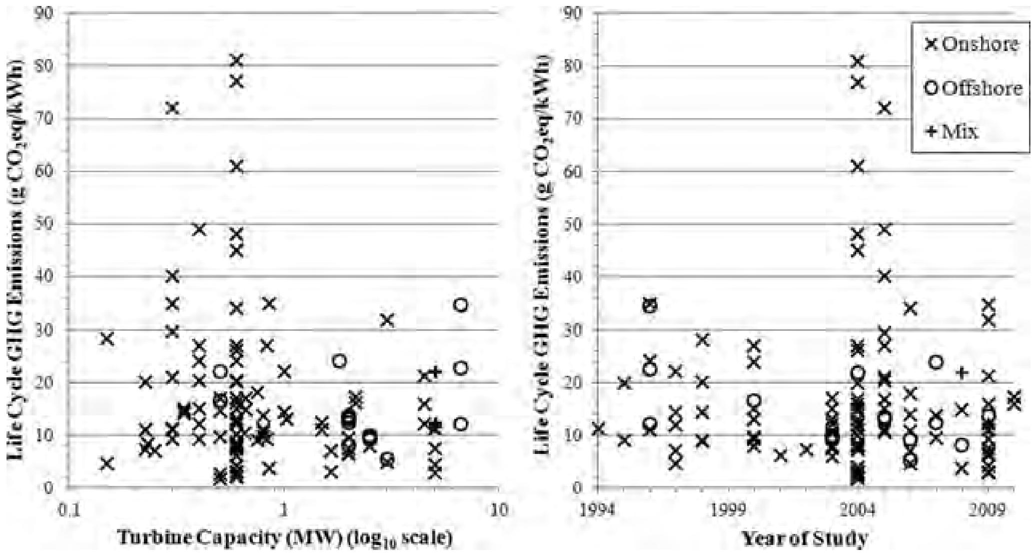

Figure 2 Published life cycle greenhouse gas (GHG) emissions of utility-scale wind power technologies by rated capacity (left) and year of study (right) for estimates that pass screening.

more. This harmonization step reduced the IQR by 14% and the total range by 42%. Figures 3d and 4d display that, on average, low-end GHG emission estimates increased while high-end estimates decreased as a result of this harmonization step. These results suggest that the value chosen for capacity factor in wind power LCAs significantly influences resulting estimates of life cycle GHG emissions.

Harmonization of System Boundary

Sixty-seven estimates of life cycle GHG emissions from 24 references disaggregated GHG emissions into life cycle phases. However, the system boundary for only 22 of those 67 estimates included all three previously defined life cycle stages: upstream, ongoing, and downstream. For the remaining 45 estimates, the median values for the missing life cycle stages, reported in table S2 in the supporting information on the Web, were added. Two sets of median add-on values were used, one for onshore and one for offshore technologies.

Harmonizing for system boundary logically resulted in an increase in the median estimate for both onshore and offshore studies, as add-on values were applied. Harmonization by system boundary did not, however, reduce the variability in life cycle GHG emission estimates. The IQR remained constant and the total range increased by 2.1%. Plots of this harmonization step (figures 3e and 4e) illustrate the small vertical translation of the individual estimates that were harmonized ($n = 45$), only two of which were offshore estimates. The majority of the life cycle GHG emission estimates remained constant because they either did not report disaggregated emissions or because, although disaggregated GHG emissions were reported, they already accounted for all three life cycle stages.

Cumulative Harmonization of All Parameters

Harmonizing for GWPs, system lifetime, capacity factor, and system boundary resulted in a significantly tighter distribution than the published GHG emission estimates for wind power systems (figures 3f and 4f). The published GHG emission estimates ranged from 1.7 to 81 g CO_2-eq/kWh, whereas harmonized estimates comprised a much smaller range of 3.0 to 45 g CO_2-eq/kWh, a decrease of 47% in the total spread of the data. The IQR decreased from 12 to 10 g CO_2-eq/kWh, a 14% reduction. The central tendency remained fairly constant through the harmonization process, with the median value decreasing from 12 to 11 g CO_2-eq/kWh. The change in IQR being considerably less than the change in total range implies that the lowest and highest 25% of the GHG emission estimates were more affected by the harmonization process than the middle 50% of the estimates. Harmonization of capacity factors resulted in a 42% reduction in total range, compared to the 47% reduction resulting from cumulative harmonization of all parameters. This effect implies that variability in assumed capacity factor is the largest contributor—of the harmonization parameters investigated—to variability in published estimates of life cycle GHG emissions of wind power systems.

These findings suggest that the harmonization process, through systematically adjusting estimates to reflect a consistent set of several important parameters, increased the precision of life cycle GHG emission estimates in the literature while having little effect on published central tendency. Figure 5 provides a side-by-side comparison of the published data and the harmonized data, which demonstrates the central tendency and variability of the data.

Overlay plots presenting the progression from published estimates to harmonized estimates showing each successive

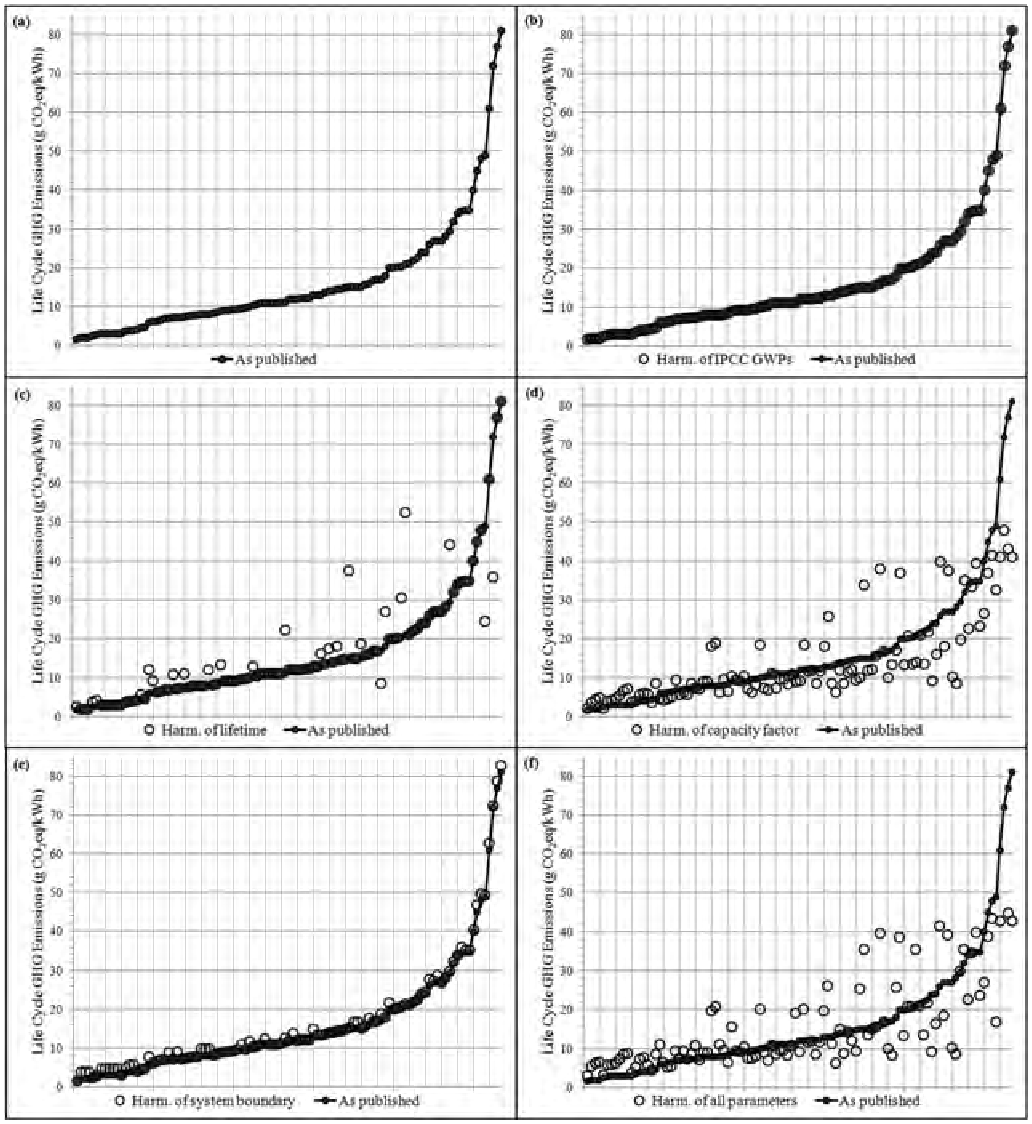

Figure 3 Life cycle greenhouse gas (GHG) emission estimates for onshore wind power from literature passing the screening criteria, ordinally ranked from smallest to largest published value. Frame descriptions: (a) published GHG emission estimates, (b) harmonization of global warming potentials to the most recently published values (Forster et al. 2007), (c) harmonization of operating lifetime to 20 years, (d) harmonization of capacity factor to 30%, (e) harmonization of system boundary to include the ongoing and downstream life cycle stages, and (f) cumulative harmonization of all parameters.

harmonization step (building upon the prior step) are given for onshore and offshore wind on a common set of axes in figures S1 and S2, respectively, in the supporting information on the Web.

Discussion

Comparing Onshore and Offshore

Based on the available literature, the range and IQR for onshore is considerably larger than for offshore, which may reflect the difference in the number of references or might reflect a true wider variability for this class of wind power technologies from range of siting circumstances, turbine size, turbine/wind farm design, and other factors. However, the median life cycle GHG emission estimates for onshore and offshore technology types are both 12 g CO_2-eq/kWh, as published, and 11 g CO_2-eq/kWh after harmonization. This similarity, combined with the tight distribution for both technology types in an absolute sense, suggests that the two technology types may not have significantly different life cycle GHG emissions. However, it should be remembered that these summary statistics reflect the technologies as they are represented in the

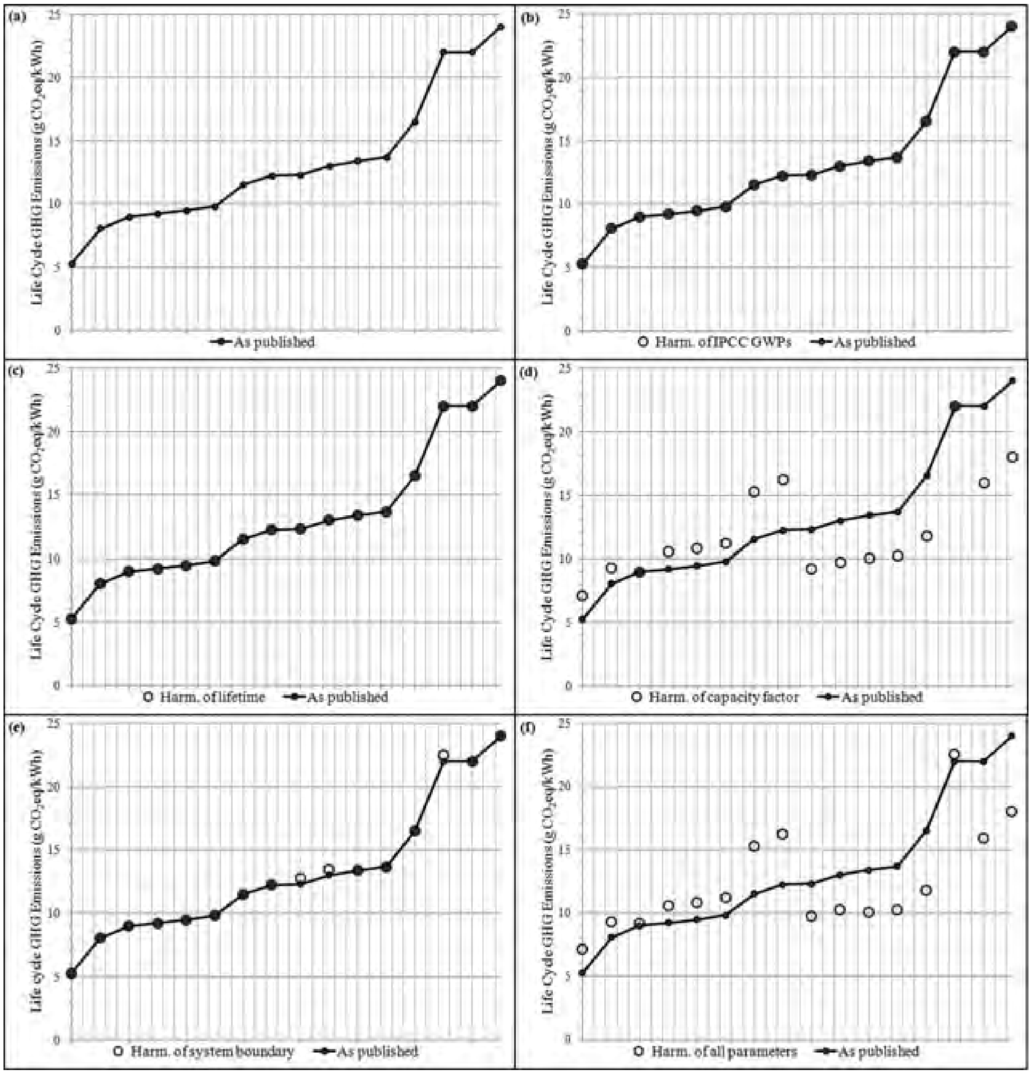

Figure 4 Life cycle greenhouse gas (GHG) emission estimates for offshore wind power from literature passing the screening criteria, ordinally ranked from smallest to largest published value. Frame descriptions: (a) published GHG emission estimates, (b) harmonization of global warming potentials to the most recently published values (Forster et al. 2007), (c) harmonization of operating lifetime to 20 years, (d) harmonization of capacity factor to 40%, (e) harmonization of system boundary to include the ongoing and downstream life cycle stages, and (f) cumulative harmonization of all parameters.

literature and perhaps not the true distribution of deployed technologies.

Limitations of this Analysis

Focus on Life Cycle Greenhouse Gas Emissions

The broad goal of the current phase of the LCA Harmonization Project is to clarify estimates of life cycle GHG emissions and better inform decision making and future analyses, where such estimates would be useful. However, to provide a more comprehensive perspective of the environmental and social impacts of power-generating technologies, other parameters, such as human health impacts, water consumption, and jobs created, should also be assessed.

Pooling Empirical and Theoretical Data

Some practitioners only consider empirical LCAs valid for current technologies because of the potential for modeled estimates to differ from measurements of the same parameter (e.g., Kubiszewski et al. 2010). Table 1 characterizes each study as either empirical or theoretical on balance, despite this characteristic being a continuum rather than a dichotomous choice. (In truth, almost all LCAs have some modeled estimates because empirical data are not always available for every process in the life cycle.) LCAs based on both types of data were included in this analysis. Including studies that are based, at least in important aspects, on parameters not empirically grounded could contribute some additional uncertainty to the results. However, given the similarity of results for GHG emission

Table 2 Summary statistics for each harmonization step, grouping the two system boundary harmonization steps (addition of ongoing and downstream life cycle stages) into one

Statistical measure	*As-published life cycle GHG (g CO_2-eq/kWh)*	*Harmonized by GWPs (g CO_2-eq/kWh)*	*Harmonized by lifetime (g CO_2-eq/kWh)*	*Harmonized by capacity factor (g CO_2-eq/kWh)*	*Harmonized by system boundary (g CO_2-eq/kWh)*	*Harmonized by all (g CO_2-eq/kWh)*
All values						
Mean	16	16	16	14	16	15
SD	14	14	13	10	14	10
Minimum	1.7	1.7	2.0	2.1	1.7	3.0
25th percentile	7.9	7.9	8.1	7.2	8.1	8.5
Median	12	12	12	10	12	11
75th percentile	20	20	21	17	20	18
Maximum	81	81	81	48	83	45
IQR	12	12	13	10	11.6	10
Range (maximum–minimum)	79	79	79	46	81	42
Change in mean (%)[a]	n/a	<1%	3.3%	−12%	3.4%	−5.6%
Change in SD (%)[a]	n/a	<1%	−5.6%	−27%	<1%	−28%
Change in median (%)[a]	n/a	0%	2.0%	−15%	1.5%	−10%
Change in IQR (%)[a]	n/a	0%	11%	−14%	0%	−14%
Change in range (%)[a]	n/a	<1%	<−1%	−42%	2.1%	−47%
Count of estimates[b]	126	6	109	118	82	126
Count of references[b]	49	3	42	44	26	49
Onshore						
Mean	16	16	17	14	17	15
SD	15	15	14	11	15	11
Minimum	1.7	1.7	2.0	2.1	1.7	3.0
25th percentile	7.4	7.4	7.9	7.0	7.9	8.4
Median	12	12	13	9.8	12	11
75th percentile	20	20	22	18	21	20
Maximum	81	81	81	48	83	45
IQR	13	13	14	11	13	11
Range (maximum–minimum)	79	79	79	46	81	42
Change in mean (%)[a]	n/a	<1%	3.5%	−13%	3.8%	−5.7%
Change in SD (%)[a]	n/a	<1%	−5.8%	−27%	<1%	−29%
Change in median (%)[a]	n/a	0%	4.6%	−18%	1.2%	−9.4%
Change in IQR (%)[a]	n/a	0%	12%	−13%	0%	−10%
Change in range (%)[a]	n/a	<1%	<−1%	−42%	2.1%	−47%
Count of estimates[b]	107	5	93	104	74	107
Count of references[b]	44	3	35	41	22	44
Offshore						
Mean	13	13	13	12	13	12
SD	5.2	5.2	5.2	3.9	5.3	3.9
Minimum	5.3	5.3	5.3	7.2	5.3	7.2
25th percentile	9.4	9.4	9.4	9.6	9.4	10
Median	12	12	12	11	13	11
75th percentile	14	14	14	15	14	15
Maximum	24	24	24	22	24	23
IQR	5.0	5.0	5.0	5.8	5.0	5.5
Range (maximum–minimum)	19	19	19	15	19	15
Change in mean (%)[a]	n/a	<1%	<−1%	−7.2%	<1%	−6.4%
Change in SD (%)[a]	n/a	<1%	<1%	−25%	1.2%	−24%
Change in median (%)[a]	n/a	0%	0%	−13%	2.0%	−13%
Change in IQR (%)[a]	n/a	0%	0%	17%	0%	10%
Change in range (%)[a]	n/a	0%	0%	−21%	0%	−18%
Count of estimates[b]	16	1	16	14	8	16
Count of references[b]	12	1	11	10	6	12

Notes: Statistics are reported to two significant digits with the exceptions of changes that are less than 1%, or if there is no change 0% is reported. GHG = greenhouse gas; g CO_2-eq/kWh = grams carbon dioxide equivalent per kilowatt-hour; GWP = global warming potential; SD = standard deviation; IQR = interquartile range.

[a]Percent change statistics were calculated with all references in the category (all values, onshore, or offshore) whether harmonized or not.

[b]Counts of estimates and references for each harmonization step only include the estimates that were harmonized for that step. The counts for the "harmonized by all" column include estimates that were harmonized by at least one parameter.

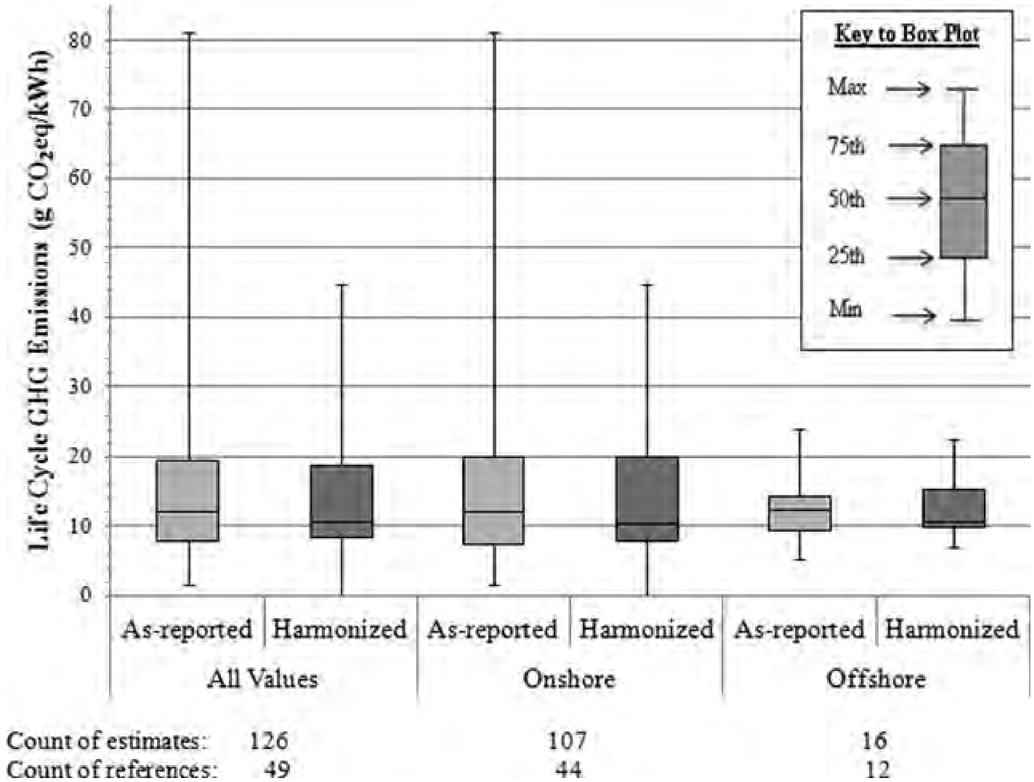

Figure 5 Side-by-side comparison of central tendency and spread of published greenhouse gas (GHG) emission estimates passing our screening criteria and the corresponding harmonized estimates.

estimates of wind power systems between studies characterized as empirical and theoretical, any additional uncertainty from combining the two types of studies is likely insignificant.

Remaining Dimensions of Inconsistency

The light level of harmonization performed for life cycle GHG emission estimates for wind power technologies included harmonizing system boundaries at the level of major life cycle phase, GWPs, system lifetimes, and capacity factors for the pool of estimates that passed the screening criteria. This extent of harmonization was deemed sufficient for reducing variability in published life cycle GHG emission estimates of wind power systems, as the published estimates already comprise a relatively tight dataset. However, additional dimensions of inconsistency across studies are known. Harmonization along these dimensions could potentially further reduce the variability in published estimates. Remaining parameters not harmonized here include upstream electricity mix used in the manufacturing processes (which determines the GHG emission intensity of input electricity); a more detailed system boundary harmonization to account for each individual subprocess that comprises the more general upstream, ongoing, and downstream life cycle stages used in this analysis; harmonization to either include or exclude transmission and distribution infrastructure for all estimates so that individual turbines can more accurately be compared to wind farms; and wind power class. Transmission and distribution losses (typically 5% to 10% of generated electricity) are also excluded, which could increase life cycle GHG emissions by a similar magnitude if the functional unit is chosen as delivered electricity rather than the more common generated electricity. Another effect of harmonization by additional parameters could be to alter the central tendency of life cycle GHG emission estimates, for instance, as has been shown in Lenzen and Wachsmann (2004) and Pehnt (2006) regarding changes to the GHG intensity of background energy systems.

Accuracy of the Central Tendency of Literature Estimates to True Life Cycle Greenhouse Gas Emissions

The literature collected consists solely of attributional LCAs, which evaluate the technology in isolation, with few exceptions such as Pehnt (2006). Consequential LCAs consider impacts to other systems caused by the studied technology. Potential consequential effects not covered in the reviewed literature include changes in consumption owing to changes in the retail price of electricity from the addition of wind power; lowering the GHG intensity of the electrical grid, which reduces embodied GHG emissions of industrial products, including newly manufactured wind turbines; GHG emissions caused by changes in land use to accommodate wind farms; and the combustion-based technologies in the electrical grid having to respond to accommodate the intermittency and nondispatchable nature of wind power. The thermal efficiency of fossil-based power plants is reduced when operated at fluctuating and suboptimal loads to supplement wind power, which may degrade, to a certain extent, the GHG benefits resulting from the addition of wind to the grid. A study conducted by Pehnt and colleagues (2008) reports that a moderate level of wind penetration (12%) would result in efficiency penalties of 3% to 8%, depending on the type of conventional power plant considered. Gross and colleagues (2006) report similar results, with efficiency penalties ranging from nearly 0% to 7% for up to 20% wind penetration. Pehnt and colleagues (2008) conclude that the results of adding offshore wind power in Germany on the background power systems maintaining a level supply to the grid and providing enough reserve capacity amount to adding between 20 and 80 g CO_2-eq/kWh to the life cycle GHG emissions profile of wind power, depending on the various conditions of the energy economy that determine the grid's composition. Thus, considering consequential effects on the background energy system can be significant relative to the attributional life cycle GHG emissions of wind power, as well as for the comparison of wind to other renewable electricity generation technologies (which themselves should be considered on a consequential basis), but should not fundamentally alter the comparison to fossil fuel-based technologies.

Some consequential effects of wind power systems listed above could improve the life cycle GHG emissions profile while others increase it, and all are dependent on specific circumstances of the systems in which wind power is embedded. Thus the answer could change depending on how the question is asked. Therefore the estimates found through this meta-analysis aren't necessarily any more accurate than the underlying LCA literature regarding true (and complete) life cycle GHG emissions, although, for many purposes, knowing the GHG emissions of this technology in isolation, which this study clarifies, could be desirable.

Clustering Bias

This study analyzed 126 distinct life cycle GHG emission estimates of wind power systems. However, these 126 estimates were generated from only 49 different studies and were produced by only 42 different primary authors (not accounting for additional overlap in authors where primary authors were also coauthors of other studies). Thus, there is potential bias in the results of this meta-analysis from clustering, such as multiple scenarios produced within the same study or multiple studies published by the same author(s). In both of these cases, estimates are more likely to be similar to one another than to the rest of the pool of estimates due to commonalities in methods, assumptions, the particular system studied, and data sources. The extent to which these two types of data clustering could cause bias in the results was not quantitatively accounted for or examined. Each of the 126 estimates was treated as independent throughout the analysis. As a result, large clusters within the dataset have potentially caused the summary statistics to be somewhat skewed in their direction. The cluster with the greatest potential to cause bias, due to the largest number of estimates produced from just one study (Lenzen and Wachsmann 2004), generated 25 GHG emission estimates that ranged from 2 to 81 g CO_2-eq/kWh. Given the breadth and even distribution of the range of estimates from this reference, author-based clustering from this study likely does not significantly skew the distribution of results found from harmonization. Other potential clusters in the dataset are considerably smaller in the number of estimates and thus would appear to present a small risk of potential bias.

There is also a third type of clustering bias inherent to LCAs, which is overlap in data sources. LCAs of any one type of system or product that employ common databases or software packages are more likely to have similar results than those using different data sources. The pool of publications that passed the screening criteria contains articles that used common data sources, for example, the Ecoinvent database. One might be able to quantitatively assess the influence of clustering by data source by defining a hierarchical influence tree for each article, statistically evaluating the extent of correlation and then perhaps using the correlation metric to weight the calculation of means. However, because of the large number of data sources for any given LCA, questions of cut-off in modeling data source influence, the subjective nature of assigning a quantitative measure of influence to each source, and other issues such an analysis were beyond the scope of this study. Nevertheless, given the tight distribution of published results, any bias in the distribution is not likely consequential when considering contexts of decision making and comparisons to other electricity generation technologies.

Sample Sizes

Another limitation of this analysis is the relatively small number of offshore wind studies compared to the much larger pool of onshore studies. There were only 12 publications producing 16 life cycle GHG emission estimates for offshore turbines that passed the screens for quality. With such a small dataset, summary statistics can easily be skewed by one or two outlying values. However, the published offshore GHG emission estimates fell within such a tight range that an outlier estimate causing biased results was not a serious concern. Additionally, only one study passing our screens considered deep offshore wind (Weinzettel et al. 2009), so this is a technology for which additional LCA studies are required to be able to assess with any amount of confidence how its life cycle GHG emission profile compares to onshore and shallow offshore wind technologies.

Conclusions

Life cycle GHG emissions of wind-powered electricity generation published since 1980 range from 1.7 to 81 g CO_2-eq/kWh. Although this is already a tight range, upon harmonizing the data to a consistent set of GWPs, system lifetime, capacity factors, and gross system boundary, the range of life cycle GHG emission estimates was reduced by 47%, to 3.0 to 45 g CO_2-eq/kWh. The first and third quartiles stayed relatively constant through the harmonization process, revealing that the middle 50% of the data did not change nearly as much as the lowest 25% and highest 25% of the estimates. The parameter found to have the greatest effect on reducing variability is capacity factor.

The extensive overlap in the distributions of estimates for onshore and offshore technologies suggests that their life cycle GHG emissions may not be notably different. An exception to this may be deep offshore wind technology, for which the literature provided only one estimate. Therefore, with deep offshore wind being a nascent technology on which there is sparse LCA literature to date, as well as a technology that may have considerably different material requirements due to design differences, this may be an area where life cycle GHG emissions of wind power systems have the potential to significantly differ from previously published studies and warrants further investigation.

The harmonization process decreased the variability and increased the precision of the previously published estimates by systematically aligning common system parameters across studies to a consistent set of values. However, improved precision does not imply improved accuracy. There are many consequential effects of deployment of wind power not typically considered in the majority of wind LCAs, which are attributional in nature, and these effects could increase or decrease previously published estimates of life cycle GHG emissions. Another issue is truncation error often inherent in process-based LCAs, which form the majority of LCAs considered in this article. In this respect, the upper end of the range exhibited in this article may be closer to the true life cycle GHG emissions than those estimates at the lower end.

This study ultimately concludes that, given the large number of previously published life cycle GHG emission estimates of wind power systems and their narrow distribution, it is unlikely that new process-based LCAs of similar wind turbine technologies will greatly differ. Additional consequential LCAs would enhance understanding of the true life cycle GHG emissions of wind power, although even those are unlikely to fundamentally change the comparison of wind to other electricity generation sources.

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Notes

1. Results from the whole LCA Harmonization project, including this article, can be visualized and downloaded at http://openei.org/apps/LCA.
2. One gram (g) = 10^{-3} kilograms (kg, SI) ≈ 0.035 ounces (oz). One kilowatt-hour (kWh) ≈ 3.6 × 10^6 joules (J, SI) ≈ 3.412 × 10^3 British thermal units (BTU). Carbon dioxide equivalent (CO_2-eq) is a measure for describing the climate-forcing strength of a quantity of greenhouse gases using the functionally equivalent amount of carbon dioxide as the reference.
3. One megawatt (MW) = 10^6 watts (W, SI) = 1 megajoule/second (MJ/s) ≈ 56.91 × 10^3 British thermal units (BTU)/minute.
4. One megawatt-hour (MWh) ≈ 3.6 × 10^9 joules (J, SI) ≈ 3.412 × 10^6 British thermal units (BTU).

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Supporting Information

Additional supporting information may be found in the online version of this article:

Supporting Information S1: The supporting information provides further detail on the screening process, GHG emissions by life cycle and harmonization stage, and rationale for the system boundary harmonization approach.

Please note: Wiley-Blackwell is not responsible for the content or functionality of any supporting information supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

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Safety & Airspace Regulation Group

CAA Policy and Guidelines on Wind Turbines

CAP 764

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The latest version of this document is available in electronic format at www.caa.co.uk, where you may also register for e-mail notification of amendments.

Contents

Revision History

Issue 1 July 2006

Neither aviation nor the wind energy industry is at a steady state and both can be expected to evolve in ways that may impact the other. Combining the current drive for renewable energy and the increasing number of wind farms with the finite land resource in the UK, means that wind turbines and aviation are being required to operate closer and closer together. However, providing a suitable environment that allows the co-existence of wind turbines and aviation is extremely complicated and new or improved mitigation solutions are being developed all the time. Therefore, it is expected that this CAP will be a living document, which will be updated periodically to reflect the outcome of any further research into the interaction between wind turbine developments and aviation. It will also be revised to take account of changes in regulations, feedback from industry, and recognised best practice.

Issue 2 February 2009

The way in which Aviation Stakeholders and Wind Turbine Developers interact has matured since the initial release of CAP 764 in 2006. This revision includes updates on Government renewable energy policy and details of how all interested parties interact. Additionally, the scope of the document has been widened to include all aspects of aviation that may be affected by Wind Turbines. The appendix detailing the method for determining if a wind turbine is in line of sight of an aeronautical radar station has been simplified.

Issue 3 May 2010

This revision is published to update references to the Air Navigation Order which has been completely re-numbered and to incorporate editorial corrections.

Issue 4 July 2011

This revision follows extensive consultation amongst the aviation and renewable energy communities. Whilst remaining an aviation stakeholder-focused document, CAP 764 has been amended in an attempt to broaden its appeal to all interested wind energy parties with the intention of becoming the ‘go to’ document for aviation and wind energy stakeholders alike. It is important that this document is read in conjunction with the CAA Wind Energy web pages, which provide amplifying information, and which will enable currency and relevancy to be maintained in between the biennial revisions of CAP 764.

A re-issue to issue 4 was made in August 2011 incorporating corrections to the Glossary, Chapter 2, Pages 4, 8 and 9, Chapter 3, Pages 6 and 7.

Revisions included in Amendment 1 to Issue 4

This revision includes changes to Offshore Helicopter Operations, Consultation Zones around Offshore Helidecks, Helicopter Main Routes and Facilitation of Helicopter Support to Offshore Installations.

Issue 5 June 2013

This revision is in the new CAA format and as such paragraph numbering has been updated. In addition, previous paragraphs detailing the impact of wind turbines on aviation and specifically radar have been updated. This is supplemented by an updated overview and analysis of the various mitigation techniques available. It replaces Issue 4 completely.

Issue 6 February 2016

Issue 6 is publicised following a lengthy consultation with both external and CAA stakeholders. It simplifies radar effects paragraphs and returns the more complicated radar detail to the CAP 670. Potential Mitigation Measures were also taken directly from the CAP 670 therefore detailed explanations are removed from the CAP 764 with only a summary retained. Issue 6 also incorporates CAA Policy Statements on the 'Lighting of Wind Turbine Generators in United Kingdom Territorial Waters (22 November 2012)' and the 'Failure of Aviation Warning Lights on Offshore Wind Turbines (27 April 2012)'. CAA Policy Statement 'Lighting of En-Route Obstacles and Onshore Wind Turbines (1 April 2010)' remains extant. Appendices concerning radar assessment methodology and references are removed, the latter being comprehensively covered by hyperlinks and footnotes within the document. It should be noted that hyperlinks were verified on publication. Issue 6 has been comprehensively reviewed and updated where necessary to reflect current information and practices. It replaces Issue 5 completely.

Foreword

Introduction and background

The Department for Transport (DfT) 'Aviation Policy Framework[1], presented to Parliament in March 2013, provided a high level strategy setting out Government objectives for aviation. The aviation sector is seen as a major contributor to the economy and the Government seeks to support its growth within a framework which maintains a balance between the benefits of aviation and its costs, particularly its contribution to climate change and noise.

Whilst recognising the need for further aviation capacity in the UK in order to promote economic growth, the strategy is also based on the requirement for a balanced approach which addresses the wider impacts of aviation and the need for sustainable development.

The Government is also committed to reducing greenhouse gas emissions within the UK and, in turn, this means there is now a shift towards economically viable renewable energy sources rather than carbon fuels. The 2008 Climate Change Act established the world's first legally binding climate change target which aims to reduce the UK's greenhouse gas emissions by at least 80% (from the 1990 baseline) by 2050. In addition, Directive 2009/28/EC of the European Parliament and of the Council set the national overall target for the share of energy from renewable energy by 2020 as 15% for the UK. However, it is UK Government policy that 30% of the UK's electricity supply should come from renewable sources by 2020; the Scottish parliament has adopted a more ambitious 100% electricity demand equivalent from renewables by 2020.

It is anticipated that wind energy will provide a significant contribution to renewable energy targets. In order to harness this energy supply, both on- and offshore wind turbine developments are being constructed, which range in size from single structures to developments encompassing many hundreds of wind turbines. Moreover, the installation of Micro Wind Turbines (MWT) is becoming increasingly prevalent. The physical characteristics of wind turbines, coupled with the size and siting of the developments, can result in effects that can have a negative impact on aviation.

Both wind energy and aviation are important to UK national interests and both industries have legitimate interests that must be balanced carefully. Therefore it is important that the aviation community recognises the Government aspiration for wind turbine developments to play an increasing role in the national economy. As such, the aviation community must engage positively in the process of developing solutions to potential conflicts of interest between wind energy and aviation operations. In a similar vein, wind turbine developers

[1] DfT Aviation Policy Framework March 2013

must understand the potential impact of developments on aviation, both at a local and a national level, and to fully engage with the aviation industry to develop suitable mitigation solutions.

Those involved in addressing wind energy and aviation issues must do so in a positive, co-operative and informed manner. Whilst the aims and interests of the respective industries must be protected, a realistic and pragmatic approach is essential for resolving any conflicts between the Government's energy, transport and defence policies.

Aim of this publication

Being a CAP, this document is aimed primarily at providing assistance to aviation stakeholders to help understand and address wind energy related issues, thereby ensuring greater consistency in the consideration of the potential impact of proposed wind turbine developments. However, it is acknowledged that other users such as Local Planning Authorities (LPAs)[2], wind energy developers and members of the general public will also refer to it.

Consequently, it is hoped that some of the issues and questions often posed by these groups have, where appropriate, also been discussed.

Scope

This document provides CAA policy and guidance on a range of issues associated with wind turbines and their effect on aviation that will need to be considered by aviation stakeholders, wind energy developers and LPAs when assessing the viability of wind turbine developments.

It is not the intention or purpose of this CAP to provide instruction on the need or means to object to wind turbine developments; this must remain the decision of individual aerodrome operators, service providers or other organisations. Furthermore, it should also be noted that within the framework of these guidelines, specific circumstances will have to be addressed on a case-by-case basis, as it is not possible or appropriate to prescribe a standard solution. This document should be read in conjunction with specific policy and/or legislative documentation as referenced in the text, as well as the CAA Windfarms web pages.

Significant effort has been spent developing a cohesive approach to wind energy across the civil and military spectrum of aviation. It is an aspiration to create a joint and integrated publication that details both civil and military aviation policy on wind turbines. However, until this is achieved, the Ministry of Defence (MoD), through Defence Infrastructure Organisation (DIO), must continue to be consulted separately on all developments that may affect their sites (both aviation and others).

[2] The term 'LPA' throughout this document is used generically to refer to Planning Authorities within England, Scotland, Wales and Northern Ireland.

Feedback

Stakeholders are encouraged to provide feedback on their experiences with wind turbine development so that this CAP can be updated appropriately. This CAP will be reviewed biennially and, due to the lengthy process that must be followed, minor amendments cannot be made. However, interim amendments and supplementary guidance will be published through additional CAA Policy Statements or on the CAA Wind Energy web pages to maintain the currency and relevance of CAA guidance and policy.

Contact details

General enquiries concerning this publication can be addressed to windfarms@caa.co.uk. Additional contact details, including postal addresses, are provided at Appendix B.

Glossary

A list of specialised words or terms with their definitions follows:	
AAA	Airspace, ATM and Aerodromes (CAA)
ACP	Airspace Change Process
AD	Air Defence
AIP	Aeronautical Information Publication
ANO	Air Navigation Order
ANSP	Air Navigation Service Provider
AOA	Airport Operators Association
ATC	Air Traffic Control
CAA	Civil Aviation Authority
CAS	Controlled Airspace
CAP	Civil Aviation Publication
CFAR	Constant False Alarm Rate
CNS	Communications, Navigation And Surveillance
DECC	Department Of Energy And Climate Change
DfT	Department For Transport
DIO	Defence Infrastructure Organisation (Formerly Defence Estates)
DME	Distance Measuring Equipment
DTM	Digital Terrain Mapping
DVOF	Defence Vertical Obstruction File
DZ	Dropping Zone
EASA	European Aviation Safety Agency
EM	Electromagnetic
FT	Feet
GA	General Aviation

A list of specialised words or terms with their definitions follows:	
HMR	Helicopter Main Route
IFP	Instrument Flight Procedures
ILS	Instrument Landing System
JAR	Joint Aviation Requirements
KM	Kilometre(S)
LF	Low Flying
LOS	Line Of Sight
LPA	Local Planning Authority (also refers to planning authorities of devolved governments)
m	Metre(s)
MAP	Missed Approach Procedure
MATS	Manual of Air Traffic Services
MHz	Mega Hertz
MoD	Ministry of Defence
Mode S	Mode Select
MSD	Minimum Separation Distance
MW	Mega Watts
MWT	Micro Wind Turbine
NAFW	National Assembly for Wales
NAIZ	Non-Automatic Initiation Zones
Navaids	Navigation Aids
NDB	Non Directional Beacon
NERL	NATS En Route plc
NM	Nautical mile(s) (1853 m or 1.15 Statute Miles)
ODPM	Office of the Deputy Prime Minister
OLS	Obstacle Limitation Surface
PPG	Planning Policy Guidance Note

A list of specialised words or terms with their definitions follows:	
P-RNAV	Precision Area Navigation
PSR	Primary Surveillance Radar
RAM	Radar Absorbent Material
RCS	Radar Cross-Section
RF	Radio Frequency
RNAV	Area Navigation
SARG	Safety and Airspace Regulation Group (CAA)
SID	Standard Instrument Departure
SMS	Safety Management Systems
SSR	Secondary Surveillance Radar
STAR	Standard Instrument Arrival Route
TMZ	Transponder Mandatory Zones
VFR	Visual Flight Rules
VOR	VHF Omni Directional Range

Chapter 1

CAA Responsibilities

General

1.1 The CAA is responsible for safety and airspace regulation of civil aviation in the UK under the Civil Aviation Act 1982 and the Transport Act 2000. The CAA's Safety and Airspace Regulation Group (SARG) is responsible for the regulation of licensed aerodromes and Air Traffic Services (ATS) in the UK; the planning and regulation of all UK airspace, including the communications, navigation and surveillance (CNS) infrastructure, and also has the lead responsibility within the CAA for all wind turbine related issues. Within SARG, wind turbine related issues are addressed by CAA Infrastructure.

1.2 Legislative provisions affecting all development, including wind turbines, are set out for England and Wales in Town & Country Planning (Safeguarded Aerodromes, Technical Sites and Military Explosives Storage Areas) Direction 2002 (ODPM Circular 01/2003). Similar provisions are set out for Scotland in the Town & Country Planning Safeguarded Aerodromes, Technical Sites and Military Explosives Storage Areas (Scotland) Direction 2003 (Scottish Planning Circular 2/2003), and for Northern Ireland in the Planning Policy Statement 18: Renewable Energy. These provisions only apply formally to those aerodromes and technical sites that are officially safeguarded; moreover, statutory consultees are limited to the MoD, NATS En Route Ltd (NERL) and affected service providers.

1.3 At all times, responsibility for the provision of safe services lies with the ATS provider or Air Navigation Service Provider (ANSP). It should be noted that the CAA does not have regulatory powers to approve or reject planning applications.

1.4 The CAA policy on wind energy is that:

1. Wind turbine developments and aviation need to co-exist in order for the UK to achieve its binding European target to achieve a 15% renewable energy commitment by 2020, and enhance energy security, whilst meeting national and international transport policies. However, safety in the air is paramount and will not be compromised. As the independent aviation regulator, the CAA is well placed to provide clarification to both the aviation industry and the wind energy industry;
2. Due to the complex nature of aviation operations, and the impact of local environmental constraints, all instances of potential negative impact of proposed wind turbine developments on aviation operations must be considered on a case- by-case basis;

3. It is CAA policy to provide the best and most timely advice to aviation and wider wind development stakeholders through consultation, the publication of CAP 764 and its associated web pages on the CAA web site;
4. Such clarification, advice and guidance is provided through the publication of this and associated official CAA and government documents, along with the CAA Windfarms web pages.

Aerodrome and Communications Navigation and Surveillance (CNS) site safeguarding[3]

1.5 Many civil aerodromes in the UK are certificated in accordance with EU Regulation 139/2014 (Aerodromes) or licensed in accordance with the Air Navigation Order (ANO) 2009 as amended. Under either of these provisions, the CAA is responsible for being satisfied that a certificated or licensed aerodrome complies with the relevant requirements and is safe for use by civil aircraft, having regard in particular to the physical characteristics of the aerodrome and its surroundings. Aerodrome operators are required to have procedures for safeguarding, to monitor the changes in the obstacle environment, marking and lighting, and in human activities or land use on the aerodrome and in the areas around the aerodrome. In addition, a requirement is placed on the licensee to take all reasonable steps to ensure that the aerodrome and its surrounding airspace are safe at all times for use by aircraft.

1.6 'Statutory' or 'official' safeguarding is a process of obligatory consultation between an LPA and consultees and is designed to safeguard technical sites and certain aerodromes in the UK. However, the same process of consultation can take place for aerodromes and technical sites that are not given this statutory protection; this process is known as unofficial safeguarding.

1.7 Certain civil licensed aerodromes (selected by Government on the basis of their importance to the national air transport system) are officially safeguarded. All EASA certificated aerodromes are deemed to be officially safeguarded. In particular, such safeguarding ensures that the operations and development of the aerodromes are not inhibited by buildings, structures, erections or works which infringe protected surfaces, obscure runway approach lights or have the potential to impair the performance of aerodrome CNS. A similar official safeguarding system applies to certain military sites, including aerodromes,

[3] Further information can be found in:

- England and Wales: Joint ODPM, DfT, Planning Circular 1/2003 guidance on Safeguarding, Aerodromes, Technical Sites and Military Explosives Storage Areas
- Scotland: Planning Circular 2 2003
- Graphics of safeguarded technical sites can be found at:
- http://www.nats.aero/services/information/wind-farms/self-assessment-maps/

selected on the basis of their strategic importance.

1.8 In general, aerodrome safeguarding is limited to the vicinity of the aerodrome (the definition of 'vicinity' will vary depending upon the activity that takes place at that aerodrome). The CAA Aerodromes Team conducts oversight audits at certified and licensed aerodromes to confirm compliance to the applicable rules.

1.9 CAP 793 (Safe Operating Procedures at Unlicensed Aerodromes) provides guidance for unlicensed aerodromes.

1.10 Where an Instrument Landing System (ILS) is used at an aerodrome, safeguarding criteria are used to protect the ILS radio signals from corruption. Technical safeguarding aspects are detailed in CAP 670 (Air Traffic Services Safety Requirements) GEN 02.

1.11 Aerodrome operators are responsible for liaising with LPAs to prevent operational airspace being infringed by new development. One significant consideration is the protection of the Obstacle Limitation Surface (OLS)[4] that should be applied for aerodrome safeguarding. The CAA may be required to explain technical matters to local or central government if a contested development proposal is referred to Ministers for decision.

1.12 The safeguarding of unlicensed aerodromes falls within the advice promulgated in the aforementioned national circulars, which, at Paragraph 13 of Annex 2 state: "Operators of licensed aerodromes which are not officially safeguarded and operators of unlicensed aerodromes and sites for other aviation activities (for example gliding or parachuting) should take steps to protect their locations from the effects of possible adverse development by establishing an agreed consultation procedure between themselves and the local planning authority or authorities. Local planning authorities are asked to respond sympathetically to requests for non-official safeguarding."

1.13 The safeguarding of unlicensed aerodromes is therefore a matter of discussion between the operator and the LPA and the need for constructive liaison from an early stage is evident. CAP 793 provides guidance. Both official and unofficial safeguarding are discussed further in Chapter 3 of this document.

1.14 In all cases, regardless of the status of the aerodrome, any development that causes pilots to experience an increase in difficulty when using an aerodrome may lead to a loss of utility. The CAA considers that if the aerodrome operator

[4] OLS is the hypothetical boundary which indicates the extent of a volume of airspace which should be kept free of obstacles, so far as is reasonably practicable, to facilitate the safe passage of aircraft. It is used collectively to refer to other terms which are fully defined in Chapter 4 of Annex 14 to the Chicago Convention and incorporated into UK civil aviation regulation within CAP 168. OLS comprises of: approach surface, balked landing surface, conical surface, inner approach surface, inner horizontal surface, inner transitional surface, take-off climb surface and transitional surface.

advises that the aerodrome's established amenity would be affected by a development, their advice can generally be considered as expert testimony in the context of the operation of the aerodrome. However, such comment requires robust evidence, and may be subjected to scrutiny by the CAA (or any other party with equivalent expertise), should disagreement between the aviation operator and the wind energy developer arise. Notwithstanding that the CAA has no regulatory oversight of unlicensed aerodromes it is recommended that developers and planning authorities give similar consideration to comments and evidence from the operators of unlicensed aerodromes.

1.15 It is recommended that aerodrome operators that are not officially safeguarded have agreed unofficial safeguarding maps with LPAs.

1.16 The safety of aircraft in UK airspace is often dependent on ground-based navigation and radio aids. DfT Circular 1/2003 and Scottish Circular 2/2003 provides for the safeguarding of civil technical sites currently owned by NERL and military technical sites owned by the Secretary of State for Defence.

Airspace management

1.17 SARG, as the airspace regulatory authority, is responsible for developing, approving, monitoring and enforcing policies for the safe and efficient allocation and use of UK airspace and its supporting infrastructure, taking into account the needs of all stakeholders, national security and environmental issues.

1.18 SARG is directed by the Secretary of State for Transport to act with impartiality to ensure that the interests of all airspace users (including General Aviation (GA) stakeholders) and the community at large are taken into account in respect of how UK airspace is managed. To this end, formal consultation with airspace users, service providers and other relevant bodies shall be conducted with the aim of obtaining consensus, wherever possible, before making changes in the planning or design of UK airspace arrangements. The environmental impact of proposals for change shall be taken into consideration by ensuring that consultation is conducted with the appropriate authorities, to lessen or mitigate such impact to the maximum extent possible.

1.19 The Airspace Change Process (ACP) is mandatory for the majority of airspace change requests. It is a robust process that ensures that all appropriate stakeholders are consulted; CAP 725 refers.

Approvals for equipment and service provision

1.20 In order to provide an ATS in the UK, a service provider must be granted an approval by the CAA. EC 1035/2011, EC 550/2004 and relevant sections of the ANO (2009) as amended apply.

1.21 Where service providers use a remote feed of surveillance data from a contracted source, they remain responsible for gaining the requisite approvals for the use of data as part of a surveillance service. ANSPs must have effective processes and procedures to:

1. Safeguard their service through being able to recognise when wind turbine developments may affect their service, and by participating in planning activities;
2. Be able to assess the likely effect of a wind turbine development on their service. It is not automatically the case that a wind turbine development will result in a degradation to the service. The service provider must first assess whether the planned development will technically impact upon the CNS systems used. Where it is assessed that there will be a technical impact, the service provider must then assess whether this has any operational significance (see also Chapter 2);
3. Be able to establish what reasonable measures may be put in place to mitigate the effect of a wind turbine development. At all times, a collaborative approach between the service provider and the wind turbine developer is required to ensure an appropriate (i.e. reasonable, achievable and timely) mitigation is identified.

1.22 Where a service provider has to make a change to equipment or operational procedures in order to safely accommodate a wind turbine development then the following must be addressed:

1. The service provider must perform a safety assessment on the change. The final safety assessment cannot be made until all changes have been implemented and wind turbine developments are operational;
2. As part of the safety assessment, the service provider should at least consider the issues raised in Chapter 2 of this CAP concerning the impact of wind turbines on aviation;
3. Where considering mitigations to address the impact of the wind turbine development, service providers are advised to review the issues and limitations summarised in Chapter 2. Full details are available in the CAA CAP 670;
4. All significant changes to an ATS must be notified by an ANSP to their SARG Regional Inspector who may wish to see evidence that the change has been managed safely and in accordance with the ANSPs change management processes. Where appropriate, an updated or amended Safety Case may be required;
5. ANSPs that fail to properly address the effects of a wind turbine development on a service may have the existing Certificate withdrawn by the CAA, or

variations applied to the Designation which may result in the closure of that service.

Advice to Government

1.23 In discharging its role as an independent regulator, the CAA is required to provide advice to Government as required. To this end, the CAA is proactive with appropriate Government departments in respect of wind energy related issues. The CAA is a member of the DECC (Department of Energy and Climate Change) Aviation Management Board and its sub-groups to provide expert input on aviation aspects of the Government's renewable energy programme. Details of these groups are contained in Appendix A.

Chapter 2

Impact of wind turbines on aviation

Introduction

2.1 The development of sites for wind turbines has the potential to cause a variety of negative effects on aviation. These include (but are not limited to): physical obstructions; the generation of unwanted returns on Primary Surveillance Radar (PSR); adverse effects on the overall performance of CNS equipment; and turbulence. Whilst it is generally the larger, commercial turbines that have the greatest impact on aviation, the installation of other equipment may also affect operations. Smaller turbines, and the preliminary activities for larger turbines (such as the erection of anemometer masts on potential development sites), could have a negative impact on aviation and so require assessment. Moreover, the cumulative effects of wind turbines on aviation need to be assessed if developments proliferate in specific areas.

2.2 This chapter aims to provide a summary of the issues that aviation stakeholders should consider when assessing the impact of a proposed wind turbine development. It is not intended to be exhaustive because local circumstances may raise issues that are unique to a specific case. For this reason, the local aerodrome operator, ANSP and ATS providers may be best qualified to interpret what this impact might be; however, they must demonstrate a thorough assessment of how it will affect the safety, efficiency and flexibility of their specific operations. Robust evidence may be required: see also para 1.14.

Wind turbine effects on PSR[5]

2.3 The following section describes the various effects that wind turbines have caused on Air Traffic Control (ATC) PSRs during the trials conducted as part of many research projects around the UK and the rest of the world.

2.4 ANSPs must therefore consider the possibility that their radars be affected by each of these phenomena as a result of wind turbines within the coverage range of their surveillance systems.

2.5 In basic terms, a PSR transmits a pulse of energy that is reflected back to the radar receiver by an object that is within its Line of Sight (LOS)[6]. The amount of reflected energy picked up by the receiver will depend upon a number of factors

[5] The following paragraphs are intended as a summary only. Full explanations and detailed technical discussion are available in the CAA CAP 670: ATS Safety Requirements at SUR 13.

[6] Note radar line of sight is different to visual line of sight.

such as the size, shape and orientation of the object[7], as well as receiver sensitivity and the weather. In general terms, the larger a wind turbine is, the more energy will be reflected and there is an increased chance of it creating false returns to radar (i.e. returns that are not aircraft). These unwanted returns are known as 'clutter'[8]. Issues may be compounded by increasing numbers of wind turbines which could potentially cause greater areas and densities of clutter.

2.6 Providing that it remains within radar LOS, generally the closer a wind turbine is to a radar station, the greater the likelihood its reflected energy will be picked up by the radar receiver. It also follows that the taller a turbine is, the greater the distance from the radar that it will remain within radar LOS (unless the turbine is hidden by terrain). A characteristic that makes wind turbines more unpredictable is the fact that because the turbines rotate to follow the wind, the cross-sectional area presented to the radar at any given time, and therefore the RCS of the turbine, will vary depending upon wind direction. This presents challenges to generating a 'standard' turbine RCS for radar modelling purposes. Given that aviation safety issues are involved, a conservative approach should generally be adopted.

2.7 Typically, radar returns from a wind turbine comprise reflections from both stationary and moving elements: these provide different challenges for the radar. While the reflected radar signal from stationary elements, such as the tower, can be removed using stationary clutter filters in the radar processor, rotating wind turbine blades can impart a Doppler shift to any radar energy reflecting off the blades. Doppler shifts are used by a number of radars to differentiate between moving objects, namely aircraft, and stationary terrain with the latter being processed out and not displayed to the operator. The radar may therefore detect Doppler returns from moving wind turbine blades and display them as returns on the radar screen. Furthermore, at sites with more than one turbine, the radar may illuminate a blade or blades from one turbine on one antenna sweep, then illuminate the blades of a different turbine on the next sweep. This can create the appearance on the radar screen of returns moving about within the area of the wind farm, sometimes described as a "twinkling" appearance or "blade flash effect". These moving returns can appear very similar to those that would be produced by a light aircraft. The appearance of multiple false targets in close proximity can trick the radar into initiating false aircraft tracks. False PSR returns can also 'seduce' real aircraft tracks away from their true returns as the radar attempts to update an aircraft track using the false return. This can lead to degradation of radar tracking capability.

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7 Which together contribute to the Radar Cross Section (RCS) of the obstacle.

8 Note that the term 'clutter' refers simply to unwanted false returns and can be generated by a number of means, not simply from wind turbines.

2.8 The large RCS of wind turbines and the blade flash effect can also lead to a decrease in radar sensitivity. This can result in the loss of small targets and a reduction in the maximum range at which the smallest targets can be detected. Wind turbines can also create a shadow above and beyond the wind farm so that aircraft flying within this shadow may go undetected.

Wind Turbine Effects on secondary surveillance radar (SSR)[9]

2.9 In general terms, SSRs differ from PSRs as rather than measuring the range and bearing of targets through detecting reflected radar signals, an SSR transmits an interrogation requesting a dedicated response. Upon receiving an interrogation, the aircraft then transmits a coded reply which the SSR can use to ascertain the aircraft's position as well as decode other information contained within the response.

2.10 Wind turbine effects on SSR are traditionally less than those on PSRs but can be caused due to the physical blanking and diffracting effects of the turbine towers, depending on the size of the turbines and the wind farm. These effects are typically only a consideration when the turbines are located very close to the SSR i.e. less than 10 km.

2.11 SSR energy may be reflected off the structures during both the interrogation and reply phases. In effect, the signals are bounced off the wind turbines and can therefore arrive at the intended target from a false direction. This can result in aircraft, which are in a different direction to the way the radar is looking, replying through the reflector and tricking the radar into outputting a false target in the direction where the radar is pointing, or at the obstruction.

Surveillance service impact assessment

2.12 Prediction of the effect of wind turbines on any particular radar site is a complex task depending on many factors including terrain, the weather, the maximum height of both radar and wind turbines, radar LOS, the operational range of affected radars, diffraction and antenna beam tilt.

2.13 There are a number of models that are employed to demonstrate potential impacts of wind turbine developments on radar. Such models are constantly developing and will offer some guidance as to the likelihood of wind turbines presenting a radar return; although the nature of wind turbine operations vary due to the unpredictability of different turbine types, variable turbine rotation speed and the times of operation of individual turbines. Therefore, the degree of certainty as to whether a turbine, or group of turbines, will be displayed or not in marginal ‘radar/radio LOS’ cases cannot be guaranteed. In such cases, and

[9] The following paragraphs are intended as a summary only. Full explanations and detailed technical discussion are available in the CAA CAP 670: ATS Safety Requirements at SUR 13.

where aviation safety is a potential issue, safety consideration should always be applied in a conservative manner.

2.14 The CAA does not endorse any one specific radar modelling tool. Nor, given the multitude of factors affecting RCS, can a ‘standard’ RCS be identified for micro, medium and large wind turbines. It is strongly suggested that developers engage with the appropriate ANSP prior to commissioning a propagation assessment in order to ensure that the proposed model is suitable and is acceptable to the ANSP. Failure to do this could result in later disagreement and conflict once results are released. ANSPs are encouraged to consider publishing clear guidance as to which radar models they would consider acceptable to their requirements.

2.15 Eurocontrol has provided basic international guidelines on how to assess the effects of wind turbines on radar. It should be noted that these guidelines do not overwrite national planning jurisdictions or requirements, but are included here as a source of further potential information.

2.16 If the radar station likely to be affected by a proposed wind turbine development belongs to NATS, useful self assessment guidance is available at: http://www.nats.aero/services/information/wind-farms/self-assessment-maps/.

2.17 If the wind turbine development is likely to affect an MOD radar station; it is recommended that the MOD should be contacted at the earliest opportunity. Further guidance can be found on the MOD Windfarms Safeguarding web site

Mitigation

2.18 The following paragraphs give a summary of some of the mitigation methods that are available to help counter the effects of wind turbines, primarily on PSR and SSR related issues. More detailed explanations and analysis of mitigation techniques are contained within the CAA CAP 670: ATS Safety Requirements at SUR 13. Not all the mitigation methods will be suitable in all circumstances and more than one method may be required to mitigate risks to an acceptable level. The definition of ‘acceptable’ will have to be made on a case by case basis.

2.19 It is the responsibility of the developer to consult with the aviation stakeholder to discuss whether mitigation is possible and, if so, how it would best be implemented. It must also be noted that most mitigation methods would be subject to a standard safety assessment process by the ANSP who, in turn, would need to demonstrate that the system is safe in order to gain CAA approval (where applicable). Accordingly, where a wind turbine development is likely to impact upon the provision of an ATS, then the developer and ANSP should co-operate to mitigate such impacts wherever possible.

2.20 In determining the appropriateness of radar mitigations, stakeholders need to be aware of the potential impact of the Government’s Spectrum Release

Programme. This work stream, overseen by the Government Public Expenditure Committee (Assets) seeks to release 500MHz of spectrum from “public infrastructure” use by 2020 to boost growth in the UK economy. The CAA has been tasked to undertake a major piece of work in support of this programme. This aims to deliver a release from 2.7-2.9MHz (which is currently used by S-Band PSR) by reviewing how non-cooperative surveillance can be best delivered to meet the operational and safety requirements of ANSPs and consistent with the Future Airspace Strategy (FAS). In parallel, there is an aspiration to use this opportunity to develop a strategic approach to windfarm mitigation in how non-cooperative surveillance is deployed. This significant programme is being managed as a phased approach with GO/NO GO decision points at appropriate milestones. The CAA will be providing updates on progress via the web page listed at footnote 13, below, at suitable intervals to keep stakeholders informed.

Summary of mitigation techniques

2.21 Mitigation techniques can be categorised in to several key types. This section provides a summary of each category. More detailed explanation is available in the CAP 670: ATS Safety Requirements.

Work-rounds

2.22 Work-rounds are interim measures which would enable an ANSP to continue providing an ATS using surveillance radar, potentially under reduced operational efficiency or an increased level of risk, whilst a long-term full mitigation solution is being progressed. Work-rounds can include moving the locations of the wind turbines (where feasible), introducing sector blanking, re-routing traffic, or using SSR only.

In-fill radars

2.23 Several manufacturers are known to have developed in-fill solutions specifically designed for the purpose of wind farm mitigation on ATC radars. This either involves combining the target data from a radar that does not have line-of-sight to the wind farm or from a radar with a smaller coverage area that is situated somewhere within the wind farm or where the wind farm is within its within LOS such that the airspace above the wind farm area can be monitored using the in-fill radar, therefore a complete air situation picture can be produced by combining the two results.

Three- Dimensional radars

2.24 Traditional ATC primary radars measure only the range and bearing of the target and do not measure altitude data. They are therefore classed as two dimensional radars. Some PSRs can provide three-dimensional information and can therefore be used as in fill radars above wind farm affected areas.

High Pulse Repetition Frequency (PRF) radars

2.25 Some manufacturers have also developed radars that utilise a high transmitter PRF. This technique makes it possible to discriminate between aircraft and wind turbines by analysing their Doppler signatures and remove the turbine clutter from the display. Such radars may be used as in-fills or if sufficient range is achievable, the radar may be used as an alternative to a conventional PSR.

Spectrum filters

2.26 Some manufacturers have attempted to develop a solution that is based on modifying their existing radars by incorporating software to compare target return Doppler signatures with the aim of giving the system the ability to discriminate between turbines and aircraft.

Predictive and multi-sensor trackers

2.27 There have been proposals to employ specialist tracking systems to overcome the impact of wind turbine farms on radar. Such solutions offer the addition of plot extraction and predictive tracking to any compatible radar. Although this may not provide a complete solution to address all potential effects they may offer some potential for the radar processing system to make a semi-intelligent assessment of returns from the vicinity of a wind turbine farm in order to distinguish clutter, including that induced by turbines, from aircraft.

Transponder Mandatory Zones (TMZ) and surveillance by co-operative ground sensor

2.28 Under current UK regulations or proposals not all UK airspace will require an SSR transponder to be fitted and used by aircraft. However it is recognised that in certain circumstances and in certain areas, mandatory transponder carriage can provide significant safety benefits. The CAA has regulatory powers to create TMZs for a number of reasons, one of which may be to help mitigate wind turbine effects on a PSR. External bodies can also request TMZs; however, the Airspace Change Process (ACP) (CAP 725) must be followed. The ACP ensures that the requirement for a TMZ is fully justified and that the effect upon all airspace users is fully consulted and assessed. Proposals for a TMZ should be submitted to CAA Airspace Regulation[10]. A CAA case officer will assess the proposal and make recommendations to CAA Director SARG (formerly Director Airspace Policy) as appropriate. Consideration of the feasibility of a TMZ to mitigate a specific and identified risk should include: effect on other airspace users; the creation of ‘choke points’ within Class G airspace; whether the affected ATC system is capable of PSR blanking; and the likelihood of the CAA approving SSR-only operations.

[10] Contact via AROps@caa.co.uk

2.29 Offshore SSR Only and TMZ. Despite offshore uncontrolled airspace being largely free of non-transponder equipped aircraft, this cannot be taken to mean that SSR only operations, or TMZs, would enjoy an easier approval process. In many instances, the ability to identify non-transponding aircraft (for example, following equipment failure) will be required to maintain safety cases.

2.30 Effect of TMZ on ATS Provision. TMZs are only viable when it is acceptable that the use of a non-co-operative surveillance technique (such as PSR) is not necessary for security reasons or for the detection of targets that are possibly undetected by SSR or other co-operative surveillance technique being used. It must be noted that, for Air Defence reasons, TMZs may not be suitable in all areas.

2.31 ANSPs may choose to provide surveillance by a suitable co-operative sensor over the wind farm area, in addition to the main PSR, as mitigation to the wind farm clutter on a surveillance display.

Risk assessment and mitigation of possible hazards introduced by wind turbines

2.32 Any new hazards should be identified and assessed to determine if mitigations are adequate to reduce risks to an acceptable level; this should be in accordance with the service provider's Safety Management System (SMS) Risk Assessment and Mitigation process. Ultimately, failure to address such issues may result in withdrawal or variation of the article 169/ 205 Approval/Designation thereby preventing the provision of the air navigation service.

2.33 In assessing proposed developments and mitigations submitted by wind turbine developers, it is not unreasonable for an aviation stakeholder/ANSP to request sufficient technical information from the developer that would support the production of an adequate safety case. The responsibility for completing the safety case lies with the ANSP. However its completion should be a co-operative effort between the developer and the ANSP with any necessary commercial considerations subject to agreement between the two.

Aeronautical navigation aids and communication systems

2.34 A wide range of systems, including aids such as ILS, VOR/DME, and Direction Finders, together with air-ground communications facilities, could potentially be affected by wind turbine developments. Wind turbines can affect the propagation of the radiated signal from these navigation and communication facilities because of their physical characteristics, such as their situation and orientation in relation to the facility. As a result, the integrity and performance of these systems can, potentially, be degraded.

2.35 The CAA has been made aware of research that indicates the possibility of wind turbines adversely affecting the quality of radio communication between Air Traffic Controllers and aircraft under their control. Accordingly, as a work-stream under the DECC Aviation Management Board, the CAA are working in conjunction with NATS and others to test a variety of civil VHF aircraft radios and a smaller number of military UHF airborne radios against a simulated wind farm signature waveform. This research will be published in due course and in the interim, updates will be provided to the Aviation Management Board[11]. Until further information is available, issues concerning wind turbines and VHF communications should be dealt with on a case-by-case basis and reference made to the guidance contained in Section GEN-01 of CAP 670. Information regarding the technical safeguarding of aeronautical radio stations at aerodromes, including examples of the minimum dimensions for those areas that must be safeguarded, is contained in GEN-02 of CAP 670. However, aerodrome operators and ANSPs are advised to consider each proposal carefully and if necessary, seek specific technical advice.

Air Traffic Services

2.36 Where an ANSP determines that it is likely that a planned wind turbine development would result in any of the above effects on their CNS infrastructure, this may not, in itself, be sufficient reason to justify grounds for rejection of the planning application. The ANSP must determine whether the effect on the CNS infrastructure has a negative impact on the provision of the ATS. The developer should pay for an assessment of appropriate mitigating actions that could be taken by the ANSP and/or wind energy developer to deal with the negative impact. The position of an ANSP at inquiry would be significantly degraded if they had not considered all potentially appropriate mitigations. It is essential that wind energy developers form a relationship with the relevant ANSP in order to deal with the impact that their development may have, prior to making an application.

2.37 Where possible, it can be beneficial for the ANSP to record or plot real traffic patterns over a period of time using the radar system, and to use this to identify the prevalent traffic patterns. This can then be compared to the location of the proposed wind turbine development. Where appropriate and feasible, the recorded traffic data above a particular project may be released for further analysis.

2.38 When examining the effects of wind turbines on ATS, particular attention should be paid to the following:

[11] Minutes of meetings and other information can be found on the Aviation Management Board Web Page https://www.gov.uk/government/groups/aviation-management-board-aviation-advisory-panel-and-fund-management-board

1. Departure Routes including Standard Instrument Departures;
2. Standard Instrument Arrival Routes;
3. Airspace Classification.
4. Area Navigation (RNAV) and Precision Air Navigation routes;
5. Sector Entry and Exit points;
6. Holding points (including the holding areas);
7. Missed Approach Routes;
8. Radar Vectoring Routes;
9. Final Approach Tracks;
10. Visual Reporting Points;
11. Published Instrument Flight Path for the aerodrome;
12. Potential impact on navigation aids and voice communications;
13. Future airspace and operational requirements where aerodrome growth is anticipated (Para 2.49 provides comment on future requirements).

2.39 Factors such as the type of radar service being applied and the airspace classification must also be considered when trying to assess the adverse impact of wind turbine effects.

Offshore helicopter operations

2.40 Wind energy developments (including anemometer masts) within a 9 NM radius of an offshore helicopter installation could introduce obstructions that would have an impact on the ability to safely conduct essential instrument flight procedures to such facilities in low visibility conditions. Consequently, any such restrictions have the potential to affect not only normal helicopter operations but could also threaten the integrity of offshore installation safety cases where emergency procedures are predicated on the use of helicopters to evacuate the installation.

2.41 Chapter 3 provides background information on the issues related to wind energy developments and offshore helicopter activities including Helicopter Main Routes (HMRs).

Maritime and Coastguard Agency (MCA)

2.42 The MCA’s mission is to deliver safety at sea, counter pollution response and the coordination of maritime Search and Rescue (SAR) throughout the UK SAR Region and UK Pollution Control Zone. In the context of aviation, the MCA will (from early-2016) provide the SAR helicopter service for the UK.

2.43 The increasing numbers and geographical extent of offshore wind farms not only has the potential to increase the probability of a maritime SAR incident but also could constrain the MCA's ability to respond to such an incident. It is therefore strongly recommended that developers consult with the MCA at the earliest opportunity such that mitigating measures can be designed in from the outset. The following guidance has been provided by the MCA but should not be taken as being exhaustive and does not remove the recommendation to consult; further detail can be found in Maritime Guidance Note 371 and contact details for the MCA are listed at Appendix B.

2.44 The nature of SAR activity necessitates the requirement to conduct SAR within the confines of offshore wind turbine developments. Given the distance offshore of some UK windfarms, helicopters may be the only viable means of SAR. While in clear weather, searches can be conducted from above the maximum blade tip height, operations in poor weather and rescues themselves may necessitate SAR operations within a windfarm below blade tip height. As technology progresses and turbine heights increase, this issue is exacerbated. Furthermore, when faced with the prospect of long transits to a SAR area, the presence of adjacent windfarms along the transit route can provide obstacles to SAR helicopters if conditions do not permit transits to be flown above maximum blade height.

2.45 The MCA has provided the following guidance to mitigate SAR risks:

1. Turbines are positioned in straight lines with a common orientation across the whole development, creating safe lanes for SAR access.
2. Safe lanes are constructed across the width of the development rather than the length.
3. Curved or non-linear designs should be avoided.
4. High density perimeter turbines can compromise the safe lanes and should be avoided.
5. The wind farm should be fitted with lighting that is controllable from the development control room and which is NVG compatible.
6. The control room for the development should be equipped with VHF (air and maritime) communications with remote antennas in the wind farm to facilitate SAR communications.
7. Turbines should be marked with geographically logical numbering to facilitate navigation within the wind farm.
8. Substations and meteorological masts should be aligned with turbines so as not to impede SAR lanes.

9. Where possible, SAR lanes should be aligned with those of adjacent wind turbine developments or buffer zones created.

Cumulative effects

2.46 There is no doubt that, while developments with small numbers of wind turbines can have an adverse effect on aviation operations, it is the proliferation of developments, and the resulting cumulative effect, that is of far more significant concern. It may be possible to successfully mitigate the effects of a single turbine or small development; however, the combined effect of numerous individual turbines or multiple wind turbine developments can be hard, if not impossible, to mitigate. Therefore it is feasible that ANSPs may lodge objections to subsequent developments in areas where they had previously been able to accommodate proposed wind turbine developments.

2.47 The cumulative effect of geographically separated wind turbine developments may have more impact on aviation than if such developments were located in close proximity to each other. For example, individual areas of clutter separated by 5 NM could have more impact on the provision of ATS than one slightly larger area of clutter. This does not mean to suggest that large areas of clutter are always more preferable; however, this should be taken into consideration and discussed with the ANSP.

2.48 For aerodrome operators or en route service providers, there is a difficulty in protecting aviation activity from these cumulative effects, in part because planning applications are generally dealt with on a 'first come, first served' basis. All approved applications[12] must be taken into account when considering future applications. This could lead to a situation whereby viable applications are objected to on the grounds of cumulative effect even though other, potentially less viable, projects have not been completed due to the inability, for a variety of reasons, to satisfactorily resolve suspensive conditions.

2.49 The basis for an objection based on cumulative effect would be that the safety and efficiency of the aerodrome or en-route service may not be maintained or that the growth of an aerodrome or en-route service may be constrained. However, the decision concerning how firm these future plans have to be in order to be considered would be within the remit of the LPA. Nevertheless, airports are encouraged to produce 'Master Plans' indicating their future development plans. It is anticipated that these may be taken into consideration by an LPA.

2.50 It is recognised that many potential developments fail to reach maturity within the formal planning stage. Nevertheless, it is in the interests of aviation stakeholders

[12] Including developments subject to 'suspensive conditions': where planning approval is granted subject to final agreement between an aviation stakeholder and a developer concerning an appropriate mitigation solution.

to take all developments about which they are aware into account until they have been formally notified that a proposal has been abandoned. Therefore, it is in a wind turbine developer's interest to inform all involved parties when such developments are abandoned or postponed.

Turbulence

2.51 Turbulence is caused by the wake of the turbine which extends down-wind behind the blades and the tower, from a near to a far field. The dissipation of the wake and the reduction of its intensity depend on the convection, the turbulence diffusion, the topography (obstacles, terrain etc.) and the atmospheric conditions.

2.52 There is evidence of considerable research activity on modelling and studying the wake characteristics within wind developments, using computational fluid dynamics techniques, wind tunnel tests and on site LIDAR measurements. A literature survey was recently conducted by the University of Liverpool and CAA[13] to establish the scale and the advances of current research on this front.

2.53 It is recognised that aircraft wake vortices can be hazardous to other aircraft, and that wind turbines produce wakes of similar, but not identical, characteristics to aircraft. Although there are independent bodies of knowledge for both of the above, currently, there is no known method of linking the two. Published research shows measurements at 16 rotor diameters downstream of the wind turbine indicating that turbulence effects are still noticeable[14]. Measurement work has been focused on the near wake due to technical challenges of the experimental set up, while modelling studies are capable of examining the wake turbulence further downstream[15][16]. Although models can be used to study the effects of the far wake, verification and validation processes of these models are still ongoing[17].

2.54 There are currently no Mandatory Occurrence Reports (MOR)[18] or aircraft accident reports related to wind turbines in the UK. However, the CAA has received anecdotal reports of aircraft encounters with wind turbine wakes

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[13] http://www.liv.ac.uk/flight-science/cfd/wake-encounter-aircraft/

[14] Wind Turbine Wake Analysis, L.J. Vermeer, J.N. Sorenson, A Crespo, Progress in Aerospace Sciences, 39 (2003) 467-510.

[15] Calculating the flow field in the wake of wind turbines, J.F. Ainslie, Journal of Wind Engineering and Industrial Aerodynamics, 27 (1988) 213-224.

[16] Turbulence characteristics in wind-turbine wakes, A Crespo and J Hernandez, Journal of Wind Engineering and Industrial Aerodynamics 61 (1996) 71-85.

[17] Investigation and Validation or Wind turbine Wake Models, A Duckworth and R.J. Barthelmie, Wind Engineering, 32 (2008) 459-475. Also http://www.liv.ac.uk/flight-science/cfd/wake-encounter-aircraft/

[18] CAP 382 - The Mandatory Occurrence Reporting Scheme - comment verified against CAA database up to 30 June 2015.

representing a wide variety of views as to the significance of the turbulence. Although research on wind turbine wakes has been carried out, the effects of these wakes on aircraft are not yet known. Furthermore, the CAA is not aware of any formal flight trials to investigate wake effects behind operating wind turbines. In the UK wind turbines are being proposed and built close to aerodromes (both licensed and unlicensed), including some developments on aerodrome sites, indicating an urgent need to assess the potential impact of turbulence on aircraft and in particular, to light aircraft and helicopters.

2.55 The CAA has so far investigated the effects of small wind turbine wakes on GA aircraft[19]. The results of this study show that wind turbines of rotor diameter (RD) of less than 30m should be treated like an obstacle and GA aircraft should maintain a 500ft clearance. Regarding wind turbines of larger RD than 30m; these are subject to further investigations. Until the results of these investigations are available, discussions between aerodrome managers and wind farm developers are encouraged, taking note of existing CAA safeguarding guidance. As the results of this research become available the CAA Wind Energy web pages will be updated.

2.56 Pilots of any air vehicle who firmly believe that they have encountered significant turbulence, which they believe to have been caused by a wind turbine, should consider the need to report this through the existing MOR scheme.

2.57 Until the result of further research is known, analysis of turbulence can only be undertaken on a case-by-case basis, taking into account the proximity of the development and the type of aviation activity conducted. Whilst being a consideration for all aircraft (particularly in critical stages of flight), turbulence is of particular concern to those involved in very light sport aviation such as gliding, parachuting, hang-gliding, paragliding or microlight operations as in certain circumstances turbulence could potentially cause loss of control that is impossible to recover from.

Wind turbine wake physics

2.58 Wind turbine wake is dependent on many parameters. The thrust generated by rotor, the tip velocity ratio (blade tip velocity to wind speed), wind direction and speed, turbulence level in free stream, weather condition and the geometry of wind turbine all have impacts on the characteristics of the wake. Due to all these parameters, it is difficult to scale wake results from a small to a large wind

[19] http://www.liv.ac.uk/flight-science/cfd/wake-encounter-aircraft/

turbine. For this reason the work carried out by Liverpool University[20] is, at present, restricted to small wind turbines of less than 30m of RD.

2.59 The wake of a wind turbine can be divided into a near and a far region. The near wake is the area just downstream of the rotor up to one RD, where the effect of the rotor properties, including the blade aerodynamics and geometry determine the flow field. Near wake research is mainly focused on the wind turbine's performance and the physics of power extraction. The far wake is the region beyond the near wake, where the details of the wake are less dependent on the rotor design. The main interest in this area is the wake interference with other wind turbines (e.g. in a wind farm) or passing-by aircraft (wind turbine wake encounter). Here, flow convection and turbulent diffusion are the two main mechanisms that determine the flow field.

2.60 LIDAR field measurements on a WTN250 wind turbine at East Midlands Airport, UK, indicated that statistically, the wake velocities recovered to 90% of the free stream velocity at the downstream distance of 5 RD. It is expected that the work conducted by Liverpool University will continue with LIDAR surveys of larger wind turbines to provide reliable wake data to allow the study of the encounters using flight simulations. These results will be made public as soon as they become available.

2.61 Based on the models described in the Liverpool University Research Paper[21], schematics of the wake region for small wind turbines are given in the following figures. The figures show the zone where wake encounter has potential to cause severe impact on the encountering GA aircraft.

Figure 1: Schematic of the wind turbine wake. The effect of wake is weaker beyond 5-RD downwind for the wind turbines of diameter < 30m.

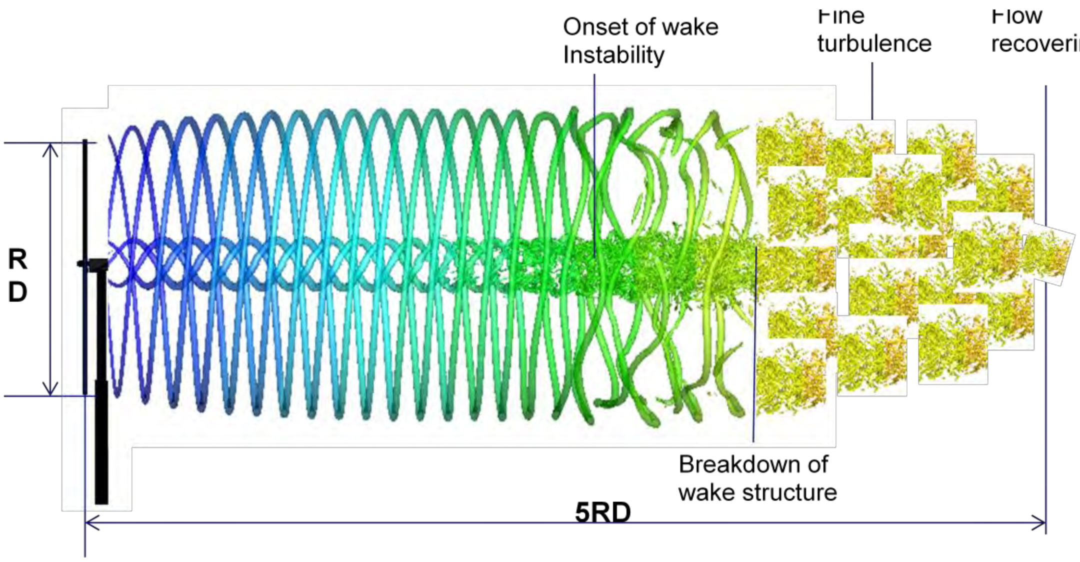
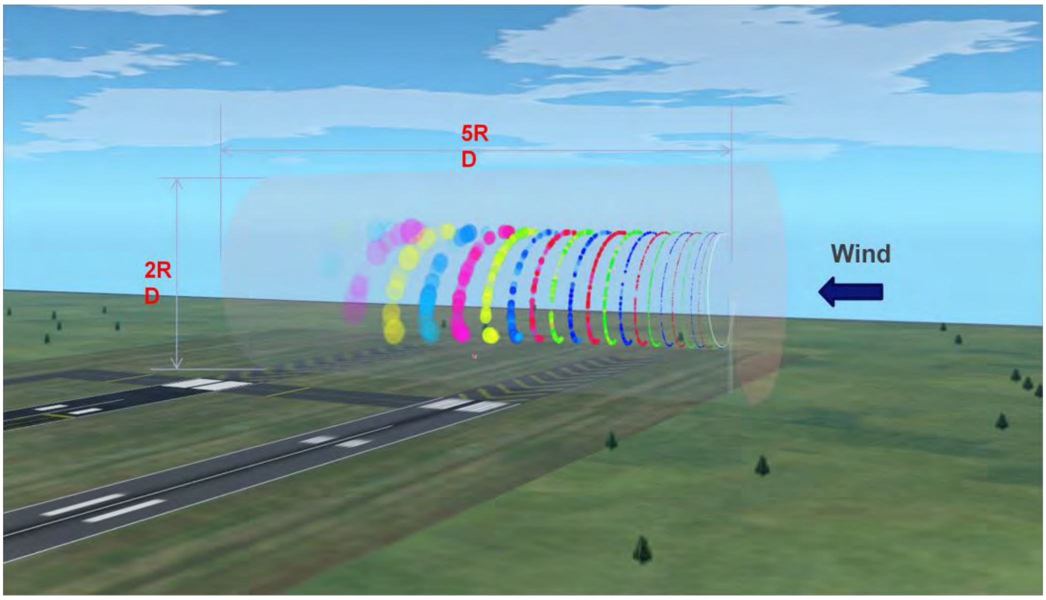


Figure 1:

[20] http://www.liv.ac.uk/flight-science/cfd/wake-encounter-aircraft/

[21] http://www.liv.ac.uk/flight-science/cfd/wake-encounter-aircraft/

Figure 2: The cylindrical region downwind the rotor should be avoided. Its size is 5RD (downwind) by 2RD (vertical). Coloured helices indicate wake vortices and decay.



Economic issues

2.62 As a result of the role and responsibilities of the CAA and aviation stakeholders, action will be taken to maintain the high standards of safety, efficiency and flexibility. However, it is possible that aviation activity might have to be constrained as a consequence of proposed wind energy developments. Even in circumstances where a proposed development may not affect a current activity, future expansion (for example, as listed in an Aerodrome Master Plan) may be restricted were it to go ahead. This could eventually have an economic impact on the aerodrome, ANSP or activity, and this aspect should be taken into consideration when assessing the impact of any proposed wind turbine development. Therefore, it is considered entirely appropriate for an aerodrome to include an assessment of the economic impact that may arise from a proposed wind turbine development. However, it is important to note that comments made in this respect need to be unambiguous in order to allow an LPA to ensure that this important aspect is taken into account appropriately.

En-route obstructions

2.63 It is possible that an existing or proposed wind turbine development that does not infringe an aerodrome OLS may nevertheless have a potential impact upon local aviation activity. For example, a development beyond an OLS, but only marginally clear (laterally or vertically), of Controlled Airspace (CAS), might be assessed as having a potential adverse impact upon operations within Class G (uncontrolled) airspace due to the potential for the creation of 'choke points' where aircraft are forced into a reduced volume of available airspace

2.64 Whilst the CAA will highlight such issues away from the immediate vicinity of aerodromes, aerodrome operators/licensees should be cognisant of these issues when engaging with other parties on wind turbine associated matters. Further related comment is contained at Chapter 3 (Obstructions, Lighting and Marking).

Figure 3: Difficulties in visually acquiring anemometer masts.

2.65 Wind turbine developers should be aware that anemometer masts are often difficult for pilots to acquire visually (see Figure 3 above), and so aviation stakeholders may assess that individual masts should be considered a significant hazard to air navigation and may request (either during the planning process, or post-installation) that masts be lit and/or marked. Typically, there is no legal mandate for structures smaller than 150 m (492 ft) to be lit. Whilst the CAA would not in isolation make any case for lighting and/or marking of structures that is not required under existing regulation, the CAA would typically support related aviation stakeholder proposals to aid the visual conspicuity of anemometer masts on a case by case basis. Individual cases should not set a precedent for future requests. The MCA is likely to require that all offshore masts are lit to mitigate the risks to SAR helicopters. In addition, onshore masts have to potential to pose a risk to general aviation. To that end, the General Aviation Awareness Council (on behalf of other GA representative bodies) and a number of helicopter operators, with the in principle agreement of RenewableUK (the

UK's leading not for profit renewable energy trade association), have asked that the following request be relayed by the CAA on their behalf[22]:

"Anemometer masts and/ or their guy wires should be equipped with aids to increase their daytime visual conspicuity where a risk based proposal demonstrating specific need for such measures has been submitted by the aviation stakeholder. Noting that the deployment of any such measure can only be mandated by the relevant Planning Authority, it is acknowledged that such visual conspicuity aids should not impact upon the integrity of the structure itself, the data generated or risk to personnel these aspects are for the developer to consider/assess.

The most effective means of achieving this may be the use of orange marker buoys on the guy wires, such as those that may be fitted to overhead power cables (the use of which has some basis in international regulatory direction). However it is noted that in some locations the structural loads imposed by such markers may be unacceptable. In such cases, the goal of increasing the visual conspicuity of masts and supporting guys might be achieved by different means, which generally place little or no additional structural load on the mast/guy combination. Such means include:

1. *Painting all or part of the mast; options could include alternate contrasting stripes, such as orange and white, or a single contrasting colour (noting that it may need to contrast with terrain, or sky, or both) and/or,*
2. *Reflective bird flight deflectors of minimum 120mm diameter fitted to the guy wires at intervals, and/or*
3. *High visibility sheaths enveloping the supporting guy and/or*
4. *Ground mats, or construction such as a box, of a contrasting colour scheme to the ground at the foot of the mast.*

Whichever method is chosen it will need to satisfy all other relevant planning considerations. For example, bird deflectors may be required for bird protection reasons, and visual intrusion concerns may need to be taken into account. It is envisaged that the norm would be that one method would suffice."

It is recommended that agreement should be sought, through dialogue between the aviation stakeholder, the developer and the LPA regarding the most appropriate method of mitigation. However, should the LPA require further input regarding the general requirement for increasing the visual conspicuity of lattice masts or the specific need in any particular case, enquiries should be forwarded

[22] This text is routinely replicated in CAA Correspondence when asked to comment on related planning applications.

to the GAAC at GAAC, Bicester Airfield, Skimmingdish Lane, Bicester, Oxon, OX26 5HA (e-mail planning@gaac.org.uk).

2.66 Where such obstacles affect operations on an aerodrome, it is the responsibility of the aerodrome operator to ensure appropriate publication in the UK Aeronautical Information Publication (AIP), and to ensure that they establish an effective working relationship with their LPA to ensure that they are consulted when appropriate.

Emergency Services Aviation Support Units (ASUs)

2.67 Since the inception of emergency aviation, there has been a dramatic rise in the number of police and air ambulance operators as well as a small number of fire brigade operations. Due to their unique operating nature, it is difficult to predict the impact of wind turbine developments on these ASUs. It is important, therefore, for emergency service ASUs to engage with all relevant LPAs within their operating area to ensure that they are consulted when planning applications are made. The CAA encourages developers and LPAs to consult with local ASUs, and would be supportive of claims to mark or light turbines that do not fall under article 219 of the ANO where a case by case assessment demonstrates there is a justifiable benefit.

2.68 Police ASUs are licensed by the CAA to operate below 500 feet Above Ground Level (AGL) in order to carry out their duties. Police helicopters will routinely follow main roads and motorways but may also transit along open land, sometimes in difficult weather conditions, during their operations and may need to land anywhere; although they will also have specifically designated landing sites. It should be noted that while some Police ASUs fly with Night Vision Goggles (NVGs), their use is not currently universal. Police Aviation in England and Wales is centrally coordinated by the National Police Air Service (NPAS) which is administered by the West Yorkshire Constabulary. Maps showing NPAS helicopter bases can be found on the NPAS Website. NPAS have recently established a single email address for windfarm consultations and advice: npas.obstructions@npas.pnn.police.uk which should be used for correspondence. The Scottish Police ASU, based in Glasgow, is not currently part of NPAS and should be contacted directly where appropriate.

Military impact

2.69 Wind turbine developments can have a detrimental effect on military operations. Military aviation operations predominantly take place in Class G airspace and can differ markedly from civil operations, particularly with respect to operational low flying, and the sensitivity of military CNS facilities. The DIO are to be consulted in all cases where a proposed wind turbine development may affect military operations. More information is available from the DIO Website.

Chapter 3

Safeguarding considerations

General considerations

3.1. There are a significant number of certificated or licensed aerodromes in the UK. In the region of one third of these, along with en-route CNS, have been designated by the Government as aerodromes to be safeguarded by statutory process, this is known as 'official safeguarding'. As part of this process, CAA certified maps of these officially safeguarded aerodromes and en route technical sites are produced and a Statutory Direction obliges associated LPAs to consult the aerodromes operators about proposed developments that fall within the boundaries specified on the maps.

3.2. Those aerodromes and CNS sites that are not safeguarded by statutory process can be unofficially safeguarded by agreeing protection measures with their LPA.

3.3. Further information about aerodrome safeguarding can be found on the Publications Section of the CAA website.

Safeguarding maps

3.4. Maps of officially safeguarded aerodromes and en route CNS technical sites are produced and submitted to LPAs. These maps denote the areas where consultation should take place with the aerodrome operator.

3.5. Other aerodromes may produce a safeguarding map and request that their LPA recognise their wish to be included in consultation for planning purposes. It is the published advice of the Government[23] that all aerodromes should take steps to protect their locations from the effects of possible adverse development by agreeing a safeguarding procedure with the LPA.

Wind turbine safeguarding maps

3.6. In order to assist the consultation process with wind turbine developers and in providing a diagrammatic illustration of the related aviation issues in discussion with LPAs, a number of aerodromes have developed specific wind turbine safeguarding maps, which graphically depict the aviation operator's assessment of the desirability and feasibility of wind turbine developments. Areas are shown where development would be either undesirable, undesirable but possible, or acceptable (albeit potentially with constraints to address cumulative effects and

[23] The Town and Country Planning (Safeguarded Aerodromes, Technical Sites and Military Explosives Storage Areas) Direction 2002

proliferation issues). Other aerodromes have simply prepared radar consultation zone maps, given the dynamic nature of cumulative effects.

Safeguarding of technical sites

3.7. There is a statutory process to safeguard certain sites which are integral to the provision of en-route ATS. Radar and radio stations, navigation beacons and some microwave communications links are subject to such arrangements[24]. LPAs have an obligation to consult the operators of such sites as defined in official safeguarding maps. Developers may also request discussion with site operators in order to provide necessary mitigation. The International Civil Aviation Organization (ICAO) Eur Doc 015 and CAP 670 are sources of guidance to provide a basis for such discussion.

Obstructions, lighting and marking

3.8. The treatment of land-based obstacles to air navigation is covered by existing legislation. Obstacles located close to licensed aerodromes are covered under Section 47 of the Civil Aviation Act 1982. Government aerodromes are similarly covered under the Town & Country Planning Act (General Permitted Development) Order 2000. article 219 of the ANO 2009 details the requirement for the lighting of land-based tall structures located outside of the safeguarded areas of licensed and government aerodromes.

3.9. Onshore Obstacle Lighting Requirement ICAO regulations (Annex 14 Chapter 6) and article 219 of the ANO 2009 require that structures away from the immediate vicinity of an aerodrome, which have a height of 150 m (492 ft) or more AGL are:

1. Fitted with medium intensity steady red lights[25] positioned as close as possible to the top of the obstacle[26], and also equally spaced at intermediate levels, so far as practicable, between the top lights and ground level with an interval not exceeding 52 m;
2. Illuminated at night, visible in all directions and any lighting failure is rectified as soon as is reasonably practicable;

[24] ICAO EUR DOC 015 recommends safeguarding zones for VORs.

[25] 'Medium intensity steady red light' means a light that complies with the characteristics described for a medium intensity type C light as specified in Volume 1 (Aerodrome Design and Operations) of Annex 14 (Third edition November 1999) to the Chicago Convention.

[26] In relationship to wind turbines, the requirement to fit aviation obstruction lighting 'as close as possible to the top of the obstacle' is typically translated to mean the fitting of lights on the top of the supporting structure (the nacelle) rather than the blade tips. However, any case by case study related to onshore turbines with a maximum height at or above 150m AGL may conclude that additional or amended lighting specifications are required.

3. Painted appropriately: the rotor blades, nacelle and upper 2/3 of the supporting mast of wind turbines that are deemed to be an aviation obstruction should be painted white, unless otherwise indicated by an aeronautical study.

3.10. In addition, the CAA will provide advice and recommendations regarding any extra lighting requirements for aviation obstruction purposes where, owing to the nature or location of the structure, it presents a significant hazard to air navigation. However, in general terms, structures less than 150 m (492 ft) high, which are outside the immediate vicinity of an aerodrome, are not routinely lit; unless the 'by virtue of its nature or location' argument is maintained. UK AIP ENR 1.1 para 5.4 'Air Navigation Obstacles' refers.

3.11. When input is sought, the CAA routinely comments to the effect that, in respect to a proposed wind turbine development, there might be a need to install aviation obstruction lighting to some or all of the associated turbines, when specific concerns have been expressed by other elements of the aviation industry; i.e. the operators. For example, if the MoD or a local aerodrome suggest and can support such a need, the CAA (sponsor of policy for aviation obstruction lighting) would wish, in generic terms, to support such a claim. However, this would only be done where it can reasonably be argued that the structure(s), by virtue of its/their location and nature, could be considered a significant navigational hazard. That said, if the claim was clearly outside credible limits (i.e. the proposed turbine(s) was/were many miles away from any aerodrome or it/they were of a height that was unlikely to affect even military low flying), the CAA would play an 'honest-broker' role. It is unusual for the CAA, in isolation, to make a case for aviation warning lighting unless article 219 demands such lighting.

3.12. All parties should be aware that, in any case where a wind turbine development lies (or would lie) outside any aerodrome safeguarding limits and the turbine height was less than 150 m (492 ft) (and therefore the provisions of article 219 of the ANO 2009 would not apply), the aviation industry, including the CAA, is not in a position to demand that the turbines are lit. In such cases the decision related to the fitting of aviation warning lighting rests with the relevant LPA, which will necessarily need to balance the aviation lighting requirement against other considerations (e.g. environmental). If deemed as an aviation obstruction, and thus requiring a specific marking scheme, the CAA advice on the colour of wind turbines would align with ICAO criteria.

3.13. Whilst anemometer masts are likely to remain below the threshold that requires they be lit, there may be instances where their lighting is deemed prudent.

Offshore obstacle requirements

3.14. Whilst the mandated requirement for the lighting of wind turbines generators in UK territorial waters[27] is set out at article 220 of the UK ANO (2009) as amended, additional guidance is provided below.[28]

3.15. The article requires medium intensity (2000 candela) steady red lighting mounted on the top of each nacelle and requires for some downward spillage of light. The article also allows for the CAA to permit that only turbines on the periphery of any wind farm need to be equipped with aviation warning lighting. Such lighting, where achievable, shall be spaced at longitudinal intervals not exceeding 900 metres[29]. There is no current routine requirement for offshore obstacles to be fitted with intermediate vertically spaced aviation lighting, however, given the potential increase in maximum height of the next generation of offshore wind turbines with nacelle heights potentially approaching 150m above sea level, additional lighting may be required. The CAA will consider such applications on a case by case basis.

3.16. To resolve concerns from the maritime community, work has been undertaken to develop an aviation warning lighting standard which is clearly distinguishable from maritime lighting. Where it is evident that the default aviation warning lighting standard (article 220) may generate issues for the maritime community, a developer can make a case, that is likely to receive CAA approval, for the use of a flashing red Morse Code Letter 'W' instead. There is, however, no intent to change the lighting intensity specifications set out in article 220; indeed those specifications remain the default aviation warning lighting requirement.

3.17. Where flashing lights are used, they are to be synchronised to flash simultaneously[30]. Where the Flashing Morse W standard is approved by the CAA and utilised, the recommendation is for a 5 second long sequence, visually synchronised across aviation and maritime lighting sequences.

3.18. Attention is drawn to the provisions that already exist within article 220 that require the reduction in lighting intensity at and below the horizontal and allow a further reduction in lighting intensity when the visibility in all directions from every wind turbine is more than 5km. All offshore wind turbine developers are expected

[27] Taken to apply to any wind turbine generator or meteorological mast that is situated in waters within or adjacent to the United Kingdom up to the seaward limits of the territorial sea. However, the CAA will provide similar planning advice related to the lighting of wind turbines and meteorological mast beyond the limits of UK Territorial Waters.

[28] This guidance replaces CAA Policy Statements 22 November 2012 'Lighting of Wind Turbine Generators in United Kingdom Territorial Waters' and 27 April 2012 'Failure of Aviation Warning Lights on Offshore Wind Turbines'.

[29] ICAO Annex 14 Volume 1 paragraph 6.3.14.

[30] ICAO Annex 14 Volume 1 paragraph 6.4.3.

to comply fully with the requirement aspect and to make full use of the additional allowance that exists within article 220.

3.19. In addition to the article 220 mandated lighting, there may also be lighting requirements associated with winching and SAR operations. The lighting needed to facilitate safe helicopter hoist operations to wind turbine platforms is set out in CAP 437. Information on SAR Requirements can be found in Maritime Guidance Note 371 and a summary of relevant aspects can be found in Chapter 2 of this document. It is recommended that SAR lighting requirements are agreed with the MCA at the earliest possible opportunity.

3.20. As offshore wind farms are developed, meteorological masts may be deployed to ascertain the wind resource characteristics. These masts can be in excess of 100 m tall and are extremely slender rendering them potentially inconspicuous to aviators flying over the sea, particularly when there are no other structures nearby. This is potentially hazardous, particularly during helicopter operations when it may be necessary to descend in order to avoid icing conditions. Consequently the CAA recommends that all offshore obstacles (regardless of their location within or outside of territorial waters) that are over 60 m (197 feet) above sea level should be fitted with one medium intensity steady red light positioned as close as possible to the top of the obstacle.

3.21. The CAA does not typically request specific markings for offshore obstacles. However, any aviation stakeholder that considered a particular structure to be a significant navigational hazard could make a case for it to be lit and/or marked to increase its visual conspicuity. The request (as opposed to mandate) for such lighting and/or marking would need to be negotiated with the owner of the structure or, if at the planning stage, the relevant planning authority. If asked for comment, it would be unlikely that the CAA would have any fundamental issue associated with an appropriate aviation stakeholder's case for lighting/marking of any structure that could reasonably be considered to be a significant hazard.

3.22. For military aviation purposes the MoD may suggest an additional offshore lighting requirement. Whilst it is possible that the lighting standard described above will meet the MoD needs, it is recommended that in all cases developers additionally seek related input from the DIO.

Failure of offshore lighting

3.23. Article 220 (7) of the ANO 2009 states “In the event of the failure of any light which is required by this article to be displayed by night the person in charge of a wind turbine generator must repair or replace the light as soon as reasonably practicable.” It is accepted that in the case of Offshore Obstacles there may be occasions when meteorological or sea conditions prohibit the safe transport of staff for repair tasks. In such cases International Standards and Recommended Practices require the issue of a Notice to Airmen (NOTAM).

3.24. The CAA considers the operator of an Offshore Wind Farm as an appropriate person for the request of a NOTAM relating to the lighting of their wind farm. Should the anticipated outage be greater than 36 hours then the operator shall request a NOTAM to be issued by informing the NOTAM section (operating 24 hours) of the UK Aeronautical Information Service (AIS) by telephoning +44 (0) 20 8750 3773/3774 as soon as possible. AIS will copy the details of the NOTAM to the operator and to the CAA.

3.25. The following information should be provided:

1. Name of wind farm (as already recorded in the AIP[31]).
2. Identifiers of affected lights (as listed in the AIP) or region of wind farm if fault is extensive (e.g. North east quadrant/south west quadrant/ entire or 3 NM centred on position 515151N 0010101W).
3. Expected date of reinstatement.
4. Contact telephone number.

3.26. Note that if the turbine or wind farm does not have a listing in the AIP then it will not be possible to issue a NOTAM. Typically all offshore turbines of a maximum blade tip height of 300 feet or more will be recorded within the AIP.

3.27. In order to expedite the dissemination of information during active aviation operations the wind farm operator may also consider establishing a direct communication method with aviation operators in the area. These may include:

1. Air Traffic Service Units e.g. Aberdeen Radar or Anglia Radar.
2. Local airports.
3. Local helicopter operators.

3.28. The information will be the same as in the NOTAM request, and should also include a note that a NOTAM has been requested, or if available, the NOTAM reference.

3.29. If an outage is expected to last longer than 14 days then the CAA shall also be notified directly at windfarms@caa.co.uk (normal working hours) to discuss any issues that may arise and longer term strategies.

Consultation zones around offshore helidecks

3.30. For many years, the CAA has emphasised the importance of operators and developers taking into consideration all existing and planned obstacles around offshore helicopter destinations that might impact on the safe operation of

[31] UK Aeronautical Information Publication (www.ais.org.uk) En Route Supplement 5.4.

associated helicopter low visibility approaches in poor weather conditions. In order to help achieve a safe operating environment, a consultation zone of 9 NM radius exists around offshore helicopter destinations. This consultation zone is not a prohibition on development within a 9 NM radius of offshore operations, but a trigger for consultation with offshore helicopter operators, the operators of existing installations and exploration and development locations to determine a solution that maintains safe offshore helicopter operations alongside the proposed development. This consultation is essential in respect of established developments. However, wind energy lease holders, oil and gas developers, and petroleum licence holders are advised to discuss their development plans with each other to minimise the risks of unanticipated conflict at a later date. Topics for discussion within any such consultation should include, but are not limited to:

1. Prevailing weather conditions, including predominant wind direction;
2. Manning status of the installation;
3. Frequency of flights to the installation and predominant routes;
4. Performance limitations of offshore helicopter types utilising the helideck;
5. Established helicopter instrument and low visibility approach procedures;
6. Mandated constraints on approaches to helidecks on installations;
7. Long term access to well and subsea infrastructure;
8. Concurrent wind farm operations and oil and gas operations to well and subsea infrastructure;
9. SAR operations to the installation in the event of an emergency;
10. Location and height of potential obstacles including proposed wind turbines.

3.31. The following paragraphs provide, in layman’s terms, an explanation of the reasoning behind the need for the 9 NM consultation zone. While procedures will differ depending upon the installation, operator and aircraft type involved, the following notes are based upon Commission Regulation (EU) No 965/2012 (the European Air Operations Regulation), improved flight procedure documentation and the practical application of such requirements:

1. Basic Requirement. The 9 NM consultation zone aims to provide a volume of obstacle-free airspace within which a low visibility approach profile and, in the event of a pilot not being able to complete his approach, a missed approach can be flown safely. Such profiles must allow for an acceptable pilot workload, a controlled rate of descent, one engine inoperative performance and obstacle clearance.

2. Approach. Routinely, helicopters making manually flown radar/GPS approaches and, in the future, autopilot-coupled approaches, to offshore installations will commence the approach from not below 1500 ft Above Mean Sea Level (AMSL) or 1000 ft above obstacles, whichever the higher. As helicopters approaching offshore installations must make the final approach substantially into wind, the approach could be from any direction. The obstacle-free zone must, therefore, extend throughout 360° around the installation to prevent restrictions being placed on the direction of low visibility approaches and departures. Additionally, during the approach, all radar contacts have to be avoided by at least 1 NM which could interfere with the necessary stable approach path if manoeuvring is required. The approach sequence and descent below 1500 ft routinely commences from about 8 NM downwind of the destination installation and the final approach starts at around 5–6 NM and 1000–1500 ft. The helicopter descends to a minimum descent height (at least 200 ft by day and 300 ft at night), which is commonly achieved within 2 NM of the helideck having descended on a ‘glide path’ of between 3–4°. Thereafter, it flies level at that height towards the Missed Approach Point (MAPt). As the helicopter approaches the MAPt, a minimum of 0.75 NM from the offshore destination, the pilot must decide whether or not he has the required the necessary visual references to proceed to land or, if not, conduct a go-around following a missed approach procedure.
3. Go-Around and Missed Approach Procedure (MAP). Upon initiating a go-around, the pilot will follow a MAP whereby the helicopter is either turned away from the destination structure by up to 45° and climbs, or climbs straight ahead depending on the procedure being used. The anticipated rate of climb during the missed approach phase is based upon one engine inoperative performance criteria and could be quite shallow (1–2°). For obvious safety reasons, a go-around involving a climb from the minimum descent height needs to be conducted in an area free of obstructions as this procedure assures safe avoidance of the destination structure.
4. Departure Procedure. On departure from an offshore installation the aircraft will be climbed vertically over the deck to a height determined by its performance criteria and is committed to the take off once a nose down attitude is adopted. If during this phase an engine failure is experienced then the anticipated rate of climb will be the same as described above for the MAP; however, the climb could start from as low as 35 ft above sea level dependent on deck height. The distance to climb to a safe altitude by which either a turn can be carried out, or straight ahead, to reach separation from obstacles will be dependent on aircraft one engine inoperative performance criteria. The aircraft can be up to 10º either side of the departure heading and the radius of any turn carried out can be up to 1000 m.

3.32. In summary, obstacles within 9 NM of an offshore destination would potentially impact upon the feasibility to conduct some helicopter operations (namely, low visibility or missed approach procedures) at the associated site. Owing to the obstruction avoidance criteria, inappropriately located wind turbines could delay the descent of a helicopter on approach such that the required rate of descent (at low level) would be excessive and impair the ability of a pilot to safely descend to 200/300 ft by the appropriate point of the approach (2 NM). If the zone is compromised by an obstruction, it should be appreciated that routine low visibility flight operations to an installation may be impaired with subsequent consequences for the platform operator or drilling unit charterer. One such consequence could be that the integrity of offshore platform or drilling unit safety cases, where emergency procedures are predicated on the use of helicopters to evacuate the installation, is threatened. Additionally, helicopter operations to wind farms may impact on oil and gas operations. It is therefore essential that the installation operators, helicopter operators and other interested parties are engaged in the consultation process.

Helicopter Main Routes (HMR)

3.33. HMRs, as defined in the UK AIP, have been in use over the North Sea and in Morecambe Bay for many years. Whilst such routes have no lateral dimensions (only route centre-lines are charted) they provide a network of offshore routes utilised by civilian helicopters. Wind turbine developments could impact significantly on operations associated with HMRs: the effect will depend on the degree of proliferation, and so a small number of individual turbines should cause minimal effect. However, a large number of turbines beneath an HMR could result in significant difficulties by forcing the aircraft to fly higher in order to maintain a safe vertical separation from wind turbines. The ability of a helicopter to fly higher would be dependent upon the 0° isotherm (icing level); this might preclude the aircraft from operating on days of low cloud base if the 0º isotherm was at 2000 ft or below as the aircraft must be able to descend to a clear area below cloud and with a positive temperature to safely de-ice if necessary.

3.34. There should be no obstacles within 2 NM either side of HMRs but where planned should be consulted upon with the helicopter operators and ANSP. The 2 NM distance is based upon: operational experience; the accuracy of navigation systems; and, importantly, practicality. Such a distance (2 NM) would provide time and space for helicopter pilots to descend safely to an operating height below the icing level. For the purpose of transiting wind turbine developments under Visual Flight Rules, corridors may be established that are no less than 1 NM wide. Additionally, helicopters (like all aircraft), are required by Commission Implementing Regulation (EU) No 932/2012 (the Standardised Rules of the Air Regulation) to avoid persons, vessels, vehicles and structures by a minimum distance of 500 ft; this applies equally to the avoidance of wind turbines and any other structure.

3.35. Notwithstanding the above, low level coverage is of particular importance in the provision of full ATS to offshore helicopter operators, and ANSPs will need to give careful consideration to any proposed development that impact on the supporting PSR feed. Moreover, dependent on the level and type of service provided prior to the installation of wind turbines, it may prove necessary to maintain a buffer greater than 2 NM from HMRs in order to maintain the previous service provision by an ATS provider or ANSP. Further guidance is available from SARG.

Facilitation of helicopter support to offshore installations

3.36. In order to facilitate construction or maintenance flights within the boundaries of wind turbine developments, consideration should be given to the use of flight corridors being built into the development layout plans. Such corridors should be oriented and their width designed in consultation with the helicopter operators, given that it will be governed by the VFR performance of the aircraft in use. The layout of the turbines may also need to consider the requirements of the MCA with regards to SAR within the field.

Military requirement for Infra-Red (IR) lighting

3.37. Low flying is a vital element of military operations in areas of conflict, and a large proportion of the flying will be undertaken at night. Low flying training across the UK can take place as low as 100 ft for fast jet aircraft in Tactical Training Areas, and 250 ft in Low Flying Areas. Helicopters fly tactically down to 50 ft and routinely down to100 ft during training sorties in all areas.

3.38. The MoD have recently published Obstruction Lighting Guidance which is also available via the Aviation and Radar page on the RenewablesUK Website. The majority of night time flying by MoD aircraft is undertaken by crews equipped with NVGs; therefore IR vertical obstruction lights will be suitable in most occasions.

3.39. An application for onshore wind turbines will receive notification from DIO indicating whether IR lights will be suitable. In some cases a combination IR / red lighting will be required, for example geographical choke points or to denote the extremities of a larger wind farm.

3.40. Careful attention needs to be taken to ensure that the IR light chosen by the wind developer meets the MoD's requirements, as some IR (Light Emitting Diode) lights are not compatible with military NVGs.

3.41. Requests for clarification should be addressed to the DIO. Contact details are included in Appendix B.

Parachute drop zones

3.42. Parachutists drop from heights up to 15,000 ft AGL within a published Drop Zone (DZ), normally out to a minimum of 1.5 NM/2.8 km radius from the centre of the Parachute Landing Area (PLA).

3.43. Hazards to PLAs are categorized as:

1. Special Hazard. A hazard which could constitute a special risk to parachutists and if parachutists were to come into contact with may result in serious or fatal injury" e.g. stretches of open water, deep rivers, electricity power lines, wind turbines of a height greater than 15m to blade tip at its highest point, densely built up areas, cliffs and quarries.
2. Major Hazard. Obstacles, either natural or artificial, which because of their size may be difficult to avoid and which, if struck by a parachutist, may result in injury; i.e. large hangars, buildings, woods etc.;
3. Minor Hazard. Any object, either natural or artificial, which should be easily avoided but which if struck by a parachutist may result in injury; i.e. hedges, fences, ditches etc.).

3.44. CAP 660 (Parachuting) refers.

3.45. Wind turbines pose a special risk to parachutists and if parachutists were to come into contact with may result in serious or fatal injury; those over 15 m high are considered by the British Parachute Association (BPA) to be a Special Hazard. Wind turbines of 15 m or below are considered Major Hazards.

3.46. PLAs to be used by all designations of parachutists should provide a large open space of reasonably level ground, which can contain a circle of 250 m radius free from Major Hazards and largely free from Minor Hazards. These PLAs should be bordered on at least three sides by suitable overshoot areas, where parachutists may land if they are unable to land on the PLA: these overshoot areas should be free from Special Hazards and largely free of Major Hazards.

3.47. Wind turbines over 15 m high (50 feet) are considered a rotating special hazard and as such if located within the designated DZ would likely result in restrictions being placed upon any parachute activity within that DZ.

3.48. It is worthy of note that any obstacle over 300 ft (91.4 m) in height is no longer considered by the BPA to be just a ground obstacle to parachutists, but also an air obstacle, given that it protrudes into airspace within which parachutists (particularly in an emergency situation) may not yet have taken control of their canopies, and so could result in an aerial collision.

Very light aircraft

3.49. Due to the potential for sudden loss of lift within areas of turbulence, very light aircraft are operated away from areas of known turbulence or only in areas where turbulence is consistent and predictable (such as hill sites used by hang-gliding/paragliding clubs). Introducing a wind turbine to a location that is frequented by very light aircraft may result in that location becoming unviable or less attractive to visiting pilots if the turbine generates turbulence that may exceed the aircraft's operating limits.

Chapter 4

Wind turbine development planning process

Pre-planning and consultation

4.1. The weight of relevant knowledge accrued by wind turbine developers and ANSPs over the past decade has been substantial: issues are better understood, and proper procedures for effective consultation are in place. Developers are required to undertake their own pre- planning assessment of potential civil aviation related issues. It should also be noted that NATS, the MoD and certain airports also offer pre-planning services. Table 1 provides an overview of considerations, and the following paragraphs detail what developers will need to consider, conducting associated consultations as appropriate.

Table 1: Overview of consultation considerations

	CNS Facilities	Obstacle Considerations
Aerodrome *(Consultation required with aerodrome licensee/manager)*	▪ Safeguard PSR and SSR ▪ Safeguard Approach Aids ▪ Safeguard Navigation Beacons ▪ Safeguard VHF	▪ OLS ▪ Impact on procedures ▪ Need for lighting to aid night time conspicuity ▪ Anemometer masts
En Route *(Consultation required with MoD and NERL)*	▪ Safeguard PSR and SSR ▪ Safeguard Navigation Beacons ▪ Safeguard VHF	▪ >300 ft/91 m Chart and entry to AIP ▪ >150 m (492 ft) Lighting in accordance with article 219 of ANO (2009) ▪ Marking of turbine (upper 2/3 white in accordance with ICAO guidance) ▪ Potential for additional lighting requirements where turbines may be considered as a significant hazard to air users ▪ Anemometer masts ▪ Emergency Service ASUs and HEMS (including MCA in remote areas)
Offshore *(Consultation*	▪ Safeguard PSR and SSR	▪ Offshore Lighting in accordance with article 220 of ANO (2009) and CAP

	CNS Facilities	Obstacle Considerations
required with MoD NERL and MCA)	▪ Safeguard Navigation Beacons ▪ Safeguard VHF	764 ▪ HMR ▪ Operations around oil and gas platforms ▪ Anemometer masts ▪ Search and Rescue requirements

4.2. Aerodromes. Whilst not definitive, it should be anticipated that any wind turbine development within the following criteria[32] might have an impact upon civil aerodrome[33] - related operations:

1. Unless otherwise specified by the aerodrome or indicated on the aerodrome's published wind turbine consultation map, within 30 km of an aerodrome with a surveillance radar facility. The distance can be far greater than 30 km depending upon a number of factors including the type and coverage of the radar and the particular operation at the aerodrome;
2. Within airspace coincidental with any published Instrument Flight Procedure (IFP) to take into account the aerodrome's requirement to protect its IFPs;
3. Within 17 km of a non-radar equipped licensed[34] aerodrome with a runway of 1100 m or more;
4. Within 5 km of a non-radar equipped licensed aerodrome with a runway of less than 1100 m;
5. Within 4 km of a non-radar equipped unlicensed aerodrome with a runway of more than 800 m;
6. Within 3 km of a non-radar equipped unlicensed aerodrome with a runway of less than 800 m.

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[32] Aerodrome criteria are generically based upon the safeguarding requirements and guidance contained in Regulation EC 139 of 2014, CAP 168 and CAP 793 (both current and historical). The ranges quoted are for guidance only. If proposed developments lie marginally outside the ranges highlighted, but nevertheless in close proximity to other developments, developers are advised to consider the potential proliferation issues. The object of any pre-planning process is to identify all possible aviation concerns to the developer at an early stage and as such, the assessment should err on the side of caution.

[33] In this context the term 'aerodrome' includes any site used regularly by aircraft (including helicopters and gliders) for take-off and landing. The CAA-sponsored, NATS-produced VFR charts depict all such sites known to the CAA, although effects on uncharted aerodromes must still be considered.

[34] Licensed in accordance with Part 27 of ANO (2009) as amended.

4.3. The figures above are for initial guidance purposes only and do not represent definitive ranges beyond which all wind turbine developments will be approved or within which they will always be objected to. These ranges are intended as a prompt for further discussion between developers and aviation stakeholders in the absence of any other published criteria.

4.4. Many modern gliders have a glide ratio of at least 50:1 and the most modern gliders can exceed that, with further progress expected in future. Developments of wind turbines within 10 km of a gliding site or where the maximum height of the structure is within a 50:1 angle of a gliding site will present additional considerations beyond those associated with powered aircraft. Therefore, notwithstanding the CAA recommended distances quoted above, the British Gliding Association (BGA) requests that relevant gliding sites and the BGA are consulted where proposed developments are within 10 km of any charted glider launch site.

4.5. Aerodrome operators should address physical safeguarding issues in accordance with the guidance contained within relevant EASA documentation, CAP 168 and CAP 738 as applicable. Operators of unlicensed aerodromes should refer to CAPs 793 and 738 as applicable and are strongly advised to engage with their LPA to ensure that their activities and requirements are well understood. At the very least, unlicensed aerodromes should subscribe to their LPA's Weekly Planning List, which will provide them with information on all planning applications – including wind turbines and anemometer masts – and therefore provide a mechanism for effective self-briefing for their associated pilots.

4.6. Non-aerodrome related activity. Developers should also consider the potential for wind turbines to impact upon known general aviation activity that are annotated on CAA-sponsored, NATS-produced VFR charts, but which are not related to a recognised or single aerodrome (for example, charted fee-fall parachute DZ and hang/ para-gliding winch launch sites). Typically, developers will need to engage direct with relevant aviation operators where a development would be within 3 km of any such site.

4.7. NATS. There may be issues related to en route CNS facilities. Accordingly, details of any proposal need to be considered by NATS. Developers need to undertake related consultation as appropriate as NATS will be consulted by the LPAs. NATS Windfarm web pages provide support.

4.8. Lighting and marking. There might be a need to install aviation warning lighting to some or all of the turbines if increased conspicuity is deemed necessary.

4.9. Charting. In terms of obstacle charting requirements in the UK, a threshold exists at 300 ft (91.4m)[35]

1. Structures with a maximum height of 300 ft (91.4m) above ground level or higher:

   a) There is an ICAO Annex 15 requirement for all obstacles (temporary or otherwise) over 300 ft (91.4m) AGL to be promulgated in the UK AIP and charted on civil aviation charts. Accordingly, any such structure is required to be notified to the Defence Geographic Centre (DGC) who provides the source of obstacle data, published in the UK AIP at ENR 5.4 no later than 10 weeks prior to construction. Information provided should include the type of structure and name of location, an accurate location of the structure(s) in WGS 84 latitude and longitude (degrees, minutes and 1/100 second), an accurate maximum height AMSL/AGL, the lighting status of the turbines and date for the completion of construction. In addition, the developer should also provide the maximum height of any construction equipment required to build the turbines. Removal of turbines is also required to be notified and expected date of removal. The DGC prefer notifications to be submitted electronically: mail to dvof@mod.uk.

   b) In order to ensure that aviation stakeholders are aware of the turbines while aviation charts are in the process of being updated, developments should also be notified through the means of a NOTAM. To arrange an associated NOTAM, a developer should contact CAA Airspace Regulation[36] (AROps@caa.co.uk / 0207 453 6599) no later than 14 days prior to the commencement of construction with the same information as required by the DGC. Of note, if the obstacle falls within an Aerodrome Traffic Zone or Military Aerodrome Traffic Zone, it is the responsibility of that aerodrome to issue the NOTAM.

2. Structures with a maximum height below 300 ft (91.4m) above ground level. In the interest of Aviation Safety, the CAA also requests that any feature/structure 70 ft (21.3m) in height, or greater, above ground level is also reported to the DGC. It should be noted that NOTAMs would not routinely be required for structures under 300 ft (91.4m) unless specifically requested by an aviation stakeholder.

4.10. Emergency ASUs. For completeness it would also be sensible to establish the related viewpoint of local emergency ASUs. This is because of the unique nature of their operations in respect of operating altitudes and potentially unusual

[35] The effective height of a Wind Turbine is the maximum height to blade tip.

[36] Previously named Airspace Utilisation with the email address AUSOps@caa.co.uk. The AROps email address should now be used for all correspondence and NOTAM requests.

landing sites. In addition, The MCA is responsible for the provision of SAR services onshore and offshore. It is recommended that the MCA is consulted on all offshore developments and one of the factors that it will consider is the implications of a development on SAR operations (with surface craft and helicopters). Further information is available in Chapter 2.

4.11. Cumulative effect. The growth in the number of wind turbine developments (either under consideration, in planning, under construction, or operational), is significant. It is possible that the cumulative effect of a number of wind turbine developments in any particular area might potentially result in difficulties for aviation that a single development would not have generated. See also Chapter 2.

4.12. Cross-boundary. In order to delineate responsibility for the provision of flight information services to aircraft, airspace is divided up into internationally recognised Flight Information Regions (FIRs). Airspace in the UK is divided into the London and Scottish FIRs which together form the UK FIR. Coordinates for these boundaries are listed in the UK Aeronautical Information Publication Section ENR 2.1. Offshore developments have the potential to straddle these boundaries, one example being the consented East Anglia ONE development, part of which is in the Dutch FIR. Airspace outside the UK FIR is the responsibility of other European aviation authorities, whose regulations may differ from those that apply in the UK. Accordingly, wind turbine developers should contact the CAA for specific guidance in all instances where developments are likely to approach the limits of the UK FIR.

Formal planning

4.13. Regardless of whether voluntary pre-planning has been undertaken, all proposals for wind turbine developments must eventually move into a formal approval process either through the Electricity Act 1989, the Planning Act 2008, or through the Town and Country Planning Acts[37] . The process is outlined in the subsequent paragraphs, although these guidelines do not purport to be a comprehensive guide to planning procedures.

England and Wales

4.14. In England, LPAs currently handle consent applications for land-based generating stations with a capacity up to 50 MW in accordance with the polices set out in the National Planning Policy Framework (NPPF) and following the procedure set out in the Town and Country Planning Act 1990. The Planning Act 2008 sets out thresholds above which certain types of infrastructure development

[37] Taken to include the Town and Country Planning Act 1990 and Town and Country Planning Act (Scotland) 1997.

are considered to be nationally significant. Currently, land-based electricity generating stations with a capacity over 50MW and offshore generating stations with a capacity above 100MW are classified as Nationally Significant Infrastructure Projects (NSIPs), however, it is the Government's published intention to amend legislation so that all applications for onshore wind energy developments are handled by local planning authorities[38]. Any developer wishing to construct an NSIP must first apply for a type of consent known as 'development consent'. For such projects, the Planning Inspectorate examines the application and will make a recommendation to the relevant Secretary of State, who will determine the application. In Wales, onshore applications over 50 MW and offshore applications over 100MW are currently decided by the relevant UK Secretary of State following the recommendation of the Planning Inspectorate. Applications for developments under 50 MW are dealt with by the relevant LPA under the Town and Country Planning Legislation (Wales). The Welsh Government has published planning advice on renewable energy in the form of Technical Advice Note (TAN) 8 and in the Planning (Wales) Act 2015. In addition, the UK Government has expressed the intent to devolve powers to Welsh Ministers for the consenting of energy schemes both onshore and offshore of up to 350 megawatts capacity[39].

Scotland

4.15. In Scotland, there is currently a similar division of responsibility. Applications for onshore stations of a capacity up to 50 MW are made to the relevant LPA under the Town and Country Planning Act (Scotland). Onshore developments with a capacity greater than 50 MW require consent from the Scottish Government. These applications are handled on behalf of the Scottish Ministers by the Energy Consents Unit (ECU) under Section 36 of the Electricity Act (1989). In Scotland, applications for marine energy (including offshore wind) are made to Marine Scotland.

Northern Ireland

4.16. Previously in Northern Ireland, the Planning Service (an Agency within the Department of the Environment), handled all proposals for land-based generating stations irrespective of capacity. From 1 April 2015, the responsibility for planning has been shared between 11 new councils and the Department of the Environment. Applications will be classified as either 'local', 'major' or being of 'regional significance'. Criteria for assessing the classification of developments are contained within The Planning (Development Management) Regulations (Northern Ireland) 2015. An application deemed to be of regional significance

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38 Dept of Communities and Local Government online guidance on Renewable and Low Carbon Energy dated 18 June 15.

39 The Queens Speech 27 May 2015 - contained within the proposed Wales Bill.

must be made to, and will be determined by, the Department of the Environment. Councils will be responsible for determining major and local development applications. In Northern Ireland, offshore wind farm proposals are the responsibility of the Department of Enterprise, Trade and Investment.

Micro wind turbines

4.17. The legislation to allow permitted development rights for householders to install MWTs on their premises came into force on 1 December 2011. Details of the order can be found in Class H and I of Part 14 in Schedule 2 of The Town and Country Planning (General Permitted Development) (England) Order 2015. The same legislation came into force in Wales on 22 May 2012. The legislation applies to both building mounted and free standing turbines that do not exceed 15 metres and 11.1 metres above the ground respectively. The Planning Portal hosts the Domestic Wind Turbine Safeguarding Land Tool, which establishes whether or not a proposed wind turbine will be located on safeguarded land. If the proposed turbine is not on safeguarded land it has successfully met one of the requirements of being eligible for permitted development. All turbines that do not meet the above requirements are currently processed in a manner relevant to all other scales of wind turbine development.

CAA involvement

4.18. Currently, the CAA can provide the following input to formal planning submissions for wind turbine developments:

1. Identification of aviation stakeholders that would potentially be affected;
2. Reviewing the aviation section of the Environmental Statement for accuracy and completeness;
3. Consideration of regulatory requirements;
4. Consideration of whether all other aviation issues known to the CAA have been taken into account (including other potential developments).

4.19. It should be noted that the CAA is currently only a statutory consultee for onshore developments in excess of 50MW and for offshore developments in excess of 100MW. Responses to other planning submissions will be made, resource permitting.

Promulgation of wind turbine developments

4.20. The need to promulgate the existence of tall structures that might constitute a significant aviation obstruction is self-evident. LPAs routinely advise the DGC of also report such information to DGC. Through the updated promulgation of a database document, the SARG Aeronautical Charts and Data section is advised of all such developments and update aviation charts accordingly. All structures (including wind turbines and anemometer masts) in excess of 300 ft in height are depicted on charts and details of each wind turbine are promulgated in the UK AIP, ENR 5.4 (CAP 32) 9.2. By exception, structures less than 300 ft high may be promulgated for civil aviation en-route purposes if their presence is deemed to be of navigational significance.

Call-ins and inquiries

Call ins

4.21. Whilst the aviation industry has no powers of veto, there is a legal obligation placed upon LPAs to give warning if they are minded to grant planning permission against advice given by a statutory safeguarding consultee (ODPM/DfT/ NAFW Circular 1/2003 and Scottish Executive Circular 2/2003 refer). This process offers an opportunity for the CAA to establish whether a solution is apparent or, if it fails to resolve the issue, to refer the matter for a decision by central Government. This procedure is always a last resort, as it is anticipated that communication and cooperation can obviate the need for it.

Inquiries

4.22. In the event that a planning application is referred to a planning inquiry, the CAA may be requested by the LPA to provide expert witness evidence. This may be by providing written statements or by attendance at the Inquiry.

Consistency, accuracy and use of consultants

4.23. When aviation stakeholders are consulted over wind turbine developments, either at the pre-planning stage or once the formal planning application process has begun, it is critical that the responses made are consistent, factually accurate and cover all relevant aspects. It should be noted that these responses may be subject to challenge and CAA is often asked to provide an impartial regulatory perspective on what has been submitted.

4.24. In submitting a wind turbine development proposal, developers will regularly employ subject matter experts in the form of consultants to prepare reports to identify potential issues and address any issues raised by aviation stakeholders. This may be in the pre-application stage or to seek to address aviation concerns following aviation objections. In addition, as part of the formal process, developers are often required to submit an Environmental Impact Assessment which will include an assessment of aviation issues and mitigations, often based on supporting reports commissioned by the developers. If asked for comment, CAA will request that LPAs pursue any assertions or statements made in respect of aviation with the appropriate aviation stakeholder, developer or consultant.

CAA provision of advice

4.25. The CAA is often approached for comment and advice concerning the validity of objections raised or the suitability of mitigations proposed. However, it is incumbent upon the developer to liaise with the appropriate aviation stakeholder to discuss – and hopefully resolve or mitigate – aviation related concerns without requiring further CAA input. However, if these discussions break down or an impasse is reached, the CAA can be asked to provide objective comment. It must be remembered that the CAA has no powers to either prevent wind turbine developments going ahead or to require that an aviation stakeholder remove their objection. Nevertheless, by involving the CAA at an appropriate stage, it is hoped that some form of agreement can be reached that prevents the need for costly Planning Inquiries that feature aviation as a key issue.

4.26. Of further note is that as the UK's independent civil aviation regulator of, the CAA will not typically provide comment on MoD objections or arguments unless such comments have been requested by the MoD. However, in circumstances where there is a mixture of civil and military objections and where it is appropriate to do so, the CAA could facilitate discussions between all the parties (including the MoD).

APPENDIX A

DECC Governance and meeting structure

A1 In addition to work to improve the processes of consultation and assessment, there is a substantial amount of other activity going on to identify, develop and implement solutions to the potential impacts that wind turbines can have on radar systems. It was recognised that it would be beneficial to draw this work together within a single plan in order to have a coordinated approach to finding solutions to the wind turbine – radar issue. Therefore, together with stakeholders in the aviation and wind development sectors, DECC and several partners jointly developed an Aviation Plan to move work forward so that wind turbine developments could be developed while, at the same time, the maintenance of national security and the continued safe operation of our aviation environment were ensured. The structure and principles of the Aviation Plan were endorsed by the Wind Energy, Defence and Civil Aviation Interests Working Group in March 2008.

A2 The overall aim of the Aviation Plan is to provide an evolving suite of generic mitigation solutions to which wind turbine developers and their aviation stakeholders can turn when discussing the best potential solutions for any particular wind proposal. The development of this suite of generic solutions is an on-going process and builds on a number of solutions that are already available to wind turbine developers.

A3 The governance of the Aviation Plan is the responsibility of an Aviation Management Board (AMB), which in turn is supported by a technical-level Aviation Advisory Panel (AAP). RenewableUK have taken on the responsibility of establishing an industry funding mechanism that will part- support, financially, the work-streams within the Plan, which is managed by the Fund Management Board. All meetings sit quarterly.

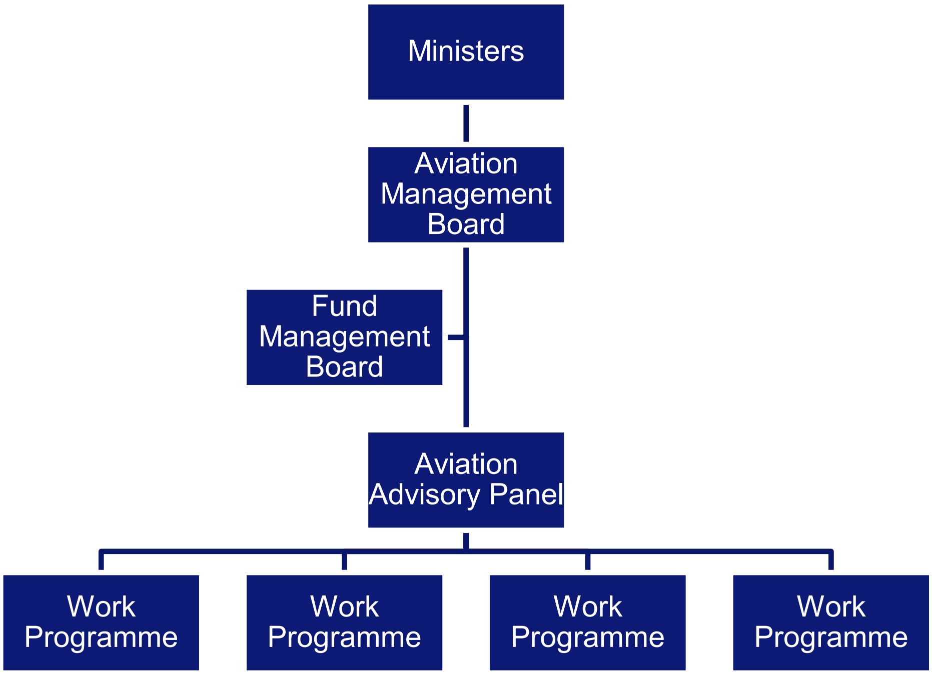

Figure A-1: AMB Governance

A4 The value of the Aviation Plan as a tool for enabling the development of mitigation solutions has been recognised by key stakeholders that have an interest in radar systems and wind turbine developments. To ensure the success of the plan, a number of these have agreed to sign off a second Memorandum of Understanding[40] to commit to the full implementation of the Aviation Plan and its approach to ensuring the timely and effective delivery of solutions to reduce the effect of wind turbines on aviation interests.

[40] https://www.gov.uk/government/publications/wind-turbines-and-aviation-radar-mitigation-issues-memorandum-of-understanding-2011-update

APPENDIX B

Contact Information

CAA Contacts

CAA Windfarms

Windfarms

Infrastructure

Safety and Airspace Regulation Group

CAA House

45-59 Kingsway

London

WC2B 6TE

Tel: 020 7453 6534

http://www.caa.co.uk/Safety-Initiatives-and-Resources/Safety-projects/Windfarms/Windfarms/

windfarms@caa.co.uk

CAA Aerodromes

For information on aerodrome licensing criteria, obstacle limitation surfaces and call-in procedures, contact:

Civil Aviation Authority

Aerodromes Standards Department

Safety and Airspace Regulation Group

Aviation House

Gatwick Airport South

West Sussex

RH6 0YR

CAAAerodromeStandardsDepartment@caa.co.uk

CAA Air Traffic Standards

Where a service provider has to update the safety documentation for a service as a result of a wind turbine development, then they should follow standard practice and contact their regional inspector for approval as necessary. Contact details are below:

CAA En-Route Regulation

Safety and Airspace Regulation Group Aviation House – 2W

Gatwick Airport South

West Sussex

RH6 0YR

Tel: (+44) (0)1293 573060, Fax: (+44) (0)1293 573974

ats.enquiries@caa.co.uk (mark to 'En-Route Regulation')

CAA Southern Regional Office (Gatwick)

Regional Manager ATS Safety Regulation (Southern Region)

Air Traffic Standards Division

Safety and Airspace Regulation Group

Civil Aviation Authority

Aviation House

Gatwick Airport South

West Sussex

RH6 0YR

Tel (+44) (0) 1293 573330, Fax: (+44) (0) 1293 573974

ats.southern.regional.office@caa.co.uk

CAA Northern Regional Office (Stirling)

Regional Manager ATS Safety Regulation (Northern Region)

Air Traffic Standards Division

Safety and Airspace Regulation Group

Civil Aviation Authority

First Floor, Kings Park House

Laurelhill Business Park

Stirling

Scotland

FK8 9JQ

Tel: (+44) (0) 1786 457400

ats.northern.regional.office@caa.co.uk

ATCO Training and Area Control Centres

Enquiries about ATS at Area Control Centres and air traffic controller training establishments should be addressed to:

En Route and College Regulation

Air Traffic Standards

Civil Aviation Authority

Safety and Airspace Regulation Group

Civil Aviation Authority

Aviation House

Gatwick Airport South

West Sussex

RH6 0YR

Tel: (+44) (0) 1293 573259

Fax: (+44) (0) 1293 573974

Other Contacts

The Airport Operators' Association

3 Birdcage Walk

London SW1H 9JJ

www.aoa.org.uk

Tel: (+44) (0) 20 7799 3171

General Aviation Awareness Council

RAeS House

4 Hamilton Place

London

W1J 7BQ

www.gaac.org.uk

Tel: 020 7670 4501

Fax: 020 7670 4309

British Gliding Association Limited

8 Merus Court

Meridian Business Park

Leicester

LE19 1RJ

Tel: +44 (0) 116 289 2956

Fax: +44 (0) 116 289 5025

office@gliding.co.uk

British Parachuting Association

Wharf Way

Glen Parva

Leicester

LE2 9TF

www.bpa.org.uk

Tel: +44 (0)116 278 5271

Fax: +44 (0)116 247 7662

skydive@bpa.org.uk

Defence Geographic Centre

UK DVOF & Powerlines

Air Information Section

Defence Geographic Centre

Elmwood Avenue

Feltham

Middlesex

TW13 7AH

Tel: (+44) (0) 208 818 2702

DVOF@mod.uk

Department for Environment, Food and Rural Affairs

Nobel House

17 Smith Square

London

SW1P 3JR

https://www.gov.uk/government/organisations/department-for-environment-food-rural-affairs

Department of Energy and Climate Change

Kieran Power

3 Whitehall Place

London

SW1A 2AW

Tel: 0300 068 6189

www.decc.gov.uk

kieran.power@decc.gsi.gov.uk

Department for Transport

Great Minster House

76 Marsham Street

London

SW1P 4DR

https://www.gov.uk/government/organisations/department-for-transport

Maritime and Coastguard Agency

For general enquiries:

SAR Operations Officer

HM Coastguard

Maritime and Coastguard Agency

Southampton

UK

Tel: (023) 8032 9332

Fax: (023) 8032 9488

https://www.gov.uk/government/organisations/maritime-and-coastguard-agency

Roly.McKie@mcga.gov.uk

For Maritime lighting requirements:

MCA Navigation Safety Branch,

HM Coastguard

Maritime and Coastguard Agency

Southampton

UK

Tel: (023) 8032 9523

Fax: (023) 8032 9488

National Police Air Service (England and Wales)

NPAS HQ

Head of Estates and Infrastructure

West Yorkshire Police

Laburnum Road

Wakefield

West Yorkshire

WF1 3QP

Tel: 01924 292520

npas.obstructions@npas.pnn.police.uk

http://www.npas.police.uk/

Ministry of Defence – Defence Infrastructure Organisation (formerly Defence Estates)

Kingston Road

Sutton Coldfield

West Midlands

B75 7RL

0121 311 3847

dio-safeguarding-wind@mod.uk

www.mod.uk/DIO

NATS Safeguarding

NATS Corporate and Technical Centre

4000-4200 Parkway

Whiteley

Hants

PO15 7FL

NATSSafeguarding@nats.co.uk

National Assembly for Wales

Planning Division

Cathays Park

Cardiff

CF10 3NQ

0300 0603300 or 0845 010 3300

Planning.division@wales.gsi.gov.uk

http://gov.wales/topics/planning/?lang=en

DOE Northern Ireland Planning

DOE Planning

Causeway Exchange

1-7 Bedford Street

19-25 Great Victoria Street

Belfast

BT2 7EG

www.planningni.gov.uk

Department for Communities and Local Government

Eland House

Bressenden Place

London

SW1E 5DU

https://www.gov.uk/government/organisations/department-for-communities-and-local-governmentw

Office of Gas and Electricity Markets (OFGEM)

9 Millbank

London

SW1P 3GE

70 West Regent Street

Regents Court

Glasgow

G2 2QZ

https://www.ofgem.gov.uk/

RenewableUK

Greencoat House

Francis Street

London

SW1P 1DH

http://www.renewableuk.com/

Scottish Executive

Energy Consents Unit

4th Floor

5 Atlantic Quay

150 Broomielaw

Glasgow

G2 8LU

econsentsadmin@scotland.gsi.gov.uk

http://www.energyconsents.scot/

01-29-20
EXHIBIT
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Wind Energy and Aviation Safety, Fatalities

windaction.org/posts/46562-wind-energy-and-aviation-safety-fatalities

Lisa Linowes - April 4, 2017 Safety Injury
USA

Earlier this year, a single engine plane collided with a wind turbine in Germany killing the pilot and shattering the aircraft. The appalling tragedy was reported as a rare occurrence, but few realize that in the U.S. alone at least ten people have lost their lives in fatal aviation accidents involving collisions with U.S. sited wind turbines and meteorological (MET) towers.

The table below lists these accidents, six in all.

Date	Location	Fatality	Activity	Information
Dec 15, 2003	Vansycle, OR	Yes, 2	Transport (MET)	NTSB Accident ID SEA04LA027
May 19, 2005	Ralls, TX	Yes, 1	Ag Spray (MET)	NTSB Accident ID DFW05LA126
Jan 10, 2011	Oakley, CA	Yes, 1	Ag Spray (MET)	NTSB Accident ID WPR11LA094
Aug 5, 2013	Balko, OK	Yes, 1	Ag Spray (MET)	NTSB Accident ID CEN13FA465
Apr 27, 2014	Highmore, SD	Yes, 4	Transport (Turbine)	NTSB Accident ID CEN14FA224
Aug 19, 2016	Ruthton, MN	Yes, 1	Ag Spray (MET)	NTSB Accident ID CEN16LA326 [1]

Wind and Collisions

The most widely reported incident occurred the night of April 27, 2014, just ten miles south of the airport in Highmore, South Dakota. All four passengers, including the pilot, were killed when their plane struck an operating wind turbine owned by NextEra. According to the National Transportation Safety Board (NTSB) report, the facility was not marked on the sectional charts covering the accident location.

NTSB also reported that the light on the turbine tower was not operational at the time of the accident, and the outage was not documented in a notice to airmen (NOTAM)[2]. NTSB investigators opined that "[i]f the pilot observed the lights from the surrounding wind turbines, it is possible that he perceived a break in the light string between the wind turbines as an obstacle-free zone."

The other five incidents involved collisions with wind project meteorological (MET) towers. MET towers are erected at proposed wind energy sites for assessing wind speed and direction. The towers, made from galvanized tubing 6-8 inches in diameter and secured with guy wires, can be erected in a matter of hours and, in many cases, without notice to the local aviation community. Their rapid deployment means the navigable airspace of an area could quickly become hazardous for low-flying aircraft. Generally, the towers stand under 200-feet, thus below the threshold for requiring FAA notification, are unlit and usually devoid of any markings, so they are difficult to see.

In the three fatalities from 2003, 2005, and 2011, final NTSB reports cited the unmarked towers and the inability of the pilot to see the towers as the probable causes for the accidents. In the 2013 fatality, the MET tower was marked but sun glare impaired the pilot's ability to avoid the tower.

NTSB Recommendations and FAA Delays

The NTSB is well aware of the hazards these towers pose. On May 15, 2013, the agency filed the following safety recommendations with the FAA related to MET tower aviation risks: [3]

- Amend 14 [CFR] Part 77 to require that all [METs] **be registered, marked, and—where feasible—lighted**.
- **Create and maintain a publicly accessible national database** for the required registration of all [METs].

The FAA delayed acting on its MET-tower safety recommendations claiming limited resources and competing priorities so it wasn't until December 2015, [4] before updated rules for marking MET towers were released. Still, the FAA stopped short of mandating them. Eight months later (August 2016), a 6th fatality occurred when a pilot collided with an unmarked MET tower in Minnesota.

Following FAA's delays, Congress acted by passing the "FAA Extension, Safety, and Security Act of 2016," which mandates that towers between 50 and 200-feet having an above-ground base of 10-feet or less in diameter be marked. Specific provisions in the bill explain the types and location of towers for which the law applies. The FAA is again tasked with creating rules to implement the regulation [5] but with a deadline of July 2017.

Encroachment and Fatal Risks

Other aviation fatalities have happened involving wind turbines but without direct collisions and where blame was attributed to the pilot. One such incident occurred on February 8, 2008 when Philip Ray Edgington, an experienced American Airlines pilot, was flying his vintage Cessna 140 airplane near Grand Meadow, Minnesota, at an elevation between 300 and 600 feet above ground level (agl).

On that fatal day, Mr. Edgington came upon an array of 400-foot tall turbines, whereupon "the airplane made a 90-degree course change, which was followed by a figure-8 turn at varying altitudes between 800 and 1,500 feet agl." The NTSB reported that the craft "impacted terrain in a nose-low, left-wing-down attitude. The 300-foot-long debris path and fragmentation of the airplane were consistent with a high-speed impact."

The probable cause of the accident according to the NNTSB was "The pilot's continued visual flight into an area of known instrument meteorological conditions in an airplane not equipped for instrument flight, and his failure to maintain control of the airplane while maneuvering at low altitude."

Pilot error may be the strict legal explanation for the accident, but there should be no question the wind turbines played a role.

Wind turbines and associated MET towers are encroaching on aviation air space, and safety concerns are growing worldwide. In September 2015, Royal Air Force pilots produced a catalogue of near misses with wind farms in the United Kingdom. Recreational and light-craft pilots are also sounding the alarm. According to microlight aircraft instructor Colin MacKinnon in the UK, millions have been spent "to investigate the impact and guarantee the safety of commercial aviation" but "very little has been done for the general aviation sector which is us." The general aviation sector is the primary user of low-elevation flight space.

Recommendations:

As the Trump Administration undertakes its review of existing agency rules, we recommend the following actions be considered in order to secure the safety of our airspace for all aviators.

- FAA quickly adopt new rules governing the safe siting of wind MET towers; Mandate that rules apply immediately to all new *and* existing MET towers unless specifically exempted by law;
- Mandate full review and update of SkyVector sectional charts to ensure wind turbine installations and MET towers are correctly represented;
- Follow the NTSB recommendation to create and maintain a national database of wind-related towers with full public access;

- Institute periodic review and enforcement to ensure all FAA required turbine safety equipment including lighting is operating properly. Apply punitive fines for developers who fail to maintain all safety equipment.

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[1] We note that the NTSB preliminary report makes no mention of the met tower, only the guy wire.

[2] NOTAM: a written notification issued to pilots before a flight, advising them of circumstances relating to the state of flying.

[3] Special Investigation Report on the Safety of Agricultural Aircraft Operations NTSB/ SIR-14/01 PB2014-105983 Notation 8582 Adopted May 7, 2014 (Recommendations were also filed with the American Wind Energy Association (AWEA), Department of the Interior (DOI), U.S. Department of Agriculture (USDA), Department of Defense (DOD), 46 states, 5 territories, and the District of Columbia.)

[4] Advisory Circular U.S. Department of Transportation Federal Aviation Administration, Obstruction Marking and Lighting December 4, 2015, AC No: 70/7460-1L

[5] NAAA Newsletter: Everything You Need to Know About New Tower Marking Requirements.

01-29-20
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Report No. K-TRAN: KU-13-6 ▪ FINAL REPORT ▪ January 2014

Wind Farm Turbulence Impacts on General Aviation Airports in Kansas

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The University of Kansas

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16 Abstract

Wind turbines and wind farms have become popular in the State of Kansas. Some general aviation pilots have expressed a concern about the turbulence that the spinning blades are creating. If a wind farm is built near an airport, does this affect the operations in and out of that airport? Other problems associated with wind farms are their impact on agricultural aviation and their influence on radar detection of aircraft in the vicinity of a wind farm.

This research project has three objectives:

1. Determine the amount and pattern of the turbulence from a single wind turbine.
2. Determine the amount and pattern of wind turbulence from a wind farm, both in a horizontal direction and in a vertical direction.
3. This information will result in recommendations concerning the location of wind farms and their impacts of the safe operation of airports and other aviation activities.

The results of this project support the findings in the literature search that the turbulence from a wind turbine can impact operations at a general aviation airport. Two case studies were used to illustrate the impact of turbulence from a wind turbine on a general aviation airport. This project analyzed the roll hazard and the crosswind hazard resulting from a wind farm located near a general aviation airport. The wind turbine wake model is based on a theoretical helical vortex model and the decay rate is calculated following the aircraft wake decay rate in the atmosphere.

The roll hazard analysis showed that for the Rooks County Regional Airport, the potential roll hazard index is in the high range as far out as 2.84 miles. For the Pratt Regional Airport, the roll hazard index is in the high range as far out as 1.14 miles. These numbers are based on a gust wind of 40 mph that is below the turbine brake wind speed of 55 mph. As the results show, the scenario is different according to the relative locations and orientations of the airport and the nearby wind farm. Therefore, the analysis has to be performed for each specific regional airport.

The crosswind hazard analysis for the Rooks County Regional Airport showed part of the airport in the high range even under the mild wind condition at 10 mph. The wind turbine wake increases the crosswind component to more than 12 mph which is considered high risk crosswind for small general aviation aircraft. For the Pratt Regional Airport, the crosswind hazard is relatively small under the mild wind condition (10 mph). When there is a gust of 40 mph wind, the turbine wake induced crosswind puts the majority of runway areas to high hazard areas at both of the airports.

It is recommended that additional studies should be performed to draw the proper correlation between the hazard index developed in this study and the safe operation of aircraft at low airspeeds and at low flight altitudes operating near or at a general aviation airport.

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Final Report

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

NOTICE

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Chapter 1: Introduction

Wind turbines and wind farms have become popular in the State of Kansas. Figure 1.1 shows the proposed and existing wind farm projects in Kansas as of February 2013. However, some general aviation pilots have expressed a concern about the turbulence that the spinning blades are creating. If a wind farm is built near an airport, does this affect the operations in and out of that airport? Other problems associated with wind farms are their impact on agricultural aviation and their influence on radar detection of aircraft in the vicinity of a wind farm.

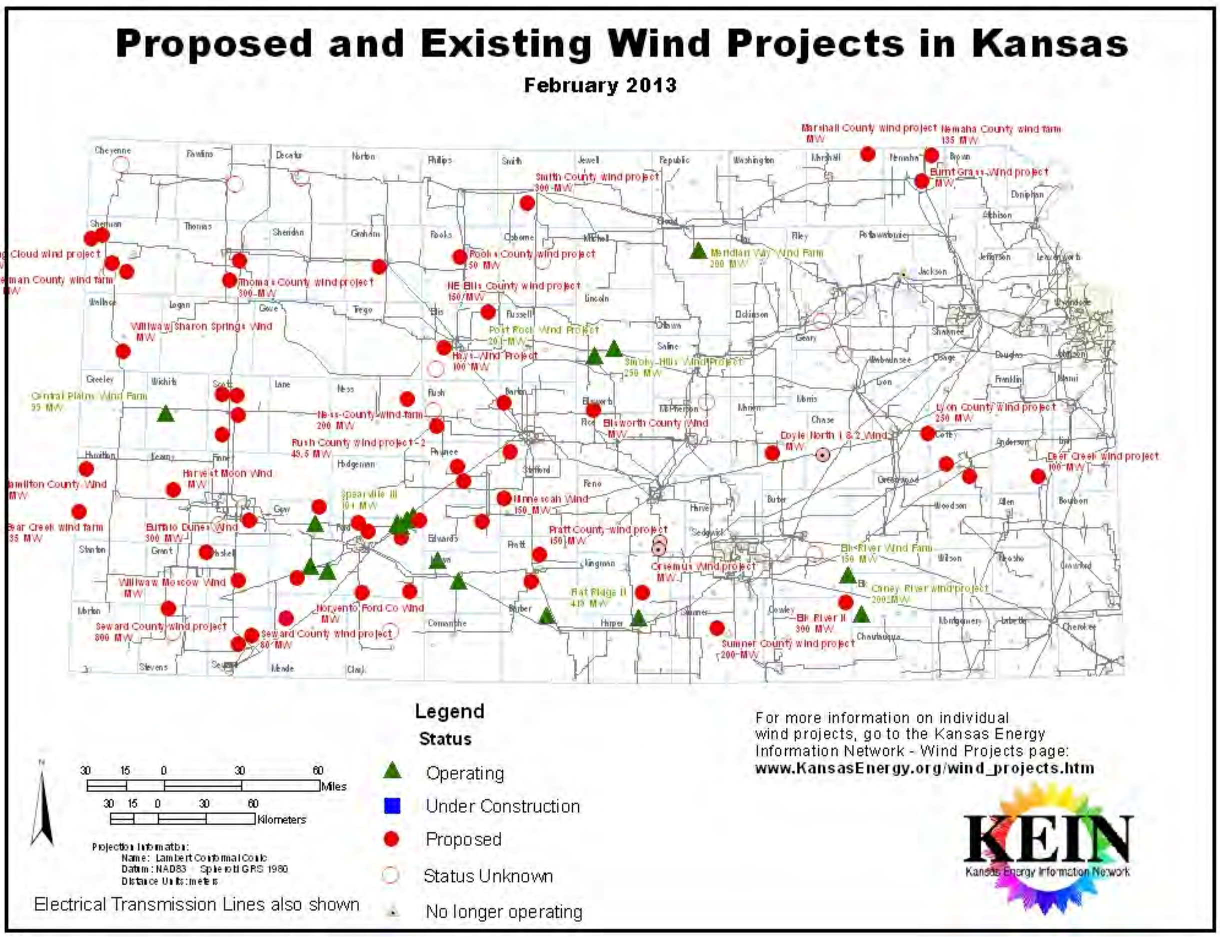

FIGURE 1.1
Proposed and Existing Wind Projects in Kansas

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1. Determine the amount and pattern of the turbulence from a single wind turbine.

2. Determine the amount and pattern of wind turbulence from a wind farm, both in a horizontal direction and in a vertical direction.
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There were five tasks in this project:

1. Determine the amount and pattern of the turbulence from a single wind turbine.
2. Determine the amount and pattern of wind turbulence from a wind farm.
3. Locate the existing and planned wind farms in the State of Kansas.
4. Locate the existing general aviation airports and their proximity to existing and proposed wind farms.
5. Write the final report

Chapter 2: Literature Search

2.1 Wind Turbine Specifications

After going through the popular wind turbine models of the top 10 wind turbine manufacturing companies in the world, the height of the wind turbine hub varied from 165ft to a maximum of 450ft. Many times the height of the hub is site specific, as it depends on the height at which the wind speed is the maximum. The rotor diameters vary from around 260ft to a maximum of 500ft, though the average diameter is around 300ft. The rated power of the wind turbines is between 8.0 MW to 0.6 MW (www.aweo.org/windmodels).

Johan Meyers (Katholieke Universiteit Leuven, Belgium) and Charles Meneveau (Johns Hopkins University) tried to find the optimal turbine spacing in a fully developed wind-farm. The researchers used the computational studies based on the Large Eddy Simulation, which allows them to predict the wind velocity at the hub height as a function of wind turbine spacing and loading factors. In this research, they used this simulation to predict the optimal spacing as a function of above parameters along with ratio of turbine costs to land surface costs. They found out that for realistic cost ratios the average optimal turbine spacing should be 15 times the diameter of the rotor as against the conventional 7 times. The above is true for large wind farms on flat terrain whose length exceeds the atmospheric boundary layer (height of approximately 1 km). The optimal spacing of wind turbines in small wind farms may depend on the location, as the turbines in the front will be operating under powerful winds compared to the one behind (Meyers and Meneveau 2012).

Ivan Mustakerov and Daniela Borissova studied the problems associated with optimal wind farm design in Bulgaria. The authors developed an optimization model for wind turbine type, number and placement based on given wind conditions and wind farm area being developed. To determine the optimization criteria they used wind farm investment cost and total power as functions of wind turbine type and number. The researchers considered two main wind directions regarding uniform and predominant wind directions for wind farm of shapes – square and rectangular. After testing a d eveloped wind farm numerically, they observed that the different practical requirements and restrictions define the different choices. Their results also confirmed that using big size turbines is more profitable than a large number of small size turbines. The numerical tests show that the developed optimization approach can be applied to wind farm design (Mustakerov and Borissova 2009).

2.2 Wind Terminology

Start-up speed: Speed at which the rotor and blade assembly starts to rotate.

Cut-in speed: The minimum speed at which the wind turbine will generate usable power, generally between 7 and 10mph.

Rated speed: It is the minimum speed at which the wind turbine will generate its designated rated power. It is generally between 25 and 35mph for most of the turbines.

Cut-out speed: The speed at which the turbines stop generating power and shuts down, usually between 45 and 80mph (www.energybible.com 2012).

2.3 Wind Farms and Aviation

2.3.1 Turbulence Impact Assessment

EMD International A/S conducted a study on the turbulence impact from a wind farm located off shore. This study was undertaken because some sailors and recreational users off the coast of the island Hiiumaa complained about the turbulence. In this study the actual locations of the wind turbines were not considered, but a large number of turbines were selected. The turbulence was calculated to be 8m/s at a 10 m height on off shore locations. The size of the wind farm considered in this study was 636 MW, distributed on 212 uni ts. For calculations Vestas V90-3 was used, which has a nominal power of 3 MW, a rotor diameter of 90m and a hub height of 80m. The turbulence of wind was described by turbulence intensity, which is the ratio of wind speed changes to mean wind speed. Turbulence depends on t he terrain; sea surface causes little turbulence while forest area causes very high turbulence. The higher the turbulence, the longer is the distance required for dissipation. The wind turbines add wake to the wind turbulence. The wake can be recognized up t o 2000m (about 6600ft) downwind side of the turbine. The wake turbulence is the largest behind the turbine and decreases further downstream. The turbulence from turbines has a short and predictable spectral size unlike the natural turbulence. They concluded that the maximum turbulence from a single turbine is at 200m and is almost negligible after 500m. The researchers concluded that the turbulence impact of the turbines is negligible beyond a few hundred meters, when compared with the turbulence on land (EMD International A/S 2010).

2.3.2 CAA Policy and Guidelines on Wind Turbines

The Civil Aviation Authority (CAA) in England is the statutory corporation which oversees and regulates all aspects of civil aviation in the United Kingdom (UK). The study focused on the issues related to the UK but lessons still can be applied here. There was also recognition in their report that both aviation and wind energy were important to natural interests and each side should cooperate to find solution to potential problems. The CAA published this document to give the aviation stakeholder a better understanding of the wind turbine related issues. In Chapter 2 of their report, they identified several impacts of wind farms on aviation. They report that Primary Surveillance Radar is adversely affected. If the wind turbine falls within the line of sight of the radar, then the radar misinterprets a wind turbine as an aircraft. Sometimes wind turbines cause a loss of sensitivity in detection of aircrafts to an extent that they are lost completely. The wind turbines form an obstruction and, thus, there is a region behind the turbine in which aircrafts are masked and cannot be detected. The receiver requires a large range to detect reflected signals from small and large aircrafts. If there is an obstacle such as a wind turbine, then it reflects a significant amount of signals and thus the receiver becomes saturated. The wind turbine also affects the Secondary Surveillance Radar even though it does not rely on the reflections from an object. The turbulence caused by the wake of the turbine extends downstream of the blades. The wake intensity depends on the size and height of turbines. It has been seen that the wind turbines create wake vortices similar to aircraft vortices, these can be hazardous to an aircraft. “Published research shows measurements at 16 rotor diameters, approximately 1500m (5000ft) downstream of the wind turbine indicating that turbulence effects are still noticeable.” The measurement of effect is very difficult even though modeling studies can predict the effects further downstream. The verification and validation processes of these models are still going on. They found that very light aircrafts such as gliders, gyroplanes, microlights, etc. are more susceptible to the wake turbulence. Thus, the CAA will analyze the turbulence of wind farms near the airports on a case-by-case basis until they observe a significant pattern (Civil Aviation Authority 2011).

2.3.3 Airport Cooperative Research Program Synthesis 28: Investigating Safety Impacts of Energy Technologies on Airports and Aviation

This synthesis study was carried out to inform airport operators, aircraft pilots, airport planners and developers, legislators and regulators responsible for aviation safety of the visual and communications interference impacts of the new energy technologies on aviation. They list that the main concerns of using wind turbines are the height of the turbines and the communication system interference. In addition, the turbulence, lighting and marking of wind turbines are also a concern. Though CFR Part 77 deals with the height, size and location of aviation obstructions, this information is advisory in nature. Wind turbines are issued "No Hazard" determination if they are not located within the airport approach areas by the Federal Aviation Administration (FAA). Similar to the CAA findings, this report also states the adverse effects of wind turbines on the primary and secondary radars. They found that the turbulence from the wind turbines creates vortices at a distance of 2-6 rotor radii (250-750ft). Thus the aircrafts flying at a height of 200-400ft above ground, i.e. at the turbine level, are in danger. To minimize the effects of wind farms they have considered some mitigation options

- Appropriate siting to avoid communication system impacts.
- Re-route air traffic.
- Use of supplemental radars wherever the main radar is receiving false signals.
- Use radar absorbent materials on the turbines (Barret and Devita 2011).

2.3.4 NationAir Aviation Insurance

The NationAir Aviation Insurance (NAAI), an insurance company in Illinois, discussed the hazards of wind turbines to the aerial applicators. They say that the tax credits, and other grants and subsidies from the government drastically increased the number of wind turbines in the mid-west region. According to the NAAI Tower Policy all the recorded aerial applicator and tower collisions have been fatal. The wind turbine has hazards like wake turbulence and shadow flicker. The researchers found out that a typical commercial wind farm has 2.5 turbines per square mile, with the exception of some states like Wisconsin, where there are 10-12 wind turbines per square mile. Turbine flickers can play visual "tricks" and lead to pilot disorientation. The specific location of wind farm can drastically impact application ability and its associated cost. The researchers also say that the MET (meteorological test towers) are very dangerous as they are below 200 feet and require no painting or marking. The NAAI has developed guidelines in order to inform the tower industry about the aerial applicators concerns, they are as follows:

- Construction Petitions should be provided to zoning authorities, landowners, applicators within a half mile from towers and regional agricultural aviation organizations.
- Towers should be avoided on pr ime agricultural land or locations which will inhibit spray.
- Information on whether the land will be or will not be suitable for aerial application after construction should be provided by the developers.
- The towers should be free standing without guy wires and in a linear pattern.
- Detailed field layout should be provided to those who work in the proximity after construction is completed. (NationAir Aviation Insurance 2012)

2.3.5 Other Reports

The De Kalb County, Indiana, case concerns the major safety of the MET towers set up to monitor the wind. The cost of aerial application increases with this and many operators refuse to operate within the confines of a wind farm. The farmers with land adjacent to a wind farm development are also affected. The operators charge 50% more than usual for aerial application in a wind farm zone. Potential impact on N exRad appears to be low, but one of the weather radars operating in Fort Wayne has seen impacts from towers in the Ohio counties of Paulding and Van Wert. The researcher concludes that the wind farm development will not affect aviation in all weather conditions but only in certain conditions. All the wind farm development should be studied on a case to case basis by a third party before local approvals are given. The researchers also state that the developments, which have been proven to not have any negative impacts, should not be restricted on unsubstantiated and unproven public claims. (Stump 2012)

The Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) in Oldenburg, Germany developed a simulation which enables them to calculate the turbulence created by the wind farms, how they change the wind speed and how it affects the airplanes. The IWES conducted this research on behalf of BMR Windenergie, the operator of the wind farm, which has proposed a wind farm near an airfield. The researchers created a model of ground and wind profile of the area surrounding the proposed area of the wind farm. Over this model a grid was placed. The computer calculates the changes in the wind conditions and turbulence caused by the wind farms. Dr. Bernhard Stoevesandt said, "The true skill was creation of a grid: Because the points on the grid where the computer makes the individual calculations must lie exactly at the right place." Another challenge that the researcher faced was to depict the trail properly, which is the turbulence and wind conditions behind the rotor and determine its effects on aircraft. The researchers measured the trail at various individual points behind the rotor at actual wind farms in order to validate the simulations. The researchers carried out simulations for various wind directions, two different wind speeds and five different flight trajectories under which the airplanes will be influenced for varying lengths of time. The researchers found that the turbulence generated by the wind turbines is lower than the ordinary turbulence from the surrounding area. This finding can be applied to other airports to a limited extent, because of the fact that the surrounding terrain has a tremendous impact on the trail and, thus, it is very different for forested and hilly terrain compared to flat terrain (Stoevesandt 2012).

2.4 General Aviation

The FAA recommends a crosswind runway, if a runway orientation provides wind coverage less than 95% for any aircraft forecasted to use the airport on a regular basis. To calculate 95% wind coverage the crosswind should not exceed the following limits:

TABLE 2.1
Airport Reference Code for Maximum Crosswind

Airport Reference Code	Maximum Crosswind
A-I and B-I	12.10 mph
A-II and B-II	15 mph
A-III, B-III, and C-I through D-III	18.41 mph
A-IV through D-VI	23 mph

The Airport Reference Codes A-I or B-I are expected to accommodate single engine airplanes. Codes B-II or B-III refers to airports serving larger general aviation aircrafts and commuter type aircrafts. C-III is small or medium sized airports serving air carriers. And larger air carrier airports are with codes D-VI or D-V. (Federal Aviation Administration 2012)

Rate of change of wind speed and/or direction an aircraft experiences is called wind shear. There are two types of shear, namely vertical and horizontal, though generally they occur as a combination of both. Wind shear in aviation terms is defined as a sudden but sustained "variation in wind along the flight path of a pattern, intensity and duration that displaces the aircraft abruptly from its intended path so that substantial and timely control action is needed". Though wind shear is short lived it is probably the greatest hazard to aircrafts at low altitude. A substantial change in the lift generation linked with the aircraft inertia results in the displacement of the flight path. Terrain, constructed obstructions, thermals, and temperature inversions may cause wind shears. For a l ight aircraft, the closer to the surface a shear appears, the more dangerous it is. (Brandon 2012)

The Aircraft Owners and Pilots Association (AOPA) published two letters which state that "wind turbines have the potential to be a hazard to air navigation". "According to Greg Pecoraro, AOPA vice president of airports and state advocacy, it has become increasingly important for AOPA to educate lawmakers across the country about the effects of these systems on aviation, particularly so when the wind farms are in close proximity to airports. Aside from the obstruction itself, they can also interfere with communication and navigation, and wind patterns for all aircraft, especially gliders". Pecoraro went on to say, "If the systems (wind farms) were to be installed near arrival or departure paths of these facilities (airports), the safety of passengers and crew, as well as citizen below, would be greatly compromised" (Twombly 2009).

In an article titled, “Wind Farms Could be a Hazard to VFR Flights “ the AOPA is urging the FAA to find the 130 wind turbines proposed for the Nantucket Sound near Cotuit, Massachusetts, would pose a hazard to the many low-altitude VFR flights between the three area airports. The turbines could also disrupt local radar systems”. An AOPA Pilot Blog stated that “the National Weather Association newsletter had the statement that wind farms are showing up on NexRad radars. … They make radar returns that look a lot like a tornado vortex” (Namowitz 2012).

Another AOPA report has the title “Wind Farms Can’t Come at the Expense of Airports”. The mayor of Kentland, Indiana protected his town’s airport from a request by a local farmer to close the airport so he could build a wind turbine farm on his property” (AOPA 2010).

2.4.1 Imaginary Surfaces of Airports

To provide safe navigation of aircrafts to and from an airport, there are certain specifications to guard the airspace surrounding an airport. According to FAA, a runway protection zone should be provided at the end of a runway. It is an area on the ground beneath the approach surface, from the end of primary surface and extended to a point where the approach surface is 50ft above the primary surface. If the runway protection zone starts at any location 200ft beyond the end of the runway, then two protection zones are required, the approach protection zone and departure protection zone.

Part 77 of the Federal Aviation Regulations establishes standards to determine what would be considered as obstructions to the navigable airspace and sets requirements for notice to the FAA due to constructions and alterations; it also provides studies to explain the effects of obstructions on safe and efficient use of airspace. It is the responsibility of the airport operator to make sure that the aerial approaches to the airport are clear and protected and the land adjacent or in vicinity of the airport is restricted with measures such as zoning ordinances. Several imaginary surfaces have been established to determine whether an object is an obstruction to the airspace. These surfaces vary with the type of runway (e.g. utility, transport) and the approach planned for that runway (e.g. visual, non-precision instrument, etc.).

- Primary Surface: This surface is longitudinally centered on a runway. It extends 200ft from each end of the runway when the runway is paved; if the runway is unpaved it ends at the end of the runway. Its elevation is the same as that of the nearest point on the runway centerline.
- Horizontal Surface: This is a horizontal plane 150ft above the established airport elevation. The perimeter of this surface is constructed by swinging arcs of fixed radii from the end of the primary surfaces and the two arcs are joined by tangents.
- Conical Surface: It is a surface extending outwards and upwards from the periphery of horizontal surface at a slope of 20:1 for a horizontal distance of 4000ft.
- Approach Surface: This surface is longitudinally centered along the extended runway centerline. It extends outwards and upwards at a designated slope based on the type of approach planned or present.
- Transitional Surface: This surface extends outwards and upwards at right angles to the runway centerline and to the extended runway centerline at a slope of 7:1 from the sides of the primary surface up to horizontal surface and also from that of the approach surface. The width of the transitional surface is 5000ft from the edge of the approach surfaces.

Along with the above imaginary surfaces, existing or future objects are considered as obstructions if they are of greater height than any of following heights or obstructions:

- A height of 500ft above ground level at the site of the airport.
- A height of 200ft above ground level or above the established elevation of the airport, whichever is greater, within 3 nautical miles (3.45 miles) of the ARP (airport reference point) which has a longest runway of more than 3200ft. This is increased 100 ft for every mile up to 500 ft. at 6 miles from the ARP.
- A height within a terminal obstacle clearance area, including an initial approach segment, a departure area, and a circling approach area, that would result in the vertical distance between any point on the object and an established minimum instrument flight altitude in that area less than required obstacle clearance.

- A height that would increase the minimum obstacle clearance altitude within an obstacle clearance area along with turn and termination area on a federal airway or off-airway route.
- Any of the imaginary surfaces defined earlier. (Horonjeff, et al. 2010)

2.4.2 Operations at Airports

This is a standard operation procedure for an airport:

- First scan for traffic on the base and final approach legs. Turn on the landing and anti-collision lights, taxi on the runway and align with the runway centerline and take off.
- Departure Leg: Climb the extended runway centerline beyond departure end of runway up to 1000ft. Then look left and right to check for traffic conflict.
- Crosswind Leg: After climbing to the pattern altitude (1000ft) level off and reduce power. Go on crosswind for a half mile.
- Downwind Leg: Perform all the landing configuration tasks on this leg. Select a touchdown point on runway and descent when the spot is passed. Turn to base leg so as to achieve ½ - ¾ mile final approach leg.
- Base Leg: this leg is perpendicular to the runway. Scan for conflicting traffic on this leg. Approaching the turn point and scan for conflicts again.
- Final Approach Leg: Verify all the configurations. Keep scanning for traffic. Clear both sides of the final approach leg. (Air Safety Institute n.d.)

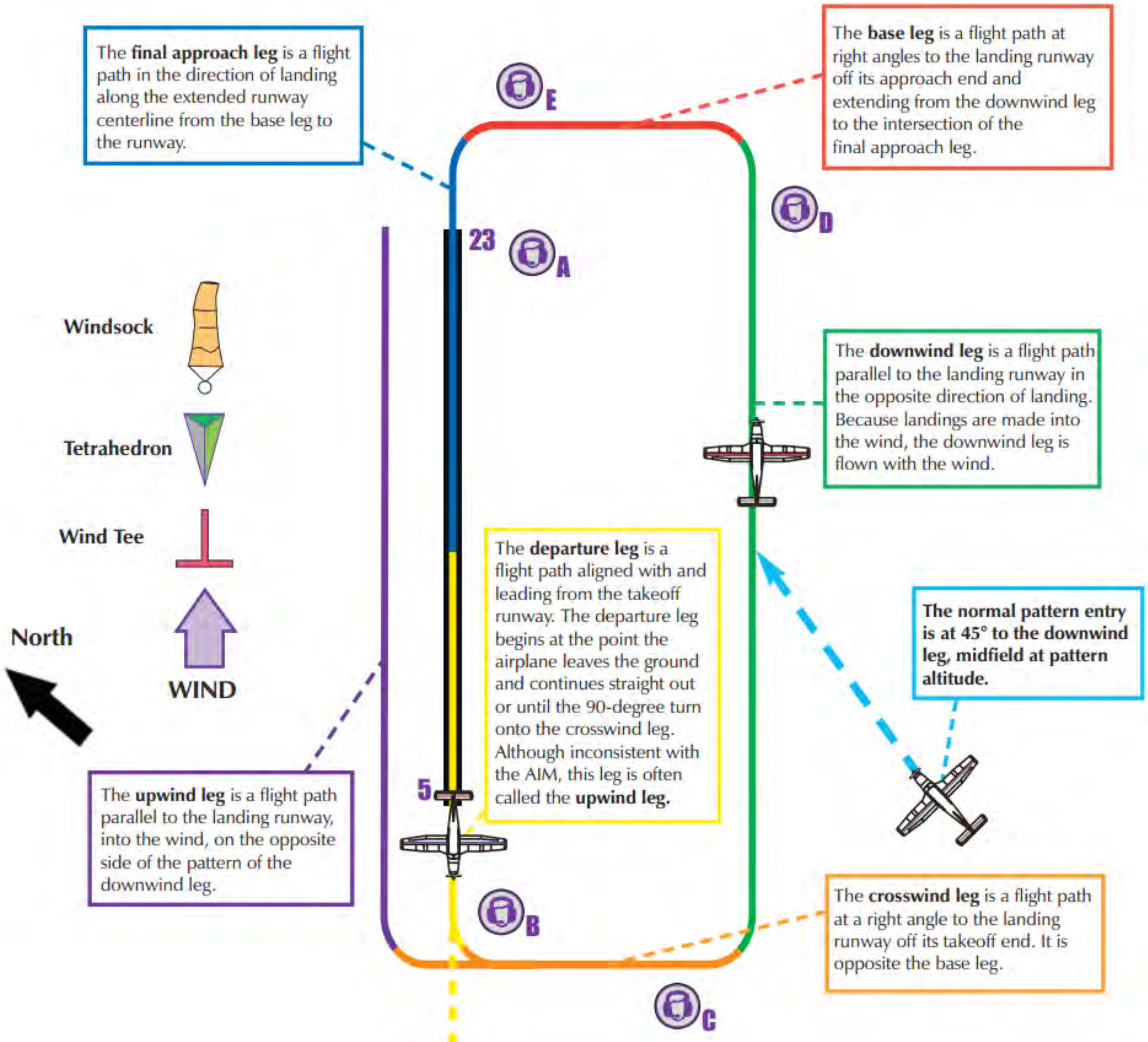


FIGURE 2.1
Non-Towered Airport Approach Traffic Pattern

Figure 2.1 illustrates the traffic pattern used when a pilot approaches a non-towered airport. The location of a wind farm in relationship to an airport can impact the operations of the airport in three ways:

1. The wind turbines should not intersect any of the imaginary surfaces
2. The wind turbines should not be in the path of the recommended traffic pattern
3. The turbulence caused by the wind farm could impact airport operations even though the turbines don't violate 1 and 2 above.

2.5 Wind Farms and the Environment, Health, Agriculture, and Economics

The National Research Council studied the impacts of the wind farms on the environment, aesthetics, cultural, recreational, social, and economics. The committee addressed the beneficial as well as harmful effects of wind farms. Though the committee studied the wind farms all over the US and world, their primary focus was on the wind farms located in the Mid-Atlantic Highland region. They concluded that wind farms had an adverse effect on ecology; birds and bat fatalities occurred due to collisions. They also observed that the new monopole turbines may have less fatalities compared to the older, lattice style turbines. They also observed that the bat fatalities were much higher compared to birds. They observed that the wind turbines had a great impact on the aesthetics of the area and this resulted in strong negative reactions. They suggest that the tools, which are available to study the project visibility and appearance as well as the landscape characteristics, should be used. Wind farms may have an impact on the recreational, sacred and archeological sites as well, as natural scenery is part of recreation and, in the case of historic or sacred sites, their appreciation can be affected. The researchers do not have clarity to evaluate such situations and solve them. The noise from the rotor and flickering of the light due to the blades can cause irritation to the people living there. The noise can be monitored using various measurement techniques and the flickering of light has not been identified even as a mild annoyance, while in Europe it has been noted as a cause of concern. The wind turbine cause electromagnetic interference and has a potential to cause interference to television broadcasts. (National Research Council 2007)

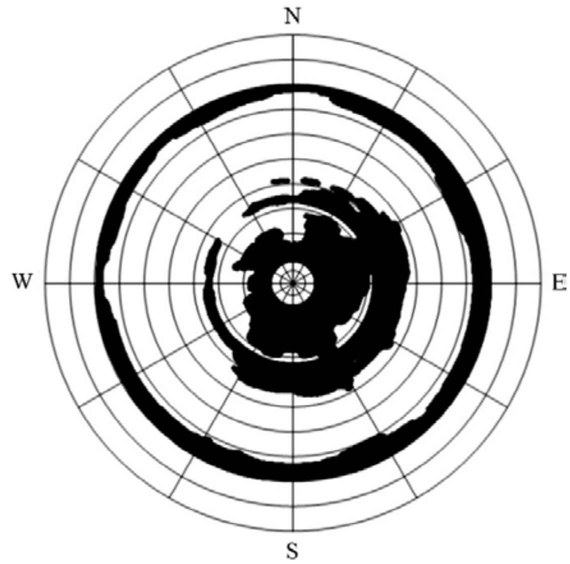
Jay Calleja, Manager of Communications for National Agricultural Aviation Association, discusses the effects of wind energy on farming. The author states that when wind turbines are erected on the farm, aerial application becomes difficult. This is not only limited to the farm in which the turbines are installed, but the neighboring farms can also be affected. If the aerial aviators decide to apply on areas in or around wind turbines they will charge more. Apart from the fact that aerial application cannot be done, there is a deeper problem that exists and that being what the damage from the construction and maintenance does to the farm drainage systems. Although the wind companies do not say that they won’t repair the damage, the amount of money that the wind companies are obligated to pay may not match the amount that is required to fix the farm drainage system. The author also gives many examples of how farmers have been affected even though they did not have wind turbines on their farms. Finally, the author concludes that the aerial applicators should educate farmers about the overall effect that wind turbine construction can have on farmlands and the ability to maximize production. (Calleja 2010)

Howard Graham studied the political and social controversy surrounding the proposed wind farm in the Flint Hills region, Kansas. The author states that even though most people of Kansas will back a wind farm project due to various reasons: they trust environmental groups, back local and state government and mistrust energy companies. Yet, in the case of Flint Hills, the Tallgrass Ranchers and Protect the Flint Hills and many environmental organizations urged the local and state authorities to ban wind turbines in Wabaunsee County, Kansas. This was done mainly based on the reason that the wind turbines will alter the social, cultural and aesthetics of the hills. All the new structures in the county require a permit. In this county "the establishment of land uses except agricultural and single-family uses" requires a conditional use. Also, the county limits the industrial structures to a maximum height of 45 feet along major roads and highways. So, the county law prohibits the industrial scale turbines in two ways: the height is more than the maximum and they cannot be erected on agricultural land as they are not permitted as a conditional use. The people residing in Flint Hills felt that erecting wind turbines was like driving a knife in their hearts. Thus, the county enacted a moratorium period of 2002-2013, during which the "County Zoning Administration shall not accept nor process applications for conditional use permits in connection with wind turbine electric generating project" till the moratorium was repealed or expired. (Graham 2008)

Michael C. Slattery, Eric Lantz and Becky L. Johnson estimates the economic impact of a 1398MW wind power development in four counties of west Texas using Job and Economics Development Impacts model. Impacts of projects are estimated at a local level (within 100 miles of the wind farm) as well as the state level. The researchers observed that during the four year construction phase almost 4100 full time equivalent jobs were created and out of these 58% were accounted for by the turbine and supply chain industry. The researchers found that, assuming 4 years of construction and a 20 year life of the wind farm, the total lifetime economic activity in the state will amount to $1.8 billion, or $1.3 million per MW of installed capacity. The total economic activity at local level over the 20 year life cycle was substantial at $ 730 million, or $0.52 million per MW of installed capacity. The researchers conclude that, with this kind of impact observed from the wind industry and the potential to increase impacts by manufacturing equipment instate and developing trained wind industry labor, Texas appears to be well equipped to have increasing impacts from wind farm development. (Slattery, Lantz and Johnson 2011)

Johannes Pohl, Gundula Hubner, and Anja Mohs studied the stress effects of aircraft obstruction markings of wind turbines. The researchers state that along with the visual impact on the landscape, the stress effect of the aircraft markings is an emerging topic for resistance. As the height of the turbines increases, the number of markings increases as well. The researchers used environmental and stress methodologies to analyze the stress impact. The researchers sent out a questionnaire to 420 residents with a direct sight of 13 wind farms. They found that no substantial annoyance was caused by the obstruction markings. They also observed that the residents exposed to xenon lights reported intense and multifaceted stress compared to those exposed to LED lights. Also, the xenon lights negatively affected the general acceptance of wind farms. The residents also report more annoyance towards non-synchronized lights compared to synchronized conditions under certain weather conditions. Thus, the authors recommend that, to increase the social acceptance of wind farms, xenon lights should be banned, synchronized lights should be used and light intensity should be adjusted. (Pohl, Hubner and Mohs 2012)

Giuseppe Carbone and Luciano Afferrante defined the setback distance and/or buffer zones to reduce the risk of damage or injury from rotor failure. Currently, the distances are based as a "Rule of Thumb" based on the height of the tower and are often overestimated. The researchers combined a 3D dynamic model of detached blade fragment with a rigorous probabilistic approach. Their results show that there are large portions which are safe, even though they are located within the maximum range of the detached blade. Figure 2.2 below shows the safe and unsafe zones around a wind turbine (Carbone and Afferrante 2013).



The external circle has a radius of 200 m and the radial distance between the two contiguous circles is 20 m. White areas are the safe regions.

FIGURE 2.2
Map of Impact Risk per Unit Area for a Detached Blade

Loren D. Knopper and Christopher A. Ollson reviewed the literature on the health effects of wind turbines and compared the peer-reviewed and popular literature. They searched for literature from the Thomas Reuters Web of Knowledge and Google. They concluded that the peer-reviewed differed from the popular literature in some ways. The reviewers found that the peer-reviewed studies the turbine annoyance was attributed to turbine noise, but were, in fact, strongly related to visual impact, attitude towards turbines and noise. The peer-reviewed articles only report health effects due to environmental stress that lead to annoyed/stressed state and does not demonstrate a link between physiological health effects of the people living close to the turbines and noise they emit. While on the other hand, they observed in popular literature that the health effects are related to the distances from the turbines. In conclusion, they observed that both type of studies had a common conclusion that being that the noise from turbine leads to annoyance to some people. They concluded that the change in the environment cause health effects and not the turbine specific variables like audible noise (Knopper and Ollson 2011).

2.6 Conclusion of the Literature Search

There is a need for more detailed information on the impact of the turbulence resulting from wind farms on a general aviation airport. The wind turbulence from a single wind turbine was simulated in the project and the methodology is presented in the next chapter of this report.

Chapter 3: Wind Turbine Wake Hazard Analysis

The potential hazard caused by wind turbine vortex wakes can be viewed as two different types: the induced roll hazard on the aircraft and the gusty crosswind from the vortex. Therefore, the wind turbine wake hazard is analyzed based on two criteria: *the roll hazard criterion and the crosswind hazard criterion*.

In the following analysis, we investigated two cases, the Rooks County Regional Airport and the Pratt Regional Airport. In each case, the potential roll and crosswind hazard range caused by the proposed nearby wind farm were studied.

The case study conditions are assumed as (www.aweo.org/windmodels):

- Wind turbine center height: h = 400 ft
- Turbine blade diameter: D = 300 ft
- Typical GA airplane wing span: L = 30 ft
- Atmospheric wind speed range: v = 10mph-40mph

3.1 Simulation of the Roll Hazard Caused by Wind Turbine Wake Helical Vortex

Under the situation of the highest wind speed V = 40 mph (58.67 ft/s), the circulation of the wind turbine wake helical vortex is $\Gamma = 5006.3$ (ft^2/s), which is calculated based on the model in Appendix A. Using this circulation value, a single turbine wake helical vortex was simulated. Figure 3.1 shows the simulated turbine wake helical vortex. The mathematical model is presented in Appendix B. The color represents the velocity magnitude.

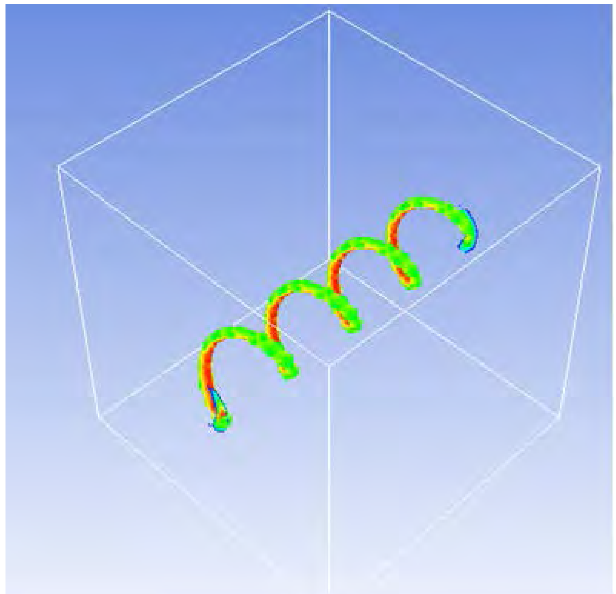


FIGURE 3.1
Wind Turbine Helical Vortex Model Used in the Case Analysis (with Color Representing the Velocity Magnitude)

Using the velocity field, the rolling moment coefficient acting on an airplane could be calculated (Appendix C). The hazard index range for the wind turbine induced rolling moment coefficient was defined as:

- Above an induced rolling moment coefficient of 0.28: high hazard
- Between 0.1 to 0.28: medium hazard
- And below 0.1: low hazard.

Please refer to the Appendix D to see how to determine these values.

3.2 The Rooks County Case

Figure 3.2 shows the aerial image and a sketch of the Rooks County Regional Airport. Runway 18-36 is the only existing runway in the center of the airport.

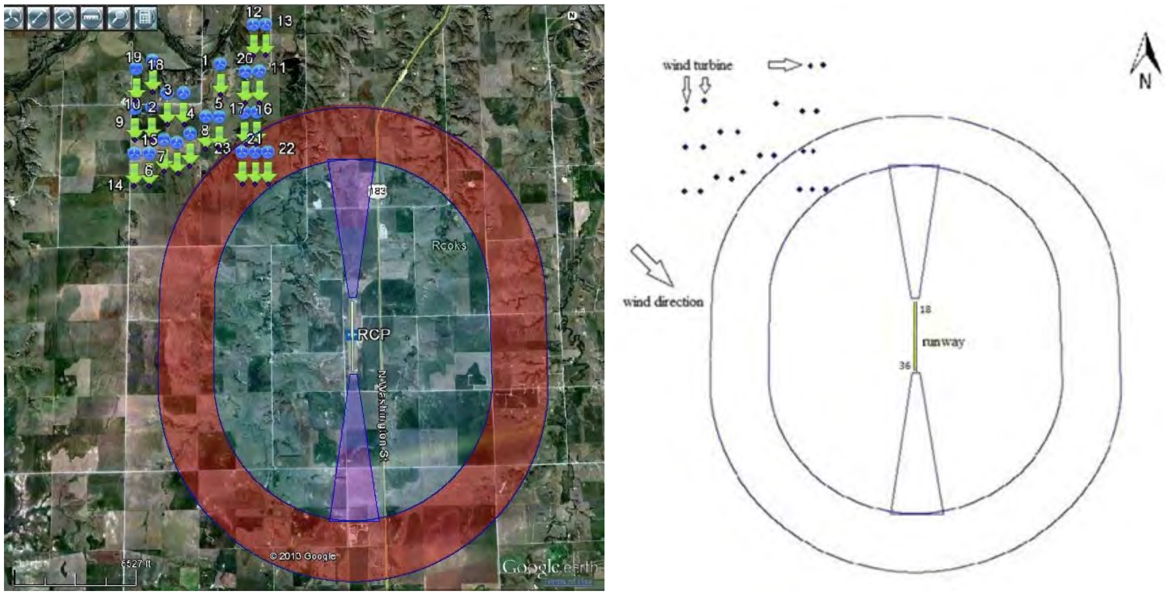


FIGURE 3.2
Rooks County Regional Airport and Wind Farm with a Scenario of a Northwest Wind

3.2.1 The Roll Hazard Analysis

Based on this decay distribution in Appendix E, the induced rolling momentum coefficient due to the wind turbine wake on the encountering aircraft, and the hazard index near the runway, can be calculated. The contours for Runway 18-36 under the 40 mph (which is assumed to be the highest possible safe wind speed under which wind turbines can operate) wind speed condition are shown in Figure 3.3. The rhombus area in Figure 3.3a is a cross section of the area where the helical vortex exists (between two red lines) and the area near the runway from south to north (between the two green lines). Figure 3.3b shows the exact rolling moment value in the area and Figure 3.3b shows the hazard index. As Figure 3.3b shows, the area around the runway is within the high hazard region (determined in 3.1).

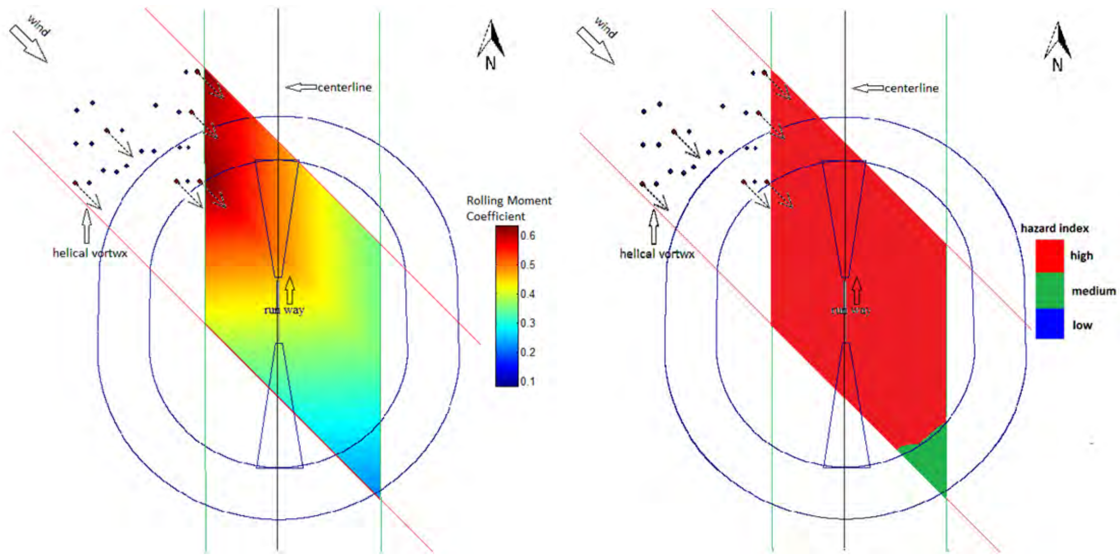


FIGURE 3.3
(a) Rolling Moment Coefficient and (b) Hazard Index around the Rooks County Regional Airport

Figure 3.4 is a plot of the end of Runway 18 and its approach surface from the airport layout plan drawing provided by the Kansas Department of Transportation. There are two approach surfaces: one is 20:1 approach surface and the other is 34:1 approach surface.

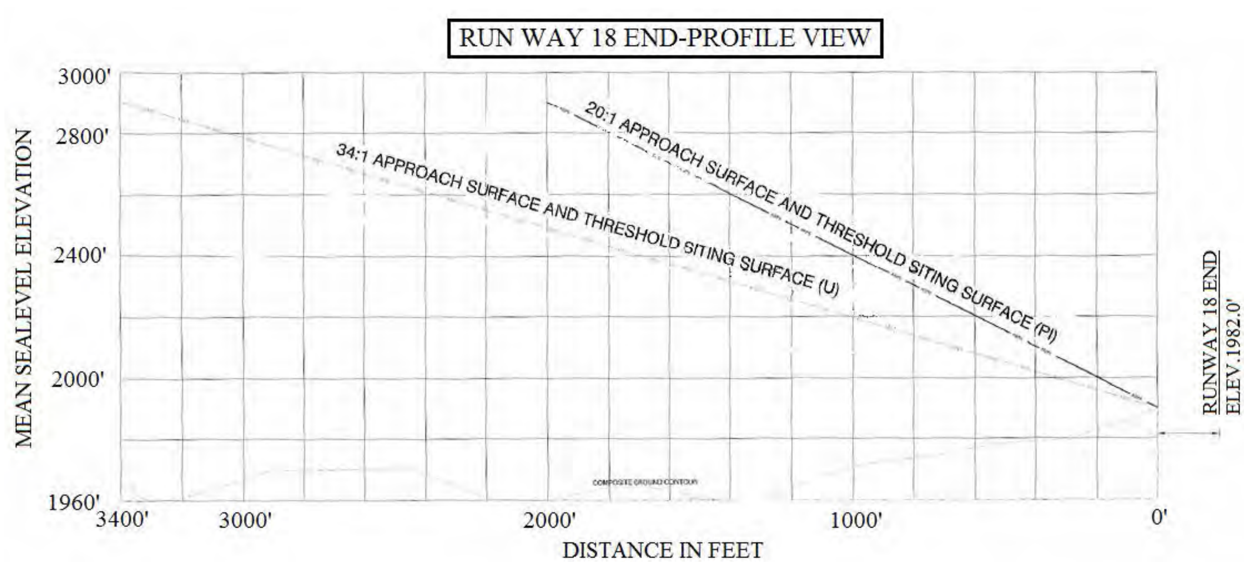


FIGURE 3.4
Approach Surface of Runway 18 in the Airport Layout Plan Drawing

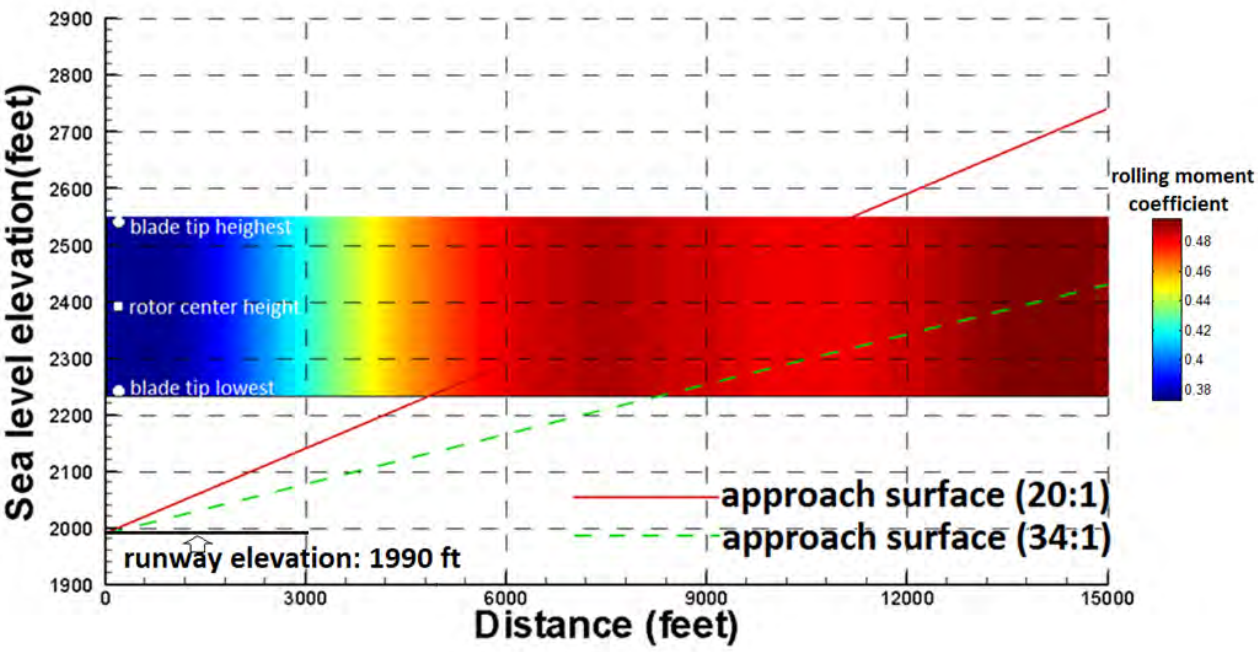


FIGURE 3.5
Rolling Moment Distribution along the Approach Aurface of Runway 18 (All in the High Hazard Index Range)

The approach surface portion in the above plot is about 100 ft. Since the turbine tower center is 400-foot high, we extended the plot following the trend and put the contours of the rolling moment coefficient in Figure 3.5 for the elevation between 2240 ft (the lowest blade tip elevation) and 2540 ft (the highest blade tip elevation). The rolling moment coefficient along this runway and the extended trend up to 15000 ft distance is always in the high hazard range. But for the approach surfaces, only within the height between two tips the airplane will experience the high hazard.

3.2.2 The Crosswind Hazard Analysis

Under the situation of the highest wind speed v = 40 mph (58.67 ft/s), the circulation of the wind turbine wake helical vortex is Γ = 5006.3 (ft^2/s). Using this circulation value, we simulated a single turbine wake helical vortex, as Figure 3.1 shows. In aviation, a crosswind is the component of wind that is blowing across the runway making landings and take-offs more difficult. Because the helical vortex can also enhance the crosswind, we need to assess the crosswind hazard in the area around the runway.

Figure 3.6 shows the aerial image and a sketch of the Rooks County Regional Airport. The wind direction is northwest. So as a component of it, the crosswind direction to Runway 18-36 is from west to east.

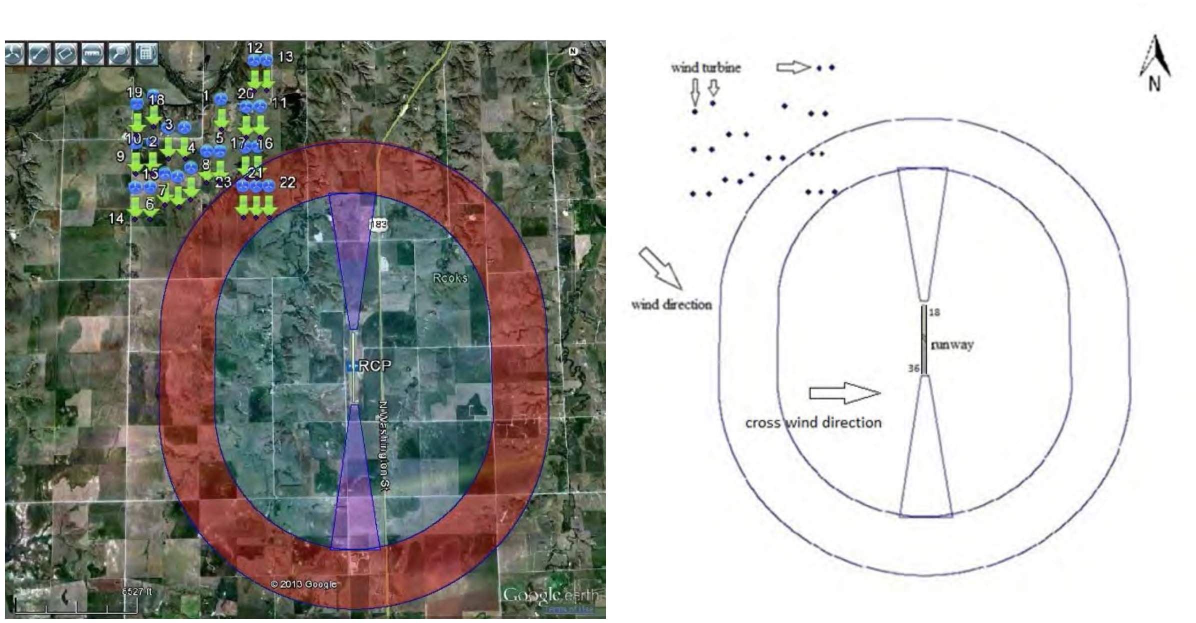
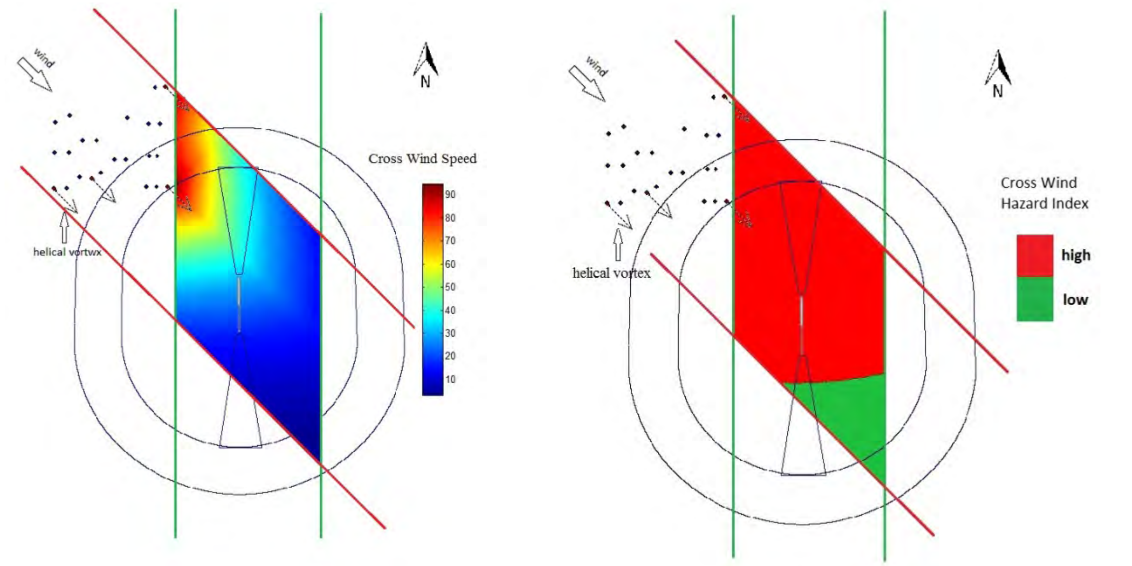


FIGURE 3.6
Wind Farm with a Northwest Wind

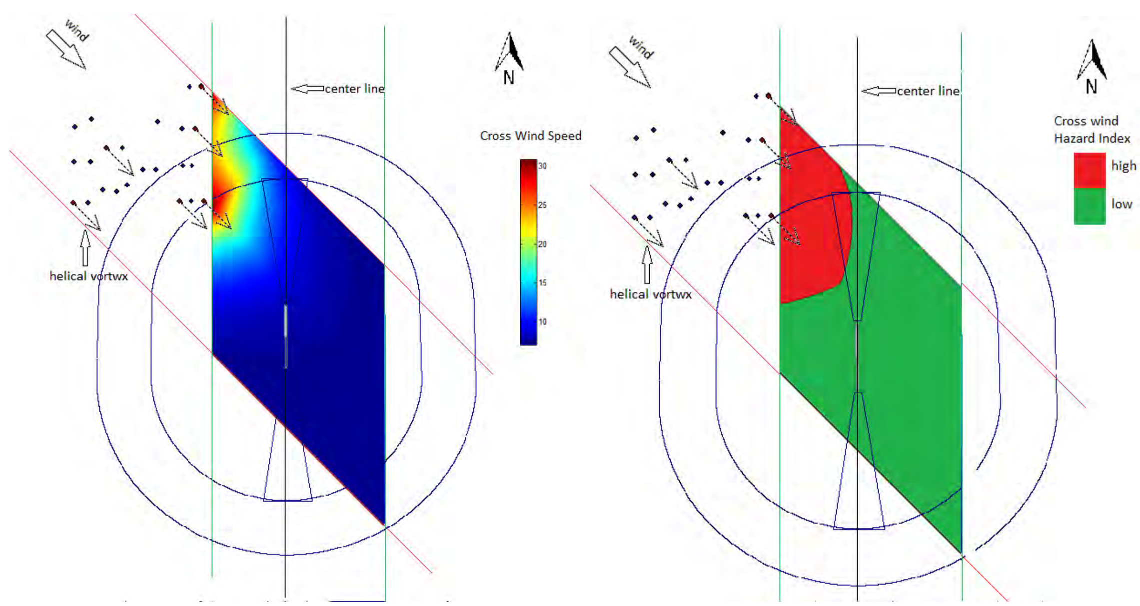
Based on the same decay distribution in Appendix E, the crosswind speed and the hazard index near the runway can be calculated (see Appendix F).

If there is a 40 mph gust, we only consider the crosswind induced by the helical vortex due to a gust-driven wind turbine wake. Any component of 40 mph gust itself is not included in the crosswind here. The contours for Runway 18-36 under the 40 mph (58.68 ft/s) gust wake are shown in Figures 3.7a and 3.7b. The rhombus area is a cross section of the area where the helical vortex exists (between the two red lines) and the area near the runway from south to north (between the two green lines). If we consider the crosswind above 12.1 mph (17.7 ft/s) as a high hazard, as shown in Table 2.1 from the literature, and below 12.1 as a low hazard, Figure 3.7b shows that a major portion of the runway is in the high hazard region.

The contours for Runway 18-36 under the 10 mph (14.67 ft/s) continuous wind speed condition, which is a mild wind condition, are shown in Figures 3.7c and 3.7d. Assuming that the 10 mph wind blows constantly, we calculated the summation of the crosswind induced by helical vortex and generated by the 10 mph wind itself. Figure 3.7d shows that a partial area around the runway is within the high hazard region.



(a) Turbine wake induced crosswind under 40 mph gust (b) Hazard index under 40 mph gust



(c) Crosswind speed under 10 mph wind (d) Hazard index under 10 mph wind

FIGURE 3.7
Crosswind Speed and Hazard around the Rooks County Regional Airport

3.3 The Pratt Regional Airport Case

Figure 3.8 shows the aerial image and a sketch map of the Pratt Regional Airport. Runway 17-35 is the only open runway.

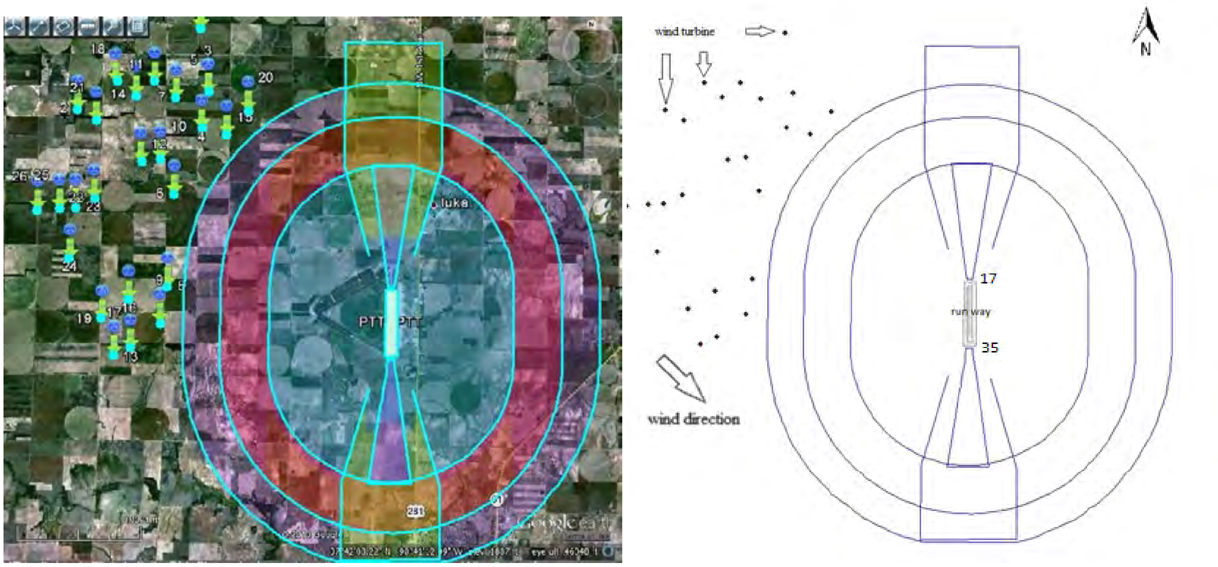


FIGURE 3.8
Pratt Regional Airport and Wind Farm with a Scenario of a Northwest Wind

3.3.1 The Roll Hazard Analysis

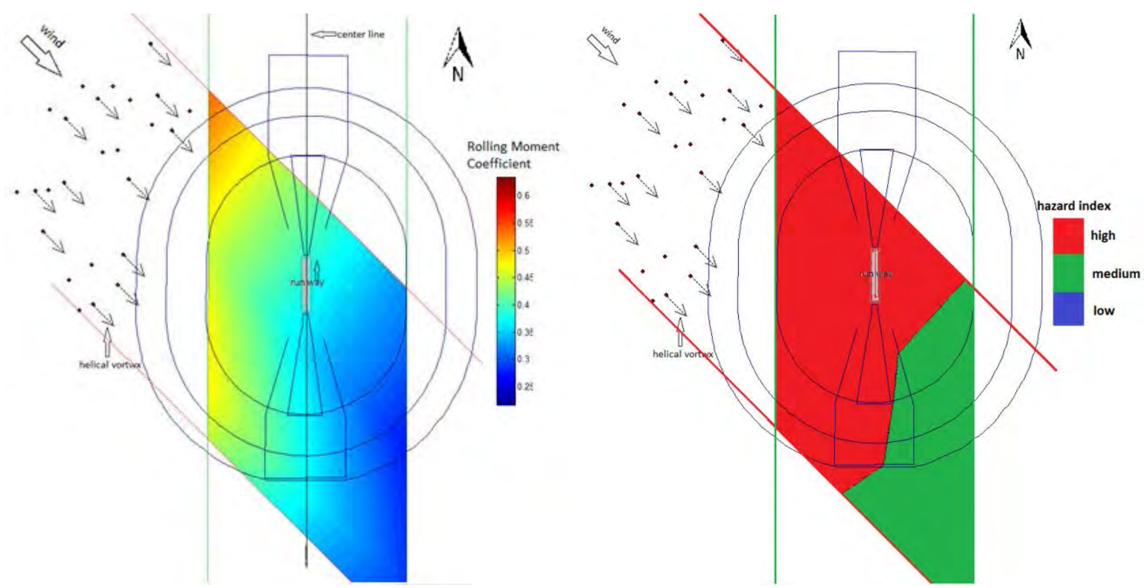


FIGURE 3.9
(a) Rolling Moment Coefficient and (b) Hazard Index around the Pratt Regional Airport

Based on this decay distribution in Appendix E, the rolling momentum coefficient can be calculated, and then the hazard index near the runway is determined. The contours for Runway 17-35 under the 40 mph wind speed condition are shown in Figure 3.9. Figure 3.9a shows the exact rolling moment value in the area, and Figure 3.9b shows the hazard index. As Figure 3.9b shows, the area around the runway is within the high hazard region.

Figure 3.10 is a plot of the end of Runway 17 and its approach surface from the airport layout plan drawing provided by KDOT. The approach surface is a 34:1 approach surface.

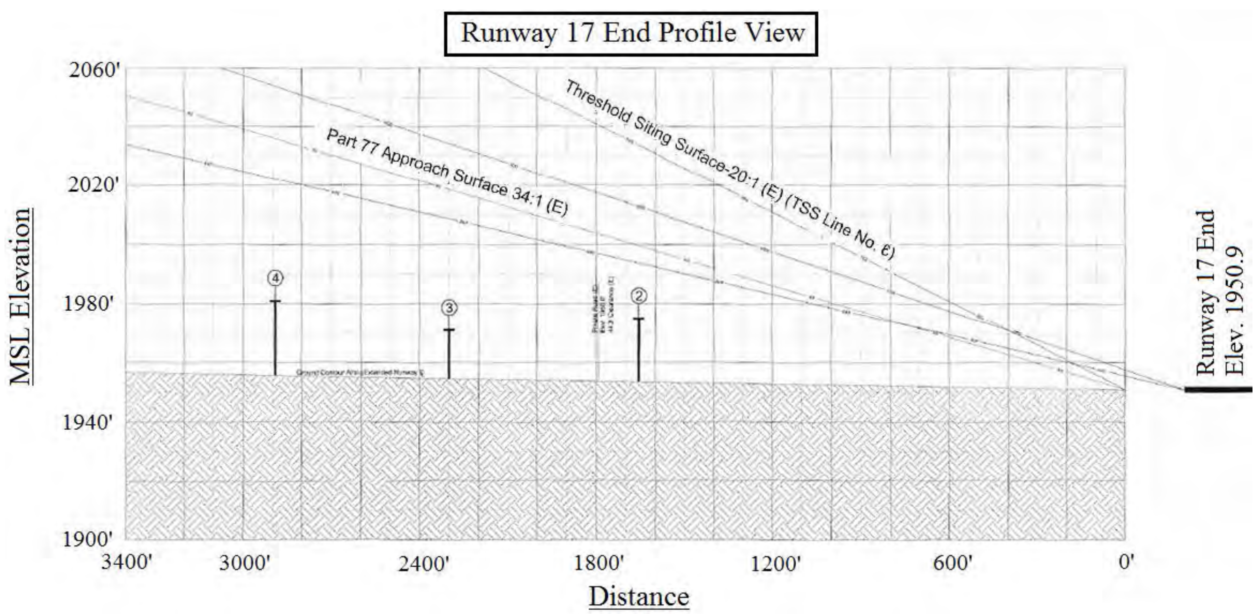


FIGURE 3.10
Approach Surface of Runway 17 in the Airport Layout Plan Drawing

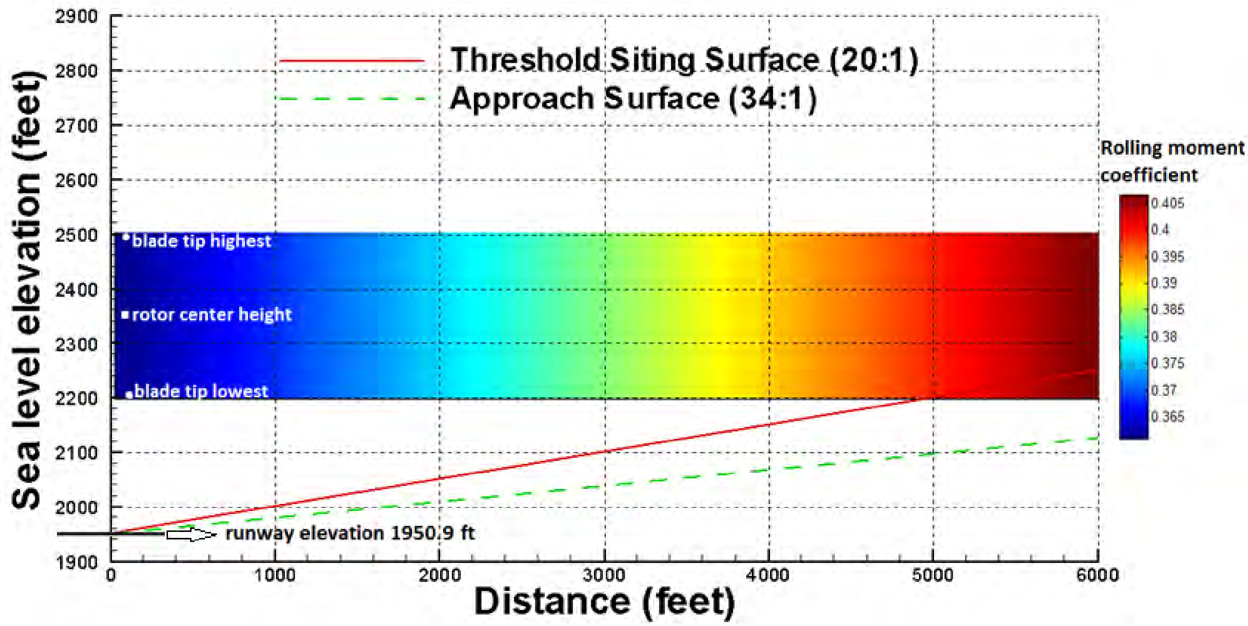


FIGURE 3.11
Rolling Moment Distribution along the Approach Surface of Runway 18 (All in the High Hazard Index Range)

We also extended the plot following the trend of the approaching surface and threshold siting surface and put the contours of rolling moment coefficient in Figure 3.11 for the elevation between 2200 ft and 2500 ft. The rolling moment coefficient along this runway and the extended trend up to 6000 ft (the limitation of the hazard area) distance is always in the high hazard range. The very end of the threshold site surface will experience the high hazard.

3.3.2 The Crosswind Hazard Analysis

Because the helical vortex can also enhance the crosswind acting on an airplane, we need to assess the crosswind hazard in the area around the runway in Pratt Regional Airport as well. Figure 3.12 shows the aerial image and a sketch map of Pratt Regional Airport. The crosswind direction to Runway 17-35 is from west to east.

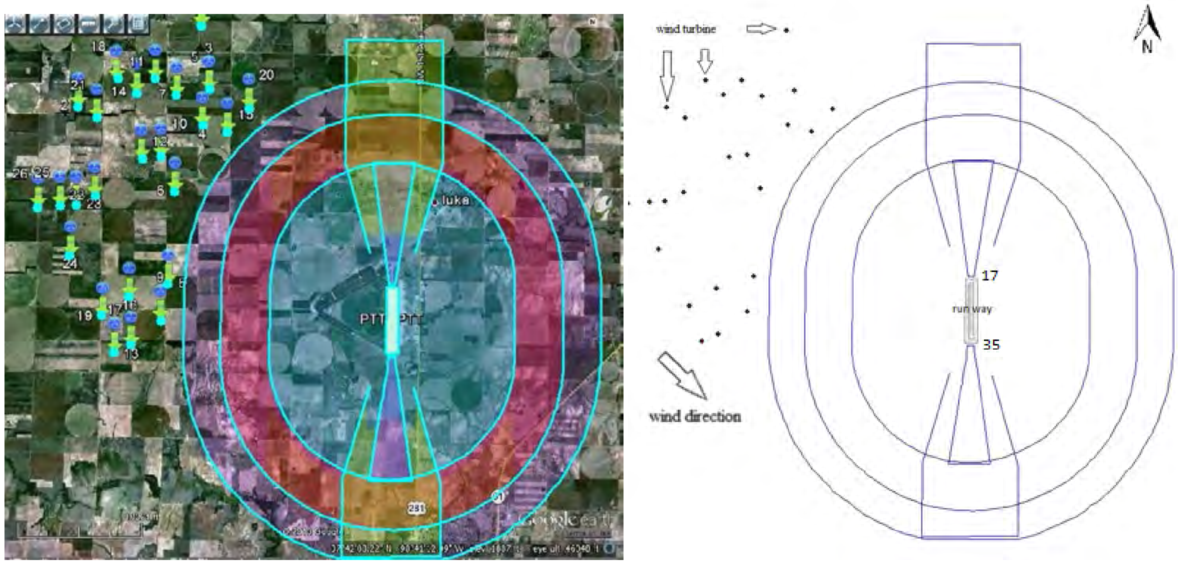
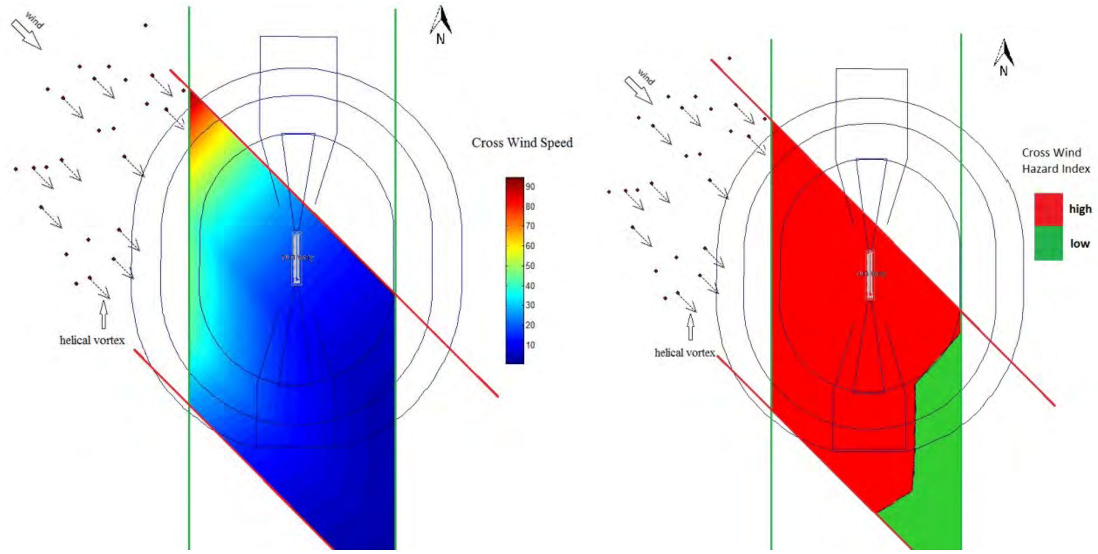


FIGURE 3.12
Pratt Regional Airport and Wind Farm with a Scenario of a Northwest Wind

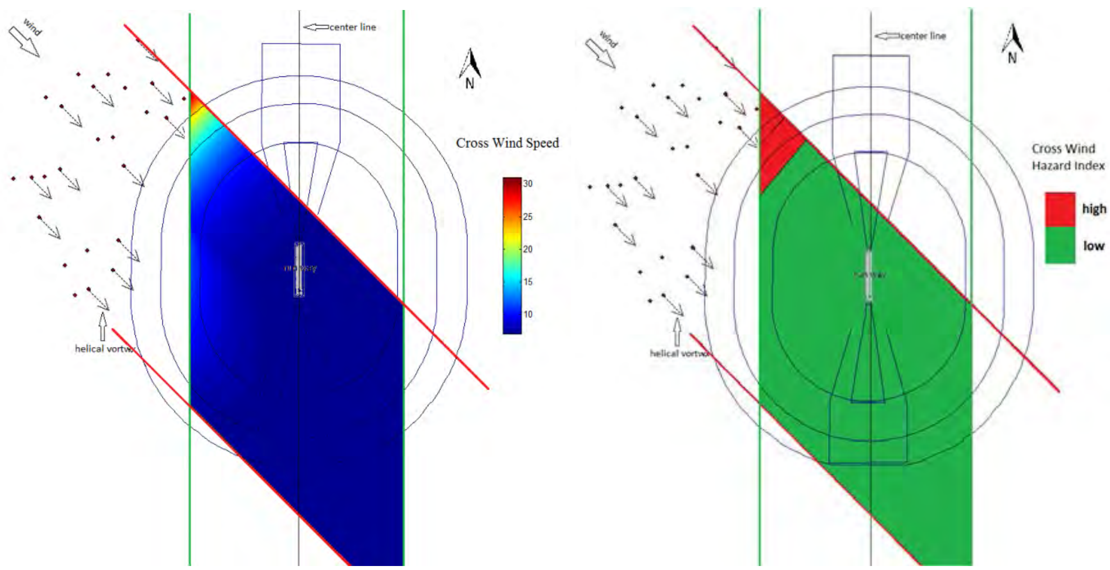
Based on the same decay distribution in Appendix E, the crosswind speed and the hazard index near the runway can be calculated (see Appendix F).

Again, the case was analyzed in two scenarios: one is the 40 mph gust, and the other is the 10 mph continuous wind. The contours of the crosswind and the corresponding hazard for the 17-35 runway under the 40 mph (58.68 ft/s) wind speed condition are shown in Figures 3.13a and 3.13b. The rhombus colorful area is a cross section of the area where the helical vortex exists (between the two red lines) and the area near the runway from south to north (between the two green lines). If we consider the crosswind above 12.1 mph (17.7 ft/s) as a high hazard, as shown in Table 2.1 from the literature, and below 12.1 as a low hazard, Figure 3.13b shows that the runway is in the high hazard region.

The contours for Runway 17-35 under the 10 mph (14.67 ft/s) continuous wind speed condition, which is a mild wind condition, are shown in Figures 3.7c and 3.7d. Figure 3.13d shows that only a very small area around the runway near the wind turbines is within the high hazard region.



(a) Turbine wake induced crosswind under 40 mph gust (b) Hazard index under 40 mph gust



(c) Crosswind speed under 10 mph wind (d) Hazard index under 10 mph wind

FIGURE 3.13
Crosswind Speed and Hazard around the Pratt Regional Airport

Chapter 4: Conclusions and Recommendations

The literature review shows that wind farms may have an adverse impact on general aviation, in general, and more specifically with aircraft operating at or near an airport. The impacts of wind turbines on aviation include physical penetration of airspace, communication systems interferences and rotor blade-induced turbulence.

The results of this project support the findings in the literature search that the turbulence from a wind turbine can impact operations at a general aviation airport. Two case studies were used to illustrate the impact of turbulence from a wind turbine on a general aviation airport. This project analyzed the roll hazard and the crosswind hazard resulting from a wind farm located near a general aviation airport. The wind turbine wake model is based on a theoretical helical vortex model and the decay rate is calculated following the aircraft wake decay rate in the atmosphere.

The roll hazard analysis showed that for the Rooks County Regional Airport, the potential roll hazard index is in the high range as far out as 2.84 miles. For the Pratt Regional Airport, the roll hazard index is in the high range as far out as 1.14 miles. These numbers are based on a gust wind of 40 mph that is below the turbine brake wind speed of 55 mph. As the results show, the scenario is different according to the relative locations and orientations of the airport and the nearby wind farm. Therefore, the analysis has to be performed for each specific regional airport.

The crosswind hazard analysis for the Rooks County Regional Airport showed part of the airport in the high range even under the mild wind condition at 10 mph. The wind turbine wake increases the crosswind component to more than 12 mph which is considered high risk crosswind for small general aviation aircraft. For the Pratt Regional Airport, the crosswind hazard is relatively small under the mild wind condition (10 mph). When there is a gust of 40 mph wind, the turbine wake induced crosswind puts the majority of runway areas to high hazard areas at both of the airports.

It is recommended that additional studies should be performed to draw the proper correlation between the hazard index developed in this study and the safe operation of aircraft at low airspeeds and at low flight altitudes operating near or at a general aviation airport.

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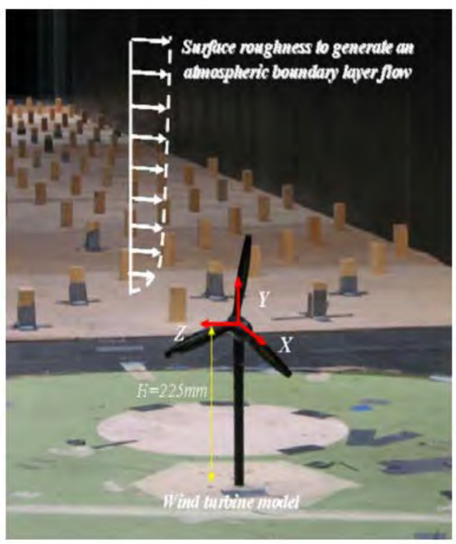
www.aweo.org/windmodels

Appendix A: Wind Turbine Wake Vortex Circulation

The experimental study referenced in this report was conducted in an aerodynamic/atmospheric boundary layer (AABL) wind tunnel located at Iowa State University as shown in Figure A.1 (Yang et al. 2012). This experiment was to simulate a radius of 45 m wind turbine using a 1:350 scale down small turbine. During the experiments, the wind speed at the hub height was set to be 4.0 m/s (i.e., U_0=4.0 m/s). The corresponding chord Reynolds number (i.e., based on the averaged chord length of the rotor blades and the wind speed at hub height) would be about 6,000, which is significantly lower than those of real wind turbines. The chord Reynolds number would have significant effects on the characteristics of wind turbine performance. However, the fundamental behavior of the helical tip vortices and turbulent wake flow structures at the downstream of wind turbines would be almost independent to the chord Reynolds number. The wind turbines with similar tip-speed-ratio (TSR) would produce similar near wake characteristics such as helical shape, rotation and tip vortices.



(Source: Yang, et al. 2012)

FIGURE A.1
Model of a Turbine in a Wind Tunnel Experiment

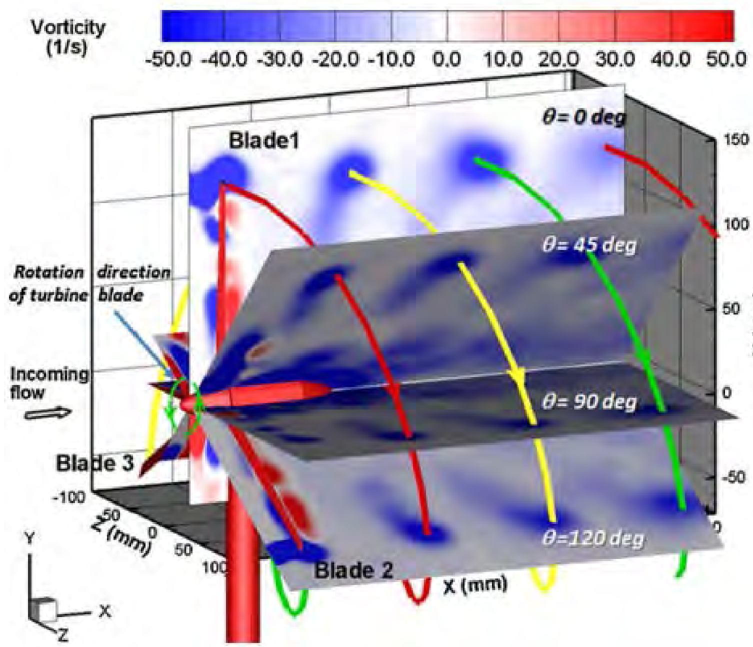
It is therefore reasonable using the data in Yang at el. (2012) to scale up the rotation based on the incoming wind speed and the dimension of the large wind turbine.

In that paper, V_0 = 4 m/s and the rotor diameter is 0.254 m and the vorticity and velocity result is shown in Figure A.2. Using the maximum of the velocity value and the area of vortex the circulation can be calculated:

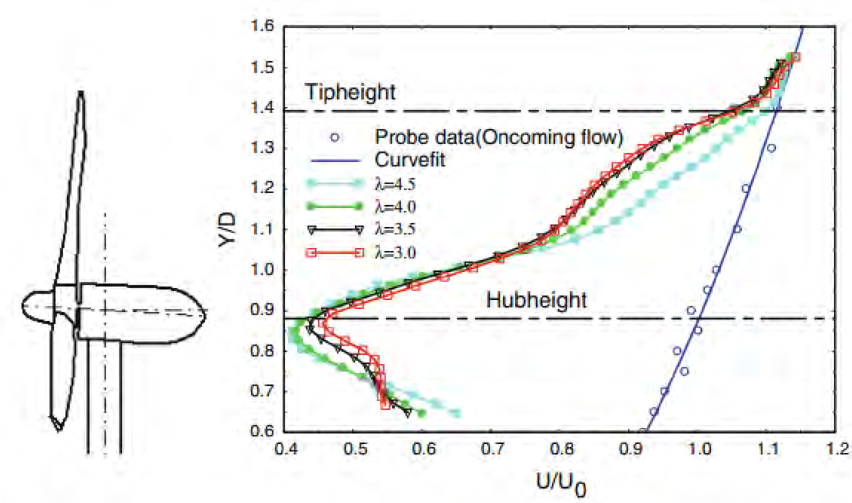
$$\Gamma = 2\pi rv = 2\pi \times 0.01\text{m} \times (4(\text{m/s}) * 1.15) = 0.289\ \text{m}^2/\text{s}$$

We thus can calculate the circulation in our case as:

$$\Gamma = 0.289(\frac{\text{m}^2}{\text{s}}) \times \left(\frac{17.88(\frac{\text{m}}{\text{s}})}{4\left(\frac{\text{m}}{\text{s}}\right)}\right) \times \left(\frac{91.44\text{m}}{0.254\text{m}}\right) = 465.1\frac{\text{m}^2}{\text{s}} = 5006.3\frac{ft^2}{s}$$



(a) Vorticity result



(b) Velocity result

(Source: Yang et al. 2012)

FIGURE A.2
Vorticity and Velocity Distribution

Appendix B: Helical Vortex Model for Wind Turbine Vortex Wake

Wind turbine wakes are modeled by helical vortices (Hardin 1982). In a Cartesian coordinate, when the radius is less than the helical radius ($r < R_{helical}$):

$$u_r = \frac{\Gamma_{helical} R_{helical}}{\pi k^2} S_2$$
$$u_\phi = \frac{\Gamma_{helical} R_{helical}}{r \pi k} S_1$$
$$w = \frac{\Gamma_{helical}}{2\pi k} - \frac{\Gamma_{helical} R_{helical}}{\pi k^2} S_1$$

where $\Gamma_{helical}$ is the circulation of the vortex filament, $R_{helical}$ is the radius of the helical vortex, and:

$$S_1(r,\phi) = \sum_{m=1}^{\infty} mK'_m\left(\frac{R_{helical} m}{k}\right) I_m\left(\frac{rm}{k}\right)\cos(m\psi)$$
$$S_2(r,\phi) = \sum_{m=1}^{\infty} mK'_m\left(\frac{R_{helical} m}{k}\right) I'_m\left(\frac{rm}{k}\right)\sin(m\psi)$$

$$\psi = \phi - z/k$$

where K'_m and I_m are modified Bessel functions of the *m*th order.

When the radius is greater than the helical radius ($r > R_{helical}$):

$$u_r = \frac{\Gamma_{helical} R_{helical}}{\pi k^2} S_4$$
$$u_\phi = \frac{\Gamma_{helical}}{2\pi r} + \frac{\Gamma_{helical} R_{helical}}{r \pi k} S_3$$
$$w = -\frac{\Gamma_{helical} R_{helical}}{\pi k^2} S_3$$

where:

$$S_3(r,\phi) = \sum_{m=1}^{\infty} mK_m\left(\frac{rm}{k}\right) I'_m\left(\frac{R_{helical} m}{k}\right)\cos(m\psi)$$
$$S_4(r,\phi) = \sum_{m=1}^{\infty} mK'_m\left(\frac{rm}{k}\right) I'_m\left(\frac{R_{helical} m}{k}\right)\sin(m\psi)$$

Appendix C: Rolling Moment Coefficient Calculation

Since we have the wind turbine wake velocity field from the helical vortex model, we can calculate the induced rolling moment coefficient on an aircraft that flies through the wake (Zheng and Xu 2008). Considering the aircraft with a wing span of $2s_F$ and flying speed W_F, we have, for the lift force acting on a spanwise element section dx_F:

$$\rho W_F \Gamma_F(x_F) dx_F = \frac{1}{2} \rho {W_F}^2 C_{LF}(x_F)\, dx_F \cdot c_F(x_F) \qquad \text{Equation C.1}$$

where Γ_F is the circulation, C_{LF} is the lift coefficient, and $c_F(x_F)$ is the chord length of the aircraft at x_F. Assuming that $\partial C_{LF}/\partial \alpha$ is approximately constant in the range of angle of attack α, we have:

$$\Gamma_F(x_F) = \frac{\frac{1}{2} W_F \Delta\alpha \cdot \partial C_{LF}}{\partial \alpha} \; c_F(x_F) \qquad \text{Equation C.2}$$

Since

$$\Delta\alpha \approx \frac{\nu}{W_F} \qquad \text{Equation C.3}$$

where ν is the vertical velocity component at the location of the wing (produced by the wake vortex system). We have

$$\Gamma_F(x_F) = \frac{1}{2} \upsilon(x_F) \frac{\partial C_{LF}}{\partial \alpha} \; c_F(x_F) \qquad \text{Equation C.4}$$

The rolling moment on the wing can then be expressed by:

$$M_{RF} = \int_{-s_F}^{s_F} \rho W_F \Gamma_F(x_F) x_F dx_F = \frac{1}{2}\rho W_F \frac{\partial C_{LF}}{\partial \alpha} \int_{-s_F}^{s_F} \upsilon(x_F)\, c_F(x_F)\, x_F dx_F \quad \text{Equation C.5}$$

And the rolling moment coefficient is:

$$C_{RF} = \frac{M_{RF}}{\frac{1}{2}\rho {W_F}^2 S_F \cdot 2s_F} = \frac{\partial C_{LF}}{\partial \alpha} \cdot \frac{1}{2S_F \cdot 2s_F} \int_{-s_F}^{s_F} \upsilon(x_F)\, c_F(x_F) x_F dx_F \quad \text{Equation C.6}$$

where S_F is the plan form area and is defined as

$$S_F = 2 s_F \bar{c}_F \quad \text{Equation C.7}$$

with $\bar{c}_F$ equal to the average chord length of the wing.

Using a Fourier series, we define

$$\Gamma_F(\theta) = 4 s_F W_F [\frac{P_0}{2} + \sum_1^N (P_0 cos2n\theta + Q_n sin2n\theta)] \quad \text{Equation C.8}$$

where θ is used to replace the spanwise coordinate of the airplane wing x_F, defined as:

$$cos\theta = -x_F/s_F. \ -1 \le x_F/s_F \le 1 \ for\ 0 \le \theta \le \pi \quad \text{Equation C.9}$$

Then from the first part of Equation C.6, the rolling moment coefficient can be expressed as

$$C_{RF} = \frac{4{s_F}^2}{S_F} \int_0^{\pi} [\frac{P_0}{2} + \sum_1^N (P_n cos2n\theta + Q_n sin2n\theta)]\, (-cos\,\theta)(-sin\theta) d\theta$$

$$= \pi/4\ (AR)_F Q_1 \quad \text{Equation C.10}$$

where $(\mathrm{AR})_F$ is the aspect ratio of the wing. Now with Equations C.4 and C.8, we have

$$\frac{\boldsymbol{v}(\boldsymbol{x_F})}{\boldsymbol{W_F}} = \frac{\mathbf{2\Gamma_F}(\boldsymbol{x_F})}{\boldsymbol{W_F}\frac{\partial \mathbf{C_{LF}}}{\partial \boldsymbol{\alpha}}\,\boldsymbol{c_F}(\boldsymbol{x_F})} = \frac{\mathbf{4}\,(\boldsymbol{AR})_{\boldsymbol{F}}}{\frac{\partial \mathbf{C_{LF}}}{\partial \boldsymbol{\alpha}}\frac{\boldsymbol{c_F}(6)}{\bar{\boldsymbol{c}}_{\boldsymbol{F}}}}\left[\frac{\boldsymbol{P_0}}{\mathbf{2}} + \sum_{1}^{N}(\boldsymbol{P_n cos2n\theta} + \boldsymbol{Q_n sin2n\theta})\right]$$

$$= \left[\frac{\boldsymbol{A_0}}{\mathbf{2}} + \sum_{1}^{N}(\boldsymbol{A_n cos2n\theta} + \boldsymbol{B_n sin2n\theta})\right]\frac{\bar{\boldsymbol{c}}_{\boldsymbol{F}}}{\boldsymbol{c_F}(\boldsymbol{\theta})}$$ **Equation C.11**

for

$$\boldsymbol{A_n} = \frac{\mathbf{4}\,(\boldsymbol{AR})_{\boldsymbol{F}}}{\frac{\partial \mathbf{C_{LF}}}{\partial \boldsymbol{\alpha}}}\boldsymbol{P_n}$$ **Equation C.12**

and

$$\boldsymbol{B_n} = \frac{\mathbf{4}\,(\boldsymbol{AR})_{\boldsymbol{F}}}{\frac{\partial \mathbf{C_{LF}}}{\partial \boldsymbol{\alpha}}}\boldsymbol{Q_n}$$ **Equation C.13**

Hence, with Equation C.10

$$\boldsymbol{C_{RF}} = \frac{\boldsymbol{\pi}}{\mathbf{16}}\frac{\partial \mathbf{C_{LF}}}{\partial \boldsymbol{\alpha}}\boldsymbol{B_1}$$ **Equation C.14**

From Equation C.11 we can see that

$$\frac{\boldsymbol{A_0}}{\mathbf{2}} + \sum_{1}^{N}(\boldsymbol{A_n cos2n\theta} + \boldsymbol{B_n sin2n\theta}) = \frac{\boldsymbol{v}(\boldsymbol{\theta})\,\boldsymbol{c_F}(\boldsymbol{\theta})}{\boldsymbol{W_F}\bar{\boldsymbol{c}}_{\boldsymbol{F}}}$$ **Equation C.15**

That is, if we perform a Fourier series expansion on $\frac{v(\theta)\, c_F(\theta)}{W_F \bar{c}_F}$, only the first coefficient of the sine series of that series is needed to calculate the rolling moment coefficient.

If we let

$$\boldsymbol{F(\theta) = \frac{v(\theta)\, c_F(\theta)}{W_F \bar{c}_F}} \qquad \textbf{Equation C.16}$$

then

$$\boldsymbol{C_{RF} = \frac{\pi}{16} \frac{\partial C_{LF}}{\partial \alpha} \frac{\pi}{2} \int_0^{\pi} F(\theta) \sin(2\theta) d\theta} \qquad \textbf{Equation C.17}$$

where C_{LF} is the lift coefficient, α is the angle of attack. In our case, $\frac{\partial C_{LF}}{\partial \alpha}$ equals to 0.075/degree, 4.2972 /rad. In addition, θ can be determined by x_F, the position of each section, and s_F the length of the wing. $\cos(\theta) = -\frac{x_F}{s_F}$

where $v(\theta)$ is the vertical velocity, $c_F(\theta)$ is the chord length, $\overline{c_F}$ is the average chord length, W_F is the flying speed, for our case, its 80 m/s. And

$$\frac{c_F(\theta)}{\overline{c_F}} = \frac{20}{13}(1 - 0.7\,|\frac{x_F}{s_F}|) = \frac{20}{13}(1 - 0.7\,|\cos(\theta)|) \qquad \textbf{Equation C.18}$$

Appendix D: Roll Hazard Index

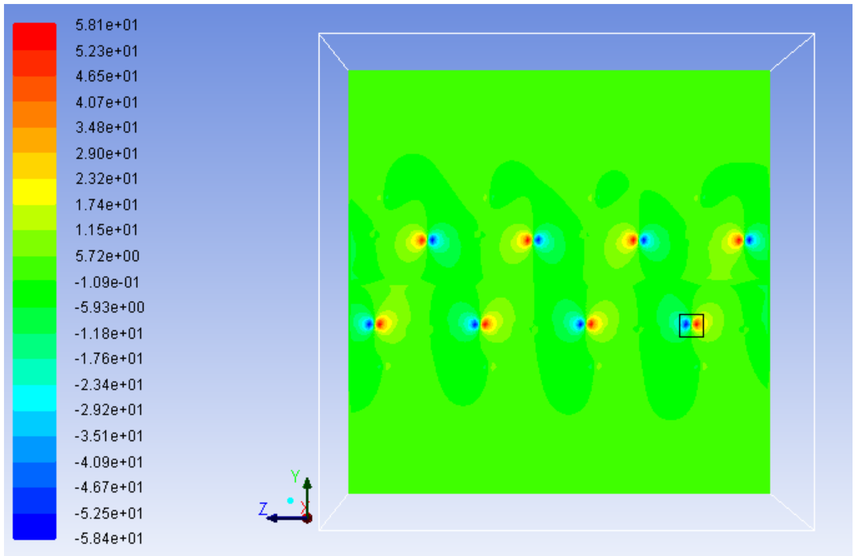


FIGURE D.1
Y-Direction Velocity on the Center X-Z Cutting Plane

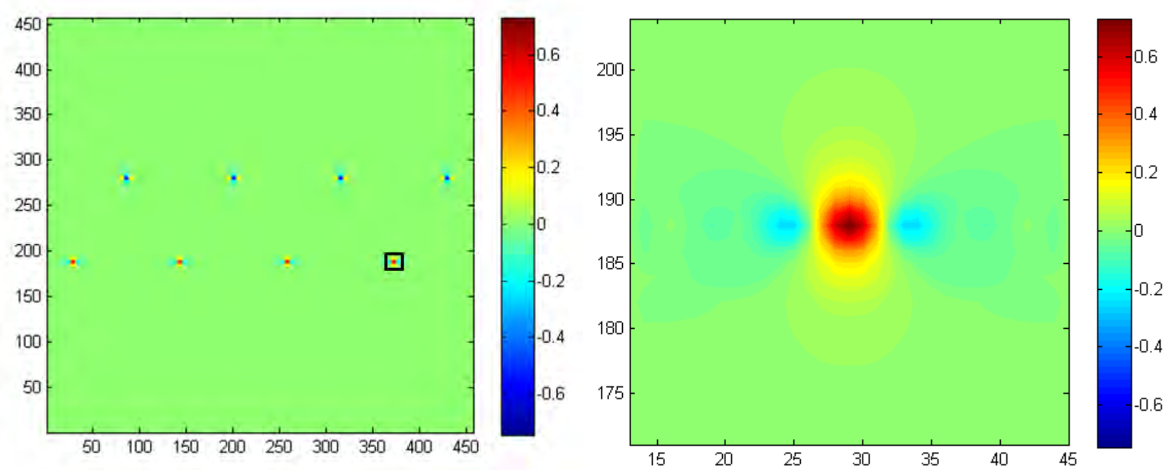


FIGURE D.2
(a) The Rolling Momentum Coefficient in the Domain and (b) in the Zoom-In Domain

In order to evaluate the roll hazard caused by the wind turbine wake, the induced rolling moment coefficient on a wake-penetrating aircraft is calculated based on the vertical component velocity distribution. Figure D.1 shows the y-direction velocity on a cutting plane. With the y-direction velocity, we can calculate the rolling moment coefficient using the relations developed in Appendix C. Figure D.2a is the resultant rolling momentum coefficient acting on a 30-ft wingspan airplane when it is passing through the turbine wake region. The highest rolling momentum coefficient occurs at the center of the helical vortex core, which can be seen in Figure D.2b in a zoom-in region.

The relative magnitude between the operable rolling moment and the rolling moment induced by the wind turbine wake is used in this study to determine the hazard index.

The rolling moment coefficient that the airplane is able to operate is modeled by this formula:

$$C_R = 2C_{l\delta_A}\delta_A;$$

For a normal airplane

$$0 < C_{l\delta_A} < 0.4$$

$$0 < \delta_A < 20°$$

So at the maximum:

$$C_R = 2C_{l\delta_A}\delta_A = 2 \times 0.4 \times \frac{20}{180} \times \pi = 0.28$$

Appendix E: Rolling Moment Coefficient Decay with Distance

The local circulation Γ_i can be calculated by the initial circulation Γ_0 and vortex span b_0 after time *t* (Zheng et al. 2009):

$$\frac{\Gamma_i}{\Gamma_0} = \exp(-C\frac{t\Gamma_0}{2\pi b_0{}^2 T_c{}^*}) \qquad \text{Equation E.1}$$

where C is a constant of 0.45, and $T_c{}^*$ is determined by the following calculation:

$$\varepsilon^* = \frac{2\pi b_0}{\Gamma_0}(\varepsilon b_0)^{1/3} \qquad \text{Equation E.2}$$

For a high turbulence case at the turbulent intensity 10%, ε is 0.01 in our case, which indicates that ε^* has a high value and the eddy-dissipation rate in the entire range can be approximately related by this formula:

$$\varepsilon^*(T_c{}^*)^{4/3} = 0.7475 \qquad \text{Equation E.3}$$

So

$$T_c{}^* = (\frac{0.7475}{\varepsilon^*})^{3/4} = (\frac{0.7475\Gamma_0}{2\pi b_0(\varepsilon b_0)^{1/3}})^{3/4} \qquad \text{Equation E.4}$$

$$\frac{\Gamma_i}{\Gamma_0} = \exp\left(-C\frac{t\Gamma_0}{2\pi b_0{}^2\left(\frac{0.7475\Gamma_0}{2\pi b_0(\varepsilon b_0)^{\frac{1}{3}}}\right)^{\frac{3}{4}}}\right) = \exp\left(\frac{-Ct(\varepsilon\Gamma_0)^{1/4}}{0.956(\pi)^{1/4}b_0}\right) \qquad \text{Equation E.5}$$

At distance S with the wind speed V_0

$$t = \frac{S}{V_0}$$ **Equation E.6**

$$\frac{\Gamma_i}{\Gamma_0} = \exp\left(\frac{-CS(\varepsilon\Gamma_0)^{0.25}}{1.2727V_0 b_0}\right)$$ **Equation E.7**

For the 18-36 runway of Rooks County Regional Airport under the northwest wind situation, the maximum induced rolling moment coefficient on the 30-ft wingspan GA aircraft caused by a wind turbine is 0.65, when the wake is close to the wind turbine. The induced rolling moment coefficient decays with distance due to atmospheric turbulence, as shown in Figure E.1. At lower wind speeds, the induced rolling moment coefficient becomes lower, and when the distance from the wind turbine increases, the coefficient value becomes lower.

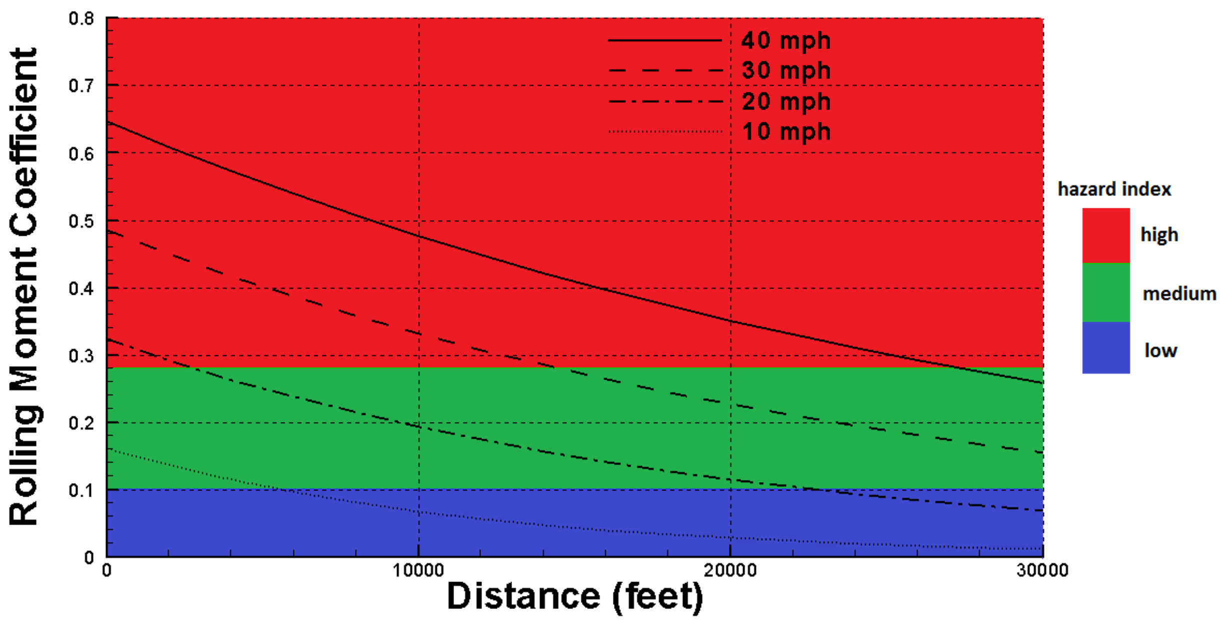


FIGURE E.1
Rolling Moment Coefficient Decay with Distance

For the 17-35 runway of Pratt Regional Airport under the northwest wind situation, the maximum induced rolling moment coefficient on the 30-ft wingspan GA aircraft caused by a wind turbine is 0.65, when the wake is close to the wind turbine. The induced rolling moment coefficient decays with distance due to atmospheric turbulence, as shown in Figure E.2. At lower wind speeds, the induced rolling moment coefficient becomes lower, and when the distance from the wind turbine increases, the coefficient value becomes lower.

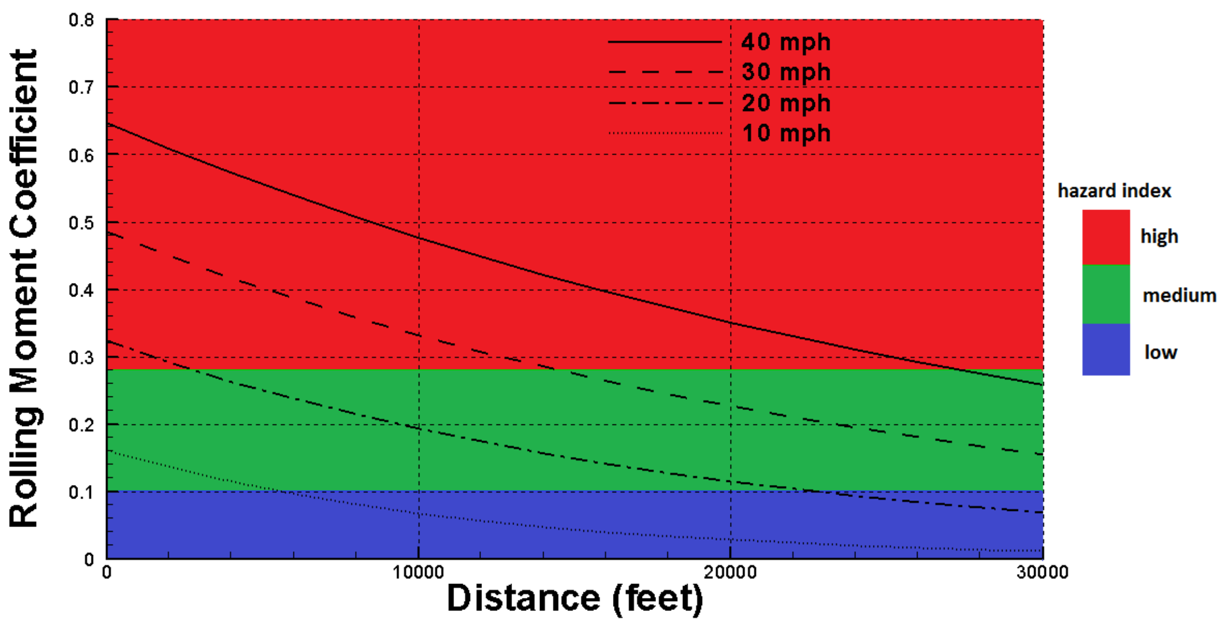


FIGURE E.2
Rolling Moment Coefficient Decay with Distance

Appendix F: Crosswind from Wind Turbine Wake on an Airplane

Figure F.1 shows the 45 degree direction velocity which is vertical to the aircraft body on a cutting plane parallel to the ground shown in Figure F.2. The maximum velocity from the turbine wake is 95.25 mph (139.7 ft/s).

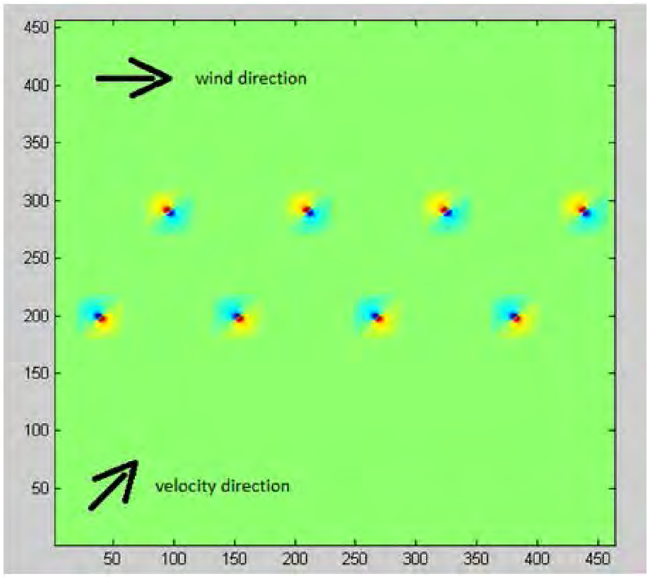


FIGURE F.1
45 Degree Direction Velocity Value from the Wind Turbine Wake on a Cutting Plane

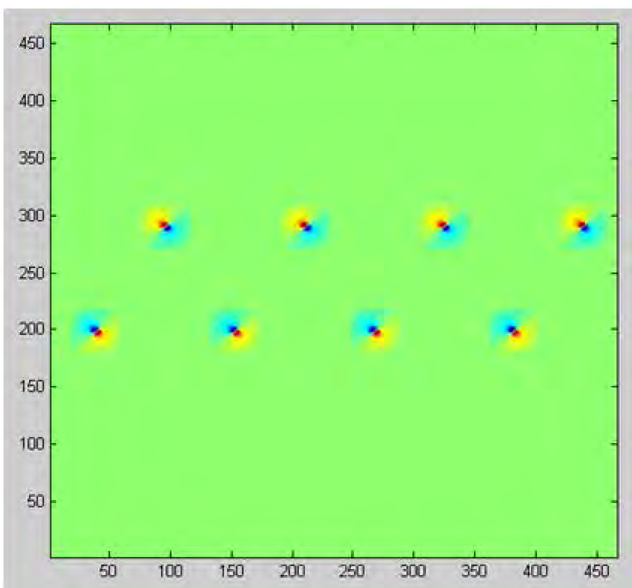


FIGURE F.2
45 Degree Direction Velocity Value Added by the Background Velocity

The value of background wind component on crosswind direction is the wind speed 40 mph multiplied by cosine 45 degree equal to 28.28 m ph ($40\ mph \times \frac{\sqrt{2}}{2} = 28.28\ mph = 41.48\ ft/s$). If we add this value to the velocity field in Figure F.1, it is what Figure F.2 shows. The maximum velocity is 123.53 mph (181.18 ft/s)

TABLE F.1
Possible Maximum Crosswind Velocity in the Wind Turbine Wake in Different Background Wind Speeds

Wind speed (mph)	40	30	20	10
Cross wind component (mph)	28.28	21.21	14.14	7.07
Max vortex induced cross wind (mph)	95.25	71.44	47.63	23.81
Max crosswind velocity (mph)	123.53	92.65	61.77	30.88

The limit, as shown in Table 2.1 in the literature, is 10.5 knot which is 12.1 mph (17.7 ft/s). Table F.1 lists the maximum crosswind velocity in different background wind speeds. If the wind is larger than 20 mph, the wind component at cross direction is already over the 12 mph limit. So we consider the 10 mph wind speed as an example to see the hazard in the airport.

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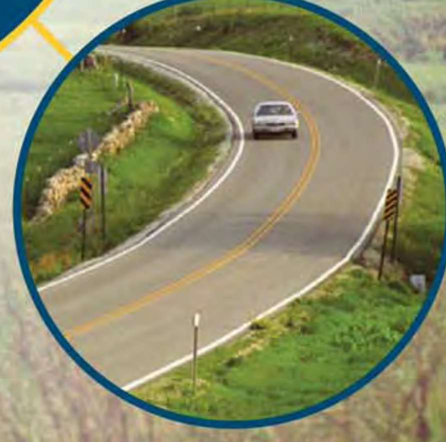

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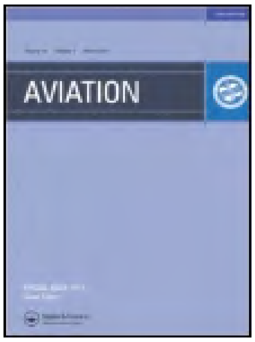

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WIND FARMS AND AVIATION

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Abstract. Wind is an increasingly important source of energy for the Slovak Republic. It is exploited by the use of turbines to generate electricity. Because of their physical size, in particular their height, wind farms can have an effect on aviation. Additionally, rotating wind turbine blades may have an impact on certain aviation operations, particularly those involving radar.

Keywords: wind farm, radar theory, air traffic management, communication navigation and surveillance.

1. Introduction

There are two types of radar used for air traffic control and air defence control and surveillance: primary surveillance radar (PSR) and secondary surveillance radar (SSR).

Primary radar operates by radiating electromagnetic energy and detecting the presence and character of the echo returned from reflecting objects. Comparison of the returned signal with that transmitted yields information about the target, such as location, size, and whether it is in motion relative to the radar.

Primary radar cannot differentiate between types of objects; its energy will bounce off any reflective surface in its path. Moreover, air traffic control primary radar has no means of determining the height of an object, whereas modern air defence radars do possess this capability, using electronic beam control techniques.

For SSR, the ground station emits "interrogation" pulses of radio frequency (RF) energy via the directional beam of a rotating antenna system. When the antenna beam is pointing in the direction of an aircraft, airborne equipment, known as a transponder, transmits a reply to the interrogation. The reply is detected by the ground station and processed by a plot extractor.

The plot extractor measures the range and bearing of the aircraft and decodes the replies of the aircraft to determine the aircraft's flight level and identity (Mode C operation).

In the Slovak Republic, all aircraft flying in controlled airspace must carry a SSR transponder. Some light aircraft do not, and aircraft that do carry them may not have them switched on, in which case they will not be visible to SSR. Most ATC units are equipped with both primary and SSR, but increasingly, radar services are provided using SSR only.

From 2008 onwards, a new type of SSR called *Mode S* will begin to be introduced in SR airspace. Mode S is a development of classical SSR that overcomes many of the current limitations of the SSR system. It is proposed, subject to formal consultation, to introduce Mode S initially in 2008 with a second phase of regulatory changes in 2008. In addition, it is proposed that the requirements for the carriage and operation of transponders will be significantly extended in conjunction with the Mode S plans for 2009.

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2. Radar functions

2.1 Air traffic control (ATC)

Radar performs two functions for air traffic control:

a) airport surveillance radar allows air traffic controllers to provide air traffic services to aircraft in the vicinity of an airport. This service may include vectoring aircraft to land, providing radar service to departing aircraft, or providing service to aircraft either transiting through the area or in the airfield circuit;

b) en route (or area) radar is used to provide services to traffic in transit. This includes commercial airliners and military traffic. Area radar has a longer range than airport radar, particularly at high altitudes.

2.2 Air defence

Air defence radar is used in two ways. On the one hand, it performs a function similar to its ATC counterparts, being used by air defence controllers to provide control services to military (usually air defence) traffic. It is, however, also used to monitor all air traffic activity within the Slovak Republic and its approaches to produce a recognised air picture (RAP) with the aim of preserving the integrity of SR airspace through air policing. The RAP is produced by allocating track identities to each radar return (or "plot") of interest. A radar plot can often fade from a radar display for a period of time due to a number of factors, but the track identity will remain, indicating that the associated plot is actually still present (Lewis 2001).

2.3 Meteorological radar

Meteorological radar uses electromagnetic (EM) energy to monitor weather conditions (predominantly cloud and precipitation) at low altitudes to assist weather forecasting. Wind profiling radar is used to measure wind speed at different altitudes.

3. The nature of the impact of wind turbines

Masking

This is the main anticipated effect on air defence surveillance radar. Such radar works at high radio frequencies and therefore depends on a clear "line of sight" to the target object for successful detection. It follows that any geographical feature or structure lying between the radar and the target will cause a shadowing or masking effect; military aircraft wishing to avoid detection readily exploits indeed this phenomenon. It is possible that, depending on their size, wind turbines may cause shadowing effects. Such effects may be expected to vary, depending upon the turbine dimensions, the type of transmitting radar, and the aspect of the turbine relative to it.

The Met Office is also concerned with the effect of masking on their sensors. Met Office radar looks at a relatively narrow altitude band that is as near to the earth's surface as possible. Due to the sensitivity of the radar, wind turbines, if they are poorly sited, have the potential to significantly reduce weather radar performance (Wind … 2001).

4. Radar returns/radar clutter

Radar returns may be received from any radar-reflective surface. In certain geographical areas, or under particular meteorological conditions, radar performance may be adversely affected by unwanted returns, which may mask those of interest. Such unwanted returns are known as radar clutter. Clutter is displayed to a controller as "interference" and is primarily a problem for air defence and airport radar operators because it occurs more often at lower altitudes.

For an airport radar operator, a wind turbine or turbines in the vicinity of his airfield can present operational problems. If the turbine generates a return on his radar screen and the controller recognises it as such, he may choose to ignore it. However, such unwanted returns may obscure others that genuinely represent aircraft, thereby creating a potential hazard to flight safety. This may be of particular concern in poor weather.

A structure, which permanently paints on the radar in the same position, is preferable to one that only presents an intermittent return. This is because an intermittent return is more likely to represent a manoeuvring or unknown aircraft, obliging the controller to act accordingly. With this in mind, it is possible that aviators and radar operators could work safely with one or perhaps two turbines in the vicinity of an aerodrome. Of greater concern is the prospect of a proliferation of turbines, which could potentially saturate an airfield radar picture, making safe flying operations difficult to guarantee.

Several turbines in close proximity to each other and painting on radar could present particular difficulties for long-range air surveillance radar. A rotating wind turbine is likely to appear on a radar display intermittently (studies suggest a working figure to be one paint every six sweeps).

Multiple turbines, in proximity to each other, will present several returns during every radar sweep, causing a "twinkling" effect. As these will appear at slightly different points in space, the radar system may interpret them as being one or more moving objects and a surveillance radar will then initiate a "track" on the returns. This can confuse the system and may eventually overload it with too many tracks. Measures can be taken to mitigate this problem, and they are amplified in Section D4, but these too have their drawbacks (Knill 2002).

5. "Scattering", "refraction" and/or "false returns"

Scattering occurs when the rotating wind turbine blades reflect or refract radar waves in the atmosphere. These are then subsequently absorbed either by the

source radar system or another system and can then give false information to that system. It may affect both primary and SSR radars. This effect is as yet not quantified but is certainly possible. It has, for example, been witnessed at Copenhagen Airport as a result of the Middelgrunden Offshore Wind Farm.
The possible effects are:

a) multiple, false radar returns being displayed to the radar operator: blade reflections may be displayed at the controller's console as spurious radar contacts;
b) radar returns from genuine aircraft being displayed, but in an incorrect location (range, azimuth, or both);
c) garbling or loss of SSR information.

The SSR code allocated to an aircraft may not be received correctly at the radar installation because of attenuation, scattering, or refraction effects. Moreover, it is possible that the aircraft altitude information derived from Mode C may also be lost or degraded.

6. Potential mitigating measures

6.1 Technical measures

Moving Target Indicator Processing

Objects that are moving cause a shift in the frequency of the returned EM energy to the radar receiver; this is known as Doppler shift. Moving target indicator (MTI) processing removes from the display any returned pulses that indicate no movement or are within a specified range of Doppler shift. This removes unnecessary clutter, eliminates unwanted moving targets (such as road traffic), and makes moving targets above a certain velocity more visible.

Rotating wind turbine blades can impart Doppler shift to EM energy reflecting off the blades. Depending on the MTI thresholds set in the radar processor, this may be displayed as a moving target. Changes in wind direction at the turbine, the position of the blade in its rotation, the blade pitch, and other factors may cause the amount of energy returned to the radar on different sweeps to vary. At single turbine sites, a radar return will be repeatedly displayed in the same position and MTI processing can be deployed. However, multiple-turbine sites cause a different effect and MTI processing is much more difficult. On one return, blades from one (or more) turbine(s) may paint on the radar; on the next sweep, the blades of a different turbine may paint. This can create the appearance of radar returns moving around within the area of the wind farm.

On both airport and air defence radar this can appear (depending on the type of radar and the processing thresholds in effect) as unknown aircraft manoeuvring unpredictably. On air defence radar such as those used in the Air Defence Slovak Republic, the overall system may well interpret the activity as an aircraft and automatically start tracking the activity (Wind … 2002).

Filters

It is technically possible with many types of radar to filter out returns from a given area to ensure they are not presented on operational displays. This is however at the expense of detecting actual aircraft in the area concerned. In the case of radar that has the ability to discriminate returns in height, it may be possible to filter out only the affected height band. On other radar, all returns in the given area will be lost and, in effect, no overall operational benefit is gained.

Non-Automatic Initiation

A measure that can be taken within the command and control system to mitigate the effects of spurious radar returns is to establish what is known as a non-automatic initiation (NAI) area. Within this area, the system does not perform its normal function of automatic track association and correlation. This would prevent the system attempting to correlate the returns from a large number of turbines to form what it perceives to be aircraft tracks. Instead, a human operator monitors the affected area to manually detect genuine aircraft tracks. Whilst this technique can help avoid problems both for surveillance and control of spurious tracks, it can be manpower intensive and requires operator expertise. Furthermore, it cannot help to overcome the effect of clutter on safety. Indeed, the use of clutter filters and NAIs may be operationally mutually exclusive.

6.2 Operational measures

The type of operations being conducted and the type of airspace within which a controller is operating are both relevant factors if radar clutter is being experienced.

Controlled airspace

Within controlled airspace, flight is only possible if approved by an ATC authority. Therefore, controllers should know of all aircraft within that controlled airspace. In this case, if radar clutter is experienced, whether from a wind turbine or other obstacle, the controller may assume that the return is not from an unknown aircraft and will not need to take any action. (There are exceptions to this rule that do not need to be explored here.)

Outside controlled airspace

Outside controlled airspace (in the Slovak Republic, categorised as Class G airspace), clutter and unknown radar returns present more of a problem. In such airspace, the radar returns of aircraft are the primary means on which the separation of aircraft is based. Clutter must therefore be avoided since it is the only way of ensuring separation from unknown aircraft.

What may occur is that radar clutter from a wind turbine may be interpreted as being a return from an aircraft, or the clutter may be obscuring a genuine radar return from an actual aircraft operating in the vicinity of that clutter.

There are two ways a controller can deal with this problem. The safest option is to simply avoid the area of clutter, usually by a range of 5 nautical miles. Naturally, this is not always possible. Alternatively, the controller may "limit" his radar service by informing the aircraft receiving the service that, due to being in an area of clutter, the pilot may receive late or no warning of other aircraft.

Controllers use both methods but each presents its own problem. The cumulative effects of clutter make vectoring to avoid clutter harder and harder. Controllers may be able to cope with one or two areas of clutter, but there is a difficult judgement as to how much proliferation is acceptable. Alternatively, limiting the service is often a last resort, and to admit that clutter may well be obscuring returns from genuine aircraft is a clear indication that flight safety may be compromised.

The significance of unwanted radar returns from wind turbines will depend not only on what type of airspace they are in or underneath, but also on their proximity to traffic patterns and routes. Wind turbines on an extended centreline of a runway are more likely to present a significant problem to controllers at longer ranges due to aircraft lining up for approaches and on departure. Similarly, airports have standard arrival routes (STAR) and standard instrument departure (SID) routes, which may also be considered problematic.

7. Conclusions

All radar is different (even if only due to the physical impact of operating locations) and creating a "rule of thumb" for wind farm development near all systems would require a level of generalisation that would probably make it worthless.

Therefore, in considering the effect of wind turbines on radar, developers need to focus on individual radar in the vicinity of their planned development. It is also important for developers to appreciate the nature and extent of any problem. For example, studies in air defence radar that take no account of the associated command and control systems may be of very limited value.

Both civil and military aviation communities have legitimate interests that must be protected, and they include protection against the adverse effects of wind turbines. There is scope for flexibility throughout the process of considering wind farm applications, however. The effects of wind turbines on the physical element of the air domain (as obstructions) are well understood and the procedures for handling them are relatively straightforward. Certainly, a flexible approach to the sitting of turbines can be expected to pay dividends. Developers must, however, bear in mind that there are some locations in which the presence of turbines is unlikely ever to be tolerated.

The effects of wind turbines on electronic systems and the measures that can be taken to overcome these effects are less clear-cut. The sitting of wind turbines will, potentially, affect the radar sensors belonging to both civil and military users in much the same ways, although the operational impact of these effects will probably not be the same. As further research is conducted and experience with existing (and currently approved) wind farms grow, all stakeholders will be able to determine more precisely what may be acceptable and what will not. No matter what, however, this is an area in which early dialogue with the relevant stakeholders is particularly recommended.

Acknowledgments

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VĖJO FERMA IR AVIACIJA

A. Novák

S a n t r a u k a

Vėjas yra vis didėjantis energijos šaltinis Slovakijos Respublikoje. Jis naudojamas generuoti elektrą turbinomis. Vėjo fermos pagal savo fizikinį dydį ir ypač pagal aukštį gali turėti įtakos aviacijai. Besisukančios vėjo turbinų mentės gali turėti įtakos tam tikroms aviacijos operacijoms, ypač susijusioms su radarais.

Reikšminiai žodžiai: vėjo ferma, radarų teorija, skrydžių valdymas, komunikacijos navigacija ir priežiūra.

01-29-20

EXHIBIT

7

A publication of the
**National Wildfire
Coordinating Group**

Interagency Aerial Supervision Guide

PMS 505 APRIL 2017

NFES 002544

Interagency Aerial Supervision Guide

April 2017
PMS 505
NFES 002544

The *Interagency Aerial Supervision Guide* standardizes federal agencies, state agencies and local agencies in the accomplishment of aerial supervision positions as defined by the Incident Command System (ICS).

This guide exists to promote safe, effective, and efficient aerial supervision services in support of incident goals and objectives. Its objectives are to:

- Standardize interagency aerial supervision operations and procedures.
- Standardize the roles, responsibilities, and scope of each aerial supervision position.
- Standardize program and training management goals to achieve standardized interagency operational and training objectives.
- Standardize all elements of the interagency aerial supervision community: Air Tactical Group Supervisors (ATGS), Aerial Supervision Modules (ASM), Leadplane Pilots (Lead), Airtanker Coordinators (ATCO), Air Tactical Pilots (ATP), Air Tactical Supervisors (ATS), and Helicopter Coordinators (HLCO).
- Provide an interagency standard operational procedural guide, available to all members of the aerial supervision community.

The National Wildfire Coordinating Group (NWCG) provides national leadership to enable interoperable wildland fire operations among federal, state, tribal, and local partners. NWCG operations standards are interagency by design; they are developed with the intent of universal adoption by the member agencies. However, the decision to adopt and utilize them is made independently by the individual member agencies and communicated through their respective directives systems.

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Tables

Chapter 1 – Aerial Supervision Administration, Roles, and Responsibilities

Program Administration

Agencies are responsible for oversight and management of their agency's aerial supervision program. In order to achieve a cohesive and highly standardized interagency program, the following roles and responsibilities of interagency program management are provided.

National, Regional, State, County, Cities, CAL FIRE, and Military Agency Program Managers

Program managers are delegated by their respective agencies and are responsible to administer the agencies aerial supervision program. Interagency scope of responsibilities should include:

- Coordinate with other agency program managers, the Interagency Aerial Supervision Subcommittee (IASS), and Interagency Geographic Area Coordination Center (GACC) Representatives to provide program coordination on an interagency basis.
- Coordinate with other agency program managers, the IASS, and interagency GACC Representatives to maintain and update a national resource qualifications list to include trainees, qualified personnel, Evaluators, and Final Evaluators.
- Ensure agency training and currency requirements are met. Annually review mission and qualification summaries.
- Participate on interagency working groups, committees, and subcommittees such as the Interagency Helicopter Operations Subcommittee, the Interagency Single Engine Airtanker Board Subcommittee (SEATB), and the Interagency Airspace Subcommittee (IASC).
- Coordinate training at the national and/or geographic level.
- Manage Evaluators and Final Evaluator designations/qualifications in order to meet agency quality assurance, standardization, and training objectives.
- Coordinate with trainee's unit/agency to track training progression and on-the-job training (OJT) needs.
- Ensure coaches are assigned to trainees.
- Provide for quality assurance and oversight of operational and training performance standards.
- Distribute aerial supervision program related information on an interagency basis.
- Coordinate with agencies that have a desire to develop or enhance an aerial supervision program.
- Coordinate operational standards with international cooperators.
- Provide input to the revision of the Interagency Aerial Supervision Guide (IASG) and interagency training management system.
- Additional roles and responsibilities may be assigned based on agency specific needs.

GACC Aerial Supervision Representatives (GACC REPS)

Aerial Supervision Specialists, assigned by the Geographic Area Coordination Group, coordinate geographic aerial supervision needs and provide quality assurance oversight of:

GACC REPS

- Should be recommended on a rotational basis and delegated in writing.

Scope of Duties

- Serve as Geographic Area Interagency Aerial Supervision point of contact.
- Coordinate with agency program managers and Geographic Area Training Representatives (GATR) to coordinate suitability flights, quality assurance observation flights, final evaluation flights, and training of federal, state, and local agencies.
- Make recommendations concerning training priorities to agency program managers and GATR's.
- May assist the GACC aircraft coordinators with tactical aerial supervision information and recommendations.
- Coordinate with agency program managers to ensure concurrent and cohesive training, training curriculum, and operations standards are met, nationally.
- Provide input to the revision of the IASG and interagency training management system.
- Participate at the National Aerial Supervision meeting (held annually).

Aerial Supervision Working Groups

There are three sub-groups of the IASS which provide subject matter expertise and technical assistance to meet IASS assigned tasking. Each group is managed under a charter from IASS.

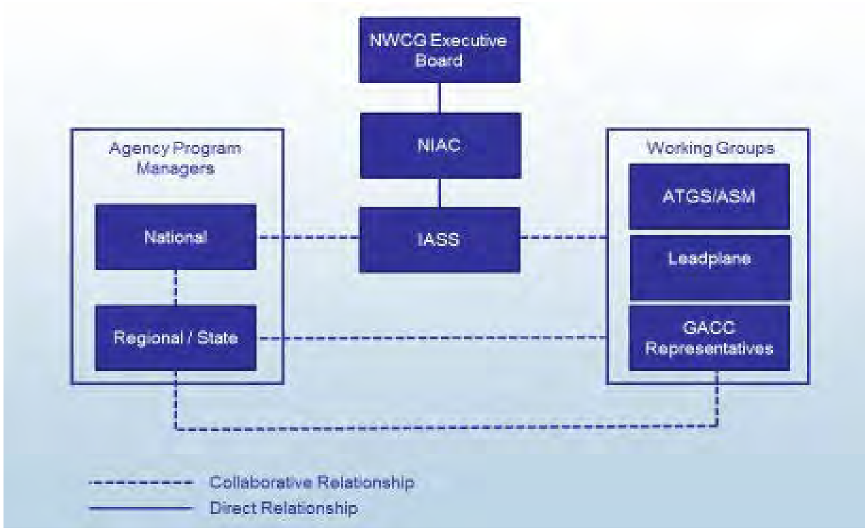
Chair/Co-chair:

- Serve as the point of contact to the IASS and manage the working group.
- Serve as the Subject Matter Expert (SME) during IASS meetings and deliberations.

Working Group Members:

- GACC Representatives.
- Agency Representatives – national, regional, and state SME's.
- Agency program managers.

Figure 1. Interagency Aerial Supervision Relationship Diagram



Aerial Supervision Resources

There are five types of aerial supervision resources and six aerial supervisor ICS positions. Although these positions are unique, they share the common purpose of facilitating safe, effective, and efficient air operations in support of incident objectives.

Helicopter Coordinator (HLCO)

The HLCO coordinates, directs, and evaluates tactical/logistical helicopter operations. The HLCO position is typically activated on complex incidents where several helicopters are assigned. A HLCO can increase the span of control of the ATGS by managing helicopters over an incident. The HLCO may provide sole aerial supervision on an incident where only helicopters are assigned, otherwise ATGS is required. When an ATGS is assigned, the HLCO is a subordinate position to the ATGS. If no ATGS is present, the HLCO works for the Incident Commander (IC), Air Operations Branch Director (AOBD), or designee. Other than the prerequisite requirements for ATGS, HLCO organizational structure, currency, and refresher requirements are recommended to mirror the ATGS program.

The HLCO is qualified to function from either an airplane or helicopter however during complexed operations the helicopter is the preferred platform..

Air Tactical Group Supervisor (ATGS)

The ATGS coordinates incident airspace and manages incident air traffic. The ATGS is an airborne firefighter who coordinates, assigns, and evaluates the use of aerial resources in support of incident objectives. The ATGS is the link between ground personnel and incident aircraft. The ATGS must collaborate with ground personnel to develop and implement tactical and logistical missions on an incident. The ATGS must be proactive in communicating current and expected fire and weather conditions. The ATGS must provide candid feedback regarding the effectiveness of aviation operations and overall progress toward meeting incident objectives. The ATGS must also work with dispatch staff to coordinate the ordering, assignment, and release of incident aircraft in accordance with the needs of fire management and incident command personnel.

On Initial Attack (IA) incidents (Type 4 and 5), the ATGS will size up, prioritize, and coordinate the response of aerial and ground resources until a qualified IC arrives. On complex incidents (Type 1, 2, or 3), the ATGS will coordinate and prioritize the use of aircraft between several divisions/groups while maintaining communications with operations personnel and aircraft bases (fixed/rotor).

In the ICS, the ATGS works for the IC on initial attack and the Operations Section Chief (OSC), AOBD, or operational designee on extended attack. The ATGS supervises the ATCO, Leadplane Pilot, and the HLCO positions when activated. The ATGS is qualified to function as an ATCO or HLCO from either an airplane or helicopter.

Airtanker Coordinator (ATCO)

The ATCO coordinates, directs, and evaluates airtanker operations. When an ATGS is assigned the ATCO is a subordinate to the ATGS position. If no ATGS is present the ATCO works for the IC, OPSC, AOBD, or designee.

An ATCO can increase the effectiveness of an operation by assisting the ATGS by through management of the airtankers assigned to an incident. The ATCO is not authorized for low-level flight operations.(Flights Below 500 ft Above Ground Level (AGL))Leadplane Pilot.

The Leadplane position is identical to the ATCO except the pilot is qualified and authorized for low-level flight operations. A Leadplane Pilot is not recognized in ICS and is classified as an ATCO by default. The low-level capabilities of a Leadplane enhance the safety and effectiveness of airtanker operations in the often turbulent, smoky, and congested airspace of the fire environment.

Aerial Supervision Module (ASM)

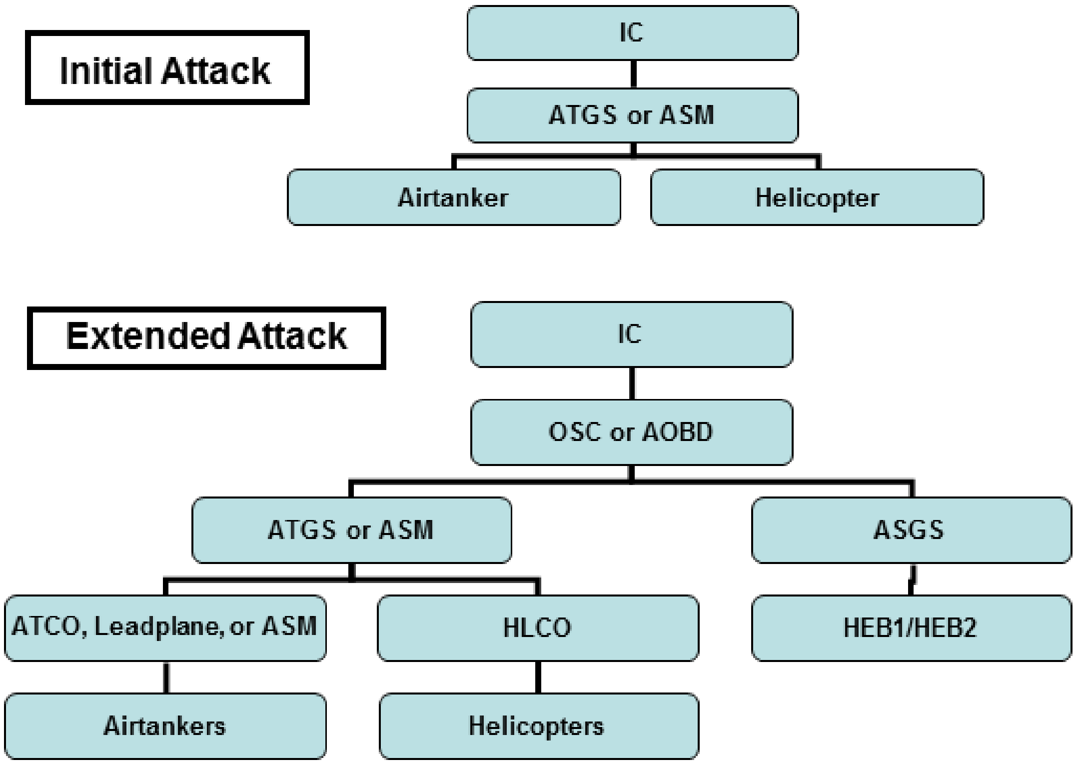
An ASM is a two-person crew functioning as the Lead and ATGS from the same aircraft. The ASM crew is qualified in their respective positions and has received additional training and authorization.
An ASM can be utilized as a Lead, ATGS, or both, depending on the needs of incident management personnel. An ASM consists of an ATP and ATS.

ATP – The ATP is a qualified Leadplane Pilot who has received specialized training and authorization to function as an ASM crewmember. The ATP functions as the Leadplane Pilot and utilizes Crew Resource Management (CRM) skills to evaluate and share the incident workload with the ATS.

ATS – The ATS is a qualified ATGS who has received specialized training and authorization to function as an ASM crewmember. The ATS is an ATGS who also utilizes CRM to evaluate and share the incident workload with the ATP.

The following chart depicts the relation of Aerial Supervision to other resources in ICS.

Figure 2. Aerial Supervision organization during Initial Attack and Extended Attack



Chapter 2 – Training, Certification, and Currency

The policies governing Training, Certification, and Currency shall comply with the employee's agency policy requirements. Additional requirements described within this guide shall be considered recommendations unless specifically adopted by the applicable agency as policy. The purpose of any additional requirement and/or standard is to achieve the highest level of safety and performance.

Helicopter Coordinator (HLCO)

HLCO is used in conjunction with ATGS/ASM or as stand-alone aerial supervisors of helicopters. Large incidents can have more than one HLCO operating at the same time.

HLCO Position Duties

- A qualified HLCO or ATGS will oversee OJT during all missions.
- Only qualified HLCO's can recommend certification of a HLCO.
- Coordinates, directs, and evaluates tactical/logistical helicopter operations.
- Provide sole aerial supervision on an incident where only helicopters are assigned, otherwise ATGS is required.

HLCO Initial Training

- S-378 or equivalent

HLCO Certification

- Completion of Position Task Book (OJT)

HLCO Supplemental Training

- Attend RT-378 triennially
- 7 Skills CRM training
- S-271 Helicopter Crew Member
- S-372 Helicopter Manager
- Load Calculations

HLCO Currency

- 1 mission every 3 years

Air Tactical Group Supervisor (ATGS)

Aerial supervision operations place a high demand on communication and management skills. Application of fire behavior knowledge combined with ground fire resource capability must be correlated with tactical aircraft mission planning.

ATGS Position Duties

- Safely and effectively utilize aircraft in support of incident management objectives.
- Coordinate incident airspace and manages incident air traffic.

- Coordinate, assigns, and evaluates the use of aerial resources in support of incident objectives.
- Collaborate with ground personnel to develop and implement tactical and logistical missions on an incident.
- Communicate current and expected fire and weather conditions.
- Provide candid feedback regarding the effectiveness of aviation operations and overall progress toward meeting incident objectives.
- Work with dispatch staff to coordinate the ordering, assignment, and release of incident aircraft in accordance with the needs of fire management and incident command personnel.

ATGS Initial Training, Certification, and Currency

- Candidates will meet prerequisite experience requirements and mandatory training requirements listed in the PMS 310-1 or Forest Service Fire and Aviation Qualification Guide.

ATGS Classroom Training

- S-378, ATGS (State and Local Government) OR National Aerial Supervision Training Academy (S-378) OR California Aerial Supervision Academy (S-378)

Note: United States Forest Service (USFS) and Department of The Interior (DOI) employees must attend and pass the National Aerial Supervision Training Course or the California Aerial Supervision Course.

ATGS Agency Approved CRM Training

- Federal and federally sponsored Administratively Determined (AD) employees will complete Crew Resource Management 7 Skills (N-9059) facilitated by an authorized instructor.
- State employees will follow state CRM training requirements.

ATGS Mission Training Requirements

The flight training program should include a variety of work experience and be of sufficient duration to ensure that the individual can independently function as an ATGS following certification.

- Observing an ATGS Evaluator during ongoing incident operations.
- All OJT will be under the direct supervision of an ATGS Evaluator in the same aircraft.
- Prior to final certification, candidates must undertake an OJT program under the supervision of an ATGS Evaluator that provides a variety of experience in initial and extended attack scenarios.

ATGS Candidate Evaluations

- The candidate shall receive a written evaluation at the completion of all missions from the ATGS Evaluator as an integral part of the mission de-briefing. Multiple missions may be combined.
- The Aerial Supervision Mission Evaluation Form is the standard performance assessment tool.
- The candidate will retain a copy of the Mission Evaluation to supplement information completed by the ATGS Evaluator in the candidate's task book.

ATGS Training Opportunities

Agency program managers can assist in the development of candidates by assigning a coach and providing a variety of training opportunities in different locales, fuel types and incident complexities. Training opportunities may include the following:

- Assignments to work with full-time, dedicated/exclusive use ATGS at an air attack base.
- Assignments to a national or geographic area Incident Management Team (IMT).
- Details or training assignments in other geographic areas to increase the depth of experience.
- Participate as a passenger on other tactical aircraft during missions (subject to approval from the National Program Manager, Regional Aviation Manager (RAO), Contracting Officer, Contractor and Pilot in Command (PIC)).

ATGS Certification Process

Upon completion of the task book, the agency Final Evaluator will:

- Perform a final Mission Evaluation.
- Return the completed task book to the ATGS trainee along with recommendations.
- Notify the appropriate agency program manager.
- Trainee is responsible for submitting completed position task book, training documentation, and final recommendation to certifying official.

ATGS Supplemental Training

The following training opportunities should be considered prior to initial certification or as supplemental or refresher training for individuals currently certified as ATGSs. The GACC Rep, agency program manager, or training official can assist in the development of candidates by providing a variety of training opportunities in different locales, fuel types and incident complexities. Related aviation training opportunities should be made available to candidates to provide valuable knowledge, experience and skills applicable to the ATGS. Training opportunities may include the following:

- Pinch Hitter pilot course.
- Private pilot ground school.
- National Aerial Fire Fighting Academy (NAFA & NAFA II).
- Participation in aerial reconnaissance or aerial detection missions.
- Observing or participating in large helibase operations.
- Orientation to airtanker base and retardant operations.
- Orientation to or observation of aircraft dispatch operations.
- Assignments working with full-time, exclusive use ATGS at an air attack base.
- Peer-to-peer observation and cross training is recommended to enhance skills, provide avenue to observe other qualified ATGS's, and enhance operational standardization.
- Assignments to a national or geographic area IMT.

ATGS Currency Requirements

All ATGS will meet the requirements stated in the PMS 310-1and forward an annual mission summary[1] 1 to the appropriate agency program manager/RAO.

In addition:

- Annually perform, document, and report a minimum of five missions. (Failure to maintain ATGS mission currency requires a passing evaluation by a Final Evaluator on an actual or simulated mission).
- Each mission may be documented as a "Shift" in the appropriate qualification management system (see glossary).
- Attend a triennial RT-378.
- Attend a triennial CRM 7 Skills Refresher (RT9059F) or agency approved CRM refresher course.
- Recertification-See 310-1 or agency specific policy.

Note: USFS qualified ATGS's must meet the Forest Service Fire and Aviation Qualifications Guide and the PMS 310-1 for ATGS currency. California Department of Forestry (CALFIRE) supports the above currency requirements and manages them internally.

ATGS Refresher Training (RT-378)

Required Elements

- Proficiency exercise
- Risk management/ System Safety
- Mission procedures
- FTA management
- Fire and Aviation Weather
- Lessons Learned/Case Studies
- Agency approved CRM refresher
  - Federal and federally sponsored AD employees will complete the 7 Skills CRM refresher (1.5 hours minimum) facilitated by a federally authorized instructor.
  - State employees will follow state CRM training requirements.

Optional Elements

- Radio programming
- Map reading and navigation
- Strategy and tactics
- Aviation incidents/accidents from the preceding season
- Payment documents
- Contract and aircraft fleet updates
- Issues and concerns from national and/or regional user groups (fire management, dispatch, hotshots, ICs, etc.)

[1] Annual Mission Summaries, Individual Mission forms, and Mission Evaluation forms are components of the Aerial Supervision Log Book (NFES 1150).1

- Communications brevity
- Electronic flight bags

Proficiency Exercise

All ATGS will demonstrate proficiency in the required refresher elements and complete a moderate complexity (a mix of at least four fixed and rotor wing aircraft) mission or flight/Sand Table Exercises (STEX) exercise (appendix B). Students will be evaluated utilizing the Aerial Supervision Mission Evaluation form (PMS 509)

The exercise will represent a typical IA and will require the ATGS to demonstrate the minimum acceptable skill set of the position including Fire Traffic Area (FTA) entry, determining FTA altitudes, initial aircraft briefings, aircraft separation, communication with air and ground resources, and situational awareness.

Performance will be documented on a Mission Evaluation, reviewed with the participant, and forward a copy to the appropriate agency program manager. Failure to demonstrate an acceptable level of proficiency will require the ATGS performance deficiency or decertification process to be implemented.

Documentation packet (or agency record of completion) will be issued to attendees who complete the refresher. Documentation will be forwarded to the appropriate agency program manager and the training official.

ATGS Mission Evaluation

The standard method for evaluating ATGS performance is an actual or simulated mission utilizing the Aerial Supervision Mission Evaluation form. ATGS (Evaluator/Final Evaluator) conducts mission evaluations for the following purposes:

- ATGS training
- ATGS certification
- ATGS currency
- ATGS performance deficiencies

ATGS Performance Deficiencies

If an ATGS is observed performing unsafely/deficiently:

- The event will be discussed with the individual, and documented. Documentation should consist of recommendations on how to bring ATGS up to currency standards; additional academics, coaching, mentoring, observations, etc.
- The recommendations will be forwarded to the appropriate RAO/agency program manager, and the individual's supervisor or sponsoring agency/official. The ATGS may be made unavailable for

  ATGS assignments in the appropriate dispatch status system until the certifying official reviews the recommendations.

Air Tactical Group Supervisor Coach

ATGS Coaches serve as a point of contact and SME for the trainee throughout the training process.

Position Requirements

- Qualified ATGS

Responsibilities

- Help develop a training plan for the candidate.
- Coordinate with the agency program manager and employee supervisor.
- Assure training is on track and that all requirements are being scheduled so as not to delay progress.
- Assist with any problems regarding agency and training requirements.
- Coaches should be an independent, nonpartisan person outside the employee's standard chain of command.

Air Tactical Group Supervisor Evaluator

ATGS Evaluators should provide consistent ATGS instruction, evaluation, and feedback on ATGS missions.

Position Requirements

- One year following ATGS qualification while maintaining currency.
- Attend a regionally sponsored ATGS Evaluator workshop triennially (by 2019). Documentation shall be forwarded to the appropriate GACC representative.
- ADs are authorized for this position providing they meet the position requirements.
- Maintain ATGS currency as defined by agency training policy.
- The agency program manager/ appropriate RAO will track ATGS Evaluator. State agency aviation program managers have the ability to designate state employed ATGS Evaluators.

Responsibilities

- Utilize applicable methods to promote ATGS trainee progress and ultimate certification.
- Utilize training aids, best practices, forms, and policy documents to maximize the training experience.
- Review and complete applicable position task book elements.
- Document strengths, focused improvement areas utilizing the Aerial Supervision Mission Evaluation Form (PMS 509 Form 4) located at: https://www.nwcg.gov/products/509/aerial-supervision-logbook-forms
- Provide feedback to the trainee's supervisor/coach.
- Share progress reports with ATGS trainee's GACC Representative.
- Coordinate with trainee's supervisor to recommend and schedule final evaluation flight.

Air Tactical Group Supervisor Evaluator Workshop

Workshops should prepare ATGS Evaluators to apply current and consistent training procedures. The Evaluator workshop should be integrated with RT-378.

Target Group

Qualified ATGS (one year)

Workshop Instructor Requirement

ATGS Evaluator

Course Prerequisite

None

Course Level

Regional, state, or area

Course Content:

- Instructional methods
- Utilization of the Mission Evaluation Form (PMS 509 form 4) located at: https://www.nwcg.gov/products/509/aerial-supervision-logbook-forms
- Mission flights
- Lecture
- STEX
- After Action Review (AAR)
- Interagency/Regional consistency
- CRM/Human Factors – How to provide constructive criticism
- Training Aids
- Policy

Air Tactical Group Supervisor Final Evaluator

This section describes the qualifications, training, certification, and currency requirements necessary to perform as an ATGS Final Evaluator.

ATGS Final Evaluator Duties

- Provide final ATGS trainee evaluation and complete Final Evaluator verification page in the ATGS position task book.

Position Requirements

- One year of experience as an ATGS Evaluator.
- Attend a nationally sponsored ATGS Final Evaluator Workshop triennially (by 2019). Documentation shall be forwarded to the appropriate GACC representative.
- AD employees are NOT authorized to perform this function.
- Maintain ATGS currency as defined by agency training policy.
- The appropriate RAO /agency program manager will provide a letter of authorization to the ATGS Final Evaluator upon completion of the requisite training.

Note: State agency aviation program managers have the ability to designate state employed ATGS Final Evaluators.

Responsibilities

- Coordinate with ATGS Instructor and trainee's supervisor to schedule and implement a final evaluation.
- Perform final evaluation and complete Aerial Supervision Mission Evaluation form.
- Complete the Position Task Book (PTB).
- Complete Final Evaluator Verification OR,
- Complete an Evaluation Record (experience block) to document further training recommendations.
- Review evaluation with ATGS trainee.
- Contact trainee's supervisor and review the final evaluation.

Air Tactical Group Supervisor Final Evaluator Workshop

Objective

Prepare ATGS Final Evaluators to perform ATGS trainee final evaluations. The Final Evaluator Workshop should be integrated with the Aerial Supervision Academy or equivalent.

Target Group

ATGS Evaluators

Instructor Requirement

ATGS Final Evaluator

Course Prerequisite

None

Course Level

National

Course Content

- Policy
- Documentation
- ATGS PTB
- Aerial Supervision Mission Evaluation (PMS 509)
- CRM/Human Factors – How to provide constructive criticism
- Agency specific qualification/certification processes

Airtanker Coordinator (ATCO)

The ATCO may not be authorized for low-level (below 500' AGL) operations.

Position Duties

- Coordinates, directs, and evaluates airtanker operations.
- Works under the ATGS.

Leadplane Pilot (Lead)

The primary mission of the Leadplane Pilot is to ensure the safe, efficient and effective use of airtankers in the management of wildland fire. The term "Leadplane Pilot" is used to address a specialized function. The ICS does not include this position in the organization but uses the term ATCO. The differences between the functions of the two positions are addressed below.

Leadplane operations place a high demand on not only pilot skills, but on a person's management skills. Pilot skills, mission management, and application of fire behavior knowledge, all correlate with successful mission performance.

A Leadplane Pilot is an aerial firefighter. As such, National Wildfire Coordinating Group (NWCG) firefighter training titles are used in lieu of standard Federal Aviation Administration (FAA) pilot terminology. For purposes of Leadplane Pilot training:

- An “Instructor” is herein referred to as an “Evaluator.”
- A “Pilot Examiner or Check Airman” is herein referred to as a “Final Evaluator.”
- An interagency Leadplane Pilot call sign/qualification list is maintained by the USFS Washington Office (WO), Branch Chief Pilot Standardization and published annually in the National Mobilization Guide.

Leadplane Pilot Qualifications

Candidates for Leadplane Pilot designation must be federal or state (or state contract) employees who have the appropriate FAA pilot and medical certifications. Forest Service candidates shall possess, as a minimum, the flight experience listed in the Forest Service Handbook (FSH) 5709.16. DOI pilots shall meet, as a minimum, the requirements of 351 Departmental Manual (DM) 3. State contract employees shall possess, at a minimum, the flight experience listed in FSH 5709.16 Trainees shall complete the mission training and certification requirements of this section.

Deviations or Exceptions

The WO Branch Chief, Pilot Standardization in coordination with the appropriate RAO (USFS), the National Flight Operations Manager (BLM), or appropriate State Aviation Official may authorize deviations or exceptions from the training requirements. Approved deviations or exceptions will be in writing. Documentation will be maintained by the appropriate agency official and a copy will be carried in the trainees training folder.

Leadplane Pilot Initial Training Curriculum

Every effort shall be made to limit the number of Leadplane Pilot Evaluators assigned to provide training for each candidate during Phases 1 and 2.

Leadplane Pilot Training

This defines the Leadplane Pilot program of instruction.

- Organizational Course of Instruction
- I-200 Basic ICS
- S-370 Intermediate Aviation Operations, if available. If not available, S-270 Basic Aviation Operations
- S-290 Intermediate Fire Behavior
- National Air Attack Academy (Alternate delivery S-378) or CALFIRE Air Attack Academy

- Interagency Aerial Supervision Academy (Initial Leadplane Pilot Training Course)

Note: The above courses shall be completed prior to entering Phase 3 Operational Flight Training

Leadplane Pilot Supplemental Training

Candidates should obtain additional training beyond agency minimum requirements prior to proceeding with Operational Training.

- Wildland fire suppression experience
- Low-level and mountain flying experience
- Fire suppression tactics
- Dispatch Center orientation and operations
- Helicopter Operations

Additional courses to be completed at the next available opportunity after initial qualification:

- NAFA or NAFA II
- Agency approved Crew Resource Management 7 Skills (N-9059)

Operational Flight Instruction

Training is divided into three phases. Each phase is to be completed before progressing to the next phase. Identified deficiencies shall be documented and corrected prior to the candidate's progress to the next phase.

Documentation of Training

The pilot is responsible for maintaining their individual training folder. The folder shall include the following:

- Course completion certificates
- Record of ground and flight training including documentation of corrected deficiencies
- Sign-offs for each phase of flight training

Flight Training Records

Leadplane Pilot Evaluators will provide the trainee with a written documentation of each training flight. The original copy will be retained by the trainee in their training folder. A copy of the phase training completion form will be sent to the appropriate RAO and a copy forwarded to the WO Branch Chief, Pilot Standardization (USFS), the National Flight Operations Manager (BLM), or the appropriate State Aviation Officer. The Leadplane Evaluator will retain a copy for their records.

Leadplane Training / Check Form

- The Leadplane / Check Form is to be used to record all Leadplane training and checkrides.

Initial Leadplane Pilot Training Process

The Initial Leadplane Pilot Training Course should be taken before entering Phase 1 but shall be accomplished before completing Phase 2.
Note: The Leadplane Evaluator may alternate between the left and right (front and back) seats during Phases 2 and 3.

Phase 1

- Minimum of two operational periods of observing and assisting an ATGS on missions.
- Minimum of two missions of Leadplane Tactical Flight Training comprised of low levelflight, mountainous terrain flight, proximity flight, and Leadplane/airtanker simulation.

Note: Flight time obtained in the Initial Leadplane Pilot Training Course can be used to meet this requirement.

- Phase Check –This check will evaluate the following in a non-fire environment.
  - Oral – The trainee shall pass an oral review covering all activities under Phase 1. The oral will consist of questions involving (1) specific safety-of-flight and key operational issues, (2) discussion questions designed to determine if the trainee has the base knowledge that should be gained from Phase 1 activities, and (3) general questions to establish that the trainee has an understanding of the operational issues that are necessary to progress to Phase 2 (Appendix A).
  - Flight Check – The flight check shall include low-level mountain flying, airspeed control, tactical low-level patterns and join ups.

Phase 2

- Minimum of 3 missions observing in the right seat fire missions with a Leadplane Evaluator.
- Ride as an observer on a variety of airtankers, during fire missions.
- Minimum of 15 Leadplane missions on fires of various size and complexity as the flying pilot in the left seat under the supervision of a Leadplane Evaluator.
- Phase Check – A Leadplane Final Evaluator will administer the Phase Check.
  - Oral – The trainee shall pass an oral review covering all activities under Phase 2. The oral will consist of questions involving (1) specific safety-of-flight and key operational issues, (2) discussion questions designed to determine if the trainee has the base knowledge that should be gained from Phase 2 activities, and (3) questions designed to determine that the trainee has the knowledge to address situations that can arise when performing the Leadplane mission.
  - Flight Check – The flight check to determine that the trainee (1) can safely perform the Leadplane mission, (2) operate within the designated mission profiles, and (3) has been exposed to varying fire size and complexities. Any identified problem areas will be satisfactorily resolved.

Phase 3

All required ground training shall be completed prior to initiating Phase 3.

- Minimum of ten Leadplane missions on fires of varying size and complexities as the flying pilot under the supervision of a Leadplane Evaluator.
- A portion of the Leadplane missions shall be flown in other regions/states if not accomplished in Phase 2.
- Additional flights in airtankers as necessary.
- Final Leadplane Progress Check – A Leadplane Pilot Evaluator will make a final progress check upon completion of the Phase 3. This will consist of an oral review covering all aspects of Leadplane Pilot operations.
- Complete Records Review – Complete records review of the training folder by the candidate's coach to determine that all requirements have been met and signed off. The

coach will than schedule a final check ride.

Final Evaluation and Qualification

To be designated as a Leadplane Pilot, candidates shall have:

- Satisfactorily completed all operational flight training and acquire the necessary operational flight experience.
- Undergone a complete oral and operational evaluation. The evaluation consists of:
  - A Phase 3 sign-off by a Leadplane Evaluator who has instructed the candidate during Phase 3, attesting to the candidate's mission competence.
  - A final flight check (which may require multiple missions to allow the Leadplane Final Evaluator to observe adequate performance in complex environments) by a Leadplane Final Evaluator certifying that the candidate has completed the required training and recommends they be approved to perform as a Leadplane Pilot.
- The WO Branch Chief, Pilot Standardization in coordination with the appropriate RAO (USFS), the National Flight Operations Manager (BLM), or appropriate State Aviation Official will issue a letter of designation upon successful completion of Leadplane training.

Leadplane Pilot Currency

Experience – Leadplane Pilots shall complete 30 Leadplane missions in a three-year period. Pilots not meeting the 30-mission requirement shall pass a flight check on a Leadplane fire mission. A mission consists of a flight on an actual fire where retardant is delivered. Each fire flown during a single flight counts as a mission.

Annual Leadplane Refresher

A Leadplane refresher will occur annually and consist of ground school and flight training.

Required Ground School Refresher Elements

- Target Description Exercise
- Safety
- Communications
- Tactics
- Airtanker operations

Optional Ground School Refresher Elements

- ICS
- Pre-season Update: (airtanker crew assignments, Expected fire behavior, Long-term weather prognosis)
- Fire Size-Up
- Additional elements may be added based on national trends and needs.

Required Flight Training Refresher Elements

Flight Training shall be a minimum of three flight hours and include:

- Target Description
- Leadplane Tactical Flight Profile
- Communications
- Escape Routes

- Emergency Procedures
- Annual Leadplane Pilot mission competency check by a Leadplane Evaluator

Standardization Evaluation

Leadplane mission checks may be conducted at any time for all qualified Leadplane Pilots with not prior notice. The results will be forwarded to the appropriate RAO and WO Branch Chief, Pilot Standardization (USFS), the National Flight Operations Manager (BLM), or appropriate State Aviation Official and the Leadplane Pilot briefed on the evaluation.

Air Tactical Pilot/ASM Training

See ASM section.

Modular Airborne Fire Fighting System (MAFFS)

MAFFS qualification is an additional required endorsement. Leadplane Pilots are required to attend the first available MAFFS training session after initial Leadplane qualification.

Qualifications

- Be a qualified Leadplane Pilot.
- Shall have completed MAFFS Leadplane Pilot training.

Certification

- Attend MAFFS Training Session.
- Interim certification may be granted upon initial Leadplane qualification based on actual MAFFS operational experience obtained during initial Leadplane training. Leadplane Pilots who obtain interim MAFFS certification shall attend the next MAFFS training session.

Currency

Leadplane Pilots shall attend the MAFFS training session every four years at a minimum.

Region 5 South Ops Familiarization

Leadplane Pilots shall receive instruction by an experienced Leadplane Evaluator in South Ops before operating alone in that area. The WO Branch Chief, Pilot Standardization in coordination with the appropriate RAO (USFS), the National Flight Operations Manager (BLM), or appropriate State Aviation Official may waive this requirement if the Leadplane Pilot received instruction in this area on fire missions during Phase 1 or Phase 3 Leadplane training.

Supplemental (AD) Leadplane Pilots

AD pilots shall maintain the same currency and training requirements stipulated for agency pilots. The USFS WO will publish a list of supplemental Leadplane Pilots on an annual basis.

Leadplane Pilot Coach

This section describes the qualifications, training, and currency requirements necessary to perform as a Leadplane Coach. Leadplane Coach: Serves as a point of contact and SME for the trainee throughout the training process.

Position Requirements

- Qualified Leadplane Pilot

Responsibilities

- Help develop a training plan for the candidate.
- Coordinate with the appropriate RAO/agency program manager and employee supervisor.
- Assure training is on track and that all requirements are being scheduled so as to not delay progress.
- Assist with any problems regarding agency and training requirements.
- Coaches should be an independent, nonpartisan person outside the employee's standard chain of command.

Leadplane Pilot Evaluator

Leadplane Pilot Evaluator provides consistent Leadplane instruction, evaluation, and feedback on Leadplane missions.

Qualification Requirements

- Current Leadplane Pilot with a minimum of two seasons experience after initial qualification.
- Multi-region experience as a qualified Leadplane Pilot.
- MAFFS Qualified.
- Possess the appropriate FAA flight instructor certificate.
- Region 5 South Ops Experience.
- Attend Leadplane Evaluator workshop biennially.

Responsibilities

- Utilize applicable methods to promote Leadplane trainee progress and ultimate certification.
- Utilize training aids, best practices, forms, and policy documents to maximize the training experience.
- Review and complete applicable phase training documentation.
- Document strengths, area for improvement, and focus areas utilizing the Leadplane Pilot Training/ Check Form.
- Provide feedback to the trainee's supervisor/coach.
- Share progress reports with Leadplane Evaluator community.
- Coordinate with trainee's supervisor to recommend and schedule final evaluation flight.

Certification Process

- Pass a Leadplane Pilot Final Evaluator oral and flight check.
- The WO Branch Chief, Pilot Standardization in coordination with the appropriate RAO (USFS), the National Flight Operations Manager (BLM), or appropriate State Aviation Official will issue a Leadplane Pilot Evaluator designation letter.

Currency

- Maintain Leadplane Pilot currency
- Maintain MAFFS currency
- Attend biennial Evaluator Workshop

Leadplane Pilot Evaluator Workshop

Objective

- Prepare Leadplane Evaluators to apply current and consistent training procedures.
- Target Group: Qualified Leadplane Pilots with 2 years of experience.
- Workshop Instructor Requirement –Leadplane Pilot Evaluators and Final Evaluators.

Nomination Process

The Leadplane working group, in conjunction with the WO Branch Chief, Pilot Standardization and the appropriate RAO (USFS), the National Flight Operations Manager (BLM), or appropriate State Aviation Official will nominate pilots who meet the qualifications and whom they consider to have the experience, aptitude, dedication, and ability to perform the duties of a Leadplane Pilot Evaluator.

Course Prerequisite

- Multi-region experience as a qualified Leadplane Pilot
- MAFFS Qualified
- Possess the appropriate FAA flight instructor certificate
- Region 5 South Ops Experience

Course Level

National Interagency

Course Content

- Instructional methods
- Utilization of the Leadplane Pilot Training/ Check Form
- Mission flights
- Lecture
- STEX
- AAR
- Standardization of instruction
- CRM/Human Factors – How to provide constructive criticism
- Training Aids
    - Policy

Leadplane Pilot Final Evaluator

Leadplane Pilot Final Evaluator provides final Leadplane Pilot trainee evaluations. The Leadplane Pilot Final Evaluator makes the recommendation for certification to the appropriate agency program manager.

Qualification Requirements

- Current Leadplane Pilot with a minimum of three seasons as a Leadplane Evaluator.
- MAFFS Qualified.
- Possess the appropriate FAA flight instructor certificate.
- Attend Leadplane Final Evaluator workshop biennially.

Responsibilities

- Coordinate with Leadplane Evaluator and trainee's supervisor to schedule and implement a final evaluation/check ride.
- Perform final evaluation/check ride and complete Leadplane Pilot Training/ Check Form.
- Contact trainees supervisor and review the final evaluation.

Certification

- Pass a Leadplane Pilot Final Evaluator oral and flight check.
- The WO Branch Chief, Pilot Standardization in coordination with the appropriate RAO (USFS), the National Flight Operations Manager (BLM), or appropriate State Aviation Official will issue a Leadplane Pilot Final Evaluator designation letter.

Currency

- Maintain Leadplane Pilot currency
- Maintain MAFFS currency
- Attend biennial Final Evaluator Workshop

Leadplane Pilot Final Evaluator Workshop

Objective

Prepare Leadplane Final Evaluators to apply current and consistent training procedures.

Target Group

Qualified Leadplane Evaluator Pilots with 3 years of experience

Workshop Instructor Requirement

Leadplane Pilot Final Evaluator

Nomination Process

The Leadplane working group, in conjunction with the WO Branch Chief, Pilot Standardization and the appropriate RAO (USFS), the National Flight Operations Manager (BLM), or appropriate State Aviation Official will nominate pilots who meet the qualifications and whom they consider to have the experience, aptitude, dedication, and ability to perform the duties of a Leadplane Pilot Final Evaluator.

Course Prerequisite

- Multi-region experience as a qualified Leadplane Pilot Evaluator.
- MAFFS Qualified.
- Possess the appropriate FAA flight instructor certificate.

Course Level

National Interagency

Course Content

- Final evaluation methods
- Mission flights
- Standardization of final evaluation
- CRM/Human Factors – How to provide constructive criticism
- Policy

Leadplane Pilot/Trainee Performance Deficiencies

If a Leadplane Pilot/Trainee is observed performing unsafely/deficiently:

- The event will be discussed with the individual, and documented as appropriate.
- Depending on the agency, the documentation will be forwarded WO Branch Chief, Pilot Standardization and the appropriate RAO (USFS), the National Flight Operations Manager (BLM), or appropriate State Aviation Official. The individual may be made unavailable for Leadplane Pilot/Trainee assignments in the appropriate dispatch/status system.

Aerial Supervision Module (ASM)

An ASM is a crew of two specially trained individuals who retain their individual Leadplane Pilot and ATGS qualifications. Each crewmember has specific duties and responsibilities that fall within their area of expertise. These vary in scope based on the mission and task loads of each crewmember.

The ATP serves as the aircraft commander and is primarily responsible for aircraft coordination over the incident. Following Leadplane qualification, it is recommended that Leadplane Pilots acquire one year of Leadplane experience in multiple geographic regions prior to operating as an ATP. This does not preclude the Leadplane Pilot from attending ASM training or flying with an ATS to gain additional fire fighting and retardant use experience.

The ATS serves as the mission commander who develops/implements strategy/tactics in conjunction with the IC and Operations personnel. When no IC is present the ATS assumes those responsibilities until qualified ground personnel arrive. ATS initial candidates must be qualified as an ATGS Evaluator. This does not preclude the ATS candidate from attending ASM training.

The ASM is designed for IA operations, but can provide IMTs with the flexibility of being able to alternate between operational functions until dedicated aerial supervision resources can be assigned to the incident.

ASM Resource Status, Ordering, and Identification

ASM resource identification and status are reported using the following procedures:

Tactical Aircraft Report – The National Interagency Coordination Center (NICC) and GACC report the status of the ASM crews as a national resource. The ATPs Leadplane Pilot designator is used in conjunction the federal ASM designator to identify the ASM. The State of Alaska ASM designator is A, Alpha. The Forest Service and BLM ASM designator is B (Bravo). The CALFIRE ASM designator is C (Charlie).

Resource Ordering – Federal ASMs are a national resource and will be ordered in the same manner as Leadplanes or other national resources. The ATS and Leadplane Pilot should be rostered as subordinates to the aircraft on the resource order.

Flight and Duty Day Limitations

The ATS, when assigned to an ASM, will have the same flight and duty limitation as the ATP and are considered a crewmember. The ATS will match the ATP tour of duty for consistency and resource availability.

ASM Utilization

The ASM is a shared national resource and can be utilized in the following capacities:

- ASM, Leadplane, ATGS, Detection/Recon, All Risk, FEMA ESF4, etc.

Authorized Passengers

The following positions are authorized to be on board the aircraft during ASM operations:

- Air Tactical Pilot/Air Tactical Pilot Trainee
- Evaluator Pilot/Final Evaluator Pilot
- ATS/ATS Trainee
- Evaluator ATS/Final Evaluator ATS

Other passengers must be authorized in writing by the appropriate WO Branch Chief, Pilot Standardization or WO Branch Chief, Aviation Operations (USFS), the National Flight Operations Manager (BLM), or appropriate State Aviation Official and approved by the flight crew. This is generally limited to three total personnel on board the aircraft during low-level ASM mission operations.

Initial ASM Training (ATP/ATS)

Objective

- To establish the qualification and training requirements necessary to perform as an ASM.

Nomination

- RAO's/agency program managers will nominate candidates to attend ASM initial training.

Documentation of Training

It is the responsibility of the ATS/ATP candidate to maintain and update a training and experience folder which will include:

- Course completion certificates.
- Certification page of ATGS PTB for ATS.

- Annual update of experience to agency specific Incident Qualification and Certification System.
- ATS/ATP Letter of Authorization.

Deviations or Exceptions – The WO Branch Chief, Pilot Standardization in coordination with the appropriate RAO and the WO Aerial Supervision Program Manager (USFS), the National Flight Operations Manager (BLM), or appropriate State Aviation Official may authorize deviations or exceptions from the training requirements. Approved deviations or exceptions will be in writing. Documentation will be maintained by the appropriate Agency Official and a copy will be carried in the trainees training folder.

ASM Initial/Refresher Course of Instruction

Classroom Training

- ASM initial is a national level course.

Required Classroom Elements

- Safety
- Tactical Mission CRM
- Communications (Tactical)
- Aircraft Familiarization/Differences
- Tactics (ASM Specific)
- Airtanker/ Helicopter Sequencing

Optional Classroom Elements

- Crew interaction and CRM utilization
- Incident Command System-(Aerial Supervision Specific)
- Pre-season Update: (Program Updates/Changes, Expected fire behavior, Long-term weather prognosis)
- Additional elements may be added based on national trends and needs
- Global Positioning System (GPS)/Radio/Technology- Review

Operational Mission Instruction

ASM candidates should have a variety of OJT. The following flight training requirements provide guidance for evaluating ASM candidates. Individualized training and evaluation programs should be developed to refine the skills and abilities of each trainee prior to certification.

ATS Initial Observation Flights

Two observation flights must be completed prior to front seat flight training. One of these flights must occur on a fire mission:

- Two simulated missions to occur during ASM Initial.
- Initial OJT must occur under the direct supervision of an ATS Evaluator in the same aircraft.
- After initial OJT and when mutually agreed upon by the ATP Evaluator and ATS Evaluator an ATS trainee may be authorized to continue training with an ATP Evaluator without an

ATS Evaluator onboard the aircraft. Approval will be made on a case by case basis. A final evaluation must be conducted by an ATS Final Evaluator on board the aircraft.

ASM Evaluation

The standard method for evaluating ATS performance is an actual or simulated mission utilizing the ASM Mission Evaluation form.

Recommended minimum incident complexity for final evaluation:
Crew members (ATP & ATS) work load will be balanced and at a tempo that limits verbal communication and requires nonverbal communications be utilized for a portion of the mission.

Low-level operations while coordinating a minimum of 2 air tankers and 2 helicopters in collaboration with ground resources shall occur. The ASM crew shall have operational control of the 4 aircraft, working low level on the incident. Demonstrate CRM on a moderate complexity incident.

ATS Certification

Upon completion of the task book the ATS Final Evaluator will:

- Administer a final ASM Mission Evaluation, ensuring successful performance of the ATS (T).
- Return the completed task book to the ATS trainee along with recommendations.
- Notify the appropriate agency program manager.
- The ATS trainee is responsible for submitting completed PTB, training documentation, and final recommendation to certifying official.
- The WO Branch Chief, Pilot Standardization in coordination with the appropriate RAO (USFS), BLM National Flight Operations Manager, or State Aviation Official issues a Letter of Authorization to the employee and supervisor.

ATP Certification

The ATP Final Evaluator will:

- Administer a final ASM Mission Evaluation, ensuring successful performance of the ATP (T).
- Notify the appropriate agency program manager.
- The ATP trainee is responsible for submitting training documentation, and final recommendation to certifying official.
- The WO Branch Chief, Pilot Standardization in coordination with the appropriate RAO (USFS), BLM National Flight Operations Manager, or State Aviation Official issues a Letter of Authorization to the employee and supervisor.

ATS Supplemental Training

- Attend professional simulator training as a crew
- Agency provided Pinch Hitter Course -(Aircraft Specific)
- Private Pilot Ground School/Private Pilot Rating

ASM Currency

- 5 ASM missions per year
- ATP: ASM missions can be considered Leadplane missions. Leadplane missions do not count toward ATP currency
- The annual mission summary will be forwarded to the agency program manager
- If currency lapses a final evaluation must be performed on an actual/simulated mission
- Attend an ASM refresher triennially

1 year lost currency: If the ATS has not met the 5 mission requirement in the previous 12 months, attendance to the ASM refresher portion of National Aerial Supervision Training Academy (NASTA) will be required. Classroom participation and 1 front seat role playing mission while being evaluated by a current Evaluator will occur. If the ASM Evaluator notes any non-standard practices or deficiencies additional flights shall occur prior to “recertification” with a current ASM Final Evaluator. A passing “final evaluation” must be documented during ASM initial or on an actual wildfire assignment.

2 consecutive years of lost currency: Attendance to the ASM initial portion of NASTA will be required. 8 hour ground school, classroom participation, and 3 hot seat missions while being evaluated. A passing “Final Evaluation” must be documented and forwarded to the appropriate agency program manager for “recertification”. If the evaluation is not successful the ASM Final Evaluator will forward all documentation to the appropriate agency program manager with appropriate recommendations.

Quality Assurance: agency program managers may request a Quality Assurance (QA) assessment. QA evaluations may occur during ASM refresher, ASM initial, or over an incident. The request will be made from the program manager to the NASTA course coordinator to describe intent and needs if it needs to occur during NASTA. The course coordinator will facilitate flights to ensure the QA request needs are met on a case by case basis.

ASM Deficiencies

If an ASM is performing deficiently:

- The event will be discussed with the individuals, and documented. Documentation should consist of recommendations on how to bring ASM up to currency standards; additional academics, coaching, mentoring, observations, etc.
    - The recommendations will be forwarded to the WO Branch Chief, Pilot Standardization and appropriate RAO (USFS), the National Flight Operations Manager (BLM), or appropriate State Aviation Official. The crew may be made unavailable for ASM assignments in the appropriate dispatch/status system. This may not make them individually unavailable for Leadplane or ATGS assignments.

Air Tactical Supervisor Coach

An ATS Coach serves as a point of contact and SME for the trainee throughout the training process.

Position Requirements

- Qualified ATS Evaluator

Responsibilities

- Help develop a training plan for the candidate.
- Coordinate with the agency program manager and Employee Supervisor.
- Assure training is on track and that all requirements are being scheduled so as to not delay progress.
- Assist with any problems regarding agency and training requirements.
- Coaches should be an independent, nonpartisan person outside the employee's standard chain of command.

Air Tactical Supervisor Evaluator

ATS Evaluator provides consistent ATS instruction, evaluation, and feedback on ATS missions.

Position Requirements

- Qualified ATS
- AD are authorized for this position providing they meet the position requirements
- Maintain ATS currency
- Attend ASM Evaluator Workshop
- The RAO/agency program manager will track ATS Evaluator

Responsibilities

- Utilize applicable methods to promote ATS trainee progress and ultimate certification.
- Utilize training aids, best practices, forms, and policy documents to maximize the training experience.
- Review and complete applicable PTB elements.
- Document strengths, area for improvement, and focus areas utilizing the ASM Mission.

Evaluation Form.

- Provide feedback to the trainee's supervisor/coach.
- Share progress reports with ATS Evaluator community.
- Coordinate with trainee's supervisor to recommend and schedule final evaluation flight).

ASM -Evaluator Workshop

Objective

Prepare ATS/ATP Evaluators to apply current and consistent training procedures.

- Target Group – Qualified ATS/ATP
- Workshop Instructor Requirement –ATS/ATP Evaluators and Final Evaluators

Nomination Process

The ATS working group, in conjunction with the WO Branch Chief, Pilot Standardization, appropriate RAO and the WO Aerial Supervision Program Manager (USFS), the National Flight Operations Manager (BLM), or appropriate State Aviation Official will nominate ATS/ATP's who meet the qualifications and whom they consider to have the experience, aptitude, dedication, and ability to perform the duties of an ATS/ATP Evaluator.

Course Prerequisite

Multi-Region experience as a qualified ATS/ATP

Course Level

National Interagency

Course Content

- Instructional methods
- Utilization of the ASM Mission Evaluation Form
- Mission flights
- Lecture
- STEX
- AAR
- Standardization of instruction
- CRM/Human Factors – How to provide constructive criticism
- Training Aids
- Policy

Air Tactical Supervisor Final Evaluator

ATS Final Evaluators provide final ATS trainee evaluation and complete Final Evaluator verification page in the ATS PTB.

Position Requirements

- 1 Year of experience ATS Evaluator.
- AD employees are NOT authorized to perform this function.
- Maintain ATS currency.
- Attend ASM Final Evaluator Workshop.
- The WO Branch Chief, Pilot Standardization in coordination with the appropriate RAO (USFS), the National Flight Operations Manager (BLM), or appropriate State Aviation Official will provide a letter of authorization to the ATS Final Evaluator upon completion of the requisite training.

Responsibilities

- Coordinate with ATS Evaluator and trainee’s supervisor to schedule and implement a final evaluation.
- Perform final evaluation and complete ASM Mission Evaluation form.
- Complete the PTB.
- Review evaluation with ATS trainee.
- Contact trainee’s supervisor and review the final evaluation.

ASM- Final Evaluator Workshop

Objective

Prepare ATS/ATP Final Evaluators to apply current and consistent training procedures.

- Target Group: Qualified ATS/ATP Evaluator
- Workshop Instructor Requirement –ATS/ATP Evaluators and Final Evaluators

Nomination Process

The ATS working group, in conjunction with the WO Branch Chief, Pilot Standardization, appropriate RAO and the WO Aerial Supervision Program Manager (USFS), the National Flight Operations Manager (BLM), or appropriate State Aviation Official will nominate ATS/ATP's who meet the qualifications and whom they consider to have the experience, aptitude, dedication, and ability to perform the duties of an ATS/ATP Final Evaluator.

Course Prerequisite

Multi-region experience as a qualified ATS/ATP Evaluator.

Course Level

National Interagency

Course Content

- Instructional methods
- Utilization of the ASM Mission Evaluation Form
- Mission flights
- Lecture
- STEX
- AAR
- Standardization of instruction
- CRM/Human Factors – How to provide constructive criticism
- Training Aids
    - Policy

Air Tactical Pilot Evaluator

ATP Evaluator provides consistent ATP instruction, evaluation, and feedback on ASM missions.

Position Requirements

- 1 Year following ATP qualification while maintaining currency.
- Attend ASM Evaluator Workshop.
- Pass an oral evaluation from an ATP Final Evaluator.
- Pass a flight evaluation from an ATP Final Evaluator.
- Maintain ATP currency.
- The WO Branch Chief, Pilot Standardization in coordination with the appropriate RAO (USFS), the National Flight Operations Manager (BLM), or appropriate State Aviation Official will provide a letter of authorization to the ATP Evaluator upon completion of the requisite training.

Responsibilities

- Utilize applicable methods to promote ATP trainee progress and ultimate certification.
- Utilize training aids, best practices, forms, and policy documents to maximize the training experience.
- Review and complete applicable PTB elements.
- Review document strengths, area for improvement, and focus areas utilizing the ASM Mission.

Evaluation Form.

- Provide feedback to the trainee's supervisor/coach.
- Share progress reports with ATP Evaluator community.
- Coordinate with trainee's supervisor to recommend and schedule final evaluation flight).

Air Tactical Pilot Final Evaluator

ATP Final Evaluators provide final ATP trainee evaluation.

Position Requirements

- 1 Year of experience as an ATP.
- Attend ASM Final Evaluator Workshop.
- Pass an oral evaluation from an ATP Final Evaluator.
- Pass a flight evaluation from an ATP Final Evaluator.
- Maintain ATP currency.
- The WO Branch Chief, Pilot Standardization in coordination with the RAO (USFS), the National Flight Operations Manager (BLM), or appropriate State Aviation Official will provide a letter of authorization to the ATP Final Evaluator upon completion of the requisite training.

Responsibilities

- Coordinate with ATP's supervisor to schedule and implement a final evaluation.
- Perform final evaluation and complete ASM Mission Evaluation form.
- Review evaluation with ATP trainee.
- Contact trainee's supervisor and review the final evaluation.

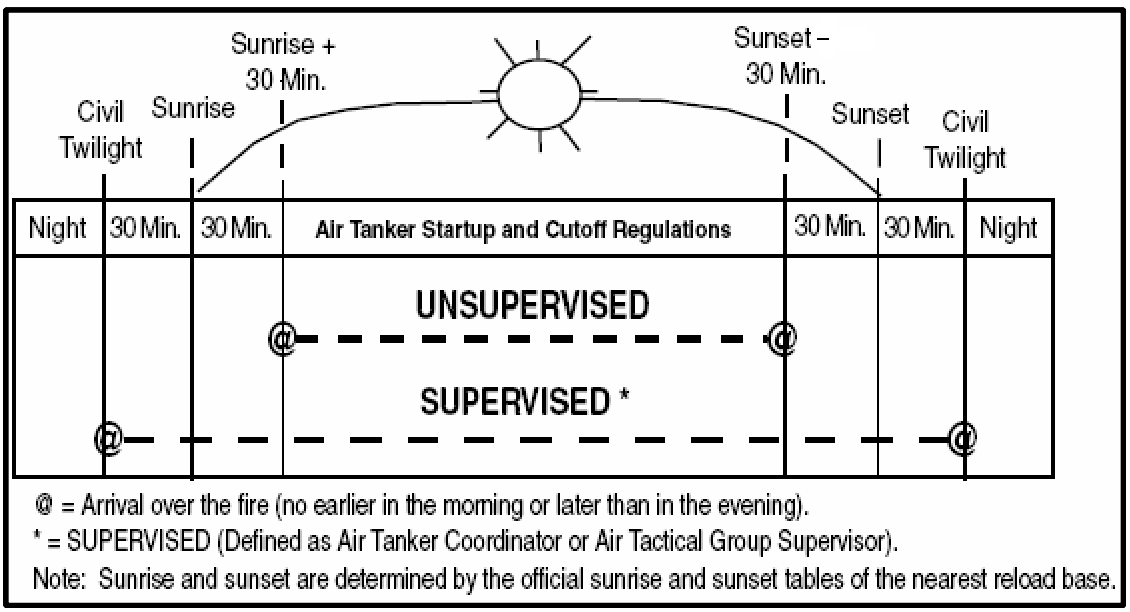
Chapter 3 – Policies, Regulations, and Guidelines

Incident aviation operations are often conducted under adverse flight conditions. Congested airspace, reduced visibility, poor weather and mountainous terrain all add risk and complexity to incident aerial supervision operations. Complexity dictates the level of supervision required to safely and effectively conduct aerial operations. Aerial supervision may be provided by a Leadplane, ATCO, ASM, ATGS or HLCO as individual resources or in any combination based on ICS models.

Retardant Operations and Low Light Conditions (Sunrise/Sunset)

Multi-engine airtankers shall be dispatched to arrive over a fire (with no aerial supervision on scene) not earlier than 30 minutes after official sunrise and not later than 30 minutes before official sunset. Retardant operations will only be conducted during daylight hours. Retardant operations are permitted after official sunset, but must have concurrence by the involved flight crews. In addition, aerial supervision (Lead, ATCO, ASM, or ATGS) must be on scene. Daylight hours are defined as 30 minutes prior to sunrise until 30 minutes after sunset as noted in the table below. Multi-engine aircraft empty of retardant may fly to assigned bases after daylight hours.

Figure 3. Multi-engine Airtanker Startup and Cutoff Regulations



In Alaska an airtanker pilot shall not be authorized to drop retardant during periods outside of civil twilight (see glossary).

- Single-engine airtankers (SEATs) and helicopters are limited to flight during official daylight hours.
- If approved by an agency, turbine helicopters (single and multi-engine) may operate at night. Flight crews might experience late dawn or early dusk conditions based on terrain features and sun angle, and flight periods should be adjusted accordingly. Daylight hours may be further limited at the discretion of the pilot, aviation manager, ATGS, ASM, or Leadplane because of low visibility conditions caused by smoke, shadows or other environmental factors.

Aerial Supervision Requirements

When aerial supervision resources are co-located with retardant aircraft, they will be launched together on the initial order to maximize safety, effectiveness, and efficiency of incident operations. Incidents with three or more aircraft assigned will have aerial supervision ordered. Federal policy dictates additional requirements as listed below.

Table 1. Incident Aerial Supervision Requirements

Incident Aerial Supervision Requirements ***ASM can perform all LEAD missions.			
SITUATION	**HLCO**	**LEAD**	**ATGS / ASM*****
Three or more aircraft assigned to incident	If no ATGS AND only rotor wing	If no ATGS AND only fixed-wing	ORDERED
Airtanker (Multi-Engine) Drops conducted between 30 minutes prior to, and 30 minutes after sunrise, or 30 minutes prior to sunset to 30 minutes after sunset.	N/A	REQUIRED IF NO ATGS	REQUIRED IF NO LEAD
MAFFS / VLAT	N/A	REQUIRED	N/A
Airtanker not IA carded	N/A	REQUIRED	N/A
Level 2 SEAT operating on an incident with more than one other tactical aircraft on scene.	N/A	REQUIRED IF NO ATGS	REQUIRED IF NO LEAD
Foreign Government Aircraft	N/A	REQUIRED IF NO ATGS	REQUIRED IF NO LEAD
Congested Area Fight Operations	CONSIDER	ON ORDER	REQUIRED
Periods of marginal weather, poor visibility or turbulence.	REQUIRED IF NOT ATGS	REQUIRED IF NO ATGS	REQUIRED
Military Helicopter Operations	ON ORDER	N/A	REQUIRED
Night Helicopter water dropping operations with 2 or more helicopters.	N/A	N/A	ORDERED
When requested by airtanker, helicopters, ATGS, Lead, ATCO, or ASM.	REQUIRED	REQUIRED	REQUIRED

- Required: Aerial supervisory resource(s) shall be over the incident when specified air tactical operations are being conducted.

- Ordered: Aerial supervisory resources shall be ordered by the controlling entity (Air tactical operations may be continued while the aerial supervision resource is enroute to the incident. Operations can be continued if the resource is not available.)
- Assigned: Tactical resource allocated to an incident. The resource may be flying enroute to and from, or on hold at a ground site.
  N/A: Not authorized or applicable to the level of supervision required for the misson/resource.

Note: A qualified smokejumper spotter (senior smokejumper in charge of smokejumper missions) may "coordinate" with on-scene aircraft over a fire until a qualified ATGS arrives.

Foreign Government Aircraft on United States Incidents

Under international cooperative agreements the US. Department of Agriculture (USDA)-USFS, DOI-BLM and state agencies may enlist the assistance of Canadian air tactical resources on United States' incidents. A Canadian Air Attack Officer flying in a Bird Dog or Leadplane aircraft will normally be assigned with Canadian airtankers. The Canadian airtanker communications system is compatible with USDA-USFS and DOI Systems. Aerial supervisors assigned to these incidents will adhere to the following policies and guidelines:

Incidents on Federal Lands

- Aerial Supervision shall be assigned to the incident as outlined in the Incident Aerial Supervision Requirements table in this chapter.
- A U.S. ATGS, ASM, or Leadplane shall supervise Canadian airtankers. In the absence of a Leadplane or ASM, the Canadian Air Attack Officer/Bird Dog is authorized to direct airtanker drops and function as ATGS (after completing an orientation).

Deviations from this policy must be specifically approved by the appropriate agency.

- Airtanker Reloads – The reload base for Canadian airtankers shall be determined by the originating dispatch.
- Canadian airtanker pilots shall be briefed on standard drop height minimums as they normally drop from lower heights.
- Canadian airtankers and helicopters operating on federal lands will be managed in the same manner as United States resources.

Incidents on Cooperator Lands

When an ATGS, ASM or Lead are assigned to a cooperator incident employing Canadian air resources; the incident will be managed as outlined in above in this chapter.

Authorization to Lead United States Airtankers

Canadian Air Attack Officers/Bird Dogs are NOT authorized to "lead" U.S. airtankers.

Flight Condition Guidelines

Aerial Supervision personnel must carefully evaluate flight hazards, conditions (visibility, wind, thunder cells, turbulence, and terrain) to ensure that operations can be conducted in a safe and effective manner. The following policies and guidelines are designed to do this:

Visibility

Regardless of time of day, when poor visibility precludes safe operations, flights will be suspended. It is recommended that all incident aircraft fly with landing and strobe lights on at all times. It is required that Leadplanes fly with landing and strobe lights on at all times. Regular position reporting is critical in marginal visibility conditions.

Night

Night air operations are approved by the Forest Service. Night air operations will be conducted in Visual Flight Rules (VFR) conditions only. Night air operations aircraft should avoid fog and smoke. Flights may need to be suspended if smoke or fog effect safe operations. All night air operations aircraft shall fly with landing and strobe lights on. Regular position reporting is critical during night air operations. Reference USFS Night Air Operations Plan.

Hazardous Conditions

Moderate to high winds and turbulent conditions affect flight safety and water/retardant drop effectiveness. A number of factors including terrain, fuel type, target location, resources at risk, cross- winds, etc., must be considered. When safety-of-flight is or may be compromised, water/retardant drops become ineffective, or at pilot recommendation aerial operations should cease. Refer to the Incident Response Pocket Guide (IRPG) PMS 461 refusal of risk process.

Evaluate thunderstorm and other hazardous weather activity for flight safety. Erratic winds, lightning, hail, and diminished visibility adversely affect aviation operations. Consider delaying operations or reassigning resources to safe operation areas. Suspend flight operations when lightning or other adverse weather conditions are present. Further reading: Interagency Aviation Accident Prevention Bulletin 13-04, MAFFS operations plan, Federal Aviation Regulations (FAR)/Aeronautical Information Manual.

Note: Any Aerial Supervisor, pilot, or ground resource can halt operations to mitigate risk or hazardous situations.

Air Attack Pilot Policy

Pilots flying air tactical missions must be Agency approved. Pilot cards must be checked prior to air tactical missions.

Air Attack Pilot Approval

Aerial supervision pilots (for ATGS or HLCO) shall be inspected and approved annually by a qualified Forest Service or Office of Aviation Services (OAS) Pilot Inspector. Qualification for air tactical missions shall be indicated on the back side of the Airplane Pilot Qualification Card.

Pilot Orientation and Training

Prior to flying their initial air tactical mission, preferably pre-season, the pilot shall receive a basic orientation/training from a qualified ATGS. As a minimum, the following shall be covered:

- General scope of the mission
- Incident air organization – emphasis on ATGS, ASM and HLCO roles
- Specific responsibilities of the ATGS

- Specific responsibilities and expectations of the ATGS pilot
- Air resources commonly assigned to, or present on, the type of incident
- Communications hardware, procedures, protocol and frequency management
- Air space management Temporary Flight Restrictions (TFRs), flight patterns, etc.)
- Operations safety
- Standard Operating Procedures
- Fuel management
- Dispatch readiness, availability for duty
- Records

Personal Protective Equipment (PPE) Policy

The following PPE is required for all interagency ATGS operations (ATGS and Pilot):

- Leather or Nomex® shoes
- Full length cotton or Nomex® pants or a flight suit
- Cotton or Nomex® shirt

The following PPE is required for all interagency HLCO operations (HLCO and Pilot):

- Leather or Nomex® shoes
- Pants and Long Sleeve Shirt made of Nomex® or a flight suit
- Leather or Nomex ® Gloves
- Flight Helmet

Leadplane and ASM

- **Policy –** The use of PPE by personnel engaged in Leadplane/ASM operations is required as per agency policy. This requirement is stated in various publications, including the USDA Safety and Health Handbook, FSH 6709.11, Chapter 3, the DOI Safety and Health Handbook, 485 DM, Chapter 20, and both departments Aircraft Accident Prevention Plans. Specific requirements for PPE differ slightly among organizations. A complete text of requirements can be found in DOI Departmental Manual (351 DM 1).

Requirements

- **Flight Suit –** One-piece fire-resistant polyamide or aramid material or equal. The useof wildland firefighter Nomex® shirts and trousers (two-piece) is authorized.
- **Protective Footgear –** Leather boots shall extend above the ankle. Such boots may not have synthetic insert panels (such as jungle boots).
- **Gloves –** Gloves made of polyamide or aramid material or all leather gloves, without synthetic liners. Leather gloves must cover wrist and allow required finger dexterity.
- **Flight Helmets –** Aerial Supervision from helicopters requires a flight helmet.

Oxygen Requirements

Flights must comply with the FAA regulations they operate under.

Part 135

14 Code of Federal Regulations (CFR) part 135.89: Supplemental oxygen must be available and used by the flight crew at cabin pressure altitudes above 10,000 feet Mean Sea Level (MSL) for that portion of the flight more than 30 minutes duration. At cabin pressure altitudes above 12,000 feet (MSL) the flight crew (including aerial supervisors) must use supplemental oxygen during the entire flight.

Part 91.211

Supplemental oxygen must be available and used by the flight crew at cabin pressure altitudes above 12,500 feet (MSL) for that portion of the flight more than 30 minutes duration. At cabin pressure altitudes above 14,000 feet (MSL) the flight crew (including aerial supervisors) must use supplemental oxygen during the entire flight. At cabin pressure altitudes above 15,000 feet, (MSL) all passengers must have supplemental oxygen available during the entire flight.

Note: Refer to aircraft contract for specific information to reference what FAR Part to utilize.

Day/Night Flight Policy

Twin-Engine Fixed-Wing

These aircraft are not limited to daylight operations. The aircraft can travel to or work over the incident before sunrise and after sunset as long as the aircraft and pilot are equipped/authorized for Instrument Flight Rules (IFR) operations. Consult agency policy for further clarification.

Single-Engine Fixed-Wing

Flight time is limited to 30 minutes prior to sunrise and 30 minutes after sunset.

***USFS* –** Use only multi-engine or turbine powered single-engine aircraft (fixed-wing or helicopter) for night flights that meet the applicable requirements in FAR Part 91 and Part 61as referenced in FSH 5709.16 or applicable contract requirements.

Helicopters

Flight time is limited to 30 minutes prior to sunrise and 30 minutes after sunset. Multi- engine helicopters are not limited to daylight operations under certain stipulations such as emergencies or lighted airports.

***USFS* –** Low-level helicopter night flight operations will primarily be conducted using Night Vision Goggles (NVG), temporary unaided flight is allowed when excessive illumination exists and becomes hazardous to NVG aided flight. Helicopters will be approved for NVG operations. Refer to agency policy and/or aircraft contract.

Flight Crew Duty Day and Flight Hour Policy

Refer to the Interagency Standards for Fire and Aviation (Red Book), Aviation Chapter, for current Interagency Interim Flight and Duty Limitations.

https://www.nifc.gov/policies/pol_ref_redbook.html

Avionics Standards

Radio Requirements

Refer to specific contract specifications and typing standards. Supervision of incident aircraft requires that the ATGS have the minimum capability of monitoring/transmitting on two Variable High Frequency (VHF)-FM frequencies, including an Air Guard, which can be continuously monitored, and two VHF-AM frequencies.

Table 2. Interagency Avionics Typing Standards

Required Avionics Equipment	Type 1	Type 2	Type 3	Type 4
Aeronautical VHF-AM radio transceiver	**2 each**	**2 each**	**2 each**	**2 each**
Aeronautical VHF-FM radio transceiver	2 each	1 each	1 each	
Panel mounted aeronautical GPS	1 each	1 each		
Handheld GPS			1 each	1 each
Required Avionics Equipment	**Type 1**	**Type 2**	**Type 3**	**Type 4**
Separate audio control systems for pilot and ATGS	X	X		
Single audio control system			X	X
Audio/mic jacks with Push-to-talk capability in a rear seat connected to co-pilot/ATGS audio control system	X	X		
Intercommunication system	X	X	X	
Plug for auxiliary VHF-FM portable radio or one additional VHF-FM transceiver	X	X		
Accessory Power Source				X
Portable Air Attack Kit				X

- **VHF-FM radio(s) –** Must be capable of simultaneously monitoring two frequencies
- (Narrowband 138 to 174 MHz).
- **Air Guard –** (168.625 MHz with transmit tone 110.9) is permanently programmed in the VHF-FM radio. This frequency must be continuously monitored.
- **Tactical Frequencies –** VHF-FM radio(s) must be capable of storing several tactical frequencies and associated Continuous Tone-Coded Squelch System tones (if applicable) such as air-to-ground, dispatch, flight following and command.

- **National Flight Following** – VHF-FM (168.650 MHz with TX and RX tone of 110.9) is used for point-to-point flight following.
- **VHF-AM radio(s)** – Two VHF-AM radios are required (see table above) that monitor 118 to 136.975MHz.

Note: USFS Region 5 and the CAL FIRE require three VHF-AM and three VHF-FM radios in the Type 1 ATGS aircraft.

In-flight Communications Failure

At time of dispatch, all aircraft must have both VHF-FM and VHF-AM radio systems in working order. In the event of a radio system failure the following will apply:

- **Total System Failure –** No ability to monitor or transmit – seek a safe altitude and route and return to base.
- **VHF-FM System Failure –** Report problem to other aircraft and dispatch (if able) on VHF-AM system and return to base.
- **VHF-AM System Failure –** Report problem to other aircraft, IC and Dispatch on VHF-FM system and return to base.

Frequency Management

- Both VHF-FM and VHF-AM frequencies are allocated to wildland agencies.
- VHF-FM is allocated by the national Telecommunications and Information Administration.
- VHF-AM is allocated by the FAA.
- VHF-AM frequencies may change from year to year.
- Additional FM and AM frequencies may be allocated during major fire emergencies.
- The agency dispatch centers may order additional frequencies through GACCs.

Communications Guidelines

Flight Following

A frequency is assigned by the dispatch center for check-ins and incident related information. National Flight Following (NFF) frequency (168.650 Tx/Rx. Tone 110.9 Tx/Rx) is the primary flight follow frequency, local units may assign an additional (VHF- AM or VHF-FM) based on unit policy. Aircraft flying long distance missions (i.e. cross-country) may be required to use the national frequency. Dispatch centers may require a 15- minute check in or a confirmation that an aircraft is showing "positive" on the automated flight following (AFF) system.

Note: Consult the local dispatch center for local procedures.

Air-to-Ground Communications

It is essential to have a dedicated air-to-ground frequency that is continuously monitored by aerial supervision resources. The ATGS must always return to air-to-ground after using other VHF-FM frequencies.

- **IA –** Many agencies have pre-assigned FM air-to-ground frequencies assigned to geographic areas. Other agencies use standard work channel frequencies.
- **Extended Attack Incidents –** Specific frequencies should be ordered to avoid radio conflicts with other incidents. Complexed incidents often require two air-to-ground frequencies to separate command and tactical air-to-ground communications. These frequencies must be ordered through the dispatch system. Once assigned to an incident frequencies and their specified use will be listed in the ICS 220 Air Operations Summary and the ICS 205 Incident Radio Communications Plan.

- **Project (large scale, long-term) Incidents –** National Incident Radio Cache (NICD) radios are programmed with five air tactical frequencies that can be used for air-to-ground communications. Other frequencies can be assigned if there are no radio conflicts with other incidents. These frequencies are assigned by the incident's Communication Unit Leader and are listed in the ICS-220 (Air Operations Summary), and ICS-205 (Incident Radio Communication Plan).

Air-to-Air Communications

Communication between all airborne incident aircraft is critical to safety and effectiveness. Air-to-air communications is usually accomplished using a VHF-AM frequency. California uses a VHF-FM for air-to-air communications which requires 3 FM radios.

- **Primary Air-to-Air** –Air-to-air frequencies are assigned on an aircraft dispatch form. Agencies may have pre-assigned air-to-air frequencies for IA specific to geographic areas. Specific frequencies should be ordered for extended attack incidents to avoid conflict with other incidents through the local dispatch center. Extended attack incidents have discreet air-to-air frequencies assigned by the incident's Communication Unit Leader and are listed in the ICS-220 (Air Operations Summary), and ICS-205 (Incident Radio Communication Plan).
- **Secondary Air-to-Air –** Air-to-air frequencies are assigned on an aircraft dispatch form. If needed due to radio congestion, a second air-to-air frequency should be established for helicopter operations. This frequency may also be used for the flight following frequency at the helibase. The ATGS should retain the primary air-to-air frequency for fixed-wing operations so airtankers enroute to the incident can check in. A discreet air-to-air frequency may be required for Leadplane operations.

Air-to-Air Continuity

The ATGS must monitor all assigned air-to-air frequencies. The ATGS must also maintain continuous air-to-air communications with other incident aircraft. Air resources under the direct supervision of the ATGS must monitor their assigned air-to-air frequency.

Air Guard

VHF-FM 168.625 (TX Tone 110.9) has been established as the USDA/DOI emergency frequency. This frequency is permanently programmed and continuously audible in the multi-channel programmable radio system.

Authorized uses of the Air Guard frequency include:

- In-flight aircraft emergencies
- Emergency aircraft-to-aircraft communications
- Emergency communications between air and ground resources
- Dispatch contact (when use of the designated flight following frequency does not result in positive communications)
- Initial call, recall, and redirection (divert) of aircraft when assigned frequencies fail to work

Air-to-Air Enroute Position Reporting

During periods of poor visibility a VHF-AM or FM frequency may be established for assigned aircraft position and altitude reporting (calls in the blind).

Backcountry Airstrips / Uncontrolled Airstrips

When there is a potential conflict between agency aircraft and public users of back country airstrips announce intension relating to fire activity on the appropriate back country frequency. The Air Attack Pilot should monitor Unicom / Multicom / Common Traffic Advisory Frequency and brief the ATGS regarding traffic.

Conflicting Radio Frequencies

When multiple incidents in relatively close proximity are sharing the same tactical frequencies, interference can seriously impair operations. The ATGS must recognize this and request different frequencies through dispatch or the IMT Communications Unit Leader. ATGS may select a "LOW" transmit power setting, if available to attempt to mitigate interference issues. A local (geographic area) frequency coordinator and the National Incident Radio Support Cache should be involved when assigning frequencies where several incidents are in close proximity.

Tone Guards

Tones have been established to allow the use of assigned frequencies selectively. The tone can be programmed, or selected, on VHF-FM radios for both receive and transmit frequencies positions When tones are assigned incident aircraft shall use them as directed. When frequencies are protected in the "receive" position only radios that have specified tone in their "transmit" position will be heard.

Air Resource Identifiers

- ATGS identifier is "Air Attack"
  - Enroute to/from incident – options include:
- Unit name (ex. Beaver Air Attack)
- Unit assigned identifier (ex. Air Attack 621)
- Aircraft "N" number (ex. Air Attack 81C)
- Working an incident – use incident name (ex. Cougar Air Attack)
- HLCO identifier is "Helco" Helicopters enroute to and from incidents will use their unit identifier or Tail Number (last 3) until they assume incident HLCO duties
- The federal ASM identifier is "Bravo", state of Alaska units use "Alpha", and CALFIRE uses "Charlie"
- Lead identifier is "Lead"
  - Leadplanes – Pilots are assigned a one or two-digit identifier (ex. Lead 1 is "Lead one" and Lead 0-1 is "Lead zero one").
- Airtanker: Tanker plus identification number (ex. Tanker 21 is "tanker-two-one").
- Scooper: Scooper plus identification number (ex. Scooper 260 is "Scooper two-six-zero").
- Helitanker: Helitanker and identification number (ex. Helitanker 742 "Helitanker seven-four-two"). Applies to Interagency Airtanker Board approved Type 1 fixed tank helicopters.
- MAFFS: MAFFS plus identification number (ex. MAFFS 6).
- Helicopter: Copter plus last three characters of N-number (ex. Copter 72 Delta is "Copter seven-two-delta") or a locally assigned agency identifier (ex. Copter 534 is "Copter five-three-four").
- Smokejumper Aircraft: Jumper plus last two characters of N-number (ex. Jumper 41) or an agency assigned identification number.
- Other Fixed-Wing: Other fixed-wing are identified by "make or model prefix" plus last three characters of N-number (ex. Cessna 426).

- Other Identifiers:
  - Air Ops: Air Operations Director
  - Air Support: Air Support Group Supervisor
  - Operations or 'Ops': Operations Section Chief

Message Sequence

Protocol requires the resource you are calling be stated first, followed by your identification. "Tanker 23, Trinity Air Attack." Make messages as short and concise as possible.

Frequency Identification

Monitoring several frequencies when all are actively receiving makes it difficult to determine which frequency is being heard. When making initial contact, state the frequency you are transmitting on: "Lead six-eight, Bear Air Attack on Victor one-one-eight-two-five-zero"

Airspace Policy

The *Interagency Airspace Coordination Guide* covers all aspects of wildland agency airspace management. Aerial supervision personnel must be familiar with information in the guide. Dispatch centers and tanker base managers should have a copy available for reference.

Federally Designated Special Use Airspace (SUA)

Incidents may be located in, or flight routes to incidents may pass through, areas designated by the FAA as Special Use Areas. Operations through, or within these areas, may require that specific procedures be followed.

SUA "consists of airspace wherein activity must be confined because of its nature and/or wherein limitations may be imposed upon aircraft operations that are not part of those activities." These areas include Military Operations Areas (MOAs), Restricted Areas (RAs), Prohibited Areas (PAs) Alert Areas (AAs) Warning Areas (WAs) and Controlled Firing Areas (CFAs).

SUA Locations: All areas except CFAs are identified on National Oceanic and Atmospheric Administration (NOAA) Aeronautical Sectional Charts. Many of these are located in wildland areas throughout the United States.

Procedures: The Interagency Airspace Coordination Guide and the FAA Handbook 7400.2C (Procedures for Handling Airspace Matters) discuss procedures to be used when wildland aerial fire operations are requested in or through these areas. Often, flights through, or within SUA's, require authorization from the using or controlling agencies. Depending on the type of SUA involved, contact with the controlling agency may be initiated by the air resource pilot.

- **RAs –** These areas denote the existence of unusual and often invisible hazards to aircraft such as artillery firing, aerial gunnery, or guided missiles. Aircraft must obtain authorization from the controlling agency prior to entry. Many dispatch centers have a deconfliction plan for this type of airspace.
- **MOA's –** Many MOA's in the Western United States are located in airspace over agency lands. Current information regarding MOA scheduling is published in the Area Planning (AP/1B) Handbook and Charts. When wildfires occur within these areas, the responsible agency should notify the controlling agency and notify them that incident aircraft will be affected area. Do not assume that there will be no military activity in the area. Authorization is not required to enter a MOA. However, the controlling agency may alter operations in the vicinity of the incident thus increasing the margin of safety.

- **Military Training Routes (MTR’s) –** MTR’s are located over many agency lands in the United States. Centers should have daily schedule information (hot routes) and may notify the FAA and Military.
- Scheduling Activity when incident aircraft may conflict with military aircraft on or near the MTR’s. Do not assume an MTR has been de-conflicted.
- **Other Military Training Routes and Areas –** While the MOA’s and MTR’s are charted on sectional maps and the AP/IB charts, Slow Speed Low-Altitude Training Routes (SR’s) and Low-Altitude Tactical Navigation Areas (LATN’s) and other low-altitude flights are not charted and schedules are not published. Dispatch centers should alert you to these flights, if known. The ATGS will notify the dispatch center and other incident aircraft if they observe military aircraft enroute to, near or within the operations area.

Incident Airspace; the FTA

See Appendix D for FTA diagram and additional information. The airspace surrounding an incident is managed by the aerial supervisor who must implement FTA procedures. All wildland incidents, regardless of aircraft on scene, have an FTA. If an incident has an active TFR in place clearance from the controlling aircraft is required prior to TFR entry. If aerial supervision is not on scene, the first aircraft on scene will establish the FTA protocol.

The FTA is a communication protocol for firefighting agencies. It does not pertain to other aircraft who have legal access within a TFR (Medevac, Law Enforcement, Media, VFR airport traffic, IFR traffic cleared by the FAA).

Key components and procedures of the FTA include:

- **Initial Communication Ring –** A ring 12nm from the center point of the incident. At or prior to 12nm, inbound aircraft contact the ATGS or appropriate aerial resource for permission to proceed to the incident. Briefing information is provided to the inbound aircraft by the aerial supervision resource over the incident (ATGS, Lead, ATCO,ASM, or HLCO).
- **No Communication (NOCOM) Ring –** A ring 7nm from the center point of the incident that should not be crossed by inbound aircraft without first establishing communications with the appropriate aerial supervision resource.
- **Three (3) C’s of initial contact –** Communication requirements and related actions to be undertaken by the pilot of the inbound aircraft:
- **Communication –** Establish communications with the controlling aerial supervision resource over the incident (ATGS, ATCO, ASM, HLCO).
- **Clearance –** Receive clearance from aerial supervision resource to proceed to the incident past the NOCOM ring. Inbound pilot will acknowledge receipt of clearance or (hold) outside the NOCOM ring until the clearance is received and understood.
- **Comply –** Inbound aircraft will comply with clearance from aerial supervision resource. If compliance cannot be accomplished, the inbound aircraft will remain outside the NOCOM ring until an amended clearance is received and understood.
- **Departing Aircraft –** Aircraft departing incident airspace must follow assigned departure route and altitude. Aerial Supervisors must establish deconflicted routes for departing aircraft within the FTA or TFR.

TFR

Under the conditions listed below the responsible agency should request a TFRs under FAR Part 91.137. A TFR may be initiated by the dispatch center, IC, AOBD, Lead, ASM, or ATGS.

For more information, refer to the *Interagency Airspace Coordination Guide* or FAR Part 91.137.

Considerations for Requesting and Constructing a TFR The Interagency Airspace Coordination Guide covers this subject in detail. Factors which must be considered are:

- Length of operation: Extended operations (>3 hours) are anticipated. Local agency policy for the anticipated length of incident operations may apply
- Congested airspace involved: Operations are in the vicinity of high-density civil aircraft operation (airports)
- Incident size and complexity
- Potential conflict with non-operational aircraft
- Extended operations on MTR's
- Extended Operations within SUA
- The type and number of aircraft operations occurring within the incident airspace and their aeronautical requirements
- The operating altitudes to provide the ATGS a safe operating orbit
- Entry and exit points and routes to bases
- Other aviation operations in the geographic area
- Size, shape and rate of increase of the incident
- Location of the incident helibases, water sources, etc.
- Location of airports

Aerial Supervision Responsibilities regarding TFRs– During the IA phase of an incident, the aerial supervisor may initiate a request for a TFR. The aerial supervisor should provide information required on the Interagency Request for TFRs Form and radio this information to the responsible dispatch coordination center. On Type 1 or 2 incidents, the ATGS in consultation with the Lead or ASM, will advise the AOBD when the dimensions of the TFR should be increased or decreased. These changes must be forwarded immediately to the dispatch center that will initiate a new order to the FAA. The aerial supervisor should coordinate with the incident AOBD or local dispatch office as appropriate to recommend termination of an existing TFR.

Ordering a TFR – Three pieces of information are required:

- Center point in DMS format
- Vertical dimension in feet MSL
- Horizontal radius in Nautical Miles (NM) from center point
    - Non-standard/non-circular TFR dimensions require points in DMS format at each corner of the polygon.

TFR Lateral Dimensions – The suggested radius for a TFR is 7NM from the center point. Any incident helicopter operating bases within "reasonable distance" should be included (helibase, heli-dip site) within the TFR. The lateral dimensions/shape may be irregular to conform to incident airspace requirements TFRs reaching 20 NM will require a special frequency from the FAA.

TFR Vertical Dimensions – The suggested guideline for an incident TFR is 2,000 feet above the highest terrain (ground level) in the affected area or 2000 feet above the highest flying aircraft. If necessary, **3,500 feet is recommended**. The vertical and lateral dimensions of the desired airspace may conflict with FAA requirements and what they will approve. The FAA, through the dispatch center, will provide the approved TFR dimensions. If airspace needs are not met, request new TFR dimensions. Again, the adjusted TFR requires FAA approval.

TFRs for Multiple Incidents in Close Proximity – Multiple incidents in close proximity may result in overlapping restrictions. To avoid confusion the respective dispatchers and AOBDs should consolidate multiple TFR's into one manageable TFR. This will need to be negotiated between agencies and IMT's. Frequency management will also need to be considered. As long as the TFRs do not overlap, they may share boundaries.

Proper Identification of TFR Part 91.137 Paragraph – TFR Part 91.137 is divided into three sections referred to as Paragraphs (a)(1), (a)(2), and (a)(3) indicating the type of disaster event normally associated with each designation. The most commonly requested TFR for wildfire is 91.137 (a)(2).

- Volcanic eruption, toxic gas leaks, spills.
- Forest and range fires, earthquakes, tornado activity, etc. Disaster/hazard incidents of limited duration that would attract an unsafe congestion of sightseeing aircraft, such as aircraft accident sites.
- Incidents/events generating high public interest such as sporting events.

Non-Incident Aircraft TFR Policy

14 CFR 91.137 (a) 2 prescribes how TFRs are established to provide a safe environment for the operation of disaster relief aircraft. When a Notice to Airmen (NOTAM) has been issued under this CFR section, all aircraft are prohibited from operating in the designated area unless at least one of the following conditions is met:

- "The aircraft is participating in hazard relief activities and is being operated under the direction of the official in charge of on scene emergency response activities."
- "The aircraft is carrying **law enforcement** officials."
- "The aircraft is operating under the Air Traffic Control **(ATC) approved IFR flight plan.**"
- "The operation is conducted **directly to or from an airport** within the area, or is necessitated by the impracticability of VFR flight above or around the area due to weather, or terrain; notification is given to the Flight Service Station (FSS) or **ATC facility** specified in the NOTAM to receive advisories concerning disaster relief aircraft operations; and, the operation does not hamper or endanger relief activities and is not conducted for observing the disaster."
- "The aircraft is carrying properly accredited news representatives, and prior to entering the area, a flight plan is filed with the appropriate FAA or ATC facility specified in the Notice to Airmen and the operation is conducted above the altitude used by the disaster relief aircraft, unless otherwise authorized by the official in charge of on scene emergency response activities."

Note: According to FAA JO7210.3Z "Coordination with the official in charge of on scene emergency response activities is required prior to ATC allowing any IFR or VFR aircraft to enter into the TFR area." The FAA Advisory Circular 91-63C states "Notification must be given to the ATC/FSS specified in the NOTAM for coordination with the official in charge of on scene emergency response activities."

Some accommodations (for flights such as early morning agricultural spraying operations) can be made through the establishment of time specific TFRs that releases the airspace for use after hours.

ATGS, ASM and HLCO do not have legal authority to waive 14 CFR 91.137 and allow nonparticipating aviation (see previous page) to "pass through" the TFR area. They have only two options: (1) Release the TFR (through normal ordering channels) to accommodate the requests (2) Advise the requestor that they will have to continue to fly around the TFR for their own safety.

Air Operations in Congested Areas

Airtankers can drop retardant in congested areas under DOI authority given in FAR Part 137. USFS authority is granted in exemption 392, FAR 91.119 as referenced in the Forest Service Manual 5714.11. When such are necessary, they may be authorized subject to these limitations:

- Airtanker operations in congested areas may be conducted at the request of the city, rural fire department, county, state, or federal fire suppression agency.
- An ASM or Leadplane is ordered to coordinate aerial operations.
- The ATC facility responsible for the airspace is notified prior to or as soon as possible after the beginning of the operation.
- A positive communication link must be established between the ATCO or the ASM, airtanker pilots, and the responsible fire suppression agency official.
- The IC or designee for the responsible agency will advise aerial supervision personnel or airtanker that the line is clear before retardant drops.

Use of Firefighting Aircraft Transponder Code 1255

All incident aircraft will utilize a transponder code of 1255 unless another code is assigned by ATC.

Responses to Airspace Conflicts and Intrusions

When incident airspace conflicts and intrusions occur the aerial supervisor must:

- Immediately ensure the safety of incident aircraft.
- Notify incident aircraft in the immediate area of the position of the intruder.
- Attempt radio contact with intruder aircraft by use of VHF-AM (known Victor, local Unicom) and VHF-FM (assigned, local, or Air Guard) frequencies.
- If radio contact can be established, inform the intruder of the incident in progress, airspace restriction limitations in effect, and other aircraft in the area. Determine if the intruder has legitimate authority to be within the TFR.
- Request intruder depart restricted area (assign an altitude and heading if necessary). Request the intruder to stay in radio contact until clear of the area.
- If the aircraft is a legitimate "nonparticipating" aircraft and has the authority to be within the area, communicate with the aircraft and advise incident aircraft of its presence. If possible, coordinate altitudes and locations.
- For drone conflicts and intrusions please reference:
    - Unmanned Aircraft Systems: https://www.faa.gov/uas

- The ATGS may request, but not demand that the aircraft check in with the ATGS as needed. If radio contact is not established:
  - No attempt to drive, guide or force the intruder from the area should be made. The aerial supervisor must monitor intruder's position, altitude, and heading.
  - Try to ascertain the N-number without imposing a hazard.
  - The aerial supervisor must ensure that incident aircraft are informed and kept clear of intruder. This may require removing incident aircraft and curtailing operations for as long as intruder is considered a potential hazard.
  - Report intruder immediately to local dispatch office and ask them to contact the Air Route Traffic Control Center (ARTCC). The FAA sometimes has the capability of tracking an aircraft or identifying the aircraft.
  - If there is a conflict or intrusion, report it to the appropriate dispatch center. Ask dispatch to report the intrusion the local ARTCC.
  - Submit a Mishap or Aviation Safety Communiqué (SAFECOM) Report as per agency policy and procedures.

SUA Reminders

- Check with dispatch when receiving the Resource Order.
- Is the incident in SUA?
- Is the Restricted Area/MOA/MTR "hot" or about to be?
- Confirm military has been notified and what action will be taken.
- The pilot must obtain clearance/routing through or around RAs enroute to the incident.
- Always be alert for military aircraft even when SUA/MTRs are "cold."

Canadian Airtankers on U.S. Border Fires

On fires near the Canadian/U.S. border, a Canadian Air Attack Group may be dispatched to a U.S. fire.

- Normally this group includes two tankers or scoopers and a Bird Dog.
- On board the Bird Dog is an Air Attack Officer, very similar to an ATGS.
- Typically on a 'quick strike' across the border, the Bird Dog would assume control of the airspace and work the fire until/unless a U.S. ATGS is present.
- When a U.S. ATGS is on scene, the ATGS has overall responsibility for the airspace.
- The Bird Dog is in charge of directing Canadian airtanker operations much like a Leadplane under the supervision of the ATGS. The ATGS is responsible for the direction of all U.S. resources and the Bird Dog.
- Refer to policies of the local agency or your home agency with regard to utilization of Canadian air resources.
- The local unit Dispatch should coordinate flights with Air and Marine Interdiction Coordination Center at 1-866-AIRBUST.

Chapter 4 – Incident Aircraft

Aerial supervisors should have knowledge of the types of aircraft they supervise, how to communicate with them, and the logistics required to support them.

Tactical and logistical aircraft supervised and coordinated by aerial supervisors may be procured from the USDA Forest Service, DOI Office of Aviation Services, United States (US) Department of Defense, or state, county or municipal sources. Contract or procurement agreement requirements and standards will vary among the various sources. For more detailed information about air tactical and logistical aircraft, refer to the Aircraft Identification Library on the DOI/USFS Interagency Aviation Training site at: https://www.iat.gov/aircraft_library/index.asp

Very Large Airtankers (VLAT)

VLAT Operations

The Standard Operating Procedures listed below are to be considered when using VLAT on wildland fires. The Standard Operating Procedures (SOPs) below have made the operation with the VLAT cohesive and safe with other aerial resources.

VLAT Considerations

- Establish flight paths holding areas/altitudes, to avoid creating hazards to other aerial resources within the FTA.
- To avoid wake turbulence, it is required to wait a minimum of 3 minutes after the VLAT has dropped to resume aerial operations near the pattern from the drop.

Large Airtanker

The ICS recognizes four categories or classifications of airtankers based on gallons retardant/suppressant capability. The VLAT classification/type exists only in Forest Service contract language.

Airtanker Type 1

- Approved by the Interagency Airtanker Board and the contracting agency
- 3,000 minimum gallon capacity

Airtanker Type 2

- Approved by the Interagency Airtanker Board and the contracting agency
- 1,800 – 2,999 gallon capacity

Airtanker Type 3

- Approved by the Interagency Airtanker Board and the contracting agency
- 800 – 1,799 gallon capacity

Airtanker Type 4

- Approved by the DOI, and contracting agency
- Less than 800 gallons

Table 3. Airtanker Classification

(Does not account for retardant download requirements)

Type	Aircraft Make & Model	Maximum Gallons	Cruise Speed	Tank/Door System
VLAT	DC-10	11,900	380 kts	3 Constant Flow Tanks
VLAT	747	19,600	500 kts	1 Pressurized System
Type 1	C-130 (MAFFS)	3,000	300 kts	1 Pressurized System
Type 1	C-130	3,000	300 kts	1 Constant Flow
Type 1	DC-7	3,000	235 kts	8
Type 1	BAE-146	3,000	330 kts	5 Valves-Constant Flow
Type 1	RJ-85	3,050	340 kts	1-Constant Flow
Type 1	MD-87	3,000	320 kts	1-Constant Flow
Type 2	P2-V	2,450	184 kts	6
Type 3	CL-215, Scooper	1400	160 kts	2 (foam capable)
Type 3	CL-415, Scooper	1600	180 kts	4 (foam capable)
Type 3	S2 Turbine Tracker	1,200	230 kts	1-Constant Flow
Type 3	Air Tractor AT-802 F	800	140 kts	1-Constant Flow
Type 4	Air Tractor AT-802/602	600-799	140 kts	1 (in-line or horizontal)
Type 4	Turbine Thrush	400-770	122 kts	1 (in-line or horizontal)
Type 4	Turnbine Dromader	500	122 kts	1 (in-line or horizontal)

Airtanker Retardant Delivery Systems

Due to the number of approved airtanker makes/models and the number of airtanker operators there are several approved tank/door systems. The tank/door systems are (since 1970) evaluated and approved by the Interagency Airtanker Board and or contracting agency, to ensure that the systems meet desired coverage level and drop characteristics. The four basic systems used today include the following:

- **Variable Tank Door System –** Multiple tanks or compartments controlled by an electronic intervalometer control mechanism to open doors singly, simultaneously or in an interval sequence. The pilot may select a low flow rate or a high flow rate.
- **Constant Rate System –** A single compartment with two doors controlled by a computer. The system is capable of single or multiple even flow drops at designated coverage levels from.5 Gallons per 100 Sq. feet (GPC) to +8 GPC.
- **Pressurized Tank System –** MAFFS C-130s are equipped with a pressurized system to discharge their 3,000 gallons of retardant through one (18”) dispensing nozzle. The system is capable of Coverage Level (CL) 1, 2, 3, 4, 5, 6, and, 8. The line width is about 70% of other (LAT) systems, but is more continuous throughout the drop. MAFFS pattern is the same as an S2T, constant flow, setting/coverage level 8.
- **Standard Tank System –** This system is common on SEATs. Single or multiple tanks/compartments controlled manually or electronically. Some tank systems may be controlled by an electronic intervalometer control mechanism to open doors singly, simultaneously or in an interval sequence.

Use of Non-Federally Approved Airtankers:

A non-federally approved airtanker is an airtanker that is on contract with a cooperator and may not meet Forest Service or DOI contract standards or policy and may not meet National Association of State Foresters Cooperator Aviation Standards.

If a wildland fire on federal lands is threatening life and public safety, and no federally approved air tankers are available to meet the time frames, but a non-federally approved air tanker is available the designated GACC operations officer can assign the use of the non- federally approved airtanker. The GACC duty officer will notify the appropriate aviation contact(s) at the National and Regional/BLM state offices of this action. The GACC will then attempt to reassign a federally approved air tanker as soon as possible, documenting the non-federally approved airtanker's use. Once a comparable federally approved airtanker is on scene of the incident or when the threat to life and public safety has been alleviated, the non-federally approved airtanker will be released.

Non-federally approved airtankers are permitted to reload out of federal airtanker bases, following the standards established in the *Interagency Airtanker Base Guide*.

Helicopters

ICS categorizes three types of helicopters based on minimum gallons of water/retardant, lift capability, number of passenger seats, and pound card weight capacity. Operations personnel refer to helicopters by type. Density altitude will greatly affect lift capability.

Loads under high-density altitude conditions are displayed in the helicopter classification table.

- Helicopter Type 1: Heavy
- Helicopter Type 2: Medium
- Helicopter Type 3: Light

Table 4. Helicopter Classification

Helicopter Type	Aircraft	Typical Payload at 8000' Density Altitude (lbs)	Typical Payload at 11,000' Density Altitude (lbs)
Type 1 (Heavy)	Sikorsky S-64E (Aircrane)	12,700	9,117
Type 1 (Heavy)	Sikorsky S-64F (Aircrane)	15,640	10,288
Type 1 (Heavy)	Boeing 234 (Chinook)	19,063	15,363
Type 1 (Heavy)	Boeing 107 (Vertol)	4,656	3,424
Type 1 (Heavy)	Sikorsky S-61	4,038	2,221
Type 1 (Heavy)	Bell B-214	3,754	2,665
Type 1 (Heavy)	Aerospatiale 332L (Super Puma)	4,328	2,729
Type 1 (Heavy)	Aerospatiale 330 (Puma)	4,525	3,325
Type 1 (Heavy)	Kaman 1200 (Kmax)	5,288	4,588
Type 1 (Heavy)	Sikorsky CH-54 or CH-64 (Skycrane)	11,098	7,978
Type 1 (Heavy)	Sikorsky S-70 (Firehawk)	6,569	5,669
Type 2 (Medium)	Bell B-212	1,973	1,010
Type 2 (Medium)	Bell B-205A-1	1,294	642
Type 2 (Medium)	Bell B-205A-1+	1,596	896
Type 2 (Medium)	Bell B-205A-1++ (Super 205)	2,806	2,120
Type 2 (Medium)	Bell B-412	1,742	884
Type 2 (Medium)	Sikorsky S-58T	1,635	597
Type 3 (Light)	Aerospatiale 315B (Llama)	925	925
Type 3 (Light)	Bell B-206 B3 (Jet Ranger)	715	380
Type 3 (Light)	Bell B-206 L3 (Long Ranger)	950	830
Type 3 (Light)	Bell B-206 L4 Long Ranger)	1,196	767
Type 3 (Light)	Bell B-407	1,315	880
Type 3 (Light)	Aerospatiale 350-B2 (Astar)	1,083	700
Type 3 (Light)	Aerospatiale 350-B3 (Astar)	1,972	1,911
Type 3 (Light)	Hughes 500 D	515	295

Helicopter Retardant/Suppressant Delivery Systems

There are two basic delivery systems: bucket and tank systems.

- **Buckets –** Two types of helicopter buckets are used. These include:
  - Rigid Shell (100 to 3,000 gallons)
  - Collapsible (94-2000 gallons)
- **Tanks –** Internal and external tank systems have been developed for various Type 1-3 helicopters. These include:
  - Computerized metered or constant flow tank system
  - Conventional tank/door system

Note: Type 1 helicopters with fixed tanks are referred to as "helitankers."

Aerial Supervision Aircraft

All aircraft must be carded by the appropriate agency official for the mission.

In selecting an aircraft for a particular mission, the following should be considered:

Visibility

- Fixed-Wing
  - High or low-wing aircraft designed with the cockpit forward of the wings typically provide best visibility.
  - Low-wing aircraft designed with the cockpit over the wings; provide for limited visibility.
- Helicopters:
- Open cockpit designs facilitate excellent visibility. Consider potential issues derived from doors off in-flight. Can fly under smoke layers which fixed-wing may not be able to.

Speed

For large, IA, and multiple incident scenarios, aircraft speed is important. On IA incidents in particular, it is key that the aerial supervisor arrive before other aerial resources in order to determine incident objectives and set up the airspace. Twin- engine fixed-wing aircraft are usually the best choice in these situations (150+ knots cruise speed with 200+ knots desirable).

- Twin-Engine Fixed-Wing – Fast (generally greater than 150 kts)
- Single-Engine Fixed-Wing – Slower (generally less than 150 kts)
- Helicopters – Slowest (generally less than 130 kts)

Pressurization

When performing missions above 10,000ft msl., consider a pressurized aircraft.

Endurance

Consider length of mission, distance of dispatch, and area of availability.

Aircraft Performance

Consider operating environment, payload, endurance, and training needs.

Maneuverability

It is essential that the aircraft can be positioned for the particular mission observation requirements. Helicopters are excellent for target identification and for monitoring and evaluating mission effectiveness. A Type 3 helicopter is generally the best platform for a Helicopter Coordinator.

Noise Level

Excessive noise can interfere with the ability to communicate for prolonged periods of time and can contribute to fatigue. Consider use of an active noise-canceling headset to help mitigate noise related fatigue.

- Single-Engine Fixed-Wing – Highest cockpit noise level
- Twin-Engine Fixed-Wing – Less cockpit noise level
- Helicopters – Least cockpit noise level (flight helmet is required)

IA Incidents

It is generally best to be co-located with airtankers and Leadplanes at an airtanker base to facilitate briefings. It may be desirable to be located near a dispatch center for the same reason.

- **Large Incidents –** It may be desirable to be located at or near the incident to facilitate briefing and de-briefing with the Operations Section.
- **Airport Considerations:**
    - **Single-Engine Fixed-Wing –** Can generally operate from shorter airstrips than twin-engine airplanes.
    - **Twin-Engine Fixed-Wing –** Require longer runways and usually require an improved surface.
- **Helicopters –** Helicopters are advantageous if the incident is not near any airport and if it is critical for the aerial supervisor to meet with the Operations Section Chief. Helicopters are generally utilized for HLCO, however they may also be desirable for ATGS missions when visibility is limited or helicopters are meeting incident objectives.
- **Cabin space –** Mission requirements may necessitate the need for an observer or an Air Tactical trainee/instructor in addition to minimum flight crew requirements.
    - **Safety –** Consider performance capability of the aircraft for the density altitude and terrain at which operations are conducted.
    - **Aircraft and Pilot Approvals –** Aircraft must have interagency approval to be used for an air tactical mission. The approval card must be carried onboard the aircraft. Similarly, pilots used for air tactical missions must possess a current approval card.
    - **Avionics Equipment –** In addition to the above avionics requirements, the following are required:
        - Headset(s) with boom microphones
        - Voice Activated Intercom
        - Separate Audio Panels for the pilot and ATGS/ATS
        - Separate volume and squelch controls for the pilot and ATGS/ATS
        - A separate audio panel and voice activated intercom station in a rear seat may be required in aircraft to accommodate an ATGS/ATS trainee (observer) of ATGS Evaluator or ATGS Final Evaluator

- **Traffic Collision Avoidance System (TCAS/TCAD) –** The threat of midair collision is ever present in the fire environment. TCAS/TCAD is now part of the standard equipment in Leadplanes and ASM aircraft. The systems are enhanced with special features designed to improve safety and operational effectiveness on incidents. USFS Smokejumper airplanes are equipped with TCAS.

Helicopter Emergency Services: Short Haul/Hoist Extraction.

The interagency community produces a hoist/extraction guide annually. Please refer to the following document: https://www.nwcg.gov/publications/512

Smokejumper Aircraft

Smokejumper aircraft are turbine powered aircraft carrying 8 to 18 smokejumpers plus spotters and flight crew. Smokejumpers are primarily used for IA but are also used to reinforce large fires, build helispots, etc.

Modular Airborne Firefighting System (MAFFS)

https://www.fs.fed.us/fire/aviation/airplanes/maffs.HTML

Policy

The NICC mobilizes MAFFS as a reinforcement measure when suitable contract airtankers are not readily available within the contiguous 48 states. MAFFS may be made available to assist foreign governments when requested through the State Department or other diplomatic memorandums of understanding.

The Governors of California, North Carolina and Wyoming may activate MAFFS units for missions within state boundaries under their respective memorandums of understanding with military authorities and the Forest Service. Approval of the Forest Service Assistant Director, Fire Operations is responsible for initiating a MAFFS mission. Refer to the National Mobilization Guide, Chapter 20 for additional MAFFS mobilization information.

Through the Memorandum of Understanding the USDA, Forest Service will provide the following resources:

- MAFFS unit “slip-in tank” systems.
- Qualified MAFFS Leadplane Pilot.
- MAFFS Liaison Officer (MLO).
- MAFFS Airtanker Base Manager (MABM).
- VHF-FM radios.

MAFFS Home Base (Wing) Locations

Air National Guard and Air Force Reserve units utilizing C-130 are based at the following locations:

- Charlotte, North Carolina (145th AW) – Air National Guard
- Port Hueneme, California (146th AW) – Air National Guard
- Cheyenne, Wyoming (153rd AW) – Air National Guard
- Colorado Springs, Colorado (302nd AW) – Air Force Reserve

Training and Proficiency

Training will be conducted by the Forest Service, National MAFFS Training Coordinator annually for military and agency personnel. Specific training dates will be negotiated with the military airlift wings.

MAFFS Leadplane Pilot

Agency Leadplane Pilots must participate every 4 years to be re-qualified for operations with MAFFS. Qualified MAFFS Leadplane Pilots will be listed in the National Interagency Mobilization Guide.

MAFFS Flight Crews

Training of MAFFS crews will be in accordance with military qualifications and continuation training requirements. To become qualified to fly MAFFS operations, MAFFS flight crews must attend initial and recurrent training as appropriate at the annual MAFFS training session. The Air Force Mission Commander (AFMC) will certify to the Forest Service National MAFFS Training Coordinator. The status of flight crewmembers at the completion of the annual training currency requirements are as follows:

- MAFFS airdrop currency is required annually. If more than 120 days has elapsed since the last air drop, the crew's first air drop will be restricted to a target judged by the
- MAFFS Leadplane Pilot to offer the fewest hazards.
  - If more than eight months have elapsed since the last MAFFS air drop, an airborne MAFFS Leadplane Pilot supervised water drop will be required before entering the incident area.
  - Currency training will be conducted annually.

MAFFS Operations Policies

MAFFS aircraft identification – Each MAFFS aircraft will be identified by a large, high visibility number on the aircraft tail, side of the fuselage aft of the cockpit area, and on top the fuselage cabin. The MAFFS call sign will be this number (i.e., MAFFS 2).

Supervision of a MAFFS Mission

- No MAFFS mission will be flown unless under the supervision of a qualified MAFFS Leadplane Pilot. The Leadplane Pilot will communicate with the MLO/AFMC daily on flight needs of military crews.
  - International MAFFS missions will utilize a qualified MAFFS Leadplane Pilot in the MAFFS aircraft to assist the aircraft commander with tactical requirements. Headquarters (HQ) Military Airlift Command approval must be obtained prior to flying civilian personnel aboard MAFFS aircraft.
  - Lead operations will be provided on each run and the runs are restricted to one MAFFS aircraft at a time with no daisy-chain operations of multiple aircraft in trail.

Military Flight Duty Limitations

Flight time will not exceed a total of eight hours per day.

- A normal duty day is limited to 12 hours.
- Within any 24-hour period, pilots shall have a minimum of 12 consecutive hours off duty immediately prior to the beginning of any duty day.

- Duty includes flight time, ground duty of any kind, and standby or alert status at any location.

SOPs – Procedures for working MAFFS on an incident are the same as for contract airtankers. MAFFS flight crews are rotated on a regular basis. The AFMC will verify the status of the flight crews with the MLO. Leadplane Pilots should be aware that newly rotated flight crews may have restrictions on their initial air drops to accomplish currency requirements.

Operational Considerations – The procedures for using MAFFS over an incident are the much the same as those used for contract airtankers. The ATGS should be aware of the following key differences when using MAFFS aircraft:

- **Volume –** C-130s configured with MAFFS 2 (M2) normally carry 3000 gallons unless takeoff performance requires a download.
- **Load Portions –** Capable of Start/Stop drops.
- **Coverage Levels –** M2 is capable of Coverage Levels 1, 2, 3, 4, 6, and 8.
- **Retardant Line Width –** M2 has a narrower but more uniform line pattern than commercial airtankers. This is a characteristic of the nozzle on the pressurized system. Density (coverage level) at the center meets Interagency Airtanker Board criteria and remains consistent along the path of delivery.
- **Reload –** M2 can be sent to reload at pre-approved bases identified in the *Interagency Airtanker Base Directory MAFFS Supplement*. Normally, following the final air drop MAFFS aircraft will recover to the activation base for servicing by military personnel.

Communications Considerations

- **Aircraft Identifier –** The number displayed on the aircraft fuselage will identify MAFFS aircraft.
- **Radio Hardware –** MAFFS aircraft are equipped with one Forest Service supplied P-25 compliant VHF-FM radio operating over the frequency band of 138 -174 MHz. Communications may also be conducted using a VHF-AM frequency in the 118-136.975 MHz bandwidth in the same manner as other contract air tactical resources.
- **Check in Procedure –** The ATGS (or Lead/ASM) in the absence of an ATGS) must identify the location and altitude of all other aircraft operating over the incident as well as the incident altimeter setting to all MAFFS aircraft 'checking in' enroute to the incident.
- **Dispatch Communications –** The ATGS or Lead will notify dispatch whether additional loads of retardant will be required to meet operational objectives on the incident.

Military Helicopter Operations

Regular Military refers to active military, reserve units and "federalized" National Guard aviation assets. For an in depth discussion of military helicopter operations, refer to Chapter 70 of the Military Use Handbook (2006). Key portions of the parent text are included below.

Policy

Regular military helicopter assets may be provided by the Department of Defense – Support of Civilian Authority as requested by appropriate ordering entities when civilian aviation resources are depleted.

Mission Profiles

Mission profiles for regular military helicopter units are normally limited to:

- Reconnaissance or Command and Control activities
- Medevac
- Crew transportation
- Cargo transportation (internal and external loads)
- Crew and cargo staging from airports to base camps for incident support

Bucket Operations

When bucket operations are conducted, a Helicopter Coordinator (HLCO) shall be utilized whenever military helicopters are sequenced with contracted helicopter resources.

Communications

- Military Radio Hardware – Regular military aircraft are equipped with VHF-AM aeronautical radios that operate in the 118 to 136.975 MHz bandwidth.
- Agency Provided Radio Hardware – VHF-FM aeronautical transceivers compatible with agency frequencies may be provided by the agency.

Note: Until agency furnished VHF-FM radio systems can be installed, a Helicopter Coordinator (HLCO) is required. Multi-ship operations may be conducted without a Helicopter Coordinator if at least one helicopter has communications capability using civilian bandwidths for air-to-air and air-to-ground communications.

National Guard Helicopter Operations

Policy

The use of National Guard helicopters for federal firefighting purposes within their state boundaries is addressed in applicable regional, state or local agreements or memorandums of understanding between federal agencies and specific National Guard units. The aerial supervisor should coordinate with local agency officials, agency aviation management specialists or the AOBD to ensure planned use of National Guard assets complies with applicable policy and procedures specific to the local area and/or participating jurisdictions.

Mobilization Authority

The Governor can mobilize National Guard aviation assets at the request of local or state jurisdictions for incidents on private land or multi-jurisdictional incidents.

Mission Profiles

In addition to the mission profiles discussed for regular military helicopters above, National Guard helicopters routinely engage in water bucket operations in many states.

Communications and HLCO

Lack of VHF-FM communications capability may be a problem to be addressed prior to use of National Guard aviation assets on federal or multi-jurisdictional incidents. A Helicopter Coordinator (HLCO) should be "assigned" or "on order" to mitigate communications issues with ground and aviation resources on an incident.

Training & Proficiency Assessment

Operational procedures, mission training, and proficiency vary between states, National Guard units and flight crews. The ATGS should assess the proficiency of the resource and make adjustments as appropriate to provide for the safe and effective use of National Guard resources.

Water Scooping Aircraft

Canadair CL-215, 415, and AT-802 Fire Boss.

Policy and Availability

United States – Water scooping aircraft are located or utilized throughout the US and operate on a basis where water sources are conducive to operations. These aircraft are contracted by DOI, Forest Service and State Agencies.

USFS – Forest Service contracted water scoopers shall not be loaded with chemical retardant or foam per the contract.

Canada – Water scooping aircraft are widely used in Canada, especially from Quebec west to Alberta. States bordering Canada may have agreements such as the Great Lakes Compact that outline procedures for sharing resources on fires within a specified distance from the border. There may also be provisions for extended use of Canadian airtankers in the U.S. when needed and if available. Aerial supervisors should obtain a briefing on these agreements or procedures when assigned, if applicable.

Night Aerial Supervision

A technology enhanced exclusive use fixed-wing Aerial Supervision Platform may be available and stationed in R5 USFS Southern California Operations Center (SOPS). The standard hours of the aircraft availability will be 1800-0600 however can vary throughout the fire season to maximize coverage. The night aerial supervisory platform is ordered through the South Operations GACC.

Considerations

- ATGS will be trained to the standards within the USFS National Night Air Operations Plan ATGS will be familiar with FIRESCOPE Night Flying Guidelines.
- IA Resource, may be used on large fires with concurrence from SOPS GACC.
- 14 hour duty day, 8 hour flight time within 24 hours.
- 10 hours off duty between shifts.
- If planned use on extended attack or emerging incident make effort to allow ATGS to observe operations during daylight hours.
- Only Aerial Supervisors and Aircraft that are trained and carded can supervise incident aircraft during civil twilight.

Firewatch Aerial Supervision Platforms

The USFS Firewatch Aerial Supervision Helicopter is a Bell 209 Cobra Helicopter converted for use by the US Forest Service for use as an aerial supervision and intelligence gathering platform. There are two platforms in use in Region 5, Air Attack 507 and Air Attack 509. The platforms are Technology Enhanced Initial/Extended Attack ATGS platforms based in Redding, California and repositioned as needed.

Call Signs

For mission clarification:

- When in the ATGS profile the Firewatch Aerial Supervision Helicopter will use the call sign "Air Attack 507/509"
- When performing the HLCO mission, the call sign is "HLCO"
- For intelligence gathering, mapping or suppression resource support profile, the Firewatch Aerial Supervision Platform will use the call sign "Copter 507/509"
- Mission Profiles – The USFS Firewatch Helicopter will request entry into the FTA in one of the following mission profiles:

  Tactical
  - ATGS
  - HLCO
  - Crew/suppression resource intelligence support

  Intelligence
  - Live video downlink
  - Infrared imagery/video
  - Mapping

Considerations

- Clearance for the Firewatch Platform (AA 507 or 509) into the FTA as an ATGS or HLCO should be the same as any relief or IA ATGS or HLCO, one thousand feet either above or below the on scene Aerial Supervision or controlling platform for initial briefing and transition of control.
- When in the Crew / Suppression Resource Intelligence Support profile, the Firewatch Platform may request low-level, 500 AGL and below for direct crew support.
- When performing live down link operations aircraft may request 3,000 to 5,000 AGL altitudes for better "big picture" video feed.
- Work the Cobra into the traffic patterns as any direct suppression aircraft.
- Platform may request an offsite landing to pass the Remotely Operated Video Enhanced Receiver to the ground suppression resources.
- The Firewatch Helicopter is considered a Type 2 aircraft for helispot sizing purposes.
- When mapping the incident is part of the mission, the Firewatch Platform will request transition to 500 feet AGL and below to complete the mission. The Firewatch ATGS will give the Aerial Supervision Platform an initial map starting point and either a clockwise or counterclockwise rotation of the perimeter request and follow the direction of the aerial supervisor.

Unmanned Aircraft Systems:

https://www.faa.gov/uas/

Chapter 5 – Suppression Chemicals

Wildland fire suppressants and retardants are chemical agents applied to burning and adjacent fuels. Only chemicals that are on the Qualified Products List (QPL) shall be used, and only for the delivery method approved. See the Forest Service's wildland fire chemicals Web site for details: https://www.fs.fed.us/rm/fire/wfcs/index.htm.

Refer to the Interagency Standards for Fire and Fire Aviation Operations or the Web site noted above for the most current information on fire chemicals and their use.

Definitions

Suppressants (Direct Attack Only):

A fire suppression chemical applied directly to the flame base to extinguish the flame (water, foam, gel/water enhancer).

Foam Fire Suppressants

Foam fire suppressants contain foaming and/or wetting agents. The foaming agents and percentage concentrate added affect the accuracy of an aerial drop, how fast the water drains from the foam, and how well the product clings to the fuel surfaces. The wetting agents increase the ability of the drained water to penetrate fuels. These products are dependent on the water they contain to suppress the fire. Once the water they contain has evaporated, they are no longer effective. Engines, portable pumps, helicopters, and SEATs may apply foam. Some agencies also allow application of foam from fixed- wing water scoopers.

Wet Water

Wet water foam concentrates mixed at 0.1 - 0.3 percent will produce a wet water solution (low foam, high wetting ability).

Water Enhancers

- Water enhancers contain ingredients designed to alter the physical characteristics of water to increase viscosity, accuracy of the drop, or adhesion to fuels. They improve the ability of water to cling to vertical and smooth surfaces. The consistency of these products can change depending on the quality of the water used for mixing. Once the water they contain has evaporated, they are no longer effective. They are fully approved for use in helicopter buckets and engine application. Many are also approved, at specific mix ratios, for use in SEATs, and fixed tank helicopters.

Long-Term Retardant (Direct and Indirect Attack):

- Long-term retardants contain fertilizer salts that change the way fuels burn. They are effective even after the water has evaporated, hence the name, "long-term". Large airtankers, single-engine airtankers (SEATs) helicopter buckets, and ground engines may apply retardants. Some retardant products are approved for fixed tank helicopters. See the QPL for specific uses for each product.
- Recommended coverage levels and guidelines for use can be found in the *Ten Principles of Retardant Application*, NFES 2048, PMS 440-2 pocket card.
- Retardant mixing, blending, testing, and sampling requirements can be found at the Wildland

Fire Chemical Systems Web site, Lot Acceptance and Quality Assurance page: https://www.fs.fed.us/rm/fire/wfcs/laqa.htm.

- In general, one can expect chemicals to remain effective for the following amounts of time:
  - Long-Term Retardants – Days to weeks (or until removed by environmental elements such as rain or wind)
  - Foams – Minutes
  - Water Enhancers/Gels - Minutes up to possibly an hour or more (direct sunlight breaks down gels faster). Time will vary according to weather conditions (heat, humidity, wind, etc.).

Approved Fire Chemicals

Many different long-term retardants, foams and water enhancers are approved for use. Prior to approval these agents must meet rigid criteria to ensure that they are environmentally safe, effective as a retardant or suppressant, and that the chemicals do not harm aircraft surfaces. Chemical concentrates may be dry powder or liquid concentrates prior to mixing, depending on manufacture. All USDA/DOI bases must use chemicals that are either fully approved or "conditionally approved" during field evaluations for full approval.

Retardant Mixing Facilities

Long-term retardants are available from a variety of facilities including fire incident locations. Tactical effectiveness and cost effectiveness are greatly enhanced when temporary portable mix facilities are set up on or near the incident. Facilities may be ordered through the incident management system, from agency fire caches or directly from retardant manufacturers. Long-term retardants are available or can be mixed from:

- Permanent or Reload Retardant Bases.
- Remote Retardant Base: Modular retardant base entirely transportable by Type 1 helicopter, which are excellent for remote areas with no road access.
- Portable Retardant Base: Totally portable retardant mixing system used primarily to mix and load retardant into airtankers (SEATs, large airtankers and VLATs), helicopters and ground units.
- Portable Helicopter Retardant System: Similar to the Portable Retardant Base but is more specifically designed for use by helicopters.

Airtanker Base Information

Information regarding the management and operation of airtanker bases and information about specific airtanker bases can be found in the following documents:

- *Interagency Airtanker Base Operations Guide, PMS 507*: This guide defines and standardizes interagency operating procedures at all airtanker bases for contractor and government employees.
- Interagency Airtanker Base Directory – The directory is intended to aid wildland fire managers, pilots, and contractors who operate at airtanker bases (Reference NFES 38 2537).
- Wildland Fire Chemicals Web site: found at:

  https://www.fs.fed.us/rm/fire/wfcs/index.htm

Aerial Fire Chemical Application Safety

- Personnel and equipment in the flight path of intended aerial drops should move to a location that will decrease the possibility of being hit with a drop.
- Personnel near aerial drops should be alert for objects (tree limbs, rocks, etc.) that the drop could dislodge. The IRPG provides additional safety information for personnel in drop areas.
- During training or briefings, inform all fire personnel of environmental guidelines and requirements for fire chemicals application and avoid contact with waterways.
- Avoid dipping from rivers or lakes with a helicopter bucket containing residual fire chemicals without first cleaning/washing down the bucket.
- Avoid scooping from rivers or lakes with fixed-wing aircraft or helicopter buckets containing residual fire chemicals without first cleaning the tank, aircraft underbody or bucket.
- Consider setting up an adjacent reload site and manage the fire chemicals in portable tanks or terminate the use of chemicals for that application.
- Some fire chemicals may be irritating to skin. Wash exposed areas as soon as possible after contact.

Environmental and Wilderness Effects

Retardant use in wilderness can be inconsistent with the requirement to protect and preserve natural conditions. It may be allowed if it is the minimum necessary tactic to accomplish fire and wilderness management objectives. Retardant drops should be planned to minimize effects on natural resources and future recreation use of the area. "Fugitive" colored retardant is designed to fade over time and may be a recommended tool in sensitive areas.

Waterway and Avoidance Area Policy

Interagency Policy for Aerial and Ground Delivery of Wildland Fire Chemicals Near Waterways and Other Avoidance Areas.

This policy has been adopted from the 2000 and 2009 updated Guidelines for Aerial Delivery of all wildland fire chemicals, including retardant, foam and water enhancers which were established and approved by the USFS and the DOI. It has been expanded to include additional avoidance areas for aerial delivery of fire chemicals, as designated by individual agencies, and includes additional USFS reporting requirements.

Note: This policy **does not** require the helicopter or airtanker PIC to fly in such a way as to endanger his or her aircraft, other aircraft, or structures or compromise ground personnel safety.

Table 5. Aerial and Ground Delivery Policy

Aerial Delivery Policy	Ground Delivery Policy
• Avoid aerial application of all wildland fire chemicals within 300 feet (ft.) of waterways. • Additional mapped avoidance areas may be designated by individual agency. • For USFS, whenever practical, as determined by the fire IC, use water or other less toxic wildland fire chemical suppressants for direct attack or less toxic approved fire retardants in areas occupied by threatened, endangered, proposed, candidate or sensitive species (TEPCS) or their designated critical habitats.	• Avoid application of all wildland fire chemicals into waterways or mapped avoidance areas.

Definition of Waterway:

Any body of water (including lakes, rivers, streams and ponds) whether or not it contains aquatic life.

Definition of Waterway Buffer:

300 ft. distance on either side of a waterway.

Definition of Additional Mapped Avoidance Areas:

Other areas requiring additional protection outside of the 300 ft. waterway buffer. For USFS, this may include certain dry intermittent or ephemeral streams for resource protection.

Guidance for Pilots:

- **Pilots will avoid all waterways and additional mapped avoidance areas designated by individual agencies.**
  To meet the 300 ft. waterway buffer zone or additional mapped avoidance areas guideline, implement the following:
  All Aircraft: When approaching a waterway or riparian vegetation visible to the pilot (to assist in identification if waterways) or other avoidance areas, the pilot shall terminate application of wildland fire chemical approximately 300 ft. before reaching the area. When flying over a waterway, the pilot shall not begin application of wildland fire chemical until 300 ft. after crossing the far bank or shore. The pilot shall make adjustments for airspeed and ambient conditions such as wind to avoid the application of wildland fire chemicals within the 300 ft. buffer zone.

Additional guidance to pilots for any aircraft supporting a fire on USFS lands:

- USFS may have additional mapped avoidance areas for TEPCS species, waterway buffers exceeding 300 ft. or certain intermittent or ephemeral waterways identified as avoidance areas for resource protection. Any aerial supervision resource should inquire if these avoidance areas exist on any USFS fire they are providing support to.
- Prior to fire retardant application, all aerial supervision and/or pilots shall be briefed by

dispatch on the locations of all TEPCS or other avoidance areas in the vicinity.

- If operationally feasible, pilots or the aerial supervision shall make a 'dry run' over the intended application area to identify avoidance areas and waterways in the vicinity of the wildland fire.
- Pilots should be provided avoidance area maps and information at all briefings (if not dispatched from one geographic area/unit and delivering to another geographic area).

Exceptions for USDA Forest Service:

- Deviations from the policy are allowed only for the protection of life or safety (public and firefighter).

Exceptions for All Other Agencies:

- When alternative line construction tactics are not available due to terrain constraints, congested area, life and property concerns or lack of ground personnel, it is acceptable to anchor the wildland fire chemical application to the waterway. When anchoring a wildland fire chemical line to a waterway, use the most accurate method of delivery in order to minimize placement of wildland fire chemical in the waterway (e.g., a helicopter rather than a heavy airtanker).
- Deviations from the policy are acceptable when life or property is threatened and the use of wildland fire chemical can be reasonably expected to alleviate the threat.
- When potential damage to natural resources outweighs possible loss of aquatic life, the unit administrator may approve a deviation from these guidelines.
- Reporting Requirements of Aerially Delivered Wildland Fire Chemicals into Waterways, Waterway buffer areas and Mapped Avoidance Areas.
- During training or briefings, inform field personnel of:
  - environmental guidelines for fire chemical application requirements for avoiding contact with waterways;
  - additional mapped avoidance areas as designated by individual agency; and
  - their responsibility for upward reporting in the event of application, for whatever reason, into avoidance areas.
- If application of wildland fire chemical occurs or anyone believes it may have been introduced within a waterway, waterway buffered areas or other mapped avoidance areas, the following is required as appropriate:
  - they should inform their supervisor;
  - o the information will be forwarded to incident management and the agency administrator, usually through the Resource Advisor;
  - the incident or host authorities must immediately contact specialists within the local jurisdiction; and
  - notifications and reporting will be completed as soon as possible.

  Procedures have been implemented for the required reporting. All information, including reporting tools and instructions are posted on the USFS wildland fire chemicals Web site at: https://www.fs.fed.us/rm/fire/wfcs and fire retardant site at: https://www.fs.fed.us/fire/retardant/. The USFS has additional reporting requirements for threatened, endangered, proposed, candidate and USFS listed sensitive species for aerially delivered fire retardant only. This requirement resulted from the Forest Service's acceptance of Biological Opinions received from the National Marine Fisheries Service (NMFS) and the Fish and Wildlife Service (FWS) and the 2011 Record of Decision for Nationwide Aerial Application of Fire Retardant on National Forest System lands. The procedures, reporting tools and instructions can be found at the same website listed above.

Endangered Species Act (ESA) Emergency Consultation

The USFS has completed consultation with regulatory agencies (FWS and NOAA) for aerial delivery of fire retardant (only) on National Forest System lands; please refer to the USFS fire retardant site at https://www.fs.fed.us/fire/retardant/ for additional information and re-initiation of consultation requirements.

The following provisions are guidance for complying with the emergency section 7 consultation procedures of the ESA for wildland fire chemicals. These provisions do not alter or diminish an action agency's responsibilities under the ESA.

Where Threatened and Endangered (T&E) species or their habitats are potentially affected by application of wildland fire chemicals, the following additional procedures apply and shall be documented in initial or subsequent fire reports.

As soon as practicable after application of wildland fire chemical near waterways or other avoidance area as designated by agency, determine whether the application has caused any adverse effects to a T&E species or their habitat. This can be accomplished by the following:

- Ground application of wildland fire chemical outside a waterway is presumed to avoid adverse effects to aquatic species and no further consultation for aquatic species is necessary.
- Aerial application of wildland fire chemical outside 300 ft. of a waterway is presumed to avoid adverse effects to aquatic species and no further consultation for aquatic species is necessary.
- Aerial application of wildland fire chemical within 300 ft. of a waterway requires that the unit administrator determine whether there have been any adverse effects to T&E species within the waterway. If no adverse effects to aquatic T&E species or their habitats, no additional requirement to consult on aquatic species with FWS or NMFS is required.
- Application of wildland fire chemical within other avoidance areas as designated by agency requires the agency administrator to determine whether there have been any adverse effects to T&E species. If there are no adverse effects to species or their habitats there is no additional requirement to consult with FWS or NMFS.

If the action agency determines that there were adverse effects on T&E species or their habitats then the action agency must consult with FWS and NMFS, as required by 50 CFR 402.05 (Emergencies). Procedures for emergency consultation are described in the *Interagency Consultation Handbook*, Chapter 8 (March 1998). In the case of a long duration incident, emergency consultation should be initiated as soon as practical during the event. Otherwise, post-event consultation is appropriate. The initiation of the consultation is the responsibility of the unit administrator.

Chapter 6 – Aerial Supervision Mission Procedures

Aerial Supervision operations are conducted in demanding flight conditions in a high workload/multi-tasking environment. Because of this, standardization of procedures is important to enhance safety, effectiveness, efficiency, and professionalism. This chapter addresses common procedures to be observed by all Aerial Supervision Specialists as well as unique guidance for Lead, ATCO, ASM, ATGS, and HLCO personnel.

The actions listed below pertain to all positions of aerial supervision. Methods for performing these actions differ and are often refined as CRM is enhanced.

Pre-Mission Procedures

Pilot Qualification Card & Aircraft Data Card

Review these cards and verify the pilot and aircraft are authorized for air tactical missions.

Flight & Duty Limitations

Determine when pilot's duty day began and if sufficient flight/duty time is remaining. If not, order a relief pilot.

Aircraft Maintenance

Verify aircraft has sufficient time remaining before next scheduled maintenance. If not, order another aircraft.

Aircraft Preparation

Pilot Preflight Responsibilities – Include but not limited to:

- Aircraft preflight inspection.
- Calculate weight and balance of passengers and equipment.
- Fueling: Discuss fuel requirements and limitations for mission with ATGS.

Ensure proper fueling.

- Possess/wear approved PPE.
- File a flight plan as needed.
- Obtain a TFR and weather briefing.
- Cover aircraft checklist methods with aerial supervisor.

ATGS/ATS Preflight Responsibilities:

- Inspect communications system. Install auxiliary radio if required.
- Program VHF-FM tactical frequencies in radio (coordinate with pilot).
- Perform a radio check with dispatch and airbase before flying.
- Load aerial supervision kit into aircraft.
- Assist pilot as requested with duties.
- Understand aircraft performance (takeoff distance, landing distance, single-engine performance, max gross weight, fuel endurance) and document in daily diary.

Procurement Agreements

The aerial supervisor should be familiar with the basic terms of the procurement agreement/contract.

Obtain a Mission Briefing

Whether the air tactical mission is IA or a project incident, all types of aerial supervision personnel must obtain pertinent incident information. Dispatch centers must provide an aircraft dispatch form.

IA Briefings

The following information is recorded on an aircraft dispatch from as is required before responding to an incident (blank copies should be available in the aircraft for possible diverts while airborne):

- Incident name or number
- Agency responsible
- Incident location – legal location, latitude/longitude and VOR
- Frequencies and tones: Double check operating mode (N,W,D) and tones
- Flight following
- Air-to-Ground
- Air-to-Air (FM and/or AM)
- Contacts: ground and air
- Air resources assigned or to be assigned, Estimated Time Enroute (ETEs), type, and identifier
- Other resources dispatched (as practical)
- Approximate incident size and fire behavior
- Other available air resources
- Aerial and ground hazards
- Special information such as land status, watershed, wilderness, and urban interface
- Airtanker reload base options and turnaround times

Extended Attack Briefings

If possible, aerial supervision personnel should attend incident briefings. If this is not possible, critical information should be relayed by phone, radio, email, fax, or messenger. A copy of the Incident Action Plan (IAP) is essential. Aerial supervision personnel may have to seek some of this information:

- Incident objectives by division (ICS 204)
- Organization Assignment List (ICS 203) or list of key operations people
- Air Operations Summary (ICS 220) or list of assigned aircraft
- List of all aircraft by make/model and identification
- Incident Radio Communication Plan (ICS 205) or list of frequencies
- Incident Map
- Fire Behavior Report and local weather

- Air resource availability/status
- Incident Medevac Plan and Medevac helicopter assigned

Mission Safety Briefing for Pilot

Prior to departure on an air tactical mission the aerial supervisor will brief the pilot on the following:

- General scope of the mission
- Incident location: latitude-longitude and bearing-distance
- Resources assigned
- Radio frequencies
- Special information including hazards and military operations
- Expected duration of mission

Pre-Takeoff Responsibilities

Pilot Pre-Takeoff Responsibilities

- Complete the appropriate aircraft checklists.
- Complete preflight including passenger safety briefing.
- Initiate Mission Checklist (appendix C) with aerial supervisor.
- Confirm fuel supply.
- Obtain route clearances through SUA as required.
- Program GPS to incident location.

ATGS/ATS Responsibilities

- Obtain, record, and set local altimeter setting (from pilot or airport advisory).
- Program radios (AM/FM) – Check with pilot before programming the AM.
- Confirm fuel supply and flight time available for mission.
- Check with dispatch regarding status of military aviation operations (Restricted, MOA's, MTR's) and TFRs.
- Assist with start, taxi, and pre-takeoff checklists as requested by the PIC.

Enroute Procedures

After Take Off

- Record take off time (takeoff roll).
- Observe sterile cockpit protocol as previously agreed to with pilot.
- Establish flight following (See Appendix E for further examples):
  1. Call sign
  2. Departure location
  3. Number onboard

4. Fuel on board
5. ETEs
6. Destination
7. Confirm AFF

- Notify pilot of any information or situation affecting the flight (ATGS/ATS).
- Assist pilot as requested. Be an active crewmember (ATGS/ATS).
- Complete mission checklist.

Enroute Communications

Maintain communications with dispatch and other aircraft concerning:

- Incident air resource updates.
- Status of SUA (TFR, restricted, etc.).
- Coordination with responding air resources can be done on the assigned air-to-air frequency provided it does not interfere with operations over the incident.
- Monitor the fire frequencies to enhance situational awareness when you arrive on scene.

Fire Traffic Area (FTA) Entry Procedures

12 NM from the center point of the incident, aerial supervision personnel **must** follow the FTA entry procedures listed below. There are three scenarios: 1) Aerial supervision is on scene; 2) aerial supervision is not on scene, but other aircraft are; or 3) there are no aircraft on scene. See FTA entry appendix D.

Scenario 1: Aerial Supervision Is on Scene

- Notify the dispatch center of your position.
- Change to incident frequencies.
- Give 12-mile radio call to aerial supervision. Give your location and altitude.
- Obtain clearance into FTA by getting:
  - Altimeter setting
  - FTA Entry Altitude
  - Altitude of aerial supervision
  - Altitudes of other aircraft
- Enter the incident airspace, as briefed.
- Watch for other aircraft and call out a distance and clock reference when you spot the on scene aerial supervision.
- Receive transition briefing and confirm positive handoff of aerial supervision responsibilities.
- Outgoing aerial supervision will notify dispatch and incoming aerial supervision will notify IC/ground personnel and confirm objectives and priorities.

Scenario 2: Aerial supervision is not on scene, but other aircraft are

- Notify dispatch of your position.

- Change to incident frequencies.
- Give 12-mile blind radio call on Victor (AM). Give your location, altitude, and intentions. An on scene aircraft should respond on the assigned primary air-to-air frequency.
- Obtain clearance into FTA by getting:
  - Altimeter setting
  - FTA clearance Altitude
  - Altitudes and locations of other aircraft on scene
- Enter the incident airspace, as briefed with on scene aircraft.
- Watch for other aircraft and call out a distance and clock reference when you spot the on scene aircraft.
- Get status of all on scene aircraft (location, mission type, etc.)
- Call IC and get objectives and priorities.
- Notify dispatch you on scene and now the incident aerial supervision.

Scenario 3: There Are No Aircraft on Scene

- Give 12-mile call in the blind on the primary and secondary assigned air-to-air frequencies. Give your location, altitude, and intentions. See Appendix E.
- Call the IC/ground personnel on the assigned FM air-to-ground frequency and verify no other aircraft are on scene.
- Proceed to the incident. Stay at least 2,500’ AGL and watch for other aircraft.
- Get center point and record size-up information.
- Call dispatch, notify you are the on scene aerial supervision and provide size-up.
- Call the IC/ground forces and establish objectives and priorities.

Entering Incident Airspace - ATGS fixed-wing enter the airspace in a right hand orbit at 2,500 feet AGL unless the situation dictates a different altitude (smoke/terrain), Leadplanes/ASMs enter in a left orbit, or as directed by aerial supervision.

Aerial Supervisor Arriving on Scene Responsibilities

The Aerial Supervisor Must:

- Watch for aircraft and make visual/verbal contact with each one.
- Determine ground elevation to establish FTA altitudes for incoming aircraft including helicopters, airtankers, Lead/ASM, smokejumpers, relief aerial supervision, and media (“the stack”).
- Determine flight hazards – Power lines, antennas, snags, terrain, thunder storm activity, excessive wind, poor visibility, airspace conflicts, etc.
- Confirm incident objectives and priorities with the IC/ground personnel.

Standard Briefings

All aircraft will receive a briefing and clearance into the FTA. Briefings typically occur in three phases: 1) initial, 2) tactical, and 3) departure. See Appendix E for more information on standard briefings.

Initial Briefing

Clearance Information

- Altimeter setting
- Clearance altitude

Aircraft in FTA

- ATGS altitude
- Other aircraft altitudes

Hazards

- Enroute hazards

Tactical Briefing

This briefing occurs when the incoming aircraft has the drop/mission area in sight.

Define Objectives

- Identify specific hazards
- Target description
- Coverage Level
- Exit Routes
- Maneuver Clearance
- Ground and Drop Clearances
- Exit routes

Departure Briefing

Drop/Mission Evaluation

- Start
- Line
- End

Return Instructions

- Fuel/Load and Return/Hold
- Location
- Special instructions

Egress Altitude and Direction

- Ensure departing aircraft have a clear exit path from their area of operation.

Dispatch

- Notify dispatch of reload instructions (load and return, hold, released, etc).

Target Description

- Concise communication using standard terminology expedites the task accomplishment and increases safety.

- A standard target description includes the following:
  - Target location
  - Coverage level/Portion of load
  - Drop objectives/Type of drop
- Hazards
  - Clearance to drop

Methods to Describe Work Location

Long Range (Greater Than 12 Miles)

- GPS reference points – in limited visibility (inversions), lat & long references can significantly increase safety while reducing radio traffic.

Note: Be aware that the standard datum and coordinate format aviation GPS equipment is World Geodetic System (WGS) 84 and decimal minutes whereas many GPS units used by ground personnel default to a North American Datum (NAD) 27 datum and a degrees, minutes, seconds format. The use of different datums and formats may result in misinterpreting the location of a specific target. Ensure that the target location is confirmed with ground personnel.
Cardinal directions: Specify true or magnetic. Be exact! Often directions are generalized and create confusion.

Medium Range (1 to 12 Miles)

- Fire anatomy: Left and right flank, head, heel (tail in AK), etc.
- Elevation: Specify above sea level (MSL) or AGL.

Short Range (Less than 1 Mile)

Geographic features: Ridges, saddles, spur ridges, lakes, streams, etc.

- Specific activity: Dozer working, firing operation, parked vehicles, previous drop, etc.
- Incident features: Helibase, helispots, fireline, and division breaks, etc.
- Standard terminology: Standard terms are in the glossary.

Guiding Aircraft to Targets

- Clock directions, left or right, etc.
- Signal mirrors, ground panels, lights, etc.
- Have an on scene aircraft lead new aircraft to the target area.
- Discuss target locations when the other aircraft is in position to observe.

Aircraft Separation

Terrain, visibility, number and type of aircraft, TFR dimensions, and other factors influence requirements for maintaining safe separation.

Common Principles of Aircraft Separation

- Use standard aviation 'see and avoid' VFR.
- Have access to the appropriate air-to-air frequency for position reporting.
- Adhere to FTA procedures.

Aerial Supervisors ensure aircraft separation by:

- Structuring the incident airspace and briefing pilots.
- Monitor radio communications for:
  - Pilot-to-pilot position reports
  - Blind call position reports
  - Visually tracking aircraft
  - Giving specific directions to pilots as needed
  - Advising pilots on the location and heading of other aircraft

Note: The coordinates of the incident must be verified, updated, and communicated to dispatch to ensure that inbound incident aircraft can determine the appropriate points at which to initiate initial contact and/or hold if communications with controlling aircraft are not established.

Vertical Separation

- 500 feet is the minimum vertical separation for missions in the same airspace. **1,000 feet is preferred and should be used whenever possible.**
- Assigning block altitudes (with vertical range up to 500 feet) to orbiting fixed-wing is preferred in windy or active thermal conditions.
  - Assign helicopters a hard ceiling (i.e.: 4,500' and below). **Do not assign them 500' AGL.**
  - Vertical stacking airtankers is discouraged. Utilize a racetrack pattern if multiple airtankers (of any type) are on scene.
  - It is common practice to put media helicopters above the ATGS in order to keep them away from firefighting aircraft.
  - Standard operational altitudes and patterns are:

Table 6. Standard Operational Altitudes and Patterns

Mission	AGL (feet)	Normal Pattern
Media	As assigned	Right or left
ATGS – Fixed-Wing	2000 to 2500	Right
ATGS – Helicopter	500 to 2000	Right or left
Airtanker Orbit	1000 to 1500	Left – outside to observe
Airtanker Maneuvering	150 to 1000	Left
Leadplane	150 to 1000	Left
Helicopters	0 to 500 (hard ceiling)	Left or right
Smokejumper Ram-Air Chute	3000	Left
Smokejumper Round Chute	1500	Left
Paracargo	150 to 1500	Left
Streamers	1500	Left

Horizontal Separation

- Aerial supervision must ensure there is adequate visibility to conduct operations safely regardless of the airspace classification.
- Flight patterns must be adequate, i.e. not hindered by terrain.
  - Consult pilots before finalizing patterns and routes.
  - Advise pilots on location of other aircraft if visual contact has not been reported.
  - Air-to-air frequency must be accessible for pilots to give position reports.
  - Geographic references, such as a ridges or a river, can be used to separate aircraft provided aircraft maintain assigned flight patterns.
  - No-fly zones must be established to ensure safe separation when simultaneous missions at the same elevation are within close proximity.
  - Below ridges: For operations separated by a ridge, a "no-fly zone" 500 feet vertically below the ridge top can be established to ensure separation.
  - Near geographic dividing lines: If simultaneous operations near the dividing line are in conflict, a horizontal "no-fly zone" must be established or missions must be sequenced to ensure adequate separation.

Incident Entry and Exit Corridors

Aerial supervision shall determine incident entry/exit corridors as needed. All aircraft must be notified of corridors. If an entry corridor and exit corridor cannot be separated horizontally, then they must be separated vertically (refer to Incident Ingress/Egress discussion above).

Initial Points, Check Points and Holding Areas

The aerial supervisor assigns incoming aircraft to non-conflicting airspaces, or holding areas, as needed. Coordinates or a geographic reference work best.

Initial Point: A fixed-wing reporting location clearly identified by the aerial supervisor. It may be a lat/long or geographic point (landmark). Initial Points (IP's) are used to route incoming resource to a known location before engaging in tactics.

- Aircraft entering IPs will announce their direction of approach and intended destination via 'call in the blind' or 'pilot-to-pilot' reporting on the assigned primary air-to-air frequency.

Check Point: A rotor wing reporting location clearly identified by the aerial supervisor. It may be a lat/long or geographical point (landmark). Check points are used to route rotor wing aircraft to and from assignments.

- Helicopters using check points while transitioning an established route will announce their direction and intended destination via call in the blind or pilot-to-pilot reporting on the assigned air-to-air frequency (assignments are specified by the aerial supervisor and can be the primary or secondary)

Holding areas: Any known location can be used by aerial supervisors to hold resources. There can be multiple areas on an incident being used at the same time for multiple aircraft at each location.

- Pilots must be aware of other aircraft in their assigned holding area.
- Pilots must be able to communicate position reports to each other.
- Holding area must be clearly defined – by a geographic reference point or distance and direction relative to the incident aircraft will normally establish a "race track" pattern where

they are flying at the same altitude providing their own visual separation.

- Aircraft must receive clearance to depart the holding area once assigned.
- Helicopters can be held on the ground or in the air as needed to maintain adequate separation. Considerations include:
    - Pilots should be able to maintain forward flight rather than constant hover.
    - Long periods of holding helicopters should be done on the ground.

Sequencing

Aircraft may be sequenced into the same area provided each aircraft can complete its mission and exit the area before the next aircraft enters the area. Sequencing requires close supervision. Caution: Consider wake turbulence when sequencing any type of aircraft.

Sequencing Airtankers and Helicopters – Helicopters can be held at a safe distance from drop site until an airtanker has completed its drop.

Sequencing Airtankers and Paracargo – Stage aircraft 1800 apart in the same flight pattern so flights over the target area are controlled by position in orbit.

Interval Dispatching

To reduce the problem of too many airtankers over an incident at the same time, ask dispatch or the Air Tanker Base to launch airtankers at intervals (usually 10 to 15 minutes apart).

Virtual Fences and Check Points

Effective for maintaining ATC with minimal radio traffic on the air-to-air frequency.

Pilots may be required to report arrival at a virtual fence and wait for clearance from ATGS before proceeding. Geographic locations that make effective check points and virtual fences include:

- Roads
- Power lines
- Ridges
- Lakes

Helicopter Routes

Established point-to-point flightpaths for repetitive missions from helibase to helispots or sling sites, from dipsites to targets, etc. For safety, efficiency and monitoring, the ATGS, in consultation with the helibase manager and/or helicopter pilots, will ensure flight routes and communications procedures have been established and are known:

Well Defined Routes – Up one stream and down another, up one side of drainage and down the other side, up one side of a spur ridge and down the other, etc.

Air-to-Air Communications – Pilots must monitor the assigned Air-to-Air frequency in order to receive direction and maintain aircraft separation. If needed, separate Air-to-Air frequencies for helicopters and airtankers. The primary air-to-air frequency should be retained for fixed-wing operations.

Helicopter Daisy Chains

Two or more helicopters can be assigned to the same targets and dipsites for repeated water drops. The ATGS, in consultation with helicopter pilots, will establish a "daisy-chain" flight route for these operations insuring helicopters maintain the same orbit direction and separation.

Helicopter Recon Flights

These flights can be difficult to monitor. Consider the following procedures to maintain safe separation of aircraft:

- Schedule recon flights during slow periods.
- Assign a specific route for the recon (clockwise, maintain assigned altitude).
- Establish Check Points, and clearance protocol with recon aircraft.

Intersecting Routes

Intersecting aircraft routes shall be clearly identifiable geographically. Intersections shall have a minimum of 500 feet vertical separation.

Non-Standard Patterns

Occasionally terrain, visibility, wind direction or other factors require flight patterns are modified or reversed.

The mission pilot, Tanker, Lead, or HLCO shall advise ATGS of situation and request a deviation from standard procedures. The ATGS will advise other aircraft before granting the request and notify incident aircraft once non-standard maneuvers are complete.

Coordination Between Types of Aerial Supervisors

Each incident is unique and circumstances dictate that workload shifts between Lead, ATGS, HLCO and ASM as their responsibilities overlap in several areas. By prior agreement and after receiving a briefing, and positive handoff operational continuity is achieved.

It is important that ATGS, ASM/Lead, and HLCO work as a team and share workload commensurate with fire complexity, training and position authority.

Airtanker Mission Sequence between ATGS and Lead/ASM

1. ATGS and ground operations jointly determine tactical objectives.
2. ATGS briefs Lead/ASM on next target, coverage level, etc.
3. Airtanker makes 12 mile check in with ATGS or Lead/ASM.
4. If the airtanker checks in with ATGS, ATGS will brief airtanker or pass on to Lead/ASM (preferred).
5. Lead/ASM briefs airtanker on target, coverage level, etc.
6. ATGS/ASM clears conflicting air resources from the airspace and gives verbal clearance to Lead/ASM for low-level operations. The ATGS may also elect to hand off conflicting air resources to Lead/ASM in order to reduce radio traffic.
7. ATGS/ASM clears ground personnel from target area.
8. ATGS will maintain radio silence on the primary air-to-air while Lead/ASM and airtanker are working, particularly when on final approach or exiting the drop area, unless the drop needs to be called off.

9. Lead/ASM will do low-level recon to determine hazards, targets, elevations, location of people, equipment, facilities, safe patterns, exit routes, etc.
10. Lead/ASM briefs airtanker on objectives, flight route, coverage level, drift potential, and hazards.
11. Lead/ASM may make a "show-me" run with airtanker in tow on the intended target.
12. ATGS/ASM confirms ground personnel are clear of target area.
13. Airtanker makes drop(s). Airtanker may or may not require a lead.
14. ATGS pilot positions aircraft to monitor and evaluate drop.
15. ATGS evaluates drop and gets ground feedback. Lead/ASM may also be able to evaluate drop. Evaluation includes accuracy, coverage level, coverage uniformity, etc. Evaluation may reveal need to adjust to left or right, begin earlier or later. These adjustments are expressed in wing-spans or rotor-spans, not feet or yards.
16. ATGS/Lead/ASM gives feedback to the airtanker after clear of drop area (Lead/ASM and airtanker may have already heard same feedback from ground if they are monitoring assigned air-to-ground frequencies).
17. Lead/ASM and airtanker make adjustments as needed on subsequent drops.
18. Lead/ASM gives airtanker reload instructions based on instruction from ATGS.
19. ATGS/ASM informs ground when clear to return to work area.
20. Airtanker informs dispatch on status – load and return or hold.

Assuming ATCO Duties

When a Lead/ASM is unavailable due to days off, arrival delays, out of flight hours, or refueling, the ATGS will assume the ATCO. The ATGS must maintain a minimum altitude of 500 ft. AGL performing ATCO duties.

Maintaining Air Tactics Continuity

Complex air operations or air operations involving a mix of air resources requires continuous supervision by an ATGS, ASM, Lead, or HLCO. To maintain continuous supervision, the following procedures should be followed. Good planning will ensure continuity:

- Use ASM to fill gaps in ATGS coverage and manage air/ground operations in designated areas on complex incidents.
- Stagger aircraft refueling so all aircraft are not down simultaneously.
- Stagger airtankers to maintain continuous coverage.
- Monitor flight times. Anticipate the need for a relief pilot, Leadplane or other air resource. Notify dispatcher or AOBD in a timely manner.
- Anticipate fuel needs and facilitate obtaining fueling facilities near the incident.
- Recommend activation of portable reload bases to reduce turnaround time.
- Coordinate refuel and relief needs between aerial supervisors to ensure continuity of airspace management/supervision.

Relief Guidelines

Aerial supervision is mentally demanding. Long flight hours result in mental fatigue, reduced effectiveness, and compromised safety. Consider the following staffing guidelines:

- If the aerial supervisor will fly more than 4 hours on any one flight, order a relief.
- On multi-day incidents, assign a second aerial supervisor and rotate about every 3 hours.

Diversion of Aerial Resources

Higher priority incidents require diversion of air resources. A reassignment may be given through dispatch or through IC/Operations. Aerial supervision may also be diverted to manage the new incident. Upon receiving a divert notice, the aerial supervisor must release and brief the requested resources using the standard dispatch form information:

- Incident location
- Air and ground contacts
- Radio frequencies

Note: Tactical aviation resources may be diverted to a higher priority incident. The aerial supervisor should be advised by dispatch and modify incident tactics.

No Divert Request

The IC can request through dispatch a "no divert" for airtankers when an imminent threat to life exists. This requires 30-minute re-evaluation with IC and dispatch. A no divert status shall be released as soon as the threat is mitigated.

Coordination with Ground Personnel

- On Type 1 and 2 incidents, Aerial Supervisors work with Air Operations, Operations, Division Supervisors, and other line personnel.
- On Type 3 and 4 incidents, aerial supervisors work primarily with the IC, operations, ground crews, or dispatch.
- Aerial supervisors provide intelligence to tactical personnel and dispatchers in order to facilitate the dissemination of valid information provided during the briefing process.

Size Up the Fire and Get Oriented

- Size up the Fire –Make initial assessment and communicate critical safety, strategy, and tactics inputs to ground contact and/or dispatch.
- Get oriented – Develop a mental or sketched map of the incident that includes:
    - Cardinal directions
    - Landmarks: Roads, streams, lakes, mountains, improvements, etc.
    - Fire flanks, head, etc.
    - Visible work accomplished: Dozer lines, handline, retardant line, etc.
    - Record GPS coordinates to identify reference points
    - Review IAP map; note frequencies, aircraft assignments/availability, division breaks, helispots, etc.

Assign Air Resources

- Mark assignments based on Operations/ICs strategy, tactics, & mission priorities.

Determine TFR Requirements

- Vertical and horizontal dimensions
- If needed, order through dispatcher or Air Operations Director

Check for Airspace Conflicts

- Identify MOA's, MTR's, airports, etc.
- Values at risk: Life, property/structures, resources
- Current fire size and potential size estimate
- Fuel models and rates of spread
- Fire behavior elements (wind, terrain, aspect, etc.)

Recommend Strategies, Tactics, and Resources

- Direct, indirect, or parallel strategies
- Target locations and priorities
- Access
- Anchor points
- Water sources
- Potential helispots
- Location of spot fires
- Number and types of aircraft required
- Use of specialized resources (helitack, rappellers, smokejumpers, and paracargo)

Provide Air Drop Information to Ground Crews

- Advise personnel of impending airtanker, bucket, or paracargo drops in their work area and the need to clear the area.
- If drops are near power lines, determine status of lines (live or de- energized?); Advise ground personnel of danger of being near power lines during drops.
- Confirm with ground if run is to be a dry or live.
- Notify ground when drop is complete and personnel can return to work area.
- Solicit feedback from ground crews relating to drop effectiveness.
- Provide Safety Oversight to Ground Crews.
- Monitor personnel locations relative to fire perimeter, blowup areas, etc.
- Assist with locating safety zones and escape routes. Final determination must be made from ground.
- Monitor weather – advises personnel of approaching fronts or thunderstorms.
- Advise personnel on adverse changes in fire behavior.
- Direct air resources, as top priority, to protect and aid in evacuation of endangered personnel.

Determine the Procedures for Ordering Tactical Aerial Resources

- The authority to order retardant and helicopter support varies between dispatch centers, land status, and incident complexity. Determine the procedure before the mission begins and confirm with the IC.
- On extended attack incidents, Division Supervisors are typically delegated the authority. However, consult with AOBD/OSC. Ensure the procedure is stated clearly in the IAP.
- On IA incidents, the IC makes aircraft orders. The IC may choose to delegate this to the aerial supervisor. Confirm it before ordering.

Coordination with Dispatch

Provide dispatch the following information in a timely manner:

- A fire size-up including a center point and resource needs.
- Horizontal and vertical dimensions of a TFR if needed. Remember that TFRs are based on degrees, minutes, and seconds. Dispatch centers may assist with conversion of Lat/Long.
- Airspace conflicts with civilian or military aircraft.
- The need for airtankers to load and return or hold.
- Aircraft incidents/accidents.
- Projected needs for next shift – number of aircraft by type, time requested, frequencies, TFRs, etc.
- Aerial supervision flight/duty hours used and projected needs to complete the mission.
- Advise where airtankers should remain overnight (RON) when day's operations are completed.
- Advise on need for aircraft maintenance and projected availability for next day.
- Advise if airtanker has in flight difficulty, must abort load, and return to base.
- Request aerial supervision relief at least 2 hours before you need it.

Before Leaving the Incident

- Coordinate with remaining Lead, ASM, ATGS or HLCO to ensure continuity of aerial supervision.
- Notify Operations of Estimated Time of Departure (ETD), and who will supervise air operations.
- Notify air resources of ETD and whom they will report to.
- Notify the IC, Operations/Air Operations, DIVS, helibase, Lead, ASM, and HLCO when departing.
- Notify dispatch of ETE to base.
- If you are on the last shift of the day:
    - Plan your release to allow for return within daylight hours (not necessary for twin-engine aircraft).
    - Update Operations personnel on fire status.
    - Remind remaining resources of daylight restrictions.
    - Confirm with dispatch status of air resources – RON or return to home base. Inform air resources of their status.

Post Mission Procedures

- Confirm need for aerial supervision aircraft for next day and notify pilot of time, etc.
- Debrief with available air resources (ATGS pilot, airtanker pilots, HLCO, Leadplane Pilot, ASM, and helicopter pilots).
- Debrief with AOBD and dispatch.
- Attend or provide input to incident planning meeting for next day's operations.
- Request and review IAP and map for next day's operation.
- Complete payment documents.
- Submit SAFECOMs as required.
- Update logbook.

Emergency Procedures

Flight Emergencies

When a flight emergency is declared, possibly as "May day, May day, May day" the aerial supervisor manages the emergency using appropriate procedures from the list below:

- Emergency is highest priority until aircraft lands safely.
- Determine pilot's intentions for managing situation.
- Clear the airspace for the pilot as needed.
- Dedicate and clear a frequency for the emergency.
- Direct the aircraft to depart mission area and climb to a safe altitude.
- Jettison load in remote areas (or specified jettison areas) if feasible.
- If problem persists, instruct aircraft to return to base or alternate landing site.
- Alert incident medevac units.
- Prepare for suppression of a fire associated with an aircraft crash.
- Notify dispatch or airport tower for necessary crash/rescue protocol.

Missing Aircraft and Aircraft Mishap

When an aircraft crash has occurred or an aircraft is missing, on scene aerial supervision manages situation using appropriate procedures below:

- Consider ordering additional aerial supervision.
- Assign aircraft as needed to conduct search.
- Determine location. Monitor emergency frequency (121.5) if crash site is not known or if the aircraft is missing and its status is unknown.
- Assign remaining aircraft to holding areas or return to base.
- Activate incident medevac plan through medical unit.
- Assign on-site aircraft and personnel to control aircraft fire and initiate life saving measures if they can do so without jeopardizing their own safety.
- Advise IC/Operations – be discreet about aircraft and flight crew identity.
- Consider suspending non-essential aircraft operations.

- Direct ground resources to crash site.
- Direct air support operations.

Medevac of Incident Personnel

Consider the following as appropriate:

- Serve as a relay between accident site, helibase, and medical personnel.
- Determine accident site location – latitude and longitude.
- Obtain Medevac helicopter frequency – may be listed in Medevac Plan.
- Assist rescue personnel with helispot location, etc.
- Provide helispot dust abatement with helicopter buckets as needed.
- Guide Medevac helicopter to accident site.

Note: IMTs typically have an established procedure for incidents within the incident. Obtain a briefing from Air Ops.

Chapter 7 – Aerial Firefighting Strategy and Tactics

Principles that apply to ground operations also apply to air operations. Strategies are based on values at risk and resource management objectives, while tactics are based on fuel type, fire intensity, rate of spread, resource availability, and estimated line production rate.

As an aerial supervisor, you will be making mainly tactical decisions based on objectives developed by incident command personnel. The most effective aerial tactic is anchor, flank and pinch. Aerial Supervisors are obligated to assist the IC and Operations personnel with strategic advice during multiple ignition events and extended attack incidents relating to aviation resource capabilities and needs.

Note: Aerial application of suppressants and retardants should be used in support of ground resources support and be anchored.

Aerial Fire Suppression Strategies

There are three general suppression strategies:

Direct Attack

Drops next to fire edge in support of ground forces ("direct").

Parallel Attack

Generally parallel to and within a hundred feet of perimeter. Anticipate lateral fire spread, safety, and line construction rates of resources assigned. Multiple parallel drops can be used on unburned fuels to increase line width ("double wide").

Indirect Attack

Used to enhance control lines established by ground forces in advance of the fire. Also used for structure/infrastructure defense and safety zones when retardant is the most effective method of reducing fire impacts to the values at risk.

Aerial Fire Suppression Tactics

In support of direct attack strategies, place drops where ground support is available and containment or extinguishment is likely. Direct attack the head when you are assured you won't be outflanked, fire behavior is low to moderate, and your initial load has a good chance of achieving the objective. Indirect and parallel attack strategies require coordination with ground personnel as to the timing of firing operations, structure protection, etc. Consider the following patterns and considerations.

Box and "V" Pattern (Relatively Flat Terrain)

A single airtanker often can make multiple drops forming a retardant line around a small fire or "V" off the head or heel.

Parallel or Stacking Pattern (Steep Ground)

When steep terrain precludes boxing a fire, flight routes must be contoured to the slope. Generally, drops are started at the top and progress to bottom of the fire.

Full Coverage Drop (Delayed Attack Fires and Spot Fires)

To control fire intensity and spread, drops should blanket the entire fire. Multiple drops may be required to get a heavy coverage level. On small fires the chance of a partial hit on the first drop is significant. It is wise to drop a partial load on the first pass. The experience of the first drop plus feedback from the ATGS and the ground will likely increase the accuracy on the next drop.

General Tactical Considerations

Tactical plans are based on the chosen strategy and a working knowledge of the following principles.

Simplicity & Flexibility

Stick to a few basic tactical objectives. Be ready to change priorities as needed to achieve strategic objectives.

Retardant Versus Water or Foam

Unless there are environmental constraints, retardant application may be preferred compared to the use of water or foam. If long-term retardant is required, don't rely on water or foam – they normally require immediate (0-30 minute) follow up.

Proper Coverage Level

Use the proper coverage level for the fuel types.

Dense Canopies

Multiple drops may be required to penetrate canopies and treat surface fuels with proper coverage level.

Sustained Attack

Effectively lay a retardant line under normal fire conditions, while continuous drops supported by ground forces are required. Calculate turnaround time and order enough aircraft to maintain a sustained attack.

Use Down Sun

Avoid flight routes directly into sun on the horizon.

Blow Ups/Flare-ups

Direct or parallel attack is usually ineffective. Consider changing drop locations to areas which retardant will have the best chance of success.

Target Priorities

Retardant use is usually prioritized in the following order:

1. Human Safety
2. Structure/Infrastructure Protection
3. Natural Resources

Portable Retardant Plants

Where long turnaround times or lack of large airtankers will not provide a sustained attack, consider ordering a portable retardant plant and Type 1 or 2 helicopters, or SEATs. SEATs typically respond with a support vehicle which has suppressant/retardant mixing/loading capabilities. Within 24-36 hours portable plants can be delivered and set up near an incident. Some operators can provide a module consisting of a Type 1 helicopter, portable plant, retardant, and mixing crew. Not all retardants are approved for fixed tank helicopters. Consult the QPL for approved retardants.

Staggered Duty Hours

Stagger aircraft duty hours to provide availability during early morning through end of daylight.

Early Morning Drops

Often the most effective. Don't wait until it's too late to order retardant.

Wind Drift

An increase in coverage level may be required to reduce the effects of drift.

Critical Targets

On IA incidents, identify targets for attaining quick containment and establishing an anchor point.

Anchor Points

Always work from an anchor point. Roads, rivers, natural barriers or other areas where fire will naturally stop should be confirmed with the ground as a good starting point. When anchor points are compromised make every effort to re-establish to reduce the chances of the fire hooking around ground resources.

Maximize Line Production by:

- Keeping lines relatively straight; minimize angles
- Take advantage of natural barriers and lighter fuels
- Allowing pilot to select the best and safest flight route

Gaps in Line

Observe for gaps in retardant, foam or water line. Pick up gaps with subsequent drops or with ground resources.

Plan for Extending and Intersecting

Plan current drops so they can be extended or intersected effectively by future drops.

Anticipate Spot Fires

Generally downwind of smoke columns.

Control Fire Intensity

With direct drops on or next to fuels.

Effective only when immediately followed up by ground forces.

Reduce Spotting Potential

With pretreatment drops on fuel beds.

Maintain Honest Evaluations

To assist pilots with making corrections.

Use Correct Resources:

Match resources to correct tactical objectives.

Retardant Drops near Water Resources

Agency policy and Unit level tactical plans may restrict the use of airtankers and helicopters near water resources. When drops are planned in sensitive areas, the ATGS should contact the local unit or a Resource Advisor for applicable policy restrictions, (e.g.,

Interagency policy prohibits dropping retardant within 300 feet of bodies of water).

- Locate and map water resources within the tactical air operations area.
- Determine drop distances.
- Monitor wind conditions and drift and adjust restrictions as necessary.
- Use helicopters to maximize drop accuracy.

IA and Multiple Fire Operations

Assuming Control of Air Operations in Progress

Before assuming control the aerial supervisor should:

- Perform standard FTA entry protocol.

Monitor air traffic and operation's frequencies while inbound to the incident.

- Contact ground resources to determine status of air resources on-site.
- Allow safe operations to continue.
- Make assessment of the incident.
- Brief the IC and request IC's strategy and tactics and mission priorities. The experience level of an IA IC determines the ATGS role.
- Establish contact with key ground operations personnel.
- Assign resources based on incident objectives making changes as necessary.

IA Mission Priorities

During IA, aviation resources must comply with FTA protocol. Aerial Supervisors should consider the following;

Time – Typical time requirements for common missions are:

- Bucket drop: 1-2 minutes
- Helitack: 3-5 minutes
- Helicopter rappel: 10 minutes
- Airtanker: 7-15 minutes (one vs. multiple drops)
- Smokejumper: 30 minutes. (depends on number of jumpers/cargo to be dropped)

General Considerations

- Which resources are ready?
- Can any resources be held or parked?
- Can any missions be done simultaneously?
- Can any mission be done in stages?
- Conditions that if delayed may preclude mission completion, i.e. fuel remaining, pilot duty/flight time remaining.

Normal Priority – Considering all factors, the normal priority is:

- Helicopter bucket/retardant drop
- Airtanker
- Helitack/rappel
- Smokejumper

IA Responsibilities with no IC – The ATGS, in consultation with dispatch, has the following responsibilities on IA incidents with no IC:

- Make initial fire size-up
- Recommend specific resources based on fire behavior, access, response time, resource availability and capability
- Develop tactical plan
- Give periodic status reports to dispatch or responding resources
- Assist responding resources with locating the incident
- Brief ground resources on potential safety concerns and fire behavior
- Assign arriving resources based on tactical plan until a qualified IC arrives

Multiple Fire Situations

An ATGS may be activated during predicted or active lightning storms with multiple fire starts and are likely to assist with:

Fire detection – Coordinates, legal descriptions, VOR and distance, etc.

Incident Priorities are Based on the Following:

- Threat to life and property
- Land status
- Fire behavior – current and expected spread
- Environmental sensitivity
- Political considerations
- Potential resource loss

Determine Access – Roads, trails, distance, and time requirements.

Recommend IA Resources – Based on resource capability, mode of access, probable availability and response time.

Develop IA Strategy and Tactics – Based on resource objectives, fire behavior, type and numbers of air and ground resources responding within specific time frames.

- Direct Resources per strategic and tactical plans until a qualified IC arrives.
- Report Intelligence to dispatch and IC.

- Reassign Resources – to higher priority incidents if they develop.

Delayed Attack Fires – When many small fires have started in a widespread area, resources are usually in short supply. An ATGS may be assigned to assess and prioritize fires. Delayed attack fires, or fires that cannot be staffed within a few hours, may require a holding action until ground resources are available. Timely drops while the fire is small can be effective in holding or containing a fire temporarily. Retardant is much more effective than water. One Type 1 or 2 airtanker can make holding drops on three or four small fires.

During these situations the ATGS will:

- Determine delayed attack fires requiring retardant. Request resources as needed.
- Set priorities. Consider flight time between fires. If priorities are equal, consider dropping on fires in close to each other before moving to fires some distance away.
- Direct retardant drops. General covering of the entire fire is recommended when controlling both fire spread and fire intensity. While drops covering the fire reduce fire intensity, they also make burnout operations difficult if not impossible.
- Monitor status of fires. Change priorities as necessary.

Wildland Urban Interface

Consider the following in the urban interface:

Policy and Regulations

Fires in the urban interface are considered to be in “congested areas.” Refer to Chapter 4 for more detail.

- **Order a Lead/ASM –** As required under FAR 91.119 – USDA Grant of Exemption 392. Refer to Chapter 4 for specific requirements.
- **Implement a TFR –** Under 14 CFR 91.137 if the incident meets the criteria for implementation. Refer to the Interagency Airspace Coordination Guide.
- Assign an aerial supervisor.

Urban Interface Hazards

The following hazards to aircraft are often associated with urban interface incidents:

- Dense smoke and poor visibility
- Power lines (may have to be de-energized)
- Antennas
- Tall buildings
- Media aircraft
- Propane tanks

Ground Safety

Urban interface incidents often have many citizens and homeowners scattered through the operations area. This can seriously impair tactical air operations and expose ground personnel to extreme risk.

Effectiveness of Resources

It is critical that airtanker and helicopter drops be closely supervised to prevent inadvertent drops on non-incident persons and unnecessary damage to improvements. The aerial supervisor is responsible for providing the best available resources that can:

- Minimize risk to people and improvements.
- Provide assignments to aircraft which have increased maneuverability, drop accuracy, and quick turnaround times to targets.
- Drops are generally not effective on structures that are burning beyond the initial start phase.

Urban Interface Tactical Planning Principles

Apply the following principles in developing the tactical plan for air resources:

- Assess the situation and identify the following:
  - Identify air operational hazards
  - Locate non-incident people in operations area
  - Protection of evacuation routes
  - Triage structures
  - Identify possible dipsites and portable retardant plant sites
  - Determine how air resources can best support suppression objectives
- Request electrical transmission lines are de-energized. Don’t assume that they will be. Warn ground personnel not to be under or near power lines during drops.
- Determine where airtankers or helicopters can be most effective.
- Recommend location of portable retardant or water dipsites.
- Use airtankers in areas where visibility, hazards, flight routes, and target selection ensure reasonable effectiveness and acceptable risk.
- Use helicopters on targets requiring more maneuverability and accuracy.
- When possible, avoid holding patterns with airtankers over populated areas.

Chapter 8 – Tactical Aircraft Operations

Low-Level Operations (Leadplane Pilot/ASM)

Low-level flight operations involve fixed-wing aircraft flying below 500’ AGL. These missions are performed in order to ensure airtanker drop effectiveness and safety. Aircraft and flight crews are specially trained and authorized for low-level missions. Situational awareness is the responsibility of each Lead/ASM crew member to ensure safe flight operations. The Lead/ASM conducts these operations in the following manner:

Lead/ASM Tactical Flight Checklists

- High Level Reconnaissance
    - A high recon pass is executed prior to descending to low-level.
    - Look for aircraft over the incident including media and nonparticipating aircraft.
    - Analyze the terrain. Identify potential approach and departure paths while identifying prominent target features. Fly the patterns at an altitude to detect hazards. Study the lay of the land to establish emergency exits.

Note: The flight crew completes tactical checklist before conducting low-level flight.

- Low-Level Reconnaissance
    - Obtain clearance from ATGS for low level operations.
    - Check for turbulence, hazards to low-level flight, and low-level target identification features.
    - Fly the emergency exit paths to locate potential hazards not identified from a higher level.

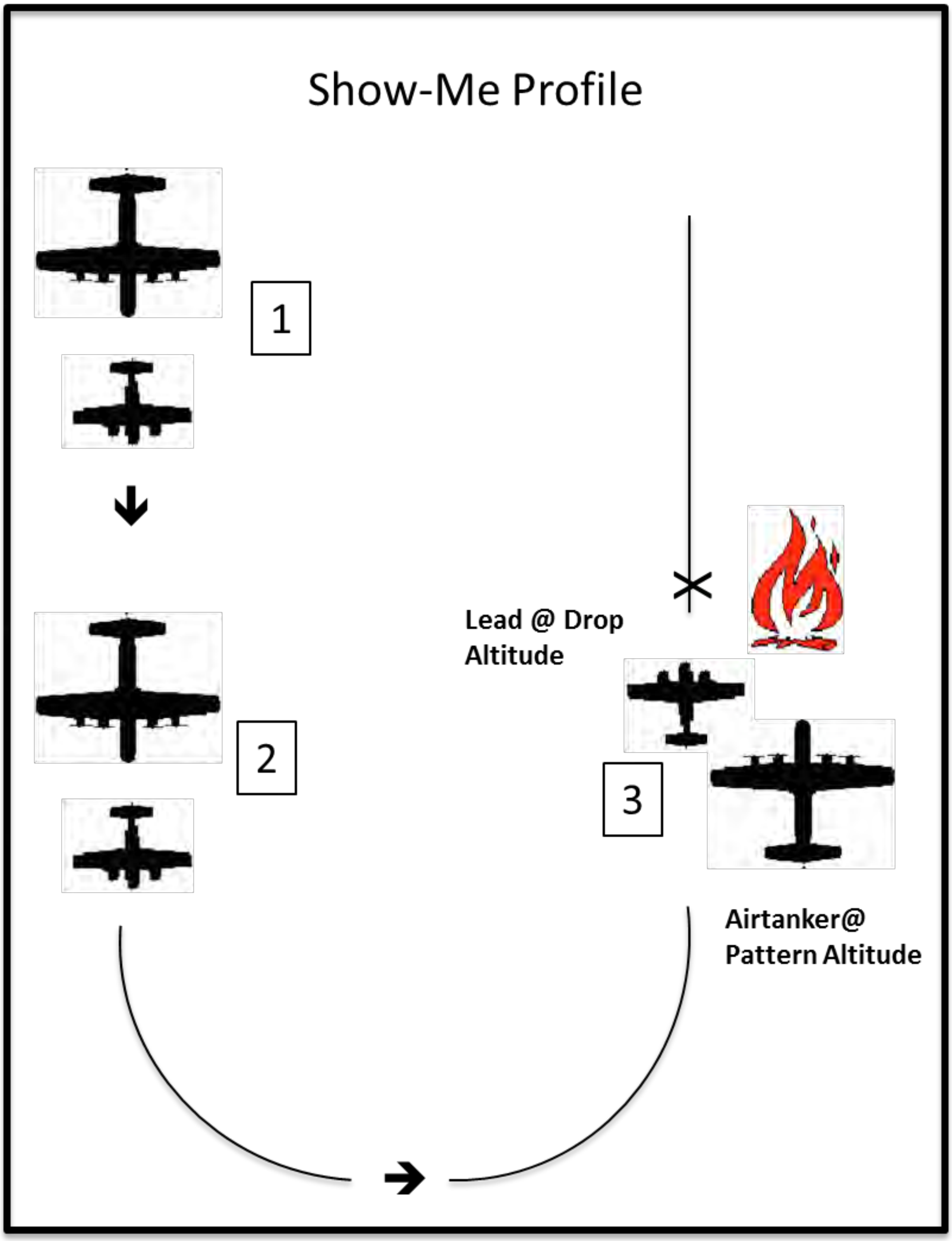
Tactical Flight Profiles

Show-me Profile – A show-me profile is a low-level pass made over the target using the physical location of the aircraft to demonstrate the line and start point of the retardant drop.

The show-me profile is normally used for the first airtanker on a specific run or when an incoming airtanker has not had the opportunity to observe the previous drop. A show-me can be used alone or before other profiles.

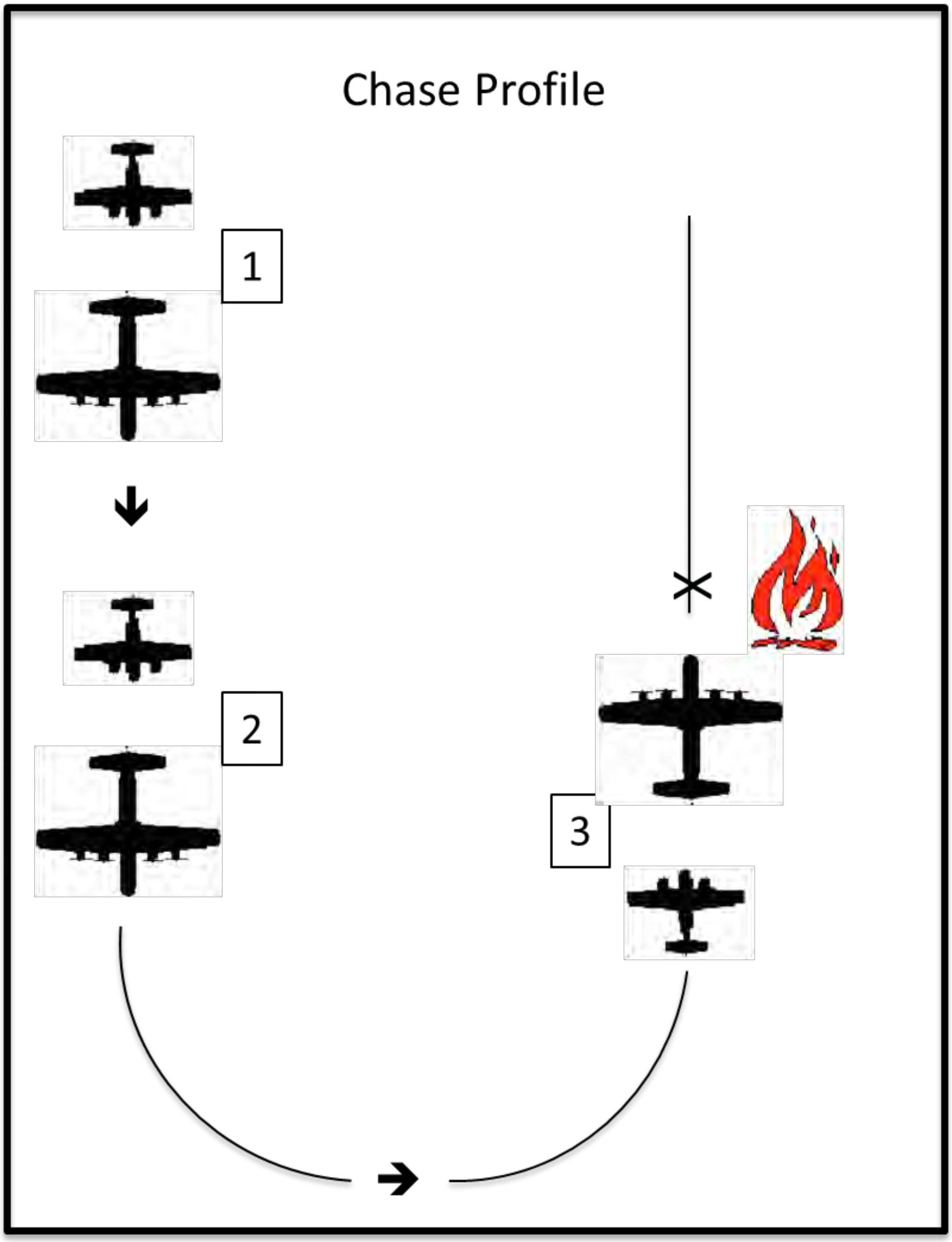
The pilot begins the run when the airtanker crew can visually identify the aircraft, hazards, line, start and exit point of the drop. The standard “show-me” is to fly the line you want the retardant on, not the drift.

Figure 4. Show-Me Profile



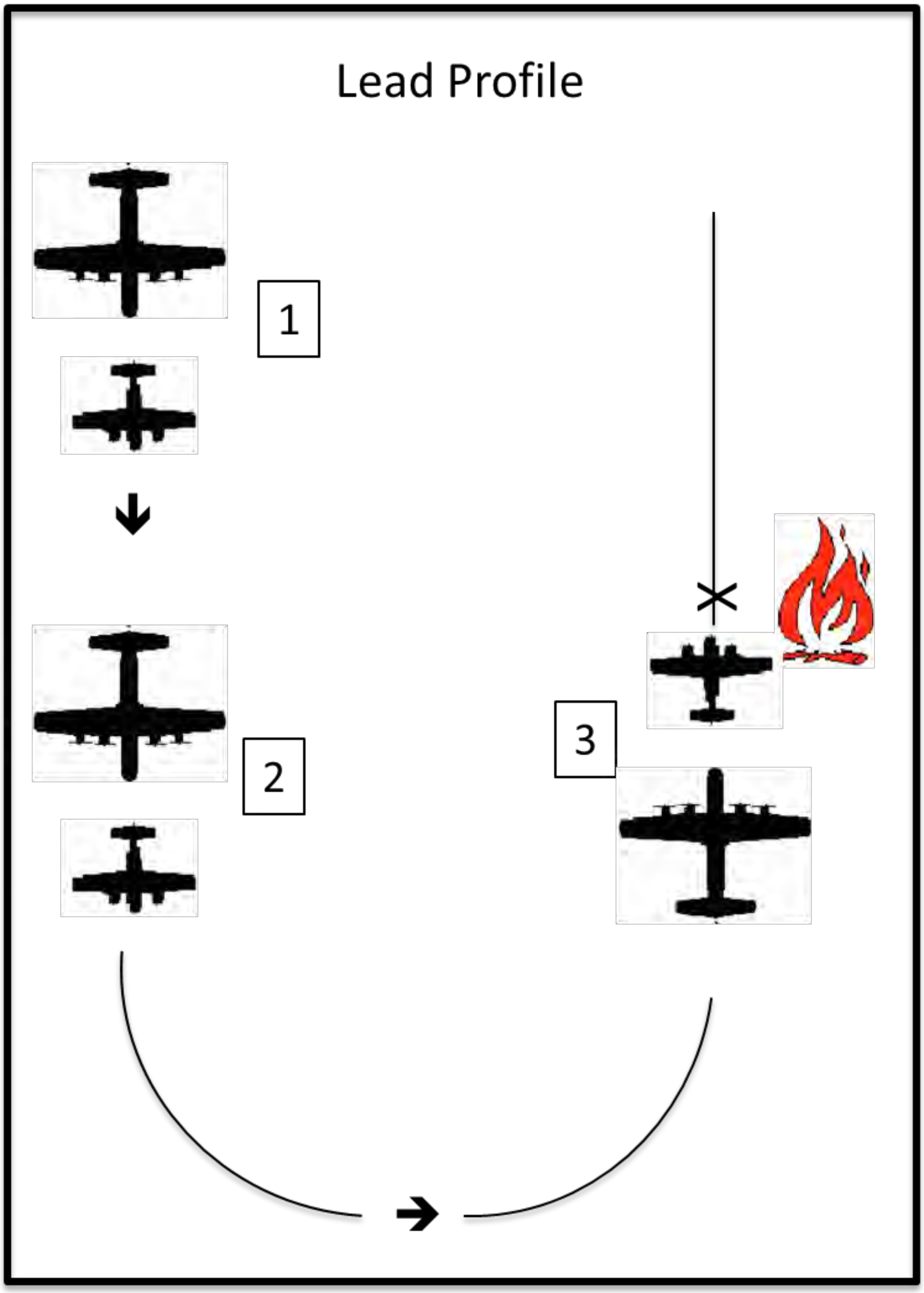
Chase Position Profile – The Chase Position Profile is an observation position in trail of and above the airtanker at a position of 5 to 7 o'clock. The Chase Position Profile is used to verbally confirm or adjust the position of the airtanker when on final, and to evaluate the drop.

Figure 5. Chase Position Profile



Lead Profile – The Lead profile is a low-level (below 500' AGL) airtanker drop pattern, made with the Leadplane approximately 1/4 mile ahead of the airtanker. The Lead Profile is used at the request of the airtanker crew, or when the line or start point is difficult to see or to describe due to lack of visibility or references.

Figure 6. Lead Profile



Airtanker Briefings

- See Appendix E and Chapter 7

Maneuvering

When leading airtankers, shallow to medium banked turns no greater than 30 degrees should be used. Extreme vigilance is required when operating beyond a 30 degree bank angle. When bank angles exceed or may exceed 30 degrees, the lead aircraft shall notify and brief the tanker. In any case, bank angle should not exceed 45 degrees. Inform the airtanker pilot ahead of time if turns in excess of 30 degrees are anticipated. Airspeed control is critical to a safe pattern. The shape, airspeed, and size of the pattern shall be well planned to minimize the airtanker pilot's maneuvering workload.

Minimum Airspeed – Airspeed during normal Leadplane operations shall not be flown below minimum controllable airspeed one engine inoperative (Vmca). Refer to agency specific aircraft flight operations handbooks or pilot operating handbooks.

Approach and Descent to the Target – The run should be downhill, down canyon, down sun with the greatest degree of safety in mind. Maintain the agreed upon airspeed in order to sustain approximately 1/4 mile separation between the Leadplane and airtanker. A descending approach with a constant rate of descent is desired, terrain permitting. Brief the airtanker pilot ahead of time if special maneuvering is anticipated. Advise the airtanker of hazards (i.e. turbulence, down air, restrictions to visibility, obstacles, etc.).

Final Approach to the Target – Power up and clean up drag devices (when applicable) to cross the target area at the briefed airspeed. Do not accelerate too soon and run away from the airtanker. The standard “live run” is to fly the expected drift line.

Drop Height

- The minimum is 200 feet above the top of the vegetation for VLAT.
- The minimum is 150 feet above the top of the vegetation for LAT.
- The minimum SEATs drop at 60 feet.
- It is important for the retardant to “rain” vertically with little or no forward movement. The airtanker pilot is responsible for maintaining safe drop heights.

Over the Target – Identify the start point with a verbal, “Here.”

Exiting the Target – Comply with the briefed exit instructions. When possible, turn off the centerline of the run before initiating a climb (be cognizant of the airtankers position at all times). Exiting is a critical maneuver at low altitude. Take every precaution to ensure that airspeed and aircraft attitude are within safe limits. (Safety-of-flight has priority over drop evaluation).

Emergency Overrun Procedures – In the event of an imminent overrun of the Leadplane by the airtanker, the airtanker crew will attempt to communicate the overrun and utilize the following standard overrun procedures unless otherwise briefed:

- Straight out flight paths: Pass the Leadplane on the right.
- Left or right turn flight paths: Pass the Leadplane outside the turn.
- Terrain or visibility limitations: When the previous two options are not available pass above the Leadplane.

Airtanker Operations

Airtanker Advantages – Often Reserved for IA:

- High cruise speed
- Long range

Reload Bases

Airtankers are loaded at either permanent or temporary retardant bases. When sending airtankers for load and return consider the following:

- Fuel Available
- Retardant Available
- Turn Around Time
- Tanker Base Approved for Specific Aircraft

Factors Influencing Drop Effectiveness

A number of factors affect drop accuracy. These factors include:

Pilot Skill – Ability to make accurate drops.

Aircraft Make and Model – Each aircraft make and model has advantages and disadvantages in different operating environments. Performance elements include power, maneuverability, pilot's visibility and airspeed control.

Tanking, Gating or Door System – Quantity of liquid, tank configuration, flow rate and door release mechanism.

Airtanker Drop Height –Increased height reduces coverage level and increases line width. The most uniform and efficient retardant distribution is attained when near vertical fall of the retardant occurs. The optimum drop height is when the momentum of the load stops its forward trajectory and begins to fall vertically.

Airtanker Speed – Airtanker drop speeds are variable depending on type of aircraft and environmental conditions. Faster speeds generally reduce peak coverage levels, increase pattern momentum, and increase low coverage length.

Diving vs. Climbing – A diving maneuver tends to shorten the pattern and increase coverage levels. Conversely, a rising maneuver tends to toss or loft retardant and elongate the pattern.

Wind – The effect of wind is to deflect retardant and greatly increase the pattern's fringe area. The effectiveness of retardant/water drops should be closely evaluated when wind velocities reach 15 kts. Retardant drops are generally not effective in winds 25 kts or greater.

- Headwind: The effect of dropping into the wind is to shorten the line length and increase coverage level.
- Crosswind drops will result in increased line width and cover a larger area at reduced coverage levels.

Flame Lengths – Direct Attack with retardants at the prescribed coverage level is generally effective in flame lengths up to 4 feet. Flame lengths from 4 to 8 feet require increasingly higher coverage levels. Retardant, unless applied in heavy coverage levels and greater widths, is not generally effective when flame lengths are greater than 8 feet. Long- term retardant is most effective when applied to available fuels outside of the fire perimeter.

Canopy Density – Drops in timber or fuel models with a dense concentration of tall trees are often ineffective. Canopy interception significantly reduces penetration to ground fuels. An open canopy allows for better penetration.

Availability of Ground Forces – Except in light fuels where extinguishing the fire with retardant may be possible, the ATGS must determine if ground forces will be able to take advantage of the retardant within a reasonable time.

Retardant Coverage Levels

Coverage level refers to the number of gallons of retardant applied on fuels per 100 square feet. Fire scientists have determined how many gallons per 100 square feet (GPC) it takes to effectively retard flammability in fuel models under normal flame lengths. Coverage levels range from.5 to greater than 8. The ATGS instructs airtanker pilots to make drops at specific coverage levels.

Recommended Coverage Levels – The chart below identifies the recommended coverage level for each fuel model. The coverage level may need to be increased under more adverse burning conditions or when retardant does not effectively penetrate a heavy tree canopy.

Table 7. Recommended Retardant Coverage Levels

Coverage Level	NFDRS Fuel Model	NFFL FB Fuel Model	Fuel Model Description
1	A,L,S	1	Annual Perennial Western Grasses, Tundra
2	C H,R	2 8	Conifer with Grass, Shortneedle Closed Conifer, Summer Hardwood
	E,P,U	9	Longneedle Conifer, Fall Hardwood
3	T	2	Sagebrush with Grass
	N	3	Sawgrass
	F	5	Intermediate Brush (green)
	K	11	Light Slash
4	G	10	Shortneedle Conifer (heavy dead litter)
6	O	4	Southern Rough
	F,Q	6	Intermediate Brush (cured), Black Spruce
Greater Than 6	B,O	4	California Mixed Chaparral; High Pocosin
	J	12	Medium Slash
	I	13	Heavy Slash

Airtanker Drop Patterns

The ATGS must know the various drop pattern options, and the coverage level required for various fuel models.

Salvo Drop –Generally used on small targets such as spot fires or targets requiring heavy coverage levels. Rarely is a full salvo ordered.

Trail Drop – With multiple tank systems, two or more doors are open sequentially and at specified intervals giving continuous overlapping flow over a desired distance at the required coverage level. The same result is obtained with constant flow systems by opening the doors partially.

Heavy Airtanker Line Length Production Table

This chart displays line production by coverage level and gallons dropped for drops made at the recommended drop height and airspeed. The chart should be used as a general guide and will need to be adjusted for specific tank systems, airtanker make and model and the actual drop conditions.

Table 8. Heavy Airtanker Line Length Production Chart (feet)

Volume Dropped (Gallons)	Coverage Level 0.5	Coverage Level 1	Coverage Level 2	Coverage Level 3	Coverage Level 4	Coverage Level 6	Coverage Level 8
800	2,246	1,114	526	311	189	38	0
1,000	2,337	1,202	607	384	255	90	0
1,200	2,429	1,289	687	458	321	142	9
1,400	2,520	1,377	768	531	387	194	46
1,600	2,611	1,465	848	604	454	245	84
1,800	2,702	1,552	929	678	520	297	121
2,000	2,794	1,640	1,009	751	586	349	158
2,200	2,885	1,728	1,090	824	652	400	196
2,400	2,976	1,815	1,170	897	718	452	233
2,600	3,068	1,903	1,251	971	784	504	270
2,800	3,159	1,991	1,331	1,044	850	556	308
3,000	3,250	2,078	1,411	1,117	916	607	345

Ten Principles of Retardant Application

- Determine the strategy; direct or indirect, based on fire size-up and resources available.
- Establish an anchor point and work from it.
- Use the proper drop height.
- Apply proper coverage levels.
- Drop downhill, down sun when feasible.
- Drop into the wind for best accuracy.
- Maintain honest evaluation and effective communication between the ground and air.

- Plan drops so that they can be extended or intersected effectively.
- Monitor retardant effectiveness and adjust its use according.

SEAT Operational Principles

For additional information see Single-Engine Airtanker Operations Guide: https://www.nwcg.gov/publications/512

- Minimum SEAT drop height is 60’ above vegetation.
- When collocated with aerial supervision utilize both resources for IA.
- SEATs are most effective on small, emerging incidents.
- Reduce turnaround times by setting up portable retardant base(s) as close as possible to the incident.
- Efficiency is maximized when time spent over the target is minimized. Leadplanes typically utilize the show-me and chase profiles.
- Integrate SEATs with other resources – Use SEATs in conjunction with helicopters and heavy tankers. SEATs are best used in groups of two or more.
- Use retardant or suppressants with SEATs – Foam and Gels work well for direct attack.
- SEAT pilots are trained to apply the **ASHE** acronym for safe operations:
    - **A**pproach
    - **S**peed
    - **H**eight
    - **E**xit

Airtanker Flight Routes

Route Safety – Approaches and exits must allow for a level or downhill flight maneuver.

Visibility – Poor visibility from smoke or sun may preclude using the safest and most effective route. Alternate routes may be acceptable, but may result in less effective drops.

Helicopter and Helitanker Operations

Helicopter Tactical Considerations

Helicopter Advantages

- Helicopters are often a very cost effective resource on extended attack and project incidents because of the following:
    - Short Turnaround Times.
    - A Type 1 helicopter with a 3-minute turnaround can deliver upwards of 45,000 gallons per hour (Boeing 234, S-64). By comparison a Type 1 airtanker will typically deliver 2000 to 3000 gallons per hour based on a one-hour turn- around.
    - Low-Speed and Drop Accuracy.
    - The ability to do hover or low-speed drops makes helicopters very accurate. Helicopters are an excellent choice for targets in confined airspaces or in steep and dissected terrain. ***Caution:*** Drops on steep slopes may dislodge rocks onto crews below.

Dipsites

- For an effective helicopter operation, good water sources are required. Sources can include wide mouth portable tanks. The ATGS should inventory suitable dipsites.
  Following are considerations:
  - Approaches should be into wind. Determine if wind direction is the same at hover level as it is at the dipsite level when using a longline.
  - Helicopters equipped with a tank and snorkel require water depth of 18 inches to 3 feet for hover filling.
  - Be aware of any local resource concerns and fire management plan restrictions – ask the local fire managers and/or dispatch for specifics.
  - Approach, departure, and dipsite must be free of hazards.
  - Avoid fast moving streams and rivers.
  - Avoid contamination of water resources from buckets or snorkels that have previously been used in foam or retardant dipsites and/or any other resource contamination concerns (i.e. Whirling disease).
  - On private lands, attempt to secure permission from the landowner before using a private water source. This may be addressed in a pre-attack plan. Anticipate the need and secure permission before the need arises.
  - Utilize dipsite managers (when available) to provide an added margin of safety at established dipsites.

Longline Bucket Operations

- Effective for dipping out of confined sources. (ex. dipsite surrounded by tall timber)
- Reduce rotor wash on the fire
- Effective for filling portable tanks

Establish Direct Communications Between Helicopters and Ground Contacts –

If Air-to-Ground is too congested; assign division frequencies for direct communications between ground contact and helicopters.

Allow Pilots to Select Drop Approach

- Cross-slope, usually most preferred
- Down slope, second choice
- Upslope or downwind, least desirable approach

Helicopter Utilization by Type

- Type 1 and 3 helicopters can work together but do not integrate Type 1 helicopters unless all pilots involved are comfortable with pattern and separation.
- Type 1 and 2 helicopters can be effective for line production.
- Use Type 3 helicopters on isolated targets requiring lower volumes of water.

Helicopter Drop Height – Critical in terms of accuracy, effectiveness, and effect of rotor wash on fire behavior. Look for flare-ups after drops.

Helicopter Delivery Systems

Some systems can regulate flow rate and are capable of multiple or partial drops. Many helicopters are equipped with units for injecting foam into the bucket or tank.

Buckets – Three basic types of buckets are:

- Rigid Shell Buckets – Some capable of multiple drops
- Collapsible buckets (and foldable) - Some capable of single drop only
- Power fill buckets- multiple drop capable

Fixed Tanks – A variety of tank systems have been developed by different operators and agencies. Most can be quickly attached to the fuselage. The tanks are generally filled using a snorkel while the helicopter is hovering over a water source. The tank can also be filled on the ground using standard cam-lock hardware. Minimum water depth requirements for the snorkel fill system are 18 inches to 3 feet. (Ex., S-64 Sky Crane with a 2500 gallon tank, foam injection, hover fills from 18 inches in 45 seconds, and provides prescribed coverage level from metered flow door system).

Helicopters – Height is critical in terms of accuracy, effectiveness, and effect of rotor wash on fire behavior. Helicopters must be high enough to not cause flare-ups. Forward air speed results in less rotor wash. Type 1 helicopters, even with a 200-foot longline, produce strong rotor wash.

Note: Caution when mixing multiple helicopters with dissimilar delivery systems (i.e., Belly Hooked Bucket, Longline, and Tanked Aircraft). Different airspeed, maneuverability, flight profile and pilot site picture have potential to impact aircraft separation.

Helicopter Drop Patterns

In a hover, a helicopter can deliver a salvo drop, while in forward flight it can deliver a trail drop.

Night Helicopter Operations

See Night Helicopter Operations Plan.

Smokejumper Operations

https://www.fs.fed.us/fire/aviation/av_library/ismog/ismog-fs.pdf

Smokejumper aircraft are dispatched with a standard load of eight jumpers and equipment to be self-sufficient for 48 hours. A typical mission takes 30 minutes over a fire. A qualified smokejumper spotter (senior smokejumper in charge of smokejumper missions) may “coordinate” with on-scene aircraft over a fire until a qualified ATGS arrives.

Ram-air smokejumpers can be deployed in winds up to 30 mph. The smokejumper spotter will determine if conditions are appropriate.

Approach to the Fire

Smokejumper aircraft normally approach the fire at 1500 feet AGL (streamer drop altitude for both the BLM and Forest Service).

Drop Mission

The drop mission is a four- part operation and takes 15-40 minutes depending on the number of jumpers being deployed. Erratic winds, changing fire behavior, and other factors can extend this time.

Jump Spot Selection

Selecting a safe jump spot sometimes requires the smokejumper airplane to make a low-level pass at approximately 500 feet AGL to identify potential hazards. Letting the smokejumper aircraft orbit above other tactical aircraft to view the fire area if the lower airspace is being utilized can save time. Jumpers can also be deployed a short distance from the fire in order to conduct simultaneous tactical operations.

Streamer Runs

The smokejumper aircraft will usually initiate a left hand pattern over the selected jump spot at a minimum of 1500 feet AGL (measured from the jumper release point). One to three streamer passes are conducted to verify the wind direction and speed.

Jump Runs

Smokejumpers are deployed in one to four person sticks depending on the size of the spot, wind, and the aircraft. Depending on the parachute system being used, jump runs will be conducted at either 1500 feet AGL (USFS round parachutes) or 3000 feet AGL (BLM square parachutes). Mixed loads can vary but the standard practice is to deploy the USFS jumpers using the 1500' AGL pattern and then climbs to the 3000' AGL pattern for the BLM jumpers.

Cargo Runs

After the jumpers are verified safely on the ground, the airplane descends to drop the paracargo. Cargo run patterns are similar in altitude to retardant drops, 150 to 200 feet over the drop point. The number of passes depends on the number of jumpers deployed, size of spot, and equipment needed. Runs vary from one pass to ten or more. The spotter will notify the ATGS or Leadplane of the number of passes anticipated and when the mission is completed.

Considerations

Priorities vary on deploying resources on incidents but it is advisable to get the firefighters on the ground as soon as possible. Unless extenuating circumstances dictate otherwise, let the smokejumper airplane come in and perform the entire 4-part operation. If it is necessary to break into the mission to deploy other tactical aircraft, interrupt the smokejumper operation between the jump spot selection and streamer run, or between the last jump run and first paracargo run. Keep in mind that the jumpers need their tools to be effective.

When other priorities and congested airspace are an issue, consider deploying the jumpers preferably using non-conflicting flight patterns or when this is not practical, a short distance from the fire.

Helicopter Rappel Operations

Type 2 and Type 3 (National Park Service) helicopters are used for rappelling. Type 3s carry up to two rappellers and a spotter; Type 2s carry up to six rappellers and a spotter.

Arrival

Rappel helicopters approach the incident at 200 to 500 feet AGL or the altitude assigned by the aerial supervisor. Upon arrival at the incident site, they will survey the area to determine the best method to deploy the firefighters. The helicopter may or may not arrive configured to rappel.

Normally, the helicopter is dispatched configured to rappel unless they know that a rappel is not necessary from intelligence provided by personnel at the site

(ATGS, ASM, Leadplane, or recon aircraft). If not configured for the rappel, the helicopter will survey the rappel location and then fly to a landing site within a few miles of the incident to reconfigure for the rappel. It takes 5 to 10 minutes to reconfigure.

Suitable Landing Site

Providing there is a suitable landing site reasonably close to the incident and the terrain, and vegetation between the landing site and the incident will not inordinately delay the firefighters walking to the incident, this alternative will be used versus rappelling.

Rappel Operation

If no landing site is available, the firefighters will rappel into the incident. The helicopter will approach the selected rappel site and perform a high hover power check (above 300 feet AGL). Once this is completed, they will descend to a stationary hover position at 250 feet AGL or lower (depending on the height of the vegetation) and perform the rappel operation. It takes each set of rappellers 15 to 25 seconds to descend on the rope. Once all the rappellers are on the ground, and their ropes released from the helicopter, the spotter deploys the cargo (cargo is sometimes deployed prior to the rappellers). The total time varies, but normally requires between 5 to 15 minutes to perform the operation.

Note: Density altitude may require the helicopter to make multiple trips to deploy partial loads. The spotter will communicate this if it is a factor.

Communications

The pilot and spotter will monitor the Guard frequency at all times and the assigned tactical frequency except on occasion when deploying personnel and cargo. When the tactical frequency is very active, the rappel helicopter may request to not monitor this frequency because a sterile cockpit is essential during the actual rappel phase. Do not communicate with the helicopter during this phase unless there is an emergency.

Considerations

The rappel helicopter has limited fuel duration over the incident. It is helpful to survey the area prior to the arrival of the rappel helicopter in order to point out potential landing sites or to relay that there are no landing sites near the incident. If delays are anticipated or required, consider directing the helicopter to land nearby to conserve fuel. Keep in mind that it is important to get the firefighters and their tools on the incident.

Water Scooper Operations (CL 215/415)

Airport Requirements

Runway – A 3,500-foot hard surface runway with a taxiway and ramp capable of supporting 36,000 lbs.

Fuel – The CL-215 requires 100 octane low lead (100 LL) while the CL- 415 requires Jet A fuel.

Foam – A supply of foam (3-55 gallon drum capacity per fuel cycle) and the necessary equipment for handling it and pumping or loading the concentrate on the aircraft should be anticipated.

***USFS* -** Forest Service contracted water scoopers shall not be loaded with chemical retardant or foam.

Scooping Site Requirements

The water source (or pickup lake) should be a minimum of one mile long, ¼ mile wide, free of obstructions, and at least six feet deep. The scooping path does not have to be straight, as the aircraft are somewhat maneuverable while scooping. Factors such as wind, elevation, and surrounding terrain will have a bearing on water source suitability. Less than a full load can be scooped on slightly smaller lakes. Both aircraft scoop at 80 kts, are on the water for about 15 seconds, and cover a distance of about 2,000 feet.

Foam Use

Concentration – Foam can be injected into the load at a concentration of 0.3% up to 3% in some aircraft models. Useful concentrations typically range from 0.3% to 1.0%. Foam concentrations greater than 0.6% are prone to drift.

Wet Foam – A typical method in using foam is to attack a hot fire with straight water or wet foam (0.3%).

Dripping Foam – After a fire has been knocked down, follow up with dripping foam (0.5%).

Dry Foam – Dry (0.6-1.0%) foam may be used instead of dripping foam after initial knockdown with wet foam.

Consistency and Water Temperature – The consistency or aeration of the foam is affected by water temperature. A slightly higher concentration may be needed for cold water and adjustments downward may be necessary for extremely warm water.

Evaluating Consistency – Foam consistency is best evaluated by ground personnel. Drops can be evaluated from the air using visibility criteria. Wet foam is visible for about 5 minutes, dripping foam for about 15 minutes, and dry foam is visible for 30+ minutes.

Environmental Limitations

- Foam is not recommended within 300' of lakes and streams.
- In steep drainages or sensitive areas, check local agency policy on foam use.
- When scooping during foam operations, some residual foam may flush out of the vent/overflow. While very diluted, some foam may be visible on the water for a short time.
- Obtain a briefing from the IC or responsible agency on the limitations of foam use, if any, prior to using.

Rinsing Tanks – Provide for two rinse loads of water prior to departing a fire.

Tactical Considerations

Tank Configuration – The CL-215 has two compartments totaling 1,400 gallons, and the CL-415 has four compartments totaling 1600 gallons. Loads can be dropped salvo, in trail, or split into separate drops. A salvo load for both airtankers is about 280' long and 65' wide. A trail drop is about 400' x 40'.

Drop Height – Drop height ranges from 100'-150’, depending on factors such as foam vs. straight water and direction of run (into wind vs. downwind).

Clearance – When dropping near ground crews, personnel must be moved at least 200' to the side. When drops are made 1000 feet or more in advance of crews, no clearance is necessary except to confirm no one is on the line.

Flight Patterns and Turnaround Times

Typical Flight Pattern – The typical flight pattern (or circuit) is oval, with a pickup into the wind and a downwind drop on the fire. This is the most common and efficient circuit and preferred by most pilots.

Turnaround Times – When water sources are located next to the fire, a 90-second turnaround time is possible.

- **CL-215 –** A rule of thumb for turnaround times for the CL-215 in an oval circuit is; turnaround time equals miles from lake to fire plus two minutes scooping (e.g. 5 miles to
- the fire from the lake is a 7 minute turn).
- **CL-415 –** Typical turnaround times for the CL-415 are: 1 mile - 3 minutes, 3 miles – 4 minutes, 6 miles - 6 minutes, 10 miles - 9 minutes, and 15 miles - 12 minutes.

Alternative Flight Patterns – If fire intensity or other reasons indicate a need for drops into the wind or crosswind, then a U-shaped circuit or a Figure 8 will be necessary.

Turnaround time will be slightly longer.

Fuel Cycle Duration

Average fuel cycle is about 4 hours. A quick turn from a close lake can shorten the cycle to 3.5 hours due to increased fuel demand.

Direct Attack and Initial Attack

Scoopers are best suited for IA fires. They are most commonly used for direct attack on the fire’s edge with drops made half in/half out. Like other air resources, they are most effective when worked closely with ground resources, although drops should not be delayed while waiting for ground resources. High intensity fires may require drops to be made into the wind.

Parallel Attack

In the event ground resources are delayed or drops advance faster than the crews, a parallel attack is effective. Drops should be placed parallel to the fire’s edge at a distance governed by rate of spread and progression rate of ground resources. The ATGS should consider an increase in foam proportion to dripping (.5%) or dry foam (.6-.8%). If the fire does not reach the drops in 30 to 45 minutes, reinforcement drops should be made. If progress by ground crews is too slow, retardant may be a better option, with foam and water used for knockdown and cooling the line.

Indirect Attack

While many scooping aircraft can be loaded with retardant at a tanker base, they are not designed to efficiently and effectively drop retardant. Therefore, their capabilities at indirect attack are limited. Narrow, wind-driven fires can be successfully attacked indirectly using foam drops, taking advantage of light fuels or fuel breaks. CL-215's and CL-415's are effective in supporting indirect tactics when used to reinforce retardant or other control lines, hot spotting, and knockdown of slopovers and spot fires.

Supervision

Scoopers are fixed-wing resources and are supervised by ATGS, ASM, Lead, or ATCO.

Scooper Aircraft Communications

Generally, communications with scooping tankers are not much different than conventional airtankers with respect to target description, clearing the line, and drop evaluations, etc.

Scooping Operation

During the scooping operation, including approach and departure from the lake, communications with the tanker should cease to allow the crew to concentrate on the pickup. The tanker will call when "up" or "off" the water, which will signify to the ATGS that it's okay to transmit.

Foam Instructions

Instructions can be given after the scooping operation on whether or not to inject foam and at what percent so the load has time to mix.

Long Turnarounds

On long turnarounds, request the tanker to give a one-mile final call and give your target description at that time.

Standard Communications

Confirm the line is clear, make the drop, and after the drop, evaluate the load. Instructions for the next load, including foam concentrations, can be given at this time if possible.

Otherwise, wait until the tanker is "up" for the next target description.

Scooper Aircraft Separation

Once in the circuit on the fire, CL-215's and CL-415's work 500 feet AGL and lower.

Separation of Scoopers in the Circuit – If two tankers are working the same circuit, which is very common, the aerial supervisor can choose to daisy-chain the two tankers or they can be worked in tandem.

- **Daisy Chaining –** One scooper is on the lake while the other drops. Generally works best for quick turnaround times.
- **Tandem –** One scooper leads the other. Generally works best, is more efficient, and requires less supervision for long turnaround times. Also allows ground resources more time between drops to work the line.
- **Four Scoopers –** If four scoopers are in a circuit, they can be sequenced singly in a daisy-chain, or they can be worked in two tandem pairs.

Mixing CL-215's & CL-415's – Both can work in the same circuit, however the CL-415's are faster and will overtake the 215's on the circuit. If possible, keep separate.

Integrating with other Aircraft – Scoopers can be successfully integrated with suppression and logistical missions of other aircraft.

Horizontal Separation – The most common separation method is to assign different aircraft types to separate parts of the fire, ex., scoopers on the right flank, helicopters on the left or conventional tankers on the left.

Sequencing – Sequencing of aircraft can be very efficient and often is necessary but requires close supervision.

- Have the scooper extend the circuit if there is a need for another aircraft to work the same area as the scooper for a short time, such as a sling load, personnel drop, or a quick recon.
- If another aircraft needs to work the same area as the scooper for a sustained period, either orbit the tanker or reassign.
- Sustained bucket operations in the same target area as scoopers is not advised except for very long scooper turnaround times.
- CL-215/415 scoopers can support conventional airtankers by sequencing them in between retardant drops to cool the fire in advance of the retardant or to assist in holding the fire as it approaches the retardant.

Canadian Scooper Terminology

Following is a short list of terms relating to the use of the scooping aircraft used by Canadian Air Attack Officers. Some of the terms are common to the U.S. and a few are slightly different.

Fire Traffic Pattern

Circuit – Flight route taken by scooping aircraft from the water source to the fire and return.

- Typical Circuit – Oval or rectangular flight route that is defined by an ‘into the wind’ pickup on the lake and a downwind drop on the fire.
- U-Shaped Circuit – A flight route resembling a “U” that is defined by an ‘into the wind’ pickup on the lake and an ‘into the wind’ drop on the fire.
- Figure-8 Circuit – An intersecting flight route in the shape of an “8” that is defined by an ‘into the wind’ pickup on the lake and can accommodate either a crosswind drop on the head or an ‘into the wind’ drop elsewhere on the fire.
- Base Leg – The leg of the bombing circuit immediately preceding and perpendicular to the final leg (base leg for pickup or base leg for the drop).
- Final Leg – The last leg of the bombing circuit direct to the target or the lake.
- Bomb Run **–** Flight path of the tanker to the target.

Target Descriptions

Tie-in – Connect the drop to a specific reference point or anchor point.

Tag on – Connect the tail end of the drop to a given point, usually the head end of the last drop.

Extend – Tag on and lengthen the line in a specific direction.

Lap on – Cover a previous drop entirely or to one side or the other. Reinforce.

Lap on left/right – Cover a previous load to the left or right to widen the drop pattern (usually about 1/3 overlap).

Roll-Up – Connect the head end of the drop to a given point or the tail end of a previous drop.

Half On/Half Off – Half the load on the fire, half on unburned fuel. Half & half or half in/half out.

Span – Distance equal to one wingspan of the tanker being used.

String Drop – Trail drop

Train Drop – Trail drop

Bull's Eye – Load was placed exactly where requested.

Head End of Drop – Where the last of the load hits the ground.

Tail End of Drop – Where the load first hits the ground.

<u>Other Terminology</u>

Bird Dog – ATGS platform except Bird Dog combines low-level lead-ins when deemed necessary with an orbit and direct method. Similar to the ASM.

Orbit and Direct – Method of supervision where Bird Dog is above the fire in a right hand pattern and gives verbal targets and direction to airtankers as opposed to providing low level lead-ins.

Lead In – Same as a Lead.

Inspection Run – Same as a low pass or dry run.

Dummy Run – Same as a "show-me."

Hold – Canadians may use this term for "go around - do not drop" as well as orbit outside the incident airspace.

Stay – May also be used to instruct a tanker to proceed to a designated location and await instruction. Hold and orbit.

Reload – Load and return.

Period of Alert – Duty day or duty time..

Chapter 9 – All Hazard Incidents

Introduction – Fire incidents have long utilized aerial supervision for coordinating aerial resources. The same principles of supervising and directing aircraft can be applied to other types of incidents commonly referred to as "all hazard incidents." All hazard incidents include volcanic eruptions, earthquakes, search and rescue operations, floods, oil spills, hurricanes and spray projects.

Air Operations Supervision

Fixed-Wing and Helicopter Coordinators

On non-fire incidents when the level or complexity of air operations exceeds the supervisory capability of the ATGS/ASM, the organization may be expanded to include a Fixed-Wing Coordinator (ATCO), Helicopter Coordinator (HLCO), or both. Both positions report to the ATGS/ASM. The roles and responsibilities are basically the same as fire incidents.

- The ATCO/Fixed-Wing Coordinator is an airborne resource which has responsibility for coordinating assigned fixed-wing aircraft. More than one Fixed-Wing Coordinator may be assigned to a large incident.
- Large or complex incidents, which have a mix of fire and other disaster operations (earthquake or volcanic eruption), require both an ATGS/ASM and a Fixed-Wing Coordinator (ATCO) to coordinate and integrate the mix of aviation assets.

Criteria for Assigning Aerial Supervision

Without adequate supervision and coordination air operations will very likely be less efficient, more costly and less safe. An ATGS/ASM should be assigned when an incident meets the criteria listed below.

- Multiple aircraft operating in incident area airspace.
    - Mix of fixed-wing and helicopter operations.
    - Mix of low-level tactical/logistical aircraft.
    - Periods of marginal weather, poor visibility or turbulence.
- Two or more branches utilizing air support.
- Mix of both civil and military aircraft operating in the same airspace or operations area.
- When conditions require airspace management, ATC and air resource mission priority setting and coordination.
- Ground stations have limited ability to communicate with flying aircraft due to terrain or long distances.

Aerial Supervision Interaction and Communication

The interaction between aerial supervisors (Lead, ATGS, ASM, and HLCO) is well understood and practiced on fire incidents. Interactions and communications protocol is far less established and will vary on other types of incidents. Although all hazard incidents retain the basic ICS organization and roles, there are incident specific technical specialist positions added to the ICS organization to supervise, coordinate and lead specific incident functions. Aerial supervisor roles may be modified to fit the incident situation and they may be coordinating directly with persons other than the traditional Operations Section Chief, Division/Group Supervisor or Strike

Team/Task Force Leader. It is critical that we understand the roles and responsibilities of the Technical Specialist positions, how they are identified, and how our role interacts with them (chain of command, communications protocol, authority, etc.).

Use of Military Aircraft

It is important to fully understand the military organization(s), their SOPs, military aircraft capabilities and limitations, and how the ICS interfaces with military operations. An assigned Agency Aviation Military Liaison (civilian) and Military Air Operations Coordinator (civilian) will work with the AOBD and aerial supervisor in assigning and coordinating military air operations.

The availability of military air tactical resources may vary dramatically due to world commitments. Refer to the Military Use Handbook for additional information and guidance.

Air Operations Associated with all Hazard Incidents

During the past few decades, aircraft have become an important tool in combating both natural and human caused incidents. Possible uses of aircraft for various types of incidents are listed in the table below.

Table 9. Possible Uses of Aircraft by Type of Incident

Air Operations	Fire	Volcanic Eruption	Earth-quake	Search/ Rescue	Flood	Hurricane	Oil Spill	Spray Project	Law Enforc.
Aerial Retardant, Spray	X	X	X				X	X	
ATCO / Leadplane	X	X	X	X	X	X	X	X	
Helicopter Rappel – Personnel	X	X	X	X	X	X			X
Helicopter Land – Personnel	X	X	X	X	X	X	X	X	X
Parachute Delivery – Personnel	X	X	X	X	X	X	X		
Parachute Delivery – Cargo	X	X	X	X	X	X	X		
Helicopter Sling Load – Cargo	X	X	X	X	X	X	X		X
Helicopter Internal – Cargo	X	X	X	X	X	X	X	X	X
Recon/Assessment – Fixed-Wing	X	X	X	X	X	X	X	X	X
Recon/Assessment – Helicopter	X	X	X	X	X	X	X	X	X
Search – Fixed- Wing	X	X	X	X	X	X			X
Search – Helicopter	X	X	X	X	X	X			X
Medevac – Helicopter	X	X	X	X	X	X	X	X	X
Medevac – Short Haul Helicopter.	X	X	X	X	X	X	X	X	X
IR Detect/Map - Fixed-Wing	X	X	X		X		X		X
IR Detect/Map – Helicopter	X	X	X		X		X		X
Helitorch	X						X		
ATGS or ATC	X	X	X	X	X	X	X	X	X
News Media	X	X	X	X	X	X	X	X	X
VIP Flights	X	X	X	X	X	X	X	X	X

Chapter 10 – Safety

Safety is the principal consideration in all aspects of aerial supervision. A safe aviation operation depends on accurate risk assessment and informed decision-making.

Risk levels are established by the severity of possible events and the probability that they will occur. Assessing risk identifies the hazard, the associated risk, and places the hazard in a relationship to the mission. A decision to conduct a mission requires weighing the risk against the benefit of the mission and deciding whether the risks are acceptable.

Examples of the Risk Management Process are available in the IRPG, the Interagency Standards for Fire and Fire Aviation Operations (Red Book), CALFIRE 8300, and the Interagency Helicopter Operations Guide (IHOG).

Factors to Consider During the Risk Assessment Process

- Any flight mission has a degree of risk that varies from 0% (no flight activity is conducted) to 100% (aircraft and/or personnel experience a mishap).
- The aerial supervisor must identify hazards, analyze the degree of risk associated with each, and place hazards in perspective relative to the mission or task.
- Hazards might not always be limited to the performance of flight, but may include hazards to personnel if the flight is not performed.
- The risk assessment may include the aerial supervisor, AOBD, Duty Officers, agency Fire Management Staff, ICs, Dispatchers, and Line Officers/Managers.
- Ultimately the PIC has the authority to decline a flight mission that he or she considers excessively hazardous.

***USFS* –** All Forest Service flights require a risk assessment. Refer to USFS Manual 5700 and USFS Handbook 5709.16.

Mitigating Risks

In some cases the aerial supervisor may have to shut down air operations. Air operations must not proceed until risk mitigation measures are implemented. Risk mitigation measures to consider:

Monitor the Overall Aviation Operation for Human Factors Related Issues

- Task saturation
- Fatigue, burnout, and stress
- Acceptance of risk as normal
- Lack of situational awareness

Monitor Effectiveness of the Overall Air Operation

- Ensure suppression objectives are truly obtainable.
    - Risk versus reward – Is the mission worth it?
    - Is there adequate ground support?
    - Are there adequate aerial resources?

- Is there enough time in the operational period?
- Monitor weather conditions for increasing winds, turbulence, thunderstorms, or decreasing visibility.
- Be proactive in communicating current fire and fire weather conditions.
- Provide realistic input regarding resource needs commensurate with successful completion/modification of incident objectives.

Utilize the Appropriate Aircraft for the Mission

- Turbine vs. piston engine
- Heavy tankers vs. SEATs
- Density altitude
- Helicopter types and delivery systems

Communications Planning

When discrete radio frequencies are used during incident operations, ensure contact frequencies such as command and air-to-ground are monitored by appropriate ground personnel. Make sure that ground personnel know how to reach the aerial supervisor.

Order Additional Frequencies

Order additional frequencies as needed for operations; as incident complexities increase, the aerial supervisor must ensure adequate radio frequency coverage. Be proactive. There can be up to a 24-hour delay from the time a frequency is ordered to the time it is assigned to the incident.

Establish Positive ATC

Hold aircraft in the air or on the ground until structured traffic patterns can be established.

Span of Control

Limit number of aircraft working an incident based on visibility, routing procedures and communications capabilities.

Obtain Input

Discuss operations safety with Leadplane, Helicopter Coordinator and pilots. Mission debriefings are an excellent source of information; Air crewmembers and support personnel will utilize AAR to critique mission effectiveness.

System Safety Assessment

The effectiveness of risk assessment and management can be increased through utilization of the current System Safety Assessment for Aerial Supervision Operations.

The following assessment of aerial supervision operations has been developed for aerial supervisors. It identifies hazards, the likelihood of encountering them and the risk associated with exposure to the hazard. Mitigations are listed for each hazard as well as the post mitigation risk.

System Safety utilization is standard operating procedure and covers all aspects of aerial supervision. It should be used for incident operations, training and review by agency air crewmembers.

Table 10. System Safety Assessment for Aerial Supervision

System – Aircraft

Sub-systems	Hazards	Pre-Mitigation Likelihood	Pre-Mitigation Severity	Pre-Mitigation Outcome	Mitigation	Post Mitigation Likelihood	Post Mitigation Severity	Post Mitigation Outcome
Avionics	Avionics failure.	Occasional	Marginal	Medium	Minimum Equipment List establishes minimum requirement. Mission requirements as determined by the flight crew. Integrate into preflight checklist.	Improbable	Negligible	Low
	Avionics package insufficient for mission complexity.	Probable	Critical	High	Contract specifications that recognize mission requirements. Ensure necessary type, configuration, and number of radios to complete mission safely. Reduce span of control. Limit operations.	Remote	Marginal	Medium
	Contract pilot unfamiliar with avionics. (Can't run radios or GPS, etc.).	Occasional	Marginal	Medium	Release, replace the pilot, Enforce contract specifications.	Remote	Negligible	Low
Aircraft Type	Reduced field of view for the flight crew.	Occasional	Critical	Serious	Ensure aircraft is appropriate for the mission. Flight profile altered to maximize visibility. Use of TCAS. Clear communication with other aircraft. Alter interior configuration (headrest, seat, windows).	Improbable	Negligible	Low
Performance Standards	Poor Engine performance (single/twin, turbine/recip) for the ATGS mission.	Occasional	Catastrophic	High	Plan for high-density altitudes. Download cargo/fuel load. Relocate to favorable location. Alter the mission. Upgrade the aircraft. Ensure aircraft is appropriate for the mission. Perform preflight planning.	Remote	Catastrophic	Serious
Contracting	Contract pilot skill/fire experience leading to sub-standard performance (i.e. working avionics, flight skills) during flight operations.	Remote	Critical	Medium	Thorough briefing. Ride along with veteran fire pilot. Use contract evaluation process. Contractor training. Computer based training. Give air attack pilots a check ride every three years.	Improbable	Critical	Medium
Fuel	Capacity and Procedure, ground fueling errors.	Frequent	Catastrophic	High	Verify adequate volume of fuel for mission. Ensure proper fueling procedures are followed for type of aircraft.	Remote	Critical	Medium

1 **System - Flight Operations**

Sub-systems	Hazards	Pre-Mitigation Likelihood	Pre-Mitigation Severity	Pre-Mitigation Outcome	Mitigation	Post Mitigation Likelihood	Post Mitigation Severity	Post Mitigation Outcome
Mission	Restricted visibility.	Frequent	Catastrophic	High	Limit exposure. Determine effectiveness of the operation (risk vs. benefit) and discontinue if warranted. Limit number of aircraft in operating area. Increase vertical/horizontal separation of aircraft.	Occasional	Critical	Serious
	Wake turbulence.	Occasional	Critical	Serious	Situational awareness assists prevention. Communication helps to avoid wake turbulence areas. Wake turbulence avoidance procedures (altitude, time, distance).	Remote	Critical	Medium
	Weather (Turbulence/wind/T-storms).	Frequent	Critical	High	Adjust tactics or shut down Air Ops. Increase vertical/horizontal separation of aircraft. Utilize human aided technology (weather radar, etc.). Encourage dispatch to obtain/communicate weather information. Utilize and share pilot reports of severe weather.	Occasional	Critical	Serious
	Poor fuel management.	Occasional	Critical	Serious	Monitor fuel quantities. Follow fuel transfer procedures.	Remote	Critical	Medium
	Controlled Flight Into Terrain due to low-level operations.	Frequent	Catastrophic	High	Ensure high level recon is completed prior to commencing low-level flight. Manage radio communication. Proper aircraft configuration. Reduce exposure time in low level. Consult sectional chart/hazard map, Consult ground personnel/other aircraft (AC). Obtain unit in-brief. Utilize local knowledge.	Remote	Catastrophic	Serious
	Operating in close proximity to other aircraft (collision potential).	Frequent	Catastrophic	High	Communication established with all aircraft. Situational awareness. TCAS Establish clear and concise directions for simultaneous operations, (virtual fence, geographic separation, altitude separation, holding/timing, Establish IP's, ingress/egress route.	Remote	Catastrophic	Serious

1 System - Flight Operations, Cont.

Sub-systems	Hazards	Pre-Mitigation Likelihood	Pre-Mitigation Severity	Pre-Mitigation Outcome	Mitigation	Post Mitigation Likelihood	Post Mitigation Severity	Post Mitigation Outcome
Mission	Reliance on technology causes distraction, low situational awareness, division of attention in the cockpit.	Frequent	Catastrophic	High	Maintain situation awareness. Maintain see and avoid techniques Prioritize mission/cockpit workload. Utilize CRM practices.	Remote	Catastrophic	Serious
	Aircraft emergency (engine out, fire, bird strike, mechanical failure, etc.).	Occasional	Catastrophic	High	Crew cross training and familiarization with a/c systems and emergency procedure checklists (pinch hitter/simulator training).	Remote	Catastrophic	Serious
	Exceeded span of control.	Occasional	Critical	Serious	Ensure roles and responsibilities are assigned and understood within aerial supervision crew. Assign aircraft to common functions and tasks with a single point of contact. Hold aircraft at base to limit the number of assigned aircraft over the incident.	Remote	Critical	Medium
	Unclear objectives / tactics.	Frequent	Critical	High	Ensure strategy and tactics are clear and understood. Use common terminology, solicit/utilize feedback.	Occasional	Critical	Serious
	ATGS performance results in hazardous operation.	Occasional	Critical	Serious	Shut down the operation, Deconflict the area. Return to base to debrief the mission. Coach, proficiency checkride, retrain / recertify.	Remote	Critical	Medium
	Unnecessary exposure due to inefficient operational use of tactical aircraft.	Probable	Critical	High	SOPs for all tactical aircraft types. Right tool for job. Training, feedback, brief/debrief.	Remote	Critical	Medium
	Aircraft operating without aerial supervision.	Frequent	Critical	High	When aerial supervision is readily available (within the dispatch area/GACC), they will be ordered for the safety, effectiveness, and efficiency of ground and/or aerial firefighting operations.	Occasional	Critical	Serious
Airspace	FTA: Aircraft not complying with procedures.	Probable	Catastrophic	High	Aerial supervision enforces FTA procedures.	Improbable	Critical	Medium
	Multiple IA incidents in same area cause confusion; near miss hazard.	Probable	Critical	High	Coordinate with dispatch and other aircraft. Ensure fire names, frequencies, locations, and aircraft assignments are communicated to all flight crews.	Occasional	Critical	Serious
	Special use airspace: Aircraft not having authorization to enter the SUA, not coordinating with controlling agency.	Probable	Critical	High	See and avoid. Know SUA areas. Establish communication with controlling agency. Thorough briefings.	Remote	Critical	Medium
	Non-incident aircraft intrusion in TFR.	Probable	Catastrophic	High	See and avoid, Inform other aircraft on scene. Re-evaluate TFR promotion.	Remote	Catastrophic	Serious

1 System - Flight Operations, Cont.

Sub-systems	Hazards	Pre-Mitigation Likelihood	Pre-Mitigation Severity	Pre-Mitigation Outcome	Mitigation	Post Mitigation Likelihood	Post Mitigation Severity	Post Mitigation Outcome
Airspace	Fires in proximity to airport/airstrip. Potential for midair collision or intrusion in FTA.	Occasional	Catastrophic	High	Implement/Validate TFR as incident expands, Deconflict SUA, Establish communication with controlling agency, Notify other aircraft. Provide TFR transition corridors for non-incident aircraft on large incidents. Increase awareness of General Aviation (GA) operators and other agency flight crews not assigned to incident.	Remote	Catastrophic	Serious
Communications	Radio frequency congestion.	Frequent	Critical	High	Exercise radio discipline/order additional frequencies as needed.	Remote	Critical	Medium
	State/County/Rural resources on different bandwidth.	Probable	Critical	High	Coordinate with cooperators to find a way to communicate with one another.	Remote	Critical	Medium
	Hazardous air operations resulting from inaccurate information disseminated through the dispatch system.	Frequent	Critical	High	Verify information at time of dispatch. Flight crews will brief/debrief with dispatchers. Provide aviation training for dispatchers. Maintain qualified dispatcher on the A/C desk.	Occasional	Critical	Serious

1 System – Personnel

Sub-systems	Hazards	Pre-Mitigation Likelihood	Pre-Mitigation Severity	Pre-Mitigation Outcome	Mitigation	Post Mitigation Likelihood	Post Mitigation Severity	Post Mitigation Outcome
Human Factors	Loss of situational awareness due to aircrew fatigue/burnout.	Probable	Critical	High	Adhere to flight and duty limitations policy. Activate phase limitations.	Occasional	Critical	Serious
	Hazardous air operations developing through ineffective CRM.	Remote	Critical	Medium	Re-evaluate task allocation. Brief and debrief.	Improbable	Critical	Medium
	Acceptance of high risk as normal. (Complacency).	Probable	Catastrophic	High	Re-evaluate risk vs. benefit. Solicit feedback from other flight crews. Utilize CRM to validate mission parameters. Validate mission, or remove the high risk taking individual from the mission.	Remote	Catastrophic	Serious
	Hazardous air operations developing due to external pressures.	Occasional	Critical	Serious	Do not allow external pressure to influence the operation. Utilize CRM to ensure an effective operation with acceptable level of risk.	Remote	Critical	Medium
	Hazardous attitude: Anti authority, macho, invulnerability, impulsiveness, and resignation.	Frequent	Critical	High	Remove the individual from the mission. Properly supervise employees. Adhere to work-rest guidelines, flight and duty limitations policy, etc. Validate and stick to incident strategy and tactics.	Occasional	Critical	Serious

Modifying Air Operations

There is no way to define an exact trigger point for adjusting, downsizing, or completely suspending aviation operations. The factors listed below should be evaluated to determine whether additional aerial supervision resources are needed or tactical/logistical missions need to be modified/suspended:

- Complexity of aviation operations
- Communications
- Topography (fire size, position on slope, location, etc.)
- Firefighter and public safety
- Poor visibility
- Wind
- Turbulence
- Fire behavior
- ATGS Fire Orders & Watch out Situation (see below)
- Aircraft incident/accident
- Aircraft/Aircrew performance

Chapter 11 – Job Aids and Resources

Required Job Aids (Lead/ASM)

A full U.S. (Contiguous United States) approach and IFR chart coverage or approved Electronic Flight Bag that is FAA and Agency approved.

Aerial Supervision Kit

Each aerial supervisor should have and maintain a kit. The following items are recommended to be on board the aircraft:

- Knee Board – Leg board/clip board
- Headset, Flight Helmet, PPE
- Frequency Guide
- Batteries – Headset, Camera, flashlight, etc.
- Flashlight
- Camera
- Overnight Bag

Consider Electronic Tablet with charging cables and or external power supply, which contain the following items:

- Maps
  - Current FAA sectional chart coverage area
  - Agency Maps
  - Retardant Base Coverage Map
  - Local Hazard Map (from Airtanker Base Manager or Dispatch)
  - Incident Map (updated daily)
  - Retardant base map
- **Air Tactical Forms** – Download from https:www.nwcg.gov
  - Fire Size-up
  - ATGS/Lead/ASM checkride
  - Initial Attack/Extended Attack ATGS Form
  - SEAT Pilot Mission Documentation Log
  - Aerial Supervision Transition Checklist
  - Leadplane, ASM, or ATGS Mission Log
  - Airtanker Briefing Checklist
  - Aerial Supervision Cost Summary
  - Pilot Flight time and Duty Day Tracking

Publications

- Interagency Smokejumper Pilot Operations Guide
- Interagency Smokejumper Operations Guide
- Interagency Standards for Fire and Fire Aviation Operations (Red Book), NFES 2724
- Tables of Sunrise and Sunset
- Radio Frequency Guide
- USFS-5700-1 Visual Signal Code Card
- Radio Programming Directions
- Recommended Retardant Coverage Levels
- Airtanker Line Length Production Charts
- Agency Specific Information and Policies
- IAP: Available daily through ATGS, AOBD or Dispatch
- Aviation Safety Communiqué (SAFECOM): USFS-5700-14 and OAS-34
- Interagency Air Space Coordination Guide
- National Interagency Mobilization Guide, NFES 2092
- Geographic (agency) Mobilization Guide
- Forest (unit) Mobilization Guide
- Agency Aviation Management Manual Handbooks
- DOI - USDA Aircraft Radio Communications and Frequency Guide
- National Airtanker Contract
- Airtanker Base Operations Guide and Directory
- Agency Aviation Plan
- Area Planning AP/1B Chart (MTR's)
- Military Use Handbook
- Interagency Single-Engine Airtanker Operations Guide (ISOG), PMS 506
- Interagency Helicopter Operations Guide (IHOG), PMS 510
- Interagency Aviation Mishap Response Guide and Checklist, PMS 503

Glossary

This document contains terms and definitions commonly used in aviation and in the 2016 IHOG.

Terms and definitions that match the NWCG Glossary of Wildland Fire Terminology are annotated with an asterisk (*).

Term	Description
Abeam	An aircraft is abeam a fix, point, or object when the fix/point/object is approximately 90 degrees left or right of the aircraft's track.
Abort	To terminate a planned aircraft maneuver.
Action Plan	Any tactical plan developed by any element of ICS in support of the IAP.
AGL	Above ground level.
AIR Attack	ICS identifier for the ATGS.
Airtanker Coordinator (ATCO)	Airborne position supervised by the ATGS. Assigns airtankers to specific targets. Supervises and evaluates drops. The position is normally filled with a Leadplane.
"A" (Alpha)	Designation for State of Alaska DNR ASM aircraft.
Anchor Point	A strategic and safe point or area, usually a barrier to fire spread, from which to start construction of the control line.
ASM	Federal designation for an Aerial Supervision Module platform with an ATP and ATS on board. This module can perform aerial supervision and low-level operations including the lead profile.
Assigned to	Tactical resource allocated to an incident. The resource may be flying enroute to and from, or on hold at a ground site.
ATP	Federally designated Air Tactical Pilot. Pilot of an ASM who is primarily responsible for aircraft safety and providing aircraft coordination over the incident. The ATP meets the Interagency training requirements for Leadplane operations and has completed ASM/CRM training.

Term	Description
ATS	The ATS is a qualified ATGS who has received specialized training and authorization to function as an ASM crewmember. The ATS is an ATGS who also utilizes CRM to evaluate and share the incident workload with the ATP.
Barrier	Any obstruction to the spread of the fire. Typically an area or strip devoid of flammable fuel.
Blowup	Sudden increase in fire intensity or rate of spread sufficient to preclude direct control.
Base (of a fire)	The part of the fire perimeter opposite the head (see origin). Also referred to as rear or heel.
"B" BRAVO	Federal designation for ASMs.
Break (left or right)	Means turn left or right. Applies to aircraft in-flight, usually on the drop run and when given as a command to the pilot. Implies immediate compliance.
Burn out	Fire set at the inside edge of a control line to consume unburned materials between the fire and the control line. Usually associated with indirect attack.
Canopy	The stratum containing the crowns of the tallest vegetation present (living or dead), usually above 20 feet.
Cardinal Points	The four chief points of the compass: North, South, East, and West.
Check Point	A rotor wing reporting location clearly identified by the aerial supervisor. See to chapter 7, page 82 for more detail.
Civil Twilight	Civil Twilight is defined to begin in the morning, and to end in the evening when the center of the Sun is geometrically 6 degrees below the horizon. This is the limit at which twilight illumination is sufficient, under good weather conditions, for terrestrial objects to be clearly distinguished.
Clock Method	A means of establishing a target or point by reference to clock directions where the nose of the aircraft is 12 o' clock, moving clockwise to the right wing at 3 o'clock, the tail at 6 o'clock, and the left wing at 9 o'clock.

Term	Description
Configuration	How the aircraft is equipped, outfitted, modified for a mission or segment of a mission. Also refers to use of drag devices (flaps, gear) to modify flight characteristics.
Congested Area	FAA (non-specific) term for areas that require additional precautions and procedures to conduct low-level flight operations. It is applied by the FAA on a case by case basis. The regulation addresses, "any congested area of a city, town, or settlement, or over any open air assembly of persons...."
Constant Flow Tank	A single compartment with two doors controlled by a computer. Capable of single or multiple even flow drops at designated coverage levels from.5 GPC to 8 GPC.
Control Line	An inclusive term for all constructed or natural fire barriers and treated fire edge used to control a fire's spread.
Cover Assignment	Airtankers ordered to a different base to provide IA coverage at the new base. Sometimes referred to as "Move Up and Cover."
Coverage Level	A numerical value representing the number of gallons of retardant mixture dropped, or prescribed, to cover fuels in a 100 sq. ft. area (GPC).
Cut Off Time	Time when operations involving low-level flight maneuvers must be suspended.
Delayed Attack Fire	A fire that, due to its lower priority and/or unavailability of ground resources, will not be staffed for several hours or possibly several days.
Direct Attack	Control effort (retardant line, fireline) conducted at fire perimeter (fire edge) - usually under low fire intensity conditions.
Divert	Change in aircraft assignment from one target to another or to a new incident.
Drift Correction	Offset flight path flown to compensate for wind induced retardant drift.
Drift Smoke	Smoke that has drifted from its point of origin and has lost any original billow form.
Drop	Aerial release of paracargo, retardant, or water/foam.

Term	Description
Drop Configuration	The type of drop the pilot selects to achieve the desired coverage level based on the aircrafts door/tank system.
Drop Zone	The area around the target to be dropped on.
Dry Run	A low pass over the target without dropping to evaluate drop conditions and/or alert ground personnel of an impending live run.
Early	Indicating drop was early or short of the target.
Engine	(In fire context) A ground vehicle crewed by firefighters that dispenses water or foam normally with fire hoses and nozzles.
Escape Route	The safest, quickest or most direct route between a firefighter's location and a safety zone.
Exit	Term used to indicate the flight route away from the drop area.
Extend/Tag on	Drop retardant so that the load overlaps and lengthens a previous drop.
False Alarm	A reported smoke or fire requiring no suppression action.
Finger	A narrow elongated portion of a fire projecting from the main body.
Federal	Term used to define DOI and its bureaus and the USDA Forest Service in reference to land ownership, protection responsibilities, contracts, aircraft and other context.
Fire Break	A natural or constructed barrier used to stop or check fires or to provide a control line from which to work.
Fireline	A control line that is void of burnable material. Fire lines are normally constructed by hand crews.
Fire Perimeter	The active burning edge of a fire or its exterior burned limits.
Fire Shelter	An aluminized, heat reflective, firefighter's personal protective pup tent used in fire entrapment situations. The heat reflection capability of the exterior is the primary function of the shelter. DO NOT drop fire retardants on the tent, as it will compromise the heat reflection capability of the shelter.

Term	Description
Fixed Tank	A tank mounted inside or directly underneath an aircraft, which contains water or retardant for dropping on a fire.
Fixed-Wing Coordination	A non-fire airborne position designed to supervise airplanes on incidents.
Flanking Attack	An attack made along the flanks of a fire either simultaneously or successively from a less active or anchor point and endeavoring to connect the two lines to the head.
Flanks	The parts of a fire perimeter that are roughly parallel to the main direction of spread. The left flank is the left side as viewed from the base of the fire, looking toward the head.
FLIR	Forward Looking Infrared.
FLIR/ATGS	ATGS aircraft equipped with FLIR. FLIR used in ATGS operations.
FM	Refer to VHF-FM.
Fuel Break	A wide strip or block of land on which the vegetation has been permanently modified to a low volume fuel type so that fires burning into it can be more readily controlled.
Fugitive Retardant	A clear retardant, without iron oxide (red color agent), or a retardant with a red color agent that fades or becomes invisible after several days exposure to ultraviolet sunrays.
Gap	A weak or missed area in a retardant line.
Go Around	Abort the retardant run.
Gel	Water, which is chemically enhanced and utilizes in direct attack operations as a suppressant.
GPC	A term relating to retardant coverage levels meaning Gallons per 100 Sq. Ft.
Head	The most rapidly spreading portion of a fire perimeter, normally located on the leeward or up slope side.
HEL CO (HLCO)	Call sign/ICS identifier of the Helicopter Coordinator pronounced “HEL-CO”.

Term	Description
Here	Term communicated by the Leadplane Pilot to the airtanker or helitanker pilot identifying the target location and starting point of a drop.
Helitanker	Heavy (Type 1) Helicopters configured with fixed tanks or a bucket for dropping water, foam, or retardant.
Hold (Holding Area)	Refer to Chapter 7.
Holding Action	Use of an aerial application to reduce fire intensity and fire spread until ground resources arrive. Common with delayed attack fires.
Hoselay	Arrangement of connected lengths of fire hose and accessories beginning at the first pumping unit and ending at the point of water delivery.
Hotshot Crew	A highly trained firefighting crew used primarily in handline construction.
Hotspot	A particularly active part of a fire.
Indirect Attack	Control line located along natural or human made firebreaks, favorable breaks in topography or at a considerable distance from the fire perimeter.
IP	Refer to chapter 7.
Intervalometer	A cockpit mounted electronic device/selector box which actuates the compartment door singly or multiple doors simultaneously or in sequence, at preset time intervals. Pilot or co-pilot selects number of doors and time interval between doors to produce the desired coverage level and line length.
Island	Green or unburned area within the fire perimeter.
Jettison	To dispose of (drop) unused retardant prior to landing.
Knock Down	To reduce flame or heat in a specified target. Indicates the retardant load should fall directly on the burning perimeter or object. Used to assist ground forces.
Late	Indicating the drop was late or overshot the target.

Term	Description
Leadplane	An airplane crewed by a qualified Leadplane Pilot tasked to lead airtankers in low-level drop runs.
Leadplane Pilot	Performs Airtanker Coordinator duties and is authorized to conduct flights below 500 feet AGL to access flight conditions, hazards, and to identify the target.
Leadplane Pilot Coach	A pilot with a minimum of 2 years' experience as a qualified Leadplane Pilot assigned to assist a trainee Leadplane Pilot to successfully complete training.
Leadplane Evaluator Pilot	Leadplane Pilot designated by the USDA-USFS or BLM to train Leadplane Pilot trainees.
Leadplane Final Evaluator Pilot	A Leadplane Pilot designated by the USDA-USFS or BLM to evaluate Leadplane Pilot trainees for initial certification and Leadplane Pilots for recertification.
Live Run	A flight over the drop area in which a discharge of cargo or retardant/water will be made.
Load and Hold	The airtanker is being ordered to reload and hold at the retardant base awaiting further instructions.
Load and Return	The airtanker is being ordered to reload and return to the fire with the load of retardant.
Low Pass	Low-altitude run over the target area used by the Leadplane Pilot and/or airtanker pilots to identify the target and assess flight conditions on the approach and exit.
MAFFS	Modular Airborne Firefighting Systems - Military aircraft equipped to drop retardant. Used in emergencies to supplement commercial airtankers.
Main Ridge	Prominent ridge line separating river or creek drainage. Usually has numerous smaller ridges (spur ridges) extending outward from both sides. Can be confusing if not covered in orientation.
*May day	International distress signal/call. When repeated three times it indicates imminent and grave danger and that immediate assistance is required.

Term	Description
Mission (Leadplane)	A Leadplane mission consists of a flight on an actual fire where retardant is dropped. Each additional fire flown during a single flight counts as an additional mission.
Mission (ATGS)	An ATGS mission consists of a flight on an actual incident where coordination of airborne resources takes place. Each additional incident flown during a single flight counts as an additional mission.
Mission (ASM)	Any aerial supervision mission (ATGS/Leadplane) flown in the ASM configuration.
MOA	A Military Operations Area (Special Use Area) found on aeronautical sectional charts.
MSL	Mean Sea Level.
MTR	A Military Training Route found on aeronautical sectional chart and AP/1B maps. Routes accommodate low-altitude training operations - below 10,000ft. MSL - in excess of 250 KIAS.
On Target	Acknowledgment to pilot that the drop was well placed.
Orbit	See Hold.
Origin	Point on the ground where the fire first started.
Overrun (Overtake)	Unintentional passing of the aircraft in the lead by the trailing aircraft.
Parallel Attack	A control effort generally parallel to the fire perimeter, usually several feet to +100 ft. away. Allows line construction before the fires lateral spread outflanks line construction operations.
Perimeter	The outside edge of the fire.
Pockets	Areas of unburned fuel along the fire perimeter.
Portion of Load	Portion of the airtanker retardant to be dropped. Portions are identified by fractions of the load (1/4, 1/3, ½), whole load, or defined start/stop points on the ground.
Pre-Treat	Laying retardant line in advance of the fire where ground cover or terrain is best for fire control action, or to reinforce a control line, often used in indirect attack.

Term	Description
Reburn	Subsequent burning of an area in which fire has previously burned but has left flammable fuel that ignites when burning conditions are more favorable.
Retardant (Long-Term)	Contains a chemical that alters the combustion process and causes cooling, smothering, or insulating of fuels. Remains effective until diluted or rinsed off.
Retardant (Short-Term)	Chemical mixture whose effectiveness relies mostly on its ability to retain moisture, thereby cooling the fire. Common short-term retardants are water and foam.
Rotor Span	The length of a rotor diameter. Used to make adjustments in alignment of flight route when dropping water/retardant.
Route (Flight)	The path an aircraft takes from the point of departure to the destination.
Running	Behavior of a fire, or portion of a fire, spreading rapidly with a well defined head.
*Saddle	Depression or pass in a ridgeline.
Safety Zone	An area used for escape in the event the fireline is overrun or outflanked, or in case a spot fire causes fuels outside the control line to render the fireline unsafe. During an emergency, airtankers may be asked to re-enforce a safety zone using retardant drops.
Scratch Line	A preliminary control line hastily built with hand tools as an emergency measure to check the spread of a fire.
Secondary Line	A fireline built some distance away from the primary control line, used as a backup against slopovers and spot fires.
Shoulder	The part of the fire where the flank joins the head. Referred to as left or right shoulder.
Slash	Debris left after logging, pruning, thinning or brush cutting.
Slopover	The extension of a fire across a control line.
Smoldering	Behavior of a fire burning without flame and slowly spreading.

Term	Description
Snag	A standing, dead (defoliated) tree. Often called stub, if less than 20 feet tall.
Special Use Mission (DOI)	Flight operations requiring special pilot skills/experience and aircraft equipment to perform the mission.
Spot Fire	A fire caused by the transfer of burning material through the air into flammable material beyond the perimeter of the main fire.
Spotting	Behavior of a fire producing sparks or embers that are carried by the wind and start new fires outside the perimeter of the main fire.
Spur ridge	A small ridge, which extends finger-like from a main ridge.
Strategy	The general plan or direction selected to accomplish incident objectives (i.e.: direct, indirect, or parallel attack).
SUA	Special Use Airspace including MOA's, RAs, PAs, AAs, WAs, and CFAs.
Suppressant	A water or chemical solution that is applied directly to burning fuels. Intended to extinguish rather than retard.
Surface Fire	Fire that burns surface litter, other loose debris of the forest floor, and small vegetation.
Tactic	Deploying and directing resources to accomplish the objectives designated by the strategy (i.e.: hoselay, handline, retardant line, or wet line).
Target	The area or object you want a retardant /water drop to cover.
TCAS	Traffic Collision Avoidance System, electronic aid that gives the azimuth, distance, and relative altitude of transponder- equipped aircraft in relation to the TCAS equipped aircraft.
TFR (91.137)	Temporary Flight Restriction. Airspace within which certain flight restrictions apply.
Tie-In	To connect a retardant drop with a specified point (road, stream, previous drop, etc.).
Traffic Pattern	The recommended flight path for aircraft arriving at and departing from an airport.

Term	Description
Traffic Pattern-Base	A flight path at right angles to the landing runway or target off its approach end.
Traffic Pattern-Crosswind	A flight path at the right angles to the landing runway or target off its upwind end.
Traffic Pattern - Downwind	A flight path parallel to the landing runway or target in a direction opposite to landing or drop direction.
Traffic Pattern - Final	A flight path in the direction of, and prior to, the landing or drop area.
Traffic Pattern - Upwind	A flight path parallel to the direction of the final before turning crosswind.
UHF	Ultra High Frequency. Common to military aircraft. Incompatible with VHF radio system. Operates in 300-3000 MHz range.
VHF	Very high frequency radio. The standard aircraft radio that all civil and most military aircraft use to communicate with FAA facilities and other aircraft.
VHF-AM	Amplitude modulation - Aircraft radio - ranges 118 MHz to 136.975 MHz. Used on wildland fire incidents for ground-to-air and air-to-air communications.
VHF-FM	Frequency modulation radio, multi-agency radio commonly used for dispatch, land-based mobile and airborne communications. Operates in range of 138 MHz to 174 MHz.
Variable Flow Tank	Delivery system with multiple tanks or compartments controlled by an electronic intervalometer control mechanism to open doors singly, simultaneously, or multiple doors in an interval sequence.
Victor	Another way of referring to VHF-AM.
Virtual Fence	Landmark or feature utilized to maintain horizontal aircraft separation.
Waterway	Any body of water including lakes, rivers, streams, and ponds whether or not they contain aquatic life.
Wingspan	The length of the airtankers wing span from tip to tip. Used to make low-level ground track adjustments. *Note:* Adjustments less than half a wingspan are given in feet.

Abbreviations

Abbreviation	Description
AFMC	Air Force Mission Commander
ASM	Aerial Supervision Module
AFS	Alaska Fire Service
AMIS	Aviation Management Information System
AOA	Aircraft Operations Area
ATCO	Airtanker Coordinator (Leadplane)
ATF	Aerial Task Force
ATGS	Air Tactical Group Supervisor
ATP	Air Tactical Pilot
ATS	Air Tactical Supervisor
BIA	Bureau of Indian Affairs
BLM	Bureau of Land Management
CO	Contracting Officer
COR	Contracting Officers Representative
CWN	Call When Needed
DM	Departmental Manual (DOI)
DOI	Department of the Interior
ECC	Emergency Communication Center
FMP	Fire Management Plan
FSM	Forest Service Manual
FSH	Forest Service Handbook
GACC	Geographic Area Coordination Center
GPC	Gallons per 100 Sq. Feet (Retardant)
HIGE	Hover In Ground Effect
HOGE	Hover Out of Ground Effect
HLCO	Helicopter Coordinator
ICS	Incident Command System
IP	Initial Point
LPE	Leadplane Pilot Evaluator
MABM	MAFFS Airtanker Base Manager

Abbreviation	Description
MAFFS	Modular Airborne Fire Fighting System
MOU	Memorandum of Understanding
NAO	National Aviation Office (BLM and USFS)
NICC	National Interagency Coordination Center
NIFC	National Interagency Fire Center
NPS	National Park Service
NWCG	National Wildfire Coordination Group
OAS	Office of Aviation Services
OFT	Operational Flight Training (Leadplane)
RAO	Regional Aviation Officer
RASM	Regional Aviation Safety Manager
ROSS	Resource Ordering and Status System
SAM	State Aviation Officer (BLM)
SEAT	Single-Engine Airtanker
SUA	Special Use Airspace
USDA	U.S. Department of Agriculture
USFWS	U.S. FWS

Appendix A – Leadplane Phase Check Oral Questions

Phase 1

- What is the difference between an ATCO and a Leadplane Pilot, and how are these positions identified in the ICS system?
- What is the role of an ATGS over a fire and how does this position interact with the Leadplane Pilot?
- What is the role of an HLCO over a fire and how does this position interact with the Leadplane Pilot?
- What is the role of an ASM over a fire?
- What is the role of an IC on a fire and how does this position interact with the Leadplane Pilot?
- What is the primary role of the Leadplane Pilot?
- What is the difference between the terms, required and ordered, as they relate to incident aerial supervision requirements?
- When is Leadplane required over a fire?
- When is an ATGS required over a fire?
- What is the purpose of the Leadplane Coach program?
- What are the PPE requirements while flying a Leadplane mission?
- How often are Leadplane Pilots required to attend recurrent flight and ground training?
- What is an FTA and how does it differ from a TFR?
- What is the standard procedure for entering and exiting the FTA for the Leadplane?
- At what altitude do you bring the tankers into the FTA? What factors might cause you to adjust this altitude?
- You are flying over a fire near the north end of Lake Chelan in Washington. Plot the fire location on a sectional. N 48 20 44 / W 120 43 14.
    - What information should you look for on the sectional prior to arriving over the fire?
    - Discuss the terrain around the fire and what conditions may exist over the fire.
    - Discuss the airspace over the fire.
    - What are some of your concerns about using retardant in this area?
    - What other frequencies should you monitor?
- What are the different types of power lines you may encounter on a fire and can you drop over or on power lines?
- What is the safest area to cross over a set of high-tension power lines?
- What is the minimum drop height for a large airtanker? What is the minimum drop height for a SEAT? Why do we have a minimum drop height?
- Can you drop next to crews on the ground?
- Describe coverage levels and how they are used.
- Is a coverage level 4 from a constant flow tank the same as a coverage level 4 from a doored tank?
- When would you brief an inbound tanker and what information would you give them?
- What is the purpose of a show-me run?
- Describe the information you would talk about with the airtanker on a show-me run.

- Describe ways you can join up with an airtanker.
- During a join up who has responsibility for separation?
- What should you do if you lost sight of an airtanker during the join up?
- What do you do in the event of an overrun?
- What is an IP and when would it be used?
- Discuss mountain flying weather, terrain, and techniques.
- What is the maximum angle of bank when exiting a run? Is there any time you can exceed this bank angle?
- At what point during the final approach to the drop area should you start to accelerate? When should you start to clean up the aircraft?
- What criteria should you use to evaluate a tankers drop? When should you give this evaluation?
- What are some possible distractions a Leadplane Pilot might incur while operating over a fire?
- What are some conditions that may warrant shutting down airtanker operations?

Phase 2

- Discuss flight following policies and options when dispatched to an incident. How does this differ in Alaska?
- What is the transponder code that is used for firefighting aircraft? Would you use that code while enroute to and from the fire?
- Describe the differences between a variable flow, a constant flow, and a pressurized tank system.
- List each operational airtanker type and identify its tank system.
- Describe the variations between SEAT tank systems and their coverage patterns.
- Discuss the individual strengths and weaknesses of SEATs and heavy airtankers while building retardant line.
- Discuss the factors that might cause the coverage level on the ground to be different from the coverage level selected by the pilot.
- How can you manage your radios and what should you be listening to?
- How would you change the way you manage your radios when you are dispatched to California?
- What should you do while enroute to a fire?
- What information should you pass on when giving a fire size-up?
- Whom might you contact with a fire size-up?
- Name the locations of the large airtanker bases in each state.
- What is the difference between a temporary and a reload base?
- What is an example of a retardant and a suppressant and what are the differences?
- What is the difference between fugitive and non-fugitive retardant, and where might they be used?
- What are some concerns with working helicopters and fixed-wing aircraft in the same area?
- What are some techniques in ensuring separation of helicopters and fixed-wing aircraft working in the same area?
- If you are diverted to a different fire, what information do you need to get from dispatch?

What will be some of your concerns?

- What should you do in the case of an aircraft accident or ground personnel accident?
- Give some examples of anchor points and describe the use of them.
- What is a tactical frequency and how is it used on a fire?
- Describe natural firebreaks and how they are incorporated in the construction of retardant line.
- Discuss unique hazards associated with dropping over flat terrain.
- Describe the air and ground resources needed to control a small fire with a high rate of spread in grassy flat lands.
- Describe the air and ground resources needed to control a small fire with a high rate of spread in mountainous terrain with heavy timber.
- You are on final approach for a retardant drop and you notice crews working in the drop area that the ATGS said was clear. What do you do? What if a house was about to burn?
- When on a base leg for a retardant drop, another tanker calls 12 miles out. What are you going to tell the inbound tanker?
- What is considered a standard pattern for the airtanker? When would you use a non-standard pattern and what might be some of your or the tanker pilots concerns for using a non-standard pattern?
- You are on final approach for a retardant run when the airtanker pilot says that they have a problem.
    - What would you do?
    - How can you help?
    - Should you follow the airtanker back to the tanker base?
- A drop is made and you see it is way off target. How would you discuss it with the airtanker crew?
- Identify some factors that influence when you would order relief.
- Discuss how you would brief a relief Leadplane arriving over your fire.
- What side of a fire line would you treat with retardant while supporting a burn out?
- You are working a fire which has made a run up the slope and is approaching the ridgeline. Where would you put the retardant?
- What problems will you have when mixing retardant drops and water drops to build line?
- Describe the difference between a simplex and a duplex frequency for the FM radio.
- Where would you find information for a specific airtanker base?
- What are the advantages or disadvantages of dropping retardant into the wind, with the wind, or crosswind?
- What are some of the difficulties and concerns when you fly a pattern that has a tail wind on base?
- What are some issues to be aware of during downwind drops in relation to groundspeed climb gradient, etc.?
- Discuss how the different airspace around an airport might influence your operations over a fire.
- Describe methods to maintain aircraft separation with a mix of airtankers over an incident.
- How do you determine the minimum visibility and wind speed while over a fire?

- Describe the difference between a fixed tank and bucket on a helicopter. How will this affect the type of dipsite they will need?
- Discuss the tactics for a fire that is spotting out in front of the head. How would you change your tactics if there were structures threatened?
- You have lost communications with the ground but can still talk with the airtanker. No one else in the air is having trouble communicating with the ground. Can you still make the retardant drop as planned?
- You are on final approach for a live retardant run when the frequency you are using for airtanker operations suddenly becomes congested with other traffic. What should you do?
- You notice a significant gap in the retardant load as it exits the airtanker. What could have been the cause and how might it be solved?
- What ways could you get a quick evaluation of the drop prior to flying back over the drop?
- What is the difference between a level 1 and a level 2 SEAT?
- What specific authorizations do you have after taking the certificate of waiver for the Grand Canyon Park Special Flight Rules Area training?

Phase 3

- You are over a fire with no ATGS and a media helicopter calls you wanting footage of the fire. Do you allow them over the fire? If so, at what altitude will you bring them in? Do they have the right to enter the FTA? Do they have the right to enter the TFR?
- You are over a fire with no ATGS and a law enforcement helicopter calls you wanting to evaluate the fire. Do you allow them over the fire? If so, at what altitude will you bring them in? Do they have the right to enter the FTA? Do they have the right to enter the TFR?
- Can GA aircraft come into an FTA or a TFR?
- What should be done if you have an intrusion in the TFR? What would you do differently if there were no TFR in place?
- You are on final approach with the airtanker preparing to drop a load of retardant when a ground crew calls and informs you that they are deploying their shelters and are about to be burned over. What do you do?
- List the locations of tactical air resources, fixed-wing and helicopters, in your region.
- How do you order more air or ground resources on a fire with an ATGS on scene? With no ATGS on scene? With no ATGS or ground resources?
- Describe a use of the Guard frequency when you are over a fire with other aviation resources.
- You, along with a jump ship and three airtankers are dispatched to a fire. You are the first aircraft on scene. The jump ship is 3 minutes out and the airtankers are 5 minutes out. Describe what you are going to do and how you are going to coordinate the air resources.
- You are working with an ATGS on a fire. The ATGS requests that you take over air tactical duties while he goes in for fuel and lunch. Can you take over for the ATGS? If so, what information do you need to get from him prior to his departure? Whom should you inform of this transfer of duties? What liabilities are you taking on?
- What are some of the concerns with mixing large airtankers and SEATs into the same pattern over a fire?
- What frequency should you monitor when you are flying near the Canadian border?
- Can a US Leadplane lead a Canadian airtanker in the US?
- Can a Canadian Bird Dog lead a US airtanker in the US?

- At what wind speed is it generally ineffective to drop retardant.
- What is the Grant of Exemption 392? Describe the terms and conditions of this grant of exemption.
- What are the general differences between the flight crew duty day, and flight hour policy phase 1, 2, and 3 restrictions?
- Can an ATGS direct a MAFFS aircraft for a retardant drop?
- When are Leadplane Pilots required to attend MAFFS training?
- What are the cut off time parameters for large airtanker operations? How do the cut off times differ for single-engine aircraft? How do the cut off times differ for aircraft in Alaska?
- You have five airtankers over a fire and they are all released back to the tanker base due to excessive wind over the fire. How should you release them back to the base? What factors will you take into consideration?

Appendix B – ATGS Refresher Training Exercise

The Goal of the ATGS refresher training exercise is to ensure the safety of aviation operations is retained as it pertains to the ATGS position.

The ATGS will demonstrate the following fundamental ATGS skills:

- FTA entry
- Determine and assign FTA altitudes for incoming aircraft
- Initial aircraft briefings
- Maintain vertical and horizontal aircraft separation
- Communication with air and ground resources
- Situational awareness

An ATGS Final Evaluator utilizing the Aerial Supervision Mission Evaluation form will evaluate this exercise.

Exercise Objective: Demonstrate Fundamental ATGS Skills Within 15 Minutes.

Exercise Elements and Role Players:

- IA fire with the following resources:
    - On scene:
        - IC
        - One engine crew
        - One hand crew
    - Enroute:
        - 2 helicopters
        - 2 airtankers
        - Dispatch

Exercise Sequence:

1. ATGS receives aircraft dispatch form with resource information and altimeter setting.
2. ATGS launches from home base and establishes contact with dispatch.
3. ATGS initiates FTA entry procedures 12 miles from incident.
4. ATGS arrives on scene, makes contact with IC and establishes objectives and priorities. Fire elevation is indicated on sand table.
5. Enroute aircraft (airtankers and helicopters) check in at 12 miles.
6. ATGS provides initial briefing.
7. Aircraft arrive on scene; ATGS provides tactical briefing based on incident objectives.
8. ATGS coordinates helicopter work and retardant drops.
9. ATGS ensures line clearance during helicopter and airtanker operations.
10. ATGS solicits feedback from IC regarding helicopter and airtanker operations.
11. ATGS gives departure briefing or additional instructions to airtankers and helicopters.
12. End of exercise.

Exercise conclusion: ATGS and Evaluator debrief utilizing the Aerial Supervision Mission Evaluation.

Appendix C – Aerial Supervision Mission Checklist

Aircraft Mission Checklist
Aerial Supervision

Preflight

• Mission fuel	Confirmed
• Weather enroute/destination	Checked
• Resource order/mission brief	Accomplished
• Standard aircraft brief	Accomplished

After Takeoff/Enroute

• GPS	Set
• Communication/radios	Confirmed/set
• Other aircraft on scene/enroute	Confirmed
• Level of supervision on scene	Confirmed
• Alternate airport(s)	Confirmed
• Time on station	Determined **/Re-evaluate***
• CRM 9re-evaluate above tasks)	Accomplished

Prior to FTA Entry

• Altimeter	Set
• Pulse / landing lights	On
• Transponder	ALT, Squawk1255 or assigned

***In the event of divert to a new incident, checklist items <u>will be re-done.</u>**

Appendix D – Fire Traffic Area Card

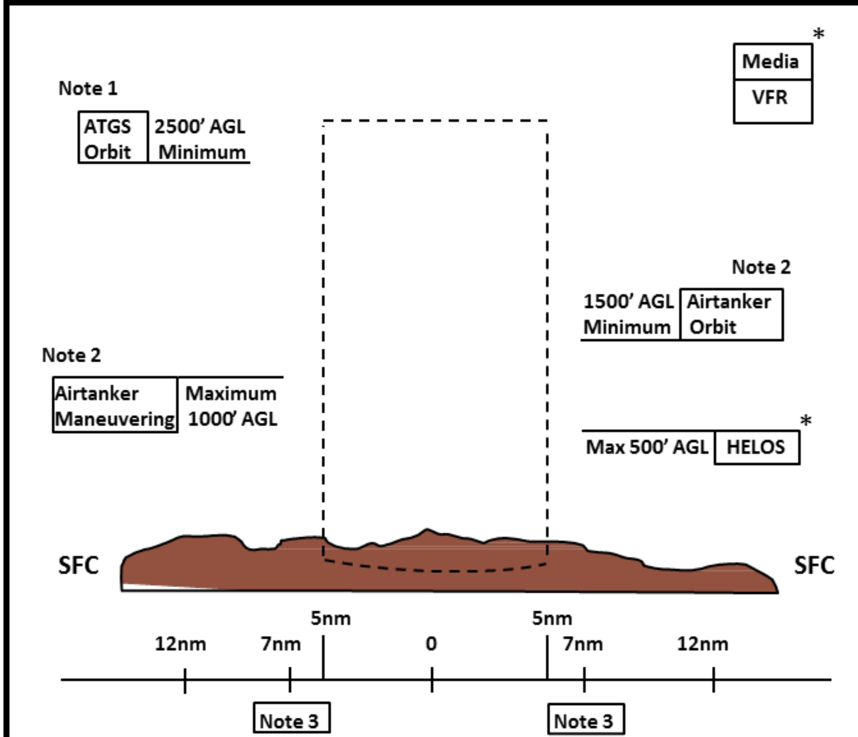
Fire Traffic Area (FTA) 09 Dec 2015

National Interagency Airspace: http://airspacecoordination.org

***** Clearance is required to enter the FTA *****

Initial Radio Contact: 12 nm on assigned air tactical frequency.
No Radio Contact: Hold a minimum of 7 nm from the incident.

Note: Airtanker maneuvering altitude determines minimum airtanker and ATGS orbit altitudes. Assigned altitudes may be higher and will be stated as MSL.



Note 1	1000' min. separation between ATGS orbit and airtanker orbit altitude.
Note 2	500' min. separation between airtanker orbit and maneuvering altitude.
Note 3	On arrival reduce speed to cross 7 nm at assigned altitude and 150 KIAS or less.

* Helicopters: Fly assigned altitudes and routes.

* Media: Maintain VFR separation above highest incident aircraft or position and altitude as assigned by controlling aircraft.

Airtanker Base	Air Guard	Air to Air	National Flight Following
As Assigned	168.625 Tx Tone 110.9	As Assigned	168.650 Tone 110.9 TX and RX

National Interagency Airspace: http://airspacecoordination.org

Incident Airspace Reminders

FTA

- The FTA is a communication protocol for firefighting agencies. It does not pertain to other aircraft that have legal access granted by the FAA within a specific TFR.
- The FTA should not be confused with a TFR, which is a legal restriction established by the Federal Aviation Administration to restrict aviation traffic while the FTA is a communication tool establishing protocol within firefighting agencies.
    - Participating aircraft must adhere to TFR policies as established by the FAA.
    - For example, if the TFR boundary of a polygon exceeds the 12-mile initial contact ring, clearance will still be required in order to enter the TFR.
    - If the TFR boundary is within the 12-mile ring, proceed with standard FTA communication procedures.

Temporary Flight Restriction (TFR) - All assigned/ordered aircraft must obtain clearance into or the incident TFR by the on scene aerial supervision or the official in charge of the on scene emergency response activities.

- **A ROSS order or Aircraft Dispatch Form is not a clearance into a TFR.**
- Aircraft not assigned to the incident must stay clear of the TFR unless communication is established with the controlling entity (ATGS, ASM, Leadplane, etc.) and authorization is given to enter/transit the TFR.
- The first responding aircraft, typically on extended attack incidents, must have reasonable assurance that there are no other aircraft in the TFR by making blind calls on the TFR frequency, other assigned air-to-air frequencies, and double checking with ground personnel (IC, OPS, or Helibase).
- There may be multiple aircraft operations areas within a TFR.
- Remember - Non-Incident aircraft may enter the TFR under the following conditions:
    - The aircraft is carrying **law enforcement** officials.
    - The aircraft is on a flight plan and carrying **properly accredited news representatives.**
    - The aircraft is operating under the **ATC approved IFR flight plan.**
    - The operation is conducted **directly to or from an airport** within the area, or is necessitated by the impracticability of VFR flight above or around the area due to weather, or terrain; notification is given to the Flight Service Station (FSS) or **ATC facility** specified in the NOTAM to receive advisories concerning disaster relief aircraft operations; and the operation does not hamper or endanger relief activities and is not conducted for observing the disaster.

Further Information: *Interagency Aerial Supervision Guide* (NFES 2544)

Appendix E – Standard Briefing Scripts

Flight Following Script

The following information is required every time you initiate flight following with dispatch.

- Call sign
- Departure location
- Number on board
- Fuel on board (hours)
- ETE
- Destination
- AFF confirmation

The transmission is as follows:

"Boise Dispatch, Air Attack 1SA on NFF."

"1SA, Boise Dispatch."

"Air Attack 1SA is off Boise, 2 on board, 4.5 hours fuel, 15 ETE to the Beaver Incident, confirm AFF?"

"1SA, Boise dispatch copies and you're positive AFF."

"Air Attack 1SA copies."

Key points

- Always identify yourself as Air Attack, Recon, Jumper, Helicopter, etc.
- Always state the frequency you are transmitting on.

FTA/TFR Calls in the Blind:

Calls in the blind Script

Receiving unit

Call sign

Location

Altitude

Intent

"Any traffic please advise."

Frequency

Example-"Beaver fire traffic, Air attack 0DT, 12 miles to the south west, 6500, inbound, any traffic please advise 122.925."

Script Standards

The following scripts are used to standardize communication procedures for aerial supervisors of aircraft assigned to all hazard incidents. “Clearance” scripts are covered in the standardized written format to ensure communications are understood. “Briefing” scripts are tailored by the aerial supervisor to meet the needs of the incident and provide assigned resources with the best information to increase effectiveness and safety.

Clearance to Enter:

Altimeter

Clearance altitude

Air attack altitude

Other aircraft and altitude

General Hazards

Example: “Tanker one-four, Altimeter two-nine-nine-two, cleared in three thousand five hundred, Air Attack is four thousand five hundred, one helicopter at or below two thousand five hundred, caution power lines and terrain.”

On Scene Briefing:

Orientation

Objective

- Coverage level
- Load portion
- Exit Instructions

Specific Hazards

Example: “Tanker one-four do you have the structure? Objective is structure defense, V the structure, coverage level eight, split load, exit left at or below three thousand, helicopters on the right, caution power lines along the road.”

Clearance to Maneuver:

Cleared to Maneuver

- Observe Pattern/Confirm Line

  (CAL FIRE Tankers call out their respective leg patterns and expect positive recognition by Air Attack)

Line is Clear

Cleared to Drop

Example: “Tanker one-four cleared to maneuver, line is clear, cleared to drop”

<u>Departure Briefing:</u>

Turn out

Altitude

Drop evaluation

Instructions

Example: "Tanker one-four depart to the west, maintain three thousand until clear of FTA, on target, load and return."

<u>Emergency:</u>

Consider Load

Acknowledge/Maintain Visual

Communicate

Example: "Tanker one-four consider load, I have you in sight, copter five-zero-two hold position, tanker traffic." notify (other aircraft, IC, dispatch, tanker base)

Appendix F – Aerial Supervision Forms

Form #	Form title	Form description
1	Annual Aerial Supervision Summary	Summarizes annual missions and hours then is sent to the appropriate GACC ATGS Cadre member annually.
2	IQCS Incident Experience Update	IQCS Responder Update form. Annual IQCS experience record.
3	Aerial Supervision Mission Log	Individual mission log which also tracks cumulative missions and flight hours, completed after each mission.
4	Aerial Supervision Mission Evaluation (ATGS/HLCO)	Utilized to evaluate individual aerial supervision performance on evaluation flights, proficiency exercises, or trainee missions.
5	ASM (ATP or ATS) Competency Check	Utilized to document acceptable performance of ASM Evaluators and Final Evaluators.
6	Aircraft Mission Checklist – Aerial Supervision	Required enroute checklist for aerial supervision
7	Aerial Supervision Transition Checklist	Reference tool for aerial supervision transitions
8	Aerial Supervision Mission Organizer	Aerial supervision mission form which helps track and organize important aerial supervision mission information
9	IASG Revision Proposal	Form used to document proposed changes to the IASG.
10	ASM Mission Evaluation	Utilized to evaluate individual ATS/ATP on evaluation flights, proficiency exercises, or trainee missions.
11	ASM Evaluator Student Evaluation form	Provides “trainees” a feedback mechanism to agency program managers and GACC Reps

Annual Aerial Supervision Mission Summary

Aerial Supervisor: Fill out this form at the end of fire season and send it to your GACC ATGS Cadre Member by 10/31.

ATGS Cadre Member: Sign this form and send it to your National Program Manager and THE ATGS's IQCS Manager and Certifying Official.

Aerial Supervisor Name:	**GACC Cadre Member Name:**	
Phone #:	Phone #:	
Fax #:	Fax #:	
Email:	Email:	
IQCS Manager Name:	**Certifying Official Name:**	
Phone #:	Phone #:	
Fax #:	Fax #:	
Email:	Email:	
Summary Year:	**Missions:**	**Hours:**

Note: BLM ATGS must document 5 missions/year to maintain currency. An ATGS mission consists of a flight on an actual incident where coordination of airborne resources takes place. Each additional incident flown during a single flight counts as an additional mission.

Aerial Supervisor Comments:
Aerial Supervisor Signature
GACC Cadre Member Comments:
GACC Cadre Member Signature

Aerial Supervision Log Book 2014 form 1

IQCS Incident Experience Update

(*Note:* this information is to be used only for updating employee records that are already established in the IQCS)

EMPLOYEE SIGNATURE		**DATE**	
SUPERVISOR		**DATE**	

EMPLOYEE WILDLAND AND PRESCRIBED FIRE EXPERIENCE

Job Code (Incident Position)	Type of Incident (Event Code)	Incident Arrival Date MM/DD/Y Y	State	Operational Periods (Shifts)	Management Type or Complexity Level (See Below)	Fuel Type (See Below)	Fire Size Class (See Below)	Incident Order # Incident Name (Resource Order) Request #
(EXAMPLE) XXXX	W	07/21/00	NM	19	1	T	G	NM-SNF-0304 FRED (C-1)
(EXAMPLE) XXXX(T)	RX	08/05/01	CA	2	3	T	C	CA-SNF-0102 WILD (O-21)

ICS Management Types	Complexity Levels	Fuel Type/ Model # (select primary carrier code G-S)	Fire Sizes (in acres)
TYPE A - national area command team assigned **TYPE 1** - national type 1 team assigned **TYPE 2** - regional type 2 team assigned **TYPE 3** - extended attack with multiple resources **TYPE 4** - initial attack **TYPE 5** - initial attack with very few resources	**TYPE 1** **TYPE 2** **TYPE 3** (For Prescribed Fires)	**G** – Grass/1-3 **B** – Brush/4-7 **T** – Timber/8-10 **S** – slash/11-13	**A** .1 - .25 **B** .26 - 9.9 **C** 10 - 99.9 **D** 100 - 299.9 **E** 300 - 999.9 **F** 1,000 - 4,999.9 **G** 5,000 +

Task Books

Initiated, But Not Completed		
Event Code	Job Code	Initiated Date
Example: W	***Example: FFT1***	***Example: MM/DD/YYYY***

Initiated And Completed (1 column per Task Book)		
Job Code, and Initiated Date ***Example: W-FFT1 MM/DD/YYYY***	Job Code, and Initiated Date	Job Code, and Initiated Date
Final Evaluator ***Example: Last Name, First Name, Middle Initial***	Final Evaluator	Final Evaluator
Title ***Example: Station Manager***	Title	Title
Home Unit ***Example: NMNPA, Northern Pueblos Agency***	Home Unit	Home Unit
Phone Number ***Example: 801-354-5678***	Phone Number	Phone Number
Certifier's IQCS Empl ID (NOT SSN) ***Example: This Person Must Be In The IQCS Data Base***	Certifier's IQCS Empl ID	Certifier's IQCS Empl ID
Title ***Example: District FMO***	Title	Title
Home Unit ***Example: ORWSA, Warm Springs Agency***	Home Unit	Home Unit
Phone Number ***Example: 801-456-9875***	Phone Number	Phone Number
Certification Date ***Example: MM/DD/YYYY***	Certification Date	Certification Date

Aerial Supervision Mission Log

Date:	**Fire Name:**
Location:	**Fire Code:**
Pilot:	**Aircraft N#:**

Resources	Type	ID	Description of Events
ASM			
Leadplane			
Large Airtankers			
SEATS			
Helicopters			
Jumpships			
Media			
Other			

Incident Complexity Level (1-5):
Geographic Area (GACC):
Agency:
Missions to Date:
Flight Time to Date:

Aerial Supervision Mission Evaluation (ATGS/HLCO)

Name:	Date:	# Missions this Incident:
Trainee: Y N	Evaluation Flight: Y N	Total Missions to Date (logbook):
Incident Name:		FT This Mission:
Incident Location:		Total FT to Date (logbook):

Incident Complexity:
____Type 1 _____Type 2 _____Type 3 _____Initial Attack________Prescribed Fire ____Other (all risk)

Airspace Complexity Elements: ____ TFR ____ WUI ____ MOA/SUA ____ ATC

# of Aircraft Assigned _____ Helicopters _____ Airtankers _____ Lead/ASM/HLCO _____ Other

Evaluation Elements (see below):	1	2	3	4	N/	Remarks
Pre -Mission Procedures						
En Route Procedures/Communication						
FTA Entry						
Determine FTA Altitudes						
Determine Hazards						
Confirm Objectives and Priorities						
Initial Briefing						
Tactical Briefing/Target Description						
Line Clearance (AC and Ground)						
Departure Briefing						
Separation (vertical, horizontal)						
Transition Routes						
IP/Holding Areas						
Checkpoints/Fences						
Helicopter Routes						
Coordination with Ground Personnel						
Provide Fire information/Sizeup						
Recommend Strategies/Tactics						
Provide Safety Oversight						
Coordination with Dispatch						
Emergencies (Aircraft, Medevac, IWI)						
Post Mission (debrief, log, payment						
Safety						
Span of Control Mitigation						
Situational Awareness						
Risk Management						
CRM (Info/task sharing w/pilot)						
FW/RW Mission Prioritization						
Aerial Supervision Transition Briefing						
Frequency Management						
Brevity						

Focus Areas – Next Mission:

Evaluation Flight Result: ____Pass ____Fail

Instructor/Check Airman: Date:

Trainee/ATGS: Date:

Evaluation Elements

4	None	No assistance required or deficiency noted.
3	Minor	Non-Critical deviations are noted, but the outcome of the event/objective was never in doubt.
2	Moderate	Coaching was required and the outcome of the event/objective was in doubt.
1	Significant	Frequent coaching was required. The outcome of the event was in doubt and safety was compromised or the individual failed to accomplish the critical task.
NA	Task/procedure not applicable to this mission.	

Evaluation Requirements: Six elements (bold text and shading) have been identified as mission critical and require a rating of 4 in order to pass the evaluation flight. All other elements require a minimum rating of 3 in order to pass the evaluation flight. Scores of 1 or 2 require remarks.

ASM Evaluator/Final Evaluator

Name:	Date:	**Crewmembers:** **ATP:** **ATS:**
Trainee: Y N	**AC Type/FT:**	
Incident Name:		**Crew Position:** ATS ATP
Incident Location:		**Type Check:** Evaluator Final Evaluator

Incident Complexity:
____Type 1 _____Type 2 _____Type 3 _____Initial Attack _____Prescribed Fire ____Other (all risk) ___Sim

Airspace Complexity Elements: ____ TFR ____ WUI ____ MOA/SUA ____ ATC ____Zoned fire

# of Aircraft Assigned _____ Helicopters _____ Airtankers _____ Lead/ASM/HLCO _____ Other

Evaluation Elements (see below):	1	2	3	4	N/	Remarks
Pre mission						
Knowledge of policy and procedures						
Pre mission intent briefing						
Aircraft setup						
Mission						
Areas of focus						
Evaluation of verbal communications						
Evaluation of non-verbal communications						
In-flight documentation methods						
Evaluation of CRM						
Evaluation of risk management procedures						
Post mission						
Utilization of ASM Evaluation form						
Review of mission						
Debriefing methods and techniques						

Recommendation:

Based on an evaluation conducted by ________________________________on __/___/____

during flight operations on the ____________________________incident I am recommending

____ for certification as an ATS/ATP (circle one)

Evaluator/Final Evaluator (circle one).

Final Evaluation Flight Result: ____Pass ____Fail

Final Evaluator Name:	Signature:	Date:
ATS/ATP E/FE Trainee Name:	Signature:	Date:

Evaluation Elements

4	None	No assistance required or deficiency noted.
3	Minor	Non-Critical deviations are noted, but the outcome of the event/objective was never in doubt.
2	Moderate	Coaching was required and the outcome of the event/objective was in doubt.
1	Severe	Frequent coaching was required. The outcome of the event was in doubt and safety was compromised or the individual failed to accomplish the critical task.
NA	Task/procedure not applicable to this mission.	

Aircraft Mission Checklist Aerial Supervision

Pre-Flight

• Mission fuel	Confirmed
• Weather enroute/destination	Checked
• Resource order/mission brief	Accomplished
• Standard aircraft brief	Accomplished

After Takeoff/Enroute

• GPS	Set
• Communication/radios	Confirmed/set
• Other aircraft on scene/enroute	Confirmed
• Level of supervision on scene	Confirmed
• Alternate airport(s)	Confirmed
• Time on station	Determined /**Re evaluate***
• Crew brief	Accomplished

Prior to FTA Entry

• Altimeter	Set
• Pulse / landing lights	On
• Transponder	ALT/Squawk 1255 or assigned code

* In the event of divert to a new incident, repeat checklist.

Aerial Supervision Transition Checklist

General Information	
Confirm all radio frequencies	
Priorities (objectives)	
Hazards and mitigations	
Aircraft Information	
Airspace setup (stack altitudes)	
Aircraft assigned	
Location and mission of airtankers	
Location and mission of other aerial supervision	
Location and mission of helicopters	
Location and mission of other aircraft	
Planned fixed or rotor missions	
Reload base locations	
Helibase/helispot locations	
Dipsite locations	
Fuel and flight hours status of helicopters	
Pumpkin time	
Ground Information	
Ground contacts	
Division breaks	
Landmarks	
Other:	
Next aerial supervision transition time	

Aerial Supervision Mission Organizer

Date:	Time off: Time on:
Fire Name:	Fire #:
Latitude:	Longitude:
Descriptive Location:	

Contacts	**Altimeter**		
IC:	**Air Attack**: ft		
Ops:	**Lead/ASM**: ft		
Frequencies			
Dispatch:	**Tankers**: ft		
A/G:	ID	ETA	# Drops
Tac:			
FW Vic:			
RW Vic:			
	Helicopters: ft		
	ID	ETA	# Drops
	Target Location:		
	Coverage Level:		
	Hazards:		

IASG Revision Proposal

Revisions to the *Interagency Aerial Supervision Guide* are due by **October 1.** Please use this form to submit revision proposals. Submit this form to the appropriate Aerial Supervision Cadre (Lead, ASM, HLCO, or ATGS) Chairperson or the appropriate Agency Aerial Supervision Program Manager.

Chapter:	
Page #:	
Section Title:	
Existing Text:	
Proposed Text:	
Comments:	
Submitted By:	Position:
Date:	Aerial Supervision Qualifications:
Email:	Phone #:

ASM Mission Evaluation

Name:	Date:	**Training:** Continued Recurrent Refresher Initial
Trainee: Y N	**AC Type/FT:**	
Incident Name:		**Crew Position:** ATS ATP
Incident Location:		**Type Check:** ATS ATP

Incident Complexity:
____Type 1 _____Type 2 _____Type 3 _____Initial Attack _____Prescribed Fire ____Other (all risk):

Airspace Complexity Elements: ____ TFR ____ WUI ____ MOA/SUA ____ ATC ____Zoned fire

# of Aircraft Assigned _____ Helicopters _____ Airtankers _____ Lead/ASM/HLCO _____ Other

Evaluation Elements (see below):	1	2	3	4	N/	Remarks
Pre-flight						
Crew Brief *						
AC and Radio Setup						
Preparation/Organization						
Fire Order Information						
General Flight						
Knowledge of Checklists *						
Aircraft Instrument Knowledge						
Procedures						
Enroute/FTA Entry						
Use of Time/Situational Awareness						
FTA Clearance *						
Radio Communications and Use						
Tactics/Objectives						
Approaching the Incident						
Tactical In-briefing *						
Hazard Identification *						
Risk Analysis/Risk Mitigation *						
Task Management *						
Drop Evaluation						
Tactics (low level)						
Personnel Location/Line Clearance *						
Routing /Sequencing *						
Situational Awareness *						
Communications *						
CRM						
Teamwork *						
Judgment *						
Verbal/Non-verbal Skills *						
Emergency Procedures						
Other						

Focus Areas – Next Mission:
1.

2.

3.

Evaluator/Final Evaluator Name:	Signature:	Date:
ATS/ATP Trainee Name:	Signature:	Date:

Evaluation Elements

4	None	No assistance required or deficiency noted.
3	Minor	Non-Critical deviations are noted, but the outcome of the event/objective was never in doubt.
2	Moderate	Coaching was required and the outcome of the event/objective was in doubt.
1	Severe	Frequent coaching was required. The outcome of the event was in doubt and safety was compromised or the individual failed to accomplish the critical task.
NA	Task/procedure not applicable to this mission.	
*	Shaded elements with an * are critical elements and must be checked with a 4 to pass a final evaluation	

Aerial Supervision Evaluator Evaluation

Trainee Name:	**Date:**
Evaluator Name:	**AC Type/FT:**
Geographic Area:	
Missions to date:	
Did the Evaluator discuss instructional methodology and utilize the appropriate methods for your learning style? **YES-NO** (if no, please explain):	
Rate the Evaluators knowledge of Aerial Supervision Policy and Training regulations, please explain**:**	
Did you receive an appropriate and documented debriefing after each mission? **YES-NO** (if no, please explain):	
Were you given opportunities to provide feedback during the debriefing process? **YES-NO** (if no, please explain):	
Did you receive appropriate focal points for your next training mission? **YES-NO** (if no, please explain):	
Rate your overall satisfaction with the quality of instruction you received during your training assignment, please explain:	
Other Comments:	

User Notes

User Notes:

User Notes:

User Notes:

The *Interagency Aerial Supervision Guide* is developed and maintained by the Interagency Aerial Supervision Subcommittee, an entity of the NWCG.

Previous editions: 2016, 2014, 2013, 2011.

While they may still contain current or useful information, previous editions are obsolete. The user of this information is responsible for confirming that they have the most up-to-date version. NWCG is the sole source for the publication.

This publication is available electronically at https://www.nwcg.gov/publications/505.

Printed copies of this guide may be ordered from the Great Basin Cache at the National Interagency Fire Center in Boise, Idaho. Refer to the annual NFES Catalog Part 2: Publications and find ordering procedures at https://www.nwcg.gov/catalogs-ordering-quicklinks.

IASS will review and publish the IASG on a 3-year cycle, with a change option annually. The Aerial Supervision Logbook will be reviewed and published on a 3-year cycle.

Change recommendations shall be submitted to the appropriate agency program manager assigned membership to the IASS. The Revision Proposal Form is available at https://www.nwcg.gov/publications/505.

01-29-20

EXHIBIT

8

Federal Aviation Administration

Memorandum

Date: December 18, 2017

To: All Regional Airports Division Managers

From: Khalil E. Kodsi, P.E. PMP, Manager, Airport Engineering Division, AAS-100

Subject: INFORMATION: Engineering Brief No. 98, Infrared Specifications for Aviation Obstruction Light Compatibility with Night Vision Goggles (NVGs)

This Engineering Brief (EB) 98 provides information about the interaction of Light Emitting Diodes (LEDs) used in obstruction lighting fixtures with Night Vision Imaging Systems (NVIS) on board both rotary and fixed-wing aircraft. In addition, this engineering brief proposes performance specifications for infrared (IR) emitters to be added to or used in conjunction with LED L-810, L-864 and L-885 obstruction light fixtures to ensure compatibility with Night Vision Goggles (NVGs) with a Class B filter.

Attachment.

FAA
Airports

ENGINEERING BRIEF NO. 98

Infrared Specifications for Aviation Obstruction Light Compatibility with Night Vision Goggles (NVGs)

1.0. Purpose.

This Engineering Brief (EB) 98 provides information about the interaction of Light Emitting Diodes (LEDs) used in obstruction lighting fixtures with Night Vision Imaging Systems (NVIS) on board both rotary and fixed-wing aircraft. In addition, this engineering brief provides performance specifications for infrared (IR) emitters to be added to or used in conjunction with LED L-810, L-864 and L-885 obstruction light fixtures to ensure compatibility with Night Vision Goggles (NVGs) with a Class B filter. These changes are necessary in order to address the concern that certain LED obstruction lighting systems fall outside the combined visible and near-infrared spectrum of NVGs with a Class B filter.

2.0. Background.

The use of NVGs is increasing in civilian aviation to conduct search-and-rescue, emergency medical transport, and other flight operations. The use of NVIS can function to increase pilot situational awareness. However, the Federal Aviation Administration (FAA) has found that with the gradual replacement of incandescent obstruction light fixtures with LED light fixtures, some pilots using NVGs are unable to acquire red-colored LED obstruction lights due to the light generated being outside of the combined visible and near-infrared spectrum of NVGs with objective lens filters.

NVIS definition: A night vision imaging system is an optical instrument that allows images to be produced in levels of light approaching total darkness. NVGs constitute one component of a NVIS. NVGs in aviation are designed to be used for flying at night, primarily during Visual Meteorological Conditions (VMC). They are mounted in a binocular form on a pilot's helmet. The term usually refers to a complete unit, including an image intensifier tube, a protective water-resistant housing, and mounting system.

The potential problem:

Pilots using NVIS equipment that filter the adverse effects of cockpit lighting might not be able to see LED-based obstruction lighting. The preceding could result in a safety hazard to both the pilot and ground personnel. NVGs function by amplifying ambient light, allowing the pilot to better see terrain and other potential hazards in dark or overcast conditions. NVGs help pilots maintain spatial orientation and general situational awareness.

LED-based lighting has largely replaced incandescent technology for red (and some white) obstruction lighting because of its reduced maintenance requirements and extended service life. Traditionally, NVIS systems were built to detect the high short wave IR emission of incandescent-based lights – this facilitated easy detection despite the presence of filters for the aircraft cockpit/avionics lighting. This is no longer true with LEDs which have little IR emission. In addition, LEDs have a relatively narrow band of spectral emission. The same cockpit lighting filters used to block red emission from the cockpit lighting may prevent the pilot from seeing LED obstruction and aviation ground lighting.

3.0. Application.

The Federal Aviation Administration (FAA) requires that the guidance in this EB be used with the other applicable documents listed in Section 6.

4.0. Description.

This EB describes the interaction of LEDs used in obstruction lighting fixtures with NVIS and provides specifications to facilitate the addition of IR emitters to L-810, L-864 and L-885 LED-based obstruction lights in order to ensure compatibility with NVIS.

5.0. Effective Date.

This EB will be effective after signature by the Manager of FAA Airport Engineering Division, AAS-100.

6.0 Applicable Documents.

a. Federal Aviation Administration (FAA)

AC 150/5345-43, *Specification for Obstruction Lighting Equipment*

AC 70/7460-1, *Obstruction Marking and Lighting*

7.0. Current Obstruction Lighting Standards and NVG Spectrum Requirements

The FAA currently has in place standards and recommended practices for the marking and lighting of obstructions. Generally, obstructions include structures with heights of 200 ft. above ground level (AGL) or greater, and structures on, or in the vicinity of airports.

7.1 *L-810, L-864 and L-885 Obstruction Lighting Fixtures*

Aviation red obstruction lights are used to increase conspicuity of obstructions during nighttime. The red obstruction light system is composed of flashing omnidirectional lights (L-864 and L-885) and/or steady-burning or flashing (L-810) lights. Recommendations on lighting structures can vary, depending on terrain features, weather patterns, geographic location, and number of structures. Specific guidance and installation criteria for obstruction lighting equipment are found in AC 70/7460-1, *Obstruction Marking and Lighting*.

AC 70/7460-1 recommends obstruction avoidance safety margins:

"A pilot in an aircraft flying at a speed of 165 kt (190 mph/306 kph) or less should be able to see obstruction lights in sufficient time to avoid the structure by at least 2,000 feet (610 m) horizontally under all conditions of operation, provided the pilot is operating in accordance with 14 CFR Part 91. Pilots operating 250 kt (288 mph/463 kph) aircraft should be able to see the obstruction lights unless the weather deteriorates to 1 statute mile (1.6 km) visibility at night, during which time period 2,000 candelas enables the light to be seen at 1.2 statute miles (SM) (1.9 km)".

AC 70/7460-1 notes that the 2,000-foot avoidance distance was intended to protect aircraft from collision with guy wires utilized on 2,000-foot structures:

"The guy wires at a 45-degree angle would be at a distance of 1,500 feet from the structure at a 500-foot elevation. Since the aircraft is to be 500 feet clear of obstacles (the guy wire), the distance of avoidance from the structure is 1,500 + 500 = 2,000 feet."

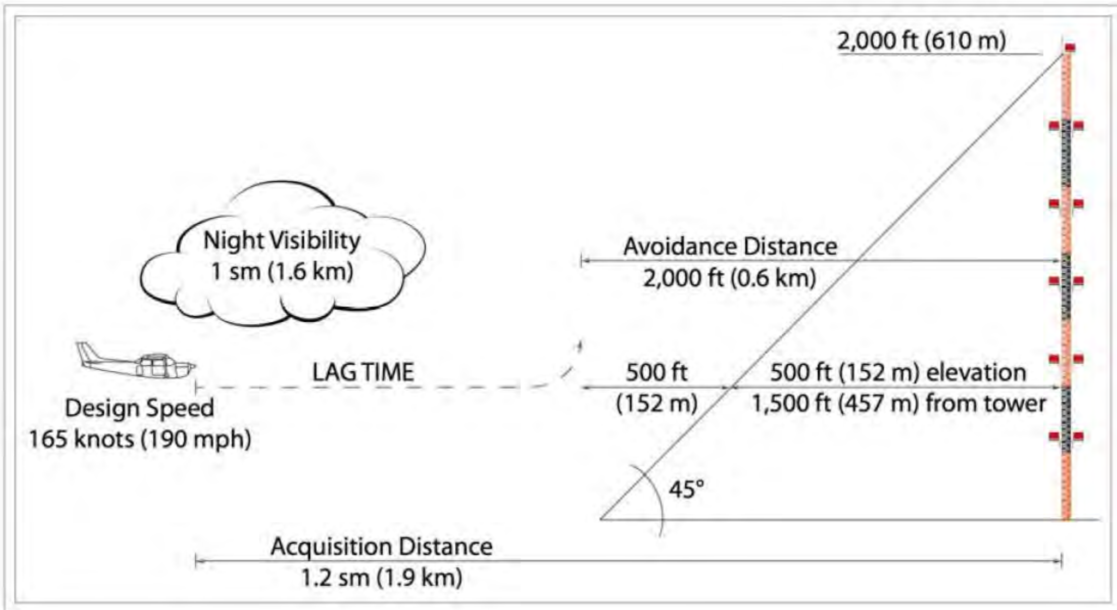


Figure 1. Illustration of Acquisition Distance Calculation

The acquisition and avoidance distances of pilots using NVG with LED based obstruction lights with an IR emitter should meet or exceed the nighttime acquisition distances of pilots without the aid of NVG. A L-810 fixture with an IR emitter should be acquired at a minimum distance of 1.4 SM and a L-864/L-885 fixture should be acquired at a minimum distance of 3.1 SM.

7.2 *NVG Operation*

The use of NVGs enables a pilot to improve his/her situational awareness during nighttime VMC. NVGs function by amplifying ambient light through a process of image intensification. Using NVGs in dark conditions, pilots can see the terrain and perform flight operations.

Figure 2. Example of View from NVG

NVGs consist of three main components: the eyepiece lenses, the objective lenses, and the image intensifier tubes, as shown in figure 3. The design and configuration of these components determine the overall performance of the NVGs. The image intensifier tubes generally are the most critical component determining image clarity, though the eyepiece and objective lenses can also affect performance.

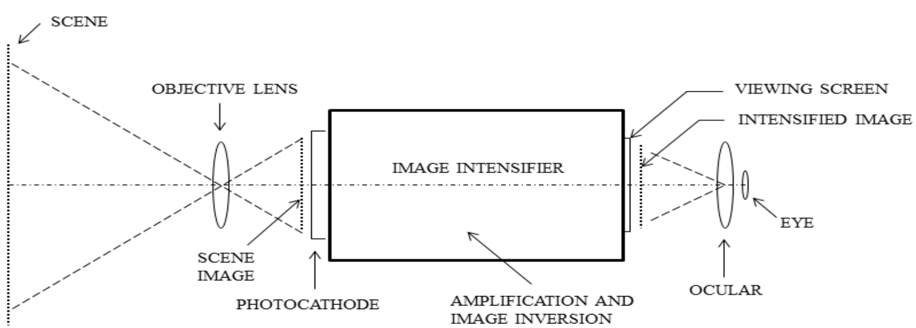


Figure 3. NVG Image Intensifier and Optical Components

Current NVGs are sensitive to light with wavelengths between approximately 450 nanometers (nm) and 920 nm. This range overlaps the visible spectrum of light (approximately 390 nm to 700 nm). If the visible light in the cockpit is not effectively filtered by the NVGs, the automatic gain control of the NVGs will be activated and will potentially reduce the visual acuity of the pilot.

As a result, filters are installed on the objective lenses of the NVGs. NVG filters currently in use include Class A, Class B, and Class C. Class A filters restrict wavelengths below 625 nm from being viewed by the NVG, allowing the use of blue, green, and yellow lighting to be used in the cockpit. Class B filters restrict lighting with wavelengths below 665 nm from being viewed by NVG, allowing the use of some red lighting in cockpit displays. Class C filters, also known as “leaky green” filters, also restrict light wavelengths below 665 nm, with the exception of a limited amount of green for a heads up display.

Class A NVG filters can view colors with wavelengths 625 nm and above, and Class B filters can view colors with wavelengths of 665 nm and above. However, because red LED obstruction lights have a limited emission range (approximately 620 nm to 645 nm) as shown in Figure 4, some red LEDs may have limited visibility using Class A filters and no visibility using Class B filters.

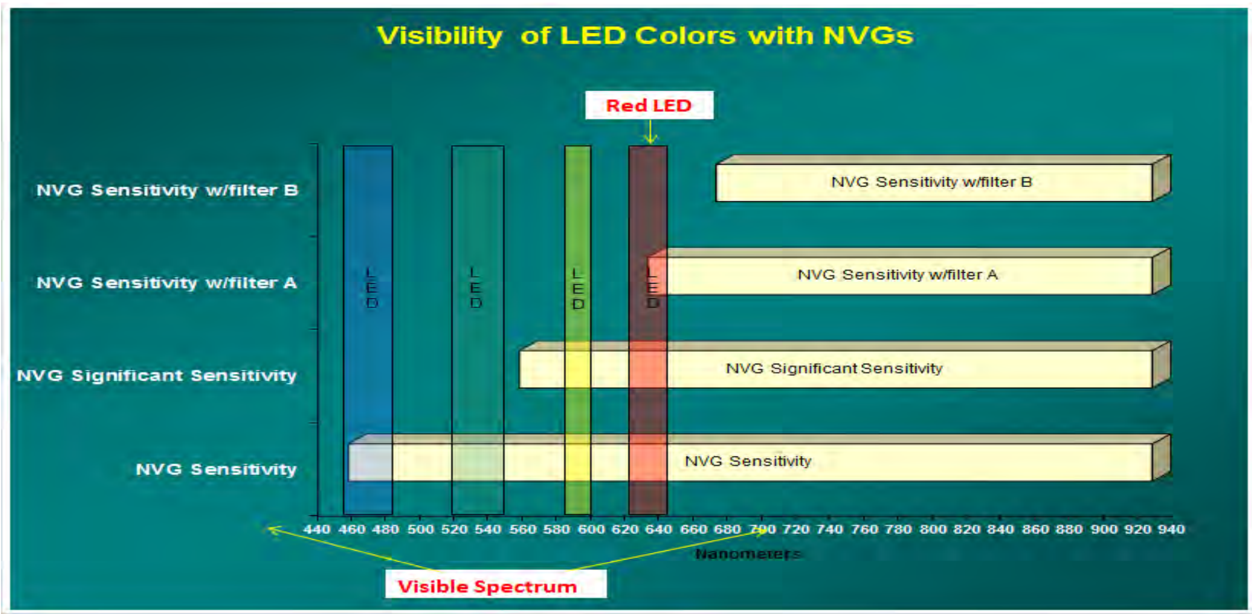


Figure 4. Visibility of LED Colors with NVG

8.0 Proposed Infrared Specifications for LED Obstruction Lights

In order to be NVG compatible, LED-based L-810, L-864 and L-885 obstruction light fixtures must include IR emitters or be used in conjunction with a standalone IR emitter. The IR emitters are to be on whenever the visible light is energized and off whenever the visible light is de-energized. IR specifications are stated below to resolve the issues precluding the acquisition of LED obstruction light fixtures by pilots using NVGs with a Class B filter.

8.1 *Output Wavelength*

The nominal IR output wavelength is 800-900 nm. This range coincides with the nominal spectral response range of NVGs, ensuring the fixtures will be visible by all current NVGs regardless of the class of objective lens filter used.

8.2 *Beam Width*

For LED-based L-810, L-864 and L-885 light fixtures, the vertical radiometric requirements of the IR radiation are to be identical to the existing FAA requirements in AC 150/5345-43 for the photometric beam width and distribution of the visible light. Therefore, the vertical beam width of IR emitters included in a LED-based L-810 light fixture or used in conjunction with a LED-based L-810 light fixture is minimum 10°, centered between +4 and +20°. The vertical beam width of IR emitters included in a LED-based L-864 and L-885 fixture or used in conjunction with a LED-based L-864 and L-885 light fixture is minimum 3°. The horizontal beam width is 360° unobstructed. The IR emissions must mimic both pulse width/duration of visible light so pilots do not experience a visual disparity when looking through and under the NVG.

8.3 *Minimum IR Radiant Intensity*

For wavelengths from 800 to 900 nm, the minimum radiant intensity for IR emitters included in LED-based L-810 light fixtures or for standalone IR emitters to be used in conjunction with LED-based L-810 light fixtures is 4 milliwatts per steradian (mW/sr) [0.004 W/sr]. The minimum radiant intensity for IR emitters included in LED-based L-864 and L-885 light fixtures or for standalone IR emitters to be used in conjunction with LED-based L-864 and L-885 light fixtures is 246 milliwatts per steradian (mW/sr) [0.246 W/sr].

The minimum IR radiant intensities for LED-based L-810, L-864 and L-885 light fixtures are based on the minimum acquisition distances for nighttime VMC stated in AC 70/7460-1 (1.4 SM for the L-810 and 3.1 SM for the L-864/L-885). These distances are necessary to provide pilots with adequate time to see the obstruction and take evasive action to avoid coming within 2,000 ft. of an obstruction.

Note: In the event of a failure of the IR emitter, the visible light must be de-energized and an alarm signal must be generated to provide indication of the failure. The IR emitter must be monitored in accordance with the monitoring requirements for FLASH/FAIL status of L-864, L-810 and L-885 visible light units in AC 150/5345-43.

Appendix I: Infrared Specifications for LED L-810, L-864 and L-885 LED Obstruction Lights

IR Wavelength (nominal)	Applicability	IR Vertical Beam Width	IR Radiant Intensity
800-900 nm	L-810 (L)	≥10°*	Minimum: 4 mW/sr
	L-864 (L) and L-885 (L)	≥3°	Minimum: 246 mW/sr

* The center of the vertical beam spread should be between +4 and +20 degrees.

EXHIBIT

2

Kieffer, Bill (FAA)

From: Norris, Lan (FAA)
Sent: Friday, February 07, 2020 1:35 PM
To: Kieffer, Bill (FAA)
Subject: FW: FAA Study / Wind Farm / Campo, CA / 19-WTW-4517 thru 19-WTW-4592

Email 2.

Lan M. Norris
Federal Aviation Administration
AJV-A540 / Obstruction Evaluation Group
Specialist - Wind Turbine Team
1701 Columbia Avenue
College Park, GA 30337
Lan.norris@faa.gov
(404) 305-6645
https://oeaaa.faa.gov

From: Norris, Lan (FAA) <Lan.Norris@faa.gov>
Sent: Friday, October 25, 2019 1:43 PM
To: Kieffer, Bill (FAA) <Bill.Kieffer@faa.gov>
Subject: FW: FAA Study / Wind Farm / Campo, CA / 19-WTW-4517 thru 19-WTW-4592

Email # 2.

Lan M. Norris
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https://oeaaa.faa.gov

From: Snow, Ed (FAA) <Ed.Snow@faa.gov>
Sent: Friday, October 25, 2019 11:30 AM
To: Norris, Lan (FAA) <Lan.Norris@faa.gov>; Peacox, Mark (FAA) <Mark.Peacox@faa.gov>; Blaul, Doug (FAA) <Doug.Blaul@faa.gov>; Boyett, Jonathan D (FAA) <Jonathan.D.Boyett@faa.gov>; Gillman, James R (FAA) <james.r.gillman@faa.gov>; Munro, Ryan A (FAA) <Ryan.A.Munro@faa.gov>; Sandfer, Kelly R (FAA) <Kelly.R.Sandfer@faa.gov>
Cc: Armstrong, Richard (FAA) <Richard.Armstrong@faa.gov>; Woods, William E (FAA) <william.e.woods@faa.gov>; Savage, Rick (FAA) <Rick.Savage@faa.gov>; Lias, Frank (FAA) <frank.lias@faa.gov>; Keeling, David V (FAA) <David.V.Keeling@faa.gov>; Quentin Baca <bacatron22@gmail.com>; Nestojko, George A (FAA) <george.a.nestojko@faa.gov>
Subject: RE: FAA Study / Wind Farm / Campo, CA / 19-WTW-4517 thru 19-WTW-4592

Mr. Norris,

Southern California TRACON (SCT) **objects** to the proposed wind farm as requested at Campo, CA - 19-WTW-4517 thru 19-WTW-4592.

Rationale

MVA - > SCT_MVA_FUS3_2018_NEW MVA in Sector SCT124 from 5,200 feet AMSL to 5,300 feet AMSL

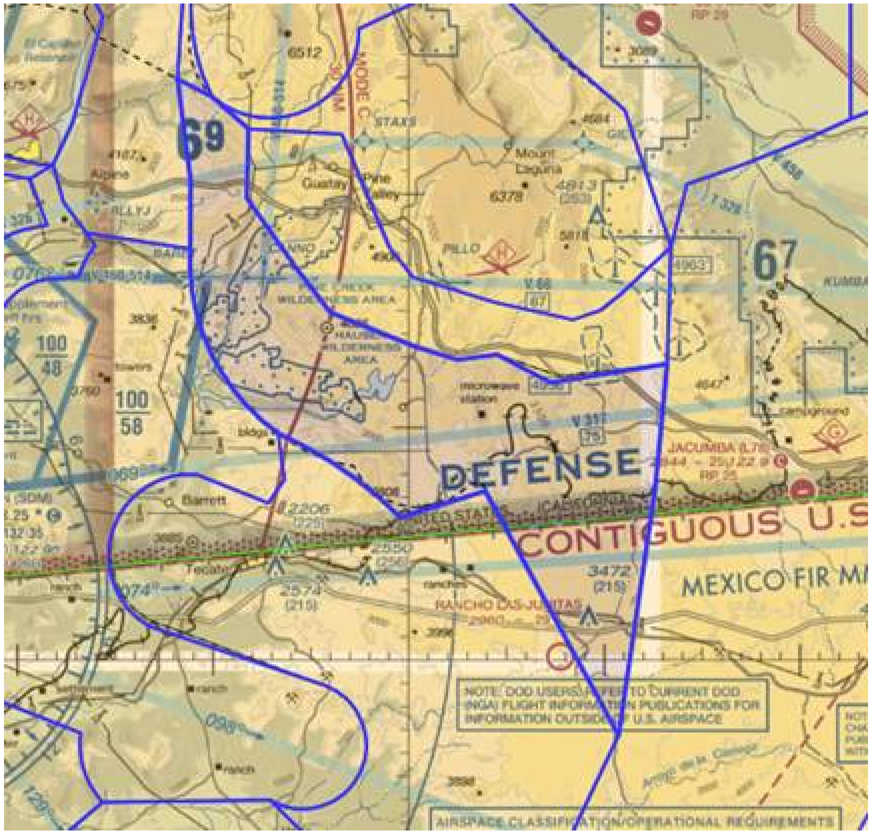
Impact minor. Raising this MVA would have a small impact on the operations at SCT.

MVA – > SCT_MVA_FUS5_2018 MVA in Sector ZZ from 5,800 feet AMSL to 5,900 feet AMSL.

Impact minor. Raising this MVA would have a small impact on the operations at SCT.

MVA - > SCT_MVA_FUS3_2018_NEW MVA in Sector SCT118 from 6,000 feet AMSL to 6,100 feet AMSL.

Significant impact. The loss of a cardinal altitude plus raising the altitude over a large area such as SCT118 would have a significant negative impact. This area is used extensively for vectoring arrivals to KSEE, KMYF, KSDM, KNZY, and KSAN.



MOCA> Increases the MOCA on the TOPGN TWO ARRIVAL (RNAV) from BLUZE to GUUSE from 7,000 feet AMSL to 7,200 feet AMSL.

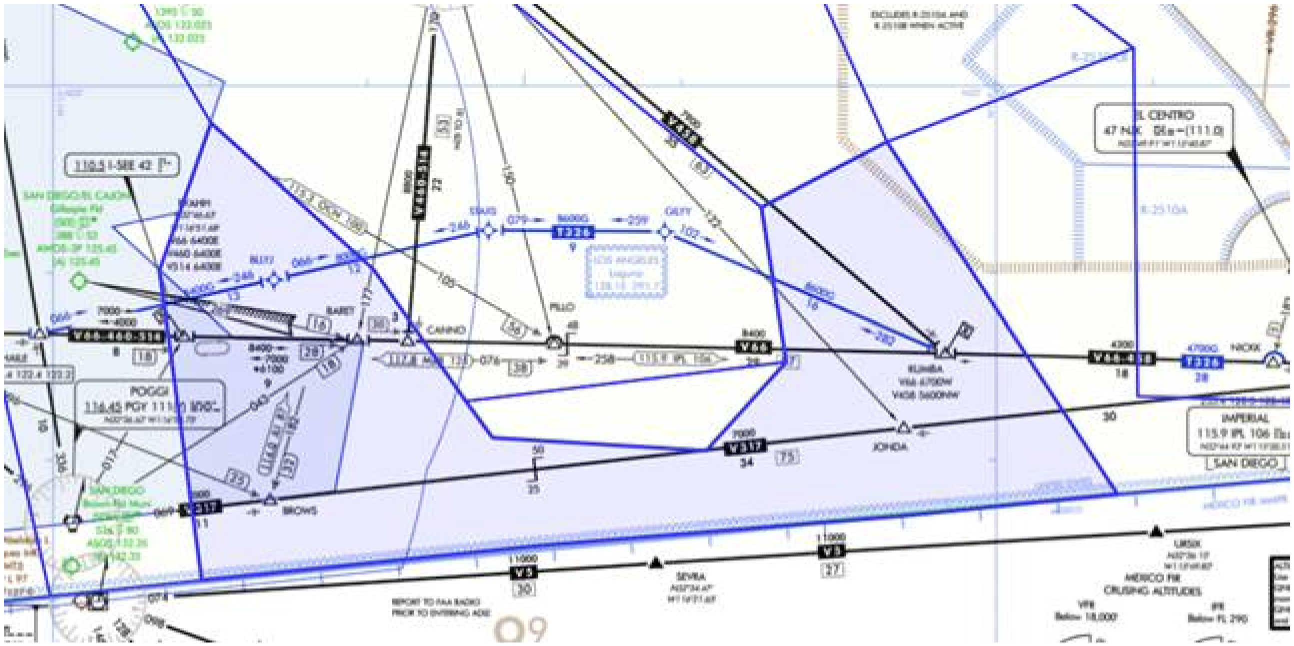
No impact to SCT operations.

MEA - > Increases the MEA on V317 from JONDA to BROWS from 7,000 feet AMSL to 7,200 feet AMSL. The NEH is 5,000feet AMSL.

Significant impact. This airway is commonly used, but more so during the winter months as a safe route for aircraft who cannot climb to higher altitudes due to icing conditions, this airway has the lowest MEA for crossing the mountains to the east. The aircraft that use this are General Aviation fixed wing aircraft from all the San Diego area airports, and military rotary aircraft (who are very ice sensitive) from MCAS Miramar and NAS North Island. The loss of the 7,000 feet MEA would be significant as it force all along the route to 8,000 feet MSL and higher.

MIA - > Increases the MIA for Los Angeles ARTCC (ZLA); ZLA_TAV_2018_V1 in LAN15 from 7,000 feet AMSL to 7,100 feet AMSL.

Significant impact. This would eliminate the use of a cardinal altitude for vectoring between Southern California TRACON and Los Angeles Center (See previous rationale) Additionally it appears that this MIA accommodates vectoring in and around the El Centro, CA area, which I would presume would have a negative impact on ZLA's operations in that area.



If this project is approved it will have a significant negative effect on operations in the target area.

Regards,

Ed Snow
Support Specialist
Airspace and Procedures
Los Angeles District
858-537-5982 Work
760-271-0816 Cell

From: Norris, Lan (FAA) <Lan.Norris@faa.gov>
Sent: Monday, October 21, 2019 2:25 PM
To: Peacox, Mark (FAA) <Mark.Peacox@faa.gov>; Blaul, Doug (FAA) <Doug.Blaul@faa.gov>; Snow, Ed (FAA) <Ed.Snow@faa.gov>; Boyett, Jonathan D (FAA)

<Jonathan.D.Boyett@faa.gov>
Subject: FAA Study / Wind Farm / Campo, CA / 19-WTW-4517 thru 19-WTW-4592

Good Afternoon ZLA/SCT,

The Obstruction Evaluation Group (OEG) is conducting further aeronautical study for the subject wind farm proposal. There are 76 proposed wind turbines filed with the FAA for a maximum height of 586' AGL. The turbines are identified by the green triangles in the image below.

The proposed structures would increase the following MVAs for Southern California TRACON (SCT):

> SCT_MVA_FUS3_2018_NEW MVA in Sector SCT124 from 5,200 feet AMSL to 5,300 feet AMSL
> SCT_MVA_FUS5_2018 MVA in Sector ZZ from 5,800 feet AMSL to 5,900 feet AMSL.
> SCT_MVA_FUS3_2018_NEW MVA in Sector SCT118 from 6,000 feet AMSL to 6,100 feet AMSL.

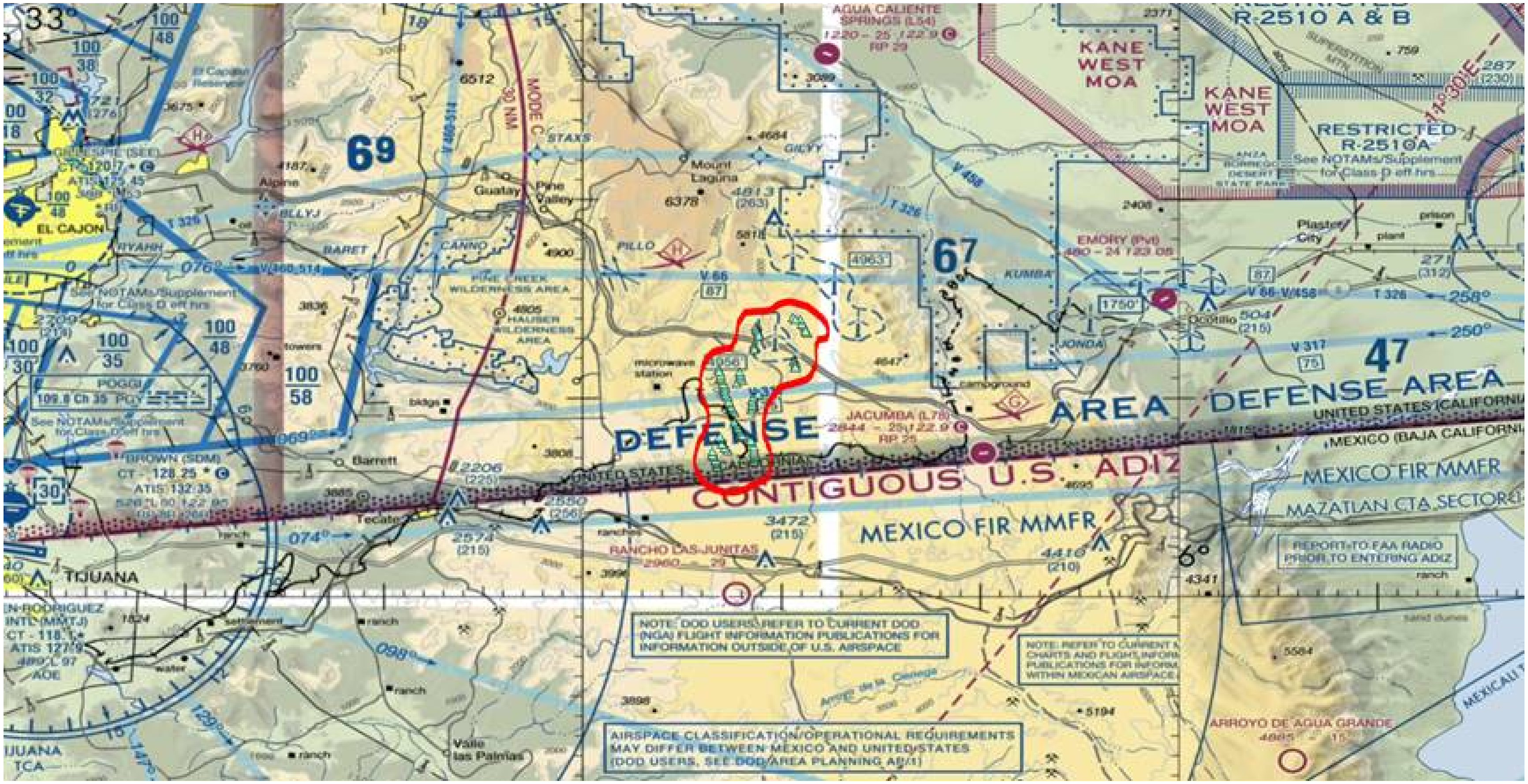
The proposed structures would also have the following effects on en route procedures:

> Increases the MOCA on the TOPGN TWO ARRIVAL (RNAV) from BLUZE to GUUSE from 7,000 feet AMSL to 7,200 feet AMSL.
> Increases the MEA on V317 from JONDA to BROWS from 7,000 feet AMSL to 7,200 feet AMSL. The NEH is 5,000feet AMSL.
> Increases the MIA for Los Angeles ARTCC (ZLA); ZLA_TAV_2018_V1 in LAN15 from 7,000 feet AMSL to 7,100 feet AMSL.

Four of the turbines would be seen (line of sight) by the San Clemente, CA (NSD) ARSR-4 radar facility. The Technical Operations Group identified the four structures as having no effect on secondary radar. If your facility finds the primary radar impact to be objectionable, we will need specific traffic count data for radar service provided to low-level, non-transponder equipped aircraft in the area of the turbines.

Please review the proposal and let us know if there any objections. We are requesting a response within 30 days of this notice. Let me know if you need additional information to complete your analysis or if you have any questions. Please forward this message to any appropriate facility contacts not included in this distro.

Thank You,
-Lan



DEFENSE AREA
CONTIGUOUS U.S. ADIZ
MEXICO FIR MMFR
KANE WEST MOA
RESTRICTED R-2510A
R-2510 A & B
AGUA CALIENTE SPRINGS (L54)
JACUMBA (L78)
EMORY (Pvt)
TIJUANA
EL CAJON
Tecate
Mount Laguna
Pine Valley
Guatay
Alpine
Barrett
Ocotillo
Plaster City
RANCHO LAS JUNITAS
ARROYO DE AGUA GRANDE
NOTE: DOD USERS REFER TO CURRENT DOD (NGA) FLIGHT INFORMATION PUBLICATIONS FOR INFORMATION OUTSIDE OF U.S. AIRSPACE
AIRSPACE CLASSIFICATION/OPERATIONAL REQUIREMENTS MAY DIFFER BETWEEN MEXICO AND UNITED STATES (DOD USERS, SEE DOD AREA PLANNING AP/1)
REPORT TO FAA RADIO PRIOR TO ENTERING ADIZ
UNITED STATES (CALIFORNIA)
MEXICO (BAJA CALIFORNIA)
MAZATLAN CTA SECTOR

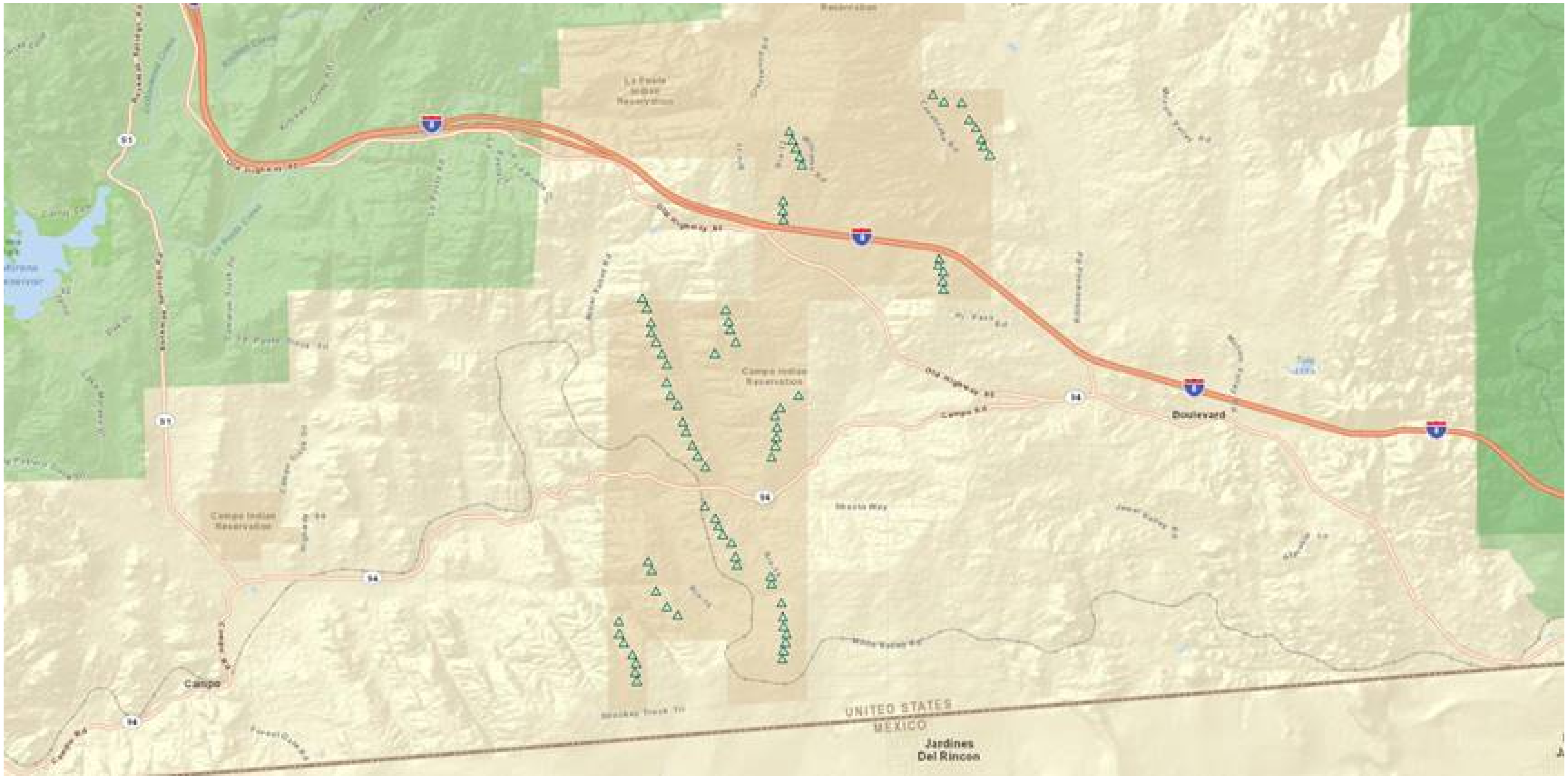


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EXHIBIT
3

Mark Ostrander

February 1, 2021

Backcountry Against Dumps
c/o Donna Tisdale
PO Box 1275
Boulevard, CA 91905-0375

Re: Review of the Wildfire Impacts from the Campo Wind Project with Boulder Brush Facilities

Dear Ms. Tisdale,

I was retained by Backcountry Against Dumps ("Backcountry") to provide an independent technical review of the impacts of the Campo Wind Project and associated Boulder Brush facilities (collectively, the "Project") on wildfire risk and wildfire suppression. This included reviewing the Bureau of Indian Affairs' ("BIA's") Draft ("DEIS") and Final Environmental Impact Statements ("FEIS") for the Project. My review and professional opinion are presented below. Overall, I conclude that the Project would cause significant fire risks and firefighting impediments.

BACKGROUND AND EXPERIENCE

I am a retired Battalion Chief and California Environmental Quality Act ("CEQA") Environmental Coordinator with the California Department of Forestry and Fire Protection ("Cal Fire") with 36 years' experience working in the field of wildfire suppression throughout Southern California, including eastern San Diego County. During my employment, I performed numerous essential tasks including both "hands-on" fire suppression activities in the field and later, in a supervisorial capacity as a manager of wildfire response campaigns on major conflagrations. I worked on over 2,000 fires - including 12 of the 20 largest wildfires in California history - during my 36 years of employment with Cal Fire. For example, I was Logistic Section Chief for Cal Fire's suppression response to the Cedar fire in 2003, a fire that engulfed approximately 285,000 acres of land throughout central San Diego County. This fire ultimately burned 3,000-plus structures and resulted in serious injuries or death to 14 people. I also managed the following additional major wildfire response campaigns as part of a Major Incident Command Team, Cal Fire Team 8: Saw Tooth, Eagle, Border 50, Martin and Esperanza, among others. Our Team was also Certified in Complex Incident Management.

PROFESSIONAL OPINION

Based on my nearly four decades of training and hands-on experience in these areas, I have formed the professional opinion that construction and operation of the Campo Wind Project and its sixty 586-foot tall wind turbines, three 374-foot tall meteorological towers, collector substation, gen-tie line and associated electrical lines and facilities (including the Boulder Brush facilities) pose not only a significant fire-ignition risk, but also an extremely hazardous impediment to effective wildfire suppression in the Campo area. In my professional opinion, the only way to significantly reduce wildfire risk from these power generation facilities is to move them to an area not known for its wildfire hazards. And the only way to significantly reduce wildfire risk from the electrical transmission lines is to underground them – that was the consistent official position Cal Fire took when I was Cal Fire's CEQA Environmental Coordinator, and it remains my expert opinion today. The analysis of the Project's cumulative wildfire risk that BIA presented in its FEIS is wholly inadequate, and relies on incorrect facts and assumptions.

The proposed construction and operation of the Project poses a significant and unacceptable risk of wildfire ignition due to the known hazard it presents to the frequent use by low-flying aircraft of the overlying airspace, resulting in airplane collisions, the known hazards of wildfire ignition posed by its energized wind turbines and power lines, the known hazard of placing a source of ignition in an area noted for its extreme wildfire risk due to heavy vegetation, aridity, high summer and fall temperatures, and frequent high winds, and by the known tendency of wind turbine motors to overheat due to mechanical failure, ignite and then disperse flaming debris onto surrounding vegetation.

Several of the worst conflagrations in San Diego County history, including the Pines and Witch fires, were ignited by power lines. The FEIS recognizes that the Project "would increase the potential for a wildfire and could impact the public and the environment by exposure to wildfire due to construction and decommissioning activities and ground disturbance with heavy construction equipment." FEIS at 131, 132. But the FEIS completely ignores the risk of wildfires posed by the Project's operation. The FEIS never identifies and discusses the many serious wildfire hazards posed by the Project's operation, including those I summarized above.

The Project's many significant risks of wildfire ignition include, for example, the following hazards not disclosed in the FEIS:

- Introduction of non-native, invasive and flammable plants;
- Vegetation contact with conductors;
- Exploding hardware, such as transformers and capacitors;
- Floating or wind-blown debris contact with conductors or insulators;
- Conductor-to-conductor contact;
- Dust or dirt on insulators causing flashover;
- Bullet, airplane, or helicopter contact with turbine towers, rotors and blades, and
- Other third-party contact, such as Mylar balloons, kites, and wildlife.

The FEIS ignores the additional wildfire risk posed by the local weather and its high aridity and temperatures during the late summer and fall, and extremely high winds during the late summer, fall and early winter. The ignition threat is especially pronounced when the Santa Ana winds blow southwest through the Project area from the Great Basin. The Project area's Mediterranean climate including mild, wet winters and hot, dry summers supports dense, drought-adapted shrub lands that are highly flammable, especially in the fall as the vegetation dries out and becomes highly flammable.

The Project area is classified by Cal Fire's Fire Resource and Assessment Program as a "High" to "Very High" Fire Hazard Severity Zone. Over the past 50 years, the Boulevard area has experienced 29 wildfires greater than 10 acres in size. And in recent years, the Project area has become even more fire prone, as the area has been invaded by non-native invasive weeds, which ignite more easily and tend to spread fires more rapidly than native mountain and desert vegetation.

Wind turbines can be the source of wildfire ignitions due to lightning strike, wind turbine collapse, power collection line failure, turbine malfunction or mechanical failure, and bird-related collisions. The risk of lightning strikes is greatly exacerbated by the installation of this Project's very tall turbines–up to 600 feet–which act as lightning rods by attracting the strikes that hit them. When mechanical or electrical failures cause turbines to catch fire, they may burn for many hours or even days due to the large quantity of combustible materials in the nacelle and the limited ability of fire suppression crews to effectively fight fires that are hundreds of feet above the ground.

Once a fire starts in a turbine, it can be fueled by up to 200 gallons of hydraulic fluid and lubricants in the nacelle. The nacelle itself is constructed of flammable resin and glass fiber, and internal insulation can become contaminated by oil deposits, adding to the overall fuel load. Wind-blown flaming debris from a turbine fire can ignite vegetation over a wide swath of the surrounding area, particularly when high winds carry the debris hundreds or even thousands of feet down wind.

The Project poses a significant impediment to wildfire fighting in the area for at least three reasons. First, modern fire suppression response depends heavily on retardant and water drops by large aircraft and helicopters as close as possible to the leading edge of wildfires. To be effective, retardant and water drops must be low enough so that the retardant retains sufficient thickness and density to smother the fire, and is applied as quickly as possible following ignition. Delay in the delivery of retardant or water drops, or failure to deliver retardant or water directly to the leading edge of a wildfire, allows the fire to build heat, momentum, size, and speed. Once a wildfire has reached a critical size, temperature and speed, it is extremely difficult to contain, much less control.

Second, the presence of structures nearly 600-feet in height above the ground surface makes aerial delivery of retardant or water to the Project site extremely difficult, if not impossible. The mere presence of the 600-foot-tall turbine towers would create a large zone in which it is dangerous for low-flying aircraft to operate, either for fire-spotting purposes or to drop retardant and water. Additionally, the electrification of both the towers and the connecting lines, substation and gen-tie line greatly increases the safety risk to those aircraft and their crew, including electrical shock from both direct line collision and through contact with smoke that can conduct electricity between lines. The end result is a severe impairment of aerial fire suppression abilities, which the FEIS completely ignores. FEIS at 131-132.

Third, in addition to impeding aerial firefighting, construction of the Project would impede effective ground attack against any wildfires in the vicinity of the Project. The deployment of fire crews within 100 to 1,000 feet (depending on conditions) of electrified structures is unsafe and forbidden by applicable safety rules and regulations due to the serious hazard of electrical shock from the wind turbines, substations, gen-tie lines and other electrified facilities. These are well-established safety practices and procedures used by all of the major fire suppression agencies, including Cal Fire. Wildland firefighters working around energized wind turbine facilities are exposed to electrical shock hazards, including direct contact with downed power lines, contact with electrically charged materials and equipment due to broken lines, contact with smoke that can conduct electricity between lines, and the use of solid-stream water applications around energized lines.

Because of the limitations on ground-based firefighting resulting from these safety risks and the precautions taken to reduce them, the construction and operation of the Project would prevent effective hand crew and heavy equipment fire suppression response within a 1,000- to 2,000-foot-wide swath of land extending along the Project's perimeter and tie line route. This means that any fire in the area will generally get larger as the fire crew waits for it to pass through the Project area to a safer distance from which to work the fire. Consequently, if a fire were to occur during extreme weather conditions and could not be initially contained, it could grow to be a major fire. This represents a potential major impact to firefighting efforts that would last for the life of the Project. This threat is exacerbated by the recent reductions in firefighting capacity in San Diego County. Due to state budget cuts, Cal Fire and the California Department of Corrections and Rehabilitation depopulated (eliminated) two fire camps in the county on December 12, 2020, including the camp closest to the Project (McCain Valley Conservation Camp in Boulevard) and Rainbow Conservation Camp in Fallbrook. The only way to fully eliminate the Project's numerous wildfire and firefighter safety risks is to not build the Project at this hazardous site.

CONCLUSION

For these reasons, I conclude that the proposed construction and operation of the Project poses not only a significant fire-ignition risk, but also an extremely hazardous impediment to effective wildfire suppression in the area. In my professional opinion, the only way to significantly reduce wildfire risk from the Project is either not build the Project, or move the Project out of the area to a safer location, and underground all its power lines.

Respectfully submitted,

Mark Ostrander

EXHIBIT

4

Impact of Renewable Energy Sources on Birds of Prey

Chapter · July 2018

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Editors

Birds of Prey

Biology and conservation in the XXI century

Springer

Contents

Chapter 13
Impact of Renewable Energy Sources on Birds of Prey

James F. Dwyer, Melissa A. Landon, and Elizabeth K. Mojica

Introduction

Renewable energy, defined as energy generated from natural processes that are replenished over time (Johnson and Stephens 2011), is increasingly important in global energy portfolios. This chapter begins by reviewing reasons for shifting from fossil fuels to renewable energy, including reasons which have nothing to do with environmental concerns but are nevertheless driving advances in the renewable sector. The chapter then focuses on birds of prey, describing actual and potential direct and indirect mortality, habitat loss, avoidance, and displacement resulting from the development and operation of renewable energy facilities. The chapter considers renewable energy facilities themselves, including wind, biofuel, solar, hydro, geothermal, and oceanic energy sources. Transmission connections linking renewable facilities to the existing electric transmission grid are considered, as are potential offsite impacts where the materials used to construct renewable infrastructure are mined and manufactured. The chapter closes with a discussion of mitigation strategies designed to reduce or compensate for negative impacts for birds of prey and a discussion of potential benefits of renewable energy facilities for birds of prey. The latter are important to understand when evaluating the overall balance of costs and benefits of renewable energies on birds of prey.

Knowledge of the connections between global conflicts and international dependencies on fossil fuels is important in understanding how macroeconomic forces independent of environmental concerns drive the advancement of renewable energy technologies. Because "green" initiatives may not in fact be grounded in environmental concerns, but be grounded instead in economics and national interests, potential negative environmental impacts of renewables and their high initial investment costs may carry little weight in the overall discussion, a paradox not readily apparent without consideration of the context of global competition over traditional energy reserves.

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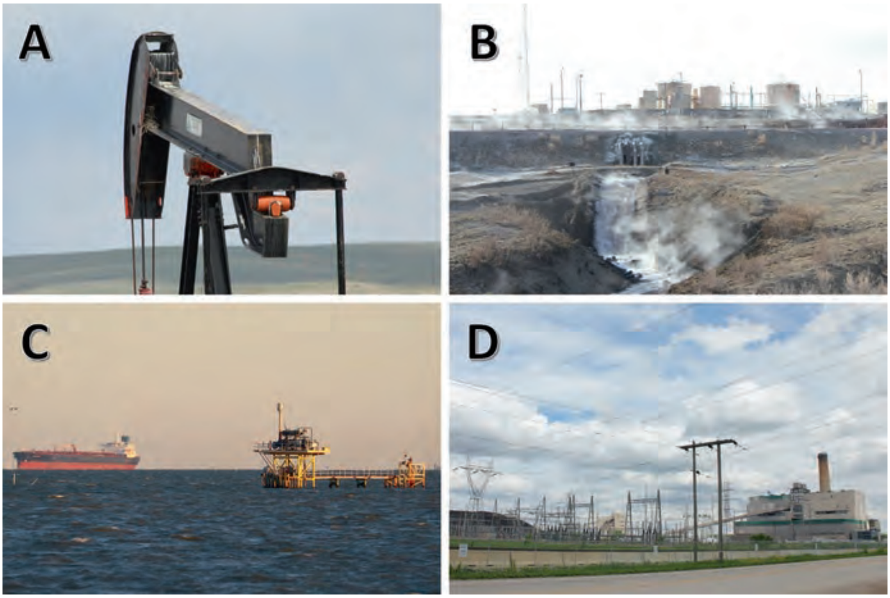

Fig. 13.1 (**a**) A pump designed to extract liquid and gas fossil fuels from terrestrial deposits; note great horned owl (*Bubo virginianus*) nest and whitewash. (**b**) Collection facility for traditional liquid and gas fossil fuels from terrestrial deposits. (**c**) Transport (left) and collection (right) of traditional fossil fuels, (**d**) Traditional coal-burning electricity generation station

Fossil fuels have been the primary energy source for developing and developed nations since the Industrial Revolution of the early 1800s when coal began to be used to power steam-driven machines and energy-intensive metallurgic and chemical processes. Emissions from these machines and processes were recognized almost immediately as harmful, triggering early environmental responses to protect urban air and water. From the late 1800s through the early twenty-first century, fossil fuels remained the primary solution to global energy needs as petroleum and natural gas products made the storage and use of chemical energy more efficient and economical (Fig. 13.1).

The resulting dependence of national and international economies on fossil fuels has created two fundamental problems. The first is a globally ubiquitous reliance on fossil fuels often derived from outside national boundaries. This reliance can place less developed nations with large reserves at the center of conflicts for control of those reserves and can place more developed nations without large reserves at the mercy of nations with reserves. Shifting energy sources from fossil fuels to renewables offers nations the ability to achieve energy independence.

The second fundamental problem created by the global reliance on fossil fuels is the impact of combustion products on the global climate. Greenhouse gases released during combustion of fossil fuels are contributing to global climate changes. Shifting energy sources from fossil fuels to renewables offers nations the ability to achieve energy independence and offers potential environmental benefits. These benefits are not without their own potential costs however, and it is those potential costs, as exerted on birds of prey populations, that are discussed here.

Effects at Renewable Facilities

Potential effects to birds of prey at renewable facilities include direct mortality and indirect effects resulting from habitat loss, avoidance, and displacement. Direct mortality is defined as death occurring as an immediate consequence of an interaction between a bird of prey and a component of renewable infrastructure. For example, a golden eagle (*Aquila chrysaetos*) killed when struck by a rotating wind turbine blade or killed when colliding with the suspended high-voltage wires of a transmission power line connecting a renewable facility to the electric grid. Habitat loss is defined as occurring when the landscape occupied by birds of prey is converted to non-habitat, for example, the displacement of prey species resulting from conversion of hunting habitat to a mirror field for a solar plant or the removal of a nest tree when creating an agricultural monoculture for biofuel production. Avoidance and displacement are similar processes occurring at different scales. Both occur when habitat persists, but is no longer used. Avoidance is defined as a shift in use of specific portions of a renewable facility, not the entire site (Band et al. 2007). Displacement occurs when an entire site is abandoned (Band et al. 2007).

These effects rarely occur in isolation but are instead likely additive, co-occurring with one another and with other anthropogenic and natural agents of mortality. Additive effects can be problematic, even at low rates, because most birds of prey are k-selected species with relatively little annual reproduction and breeding often delayed during multiple years of maturation. Population persistence for many bird of prey species requires individual breeding adults to produce young over an entire lifetime. Mortality of breeding adults can have substantial effects on the population (Bellebaum et al. 2013). For example, at some sites, griffon vultures (*Gyps fulvus*) and red kites (*Milvus milvus*) cannot maintain stable local populations with additive mortality from wind farms (Carrete et al. 2009; Bellebaum et al. 2013).

Wind Resource Areas

Direct effects of wind energy facilities (Fig. 13.2) on birds of prey involve mortality occurring when rotating turbine blades strike birds in flight. Impacts are largely species-specific. Directly affected species are characterized by low-altitude flight when gliding on local winds and on thermal and orographic lifts (Katzner et al. 2012; de Lucas et al. 2008). Because wind turbines are designed and specifically placed to harvest the kinetic energy in some of these same winds, low-altitude flight behaviors largely dictate risk by placing birds of prey and rotating turbine blades

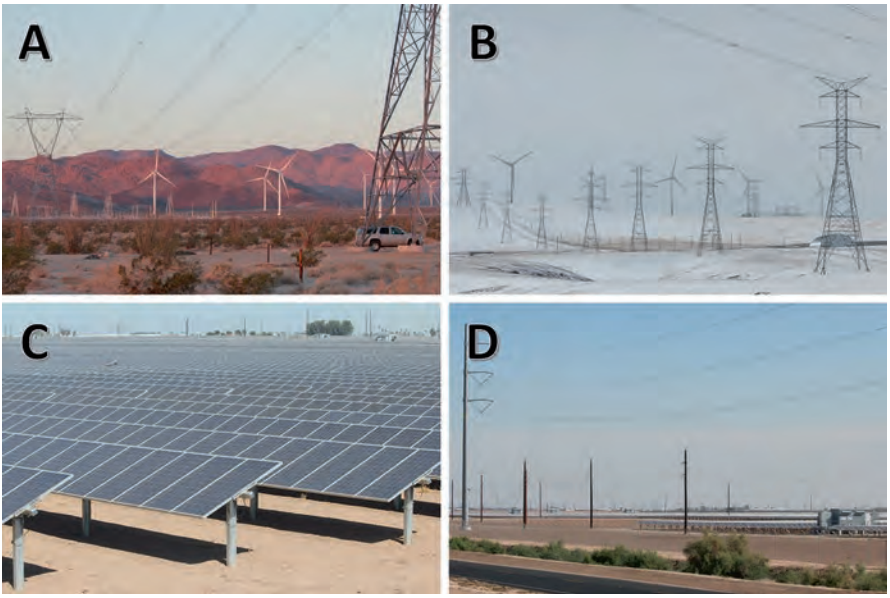

Fig. 13.2 (**a**) A wind resource area in desert habitat; note substation under construction in the background will provide a connection from the wind resource facility to the existing transmission power line network. (**b**) A wind resource area above agricultural fields, potentially facilitating both wind energy and biofuel production. (**c**) Close view of a solar field illustrating the bare and leveled earth (non-habitat) typical of such facilities. (**d**) Wide view of a solar field, illustrating fencing and bare earth designed to limit attractiveness as habitat and illustrating associated distribution and transmission lines

together in the same airspace. Hunting in these airspaces has been hypothesized to hinder the ability of a bird of prey to recognize turbines as a flight hazard (Orloff and Flannery 1992; Smallwood et al. 2009), so species habituated to hunting within wind resource areas can be at higher risk of collision. Collision risk can also increase along flight corridors where large numbers of migrating birds of prey funnel along narrow ridges and coastlines supporting wind energy facilities (Barrios and Rodriguez 2004; Katzner et al. 2012; de Lucas et al. 2012) or where communal roosts occur near wind resource areas (Carrete et al. 2012). Intraspecific and inter-specific interactions during flight also increase risk for collision because birds of prey can be distracted and less likely to recognize flight hazards (Dahl et al. 2013; Smallwood et al. 2009).

Though at least 34 bird of prey species have been documented in collisions with wind turbines, population-level impacts from direct effects are unknown for most species (Beston et al. 2016); only griffon vultures (Carrete et al. 2009), red kites (Bellebaum et al. 2013) and golden eagles (USFWS 2013) are currently known to be at risk of population-level effects from these collisions.

Species-specific behaviors also drive indirect effects of wind resource areas. Species avoiding or displaced by wind resource areas tend not to be affected by direct mortality but may abandon breeding territories (Dahl et al. 2013), shift local space use (Walker et al. 2005), or decrease in local abundance (Garvin et al. 2011; de Lucas et al. 2004). Some species show avoidance behaviors for individual turbine structures by adjusting flight paths to fly between or around turbines (Cabrera-Cruz and Villegas-Patraca 2016; Hull and Muir 2013; de Lucas et al. 2004) or adjust altitude to fly over turbines in their path (Johnston et al. 2014; de Lucas et al. 2004). There is limited evidence of net population loss in birds of prey from avoidance or displacement attributable to wind resource areas, but effects could be important for threatened species when considered with direct effects (Martínez et al. 2010).

Biofuels

Biofuels primarily describe energy resources developed from agriculture and most often describe production by industrial farms focused on extracting the greatest possible crop yields per acre. Yields are maximized by eliminating as many non-producing inclusions as possible and by promoting maximum growth through regular inputs of synthetic chemicals. Eliminating inclusions requires conversion of potential nest groves and bird of prey hunting habitat to cropland. Chemical inputs regularly consist of fertilizers to maximize crop yields, and pesticides, rodenticides, and herbicides, to protect monoculture crops from competing organisms in the environment. Collectively, these processes contribute to agricultural intensification which has been at least partly responsible for declines in farmland bird populations (Campbell et al. 1997; Uden et al. 2015).

Meeting increasing demand for ethanol requires increasing cropland in production, and consequently, the development footprint of biofuels is expected to be one of the fastest growing of all renewable energy sources in the next two decades (Johnson and Stephens 2011). Impacts of biofuel energy production on birds of prey occur primarily due to indirect effects triggered by the loss of breeding and foraging habitats when stands of trees used for nesting and open spaces used for hunting are converted to biofuel monocultures. Indirect effects include habitat loss, decreases in prey abundance, and potential biochemical effects from exposure to toxic chemicals. Direct effects are generally limited to rare occurrences of nestling mortality when nest trees are removed during breeding seasons, though exposure to bioaccumulating chemicals may also have effects that have not yet been identified.

Solar Facilities

Solar energy facilities also have the potential to impact birds of prey. Direct effects most often include electrocution on collection power lines, collisions with mirrors, and thermal trauma in solar flux fields (Kagan et al. 2014; McCrary et al. 1986). Electrocution can occur when a bird of prey simultaneously contacts two differently energized conductors or an energized conductor and a path to ground (APLIC 2006, in this book Chap. 12). Collisions occur when birds apparently mistake reflections of the sky in mirrors as the sky itself and attempt to fly through a mirror, perhaps in pursuit of prey.

Solar flux fields are the areas of concentrated light surrounding the collection tower(s) at thermal solar plants. Mirrors are used at these facilities to concentrate solar energy on a single area where water within a container is heated to produce steam which powers a generator. The air around the collection tower can reach 500–800 °C (McCrary et al. 1986; Diehl et al. 2016). Damage to feathers occurs at 160 °C (Wendelin et al. 2016), so flight through a solar flux field can result in burns to feathers and tissues, causing immediate mortality or limiting or eliminating the ability to fly, depending on individual exposure. Unlike other renewable energy technologies like wind turbines, which are relatively benign when not operational, solar flux fields can be dangerous to birds even when solar flux fields are not focused on collection towers (Wendelin et al. 2016). This can occur because mirrors in standby positions often focus solar energy just above collection towers. Heat in these standby positions can be intense enough to harm birds.

Morbidity and mortality of birds of prey in solar flux fields appear relatively rare, but when cases do occur, taxonomic patterns are emerging. Specifically, falcon (Falconiformes) species may be more susceptible, apparently because falcons are attracted to hunt aerial prey concentrated near collection towers (WEST 2016). Alternatively, in both active and standby positions, warm air rising above collection towers may attract buteos and vultures seeking thermal air currents to power flight, and these birds may inadvertently enter solar flux zones regardless of the presence or absence of potential prey.

Indirect effects of solar energy facilities include habitat loss, displacement, and avoidance (Hernandez et al. 2014). Unlike wind energy facilities where some of these effects might be temporary, with birds returning after construction, solar facilities eliminate habitat from within the facility, creating a flat bare earth-scape unattractive for hunting or nesting by birds of prey. Habitat loss at solar energy facilities is generally greater per megawatt generated than at wind facilities because wind resource areas retain most of the habitat below turbines, whereas solar facilities cover much of the facility in mirror arrays. Birds of prey and other wildlife species also may avoid habitats in and around solar facilities as a result of increased human activity and habitat alteration (DeVault et al. 2014).

Other Renewable Facilities

Other renewable energy sources include geothermal, hydroelectric, and oceanic. There are no substantial direct mortality effects to birds of prey documented for these energy sources. Geothermal power stations use heat energy from within the earth's crust to generate electrical energy. Facility footprints are similar to those of liquid and gas fossil fuel extraction facilities, with impacts to birds of prey limited to indirect effects resulting from disturbance during construction and operation. Roads to extraction wells increase habitat fragmentation (Jones and Pejchar 2013), impacting edge-sensitive species. Geothermal emissions often contain vaporized toxins which, while less than coal burning plants, release toxins into the air including hydrogen sulfide, carbon dioxide, ammonia, methane, and boron, mercury, and other heavy metals (Kagel et al. 2007), so indirect effects could also include reactions to toxic emissions.

Hydroelectric and oceanic renewable energy facilities use the energy of flowing rivers or tides to turn turbines and generate electricity. Hypothetically, aquatic hunters like osprey (*Pandion haliaetus*) could become entrapped in the machinery of hydroelectric or oceanic renewable energy infrastructure, but neither of these potential agents of mortality has yet been documented. This indicates that even if mortality occurs, levels are sufficiently low to preclude population impacts. Indirect effects likely do occur, though are not necessarily negative. Construction of reservoirs to store water for a hydroelectric dam floods and destroys bottomland habitats used as nest sites by some bird of prey species, but this habitat loss may be offset by creation of new reservoirs with far more shoreline hunting and nesting habitat than existed previously.

Effects of Transmission Linkages

Renewable facilities are connected to the existing electric system through construction of new transmission lines (Fig. 13.3), termed connections, interconnections, links, or linkages (hereafter interconnections). These interconnections have the potential to create avian collision and habitat fragmentation concerns well away from, but directly attributable to, renewable energy facilities. Post-construction environmental impacts of renewable energy infrastructure are generally considered only within the footprint of renewable energy facilities, but may not include the associated interconnections even though transmission lines are associated with avian collision mortalities (Bevanger 1998; Loss et al. 2014; Rogers et al. 2014). Because renewable interconnections have not yet been thoroughly studied with respect to potential impact to birds of prey, this section summarizes knowledge of potential impacts of transmission lines in general.

Direct effects of power lines on birds occur through mortality caused by electrocution and collision (Bevanger 1998; Loss et al. 2014). Electrocution is limited mostly to distribution lines (<69 kV) where clearances are minimal and birds can simultaneously contact multiple energized components or energized and grounded components (APLIC 2006, in this book Chap. 12). Transmission clearances designed to prevent electrical energy from arcing across conductors generally include separations greater than birds can bridge with extended wings, though there are exceptions on certain configurations used for lower transmission voltages (69–138 kV). Because electrocution is generally of little concern at the transmission voltages used in renewable energy interconnections, and because detailed

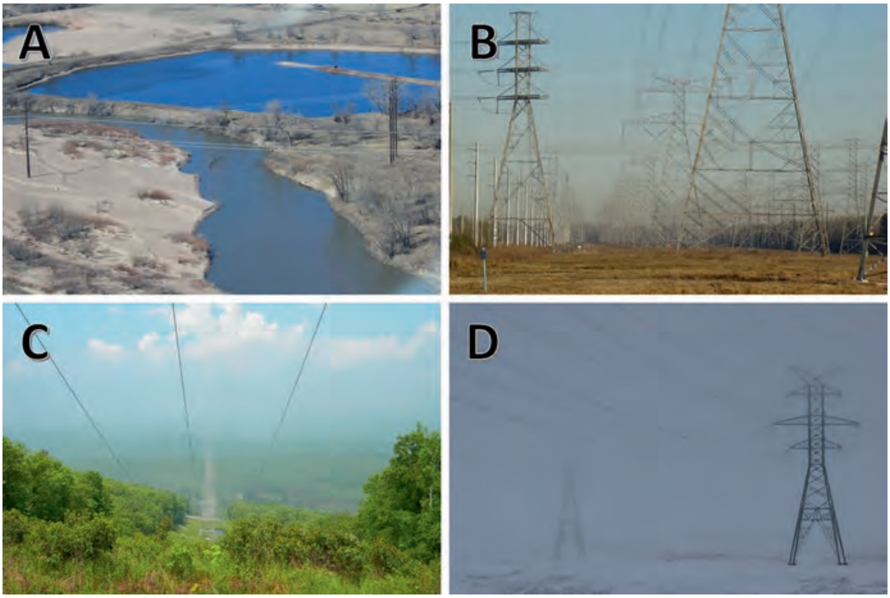

Fig. 13.3 Transmission line issues: (**a**) Transmission line bisecting a water source used by birds as a movement corridor. (**b**) Numerous transmission lines within a transmission corridor. (**c**) Overhead shield wires are less visible than conductors. (**d**) Transmission line partially obscured by fog

discussion of avian electrocution is available elsewhere in this book (in this book Chap. 12), this chapter does not address avian electrocutions.

Avian collision mortality is an ongoing global concern (Sporer et al. 2013; Rioux et al. 2013; Loss et al. 2014), though most research on the topic is not bird-of-prey-specific. Collisions involving transmission lines occur when a flying bird hits suspended wires, most often at night. Transmission lines are typically constructed with relatively thin overhead shield wires at the top and thicker energized conductors below. Birds appear to adjust flight altitudes upward to avoid large-diameter energized wires and then collide with smaller, less visible overhead shield wires (Murphy et al. 2016; Ventana Wildlife Society 2009; Martin and Shaw 2010). Transmission lines do not pose consistent risk. Rather, collision risk varies as a function of avian species and populations in the area of a given line, the surrounding habitat, and the line design (Bevanger and Brøseth 2004; Mojica et al. 2009; Rollan et al. 2010). Among birds, factors affecting collision risk include size, maneuverability, and flocking behavior (Jenkins et al. 2011; APLIC 2012). Transmission lines bisecting daily movement corridors, such as those located between roosting and foraging sites, also have been most associated with avian collisions (Bevanger and Brøseth 2004; APLIC 2012), with risk exacerbated during low-light, fog, and other inclement weather conditions (APLIC 2012; Hüppop and Hilgerloh 2012).

Birds of prey are at relatively low risk for power line collisions in general (SAIC 2000; Rioux et al. 2013), though large raptors with high wing loading and poor in-flight maneuverability like bustard species and condor species are collision prone.

In part, collision risk is low for birds of prey because they tend to fly diurnally during good weather (Ligouri 2005) and appear to detect and avoid transmission lines (Pope et al. 2006; Luzenski et al. 2016). Though risk for birds of prey is low compared to some other avian groups, collisions involving birds of prey do occur (Olendorff and Lehman 1986; Rollan et al. 2010, in this book Chap. 12). For example, California condors (*Gymnogyps californianus*) have collided with power lines (Snyder 2007), the Ventana Wildlife Society (2009) documented collisions by a northern harrier (*Circus cyaneus*) and a white-tailed kite (*Elanus leucurus*), and Mojica et al. (2009) documented multiple carcasses of bird of prey species (bald eagle (*Haliaeetus leucocephalus*), osprey, and owls) under distribution lines. Studies have shown certain African birds of prey are vulnerable to colliding with lines in foraging habitats (Boshoff et al. 2011; Rollan et al. 2010). Peregrine falcons can be at risk because they attain high speeds when pursuing prey near the ground (Olendorff and Lehman 1986). Mañosa and Real (2001) documented both collisions of breeding Bonelli's eagle (*Hieraaetus fasciatus*) and high turnover rates of pairs nesting within 1 km of power lines in Catalonia, Spain. González et al. (2007) documented infrequent collision as a cause of mortality in a study examining 267 records of nonnatural mortality of the Spanish imperial eagle (*Aquila adalberti*).

Indirect effects of transmission lines on birds of prey are not well studied but are likely low following initial disturbance and acclimation during and following construction given the fact that many birds of prey readily nest on or near transmission lines. Transmission lines can create corridors for human incursion into otherwise natural landscapes because maintenance access roads and rights-of-way may be used for recreational activities (hiking, running, mountain biking, cross-country skiing, all-terrain vehicles, etc.). Some bird of prey species respond negatively to recreational human traffic (Steidl and Anthony 1996), but no firm connection has yet been established to confirm widespread impacts with respect to power lines.

Power lines generate strong electromagnetic fields, UV discharges, and acoustic signatures which can affect animal health and behavior (Phernie et al. 2000; Tyler et al. 2014). Recent research suggests that avoidance by reindeer (*Rangifer tarandus*) may be linked to their ability to detect ultraviolet light emitted by transmission lines (Tyler et al. 2014). At least some birds also see in the ultraviolet spectrum (Lind et al. 2014), but the potential implications of this for indirect effects have not been investigated in birds of prey (in this book Chap. 12).

Offsite Effects

Offsite effects are indirect by definition. The natural resources used in constructing renewable infrastructure are typically harvested from areas well beyond the boundaries of renewable project sites. This has the potential to shift some of the environmental costs of renewable energy away from project sites where resources are used, to mine and factory sites where resources are extracted and processed. Consequently, offsite mining should be considered when developing a comprehensive understanding of potential impacts of renewable energy sources on birds of prey.

Effects of mines on birds of prey are site-specific and species-specific. For example, peregrine falcons and gyrfalcons (*Falco rusticolus*) breeding near two diamond mines in Northwest Territories, Canada, showed no difference in nest occupancy or breeding success as a function of distance from mine footprints, despite those footprints expanding during the study (Coulton et al. 2013). In contrast, prairie falcons (*Falco mexicanus*) in New Mexico appeared to avoid an entire mountain range where mining and blasting for various minerals was common but did nest in two adjacent ranges with similar habitats but less mining activity (Bednarz 1984). Mild responses to the vibration and noise associated with mining may derive from the occurrence of such natural events as thunder and landslides (Holthuijzen et al. 1990), with which birds of prey are presumably familiar both individually and over evolutionary time. Across studies, with few exceptions, evidence of disturbance by mining activity seems isolated and in some cases can be offset by relocating birds of prey nests prior to the advance of mine operations (McKee 2007). However, at least some mine sites likely included nesting territories prior to initiation of mining activities. In these cases, productivity from directly affected territories likely was reduced at least while affected individuals sought alternate nest sites. Even these impacts may be minimized, however, with measures specifically designed to support birds of prey populations, for example, through installation during reclamation of permanent structures designed to serve as nest substrates (Harshbarger 1997) and through the use of unreclaimed anthropogenic cliffs used for nesting (Moore et al. 1997). Mines also are associated with environmental pollution. Mining and smelting can lead to increased levels of lead in ospreys and American kestrels (*Falco sparverius*) nesting downstream (Henny et al. 1991, 1994) and in Eurasian eagle owls (*Bubo bubo*; Espin et al. 2014), though to our knowledge, definitive links to survival or productivity specifically related to mine sites have not been established. Though reductions in nesting attempts or productivity appear minimal overall, spills, pollution, and sedimentation from mine sites may have effects that are difficult to link conclusively to evidence of impacts specifically affecting birds of prey.

Though mining does have deleterious ecological consequences, and some examples involving birds of prey can be identified, overall it appears that offsite indirect impacts are either small or difficult to quantify and isolate (Anderson et al. 2008). Regardless of potential effects associated with renewable infrastructure, mined materials would also be necessary for fossil fuel extraction, which renewable energy facilities are designed to replace. That being so, it appears that indirect effects of extractive industries on birds of prey are minimal and offset by equivalent needs across energy sources.

Mitigation

Renewable energy facilities have the potential to bring together ecologically novel combinations of juxtaposed land covers like water bodies in deserts, prominent features like tall perches where none existed naturally, potential risks to wildlife like electrocution and mirror collisions, and potentially, unique combinations of species drawn to these features from their respective native habitats. Consequently, the removal and addition of biotic and abiotic materials at renewable energy facilities may require novel mitigation strategies applied to microclimates and biological communities which may not occur naturally. The rotor-swept zones of wind resource areas and the heated-air zones of solar tower collection areas have no natural analogues and thus no evolutionary context preparing wildlife for the risks encountered in these areas.

It should be incumbent on those creating these new landscapes, to also provide new and effective mitigation. With regard to mitigation of bird of prey mortalities at wind resource areas, innovative techniques are being developed to compensate for mortality at the renewable sites by mitigating the electrocution of birds of prey elsewhere (Fig. 13.4), creating a net benefit overall (USFWS 2013).

Wind energy facilities can also adjust turbine operations to prevent collisions by curtailing operations when birds of prey are flying within the wind resource area, and by increasing minimum operational wind speeds to wind speeds above those within which birds of prey generally choose to fly (USFWS 2013). At solar facilities with collection towers, successful mitigation involves spreading the aim points of mirrors apart to reduce the peak flux value to <4 kW/m^2 when the facility is in standby mode and not actively producing power (Multiagency Avian-Solar Collaborative Working Group 2016). For both wind resource areas and solar facilities, direct and indirect effects may be minimized by siting facilities away from

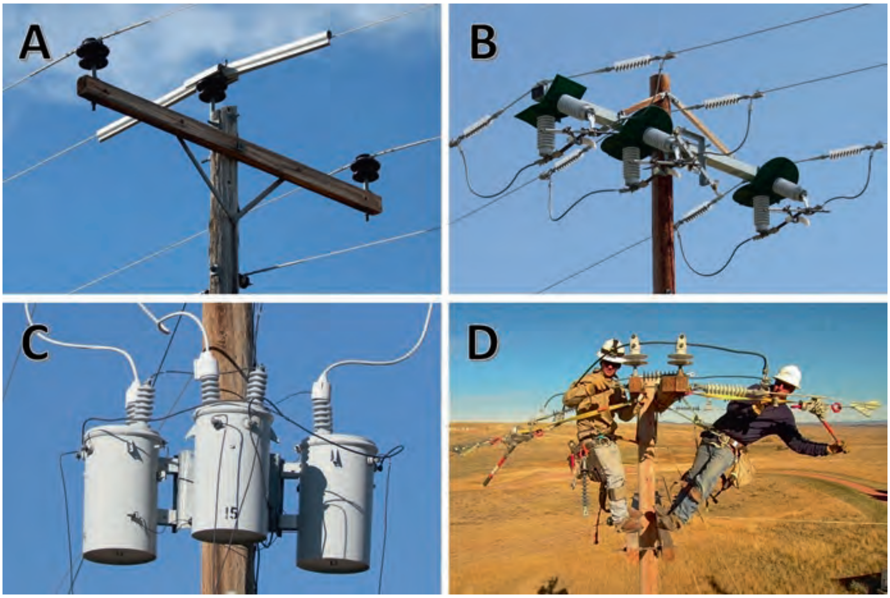

Fig. 13.4 Retrofitted power poles: (**a**) Insulation on center wire. (**b**) Insulation on connecting wires and on switches. (**c**) Insulation on connecting wires and on energized components of equipment. (**d**) Installation of insulation on equipment. (See in this book Chap. 12 for additional technical details on electrocution of birds of prey)

concentrated populations of birds of prey at migration, foraging, or roosting sites. Collisions involving birds of prey and transmission interconnections can be mitigated by marking transmission lines to increase their prominence to approaching birds of prey so lines can be avoided (in this book Chap. 12).

Unlike compensation programs for wind and solar energy, which are still in their infancy, compensation programs for biofuel monocultures are well established within a general framework of minimizing agricultural impacts to natural systems to the extent practical. Mitigation for biofuel monocultures may be achieved through existing mitigation programs, such as the US Department of Agriculture's Conservation Reserve Program which enables farmers to remove environmentally sensitive land from agricultural production in exchange for an annual payment. These types of programs tend to be successful if three obstacles can be overcome. First, because participation is voluntary, individual decisions may be influenced by the value of the payment compared to the value of potential crop yields. This mitigation strategy may lose effectiveness if demands for biofuels, and other crops competing in the market place for the same land, result in crop profits per acre that are greater than payments (Johnson and Stephens 2011). Second, compensation may undermine an individual's sense of responsibility for the land (Ramsdell et al. 2016), potentially resulting in a reduced sense of stewardship over the long term and enabling landowners to justify conversion of natural habitats if compensation programs terminate. Third, compensation programs may not be practical in developing countries lacking the necessary financial or political resources. Despite the potential obstacles involved in compensation-based mitigation programs, these solutions are nevertheless the best currently available, at least in areas like the USA where most arable farmland is privately owned and decisions affecting land use are primarily market driven. Though not necessarily focused on bird of prey concerns, these approaches often result in habitat patches that can contain hunting habitat or potential nest sites, creating focal locations which allow bird of prey populations to persist within areas dominated by agriculture.

Siting new facilities in previously disturbed habitat like nonproductive agricultural fields also can reduce impacts to birds from loss of breeding and foraging habitat (Pearce et al. 2016). Birds of prey can be intentionally displaced from solar projects when nesting sites are destroyed during construction. Burrowing owls (*Athene cunicularia*) have been successfully translocated to new breeding sites away from solar facilities (Multiagency Avian-Solar Collaborative Working Group 2016).

Benefits to Birds of Prey

Birds of prey also can benefit from renewable energy facilities and transmission linkages, primarily through provision of new nesting opportunities (Fig. 13.5) since birds of prey routinely nest on transmission structures. For example, bald eagles and osprey regularly nest on utility structures (Buehler 2000; Poole et al. 2002).

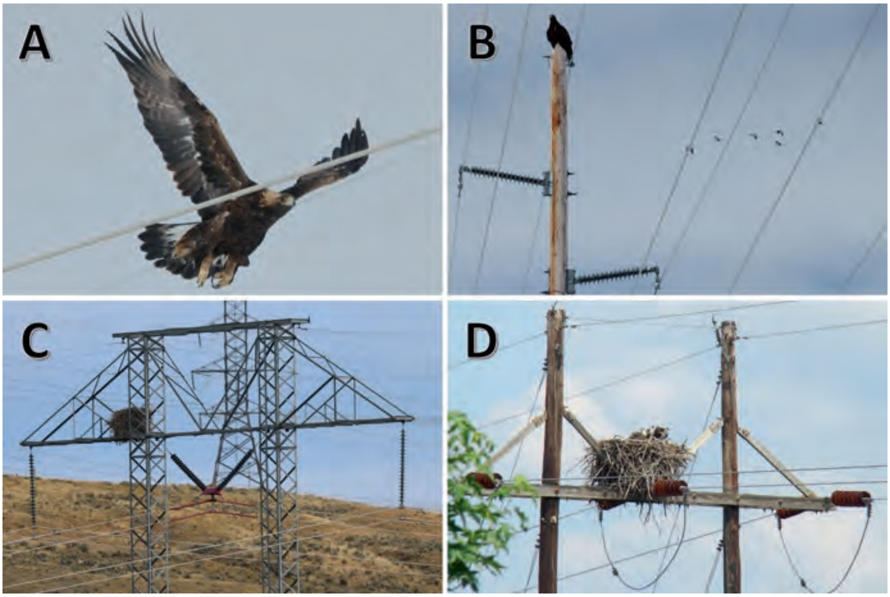

Fig. 13.5 (**a**) A golden eagle (*Aquila chrysaetos*) departing a transmission tower, potentially benefitting through hunting opportunities and, simultaneously, potentially at risk of collision with transmission wires. (**b**) A golden eagle roosting atop a transmission pole. (**c**) A golden eagle nest on a transmission tower. (**d**) An osprey (*Pandion haliaetus*) nest on a transmission H-frame structure

Other species nesting on utility structures include ferruginous hawks (*Buteo regalis*; Gilmer and Wiehe 1977), hobbies (*Falco subbuteo*; Puzović 2008), common kestrels (*Falco tinnunculus*; Krueger 1998), greater kestrels (*Falco rupicoloidesa*; Ledger and Hobbs 1999), martial eagles (*Polemaetus bellicosus*; Jenkins et al. 2013), prairie falcons (Roppe et al. 1989), lanner Falcons (*Falco biarmicus*; Ledger and Hobbs 1999), upland buzzards (*Buteo hemilasius*; Ellis et al. 2009), Swainson's hawks (*Buteo swainsoni*; James 1992), tawny eagles (*Aquila rapax*; Jenkins et al. 2013), black eagles (*Aquila verreauxii*; Jenkins et al. 2013), African hawk eagles (*Hieraaetus fasciatus*; Ledger and Hobbs 1999), and white-backed vultures (*Gyps africanus*, Ledger and Hobbs 1999). Though none of these were on renewable interconnections, the consistency between transmission structures in general and transmission structures supporting renewable interconnections specifically indicates that nesting is likely. Nesting habitat can also be created from mines providing new nest substrates for cliff-nesting birds of prey like peregrine falcons (Moore et al. 1997). Habitat conversion for dams and agriculture can also increase food availability for birds of prey because dams and reservoirs create aquatic habitat and provide abundant year-round food resources for birds of prey including water snakes (Tingay et al. 2010), waterbirds (Mukherjee and Wilske 2006; Mwaura et al. 2002), and stunned or dead fish flowing through dam spillways or turbines (Sánchez-Zapata et al. 2016).

Integrated vegetation management techniques employed in rights-of-way management for renewable energy interconnections can also play an important role in maintaining and improving habitat for wildlife (Ball 2012; Rogers 2016). These activities could create hunting habitat for birds of prey or be used as migration corridors (Denoncour and Olson 1982).

Other indirect benefits may also be important. The fundamental motivators of shifting global economies from fossil fuels to renewable energies are national energy independence and reduction of greenhouse gas emissions. Energy independence is perhaps irrelevant to birds of prey, but reduction of greenhouse gas emissions and global climate change do have substantial potential benefits for birds of prey. Global climate change is associated with increased frequency and intensity of weather events. Late spring and high-intensity weather events can directly impact the productivity and survival of birds of prey. For example, breeding success is negatively correlated with precipitation during nesting in peregrine falcons (Anctil et al. 2014; Burke et al. 2015). Survival of peregrines migrating south from the Artic is negatively correlated with climatic events suggesting the species is vulnerable to weather events along the migration route (Franke et al. 2011). Reduced impacts of climate change in general will likely reduce weather-related impacts on nesting birds of prey.

Conclusions

Ultimately, the large, widely dispersed territories of most birds of prey minimize the population impacts of either direct or indirect effects at most renewable energy facilities, transmission interconnections, or mines. This is because even if a specific territory is affected by a renewable energy facility, through habitat loss, for example, the effect is unlikely to have a population-level effect. There are exceptions however. For example, collisions involving migrating or wintering birds of prey with wind turbines can result in impacts dispersed throughout breeding ranges, and large-scale biofuel monocultures can result in elimination of habitat patches far larger than a single territory. These two areas of renewable energy advancement in particular warrant ongoing consideration, mitigation, and monitoring as renewable energy facilities expand into the habitats of birds of prey.

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EXHIBIT
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Original Research Article

The management utility of large-scale environmental drivers of bat mortality at wind energy facilities: The effects of facility size, elevation and geographic location

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ABSTRACT

Wind power development can cause direct mortality of both birds and bats through collisions with turbines, but the estimates of mortality necessary to evaluate the impact of this mortality are unavailable for many facilities and regions. We used monitoring surveys from the majority of facilities in a contiguous region spanning 800 km of southwest-northeast distance and almost 900 m of elevation (Quebec, Canada) to produce estimates of mortality per facility. The distribution of these estimated mortalities is skewed low with more than two thirds of facilities having annual mortalities of less than 50 individuals. We then used this set of estimated annual mortalities to explore how changes in installed capacity (megawatts), elevation and geographic position affected estimated annual mortality, with the goal of providing guidance to conservation mangers attempting to find strategies for minimizing mortality. More installed capacity (MW) correlated with higher mortality, but installed capacity alone was a poor predictor of estimated mortality. Medium-sized facilities were the best management strategy to minimize per MW mortality. Mortality decreased with increasing elevation and decreased from southwest to northeast within this region. The cumulative effects of this mortality have the potential to be devastating for bats, particularly migratory species, which account for the majority of carcasses observed. Our results also highlight the necessity of monitoring at all facilities in order to identify the small number of high mortality facilities for effective application of mitigation measures.

1. Introduction

Bats play a key role in Earth's ecosystems. In North America, ecological services provided by bats have been valued at $3.7 to $53 billion USD per year (Boyles et al., 2011). They are major predators of nocturnal insects and contribute to the regulation of epidemic outbreaks in agricultural fields and managed forests, as well as to the control of insects transmitting diseases to humans (Reiskind and Wund, 2009). Despite both their ecological and economic importance, however, bat populations are declining in many regions and it is essential that conservation measures effectively address mortality caused by human activities. In the north-eastern part of the continent alone, six species of bat have demonstrated a degradation of their

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conservation status since 2000 (Hammerson et al., 2017). To date, many threats and limiting factors facing bat populations have been identified, including white-nose syndrome, colony eradication, disturbance during hibernation, habitat loss, changes in forest structure, chemical contamination, decreases in insect abundance and wind turbines (Boyles and Brack, 2009; COSEWIC, 2013; Frick et al., 2010; Hickey et al., 2001; Johnson et al., 1998; Kunz et al., 1977; Mann et al., 2002).

Negative effects of wind power development include a loss or alteration of habitat caused by the construction, installation, and operation of wind power facilities (Kuvlesky et al., 2007) and direct mortalities of both birds and bats caused by collisions with the turbines themselves, principally the spinning blades, which are estimated to kill hundreds of thousands of bats annually (Arnett et al., 2008; Arnett and Baerwald, 2013; Hayes, 2013; Kunz et al., 2007; Orloff and Flannery, 1992; Smallwood, 2013). These numbers, combined with the swift and continued growth of the wind industry worldwide, have caused growing concern that some bat populations might be pushed toward extinction (Frick et al., 2017). The cumulative effects of bat fatalities at wind farms must, therefore, urgently be assessed in order to determine their impacts on bat populations.

However, estimating cumulative impacts is extremely difficult for two reasons. Firstly, accurate estimates of bat population sizes are lacking for most species world-wide (see, however, Frick et al., 2017). Secondly, accurate estimates of mortality at large scales are essential, and important variability in mortality estimates between facilities may impair our capacity to produce consistent estimates of mortality across large areas. In addition, although general guidelines are available (e.g., see Strickland et al., 2011), survey methodologies frequently differ between facilities or regions, further complicating our ability to accurately estimate cumulative impacts. Consequently, the three different studies that have estimated bat mortality caused by wind energy production in the contiguous United States reported results that ranged from 196 000 to 880 000 individuals killed annually (Arnett and Baerwald, 2013; Hayes, 2013; Smallwood, 2013).

Estimation of mortality at wind farms is a significant challenge. The number of carcasses observed around the bases of turbines represents a varying proportion of total mortality. For example, vegetation may influence the probability of carcass detection by observers, and predators may remove carcasses prior to the survey, thus reducing their probability of persistence through time. The number of observed carcasses must be adjusted using site- and year-specific correction parameters (Huso, 2011; Rogers et al., 1977). Furthermore, a wider understanding of bat mortality at wind farms should correct for potential bias due to different methodologies across facilities.

In addition, environmental factors may also influence mortality at spatial scales ranging from turbine-scale to regional- or continental-scale. For example, mortality is higher closer to roosting sites (Ferreira et al., 2015), maternity sites (Piorkowski and Connell, 2010), or migration corridors (Baerwald et al., 2014). One recent study found that mortality was inversely correlated with the proportion of grassland habitat surrounding wind energy facilities (Thompson et al., 2017). However, the specific role of environment in modifying mortality rates remains largely unexplored at these different spatial scales, as does the potential to mitigate impacts by avoiding higher-risk locations or habitats.

A better understanding of the impacts of environmental factors at the spatial scale of provinces/states is particularly important because this is the scale at which much of the regulation and management decisions are made. At a regional scale, geographic variables are often used to approximate habitat patterns. For example, elevation and latitude are responsible for many well-documented patterns of species distribution and ecology (e.g., Lomolino, 2001; Willdenow, 1805). Fatalities of bats have already been noted to decrease with increasing latitude in one region, the Northeastern Deciduous Forest (Arnett and Baerwald, 2013). A clear understanding of what correlates with high-risk facility placement at a regional scale could contribute to better regulation and management decisions, and ultimately favor the sustainable development of this industry.

To date, the majority of North American studies on bat mortality in wind-energy facilities have been conducted in the United States (but see Zimmerling and Francis, 2016). However, Canada is increasingly becoming a major player in wind energy production; the country is now ranked ninth in the world for its total installed onshore capacity with 12 816 MW as of December 2018 (Canadian Wind Energy Association, 2018). Canada mostly regulates wind farm projects at the provincial scale, and among the provinces, Quebec accounts for a third of the country's installed capacity (3882 MW in 2018). Additionally, in Quebec post-construction mortality surveys are required to be conducted using a standardized methodology. However, only one published study documented bat fatalities in this vast province and results were based on only three facilities whereas the province now has more than 30 facilities in operation (Zimmerling and Francis, 2016).

In this paper, we took advantage of the unique opportunity presented by having mortality surveys carried out using a standardized methodology at all facilities in a large contiguous area to document bat mortality within and across 30 wind farms. Lastly, we evaluated the effects of facility size, geographic position and elevation on annual bat mortality in order to determine whether these parameters could be used to inform management decisions. This study contributes to a better understanding of patterns in bat mortality associated with wind-energy facilities and helps managers to design effective and targeted mitigation measures to preserve threatened bat populations.

2. Material and methods

Eight bat species are found in Quebec. Five are resident in the province, roost in colonies in caves, mines, or buildings and are active from May until October: the northern myotis (*Myotis septentrionalis*), the eastern small-footed myotis (*Myotis leibii*), the little brown myotis (*Myotis lucifugus*), the tri-colored bat (*Perimyotis subflavus*) and the big brown bat (*Eptesicus fuscus*) (Clare et al., 2014; Fabianek et al., 2015, 2011; MMACH, 2018). Three species are tree-roosting and migratory, spending only the summer months in this region: the silver-haired bat (*Lasionycteris noctivagans*), the hoary bat (*Lasiurus cinereus*) and the eastern red bat (*Lasiurus borealis*). These migratory species are generally first detected in Quebec in May and gone by the end of September (MMACH, 2018). Quebec's wind energy facilities are distributed across almost 5 degrees of latitude and 10 degrees of longitude (almost 1000 km of distance southwest-northeast) and include facilities ranging from 0 to 900 m in elevation (Fig. 1).

2.1. Carcass surveys and data compilation

All data were gathered according to a standardized protocol published by the provincial government in Quebec in 2008 (MRNF, 2008) and subsequently updated (MDDEFP, 2013). This protocol stipulated that any new facility built was to conduct carcass surveys, carcass persistence trials and searcher efficiency trials seasonally for the first three years of operation and submit reports containing both results of surveys and trials as well as estimated fatalities to the provincial government. Among the differences between the original and updated protocols, the search interval between visits was reduced from 7 to 3 days, the surveyed area was reduced from 120 $\times$ 120 m to 80 $\times$ 80 m and the spacing between transects was reduced from 10 to 5 m. All details regarding the methodology can be found in the published protocols (MDDEFP, 2013; MRNF, 2008).

Searcher efficiency (p) trials were conducted during each season of monitoring (spring, summer and fall) using decoys (small bird- or mouse-type decoys). Each searcher efficiency trial involved placing the decoys inside the sampling plots at a facility before a regularly scheduled carcass search; decoys were placed by someone not involved in carrying out the carcass search. From 1 to 30 decoys were used per trial, with the majority of trials using between 5 and 10. No field data from Quebec exist that would allow estimation of the parameter describing how searcher efficiency changes through time for carcasses that are missed during a search (bleed-through sensu Wolpert). We therefore adopted the value of 0.674 suggested by Dalthorp and Huso (2017) as the best approximation.

Carcass persistence trials were also carried out once during each season of monitoring by placing carcasses (small mouse and bird carcasses) below turbines in areas to be searched and monitoring them until disappearance or for a maximum of 28 days. Fitting a model to the raw data and determining the underlying distribution is the best way to summarize carcass

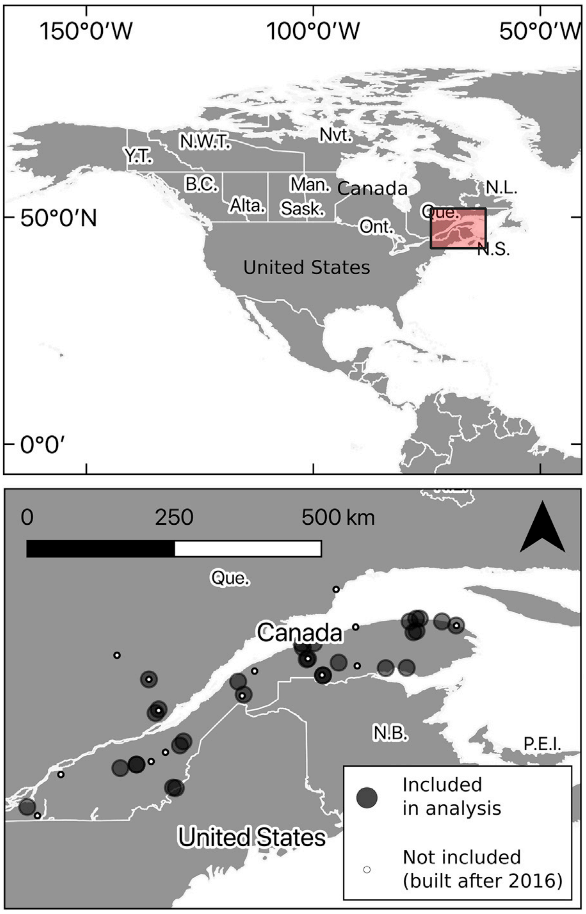

Fig. 1. Map of the study area in the province of Quebec (Canada). Wind-energy facilities are shown, distributed from the southwest to the northeast in the province.

persistence (Bispo et al., 2013). Very few surveys (15 of 65) reported raw data, however, so we parameterized a exponential distributions using the reported means ($\bar{t}$) and associated variances.

We estimated a spatial correction factor (a) that combined three sub-parameters: 1) the proportion of turbines monitored, 2) the proportion of area under each turbine that was included in carcass searches, and 3) the proportion of carcasses expected to fall into this searched area. We identified conservative values for the proportion of carcasses falling into concentric circular zones around the turbine base (60% from 0 to 40 m and 40% from 40 to 80 m) based on the published literature (Hull and Muir, 2010; Huso and Dalthorp, 2014; Korner-Nievergelt et al., 2016; Zimmerling and Francis, 2016).

The dataset available to us therefore comprised 65 annual carcass monitoring surveys carried out at 30 wind energy facilities (Fig. 1). This represents all but three facilities in operation in the province during and prior to 2015, although additional facilities have been built since (Fig. 1). The number of carcasses found per season, the searcher efficiency (p), the carcass persistence, a spatial correction factor (a) and an ordered sequence of consecutive search intervals (I) were extracted from each available report. Sometimes, parameters were missing for a particular survey (e.g., no trial for searcher efficiency carried out in the spring or no carcass persistence trial reported) and the nearest comparable estimate was used (e.g., results from a trial carried out in another year, or from a nearby facility; see Supplementary Material A for details).

2.2. Mortality estimates

2.2.1. Mortality estimates at the facility scale

We used the statistical package Evidence of Absence (eoa) to implement the Dalthorp estimator because low numbers of carcasses were found overall. Fewer than 10 surveys reported more than 15 bat carcasses and there were a large number of zero observations with 26 of 65 surveys finding no bat carcasses at all (Dalthorp, 2016; Huso et al., 2015; R Core Team, 2016). As suggested by Dan Dalthorp (personal communication), we used a three-step strategy to combine the season-specific correction factor estimates with reported carcass counts to produce estimates of mean annual mortality for each facility*-year combination. First, we used the Single Year Module to estimate a facility-specific global probability of detection (g_{season}) for each of the three monitored seasons (Spring [March 15th − June 1st]; Summer [June 1st − Aug 1st]; and Autumn [Aug 1st − Nov 15th]). Next, we used the Multiple Class Module to combine these three seasonal probabilities of detection into a single yearly probability of detection for each facility (g_{year}) using the expected proportion of carcasses arriving in each season to weight (DWP) the relative contributions of the seasons. We weighted the two monitoring seasons that covered reproductive and migratory periods (Summer and Autumn) with 45% of annual carcasses each, and the Spring period at 9% to represent early arriving or awakening individuals. The remaining 1% of annual mortality was attributed to the 'winter' falling outside of monitored periods. We recorded the median point estimate (M-50) from the discrete posterior distribution produced at this step, along with the yearly probability of detection and associated 95% confidence intervals. We then used the Multiple Years Module along with carcass counts (yearly totals) and the α (Ba) and β (Bb) parameters describing the distribution of yearly probabilities of detection (g_{year}) to produce an estimate of the average annual fatality rate (λ) and associated 95% Credible Intervals for each facility using all years of available data (years weighted equally; $\rho = 1$).

2.2.2. Mortality estimates at the regional scale

We estimated 95% Credible Intervals on combined annual mortality for the thirty facilities included in this study using the Multiple Class Module of the Evidence of Absence package. Although this module is designed to combine classes such as different types of vegetation, it can also be used to produce a single regional estimate using facilities as 'classes', since all facilities were monitored. This estimate weights the contribution of each facility (ρ) by the number of turbines installed. We also tried weighting facilities by estimated mortality; this produced results that were consistent with those obtained using size of facility and we therefore present only the results weighted by facility size. We then calculated mortality per MW using the total installed capacity accounted for by the facilities in this study (2777 MW). We used this per MW estimate of mortality in our region and the installed capacity per year to calculate one regional estimate for each of the 17 years (1999–2016; Canadian Wind Energy Association, 2016; TechnoCentre éolien, 2017). Lacking any species-specific correction parameters, we assumed that the proportion of carcasses found per species reflected the proportion of bats killed of that species to describe general trends of mortality per species in the region.

2.3. Large-scale environmental drivers of mortality

We then extracted installed capacity (megawatts) and geographic position directly from facility reports and elevation from the provincial government's digital elevation model using ArcGIS (Ministère d'énérgie et ressources naturelles, 2009). Pairwise analysis of explanatory variables revealed that longitude and latitude co-varied too tightly to include both in analyses (the most northerly facilities were also those furthest to the east; coefficient of variation 0.89). The facilities in our region were distributed along a gradient not only from south to north but simultaneously from west to east that follows the geography of the Saint Lawrence river, estuary and gulf; this gradient of geographic location represents a dominant geographic pattern in the region (Fig. 1). We therefore used a 'distance to the northeast' variable representing the linear distance from a chosen origin in the southwest of the province near Montreal (45.5 N, −73.5 W). This variable therefore represents geographic position along a southwest-northeast gradient; small values indicate facilities in the southwest of the province and larger values indicate increasing distance to both the north and east.

In order to examine the effects of facility size, elevation and geographic position on estimated mortality, we used the mortality estimates per facility (annual mortality estimated per facility for n = 30 facilities as the median of a discrete posterior distribution based on multiple years of surveys) as the response variable in an analysis of environmental factors. Since there is a portion of the variance in point estimates of mortality that depends on detection probability, we weighted mortality estimates within this analysis using global detection probabilities. Mortality estimates were distributed in a skewed manner with many low values and Poisson models were extremely over dispersed ($\hat{c}$ values > 30) so we used a negative binomial distribution with a log-link function. We tested which combination of our three environmental factors (MW, elevation and geographic gradient) best explained variations in mortality using a model selection framework based on corrected Aikaike's Information Criterion (AIC_c). We created a set of 8 models (Table 1); all models included a weights argument based on the global probability of detection at that facility (a relative ranking of global probabilities of detection). We fit a global model using the glm.nb function (MASS package) in order to estimate a global shape parameter (theta), verified model suppositions graphically, then used this theta parameter to refit negative binomial models using the glm function and calculate AIC_c values, delta AIC_c, and model weights for our candidate model set (Table 1). We retained all models having a ΔAIC_c of less than 2 (Burnham and Anderson, 2002) and used the AICcmodavg package (Mazerolle, 2015) to produce model-averaged estimates of parameters and predicted values.

3. Results

3.1. Carcass surveys and correction factors

The majority (72%) of the 268 carcasses found during surveys were migratory bats (Supplementary Material B). Of these, the most common species found was the hoary bat (47% of carcasses, found at 21 out of 30 facilities), while the silver-haired bat accounted for 18% of carcasses and the eastern red bat 6%. The three species of resident bat found during surveys (the big brown bat, the northern myotis and the little brown bat) together accounted for 18% of carcasses found overall, and were found at fewer facilities than the migratory species (7 out of 30 facilities for all resident species combined; Supplementary Material B). Two resident species (the tri-colored bat and the eastern small-footed myotis) were never identified in carcass surveys, although one individual of the tri-colored bat was detected outside of scheduled carcass surveys. Most carcasses were found in July and August (69%).

Searcher efficiencies ranged from 0.1 to 1; mean seasonal efficiencies were between 0.5 and 0.7. Reported carcass persistence values ranged from 0 to 25 days; mean values ranged from 3 to 8 days. Spatial correction factors ranged from 0.11 to 0.57 (mean ± 1 sd: 0.27 ± 0.11). Seasonal temporal correction factors ranged from 0.18 to 1 (mean ± 1 sd: 0.84 ± 0.18).

3.2. Mortality estimates

3.2.1. Mortality estimates at the facility scale

Mean annual estimated bat mortality per facility in Quebec ranged from 3 to 287 individuals while the upper limits of the 95% Credible Intervals ranged from 14 to 725 individuals (Fig. 3A–C). Mean annual mortality per MW ranged from 0.03 to 2.62 individuals. The distribution of these estimated mortalities was heavily skewed; more than two thirds of facilities had estimated mean mortalities lower than 100 individuals per year and only three had annual mortalities greater than 250 individuals per year.

The mean annual estimate was calculated from all available annual median estimated mortalities per facility (M-50), which were generally consistent between consecutive years of surveying at the same facility (Fig. 2A). Global probabilities of

Table 1
Candidate model set and AIC_c table for model selection testing the effects of installed capacity (MW), geographic position (Geog), and elevation (Elev) on estimated annual bat mortality (λ) per facility (n = 30 facilities). All models having a ΔAIC_c of less than 2 (shown in bold) were retained and used to produce model-averaged parameter estimates.

Model	K	AIC_c	ΔAIC_c	AIC_c weight	LL
λ ~ MW + Geog + Elev	**5**	**125.59**	**0.00**	**0.41**	**−56.55**
λ ~ MW + Geog	**4**	**126.06**	**0.47**	**0.32**	**−58.23**
λ ~ MW + Elev	**4**	**127.32**	**1.73**	**0.17**	**−58.86**
λ ~ Elev + Geog	4	130.47	4.87	0.04	−60.43
λ ~ MW	3	130.76	5.17	0.03	−61.92
λ ~ Geog	3	131.28	5.69	0.02	−62.18
λ ~ Elev	3	134.14	8.55	0.01	−63.61
λ ~ 1	2	137.43	11.84	0.00	−66.49

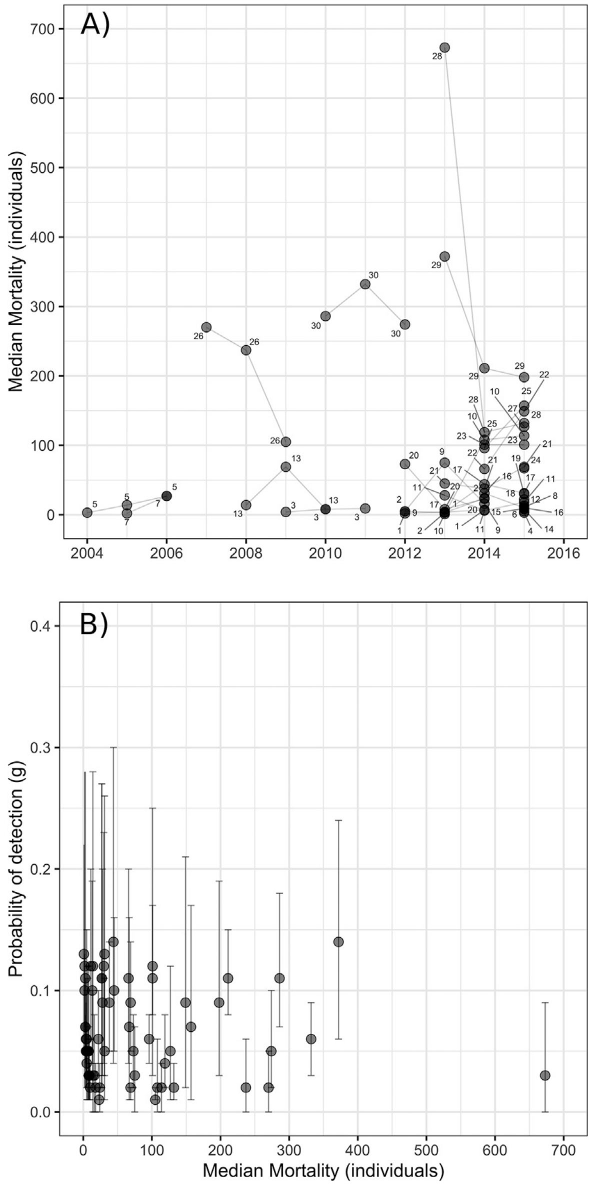

Fig. 2. (A) Median of the discrete posterior distribution of mortality per carcass survey. Facilities are identified (1–30) and consecutive years of surveys at the same facility indicated by connecting lines. (B) Probability of detection as a function of estimated mortality. Probabilities of detection, shown with 95% Confidence Intervals, are universally low (<0.3) but there is no relationship with median estimates of mortality.

detection (g) per facility*year combinations (n = 65 carcass surveys at 30 separate facilities) were very low (<0.3). However, there was no relationship between the point estimate of median mortality and the probability of detection (Fig. 2B).

3.2.2. Mortality estimates at the regional scale

Total bat mortality for 2016 in the province of Quebec falls within the 95% Credible Interval [4526, 6455], which gives an estimate of mortality per MW which falls in the interval [1.29, 1.84]. Lacking species-specific detection probabilities, the best we can do is assume that the relative proportion of carcasses found per species reflects the real proportions of species killed. If this is the case, 2016 mortality of hoary bats in Quebec (47% of carcasses) would fall in the interval [2128, 3035] individuals. At the other end of the spectrum, the eastern small-footed myotis and the tri-colored bat were never identified in carcass surveys; however, 11% of carcasses were not identifiable to species, accounting for [490, 699] individuals killed in 2016 alone. Using yearly installed capacities from 1999 to 2016, we estimated that cumulative mortality in Quebec since the first wind energy installations in this region up until 2016 falls within the interval [18 186, 25 941].

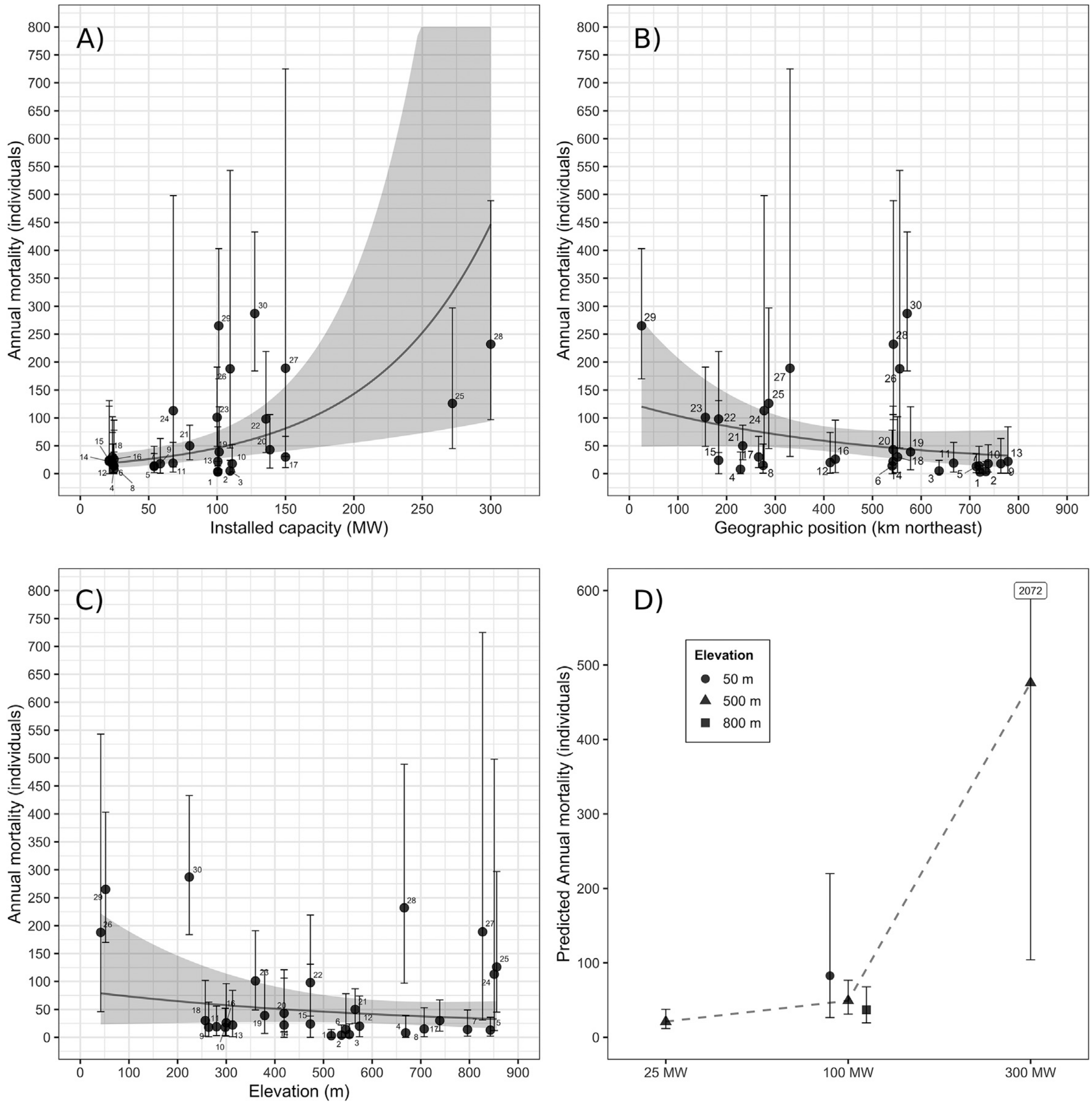

Fig. 3. Median point estimates of mortality and 95% Credible Intervals for each of the 30 facilities included in this analysis and model-averaged predictions for the effect of (A) installed capacity, (B) geographic position and (C) elevation on annual mortality. Facilities are identified (1-30) to correspond with Fig. 2 and supplementary material B. Solid lines are predictions based on the median values for the other two variables (100 MW median installed capacity; 495 m median elevation; 542 km median distance to the northeast) and shaded areas indicate the 95% confidence intervals around these predictions. (D) Predictions based on management scenarios are shown for three representative facility sizes (25 MW, 100 MW and 300 MW). For mid-sized facilities, three elevations are shown (50, 500 and 800 m). All predictions are for a median distance to the northeast (542 km).

3.3. Large-scale environmental drivers of mortality

The scale parameter (theta) for the global model was 2.13 indicating a manageable level of overdispersion and graphical model verification revealed no serious patterns in the residuals. The model selection based on AIC_c showed that three models had an important level of empirical support with $\Delta\ AIC_c < 2$ (Table 1). The three top models had an AIC_c weight of 90%, and all included installed capacity; the best-ranked model included all three variables ($AIC_cWt = 0.41$). Of the three variables, installed capacity had the strongest effect on bat mortality at wind energy facilities, with larger facilities having higher mortalities (Table 2; Fig. 3A).

In addition, facilities further to the northeast tended to have lower mortality than those to the southwest (Fig. 3B). Similarly, mortality tended to decrease with increasing elevation but the relationship was also weak (Fig. 3B). At low elevations (<250 m), mortality at two facilities was higher than expected by the predictions of model averaging and at high

Table 2
Model-averaged parameter estimates from models with Δ AIC$_c$ < 2 and upper and lower bounds of a 95% Confidence Limit for the main effects of installed capacity, geographic position, and elevation on annual bat mortality. Confidence Intervals that do not overlap with zero indicate significant effects.

	exp(β)	Lwr 95CL	Upr 95CL	units
Intercept	63.85	17.78	229.28	
Installed capacity (MW)	1.011	1.005	1.018	**megawatts**
Geographic position (Geog)	−0.998	−0.996	0.999	**kilometers**
Elevation (Elev)	−0.998	−0.997	−1.000	**meters**

elevations (>650 m), mortality at four facilities was higher than expected (Fig. 3C). The relationships with these three environmental variables appear to be weak at least partly because those facilities with higher than average mortality (the few facilities at the high end of the skewed distribution of mortality) are poorly predicted by the models.

4. Discussion

This study is unique both in having access to surveys following a standardized methodology within a large contiguous area, and in applying a single estimator appropriate for low or zero counts to all surveys. Although robust estimates of bat mortality due to wind energy at spatial scales relevant to bat populations are arguably a prerequisite for effective conservation actions, extrapolating single-facility estimates of mortality to regional or continental scales is often problematic. We found that per-facility bat mortality was influenced not only by installed capacity, but also by geographic position, and elevation. These results support the hypothesis that environmental variables and spatial context can drive variation in bat mortality, but also highlight that the few facilities with higher-than-average mortality are generally poorly predicted by these large-scale environmental variables. These results show the utility of using easily available facility descriptors such as elevation and geographic location as an inexpensive way for managers concerned about conservation to include basic environmental factors in considerations of mortality risk at wind energy facilities, but also point to the need for a more in-depth understanding of the determinants of higher-than-average mortality.

4.1. The skewed distribution of mortality among facilities: a small number of facilities account for a large proportion of regional mortality

Many wind energy facilities in our region had low estimated bat mortality (both annual and per Megawatt) and may be considered bat-friendly. This has important implications for monitoring and conservation; in particular, it indicates that monitoring at all facilities is critical in order to correctly identify those facilities with higher-than-average mortality and those facilities which are bat friendly. Effective regional or national management and mitigation measures should target those areas or facilities with high or potentially high mortality in order to have the most impact on reducing population-level mortality. Our estimate of the cumulative regional mortality for bats for the period from 1999 to 2016 was between 18 186 and 25 941 individuals. The majority of wind energy facilities in Quebec were built in the latter half of this period and the estimated regional mortality in 2016 alone accounts for approximately a fifth of this total cumulative mortality. The fact that several facilities contributed disproportionately to this mortality, however, while other facilities had both very low per Megawatt and annual mortalities, indicates that management, conservation and mitigation efforts should focus on those facilities with higher-than-average mortality. Accurate facility-by-facility estimates are therefore critical for effective conservation and management; this clearly points to the risk of using estimates from one or several facilities to extrapolate to unmonitored facilities or areas.

4.2. Regional context: large-scale environmental gradients as determinants of mortality

Many syntheses have noted variations in mortality among regions (e.g., Arnett and Baerwald, 2013). Differences in habitat availability and use and the placement of both wind energy facilities and individual turbines within facilities are likely to play a role in these differences. The results of the present study clearly show that environmental context has an important influence on mortality. Indeed, since the operational life of a facility is generally at least 25 years, and there is no plan to decommission any existing wind energy facilities over the short term (increases in installed capacity have occurred every year in this region), the estimated 2016 mortality can be used as a minimum annual mortality for future years, resulting in at least an estimated 45 260 to 64 550 bat mortalities for the next ten years in Quebec (2016–2025). This estimated mortality is low when compared to estimates produced for many other North American regions (e.g. (Arnett and Baerwald, 2013; Hayes, 2013; Smallwood, 2013; Zimmerling and Francis, 2016), and it is possible that Quebec, because it includes the northern limits of bat distributions in North America, represents a region with less bat habitat, lower population densities, and therefore lower observed mortalities overall. However, this cumulative mortality is still considerable when placed in the context of bat populations which are typically slow-growing and are facing many additional threats across their ranges.

Mortality within our study region is highest in the southwest and decreases to the northeast. The geography of the province of Quebec is dominated by the Saint Lawrence river, estuary and gulf, which extends from the southwest to the northeast. This creates a region-specific gradient of geography that contains elements of both latitude and longitude, and it is probable that the decrease in mortality further to the northeast corresponds to a regional gradient of habitat types. In the southwest of the province, agricultural areas and patches of deciduous forest dominate; this is part of the Mixedwood Plains ecozone. Further to the northeast, the river becomes the estuary and then widens into the gulf; the proportion of farmland decreases, and deciduous forests become mixed with more boreal coniferous habitats. This portion of the province falls within the Atlantic Maritime ecozone (Ecological Stratification Working Group, 1995). The significant effect of geographic position on mortality could therefore result from a decrease in high quality bat habitat in the Altantic Maritime ecozone as compared to the Mixedwood Plains ecozone. For example, large diameter trees, essential for cavity-roosting bats (Fabianek et al., 2015), are more common in the deciduous forests that dominate the Mixedwood Plains ecozone. Additionally, bat flight activity has been observed to be higher over trails and still bodies of water, and on the edges of forest stands (Krusic et al., 1996); all of these features are more abundant in the southwest of the province.

There is a well-recognized gradient in habitat with higher elevations having increasingly lower temperatures, precipitation and productivity (McCain, 2009; McVicar and Körner, 2013; Pan et al., 2016). Increasing elevations generally have lower proportions of agricultural land, fewer water features such as streams or lakes and fewer edge habitats between forest and meadow, all of which are important determinants of bat habitat use (Arnett and Baerwald, 2013; Rydell et al., 2010; Thompson et al., 2017). Mortality in our region decreased overall at higher elevations, but individual facilities with high mortality appeared to be either at low or high elevations, and not at mid-elevation sites. There did not appear to be a pattern in species-specific mortality (i.e., based on carcasses found, specific species or types – e.g., migratory bats - were not found principally at either low or high elevations); however, facilities with higher mortality tended to have more species represented in carcass surveys. This may indicate use of these sites by a larger number of bat species. In a recent study of bird diversity across an elevational gradient, temperature, precipitation and habitat heterogeneity were important determinants of species diversity (Pan et al., 2016). While both temperature and precipitation decreased with increasing elevation, habitat heterogeneity displayed a hump-shaped relationship with elevation (the highest habitat heterogeneity was found at mid-range elevations). Although the range of elevations examined in our study is much smaller than that in Pan et al. (2016), it is possible that a pattern wherein, for example, edge habitats or prime foraging areas are abundant at both low and high elevations could drive the observed pattern of bat mortality. Facilities with higher mortality at both high and low elevations may therefore be a result of increased probability of overlap between facilities and habitats used by multiple bat species. Our study provides evidence that elevation is indeed correlated with mortality and could therefore be used as a partial proxy for bat habitat. The relationship is not a simple one, however, and variability between individual facilities remains important.

4.3. *Management perspectives*

The best description of mortality in our region was not based on installed capacity alone; models including both elevation and geographic position were also retained in our model selection process. Indeed, it has already been suggested that mortality is correlated with aspects of both behavior and habitat use (e.g., foraging strategies) in both North America (Cryan and Barclay, 2009; Thompson et al., 2017) and Europe (Rydell et al., 2010). Our results indicate that using mortality per MW from one or several facilities as a basis for predicting the impact of unmonitored facilities will do a poor job of explaining patterns in mortality because it implicitly assumes that mortality can be linearly scaled based oninstalled capacity and ignores environmental differences between facilities. The relationship between installed capacity and mortality was not a clear-cut case of each successive increase in installed capacity resulting in an incremental increase in estimated mortality. Small facilities (25 MW) had low annual mortality; increasing capacity fourfold (100 MW) resulted in a doubling of estimated mortality, but further increases in capacity resulted in much larger increases in mortality. This may indicate that the larger a facility is, the more important specific spatial and environmental context becomes in determining bat mortality. The high variability among larger facilities is possibly due to differences in environmental factors such as proximity to roosting sites, migratory routes or foraging habitat, which then can magnify differences in mortality due to installed capacity, elevation and other large-scale habitat features. Some large facilities, however, have low mortality and others have very high mortality; from a management perspective, large facilities are therefore associated with a much larger gamble than multiple small facilities. Given the difficulty of obtaining and analyzing detailed spatial habitat information, our results show that even very basic environmental proxy variables such as elevation and geographic position can greatly increase our ability to explain variation in the magnitude of mortality between wind energy facilities. Using this approach to include basic information on environmental variables will allow managers to more clearly evaluate the potential mortality risk posed by proposed wind energy facilities.

From the perspective of minimizing bat mortality, our results indicate that mid-sized facilities are the best management scenario. Although annual mortality is slightly higher than at small facilities, the increase is negligible when compared with the added capacity (i.e., 1 facility of 100 MW has much less than 4× the mortality of a 25 MW facility) and the uncertainty in the upper threshold of the estimate (upper limit of the 95% Confidence Intervals) does not increase substantially. Large facilities, however, have much higher mortality and a large uncertainty associated with them (extremely high upper limit of the 95% Confidence Intervals) which indicates that they are a much riskier management scenario. Incorporating marginal decreases in mortality by targeting higher elevations and regions further to the northeast could then further reduce mortality at these medium-sized facilities.

5. Conclusions

This study is the first to document patterns of bat mortality in a contiguous region spanning 800 km of southwest-northeast distance and almost 900 m of elevation, where all facilities in the region were monitored. We showed that mortality was distributed unevenly among facilities and that cumulative mortality was relatively low as compared to other regions. In addition, we identified three predictors of bat mortality (installed capacity, elevation and geographic position) that can be used in combination by managers to more effectively take mortality risk for bat populations into account when planning wind energy facilities. We showed that: (i) more installed capacity (MW) does correlate with higher mortality, but that capacity alone is a poor predictor of estimated mortality; (ii) mortality overall decreased with increasing elevation; and (iii) mortality decreased further to the northeast. The small proportion of high risk facilities or those that observe high total bat mortality should be targeted for the application of mitigation measures during operation, in order to reduce impacts on bat populations. Although detailed information about habitat directly surrounding individual turbines may provide the best explanations of mortality, both elevation and geographical position provide useful proxies for environmental variation that can be used by mangers on provincial/state spatial scales before a more detailed understanding of how environment modifies mortality risk at the turbine scale is attained.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2019.e00871.

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EXHIBIT
6

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Fecal surveys reveal species-specific bat activity at wind turbines.

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Abstract

The reasons why bats are coming into contact with wind turbines are not yet well understood. One hypothesis is that bats are attracted to wind turbines and this attraction may be because bats perceive or misperceive the turbines to provide a resource, such as a foraging or roosting site. During post-construction fatality searches at a wind energy facility in the southern Great Plains, U.S., we discovered bat feces near the base of a wind turbine tower, which led us to hypothesize that bats were actively roosting and/or foraging at turbines. Thus over 2 consecutive years, we conducted systematic searches for bat feces on turbines at this site. We collected 72 bat fecal samples from turbines and successfully extracted DNA from 56 samples. All 6 bat species known to be in the area were confirmed and the majority (59%) were identified as *Lasiurus borealis*; a species that also comprised the majority of the fatalities (60%) recorded at the site. The presence of bat feces provides further evidence that bats were conducting activities in close proximity to wind turbines. Moreover, feces found in areas such as turbine door slats indicated that bats were using turbines as night or foraging roosts, and further provided evidence that bats were active near the turbines. Future research should therefore aim to identify those features of wind turbines that bats perceive or misperceive as a resource, which in turn may lead to new minimization strategies that effectively reduce bat fatalities at wind farms.

Keywords: attraction, bat-wind turbine interactions, DNA barcoding, roosting, wind energy

As the demand for renewable energy has grown, it has led to the rapid installation of wind power facilities worldwide. As a result, many utility-scale wind farms became operational before it was apparent that wind turbines could have a negative impact on bats (Arnett and Baerwald, 2013). Subsequently there have been reports of bat fatalities, many of which represent multiple mortality events, from operational wind facilities globally (O'Shea et al., 2016; Chou et al., 2017). The majority of these mortality events appear to involve highly mobile or migratory bat species that cover a large geographic range (Arnett and Baerwald, 2013; Lehnert et al., 2014; Roscioni et al., 2014) and can potentially be impacted by the cumulative effects of multiple wind farms (Roscioni et al., 2013). With continued wind energy expansion, there are increasing concerns that there could be population-level implications for bats (O'Shea et al., 2016, Frick et al., 2017).

Thus, understanding why bats are coming into contact with wind turbines is crucial if we are to implement minimization strategies that effectively reduce bat fatalities. One hypothesis proposed by Cryan and Barclay (2009) is that bat fatalities occur because bats are attracted to wind turbines. By identifying the source of the bats' attraction we could potentially devise more targeted minimization strategies that limit bat activity in proximity to wind turbines, which in turn would reduce bat fatalities. A possible explanation for why bats may be attracted to wind turbines is that the turbines themselves provide a resource(s) for bats, such as foraging, mating, or roosting sites (Horn et al., 2008; Rydell et al., 2016). In support of this rationale, Cryan et al. (2014) suggested that the bat behavior they observed on the leeward side of wind turbines was similar to bat behavior seen at tall trees; structures that would provide bats with roosting, foraging, and mating opportunities. Another study by Long et al. (2011) demonstrated that the light grey color of turbine towers and blades attracted insects, suggesting that wind turbines could serve as a foraging resource that would be attractive to insectivorous bats. Given that wind turbines could potentially provide or be misperceived to provide one or more resources, the next step would be to identify those features of wind turbines that could be attractive to bats. Moreover, as the resource requirements of bats are species-specific, the features of wind turbines that attract bats will likely vary among species (e.g., Ammerman et al., 2011).

For any bat species to be actively roosting and/or foraging at wind turbines, we would expect to find other signs or evidence of use by bats on or around the turbines, not just bat fatalities. For example, there are 3 signs that would indicate that bats are roosting at wind turbines: 1) the presence of roosting bats; 2) the presence of feces within or beneath a suitable roost site; and 3) staining, the brown patches left when bat urine evaporates beneath or on the walls of a roost site (Mitchell-Jones and McLeish, 2004). Furthermore, if bats were to frequently spend time, for example, foraging in close proximity to wind turbines we would expect fecal material to be deposited on the wind turbines and transformers. During post-construction fatality searches at a wind energy facility in the southern Great Plains, U.S., we discovered bat feces on a wind turbine tower. These observations led us to hypothesize that bats were actively roosting and/or foraging at the turbines. Thus over 2 consecutive years, we conducted systematic searches for bat feces around the bases of wind turbine towers at this wind facility to determine if any or all of the 6 bat species known to be in the area were active at turbines.

Our study site was Wolf Ridge Wind, LLC (33°43'53.5"N, 97°24'18.2"W) in the cross timbers and prairies ecoregion of north-central Texas. This facility, owned by NextEra Energy Resources, became operational in October 2008 and consists of 75 1.5-megawatt (MW) General Electric wind turbines (model GE 1.5xle) extended over 48 km^2. The wind turbines have a hub height of 80 m, blade length of 42 m, maximum tip height of 122 m, and are spaced at least 1 ha apart in a general east-west direction across open agricultural land used predominantly for cattle grazing (pastures), native hay harvesting, and winter wheat *Triticum aestivum* cultivation. There is an extensive shrub-woodland along the northern boundary of the wind resource area that leads down to the Red River escarpment. During a 5-year period (2009 to 2013) in which post-construction fatality monitoring took place at this site, 916 bat carcasses were collected (551 *Lasiurus borealis*, 258 *Lasiurus cinereus*, 3 *Lasionycteris noctivagans*, 22 *Perimyotis subflavus*, 49 *Nycticeius humeralis*, 30 *Tadarida brasiliensis*, and 3 unidentified bats; Bennett and Hale 2014), and species identifications were confirmed using DNA barcoding (Korstian et al., 2016).

From July to November 2011 and April to October 2012, we searched all 75 wind turbines for bat feces. These searches were conducted once a week over 2 consecutive days, in which half the wind turbines were searched the first day and the other half were searched on the second. Searchable areas at the wind turbines were separated into 3 sections: 1) the turbine tower (up to 3 m from the ground), stairs, and associated concrete pad; 2) the turbine door; and 3) the transformer and associated concrete pad. We then divided each of these sections into specific zones, parts, or sides. The turbine tower was divided into 5 zones, comprising four quarters of the turbine tower (i.e., zone 1 started after the stairwell next to the transformer), and the stairwell area leading to the turbine door (zone 5). The turbine door was divided into 4 parts including the door frame and light fixture, door face, and 2 sets of slats in the door face (an upper and lower set). Finally, the transformer next to the turbine tower was divided up by its 4 sides and top.

Searching for bat feces, we slowly walked around each wind turbine and transformer making sure we inspected 1) the door slats and gills of transformers (i.e., sides 1, 2 and 4), 2) the surface of the turbine tower, stairwell, door, light fixture, and flat surfaces of transformers (i.e., side 3 and the top), and 3) all areas with concrete, including the 0.5 m wide concrete pad surface surrounding the base of the turbine tower and 0.25 m wide concrete platform of the transformer. Once found, we placed bat fecal pellets in 1.5 ml plastic tubes and stored them at room temperature.

We extracted DNA from each fecal sample collected using the QIAamp DNA Stool Mini-kit (Qiagen Genomics, Valencia, CA). A negative control was used with each round of extraction to ensure that the extraction reagents used were not contaminated. All extractions were completed in a dedicated extraction AirClean® 600 PCR workstation to minimize contamination and the subsequent polymerase chain reactions (PCR) were conducted in a separate dedicated PCR workstation. We employed the DNA barcoding procedure described in Korstian et al. (2015) to identify each fecal sample to species. We reviewed species composition and explored whether there were any trends or species-specific patterns in the locations where fecal samples were found on wind turbines and across the wind facility.

Each of the 75 wind turbines was surveyed 53 times (22 in 2011 and 31 in 2012) for a total of 3,975 searches. Fecal samples were found in 29 of the 53 weeks the turbines were searched. We collected a total of 72 bat fecal samples from the surfaces of turbines, transformers and associated concrete pad. The most samples per month were found in July in 2011 (n = 24) and May and June in 2012 (n = 13 and n = 16, respectively), while all other months had <10 samples. DNA was successfully extracted from 56 of these samples (i.e., 78%). The DNA in the remaining 16 bat fecal samples was found to be degraded and could not be processed successfully to identify species.

Among the samples that were identified to species, all 6 bat species known to be in the wind resource area were confirmed: *Lasiurus borealis* (n = 33 samples), *Lasiurus cinereus* (n = 4 samples), *Lasionycteris noctivagans* (n = 2 samples), *Perimyotis subflavus* (n = 7 samples), *Nycticeius humeralis* (n = 9 samples), and *Tadarida brasiliensis* (n = 1 sample). Fecal samples from *Lasiurus borealis* comprised the majority (59%) of the 56 samples.

We found bat feces in all searched areas of the wind turbines, except for the lower slats of the door (Fig. 1). Nineteen fecal samples (26% of the 72) were collected from between the upper slats of the door, between the gills of the transformer, on the frame beneath the gills of the transformer, and beneath the stairwell on the plastic-covered steel rods anchoring the base of the turbine tower. Note that in order for fecal samples to be in these locations, bats would have to physically be within the structures as it is not possible for wind or water to have moved the feces into such locations. Species composition of the fecal samples in these locations comprised

Lasiurus borealis (n = 8 samples), *Perimyotis subflavus* (n = 4 samples), *Nycticeius humeralis* (n = 3 samples), *Tadarida brasiliensis* (n = 1 sample), and unknown bats (n = 3 samples).

Of the 75 wind turbines searched, we found bat feces on 41 of them: 20 wind turbines had 1 fecal sample, 13 had 2 samples, 6 had 3 samples, and 2 wind turbines had 4 fecal samples collected from them (Fig. 2). The bat fecal samples were widely distributed on turbines across the wind facility, ranging from wind turbines in close proximity to wooded areas to turbines in open cattle pastures. With regards to species-specific patterns, fecal samples from *Lasiurus borealis* were found throughout the site, whereas fecal samples from *Nycticeius humeralis* appeared to be concentrated in 2 areas, one at the western end of the wind farm and a second towards the center of the wind farm. Fecal samples from *Perimyotis subflavus* were primarily found at turbines near the scrub-woodland area located towards the center of the wind farm. Finally, despite the low number of fecal samples found for *Lasiurus cinereus* and *Lasionycteris noctivagans*, these appeared to be distributed across the wind facility.

The presence of bat feces provides further evidence that bats are conducting activities in close proximity to wind turbines. Furthermore, DNA analysis of the fecal samples confirmed that all 6 bat species known to occur in north-central Texas were active at wind turbines and concurs with fatality data reported at our study site. As expected, the majority of fecal samples were identified as *Lasiurus borealis* (59%), corresponding with the proportion of *Lasiurus borealis* carcasses found in fatality monitoring surveys at the site (60%; Bennett and Hale, 2014).

Our findings appear to support the attraction hypothesis and contribute to the mounting evidence that bats are conducting activities, such as foraging, at wind turbines (Horn et al., 2008; Rydell et al., 2016). As bat feces are small (<5 mm in length) and relatively light weight, the likelihood that pellets will be deposited onto searchable areas of a wind turbine is inevitably very low. In addition, there are numerous instances that occur during any given search interval that can remove or destroy feces. For example, over the 2 years we conducted weekly searches, the site experienced rain showers, thunderstorms, and moderate to high winds on a regular basis. The consequence of these events ultimately reduced our ability to successfully locate and collect fecal samples. Furthermore, the ecology of each bat species can also influence our ability to find feces. For example, 3 of the species identified in this study, *Lasiurus cinereus*, *Lasionycteris noctivagans*, and *Tadarida brasiliensis*, are known to forage at greater heights (i.e. above tree canopy height) than *Lasiurus borealis*, *Perimyotis subflavus*, and *Nycticeius humeralis* (Ammerman et al., 2011). Again, the higher bats fly, the less likely fecal pellets will be deposited onto the searchable areas of the wind turbines. Thus, as we were able to retrieve 72 fecal samples during our surveys, including feces from the 3 high-flying bats, it is a testament to the amount of bat activity that occurs in close proximity to wind turbines. In other words, it indicates that bats, in particular *Lasiurus borealis*, the species most frequently found in fatality searches at this site, are active at wind turbines (Bennett and Hale, 2014).

Moreover, the location of bat feces may indicate bats are using wind turbines as roost sites. We found fecal pellets in between the upper slats of the door, between and beneath the gills of the transformer, and on rods under the stairwell; an indication that bats were likely hanging in or above these areas. For most insectivorous bats, there are 2 general types of roost site: 1) day roosts and 2) night or feeding roosts. Day roosts, as the name suggests, are used by bats during the day and their purpose is to protect bats (and potentially their young) from exposure to the elements (i.e., inclement weather conditions, sunlight, and overheating) and from predators (Agosta et al., 2005; Knight and Jones, 2009). Given that the aforementioned areas from which we collected bat feces do not offer protection from the elements, it is more likely that these areas act as night roosts. Night or feeding roosts can be more exposed, as bats use these sites to simply hang and digest food between successive foraging bouts at night (Agosta et al., 2005; Knight and Jones, 2009). Thus, the slats of the doors, gills of the transformer, and the area under the stairwell all represent suitable night roosting opportunities. Furthermore, behavioral surveys using night vision technology undertaken by McAlexander (2013) noted 5 instances over 80 survey nights in which bats were observed entering or exiting the slats of doors or gills of the transformers where the bats remained beyond the length of the survey trial (10 mins) or had been prior to the start of the survey trial, respectively. These observations appear to support our findings that bats are using these structures as night roosts. In contrast, over a 5-year period in which standardized fatality monitoring surveys were conducted every other day during the bat activity season (July to September), we also searched the turbine door, stairwell, and gills of the transformer for live bats. Among these fatality monitoring surveys along with the two years of fecal surveys, we only reported the presence of live bats on a turbine once (V. J. Bennett and A. M. Hale, Texas Christian University, unpublished data). On this occasion, 4 *Tadarida brasiliensis* were found in the upper slats of the door and immediately flew away as we approached the turbine door. Note we also found 2 additional *Tadarida brasiliensis* fatalities at this turbine during that fatality monitoring survey not far from the stairwell. As *Tadarida brasiliensis* only make up a small proportion of the fatalities at our site, we considered this finding to be an unusual event. Thus, if indeed bats were effectively able to use wind turbines as day roosts, we would likely have more observations of bats roosting in wind turbines at our site during the day.

Finally, we found that the distribution of fecal samples from wind turbines across the wind facility varied by species. For example, fecal samples from *Lasiurus borealis* were collected at wind turbines in areas that had available resources such as scrub-woodland, and from areas that provided little or no obvious resources (i.e., wind turbines located in open agricultural fields). In contrast, for species such as *Perimyotis subflavus* and *Nycticeius humeralis*, fecal samples were more frequently collected from wind turbines near areas with potential resources (i.e., the scrub-woodland habitat). These observations in all three species also concur with patterns in species-specific fatalities recorded at our site, thus demonstrating that the locations of feces, and therefore where bats are active at wind turbines, correspond with bat fatalities.

Our study provides further evidence that bats are active at wind turbines as they appear perceive or misperceive them to provide a resource and may therefore be attracted to the turbines. Future studies should therefore focus on identifying the specific characteristics of wind turbines that underlie these perceptions in bats and determine if it is possible to alter these features so that bats show little or no interest in them. For example, Gorresen et al. (2015) are investigating how to use low-level ultraviolet lighting as a way to help bats discern between wind turbines and trees and Bienz (2015) has been conducting research to develop a texture coating that may be used to prevent bats from potentially perceiving wind turbine towers to be a foraging or water resource. Such information may then be used to devise minimization strategies that can be implemented to limit bat activity at wind turbines, thereby reducing bat fatalities at wind energy facilities.

Acknowledgements

This work was supported by NextEra Energy Resources [grant number 23186]. Thank you for their support of the TCU-NextEra Wind Research Initiative. Additional thanks go to the staff at Wolf Ridge Wind, LLC who were always helpful and supportive. We also thank the Department of Biology and the Institute for Environmental Studies at TCU for technical and logistical support. Finally, we would like to thank the many people who were involved with the project including M. Slattery for making this project possible, D. Cochran and L. Wyatt for helping with field surveys, and A. Schildt and J. Korstian for conducting the genetic lab work that contributed to our findings.

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FIGURE CAPTIONS

Figure 1 Number of bat fecal samples collected from searchable locations on wind turbine towers, transformers, and doors at Wolf Ridge Wind, LLC in north-central Texas. Solid color represents fecal samples that were collected from wind turbine surfaces, whereas dots identify feces that were found in structures associated with wind turbines, such as between the slats in the door.

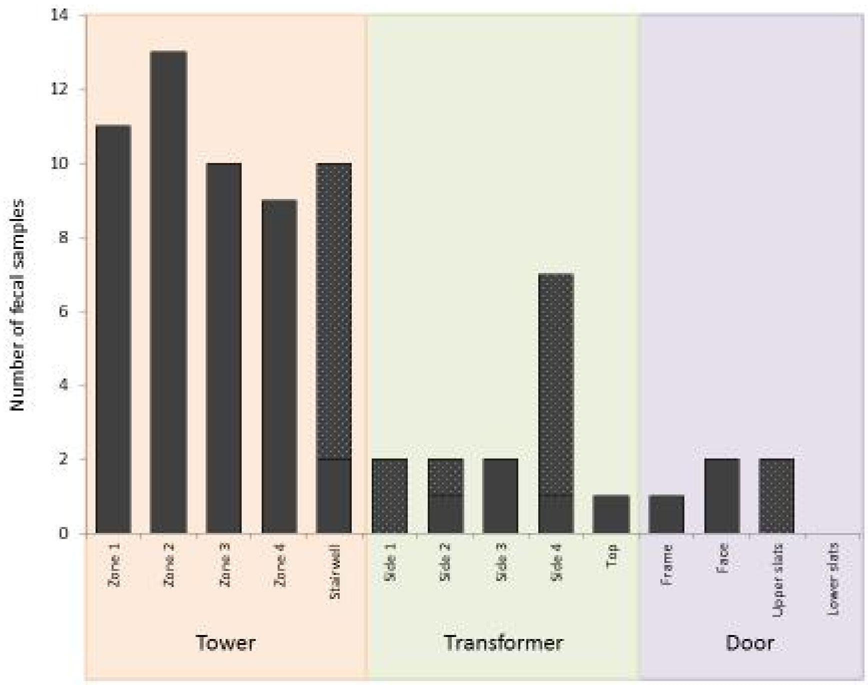


Figure 2 Number of bat fecal samples by species found on wind turbines at Wolf Ridge Wind, LLC in north-central Texas.

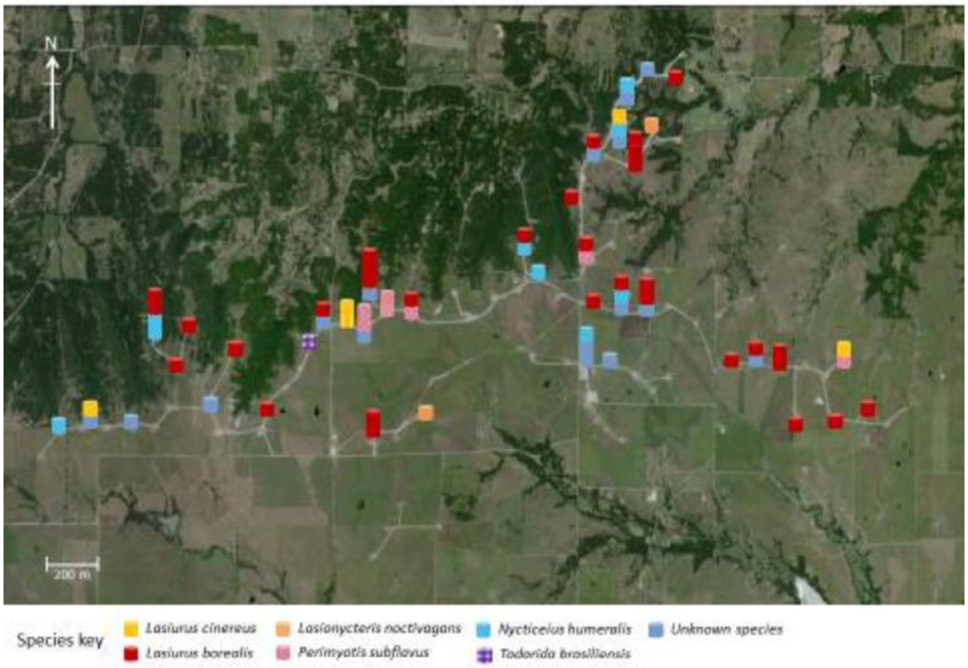


EXHIBIT
7

dBF Associates, Inc.
3129 Tiger Run Court, Suite 202
Carlsbad, CA 92010
619-609-0712

February 3, 2020

Donna Tisdale
Backcountry Against Dumps, Inc.
P.O. Box 1275
Boulevard, CA 91905

Re: Campo Wind Project
Noise / Acoustical Review

Ms. Tisdale:

dBF Associates, Inc. was retained by Backcountry Against Dumps, Inc. to review the following documents:

- Draft Environmental Impact Report for the Campo Wind Project with Boulder Brush Facilities. Dudek. December 2019.
- Draft Acoustical Analysis Report for the Campo Wind Project with Boulder Brush Facilities. Dudek. December 2019.
- Campo Wind Project with Boulder Brush Facilities – DEIR Appendix G (Noise) Addendum. December 3, 2019.

Our comments are presented below.

1. In the Acoustical Analysis Report (AAR) for the May 2019 DEIS, the project description included up to 60 wind turbine generators producing up to 4.2 megawatts (MW). The current AAR does not describe the proposed turbine power generation capability. The current AAR Section 6.1.3.1 indicates that its modeling methodology uses sound level data associated with General Electric (GE) 2.X-127 60 Hz model wind turbines, which are turbines producing between 2.0 and 2.9 MW. The AAR should use sound level data associated with the proposed turbines or justify the use of alternate data. This concern was noted in our comments on the Campo Wind DEIS dated July 2019, and has not been addressed.

   The octave band sound data is presented on page 1 of AAR Appendix B. However, the GE source document for this data is not included in the report. This document does not appear to be readily available to the public. The AAR should include its source sound level data reference(s) as an appendix. This concern was noted in our Campo Wind DEIS comments dated July 2019, and has not been addressed.

2. AAR Section 4.2.3 cites "An Ordinance Amending the San Diego County Zoning Ordinance Related to Wind Energy Turbines", the text of which has been incorporated into the County Zoning Code.

   County Zoning Code Section 6952(f)(3) states:
   Pure Tone. If the sound from a large wind turbine while operating contains a steady or intermittent pure tone, such as a whine, screech or hum, the applicable standards for noise set forth in County Code section 36.404 shall be reduced by five dBA. A "pure tone" exists if one-third of the octave band sound pressure level in the band, including the tone, exceeds the arithmetic average of sound pressure levels of the two contiguous one-third octave bands by five dBA for center frequencies of 500 Hz or more, by eight dBA for center frequencies between 160 Hz and 400 Hz, or by 15 dBA for center frequencies less than or equal to 125 Hz.

   The GE Product Acoustic Specifications for its 1.7-103 with LNTE (Low Noise Trailing Edge) and 3.6-137 Wind Turbine Generator Systems include one-third octave band sound data. The equipment manufacturer for this project should provide one-third octave band sound data for the proposed turbines.

   The AAR should evaluate pure tone noise, as directed by the County of San Diego Wind Energy Turbine (WET) Guidelines, as a threshold of significance.

   This concern was noted in our Campo Wind DEIS comments dated July 2019. The AAR has been updated to take note of the requirement, but does not contain any analysis or further discussion.

3. The previous AAR utilized ambient noise level measurements conducted with Soft dB Piccolo ANSI Type 2 sound level meters (SLMs), which are incapable of accurately measuring sound levels below 37 dB.

   The current AAR utilizes updated ambient noise level measurements conducted with ANSI Type 1 SLMs in most locations. At several locations – LT-3, LT-6, LT-8, LT-9, LT-10, LT-11, and BBF-LT-8, the updated ambient measurements reported higher ambient noise levels than in 2018.

   The current AAR incorrectly bases impact findings on the higher ambient noise levels. Despite the limitations of the Type 2 equipment, the 2018 measurements demonstrate that the ambient noise environment can be quieter than characterized by the 2019 measurements. Using the louder of the measured levels understates potential impacts.

In particular, the 2019 survey found that the noise levels at LT-9 and LT-11 were 13 dBA higher than in 2018. However, both of these deployments experienced technical difficulties. Given this large discrepancy and the circumstances, this data should be discarded and the measurements repeated.

4. GPS coordinates of ambient noise level measurements were added to the current AAR; however, site photographs were not included.

   At several locations, the microphone positions were not representative of ambient noise levels near NSLUs.

   a. At LT-1, the meter was placed approximately 50 feet from BIA Route 10, one of the two primary on-reservation roadways used by residents and border patrol agents. Homes in this area are generally over 500 feet from roadways.

   b. At LT-2, the meter was placed less than 25 feet from a long driveway road, and approximately 130 feet from a rail line.

   c. At LT-3, the meter was placed less than 10 feet from BIA Route 15, one of the two primary on-reservation roadways used by residents and border patrol agents. Homes in this area are over 200 feet from roadways, and often over 500 feet away.

   d. At LT-6, the meter was placed less than 15 feet from Miller Valley Road, the sole access road for at least nine homes. Homes in this area are generally over 250 feet from roadways.

   e. At LT-7, the meter was placed approximately 55 feet from the centerline of Old Highway 80, a 55-mph major thoroughfare in the area. There are several NSLUs in the area at a similar distance from this roadway, but many more are much further.

   f. At LT-8, the meter was placed less than 15 feet from Tusil Road (BIA Route 12). Homes in this area are generally more than 100 feet from roadways.

   g. At LT-11, the meter was placed approximately 55 feet from BIA Route 10 (Church Road), one of the two primary on-reservation roadways used by residents and border patrol agents. Homes in this area are generally over 250 feet from roadways, and often over 500 feet away.

   h. At LT-12, the meter was placed approximately 25 feet from Manzanita Road. Homes in this area are generally over 500 feet from roadways.

i. At LT-13, the meter was placed less than 5 feet from Tierra Del Sol Road, a roadway utilized by several residents and border patrol agents. Homes in this area are generally over 100 feet from roadways.

These microphone placements overstate the ambient noise environment and consequently underreport project noise impacts. The AAR should repeat these measurements at locations acoustically equivalent to NSLUs, and sufficiently removed from known transportation noise sources.

5. AAR Section 6.1.3 states "Comparison of predicted results between the CadnaA models and these Excel-based techniques at many geographic locations around and within the Project site exhibit differences of less than +/-3 dB, which is barely a perceptible difference."

   Underprediction of project noise levels by 3 dB, while barely perceptible, is meaningful. Project noise levels that are higher than predicted by 3 dB would result in impacts during several more conditions than reported in the AAR. The AAR should utilize multiple CadnaA models rather than spreadsheets, or the AAR should provide the spreadsheets as an appendix.

   This concern was noted in our Campo Wind DEIS comments dated July 2019, and has not been addressed.

6. AAR Section 6.2.2 presents wind turbine sound levels as a function of wind speed. The AAR does not discuss the wind turbine noise frequency spectrum consistency over the range of wind speeds. GE provides acoustical specifications in technical documentation for some wind turbine generator systems; these specifications show that their wind turbine noise frequency spectrums vary as a function of wind speed. The AAR modeling should use wind turbine noise frequency spectrums for each wind speed condition.

   This concern was noted in our Campo Wind DEIS comments dated July 2019, and has not been addressed.

7. AAR Section 6.3 and 6.4 find that impacts based on exceedances are expected during certain wind conditions. However, the AAR does not express the amounts or percentages of time that impacts would occur. The AAR should report, in unambiguous terms, how often impacts would occur.

   This concern was noted in our Campo Wind DEIS comments dated July 2019, and has not been addressed.

8. AAR Section 6.3.2 states "As locations of On-Reservation NSLU locations cannot be confirmed…"

   Locations of most or all on-reservation residences and any other NSLU should be readily available from tribal documentation. Alternatively, most on-reservation structures are clearly identifiable on publicly available aerial photography maps.

   In addition, the representative locations used to evaluate impacts do not indicate or approximate the number of represented NSLUs.

   The AAR should identify the quantity and locations of On-Reservation NSLUs.

   This concern was noted in our Campo Wind DEIS comments dated July 2019, and has not been adequately addressed. This omission potentially under-represents the scope of potential impacts.

9. Some measurement positions are not appropriate for use as impact evaluation locations.

   a. There is at least one home near LT-3 that is markedly closer to the proposed turbines than the measurement position.

   b. There are at least six homes or other structures near LT-4 that are markedly closer to the proposed turbines than the measurement position.

   c. There are at least four homes near LT-6 that are markedly closer to the proposed turbines than the measurement position.

   d. There are dozens of homes near LT-7 that are markedly closer to the proposed turbines than the measurement position. In particular, there are approximately six homes north of Hi Pass Road, on off-reservation land, that are poorly represented by LT-7. Further, there is a large congregation of NSLUs in the Live Oak Springs area; this is not properly evaluated.

   e. There are at least two homes near LT-8 that are markedly closer to the proposed turbines than the measurement position.

   f. There are at least eleven homes near LR-11 that are markedly closer to the proposed turbines than the measurement position.

      The analysis should evaluate the project noise levels at the closest potential NSLU(s).

In its current form, the analysis underpredicts project noise levels at NSLUs and underreports the severity and quantity of project noise impacts.

This concludes our review. Should you have any questions regarding the information provided, please contact me at (619) 609-0712 ×102.

Steven Fiedler, INCE
Principal

EXHIBIT
8

dBF Associates, Inc.

February 3, 2021

Donna Tisdale
Backcountry Against Dumps
PO Box 1275
Boulevard, CA 91905-0375

Re: Noise/Acoustical Review for the Campo Wind Project with Boulder Brush Facilities

Dear Ms. Tisdale,

dBF Associates, Inc. was retained by Backcountry Against Dumps ("Backcountry") to provide an independent technical review of the analysis of noise impacts prepared for the Campo Wind Project with Boulder Brush facilities ("Project"). This included (1) conducting measurements of noise levels in the vicinity of the Project site, and (2) reviewing the following documents:

- The Draft Environmental Impact Statement ("DEIS") for the Project,
- The Draft Acoustical Analysis Report ("AAR") for the Project,
- The Final Environmental Impact Statement ("FEIS") for the Project, and
- The Campo Wind Project with Boulder Brush Facilities – EIS Noise Response to Comments Addendum Memo ("NAM").

My review summarizes and builds on the July 8, 2019 and March 10, 2020 reports I prepared for Backcountry on the Project, its AAR and its EIS, which are included here as Exhibits 1 and 2 respectively. My review and conclusions are presented below. In sum, I conclude that the FEIS and the Acoustical Analysis Report likely underpredict Project noise levels at noise-sensitive land uses and likely underreport the severity and extent of Project noise impacts.

BACKGROUND AND EXPERIENCE

I am an expert in acoustics with over 20 years of experience conducting noise and vibration analyses of energy production, transportation, residential, mixed-use, telecommunications, and commercial/industrial projects, including large, remote wind power facilities, in Southern California including San Diego County. I am a member of the Institute of Noise Control Engineering of the USA ("INCE-USA"). I am currently a principal in the acoustical consulting firm of dBF Associates, Inc.

PROFESSIONAL OPINION

As a result of my measurement and analysis of existing noise levels in the vicinity of the Project, and careful review of the AAR and DEIS, and the NAM and FEIS, I was able to demonstrate that Dudek's noise level and impact data and analysis, as reflected in its AAR and DEIS and NAM and FEIS, are incomplete and appear to understate the noise impacts of the Project. In summary, they likely overstate the existing noise levels in the areas surrounding the Project, and consequently, likely understate the increases in noise levels that the Project will cause.

It is my professional opinion that operation of the Campo Wind Project and its sixty 586-foot tall wind turbines will create significant adverse impacts on noise levels in the surrounding areas, and in the homes of residents of those areas, and that the noise data and analysis that BIA presented in its AAR, DEIS, NAM, and FEIS are flawed and very likely understate the noise impacts of this Project.

ANALYSIS

The AAR project description describes the Project as having up to 60 wind turbine generators producing up to 4.2 megawatts ("MW"). However, section 6.1.3 of the AAR states that its modeling methodology uses sound level data for General Electric (GE) 2.X-127 60 Hz model wind turbines, which are turbines that produce between 2.0 and 2.9 MW. The modeled turbines that Dudek used to predict the Project's noise levels produce substantially – up to 52.38 percent (4.2 - 2.0 = 2.2; 2.2 / 4.2 = 52.38 percent) – less power than the Project's turbines. One would expect sound levels to be greater for wind turbines that produce more power, and less for wind turbines that produce less power. If this reasonable premise is correct, then the AAR substantially understates the noise generated by the Project's wind generators. The AAR should have used sound level data associated with the Project's turbines, rather than data associated with different, substantially less powerful, turbines. If such data was for some reason unavailable, then Dudek should have: (1) explained the justification for using data for less powerful turbines, (2) stated that the noise levels for less powerful turbines would be less than the noise level for the Project's more powerful turbines, and (3) attempted to calculate how much louder the Project's turbines would be than the less powerful turbines that the AAR did analyze. It failed to do so, with the result that the AAR, DEIS, NAM, and FEIS substantially understate the noise impacts of the wind turbines to be used for the Project.

The AAR cites in its Section 4.2.3 the San Diego County Zoning Code provisions regarding noise from wind energy turbines. County Zoning Code section 6952(f)(3) states that if "the sound from a large wind turbine while operating contains a steady or intermittent pure tone, such as a whine, screech or hum, the applicable standards for noise set forth in County Code section 36.404 shall be reduced [i.e., be made more stringent] by five dBA." The Zoning Code defines "pure tones" based on the relation between the average sound pressure levels of three contiguous one-third octave bands, and recognizes that higher frequency noises are more disturbing to the human ear. One-third octave band sound data is apparently available for GE wind turbines.

However, the AAR omits this data, and fails to evaluate the Project's pure tone noise impacts despite the fact that the Zoning Code directs that this evaluation be performed to determine the significance of noise impacts of a wind energy project. The NAM does not correct this omission.

The AAR states in Section 5.2.1 that the ambient noise level measurements were conducted with Soft dB Piccolo ANSI Type 2 sound level meters (SLMs). The Piccolo SLM has a measurement range of 37 - 105 dB. This means the lowest sound level an SLM can report - its "noise floor"– is 37 dB. Consequently, the SLM will report any measured sound levels between 0 - 37 dB as 37 dB. However, due to the remote, rural and quiet nature of the areas within and surrounding this Project location, ambient noise levels during extended portions of the measurement periods at many locations were likely below the noise floor of the Piccolo SLM. Use of this sound level meter to measure ambient noise levels would thus tend to overstate the actual background noise levels, and thereby understate the increase in ambient noise levels that the Project would cause. Therefore the Piccolo SLM was inappropriate for measuring ambient noise levels in this Project area. Dudek should have used a more sensitive noise meter that reads noise levels below 37 dB, particularly at monitoring stations LT-1 and LT-13. Its failure to do so likely overstated background noise levels, and thereby understated the Project's noise impacts.

The AAR and the DEIS do not reveal the windscreen used to protect the Piccolo SLM microphones. In its FEIS, Dudek states in Response #1-98 that the "factory-provided 35- x 25-millimeter windscreen for the ½-inch microphone . . . was appropriate for the measurements." No evidence was given to support this statement. I note that these physical measurements refer to the overall dimensions (approximately 0.98 inches in width x 1.37 inches in height); this corresponds to a windscreen material thickness of approximately 1/4 inch around the surface of the microphone. In common practice, acoustical measurements in standard wind conditions utilize 3-inch diameter windscreens, which provide over 1 inch of material thickness. In high-wind environments, 7-inch diameter windscreens are often used.

The factory-supplied Piccolo windscreen is intended for use in only very low airspeed conditions. A Soft dB representative stated: "The windscreen is not rated for a maximum wind speed. This windscreen provides minimal protection against air movement when performing a moving average such as moving the instrument at arms length." Section 6.2.2 of the AAR reports that the Project area is more likely than not to experience wind speeds above 4 meters/second (m/s) (13 miles per hour [mph]), which is a relatively high wind speed.

If the windscreens used in the measurements were not appropriate for the wind speeds in the Project area, as appears to be the case, then the resulting measurements could have overstated the actual background noise levels, and thereby understated the Project's actual noise impacts. Dudek should have disclosed the windscreens that were used in the AAR and DEIS, and explained their limitations. When Dudek subsequently disclosed this information in the NAM and FEIS, it should have addressed whether the windscreens that were used were appropriate for the wind speeds in the Project area. Since it appears that the windscreens were too small for the relatively high wind speeds in the Project area, Dudek should have used larger windscreens that were appropriate for the higher wind speeds in the area.

The AAR states in Section 6.1.3 that "[c]omparison of predicted results between CadnaA models and these Excel-based techniques at many geographic locations around and within the Project site exhibit differences of less than +/-3 dB, which is barely a perceptible difference." Underprediction of Project noise levels by 3 dB, while barely perceptible, is meaningful. Project noise levels that are higher than predicted by 3 dB would result in impacts during several more wind conditions than reported in the AAR. Also, questions have been raised about the appropriateness of using the CadnaA model to predict noise from large wind turbines. For example, Dr. Richard Carman, a noted authority in this field, has pointed out in his comments on this Project that the CadnaA model is not designed to predict noise levels for large wind turbines, and likely understates their noise impacts. Dudek should have considered and addressed this criticism. Additionally, I pointed out in my comments that Dudek's use of Excel spreadsheets in lieu of multiple CadnaA models was inappropriate because the spreadsheets may underpredict the Project's noise impacts.

The AAR in Section 6.2.2 presents wind turbine sound levels as a function of wind speed. However, the AAR does not discuss the wind turbine noise frequency spectrum consistency over the range of wind speeds. GE provides acoustical specifications in technical documentation for some wind turbine generator systems; these specifications show that their wind turbine noise frequency spectrums vary as a function of wind speed. The AAR's modeling should have used wind turbine noise frequency spectrums for each wind speed condition. Its failure to do so leaves gaps in its discussion of wind turbine noise that may understate the Project's noise impacts.

The AAR states in Sections 6.3 and 6.4 that impacts based on exceedances are expected during certain wind conditions. However, the AAR does not express the amounts or percentages of time that impacts would occur. The AAR should have reported, in unambiguous terms, how often impacts would occur. Its failure to do so likely understates the Project's noise impacts.

The AAR states in Section 6.3.2 that "the locations of On-Reservation NSLU [Noise-Sensitive Land Uses] are not known," and the FEIS states in Response #1-103 that the locations of the NSLUs are not publicly available. However, this lack of data is not disclosed in Section 5: Existing Conditions. The AAR should have identified the locations of On-Reservation NSLU or provided justification for this omission. Its failure to do so likely understates the Project's noise impacts.

The ambient baseline sound level measurement data in Appendix A of the AAR show several extended periods at multiple measurement locations during which the actual ambient hourly average sound level was very likely lower than the SLM reported, as I summarize in the next paragraph. Artificially loud ambient hourly sound levels yield inaccurately high L90 values. Overstated ambient average L90 values lead to underreporting of expected exceedances of San Diego County's Wind Energy Turbine (WET) Guidelines significance criteria. Artificially loud ambient hourly sound levels also yield inaccurately high Community Noise Equivalent Level (CNEL) values. Overstated ambient CNEL values lead to underreporting of expected exceedances of the County's cumulatively considerable significance criteria. The AAR's probable overstatement of ambient hourly sound levels very likely resulted in understatement of the Project's exceedance of WET Guidelines significance criteria, thereby understating the Project's noise impacts.

Appendix A to the AAR contains data which are suspect, do not support, and in some cases, contradict, the analysis and conclusions set forth in the AAR. These suspect data indicate that the ambient noise levels reported in the AAR likely overstate the actual ambient noise levels in the Project area, with the consequence that the AAR likely understates the Project's noise impacts. For example, at some monitoring locations the ambient noise levels recorded were higher than would be expected for a rural setting. It appears that several of these ambient noise monitors were located very close to Old Highway 80 and other noisy locations that are not representative of the environment of most of the noise-sensitive land uses in the Project area. In addition, the nighttime insect noise described in the NAM may not be the prevailing sound environment in the area during the majority of the year. There are other examples of suspect and incomplete data in Appendix A that I detailed in my report dated July 8, 2019 which is attached as Exhibit 1.

The Project's noise impacts were based on evaluating its noise levels at the "representative" sound level measurement locations, not at the positions of the actual noise-sensitive receptors. This flawed methodology under-reports Project noise levels and understates impacts. In my March 10, 2020 comments on the FEIS (Exhibit 2 here), I identified numerous examples of Dudek's use of inappropriate noise evaluation positions, including the following:

1. There is at least one home near LT-3 that is markedly closer to the proposed turbines than the measurement position.
2. There are at least six homes or other structures near LT-4 that are markedly closer to the proposed turbines than the measurement position.
3. There are at least four homes near LT-6 that are markedly closer to the proposed turbines than the measurement position.
4. There are at least four homes near LT-7 that are markedly closer to the proposed turbines than the measurement position. In particular, there are approximately six homes north of Hi Pass Road, on off-reservation land, that are poorly represented by LT-7. Further, there is a large congregation of NSLUs in the Live Oak Springs area; this is not properly evaluated.
5. There are at least two homes near LT-8 that are markedly closer to the proposed turbines than the measurement position.

6. There are at least eleven homes near LT-11 that are markedly closer to the proposed turbines than the measurement position.

The AAR, DEIS and FEIS should have evaluated the Project noise levels at the estimated hundreds of potential NSLUs, not just at thirteen single locations in a roughly 24-square mile area.

CONCLUSION

For the above reasons, it is my professional opinion that operation of the Campo Wind Project and its sixty 586-foot tall wind turbines will create significant adverse impacts on noise levels in the surrounding areas, and in the homes of residents of those areas, and that the noise data and analysis that BIA presented in its FEIS is flawed and misleading. It is my further opinion that the operation of the proposed Project poses a significant and unacceptable risk of harm to surrounding neighborhoods and the people who reside in them due to the Project's significant noise impacts.

Respectfully submitted,

Steven Fiedler, INCE
Principal

EXHIBIT
9

WILSON IHRIG
ACOUSTICS, NOISE & VIBRATION

CALIFORNIA
WASHINGTON
NEW YORK

Richard Carman, Ph.D.

February 4, 2021

Donna Tisdale
Backcountry Against Dumps
PO Box 1275
Boulevard, CA 91905-0375

Subject: Review of the Noise Analysis in the DEIS for the Campo Wind Project with Boulder Brush Facilities

Dear Ms. Tisdale,

As requested, below please find my review of the environmental noise analysis for the Draft Environmental Impact Statement ("DEIS") prepared by Dudek for the Campo Wind Project with Boulder Brush Facilities ("Project"). My review summarizes and builds on the July 7, 2019 report I prepared for Backcountry Against Dumps ("Backcountry"), which was submitted to the Bureau of Indian Affairs during the Project review and approval process and which is attached hereto as Exhibit 1. Overall, after careful review of the DEIS and its Acoustical Analysis Report, I conclude that the DEIS and its Acoustical Analysis Report are seriously deficient, and understate to a substantial degree the significant noise impacts of the Campo Wind Project.

BACKGROUND AND EXPERIENCE

I am an acoustical consultant with over 35 years of experience in the field of noise and vibration measurement, analysis and mitigation, including measurement and analysis of the noise impacts of large, remote wind energy projects such as the Project. I received my license in Mechanical Engineering from the State of California in 1974. I received my Ph.D. in mechanical engineering in 1986 from the University of California at Berkeley. I have been an acoustical consultant with Wilson Ihrig for 34 years and am now semi-retired.

As a consequence of my extensive research and analysis of noise and vibration issues, I am very familiar with acoustical evaluation and design, establishing noise criteria, assessing noise impacts, and designing their mitigation, for both outdoor and indoor noise and vibration sources. I am the primary author of numerous scholarly articles on noise and acoustics as well as noise conference presentations. I served as the Principal Investigator on two large research studies conducted under the auspices of the National Academies of Sciences, Engineering and Medicine – Transportation Research Board. Of particular relevance to the Campo Wind Project, I have conducted extensive on-site ambient noise measurements for, and evaluation of the noise effects of, several large wind turbine energy projects in San Diego and Imperial counties, including the existing Kumeyaay Wind and Tule Wind facilities in the vicinity of the rural community of Boulevard, and the existing Energia Sierra Juarez Wind ("ESJ") facility in Mexico near the hamlet of Jacumba Hot Springs in eastern San Diego County, and the existing Ocotillo Wind facility near the village of Ocotillo in western Imperial County.

ANALYSIS

The Project DEIS and its Acoustical Noise Analysis are deficient in seven significant respects, which I detail in the following discussion.

The DEIS ignores applicable noise impact criteria for operational noise

The DEIS uses the Federal Transit Administration's ("FTA's") Guidelines for Transit Noise and Vibration Impact Assessment, dated May 2006, to establish significance criteria for construction noise and vibration impact assessment. However, the DEIS ignores the equally applicable FTA impact assessment criteria for *operational* noise, which is a far more significant, long-term, source of noise from this Project than the construction noise. The FTA Guidelines are particularly suited for use in quiet rural areas such as this Project's location because the FTA Guidelines recognize that changes in ambient noise can adversely affect local communities where a very low ambient noise environment exists. The FTA Guidelines are based on the principle that the absolute noise level alone is insufficient to assess impact and that an increase in noise generated by a project can cause significant impacts where the increase is substantial relative to background noise levels.

Much of the rural land surrounding the Project Area can be characterized following FTA guidelines as "Category 2" (i.e., residential land where nighttime sensitivity is a factor), and thus use of a criterion that is adjusted to give greater weight to nighttime exposure (the day-night level expressed as Ldn or DNL) is appropriate. Where the existing ambient noise is Ldn 40 dBA or less, the threshold for Moderate Impact is 10 dBA and for Severe Impact it is 15 dBA.

The noise criteria used by the federal Bureau of Land Management (BLM) indicates that an Ldn of 35 dBA can be expected in a typical rural environment. Consequently, if for example the existing Ldn is 37 dBA, then applying only an absolute noise limit of 55 dBA as the DEIS does using the BLM's absolute criterion (which relies on an obsolete 1974 EPA document), would deem to be acceptable noise levels that would, using the FTA's relative (i.e., change in level) criteria, be classified as a Severe Impact (i.e., cause a 15 dBA or greater increase). This understatement of the Project's noise impacts relative to ambient levels in the rural environment is further exacerbated by the fact that the DEIS fails to accurately characterize the existing ambient levels and indeed, overstates them as discussed below. For these reasons and others discussed below, the DEIS likely deems acceptable Project noise impacts that should instead be considered harmful or even severe.

The DEIS fails to accurately characterize the existing ambient noise conditions due to the limitations of the noise logging instruments and insufficient duration of the measurements

The DEIS relies wholly on Dudek's Acoustical Noise Analysis. However, that analysis is based on noise measurements apparently taken by a Piccolo II, Type 2 (not a Type 1, as suggested in the DEIS) sound level meter ("SLM") with an accuracy limited by a +/- 2 dBA data logger that, according to the manufacturer's published specification data, is only capable of recording noise levels equal to or greater than 30 dBA. In other words, this instrument has a "noise floor" of 30 dBA as can be seen in the reported data in the DEIS, whereas a Type 1 SLM is capable of measuring as low as 20 dBA and lower depending on the type of microphone used. Based on ambient noise measurements in the Project Area (see Exhibit 1), ambient noise during both the day and the night are often lower than 30 dBA, reaching 25 dBA during the day and likely as low as 20 dBA at night. In such a low background noise environment, it is necessary to use a Type 1 SLM with an appropriate microphone which has a lower noise floor capable of measuring down to 20 dBA or lower and has an accuracy of +/- 1 dBA.

The Type 2's relatively high noise floor of 30 dBA and lesser accuracy than a Type 1 SLM skewed the results of Dudek's calculation of the difference between ambient (background) noise and the noise levels expected from the Project's wind turbines. The difference is considerable, and invalidates all of the DEIS' conclusions about the Project's noise impacts.

The DEIS does not reveal whether a microphone windscreen was used, and if so, what type or size. This omission is significant, because windscreens are essential to obtaining accurate noise measurements. In conducting outdoor sound measurements in low ambient noise and potentially high wind conditions, a larger windscreen is imperative to minimize artificial wind noise and ensure the accuracy of measured data. The consequence of using a windscreen that is too small (e.g., a 3-inch, rather than up to 7-inches in diameter) for the conditions (or worse, using no windscreen at all) is that there is a greater likelihood that artifacts are introduced into the measured data due to noise created by air turbulence acting on the microphone. These effects can become substantial as wind speed increases. The end result is higher levels of reported ambient noise than actually exist. Where the noise is recorded to establish background ("ambient") conditions, artificially high noise readings artificially reduce, and thereby mask, the relative difference between the noise anticipated from the Project and the existing environment. This understates the Project's actual noise impacts.

In addition to Dudek's failure to use Type 1 SLMs and apparent failure to use appropriately-sized windscreens, it is apparent that Dudek's ambient noise readings are also flawed due to other technical deficiencies in either the way that noise was measured, or the manner in which the measured noise was recorded. In particular, Dudek's noise readings for certain monitoring locations are demonstrably erroneous. For example, the data for DEIS monitoring station LT-1 indicates a minimum level ("Lmin") of 33.6 dBA for all nighttime hours. Yet the Leq (1-hour duration) for two of those hours is less than the Lmin, which is physically impossible.

Furthermore, the statistical level noise data (i.e., Ln or the noise level exceeded n% of the time) between 3 a.m. and 4 a.m. are all the same (e.g., L1 and L99 are both 35 dBA).

A close review of the data for DEIS location LT-12 likewise indicates a serious problem with Dudek's data. The statistical noise level L1 (the level exceeded 1% of the time) is less than the L5 (the level exceeded 5% of the time) for all hours of the day and the statistical noise level for the L1 is less than the L10 (the level exceeded 10% of the time) from 10 a.m. until 9 p.m., both of which are impossible. A noise level that is exceeded for a longer period cannot be greater than the level exceeded for a shorter time period (i.e., the shorter the time interval the greater the noise level). This calls into question the reliability of the instrumentation.

As noted, there are clear indications that the instrumentation used is unable to accurately measure the ambient noise when it is less than 30 dBA (i.e., the "noise floor" for the Type 2 SLM used). The combination of the 30 dBA noise floor of the Type 2 SLM and the inaccuracy of the Type 2 SLM (+/- 2 dBA) renders the data at lower ambient sound levels presented in the DEIS inaccurate and unreliable.

In addition, the ambient noise data for each location were only measured for one, 24-hour period. It is customary to measure for at least two or three days to ensure the data presented are representative and not anomalous, in particular in such low background conditions where one loud noise event can skew the Leq (average hourly level) and consequently the Ldn.

The DEIS ignores the substantial increase in ambient noise during Project operation

The DEIS ignores the FTA noise criteria when evaluating the Project's operational noise. It makes no effort to compare background (ambient) noise levels with the projected noise from the Project's operation. This is a severe shortcoming, because, as modern acoustic science recognizes and the FTA guidelines codify, humans are sensitive to increases in noise levels over ambient levels, particularly during nighttime hours. The Project's operation continues during the night because the turbines spin literally whenever the wind blows. Consequently, the Project's operational noise – unlike construction noise – occurs during the night.

It is well established that the impacts of a given noise level are worse at night than they are during the day. Nighttime noise is particularly noticeable to humans for two reasons. First, ambient noise at night is usually much quieter than ambient noise during the day. This is especially true in rural areas such as the Project site, as documented by our own measurements in the Boulevard area. Second, many studies have shown that obtaining a good night's sleep is important for both physical and mental health. Consequently, the impacts of the Project's elevated noise at night are especially significant.

The FTA noise guidelines recognize this fact as well. The FTA criteria for project operational impacts are based on the principle that the absolute noise level alone is insufficient to assess impact and that an increase in noise generated by a project can cause significant impact depending on the existing ambient noise and the amount of the increase. Therefore they require that the noise generated by a project's operation must be compared with background, or ambient, noise levels, in order to more accurately characterize the noise impacts of the project's operation.

Contrary to these guidelines, and well-established acoustic science and practice, the Project DEIS did not compare ambient noise at night with the Project's anticipated operational noise at night. Consequently, the true impact of the Project on noise levels, and on humans living in the area of the Project, is not disclosed and analyzed in the DEIS. As a result, the DEIS fails to accurately describe the Project's noise impacts. Instead, it understates them to a substantial degree.

Our measurements of the Project's anticipated operational noise at night show that it would be significant. As we noted in our comments on the DEIS, "[t]he FTA guidelines for operational noise impact assessment recognize that changes in ambient noise can adversely affect local populations." Exhibit 1, p. 4. "This is particularly important in rural areas (such as the Project area) where a very low ambient noise environment exists, and Project noise would result in a substantial increase over existing ambient noise." Exhibit 1, p. 4.

The DEIS understates the effects of low frequency noise on Noise Sensitive Land Uses

The DEIS failed to accurately assess the impact of the Project's low frequency noise (i.e., generally noise with frequencies at or below 125 cycles per second, or Hz) on Noise Sensitive Land Uses such as occupied residences ("NSLUs"). Low frequency noise impacts were evaluated in the DEIS using the CadnaA program to predict low frequency noise. The CadnaA program has explicit limitations acknowledged by the software developer DataKustic that preclude its use for predicting large wind turbine noise, which I explain below. These limitations are particularly applicable to accurately predicting area-wide low frequency wind turbine noise, for several reasons.

First, at lower frequencies, the noise emitted by wind turbines can in certain circumstances be more directional than at higher frequencies. For example, Kim, et al. (referenced in Exhibit 1) have developed a noise prediction model for amplitude modulation from large wind turbines. Their model is well supported by the literature and widely recognized by acousticians. Their model predicts that the overall sound pressure level of wind turbines is highly directional. It predicts noise levels are greatest on-axis (in the direction of the turbine rotor, which is also the direction that the wind is blowing) but that the amount of modulation (i.e., the depth of the trough between noise peaks) is greatest in the plane of the turbine blades (i.e., perpendicular to the rotor). Thus, low-frequency noise from large wind turbines is manifestly not omni-directional. Yet as shown in Appendix B to the DEIS' noise analysis report, Dudek assumed in its CadnaA model that the wind turbine noise would be omni-directional (i.e., emitted uniformly in all directions).

Second, although low-frequency noise is generally greatest in the direction of the rotor (and thus the wind), amplitude modulation effects (which as I discuss below are particularly impactful to the human ear) are greatest perpendicular to the rotor. And, since the rotor swivels to maximize alignment with the wind direction, these two highly directional impacts shift as the wind direction shifts. Yet contrary to this documented characteristic of low-frequency wind turbine noise, the DEIS incorrectly assumes in the CadnaA model that wind turbine noise is omni-directional (i.e., equal in all directions). As a consequence of this erroneous assumption, the DEIS understates the Project's noise impacts on locations where the directional noise is greatest.

Third, the wind turbine manufacturer's noise data on which the DEIS relies to estimate the wind turbines' noise levels is likely unreliable, for several reasons. First, it is difficult to accurately measure sound power (energy strength of the noise source) for mechanical sources, even under ideal conditions. In general, the larger the size of the noise source (machine), the more difficult it is to measure sound power accurately. The CadnaA wind turbine model developed by Dudek relies on sound power data. Accurate sound power measurement depends greatly on the direction in which the sound travels, and with wind turbines, as noted above the sound can be highly directional, in two different directions, and varies with both wind direction and speed. Second, except for wind turbine blade noise, the main source of wind turbine noise is the generator. Unless very sophisticated means were used, it is unlikely that the manufacturer's sound measurements were made for any fully operating wind turbine given that the hub height is 116 meters – over 380 feet. It is highly likely that the sound measurements were made with the generator on the ground. At low frequencies, this makes an enormous difference because the wavelength of lower frequency (e.g., less than 125 Hz) sound is much longer than at higher frequencies (e.g., 1,000 Hz). For example, the wavelength of sound at 31.5 Hz is 35 feet. Accurately measuring sound power with the source on the ground of low-frequency sound (e.g., with a 35-foot wavelength) poses a challenging if not insurmountable problem. Finally, as discussed below, the CadnaA model used in the DEIS noise analysis did not account for directionality. Yet the level of sound from operating wind turbines is highly directional. Accordingly, for each of these reasons the DEIS likely understated the low frequency noise impacts of the Project.

The DEIS ignores the effects of infrasound on Noise Sensitive Land Uses

The DEIS ignored the well-documented science on the harmful effects of infrasound (i.e., sound lower than 20 Hz). Infrasound from large wind turbines has been clearly documented. It is characterized by its tonal nature and a sound spectrum that consists of sharp peaks at the blade passage frequency ("bpf;" typically, 1 Hz and lower) and at each of the harmonics of the blade passage frequency (e.g., 2 x bpf, 3 x bpf, 4 x bpf, etc.).

To illustrate the distinctive sound wave signature of the infrasound emitted by wind turbines, I included as Figure 3 to my July 7, 2019 comments on the DEIS (Exhibit 1 here) a graph depicting the infrasound spectra of existing wind turbines measured in the vicinity of the Project under low wind conditions. The infrasound spectrum in Figure 3 is a classic example of noise produced by a machine with spinning blades (e.g., helicopter). Infrasound tends to increase in sound pressure level (noise level) with wind speed.

Infrasound has impacts on the human ear that are overlooked by the DEIS. The DEIS ignores the impacts of infrasound on the erroneous premise that unless noise is audible, it has no effect on the human ear. Audibility is based solely on the response of the ear's inner hair cells ("IHC"). Research by Salt and Lichtenhan (discussed in Exhibit 1) has shown that the ear's *outer* hair cells ("OHC") respond to infrasound and low-frequency noise ("ILFN") at sound pressure levels that are much lower than the IHC threshold for audibility. They have reported that ILFN levels commonly generated by wind turbines at levels that are below the threshold of audibility can cause physiologic changes in the ear.

The DEIS ignores the research of Salt and others into the effects of infrasound on humans based on a document prepared by Resource Systems Group, Inc. ("RSG") entitled Massachusetts Study on Wind Turbine Acoustics, Report 2.18.2016. However, the RSG study is completely irrelevant to evaluating the effects on infrasound because the RSG study does not evaluate the effects of noise levels below the threshold of audibility. The RSG study presumes that a sound level has no effect on the human ear unless it is audible. But this premise has no basis in science, and ignores the relevant question. The relevant question is whether a sound level – whether infrasound or not – causes physiological changes in the ear. The research by Salt and others shows that humans could be negatively impacted by sound levels significantly below the threshold of audibility. Because the DEIS ignores their research, and fails to address the relevant question whether infrasound generated by wind turbines causes harm to the human ear (or has other physiological effects), the DEIS understates the impacts of infrasound.

The DEIS ignores the effects of "amplitude modulation"

The DEIS ignores the effects of amplitude modulation by wind turbine rotors. Amplitude modulation is a rhythmic fluctuation in noise level, like the bi-tonal fluctuation of the so-called European-style emergency vehicle siren. Many studies have documented the intuitive perception that this rhythmic modulation is particularly noticeable – hence its use for emergency vehicles – and annoying to humans when it persists for other than a brief period. Pilot studies have been conducted in a laboratory setting to investigate the effect of wind turbine noise on sleep disturbance. The reported findings from one study "indicated that amplitude modulation strength, spectral frequency and presence of strong beats might be of particular importance for adverse sleep effects." Morsing, J.S., et al., *Wind Turbine Noise and Sleep: Pilot Studies on the influence of Noise Characteristics,* International Journal of Environmental Research and Public Health, 15 (2573), 2018.

As noted above, measurements conducted in the Project area demonstrate that the existing wind turbines generate amplitude modulated noise. I presented an example of this recorded wind turbine noise in Figure 2 to my July 7, 2019 comments on the DEIS (Exhibit 1 here). Figure 2 illustrated amplitude modulation measured at a distance of 4,400 feet (about 0.83 mile) from the closest wind turbine at the Tule Wind Project with peak-to-trough variation ranging from 4 to 9 dBA. These measurements demonstrate the presence of "excessive amplitude modulation" (peak-to-trough variation of 4 dBA or more) as defined by Cooper, S. in *Hiding Wind Farm Noise in Ambient measurements – Noise Floor, Wind Direction and Frequency Limitations,* reported at the International Conference on Wind Turbine Noise, Denver, 28-30 August 2013. They also demonstrate the presence of "enhanced amplitude modulation" (variation of 6 dBA) as characterized by Oerlemans, S. in *An Explanation of Enhanced Amplitude Modulation of Wind Turbine Noise*, a report for the National Aerospace Laboratory, July 2011.

The DEIS attempts to address the impact of amplitude modulation by citing the RSG study mentioned above. However, the RSG study minimizes the severity of the phenomenon by understating the actual, measured differences in noise levels associated with infrasound. For example, we measured a 9-dB difference between the trough (35 dBA) and peak (44 dBA) in sound levels that we documented and reported in Figure 2 to my July 7, 2019 DEIS comments. Whereas the RSG study claims that the modulations are rarely greater than 4 dB, our measurements at 4,400 feet from a Tule Wind Project wind turbine indicate modulation depths up to 9 dB, which is clearly an excessive modulation under either Cooper's or Oelermans' definition.

Further, the DEIS attempts to address amplitude modulation by adding 2 dB to the source levels in the CadnaA model. But the only effect this has is to increase the predicted A-weighted noise levels. This adjustment fails to address the actual impact of amplitude modulation in two ways. First, it ignores the fact that A-weighted noise impacts, which the San Diego County noise ordinance addresses, are a short-range issue. Amplitude modulation is not a short-range issue. It occurs up to long distances (e.g., 4,400 feet) from wind turbines. Consequently, amplitude modulation cannot be evaluated by applying the County noise ordinance criteria as the DEIS attempts to do. Second, the DEIS' approach to assessing amplitude modulation impact misses the point altogether. The salient feature of amplitude modulation impact is the depth of the variation (i.e., peak-to-trough range) of the noise level and not the noise level itself. CadnaA cannot be used to predict amplitude modulation, as I discuss further below.

The DEIS relies on a modeling program that cannot accurately predict wind turbine noise. The DEIS relies on the computer program CadnaA to predict noise generated by the Project's wind turbines. Although CadnaA was not intended to be applied to prediction of noise generated by large wind turbines due to its inherent limitations, in its modeling methodology the DEIS claims to overcome these limitations by introducing a factor of conservatism recommended by a wind turbine acoustics report. In spite of this claimed conservatism, however, the DEIS understates and ignores many of those noise impacts. CadnaA is simply not designed to predict noise levels for large wind turbines as the DEIS claims.

First, CadnaA incorporates the outdoor sound propagation models (i.e., formulas) contained in the guidance provided by the International Standards Organization, ISO 9613-2, Acoustics – Attenuation of sound during propagation outdoors – Part 2: General method of calculation, 1996. ISO 9613-2, however, has inherent limitations that preclude using these formulas to accurately predict wind turbine noise. These limitations include source height and wind speed. ISO 9613-2 is intended to be used for cases where the wind speed does not exceed 5 meters/second (measured at a height of 3 to 11 meters above the ground), the noise source and the receiver heights are not too dissimilar, and the source height is less than 30 meters. None of these criteria are met here. Wind speeds in the Project area are frequently greater than 5 meters per second (11 mph). The heights of the noise sources and the receiver locations are vastly different. The wind turbine noise sources are all well above 30 meters.

The DEIS states that "wind turbines were treated as point sources located at hub height (110 meters or 361 feet) relative to grade, and receptors were assumed to be 5 feet above grade." The stated accuracy of the ISO 9613-2 formulas for a mean height of the source and receiver of between 5 meters and 30 meters is +/- 3 dB. There is no stated accuracy in ISO 9613-2 for source heights greater than 30 meters. It is reasonable to believe that it would be greater than 3 dB. The proposed wind turbine hub heights are 116 meters, or 86 meters greater than the specified range of applicability of ISO 9613-2 formulas. ISO 9613-2 does not include the effects of sound refraction due to temperature or wind gradients, both of which can increase sound levels. Consequently, CadnaA does not include these effects. For each of these reasons, CadnaA would not appear to be appropriate for use in accurately predicting noise from large wind turbines.

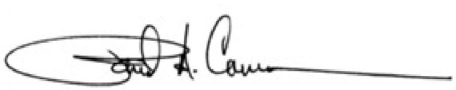
The DEIS states that the limitations inherent in CadnaA (i.e., those of ISO 9613-2) are addressed by incorporating a "conservative factor" (i.e., + 2 dB) as recommended by the RSG study. However, the RSG study is inappropriate for use in predicting the noise impacts of the Project for several reasons. First, as noted above it ignores the effects of infrasound based on the erroneous premise that a noise must be audible to affect human physiology. Second, the RSG study indicates that the 2 dB "penalty" resulted in the "greatest precision for receivers at 330 meters downwind" (i.e., at 1,072 feet). There is no mention in the RSG study of the accuracy of predictions using ISO 9613-2 at other distances or other directions (e.g., upwind or crosswind). Third, the RSG study mentions that the wind turbines in the study were 1.5 MW and larger, but it does not specify the highest rated capacity or the range of turbine capacities. The Project's wind turbines will have a rated capacity of 4.2 MW. Obviously, there is a big difference between 1.5 MW and 4.2 MW. Consequently, I question the applicability of the RSG study conclusions to the Project with regard to conservative factors that were added to the DEIS predictions. For each of these reasons, the RSG study does not appear to be applicable to the Project or its wind turbines. Accordingly, the DEIS' reliance on the RSG study to compensate for the admitted and obvious deficiencies of the CadnaA model to accurately predict the Project's noise impacts is plainly inappropriate.

PROFESSIONAL OPINION AND CONCLUSION

Based on the analysis presented above, I have formed the following professional opinion and conclusion. The DEIS and FEIS, and the Acoustical Analysis Report on which they rely, are seriously deficient in numerous critical respects, including the following seven principal deficiencies: (1) they overlook relevant criteria required for evaluation of noise impacts, (2) they fail to recognize the limitations of Dudek's noise logging instrumentation, including a "noise floor" that skewed Dudek's evaluation, (3) they ignore the substantial increase in ambient noise that will occur in the Project's operational phase, and its significant impact on Noise Sensitive Land Uses, (4) they fail to adequately address the effects of low frequency noise on Noise Sensitive Land Uses, (5) they fail to adequately address the effects of infrasound on Noise Sensitive Land Uses, (6) they fail to adequately address the effects of "amplitude modulation" associated with low frequency wind turbine noise, and (7) they rely on the computer program CadnaA to predict noise generated by the Project's wind turbines, despite the fact that CadnaA was not intended to be used for the prediction of noise generated by large wind turbines due to inherent limitations in its modeling methodology.

I conclude that the DEIS and FEIS are fundamentally flawed and understate the noise impacts of the Project, and that the Project will have significant adverse noise impacts on the Project area and the surrounding areas and their inhabitants. Those impacts have not been adequately analyzed and mitigated in the Project's DEIS and FEIS.

Respectfully submitted,



Richard A. Carman, Ph.D.

EXHIBIT
10

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Understanding stress effects of wind turbine noise – The integrated approach

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ABSTRACT

To better understand causes and effects of wind turbine (WT) noise, this study combined the methodology of stress psychology with noise measurement to an integrated approach. In this longitudinal study, residents of a wind farm in Lower Saxony were interviewed on two occasions (2012, 2014) and given the opportunity to use audio equipment to record annoying noise. On average, both the wind farm and road traffic were somewhat annoying. More residents complained about physical and psychological symptoms due to traffic noise (16%) than to WT noise (10%, two years later 7%). Noise annoyance was minimally correlated with distance to the closest WT and sound pressure level, but moderately correlated with fair planning. The acoustic analysis identified amplitude-modulated noise as a major cause of the complaints. The planning and construction process has proven to be central – it is recommended to make this process as positive as possible. It is promising to develop the research approach in order to study the psychological and acoustic causes of WT noise annoyance even more closely. To further analysis of amplitude modulation we recommend longitudinal measurements in several wind farms to increase the data base — in the sense of “Homo sapiens monitoring”.

1. Introduction

Noise problems are one of the most frequently discussed impacts of wind turbines (WT) on residents. Indeed, several studies provide empirical evidence for WT noise to be a potential source of annoyance. However, while about three dozen field studies on the noise effects of large WT (e.g., Health Canada, 2014; Michaud et al., 2016a, 2016b, 2016c, Pawlaczyk-Luszczynska et al., 2014; Pedersen et al., 2009; Pedersen and Persson-Waye, 2004, 2007; Pohl et al., 1999, 2012) and small WT (Taylor et al., 2013) indicate noise annoyance, the reported prevalence of annoyed residents is inconsistent and varies between 4.1% (Pedersen and Persson Waye, 2007) and 21.8% (Pohl and Hübner, 2012). One possible explanation for these different findings is that annoyance is not influenced solely by noise. For example, significant relations between noise levels from < 28 dB(A) to > 45 dB(A) – estimated by diffusion models – and annoyance repeatedly were found. However, the sound level explained only 12–26% of the annoyance variance (Pedersen and Persson-Waye, 2004, 2007; Pedersen et al., 2009), leaving more than 70% to be explained. Consequently, annoyance is influenced by further factors, so-called moderator variables such as visibility and financial participation. However, despite some knowledge on the moderating factors, it remains an open question under what conditions WT noise can lead to strong annoyance. Most of the mentioned studies calculated sound levels and used not local sound measurement at recipient locations, which may contribute to unexplained variance because in diffusion models local acoustical specificities were not considered.

Former studies provided valuable insight into the relation between WT noise and annoyance (e.g., Health Canada, 2014; Pawlaczyk-Luszczynska et al., 2014; Pedersen et al., 2009; Pedersen and Persson-Waye, 2004, 2007). However, they relied on a smaller range of stress indicators and moderators. Additionally, these studies remain descriptive and the indicators are not embedded in a larger stress concept. The benefit of a stress concept is to derive specific strategies for stress reduction on different stages of the stress process. Therefore, we rely on the well-established model of Lazarus (e.g., Lazarus and Cohen, 1977) enlarged by Baum et al. (1984) and Bell et al. (1990). This approach starts with the perception of a possible stressor (e.g., WT noise), followed by evaluation of the stressor (e.g., threatening), psychological and physical reactions (e.g., symptoms) and cognitive, emotional and behavioral coping (e.g., closing the window). Acoustic (e.g., sound pressure level), psychological (e.g., experiences during the planning process) and situational (e.g., distance to the nearest WT) moderators of the stress reaction were also considered.

The present study provides an interdisciplinary approach for a differentiated analysis of WT noise. This approach integrates noise

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measurement, weather and operational information connected with the WT and psychological concepts on social acceptance as well as stress psychology. To develop this integrated approach a field study was conducted involving 212 residents living in the vicinity of a wind farm in Lower Saxony, Germany. Finally, this approach offers a systematic background for recommendations regarding noise mitigation and on how to deal with WT noise.

2. Factors influencing noise annoyance by WT and stress effects

2.1. Influencing factors

Citizens and wind project operators refer to several influencing factors to explain noise annoyance. Some of these lay explanations are not mirrored by empirical evidence such as noise sensitivity, which has a rather weak impact on annoyance (e.g., Hübner and Löffler, 2013; Pedersen and Persson-Waye, 2004; Pohl et al., 2012). Socio-demographic variables such as age, gender and emotional lability, have not been proven to show significant impact (e.g., Pedersen and Larsman, 2008; Pedersen et al., 2010; Pohl et al., 2012).

A well-known moderator of noise annoyance due to WT is the visibility of WT from the property or homes of residents living nearby: on average, residents are significantly more annoyed when the WT are visible from their dwellings (e.g., Arezes et al., 2014; Pedersen et al., 2009, 2010; Pedersen and Persson Waye, 2007). This effect can be explained by the higher salience of the WT in case of visibility. In line with the explanation seems to be the finding that residents in rural and flatland regions reported higher noise annoyance than residents living in a more urban and hilly region (Pedersen and Larsman, 2008; Pedersen and Persson-Waye, 2007, 2008; Pedersen et al., 2009).

Additional relevant moderating variables that have the ability to decrease annoyance are financial participation in the wind farm (e.g., Arezes et al., 2014; Health Canada, 2014; Pohl et al., 1999; Pedersen et al., 2010), positive attitudes towards wind energy (e.g., Pawlaczyk-Luszczynska et al., 2014; Pedersen and Persson Waye, 2008; Pohl et al., 1999, 2012), and positive attitudes towards the local wind farm (e.g., Pohl et al., 1999, 2012). On the other hand, annoyance during planning and construction (e.g., Hübner and Löffler, 2013; Pohl et al., 2012) and a negative visual impact of WT on the landscape (e.g., Health Canada, 2014; Pawlaczyk-Luszczynska et al., 2014; Pedersen and Larsman, 2008; Pedersen et al., 2009) increase annoyance.

Additionally, noise annoyance is influenced by situational factors, such as weather conditions and time of day (e.g., Health Canada, 2014; Hübner and Löffler, 2013; Pawlaczyk-Luszczynska et al., 2014; Pedersen and Persson-Waye, 2004; Pedersen et al., 2009). The strongest noise annoyance occurs in the evening and night hours, especially when wind blows constantly from WT towards the dwellings or during periods of strong wind. Furthermore, residents experience higher noise annoyance outside rather than inside the home. Overall, however, the source directivity of wind turbines is still an under-researched topic especially in situations with strong amplitude modulation (AM).

In summary, moderator variables seem to better predict the annoyance caused by WT than, e.g., sound pressure level or distance to the nearest WT (e.g., Pawlaczyk-Luszczynska et al., 2014; Pedersen et al., 2009). Additionally, WT are rated more annoying than other noise sources with a similar sound level (Janssen et al., 2011; Pedersen and Persson-Waye, 2004; Pedersen et al., 2009). This finding also indicates that other factors contribute to the annoyance, such as some factors mentioned so far in combination with e.g., specific noise patterns and qualities. For example, residents felt most strongly annoyed by a noise pattern described as "swishing" (Pedersen and Persson-Waye, 2004, 2008).

2.2. Stress effects of WT noise

Sleep disturbance due to WT noise was reported in some studies (e.g., Bakker et al., 2012; Hübner and Löffler, 2013; Pedersen and Persson-Waye, 2004; Pohl et al., 1999). The proportion ranged from 6% (Bakker et al., 2012) to 11% of the residents (Pohl et al., 1999). Further symptoms caused by WT noise, such as negative mood, nervousness and irritability, occurred only to a small extent (up to 5.8% affected residents) and so far have been demonstrated in two earlier studies (Pohl et al., 1999; Wolsink et al., 1993). Further, there are only a few studies − and with heterogeneous findings − on the relationship between WT noise annoyance and disturbed work, leisure activities and alternating whereabouts (e.g., Hübner and Löffler, 2013; Pohl et al., 1999, 2012). Likewise, cognitive and behavioral coping strategies of annoyed residents have been subject only to a few studies (e.g., Hübner and Löffler, 2013; Pedersen and Persson Waye, 2007; Pohl et al., 1999, 2012). Typical reported measures include closing the windows and turning up the volume of the TV/radio.

While the aforementioned research refers to the health impacts of WT noise, other studies compare residents living near WT ($\leq$ 2 km) with those living further away ($\geq$ 3.3 km) in general (e. g., Nissenbaum et al., 2012; Sheperd et al., 2011). Although deteriorating health characteristics were reported for nearby residents, these studies are to be strongly criticized for their methods. They exclude the impacts of specific emissions, moderator variables or possible previous illness, and they do not control for the possible impact of additional noise sources (Nissenbaum et al., 2012; Sheperd et al., 2011).

2.3. Present research

The present research aims to provide a deeper understanding of the causes and consequences of WT noise stress effects. This knowledge is the base to derive recommendations for noise mitigation.

While existing research provides a basic understanding of the WT noise phenomenon, at least three open questions remain:

First, is there a greater proportion of residents living in the vicinity of a wind farm that is not only annoyed by noise but that also suffers from stress effects or even adverse health effects related to WT noise? To answer this question it is useful to assess possible stress effects by several indicators based on stress psychology concepts (Baum et al., 1984; Bell et al., 1990; Lazarus and Cohen, 1977). Further, it is unclear whether the proportion is stable over the time, since longitudinal studies thus far are missing.

Second, due to the chosen assessment methods, it is still uncertain whether the reported symptoms are directly attributed to WT noise or confounded by others stressors. The link is lacking in most studies. A first attempt to assess and directly link to WT noise was made in the late 1990s (Pohl et al., 1999). This study was mainly directed to analyse the stress impact of periodical shadow-casting but also included several items concerning noise.

Third, we need a deeper understanding of the conditions contributing to substantial annoyance.

Previous research results, illustrated above, suggest that physical factors (e.g., sound pressure level, sound quality, visibility of the wind farm) and psychological factors (e.g., stress during the planning phase, attitude toward wind energy) contribute to this.

Due to our aim to disentangle the responsible factors for WT noise annoyance, we used a case study approach with several psychological stress indicators and physical parameters.

3. Methods

3.1. Design

A longitudinal study design was chosen to test if WT noise annoyance is a stable phenomenon over time or can annoyance be influenced by information about causes and effects of WT noise. The design was based on the methodology of environmental and stress psychology in combination with noise measurement and audio recordings (Baum et al., 1984; Bell et al., 1990; Lazarus and Cohen, 1977). Using a standardized questionnaire, residents of one wind farm were interviewed face-to-face twice over a two-year period (March through April 2012, February through March 2014). Interviewers were trained students who visited the participants in their homes. Furthermore, they were able to submit complaint sheets over several months and audiotape any disturbing noises. In order to assess the generalizability of the results, the central findings were compared to findings of a nationwide sample, including more than 400 residents living in the vicinity of 13 wind farms (Pohl et al., 2012).

The wind farm was located in a rural, flat area in the German state of Lower Saxony. There were nine WT with a power of 2 MW and a total height of 150 m each (Enercon E-82). At the time of the first survey (2012), the time in operation was 37 months.

3.2. Participants

3.2.1. Recruitment

After information about the project was disseminated via radio and press releases, the participants were recruited through letters and phone calls, and at a community meeting. Based on address lists of authorities and public phone directories, letters were sent to 590 people. About the same number lived in an area with predicted sound pressure level of 25–30 dB(A) and in an area with 30–35 dB(A). There are no residents living in an area with levels > 35 dB(A). A few days later, those who received letters were called and asked to participate. Additionally, 45 persons were contacted on-site during the interview days, of whom 14 were partners of previously recruited single persons.

In the study, therefore, both randomly selected persons and persons who had directly contacted us were included. The latter was done to increase the acceptance of the study in the community. To proof possible self-selection bias we have assessed in the Wilstedt and the nationwide study possible moderators and tested their influence on WT noise annoyance, e.g., age, gender, health state, noise sensitivity, distance.

A total of 212 persons participated in the first survey; nearly two-thirds (133 persons) remained in the second one. Accordingly, one-third dropped out (“drop-outs”; 79 participants). It was controlled whether these dropouts represented extreme opinions, indicating a self-selection bias. Indeed, the dropouts differed statistically from the other participants only in terms of education level and household size. The remaining participants had a relatively higher education level and slightly larger household, compared to the dropouts (small effect size each). These socio-demographic variables had no significant influence on the central stress and attitude indicators; significant differences in the central attitude and annoyance assessments did not appear. Accordingly, analysing longitudinal effects with the remaining sample size of the second measurement time is reliable and does not lead to misinterpretation.

3.2.2. Sample characteristics

The respondents’ age ranged from 19 to 88 years, averaging 55 years (SD = 13.19). Slightly more men than women participated (47.6% women, 52.4% men). A completed junior high school qualification was held by 34.3%, 42.9% held university entrance qualifications. The majority owned property, and was married and had children. On average, the participants lived in a three-person household and lived in their community for about two decades. More than half were pensioners or had been exempted from work, one-fifth each being public servant or self-employed. Two-fifths of respondents worked at home. Only a minority of 3.8% benefited financially from the local WT, and no participant was employed by the WT industry. Participants lived an average of 1.90 km to the closest WT (SD = .37, range 1.25–2.89 km). From their homes they saw an average of nearly four WT (M = 3.93, SD = 3.35).

3.2.3. Non-response analysis

104 residents contacted via phone call refused to participate in the survey but answered four short items. More of the non-respondents were women (60.6%) than men (39.4%), and less of them had a view of the WT compared to respondents (61.5% vs. 81.6%). Both groups rather strongly approved of wind farms in general (M > 3 each) but differed in their judgment of the local wind farm: On average, respondents approved of the local WT less (M = .98, SD = 2.14) than the non-respondents (M = 1.51, SD = 1.78, small effect size). Additionally, respondents felt more annoyed by WT noise than non-respondents (M = 1.57, SD = 1.28 versus M = .43, SD = .83, large effect size). This result indicates that residents were more likely to participate when they felt more negatively affected by the local wind farm.

3.3. Questionnaires, stress indicators and moderators

The survey questionnaire included 450 items adopted from previous studies on stress effects of WT emissions (Pohl et al., 1999, 2012). Four residents – two annoyed and two not – gave feedback on a draft version concerning whether it covered their experiences and concerns properly. Based to their statements we revised the questionnaire. The complaint sheet included 25 items self-rating to describe actual noise annoyance. Complaint sheets were offered to each respondent.

3.3.1. Several stress indicators were assessed

a) The general impact of the wind farm was assessed by five items (e.g., "I feel disturbed by the wind farm" or "I experience physical complaints due to the wind farm") on a 5-point scale ranging from “not at all (0)” to “very (4)”.
b) For a general evaluation of WT noise, a semantic differential with four pairs of adjectives was used. The scale ranged from −3 (e.g., „very unpleasant“) to +3 (e.g., „very pleasant“).
c) To assess the overall noise annoyance, participants were asked to rate their noise experience on a unipolar rating scale ranging from 0 ("not at all") to 4 ("very"). In addition, the ICBEN-scale Q. V. ranging from 0 ("not at all") to 4 ("extremely") as well as the ICBEN-scale Q. N. for noise annoyance in the past 12 months (ranging from 0 to 10) were used (Felscher-Suhr et al., 2000; Fields et al., 2001).
d) To indicate temporal changes of the experienced noise annoyance since the wind farm construction a 3-point bipolar scale ranging from −1 („decreasing “) to +1 („increasing “) was applied.
e) To analyse typical situations with WT noise annoyance, participants were asked to provide a description of the noise pattern (nine items; e.g., "rush" or “swishing”), their frequency, the extent of noise annoyance, the day time, weather conditions, impaired activity, arisen emotions, etc.
f) In addition to WT noise, respondents were asked to evaluate other wind farm emissions (12 items; e.g., periodical shadow-casting, aircraft obstruction markings, landscape change) and other local annoyance sources (14 items; e.g., traffic noise, noise from maize choppers), each on a unipolar rating scale ranging from 0 ("not at all") to 4 ("very").
g) A number of 39 psychological and somatic symptoms as well as distractions linked to WT noise were assessed. Symptoms belonged to the domains (a) general performance, e.g., fatigue, concentration, (b) emotions and mood, (c) somatic complaints, e.g., dizziness, nausea, (d) pain, (e) cardiovascular system, and (f) sleep. Additionally, the frequency of the respective complaints was rated, ranging from 0 ("never") to 4 ("about every day"). In the follow-up survey, the same symptoms due to traffic noise were assessed in order to compare the impact of both noise sources.
h) As indicators for low frequency noise, participants were asked to report annoyance due to feelings of pressure and vibrations related to the WT on a unipolar rating scale ranging from 0 ("not at all") to 4 ("very").

i) Cognitive and behavioral coping responses were assessed. Five items indicated four cognitive strategies (unipolar rating scale, from 0 ("not at all") to 4 ("very")), such as trivializing or accepting. Based on 24 items, participants reported if and which behavioral strategies they applied to reduce the annoyance impact, e.g., changing rooms, closing windows or complaints to authorities.

3.3.2. *In addition to the stress indicators, several moderators were assessed*

a) Physical features: number of visible WT, distance to the nearest wind farm, calculated A-weighted Leq-sound pressure level according to ISO 9613 (1993). The distance was determined using the WT's geographical coordinates, residents' mailing addresses, and Google Earth™.
b) Past passivity or activities either in favor or against the wind farm.
c) Evaluation of the planning and construction phase: Participants were asked about stress and fairness of these processes on eight unipolar rating scales ranging from 0 ("not at all") to 4 ("very").
d) General attitude towards the local wind farm and WT were assessed by two semantic differentials with six pairs of adjectives; each on a bipolar scale ranging from −3 (e.g., „very bad") to +3 (e.g., „very good"). The two means over the items were used as attitude indicators (Cronbach's alpha .95 and .88). Additionally, residents were asked if they financially participated in the local wind farm and if they are working in the wind energy business.
e) Health indicators: The general health state was rated on a unipolar scale ranging from 0 ("bad") to 4 ("excellent"). For the assessment of noise sensitivity the mean of six items inspired by Zimmer and Ellermeier (1997, 1998) were used. Emotional lability was evaluated by a six item test of Trautwein (2004).

3.3.3. *Complaint sheet, audio recordings, emission and immission measures*

Participants were instructed to fill out the complaint sheet in case of WT noise annoyance (25 items), including items to measure annoyance, noise pattern, disturbed activities, symptoms and weather conditions. Residents also could borrow an audio recorder in order to record annoying noises induced by WT. The audio recordings were evaluated by experienced specialists from DEWI and correlated with operating data from the wind farms (e.g., wind direction, wind speed at hub height and at 10 m height, rotor speed). In the period from March 2012 to January 2013 a total of 98 complaint sheets were filled in by 11 participants, two of whom made a total of 28 evaluable audio recordings. In addition, DEWI performed emission measurements according to IEC 61400-11 Ed. 2.1 and immission measurement on the property of a strongly annoyed resident.

3.4. *Statistical analyses*

To analyse group differences in the case of interval-scaled variables, descriptive statistical values were used such as the arithmetical mean (M), empirical standard deviation (SD), and standard error of mean (SEM). In the case of nominal-scaled variables, absolute and relative frequencies (%-values) were reported. Pearson-correlations were calculated to identify moderator variables – only coefficients equal to or greater than .30 were regarded as relevant (medium effect size according to Cohen (1988)).

Chi^2-tests were used for inferential analysis of frequency distributions. To analyse mean group differences, analysis of variance (ANOVA) with repeated measurement was conducted. Least significant difference *t*-tests (LSD) were used for post hoc comparisons for ANOVA's means. A priori planned mean comparisons of two groups were analysed by *t*-tests.

Data analysis and description followed the principles of Abt's (1987) "Descriptive Data Analysis." Correspondingly, reported p-values (p) of the two-tailed significance tests only possess a descriptive function labelling the extent of group differences. Despite the multiplicity of significance tests, no alpha-adjustment was conducted, since the present analysis was not a confirmatory data analysis. P-values ≤ .05 were described as significant; p-values greater than .05 and less than .10 described as a trend. Additionally, the effect size parameters, d, and w were used to report practical significance (Cohen, 1988). The effect size categories (small, medium, large) mentioned in the results section always refer to significant group differences. Effect sizes d and w were calculated by Excel procedures. The statistical software SPSS was used for any other analysis.

4. Results

4.1. *WT noise annoyance*

Of all participants 69.3% perceived WT noise and 30.7% did not; 18.4% of total sample were not annoyed at all by WT noise (scale-point 0), 16.0% were slightly annoyed (scale-point 1), 17.9% were somewhat annoyed (scale-point 2), 10.9% were moderately annoyed (scale-point 3) and 6.1% very annoyed (scale-point 4). According to the scale criteria of Miedema and Vos (1998), 34.9% of all participants were annoyed (scale-points 2–4). However, from a stress psychological perspective, the possible appearance of symptoms should be considered as an additional criterion for strong annoyance. Therefore, we define participants with no symptoms and scale values 2–4 as "somewhat annoyed" (25.0%). If additionally, at least one symptom linked to WT noise occurred the participant was indicated as "strongly annoyed" (9.9%).

For the total sample in 2012, the average WT noise annoyance was between the levels "slightly" and "somewhat" (M = 1.58, SD = 1.28), mean score on the ICBEN-scale Q. V. was at the level "slightly" (M = 1.23, SD = 1.14) and on the ICBEN-scale Q. N. at the lower end at 3.26 (SD = 2.67). The group of strongly annoyed participants had slightly higher mean values than those of the somewhat annoyed (medium and large effect size). Since the three annoyance scales were strongly correlated (.84 to .91), only the values of the WT noise annoyance scale will be reported in the following. Until 2012, the participants on average had not observed any change of annoyance over the years of operation of the wind farm (M = .02, SD = .41). Between 2012 and 2014 there was a marginal perceived change. Only the somewhat annoyed participants experienced a slight decrease in annoyance (large effect size, Fig. 1).

4.2. *WT noise annoyance in comparison to other local noise sources*

For participants perceiving WT noise the wind farm was as annoying as local road traffic noise, maize choppers, and sand trucks, but marginally less annoying than balloon-wheel trucks (small effect size, Fig. 2). The annoyance caused by WT and sand trucks decreased marginally from 2012 to 2014 (small effect sizes) but not for road traffic noise and other sources.

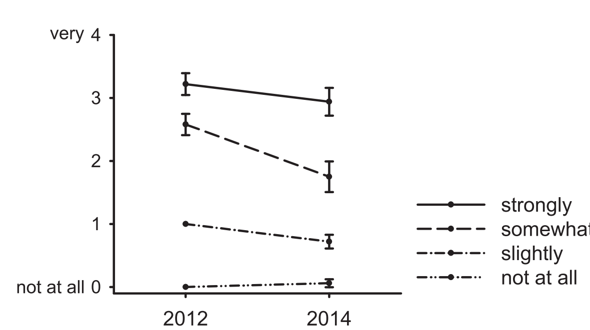

Fig. 1. Change of WT noise annoyance decrease for somewhat group only (M ± SEM, scale range: 0–4).

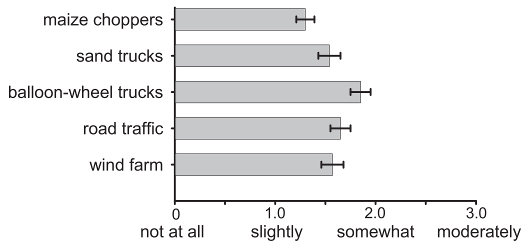

Fig. 2. WT noise annoyance lower compared to balloon-wheel trucks (2012, M ± SEM, scale range: 0–4).

4.3. Typical WT noise situation

About half of all participants (51.9%) reported in 2012 at least one typical annoying situation caused by WT noise. About half (53.6%) of this sub-sample experienced annoying noise about once a week, one-fifth (20.9%) about once a month, and 13.6% almost daily. Annoying noise occurred most frequently in the evening (33.6%) and at night (18.2%). This sub-sample felt most frequently disturbed while sleeping (30.0%), relaxation (24.5%) and leisure activities (19.1%). Most frequent emotional reactions were irritability or anger (39.1%). More than 10% of the sub-sample described WT noise as swooshing (76.4%), rumbling (72.7%), buzzing (23.6%) or grumbling (18.2%). Most frequently, the annoyance occurred during westerly winds (68.2%) – the local main wind direction – as well as during humid weather (30.9%) and frost (13.6%). The number of participants who reported a typical WT noise situation decreased clearly from 2012 to 2014 by about 22–29.3%. The pattern of noise effects remained comparable.

4.4. General impact of WT noise

In 2012, the somewhat and strongly annoyed residents assessed WT noise clearly to be more negative than the other groups (Fig. 3, medium or large effect sizes). Furthermore, the strongly annoyed participants rated WT noise more “threatening”, “harmful” and “intolerable” than the somewhat annoyed residents (medium effect sizes). Significant changes over time were only detected for the group without annoyance, which rated WT noise in 2014 slightly less peaceful and harmless than in 2012 (medium effect sizes).

4.5. Psychological and somatic symptoms

As mentioned above, only a few participants reported (9.9%) psychological or physical symptoms that they attributed to WT noise and which they experienced at least once a month (Table 1). In 2014, this

Table 1
Percentage of symptoms caused by WT noise or traffic noise at least once a month.

Symptoms	WT noise 2012	WT noise 2014	traffic noise 2014
general mental indisposition	5.7%	0%	6.0%
reduced performance and work capacity	5.2%	0%	3.0%
fatigue	5.2%	0%	4.5%
lack of concentration, reduced sustained attention	4.7%	0%	3.8%
nervousness	4.2%	0%	4.5%
tenseness	5.3%	2.3%	6.8%
negative mood	6.6%	0%	7.5%
helplessness	4.2%	3.8%	6.0%
irritability, anger, hostility	5.7%	3.0%	7.5%
general somatic indisposition	5.3%	0%	.8%
hindered falling asleep	6.7%	3.0%	3.8%
multiple awakening	4.7%	1.5%	5.3%
reduced sleep quality	6.1%	2.3%	6.0%
reduced depth of sleep	5.7%	1.5%	4.5%
overall symptom carriers	9.9%	6.8%	15.8%

proportion decreased to 6.8%. With an average of 12 symptoms, these participants clearly reported more symptoms in 2012 (M = 12.33, SD = 8.03) than in 2014 (M = 3.00, SD = 1.94, large effect size). Furthermore, strongly annoyed participants rated their general health slightly better in 2014 (2012: M = 2.00, SD = .71; 2014: M = 2.59, SD = 1.06; medium effect size). The symptoms were related to general performance, emotion, mood and sleep. From 2012 to 2014, sleep disturbance decreased, and symptoms of impaired performance did not recur. Strongly annoyed participants were not affected more by acute or chronic diseases than the other groups.

Distraction due to noise can lead to stress experience. The strongly annoyed residents in 2012 felt somewhat distracted by WT noise (M = 1.88, SD = 1.01), clearly stronger than any other group (large effect sizes). For this group the distraction decreased slightly from 2012 to 2014 (medium effect size, Fig. 4), while it remained relatively low and unchanged in the other groups.

Only a few participants showed evidence for low-frequency WT noise effects (< 100 Hz): in 2012, 8.5% reported wind farm-related feelings of pressure and 6.1% experienced vibrations in the body. Over time, these proportions decreased to 6.8% and 3.8%, respectively. The experienced annoyance induced by pressure feelings or vibrations was somewhat (2012: M = 2.17, SD = .86; M = 1.85, SD = 1.07 respectively; 2014: M = 2.00, SD = 1.12; M = 2.40, SD = 1.52 respectively). The symptom “dizziness“ was not observed. Therefore, no indicator for a negative vegetative effect of low-frequency noise could be detected (Krahé et al., 2014).

In order to evaluate stress effects appropriately, WT noise was compared with traffic noise. More participants experienced symptoms induced by traffic noise (15.8% of total sample) than WT noise; in 2014 only three participants reported complaints induced by both sources. In

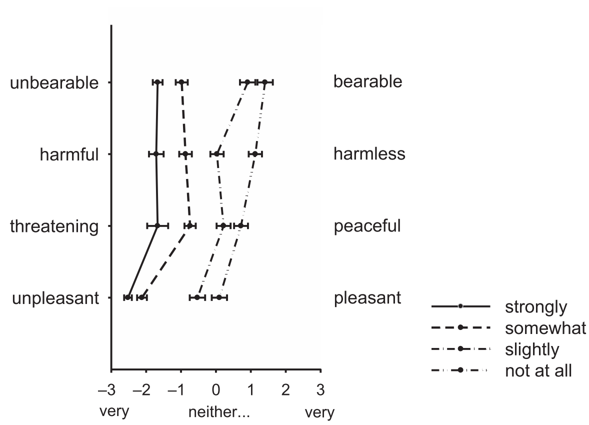

Fig. 3. WT noise impact most negative for strongly annoyed group (2012, M ± SEM, scale range: −3 – +3).

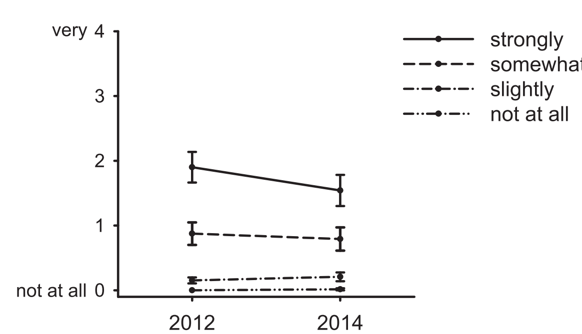

Fig. 4. Decrease of distraction induced by WT noise in the strongly annoyed group (M ± SEM, scale range: 0–4).

Fig. 5. Inefficient coping strategies in the strongly annoyed group (2012, M ± SEM, scale range: 0–4).

2014 about one-third (34.9%) of all participants was somewhat annoyed by traffic noise and 21.2% by WT noise. The pattern of symptoms for WT noise (2012) and traffic noise (2014) is very similar (Table 1).

4.6. Coping responses

Somewhat and strongly annoyed residents reported only little acceptance ("made peace", "all that bad") of WT noise in 2012 and observed it more critically than the other groups (Fig. 5, small to large effect sizes). Compared to the other groups, the somewhat annoyed participants showed a stronger emotional reassurance (i.e., had "stopped getting excited"; small to large effect sizes), which slightly increased from 2012 to 2014 (small or medium effect sizes). In contrast, cognitive coping for the strongly annoyed participants remained relatively stable. Thoughts of moving due to WT noise were only weak, even among the strongly annoyed residents (M = .81, SD = 1.25).

The most commonly used measures to reduce noise effects in 2012 were conversations with family members, friends and neighbors (32.1% of all participants), closing windows (25.9%), place leaving inside and outside the house(11.8%, 7.1%), and turning up the volume of the radio/TV (7.5%). In the groups of the somewhat and strongly annoyed participants, relatively more residents participated in conversations and closed their windows relatively more often (large effect sizes). Other measures taken were collecting signatures (13.7%) and demonstrating (9.4%), gathering information on WT noise (9.9%), and engaging in an environmental group/citizens' action committee (6.1%).

4.7. Analysis of complaint sheets and audio recordings

Ninety-five complaint sheets from 11 residents were included in the analysis, as well as 28 evaluable sound recordings from two participants. Almost all the records were made at night. WT operating data and measurements of wind speed and wind direction at hub height as well as at 10 m above ground level were included in the analysis. For the full report of this part of the project, see DEWI RS14-00017-01 (Gabriel and Vogl, 2014). Most of the complaints occurred during a southwesterly wind, which is the main wind direction, and at wind speeds at hub height of 6–9 m/s. There was a slight tendency to annoyance when the wind blew from the direction of the wind farm (downwind). The complaints occurred mainly during the night and early morning hours (83%), accumulating in the period from midnight to 3 a.m. The large number of nocturnal complaints can be explained by low background noise at nighttime, because Wilstedt is located far from any main road. Therefore, there is almost no nighttime traffic noise masking the relatively low level of sound from the WT.

Regarding the performed sound analyses, neither loudness of the broadband acoustic noise from the WT nor tonality or impulsivity is responsible for the documented complaints. Annoying WT noise has been characterized as predominantly irregular and fluctuating in loudness (71.6% pulsating swooshing). Thus – as opposed to national noise immission control regulation – it is not an absolute value of loudness, but the variation of loudness with the frequency of the rotating rotor blades, that primarily causes complaints. The perceived changes of sound are directly associated with the rotating blades. This noise characteristic is called amplitude modulation (AM). Special algorithms developed by DEWI (Vogl, 2013) were used to quantify AM in the sound recordings of perceived annoying WT noise. Examples are shown in Figs. 6 and 7 with AM for minutes or sporadic AM lasting a few seconds (typically < 10 s). This method of analysis is described in detail in report DEWI RS14-00017-01 (Gabriel and Vogl, 2014). The first algorithm calculated the physical modulation depth ΔL in dB after A-filtering. This measure is defined as the difference between the maximum and the following minimum of the sound pressure level (lower line). The second algorithm calculates the level of the pure psychoacoustic loudness variation F* (upper line) which is very similar to the fluctuation strength F developed by Zwicker and Fastl (1999).

The highest modulation depth ΔL was found in the frequency range 160–200 Hz, at wind speeds at hub height between 6 to 9.5 m/s, and WT rotational speed in the range of 14–18 U/min (average 16.2 U/min). Therefore, it can be concluded that maximum modulation occurred just below nominal rotational speed of the WT. A significant correlation of AM and wind direction could not be detected. The highest ΔL and F* values were found during nighttime.

AM can be used to explain the annoyance of WT noise (Fig. 7). We get used to regular stimuli and do not pay attention to them. New, unexpected and irregular stimuli attract attention. They trigger an orientation reaction and an alarm reaction in the case of a danger signal. The attention is directed unconsciously to such signals. This process can lead to a distraction of actions that are taking place.

4.8. General attitude towards WT and the local wind farm

In 2012 respondents reported on average a positive general attitude towards WT (M = 1.51, SD = 1.02) which remained positive with increasing annoyance level. The somewhat (M = 1.00, SD = 1.02) and strongly annoyed participants (M = .44, SD = .94) differed clearly from each other and the other three groups (medium and large effect sizes). For the somewhat annoyed residents, the attitude was marginally more positive in 2014 compared to 2012 (small effect size). No significant change was detected for the other groups. Participants reported strong involvement for the topic of wind energy (M = 3.09, SD = .78) – without significant differences between strongly annoyed (M = 3.22, SD = .76) and non-annoyed residents (M = 3.34, SD = .66).

Also regarding the local wind farm, participants reported on average a positive general attitude in 2012 (M = .73, SD = 1.64). Accordingly, attitudes towards wind energy and the local wind farm were highly

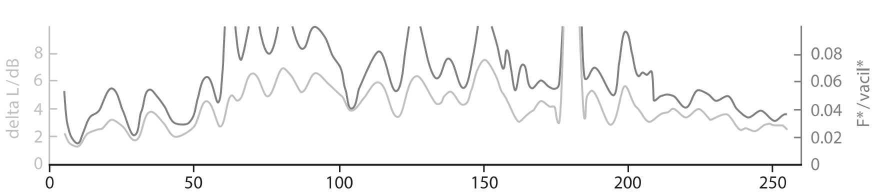

Fig. 6. Example for AM with strong modulation for minutes.

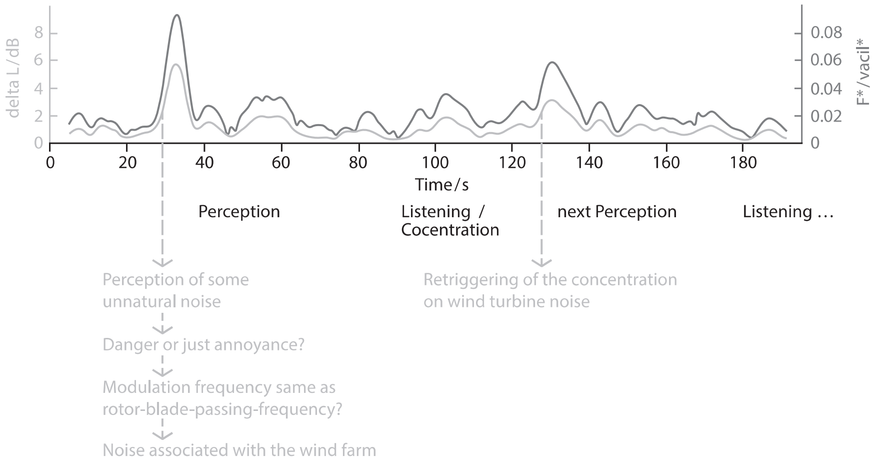

Fig. 7. Example for AM with short time perceptible modulation (upper part) and a description of the perception process of WT AM (lower part).

correlated (r = .83). In contrast, the somewhat and strongly annoyed residents showed a slightly negative attitude towards the local wind farm (M = −.60, SD = 1.42; M = −1.12, SD = 1.13 respectively) and differed clearly from each other and from the other three groups (small or large effect sizes).

Additionally, the participants were explicitly asked whether they had been wind farm opponents or proponents. Proponents (40.2%) were slightly more often represented than opponents (35.8%). Only a minority of 16.7% was ambivalent; 7.4% had no opinion on the wind farm. A further subdivision by active versus passive showed that opponents were more often active than the proponents: 30.4% of respondents indeed had been in favor of the wind farm but remained passive, and only a small proportion turned to be active (9.8%). Conversely, 26.5% had been active opponents and only 9.3% remained passive. It is noticeable that the majority of strongly annoyed residents (75.0%) had been passively or actively against the wind farm, whereas only 34.2% of the other participants showed active or passive behavior against the wind farm (small effect size).

4.9. Moderators

The analysis of relations between physical features and WT noise annoyance showed only small correlations for “distance to the closest WT“ (r = –.13) and “calculated A-weighted sound pressure level (SPL)” according to ISO 9613-2 (1993, r = .27). The SPL was on average 29.29 dB(A) (SD = 2.58, minimum = 10.23, maximum = 36.40). The correlation with “number of visible WT” was slightly stronger (r = .40).

There was a moderately negative relation between general attitude towards the local wind farm and WT noise annoyance (r = –.71). Further relevant correlations were found between “strain during the planning phase” (r = .37), “strain during the construction phase” (r = .34), “planning has been fair concerning one's own interests“ (r = –.52), “planning has been fair concerning community's interests” (r = –.52) and WT noise annoyance.

There were only small correlations between health indicators and WT noise annoyance (general health state, r = –.12; noise sensitivity, r = .26; emotional lability, r = .05), age (r = .20), and occupancy (r = .08). Women reported slightly stronger WT noise annoyance than men (M = 1.80, SD = 1.27 versus M = 1.36, SD = 1.25, small effect size).

4.10. Wilstedt sample in comparison with nationwide sample of residents of 13 wind farms

Overall, both groups rated the level of annoyance of the different WT emissions as very low to somewhat (Fig. 8). Concerning WT noise annoyance, the two groups did not differ significantly. Compared to the nationwide sample (Pohl et al., 2012), the Wilstedt sample reported

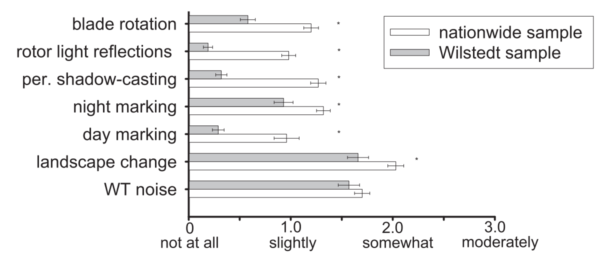

Fig. 8. Annoyance due to WT emissions comparing a nationwide and case sample (M ± SEM, scale range: 0–4, * p < .05).

significantly less annoyance due to landscape change, day and night obstruction marking, periodical shadow- casting, rotor light reflections and blade rotation (small and medium effect sizes). For both samples no statistically significant correlations were found between annoyance induced by different emissions and the distance to the nearest WT (all r < absolute value .25).

The general attitude towards the local wind farm was rated slightly positive in both groups without significant difference (Wilstedt sample: M = .43, SD = 1.67; nationwide sample: M= .30, SD = 1.92).

The general attitude towards WT was clearly positive in both groups. In the Wilstedt sample (M = 1.95, SD = .95) the attitude was slightly more positive than the comparison group (M = 1.43, SD = 1.61, small effect size). For the nationwide sample there was a strong correlation between the general attitude towards wind energy and the local wind farm (r = .78).

The gender distribution was comparable in both surveys. On average, respondents of the comparison group were four years younger than respondents of the Wilstedt sample. This difference, however, is too small to invalidate the interpretation of group differences in the mentioned features.

In conclusion, the comparison between both samples indicates Wilstedt to be a typical sample regarding WT noise annoyance. Therefore, the results regarding WT noise annoyance can be generalized. The other WT emission sources were rated more positively in the Wilstedt sample than in the nationwide sample. Therefore, the Wilstedt results for those other sources should not be generalized.

5. Discussion and recommendations

The present study is the first to extensively and differentially analyse the impact of WT noise on the experience and behavior of wind farm residents using an inter- and transdisciplinary approach. We have included a systematic approach to analyse stress effects in combination with noise audio recordings by residents and calculated sound pressure levels. It is also the first study to explore possible stress effects due to WT noise over the course of two years.

Only for a small percentage of all residents could strong WT noise annoyance be observed, which even decreased over time: in 2012 one-tenth (9.9%) was strongly annoyed, and two years later, this was true for only 6.8% of the residents. However, the WT were by no means the most potent local noise source – local traffic noise was strongly annoying for 15.8% of all participants. Residents belonging to one of the groups of strongly annoyed participants not only felt at least somewhat annoyed but also reported stress symptoms. Both noise sources – WT and traffic – led to a similar pattern of symptoms that is typical of noise effects (reduction in performance, concentration, and the incidence of irritability/anger, negative mood and disturbed sleep; Stansfeld and Matheson, 2003; Stansfeld et al., 2012). A similar pattern has already been shown in a previous study (Pohl et al., 1999). Regarding disturbed sleep, a comparable percentage (4–6%) was found in the large Dutch study by Bakker and colleagues – in this study they also found a very similar percentage of symptom-carriers due to traffic and engine noise (15%; Bakker et al., 2012). The similar results give a hint that the results could be generalize. Furthermore, the percentage of strongly WT noise-annoyed participants in Wilstedt is between the percentage of strongly annoyed residents in Switzerland (4.5%; Hübner and Löffler, 2013) and in the German state Schleswig-Holstein (15.7%; Pohl et al., 1999). The higher percentage of the Schleswig-Holstein sample is likely due to the older design of the WT and the differences regarding official directives – here the directives regarding the limitation of periodically shadow-casting of WT which was put into effect, taking into account the results of the study. The present results not being a special case is additionally proven by the comparison the Wilstedt-sample with a nationwide German sample of residents of 13 wind farms (Pohl et al., 2012). Thus, the present results suggest a generalization. The results of both studies were not distorted by extreme opinions (e.g., the general attitude towards the local wind farm or annoyance ratings). WT noise annoyance was not significantly correlated to age, general health state, emotional lability, and noise sensitivity. Overall, we concluded that our results are not influenced by a strong self-selection bias.

To better understand why some residents feel more annoyed by emissions of WT than others, we divided the participants into subgroups regarding noise perception and the level of annoyance. Compared to other groups, the strongly annoyed residents showed the strongest stress effects due to WT noise and an overall more negative evaluation of the wind farm. It can be assumed that stress began during the planning phase of the wind farm and was maintained throughout. This assumption is supported by the findings that this group had perceived a stronger annoyance due to the planning, approval and construction phase of the wind farm. Furthermore, 75% of the strongly annoyed residents reported to be actively or passively against the wind farm in the past. They showed comparatively less positive cognitive coping in terms of WT noise. As part of a stress management training, positive cognitive coping could be supported, as existing approaches show (Leventhall et al., 2008, 2012). However, the affected residents in our study responded with limited interest to such a remedial offer. Rather, a positive implementation of the planning and construction phase is more urgently recommended. There are positive experiences with early and informal resident participation (Devine-Wright, 2011; Rand and Hoen, 2017; Rau et al., 2012).

Even informal participation cannot guarantee that residents will experienced the planning process positively. Without serious resident participation, however, additional problems are more likely. For, as proven by the present results, the majority of the residents showed a positive attitude towards WT on the condition that their concerns are taken seriously. An often recurring concern by residents is the noise impact of WT. The present study was a response to the residents' complaints in Wilstedt. Their implementation and results are likely to have contributed to a decline in annoyance. Only little change in the evaluation of the wind farm was observed from 2012 to 2014. For the somewhat annoyed residents, noise annoyance decreased slightly and cognitive coping improved. For the strongly annoyed participants there was a reduction in WT noise-related distraction. The reduction of residents with noise related symptoms from 10% to 7%, and the decrease in the average number of symptoms from 12 to 3, can be interpreted as a significant change. We attribute the positive change – even after talking to some complainants – to the residents' positive evaluation of the study and the chosen approach and to the residents' active support and involvement.

For instance, the disturbing noises were independently recorded by residents and later analysed by us. Residents were informed about preliminary results (community meeting, letter with presentation of results). Additionally, plausible explanations for WT noise annoyance were offered and discussed in the plenum (e.g., AM). The aforementioned participation regarding the research process may have contributed to the positive changes. For the reported results reduced uncertainties and possible alternating interpretations of the findings and thus somewhat indirectly decreased WT noise annoyance. To our knowledge it is the first known field experiment showing that empirical information helps residents to reduce stress induced by WT noise.

This study does not provide any empirical evidence for the repeatedly asserted relationship between annoyance or acceptance of WT and distance to the residence. There is no numerically strong relationship between noise annoyance and the distance to the nearest WT or the estimated sound pressure level. Additionally, studies by Pohl et al., (1999, 2012) and Hübner and Löffler (2013) proved WT noise annoyance to be independent from the distance ($r = .03$; –.07; –.10), suggesting the existing emission protection laws are effective in general. For example, the German emission protection law determines the limits for permissible sound levels, which, among other features, determines the minimum distance.

However, an important indicator regarding the analysis of the causes was provided by the acoustic analysis of the disturbing WT noise, which has been recorded by the residents. A cause for the WT noise annoyance might be the amplitude modulation (AM), which explains the origin of certain annoying noise patterns. One explanation why AM cause annoyance is, that short-term amplitude changes may attract the residents' attention and thus disturbs current behavior. Research should be deepened in order to better understand the mechanism of action and develop technical solutions.

It became clear that there is detectable disturbing noise associated with the AM (from an acoustic point of view), but not with infrasound. Today, the data base of freely available AM data is very small (e.g., Cand et al., 2013). Further studies on AM of WT noise should broaden the database. For this, a long-term monitoring station needs to be developed that continuously records WT noise and residents' complaints.

Parallel to the sound detection, wind farm operating data and the wind speed profile (LIDAR) should be recorded in high solution, in order to improve understanding of the mechanisms of AM and check for possible dependency of the AM from the wind profile. Another interesting aspect is the overall interaction of WT in a wind farm with sporadic short modulation periods. For instance it is unknown whether AM is supported by the turbulent wake or the interaction of several WT. From the synopsis of meteorology data and WT operating data as well as sound data, knowledge regarding the causes of AM and their possible mitigation strategies can be derived.

For the development of noise mitigation strategies, the measurability of AM with an appropriate assessment tool is a necessary condition. The used algorithm must be improved because e.g., currently only the sinusoidal modulation is considered (for other methods proposed see e.g., Amplitude Modulation Working Group, 2016; Fukushima et al., 2013; Tachibana et al., 2014). To validate the evaluation of non-sinusoidal modulations and other tool modifications (in order to provide an AM-evaluation standard), hearing tests should be performed.

Overall, it appears promising to further develop the research approach used to understand in a more differentiated manner the psychological and acoustic causes and their interaction in the development and maintenance of WT noise annoyance. The present study provides insight into the mechanisms causing noise annoyance. However, replication studies are needed to further explore why some residents are strongly annoyed by WT noise and others are not, especially in comparison to traffic noise. Furthermore, the long-term effects are to be probed, e.g., whether or not and under what conditions habituation or sensitization occurs. To explore the influence of WT noise on sleep the method of ambulatory sleep monitoring would be useful. In this respect, first steps were made in the Health Canada study (2014) and in a study by Jalali et al. (2016). Both field studies did not find any relation between objective sleep parameters and WT noise exposure. Additionally it would be possible to supplement the research by including seismological studies in order to explore the transmission of low-frequency noise (< 100 Hz) through soil layers. Although no evidence of symptoms that would indicate low-frequency noise were reported by the participants, in order to address the concerns of WT opponents, low-frequency noise measurements are recommended for further studies. Overall the installation of a long-term monitoring station for WT noise as well as further studies on the effects on local residents (in the meaning of “Homo sapiens monitoring”) seem to be advisable. Homo sapiens monitoring is not recommended by the authors only but encouraged by the local residents.

Finally, it should be noted that strongly annoyed residents and explanations for the causes of their annoyance could be identified by means of the presented research paradigm. This approach complements the previous, rather epidemiological research on this subject (e.g., Pedersen and Persson Waye, 2004; Pedersen et al., 2009).

The most important and immediately realizable recommendation is to make the planning and construction process more of a positive experience for the residents. Thereby operators and authorities can preventatively reduce the likelihood of complaints after construction of the wind farm. Creating a more positive planning process includes the early and informal participation of residents and the consideration of their concerns. Although more residents seem to be strongly annoyed by traffic noise than by WT noise, a further improvement of WT technology is desirable. After all, the present study shows that citizens are not only in favor of wind energy in general but also support local installations, as long as they are developed sustainably.

Most important, the present results shows that noise annoyance can be reduced by providing empirical information to the residents.

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EXHIBIT
11

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Research Paper

Influence of visibility of wind farms on noise annoyance – A laboratory experiment with audio-visual simulations

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ABSTRACT

Noise annoyance reactions in the population due to wind farms are related to visual as well as noise-related impacts of the farms. Improved understanding of these effects may support the planning of better accepted wind farms. Recently, tools for visualization and auralization of wind farms have been developed that allow mutually studying audio-visual effects on annoyance. The objective of this study was to investigate the audio-visual effects of different wind turbine noise situations on short-term noise annoyance in a psychophysical laboratory experiment, considering serial position effects (simple order and differential carryover effects). A set of 24 audio-visual situations covering a range of acoustical characteristics (sound pressure level, periodic amplitude modulation) and visual settings (landscape with visible wind turbine, landscape only, grey background) was created. The factorial design of the experiment allowed separating audio-visual effects from serial position effects on noise annoyance. Both visual and acoustical characteristics were found to affect noise annoyance, besides the participants' attitude towards wind farms. Sound pressure level and amplitude modulation increased annoyance, the presence of a visualized landscape decreased annoyance, and the visibility of a wind turbine increased annoyance. While simple order effects could be eliminated by counterbalancing, the initial visual setting strongly affected the annoyance ratings of the subsequent settings. Due to this differential carryover effect, visual effects could be assessed reliably only as long as the participants saw the initial visual setting. Therefore, the presentation order of audio-visual stimuli should be carefully considered in experimental studies and in participatory landscape planning.

1. Introduction

The production of wind energy is growing worldwide. Between 2001 and 2016, the wind power capacity increased by a factor of 20, from some 24 to 487 GW (GWEC, 2017). As a result, landscapes suffer growing visual impacts, and increasing portions of the population are exposed to wind turbine (WT) noise. The visual and noise-related impacts of wind farms have therefore been much discussed in recent years. Regarding health effects of WT noise, noise annoyance seems most prevalent (van Kamp & van den Berg, 2018).

Literature from field surveys suggests that annoyance reactions to WT noise are often stronger than to transportation noise at comparable noise levels (van Kamp & van den Berg, 2018). Annoyance to WT noise was therefore extensively studied in field surveys (e.g., Hongisto, Oliva, & Keränen, 2017; Janssen, Vos, Eisses, & Pedersen, 2011; Klæboe & Sundfør, 2016; Michaud et al., 2016) as well as in laboratory experiments (e.g., Ioannidou, Santurette, & Jeong, 2016; Lee, Kim, Choi, & Lee, 2011; Schäffer et al., 2016; Schäffer, Pieren, Schlittmeier, & Brink, 2018). The studies reveal that annoyance reactions depend on various factors. First, specific acoustical characteristics of WT noise, which mainly consists of aerodynamic broadband noise, contribute to annoyance. Here, periodic amplitude modulation (AM), i.e., quasi-periodic temporal level fluctuations sometimes encountered, is particularly important. Periodic AM occurs at the blade passing frequency (~1 Hz). It comprises high-frequency "swishing" sound, sometimes also referred to as "Normal Amplitude Modulation", and more impulsive, mid- to low-frequency "thumping" sound ("Other Amplitude Modulation") (Bowdler, 2008; Oerlemans, 2015). It was found to be particularly annoying (Ioannidou et al., 2016; Lee et al., 2011), possibly by provoking the subjective hearing sensation "fluctuation strength" (Fastl & Zwicker, 2007). But also spectral characteristics such as low-frequency components may affect annoyance (Møller & Pedersen, 2011; Schäffer et al., 2018). Second, the visibility of WTs plays a crucial role (Janssen et al., 2011; Michaud et al., 2016; Pedersen & Larsman, 2008). Third, the living environment of residents (hilly vs. flat terrain) may affect reactions to noise

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(Pedersen & Larsman, 2008). Finally, also personal factors such as noise sensitivity (Miedema & Vos, 2003), attitude (Pedersen & Persson Waye, 2004) or familiarity with WT noise (Maffei et al., 2015), situational factors such as economic benefit (Janssen et al., 2011), and even expectations on caused health effects (Chapman, St George, Waller, & Cakic, 2013) were shown to be linked to noise annoyance.

Specific effects on noise annoyance can be effectively studied in controlled laboratory experiments. Compared to field surveys, laboratory experiments have the advantage of high control of the (noise) exposure as well as exclusion/control of effect modifiers (e.g., visibility of WTs or living environment, see above). In the past, such experiments often focussed either on the effects of acoustical characteristics of WT noise (classically in psychoacoustic studies where visual impacts may be deliberately excluded; see, e.g., Schäffer et al., 2016) or on visual impacts of wind farms (classically in landscape and environmental sciences and planning, focusing on social acceptance and visual preferences for WTs; see, e.g., Molnarova et al., 2012; Betakova, Vojar, & Sklenicka, 2015; and Scherhaufer, Höltinger, Salak, Schauppenlehner, & Schmidt, 2018). Besides the scientific interest, the results of these studies suggest practical recommendations for site planning of wind farms, such as regarding number, height, and placement of wind turbines in a landscape. However, considering audio-visual aspects mutually in such laboratory studies is important as both contribute to the perception of the studied situations (Lindquist, Lange, & Kang, 2016).

In recent years, laboratory experiments on mutual audio-visual effects on (noise) annoyance were conducted (He, Leickel, & Krahé, 2015; Maffei et al., 2013; Preis, Hafke-Dys, Szychowska, Kociński, & Felcyn, 2016; Ruotolo et al., 2012; Sun, De Coensel, Echevarria Sanchez, Van Renterghem, & Botteldooren, 2018; Szychowska, Hafke-Dys, Preis, Kociński, & Kleka, 2018; Yu, Behm, Bill, & Kang, 2017). The studies revealed that both, acoustical characteristics and visual settings, including the visibility of the noise source, affect (noise) annoyance. Here, one should consider that the experimental design, in particular the presentation order, may strongly affect the outcomes. When a number of stimuli is subsequently presented, two serial position effects may appear: simple order and/or differential carryover effects (Cohen, 2013). Simple order effects may result, e.g., from fatigue or practice. They can be averaged out and thus eliminated by counterbalancing (Cohen, 2013), either completely or partially (Latin squares), or by randomization if samples are large. For pure psychoacoustic experiments with a large number of stimuli, randomization is common practice (e.g., Nordtest, 2002). For psychophysical experiments involving also visual stimuli, in contrast, the effect of playback order may be less straightforward. Here, differential carryover effects may occur, where the rating of the stimulus is affected by previous stimuli. Differential carryover effects differ depending on the order of the stimuli. They cannot be eliminated by counterbalancing (Cohen, 2013). Here, either a sufficiently large time delay between treatments, putting a neutral task between stimuli for distraction, or a between-subjects design (i.e., assigning different participants to different stimuli) may be necessary (Cohen, 2013). As far as we know, however, studies on audio-visual effects of environmental noise sources (including WTs) did not systematically account for this effect to date.

The objective of the present study therefore was to investigate the audio-visual effects of WT noise situations on short-term noise annoyance, considering also possible serial position effects. Our hypotheses were that (i) acoustical characteristics alone contribute to noise annoyance, and that (ii) visual settings may act as effect modifiers for noise annoyance. To test these hypotheses, different situations with WT sound covering a range of acoustical characteristics (sound pressure level, periodic AM) and visual settings (landscape with a single visible WT, landscape only, grey background) were studied in a psychophysical laboratory experiment, which allowed separating the effects of the studied variables on noise annoyance.

Table 1
Factorial design of the psychophysical tests with 24 audio-visual wind turbine (WT) stimuli covering a range of sound pressure levels (L_{Aeq}) of 33.0–49.4 dB, two situations ("no" and "with") of periodic amplitude modulation (AM) of the sound, and three visual settings (WT = landscape with WT; LS = landscape only, Grey = grey background). The table shows the L_{Aeq} in dB per variable combination (same values for the three visual settings), resulting from observer distances to the WT of 100–600 m.

Distance to WT [m]	Periodic AM					
	no			with		
	Visual setting					
	WT	LS	Grey	WT	LS	Grey
100	48.6			49.4		
200	43.6			44.6		
350	38.2			39.2		
600	33.0			34.0		

2. Methods

2.1. Experimental concept and design

In this study, 24 audio-visual stimuli were systematically varied (full factorial design) with respect to three variables: distance to the WT, periodic AM of the sound (with, without) and visual setting (landscape with visible WT, landscape only, grey background) to study their individual contribution to short-term noise annoyance (Table 1). In the following, we refer to the noise annoyance studied here as "(noise) annoyance rating" (for the individual ratings) or "short-term (noise) annoyance", sometimes omitting the term "noise" in this context for sake of brevity.

The acoustical situations were similar to those studied by Schäffer et al. (2016): The distances of the observers to the WT cover a relevant sound pressure level (L_{Aeq}) range of WT noise to which residents may be exposed (Janssen et al., 2011; Tachibana, Yano, Fukushima, & Sueoka, 2014). The situations without periodic AM represent quasi-stationary WT noise, while those with periodic AM comprise "swishing" and "thumping" sound (see above).

For the stimuli with the visual settings "Landscape only" and "Landscape with WT", a hilly, rural landscape without buildings was chosen. Hilly terrain is a major landscape type of Switzerland, besides plains and mountains (Szerencsits et al., 2009). Such a setting was found to increase the risk of annoyance to WT noise, compared to urban areas or flat terrain (Pedersen & Persson Waye, 2007). Also, WTs were found to be more visible in rural than in urban areas (Pedersen, van den Berg, Bakker, & Bouma, 2009). For the case without visible landscape, a grey background ("Grey" in Table 1) was chosen, as grey is a neutral colour with respect to feelings (Heller, 2009).

2.2. Audio-visual stimuli

The audio-visual stimuli of Table 1 were synthetized using GIS-based 3D simulations with the tools of Manyoky, Wissen Hayek, Heutschi, Pieren, and Grêt-Regamey (2014), Pieren, Heutschi, Müller, Manyoky, and Eggenschwiler (2014) and Heutschi et al. (2014), as described below. For the current study, a location in a typical Swiss hilly landscape type was chosen for simulation. In this virtual environment, a single 2.0 MW Vestas V90 turbine (three blades, hub height = 95 m, rotor diameter = 90 m) was placed. The observer was set at 1.7 m above ground and at four positions situated 100–600 m away from the WT position (Table 1). The meteorological conditions were chosen as a sunny day with strong wind conditions resulting in a rotational speed of the WT of 15 rpm.

2.2.1. Visualization

Computer-generated imagery animations were created using the game engine CRYENGINE by Crytek GmbH (2015) as described in

Manyoky et al. (2014). The procedure involved (i) import of a digital elevation model and an orthophoto of an existing landscape, (ii) removing striking and recognizable landscape elements (e.g., characteristic mountain ranges) from the background to obtain a more generic setting (Ribe et al., 2018), (iii) adding 3D models for vegetation and infrastructures (e.g., road, WT), (iv) definition of a wind speed profile for movement of the WT blades and the vegetation, and (v) visual optimisations, e.g., of the colorization of the orthophoto and vegetation models and of the lighting settings, to obtain a higher level of realism.

For the current study, the landscape type "hills" of Ribe et al. (2018), which had been created in an older CRYENGINE version, was re-established in the more recent Version 3.4.8. Into the resulting visual setting, a 3D model of the WT was either placed and animated ("Landscape with WT" in Table 1), or not ("Landscape only" in Table 1). For these two settings, images were rendered for videos (Section 2.2.3) for the four observer positions (Table 1) with a widescreen aspect ratio of 16:9 (Fig. 1). The observer direction was chosen such as to see the WT to the right hand side of the visual field, to avoid a too strong focus on the WT during the experiments. In the videos both the 3D models of moving vegetation and WT with rotating blades (in clockwise direction) were animated. The rendered sets of images were complemented with a grey background image ("grey" in Table 1).

2.2.2. Auralization

The acoustical stimuli were artificially generated using digital sound synthesis as described in Pieren et al. (2014) and Heutschi et al. (2014), with the parameter settings similar to those of Schäffer et al. (2016).

The auralization process consists of three main steps, namely, emission synthesis, propagation filtering, and reproduction rendering. The synthesis of the sound emissions of the WT was done for strong wind conditions. Periodic AM of the sound was realized with a standard deviation of the level fluctuation of 3 dB and a modulation frequency of 0.75 Hz, corresponding to the rotational speed of 15 rpm. Sound propagation effects from the source to the observer locations were simulated by digital filtering (Heutschi et al., 2014), accounting for the propagation effects geometrical spreading, air absorption, ground reflection on a grassy terrain and atmospheric turbulence. The propagation situations with distances of 100–600 m resulted in a L_{Aeq} range of ~33–49 dB (Table 1).

In a final step, the synthesized sound pressure signals were rendered for surround sound reproduction with a five-channel loudspeaker setup (cf. Section 2.3.1) to generate a realistic hearing impression with directional information. Reproduction rendering was accomplished as described in Wissen Hayek, Pieren, Heutschi, Manyoky, and Grêt-Regamey (2018), using Vector Base Amplitude Panning by Pulkki (1997). This technique allows virtual sound source positioning with a loudspeaker array by calculating the individual loudspeaker feeds. In addition to the stimuli, a reference signal with a predefined sound pressure level was created for level calibration of the playback system.

To get an audio impression of the resulting stimuli with and without periodic AM, audio examples provided as supplementary material by Schäffer et al. (2016), which are very similar to those used here, may be consulted. Fig. 2 shows exemplary level-time histories, and Fig. 3 the spectra of the resulting acoustical stimuli. The standard deviations of the FAST time-weighted level fluctuations amount to ~0.8 dB and ~2.3 dB in the situations without and with periodic AM, respectively (Fig. 2), independent of the propagation distance. Due to the distinctly stronger level fluctuations and correspondingly higher L_{AF} peaks in situations with periodic AM compared to without AM (Fig. 2), the resulting L_{Aeq} of the former are ~1 dB larger than the latter (Table 1, Fig. 3).

The WT spectra reveal considerable energy at low frequencies, with spectral variations due to the ground effect (Fig. 3). As atmospheric attenuation increases with frequency, the low-frequency content becomes more pronounced with increasing propagation distance. Accordingly, the level difference L_{C-A} between the C-weighted and A-weighted sound pressure level increases from 9 dB at 100 m to 14 dB at 600 m, and the spectral slope, i.e., the L_{eq} of the unweighted sound pressure level vs. octave band, from −2.6 dB/oct at 100 m to −5.1 dB/oct at 600 m (Fig. 3a). The slope of −4.1 dB/oct at 350 m coincides with the value observed by Tachibana et al. (2014) for residential areas around wind farms.

Fig. 1. Images of the visual stimuli covering three visual settings (landscape with visible wind turbine, landscape only, grey background) for distances of 100–600 m.

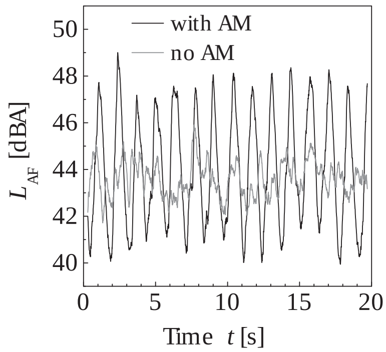

Fig. 2. Level-time histories of the A-weighted and FAST-time-weighted sound pressure level (L_{AF}) of the stimuli without ("no") and with amplitude modulation (AM), for a distance of 200 m.

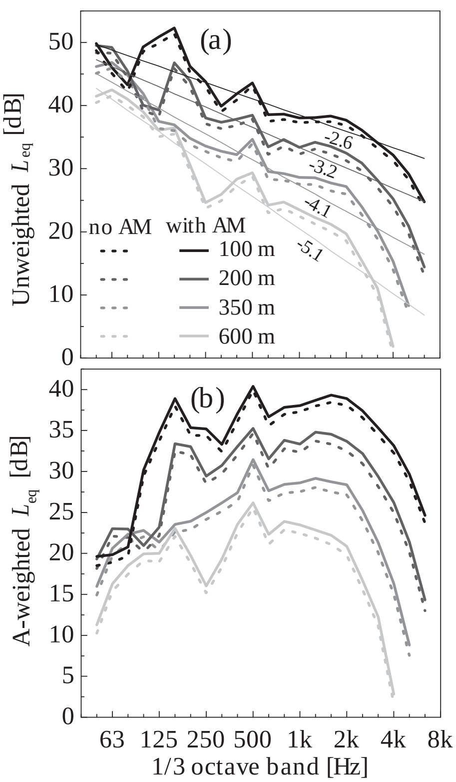

Fig. 3. (a) Unweighted and (b) A-weighted 1/3 octave band spectra (in L_{eq}) of the stimuli without ("no") and with amplitude modulation (AM), for distances of 100–600 m, in (a) with mean spectral slopes (thin solid lines: regressions per distance of the L_{eq} on 1/3 octave band) with the numbers below the lines indicating the slope in dB/oct.

2.2.3. Combination to acoustic-visual stimuli

The rendered images were stitched and encoded to videos of 21.5 s duration (stimuli of 20 s plus fade-in and fade-out), and the rendered audio data were time synchronised and linked to the videos as described in Manyoky et al. (2014) and Ribe et al. (2018). Each of the three visual settings of Table 1 was linked with two acoustical situations (with and without AM). This resulted in a total of 24 compressed videos (Multimedia container format MP4, video codec H.264, frame rate 60 fps, audio codec MPEG AAC, audio sampling rate 44.1 kHz) for playback.

2.3. Psychophysical experiments

2.3.1. Laboratory setup

The listening tests were carried out in the "Mobile Visual-Acoustic Lab" (MVAL), which is described in detail in Manyoky, Wissen Hayek, Pieren, Heutschi, and Grêt-Regamey (2016). For the experiment, the MVAL was built up in a room with low background noise and a carpet floor at the authors' institution ETH. MVAL consists of an aluminium construction (5 m × 5 m × 2.5 m) carrying black, sound absorbing curtains as walls and ceiling to exclude light and to obtain a favourable sound field. Within MVAL, five active loudspeakers (Focal CMS 50, Focal-JMlab) were arranged in a pentagon setting in a distance of 210 cm from the centre, along with a low-noise projector (Acer H6500, Acer Group) and a micro-perforated projection screen sized 2.70 m × 1.65 m. The videos were played using the VLC media player Version 2.2.4 on a laptop connected to the projector and the loudspeakers via a multichannel audio interface (Motu 896mk3, MOTU). Up to three persons simultaneously participated in the experiment. The seats were arranged at the centre of the pentagon. The audio playback chain was calibrated in level with the reference signal (Section 2.2.2) and a sound level meter located at the centre of the pentagon.

2.3.2. Experimental procedure

The experiments were conducted as a within-subject design, where all participants were exposed to all stimuli. Prior to the experiment, the participants were introduced to the research topic and task (noise annoyance rating of different situations with WT sounds). After signing a consent form to participate in the study, they answered questions on hearing and well-being as criterions for inclusion in the experiments.

The experiments were done as focused tests. The participants watched and listened to the videos, and rated them regarding noise annoyance after play-back by means of a paper-and-pencil questionnaire (supplementary data, see Appendix A). An investigator, situated at the back of the MVAL, played back the stimuli (once only), one by one, turning off the light during play back and turning it on between the stimuli for the participants to enter the ratings. Annoyance was rated with the ICBEN 11-point scale (Fields et al., 2001), where 0 represents the lowest and 10 the highest noise annoyance rating, by answering the following question (in German, modified from Fields et al., 2001): "You will be subsequently presented with 24 different situations of wind turbine sounds, which you are to rate regarding your annoyance by the sounds. What number from 0 to 10 represents best how much you felt bothered, disturbed or annoyed by the played back situation?" The experiments consisted of (i) an orientation with two stimuli to set the frame of reference, (ii) two exercise ratings to get accustomed to the task with the 11-point scale, and (iii) the actual ratings of the 24 stimuli from Table 1.

After the experiment, the participants completed a pen-and-pencil questionnaire, which assessed noise sensitivity, attitude towards wind farms, gender, age, highest educational degree achieved, landscape most frequently used for recreation, and questions about the experiment. Noise sensitivity was measured with the NoiSeQ-R by Griefahn, Marks, Gjestland, and Preis (2007) (the short form of the NoiSeQ by Schütte, Marks, Wenning, & Griefahn, 2007), which covers values of 0 (noise-insensitive) to 3 (highly noise-sensitive), and attitude towards wind farms with the questionnaire of Schäffer et al. (2016), which covers values of 0 (very negative) to 4 (very positive).

The whole test procedure lasted about one hour. Participants were compensated with 20 Swiss Francs (about 18 Euro) after completing the experiments.

2.3.3. Playback order of the stimuli

Special attention was paid to the playback order of the stimuli. Randomization is a successful strategy in many psychoacoustic experiments, including those of Schäffer et al. (2016; 2018). However for visual stimuli, some authors balanced the order of the stimuli (Ferris, Kempton, Deary, Austin, & Shotter, 2001; Maffei et al., 2013), while others randomized them, either within the same session (Szychowska et al., 2018) or over different days (Sun et al., 2018).

In a preliminary experiment preceding the present study, we played back the audio-visual stimuli of Table 1 to 40 participants (22 females, 18 males) in fully randomized order, using the same laboratory setup and experimental procedure as described above. The results are presented in Appendix B (Fig. B1). The experiment revealed that noise annoyance increases with the acoustical characteristics L_{Aeq} and periodic AM, as well as with the playback number ($p < 0.001$), which is in accordance with the findings of Schäffer et al. (2016). Further, annoyance tended to decrease with more positive attitude toward wind farms ($p = 0.051$), which corroborates the results of Schäffer et al. (2018). The visual setting, in contrast, apparently had no effect ($p = 0.15$). This finding was unexpected insofar as the visual setting differed strongly (Fig. 1) and as some participants felt that it influenced their noise annoyance rating.

For the main experiment, we therefore used a completely counterbalanced design regarding the visual setting (Cohen, 2013). The three visual settings of Table 1 were presented in three blocks in completely counterbalanced order, and the eight acoustical situations per visual setting in randomized order. With this design, the annoyance ratings of the first block correspond to a between-subject design (see above) and are free from potential visual differential carryover effects, while those of the subsequent blocks may contain such effects.

2.3.4. Participants

Forty-three participants (22 females, 21 males), all with self-declared normal hearing and feeling well and healthy, were included in the study. A large part studied or worked at the authors' institution ETH. Accordingly, the panel was quite young (19–52 years; median of 25 years) and well educated, with 67% possessing an academic degree (BSc, MSc, MAS or PhD), and another 30% studying to obtain one. The panel was moderately noise sensitive (noise sensitivity values of 0.4–2.9, median of 1.7). Further, with attitude values of 1.2–4.0 (median of 2.9), the panel was largely positive towards wind farms. The participants spent most of their spare time rather in hilly regions (50%) than in plains (35%) or mountains (15%), and somewhat more in urban (58%) than in rural areas (42%). Thus, the visual setting of the stimuli (hilly rural) corresponded to the preference of a large part of the participants. 67% of the participants had heard WT noise before.

2.4. Statistical analysis

Statistical analysis was done in IBM SPSS Version 23 and 25.

The consistency of the annoyance ratings between participants was assessed with the inter-rater reliability (Hallgren, 2012), doing a two-way random, consistency, average-measures intraclass correlation (ICC) (McGraw & Wong, 1996), where large ICC values indicate high agreement between individuals.

The noise annoyance ratings were analysed by means of linear mixed-effects models (see, e.g., West, Welch, & Gałecki, 2015), using the SPSS procedure MIXED. To that aim, the variables of Table 1 were included as fixed effects, namely, the L_{Aeq} resulting from the distance to the WT as a continuous variable, and periodic AM and visual setting as categorical variables. Potential differential carryover effects of the visual information were also considered with the variable visual setting, which describes the current visual setting and the preceding settings ("the visual history"; cf. Section 3). Given the experimental design, the variables of Table 1, as well as their interactions, were a priori tested. In addition, simple order effects (aside from differential carryover effects) of the playback number of the stimuli (continuous variable), as well as the link of the participants' characteristics to noise annoyance were studied. Finally, repeated observations (24 ratings per participant) were accounted for with a random effect for the participants. Different models of different degrees of complexity (with respect to fixed and random effects) were tested to find the optimal model with respect to completeness (include all relevant variables), performance (data representation, significance of effects) and parsimony (simplicity of the model). The goodness-of-fit of the final model was assessed with the marginal (R^2_m for the fixed effects) and conditional coefficient of determination (R^2_c for the fixed and random effects) (Johnson, 2014; Nakagawa & Schielzeth, 2013). Model assumptions were confirmed by means of residual plots, which did not reveal any obvious deviation from normality, and suggested constant variance as well as independence of the observations (except within participants, which was accounted for by the mixed-effect model).

3. Results and discussion

The observed annoyance ratings have an ICC of 0.989. This value lies in the excellent range (Cicchetti, 1994), indicating a high degree of agreement between participants (Hallgren, 2012). In the following account (Sections 3.1–3.3), the observed short-term noise annoyance is discussed. All effects discussed here were confirmed with the mixed-effects model analysis, the results of which are presented graphically along with the observations in Figs. 4–7, as well as described in more detail in Section 3.4. In Section 3.5, the study is brought into broader context.

3.1. Audio-visual effects

Fig. 4 shows the effects of the audio-visual stimuli on noise annoyance, for the first block (first 8 stimuli, free from potential visual differential carryover effects) as well as for the whole experiment (all 24 stimuli). Noise annoyance is strongly linked with the L_{Aeq}, increasing linearly by 1.7 units per 5 dB increase of the L_{Aeq} (Fig. 4a). This corroborates the well-known crucial role of the L_{Aeq} to be a determinant for annoyance in the laboratory (e.g., Lee et al., 2011; Schäffer et al., 2016) and also that an A-weighted metric is appropriate to predict (WT noise) annoyance reactions (Bolin, Bluhm, & Nilsson, 2014). Besides, periodic AM increases annoyance by about 0.6 units on the 11-point scale (Fig. 4b), which would also be evoked by a ~2 dB increase of the L_{Aeq}. This effect has also been amply observed in the laboratory (Hafke-Dys, Preis, Kaczmarek, Biniakowski, & Kleka, 2016; Ioannidou et al., 2016; Lee et al., 2011; Schäffer et al., 2016; 2018) as well as in the field (Bockstael et al., 2012; Pohl, Gabriel, & Hübner, 2018). The results on L_{Aeq} and periodic AM are also in line with the preliminary experiment (Section 2.3.3). The link of the annoyance to the L_{Aeq} and AM is similar in the first block and the whole experiment, except that annoyance tends to increase in the course of the experiment (Fig. 4a and b: 24 vs. 8 stimuli). This suggests a simple order effect.

Finally, the visual setting strongly affects annoyance (Fig. 4c), i.e., it acts as an effect modifier for noise annoyance. For the first block, annoyance increases in the order landscape only < landscape with WT < grey, by 1.2 units on the 11-point scale, which corresponds to ~4 dB increase of the L_{Aeq}. Increased annoyance to situations with visible noise source was also observed in a laboratory study of Yu et al. (2017) and a field experiment by Bangjun, Lili, and Guoqing (2003), while Sun et al. (2018) found the effect of visibility to depend on the participants' noise sensitivity. This corroborates findings of field surveys that the visibility of wind farms increases annoyance (Klæboe & Sundfør, 2016; Pedersen & Larsman, 2008; Pedersen & Persson Waye, 2007; Pedersen et al., 2009). It is also in line with the finding of Maffei et al. (2013) that the number of WTs increases annoyance (although the authors did not investigate the case without visible WT). In the laboratory, the visibility of the WT may have led to (conscious) recognition of WT noise as such, which in turn may increase annoyance (Szychowska et al., 2018; Van Renterghem, Bockstael, De Weirt, & Botteldooren, 2013). Also, it may have shifted the participants' focus to the WT noise, while the landscape alone distracted the participants from the sound. Such focussing apparently was strongest in the grey setting, which did not offer any visual distraction from the sound. Besides, the strong reactions to the grey setting might by caused by the fact that purely auditory situations are emotionally more engaging than videos (Richardson et al., 2018). Our results of the grey vs. landscape setting are also corroborated by Preis, Kociński, Hafke-Dys, and Wrzosek (2015), who for some of their tested cases found audio-visual stimuli of urban places to be linked with a higher comfort feeling than acoustical stimuli alone.

The strong effect of the visual setting on noise annoyance observed for the first block (Fig. 4c, left) is lost when averaging over the whole experiment (Fig. 4c, right). In the latter case, the annoyance varied only by 0.3 points on the 11-point scale between settings, and in a different order (landscape only > landscape with WT ≈ grey). This change was likely to be evoked by a differential carryover effect, which is not eliminated by (complete) counterbalancing and thus may change the overall results (cf. Section 1). The above indicated simple order and differential carryover effects are discussed in Section 3.3.

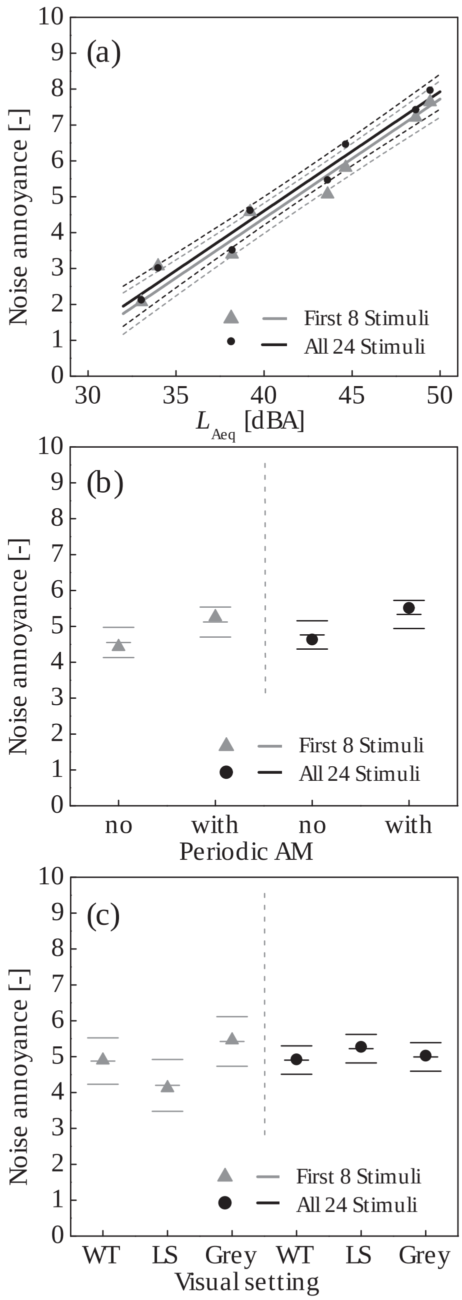

Fig. 4. Mean short-term noise annoyance as a function of the audio-visual characteristics (a) equivalent continuous sound pressure level (L_{Aeq}) (pooled data of different situations of amplitude modulation (AM) and visual settings), (b) AM (without ("no") or with; pooled data of different L_{Aeq} and visual settings) and (c) visual settings (landscape with wind turbine (WT), landscape only (LS) and grey; pooled data of different L_{Aeq} and AM), for the first block of visual setting (first 8 stimuli) and for all three blocks (all 24 stimuli). Symbols represent observations, and lines the corresponding mixed-effects model (Eq. (1)) with 95% confidence intervals, in (b) and (c) as horizontal lines. The annoyance ratings are shown at the mean playback number of either the first 8 stimuli or all 24 stimuli.

3.2. Influence of personal characteristics

The annoyance ratings were found to be lower the more positive the attitude towards wind farms, although scattering is relatively large (Fig. 5). On the 11-point scale, the ratings differ by 2.4 units within the observed range of attitude values of 1.2–4.0, corresponding to a L_{Aeq} difference of more than 7 dB. The importance of attitude was also observed by Ribe, Manyoky, Wissen Hayek, and Grêt-Regamey (2016) and Schäffer et al. (2018), as well as in the preliminary experiment (Section 2.3.3), and is also known from field surveys (Klæboe & Sundfør, 2016; Pedersen & Larsman, 2008; Pedersen & Persson Waye, 2004).

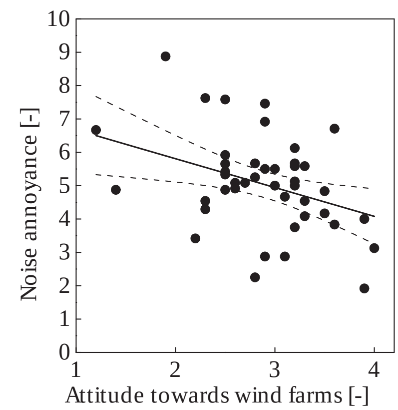

Fig. 5. Mean short-term noise annoyance (mean of all ratings per participant) as a function of the attitude towards wind farms (with values of 0 = very negative to 4 = very positive) according to Schäffer et al. (2016). Symbols represent observations, and lines the corresponding mixed-effects model (Eq. (1)) with 95% confidence intervals.

Annoyance was not linked to any other of the participants' tested characteristics (gender, age or noise sensitivity). Other laboratory studies, in contrast, found a dependency on noise sensitivity (Crichton, Dodd, Schmid, & Petrie, 2015; Sun et al., 2018) or no dependency on personal variables at all (Schäffer et al., 2016). These discrepancies may be due to the fact that in the laboratory, participants' ratings are closer to their sensory perception (corroborated also by the high ICC value found here), while in the field, personal and situational factors become much more important (Janssen et al., 2011; Michaud et al., 2016).

3.3. Simple order and differential carryover effects

Annoyance increased with the playback number of the stimuli, by about 0.6 units on the 11-point scale from the first to the twenty-fourth stimulus (Fig. 6). The same effect would also be evoked by a ~2 dB increase of the L_{Aeq}. Possibly, the participants became increasingly annoyed and/or fatigued by the stimuli, and rated the stimuli ever quicker as they got used to the sounds (practice or fatigue effect: Cohen, 2013). An increase in annoyance with playback number was also observed in the preliminary experiment (Section 2.3.3) as well as in previous laboratory experiments on noise annoyance by Schäffer et al. (2016; 2018). In contrast, an experiment with a pairwise comparison task to evaluate the subjectively perceived sound quality of speech did not reveal such effect (Sanavi, Schäffer, Heutschi, & Eggenschwiler, 2017). In fact, simple order effects were found to depend on the task and to be particularly important for simple tasks (Malhotra, 2009). This corroborates the importance of counterbalancing to eliminate such effects (Cohen, 2013).

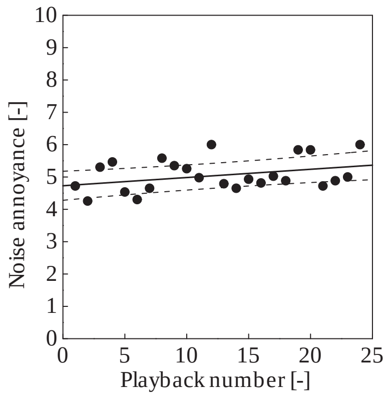

Fig. 6. Simple order effect: Mean short-term noise annoyance vs. playback number. Symbols represent observations (mean of all ratings per playback number), and lines the corresponding mixed-effects model (Eq. (1)) with 95% confidence intervals.

The potential differential carryover effects of the visual setting indicated by Fig. 4c are further presented in Fig. 7, which shows the mean annoyances per visual setting, separately for the first block of visual settings ("between-subject design", thus no visual differential carryover effect), for the second plus third block (with potential differential carryover effects), and for all three blocks. The results of the first block and of the mean of all three blocks correspond to Fig. 4c, except that the simple order effect was excluded in Fig. 7. The data of the second and third block were pooled, because the change between them was smaller than between the first and second block. This indicates that the initial and current visual settings are both determinant for ratings. This observation is congruent with findings from literature on memory, referred to as primacy and recency effect (Li, 2010; Murdock, 1962). The magnitude of annoyance of the first block strongly determines the annoyance of the following blocks. This effect of the first visual setting on annoyance seems even stronger than the effect of the current setting. Accordingly, the order of annoyance to the visual settings in the second/third block differs from the first block. This is likely to be caused by anchoring, where the magnitude of the first rating determines the magnitude of subsequent ratings (Sawyer & Wesensten, 1994). Of the possible carryover effects assimilation and contrast (Ferris et al., 2001), assimilation, i.e., bias towards the rating of the preceding (here, first) visual setting, was apparently the dominant effect here. Assimilation was also found, e.g., by Ward (1973) in a psychoacoustic experiment on loudness evaluation. As a consequence, the effect of the visual setting on the mean annoyance over the whole experiment is lost (Fig. 7, right), which was also observed in the preliminary experiment (Section 2.3.3). Even worse, the data pooled over the whole experiment suggests significant differences between visual settings in a different order than the first, unbiased block (Fig. 7). The observed carryover effect is in line with results from literature for visual assessment (Ferris et al., 2001).

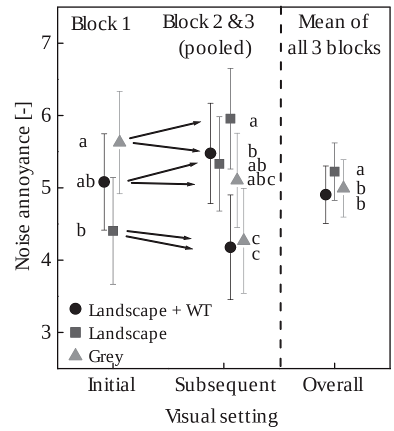

Fig. 7. Differential carryover effect: Mean short-term noise annoyance with 95% confidence intervals (mixed-effects model, Eq. (1)) as a function of the visual setting and the blocks of visual settings (initial = first block only; subsequent = second plus third block; overall = all three blocks). The data of the first block is free from differential carryover effects, while the data of the second/third block also depends on the first block, as indicated by the arrows. Values are shown at the mean playback number of all 24 stimuli to exclude the dependence on playback number (Fig. 6). For presentation purposes (better visibility of the overlapping confidence intervals) the data are slightly shifted on the x-axis. The observed mean annoyance values are very similar to the modelled values shown here except that it implicitly contains the dependency on playback number. Different letters indicate significant differences within blocks, as obtained from estimated marginal means (initial block, subsequent second plus third block) and contras analysis (overall).

Thus, the simple order effect influenced the annoyance to both, acoustical characteristics and visual setting, while a differential carryover effect was observed for the visual setting only. However, this finding cannot be generalized. First, differential carryover effects cannot be excluded a priori for acoustical stimuli. As an example, Sun et al. (2018) in their experiment presented the stimuli in different blocks over four consecutive days to minimize auditory memory of the participants. Second, the studied visual settings were either similar (landscape with vs. without WT) or without (much) information (grey). Thus, the current setting will not or only partially have erased the memory of the preceding setting(s), which might have promoted differential carryover effects. Also Maffei et al. (2013) used similar visual settings and observed only a weak effect of the number of WTs on annoyance (possibly diminished by differential carryover effects). In contrast, Szychowska et al. (2018) and Sun et al. (2018) (cf. Section 2.3.3) used very different visual settings. Here, the memory of the previous setting was probably erased by the current setting, which might have inhibited or at least reduced differential carryover effects, so that visual effects were observed over the whole experiment (contrary to our study). In conclusion, both types of serial position effects may play a role in psychophysical experiments and should be considered in experimental designs.

3.4. Statistical model

To describe the above observed effects on annoyance, the following mixed-effects model was found to be adequate:

$$Annoy_{ijk} = \mu + \beta \cdot L_{\mathrm{Aeq},ijk} + \tau_{\mathrm{AM},i} + \tau_{\mathrm{vis},j} + \gamma \cdot Ord_{ijk} + \delta \cdot Att_k + u_{0k} + u_{1k} \cdot L_{\mathrm{Aeq},ijk} + \varepsilon_{ijk}. \quad (1)$$

In Eq. (1), $Annoy_{ijk}$ is the dependent variable short-term annoyance, μ is the overall mean, τ_{AM} and τ_{vis} are the categorical variables AM (2 levels: $i = 1, 2$) and visual setting (current and first setting, described by 9 levels: $j = 1, \ldots, 9$), L_{Aeq}, *Ord* and *Att* are the continuous variables L_{Aeq}, order (playback number) and attitude towards wind farms, and β, γ and δ are their regression coefficients. The random effect terms u_{0k} and u_{1k} are the participants' random intercept and slope ($k = 1, \ldots, 43$), describing the dependence of the individual annoyance ratings on the L_{Aeq} (same model approach as by Schäffer et al., 2016), and ε_{ijk} is the error term. The index *ijk* represents the *k*th replicate observation of the *i*th AM with the *j*th visual setting. All variables of Eq. (1) are significantly linked to annoyance ($p < 0.001$ to $p = 0.01$). The model parameters are presented in Appendix C. The model explains more than 80% of the variance ($R^2_{\mathrm{m}} = 0.60$, $R^2_{\mathrm{c}} = 0.82$), indicating that it may reproduce the observations highly accurately.

3.5. Broader study context

This section aims at bringing the present study into broader context regarding (i) reproduction techniques, (ii) differences between laboratory experiments and field surveys, and (iii) practical implications.

First, our study revealed that visual impressions may strongly affect the participants' noise annoyance. However, although the audio-visual stimuli used here provided a high level of realism, the projection of the visualizations on a screen with a limited field of view does not meet human viewing habits, which may have influenced the participants' responses. For a more realistic simulation of the multisensory way in which the real environment is perceived, head-mounted displays or a Cave Automatic Virtual Environment (CAVE; e.g., Sahai et al., 2016) to present immersive virtual realities (IVR) are promising tools. They foster the participants' feeling of being present in the virtual environment (Maffei, Masullo, Pascale, Ruggiero, & Romero, 2016; Puyana-Romero, Lopez-Segura, Maffei, Hernández-Molina, & Masullo, 2017; Ruotolo et al., 2013; Yu et al., 2017). Also augmented reality (e.g., Botella et al., 2016) may provide such immersiveness. However, wearable devices such as head-mounted displays are intrusive, which in turn may affect results. Acoustically, immersiveness could be further improved by adding ambient sounds. Systematic studies on differences in results from experiments using different reproduction techniques would therefore be desirable.

Second, in interpreting the results, one should consider the inherent differences between field surveys and laboratory experiments, as discussed in detail for psychoacoustic experiments on WT noise annoyance by Schäffer et al. (2016; 2018). Laboratory experiments as performed here are an important complement to field surveys, because they allow isolating specific variables and thus systematically studying and developing a better understanding of their effects on noise annoyance (e.g., Szychowska et al., 2018; see above). However, at the same time, due to the focus on only few variables, laboratory experiments fall short of providing the whole environmental context, and hence, certain findings might not be confirmed by field surveys. For example, we observed the well-known crucial role of the L_{Aeq} in the laboratory (see Section 3.1), while its effect is weaker in the field (Brink, 2014), where other factors may play a more prominent role (e.g., Janssen et al., 2011; Michaud et al., 2016). Also, the short-term noise annoyance assessed in the laboratory is inherently different from long-term exposure in the field (Guski & Bosshardt, 1992). Therefore, it is crucial to bear in mind that results of single experiments are only revealing certain aspects of a more complex model, which needs to be built upon series of studies and meta-analyses, as proposed by Szychowska et al. (2018). The present study provides a valuable input for enhanced models, which may subsequently be validated in field surveys to prove the generalizability of the results.

Finally, the identified differential carryover effect of the first visual setting on the subsequent annoyance ratings may also have implications for planning practice, as audio-visual simulations are regarded a valuable tool for public participation in environmental planning (Maffei et al., 2016; Manyoky et al., 2016; Ribe et al., 2018). When these techniques are used, for example, to evaluate wind farm scenarios in different landscape contexts or as communication tools for residents of potential future wind parks, the presentation order of the landscapes and/or elements such as WTs (e.g., with/without) might affect the people's perception and noise annoyance, too. Hence, users of audio-visual simulations need to be aware of possible unwanted effects and of methods to avoid them. Focusing in training and teaching courses of 3D landscape simulation not only on technical but also on practical implementation aspects is, therefore, mandatory. Likewise, the presentation order should be rigorously considered in psychophysical laboratory experiments. It would be interesting to know if/how much the results of previous studies (Ferris et al., 2001; Maffei et al., 2013; Sun et al., 2018; Szychowska et al., 2018) (cf. Section 2.3.3) would have changed if the presentation order had been different.

4. Conclusions

In this study, audio-visual stimuli were systematically varied with respect to the distance of the observer from the WT, periodic AM of the sound and visual setting, accounting also for participants' personal characteristics, as well as for simple order and differential carryover effects. We are not aware of any other study on audio-visual effects of WTs, where also the playback order was explicitly accounted for.

We found that both acoustical characteristics and the visual setting affect noise annoyance, besides the participants' attitude towards wind farms. The visual setting may thus act as an effect modifier on noise annoyance. The investigated variables and their variation within the experiment ($L_{\mathrm{Aeq}} = 33$–49 dB; two situations of AM; three visual settings, playback number = 1–24; attitude value = 1.2–4.0) caused annoyance variations decreasing in the order L_{Aeq} (5.4 points on the ICBEN 11-point scale) > attitude (2.4 points) > unbiased visual setting (1.2 points, first block) > periodic AM ≈ playback number (both 0.6 points).

Our results further show that serial position effects (playback order) may affect the outcomes of psychophysical experiments. Simple order effects influenced the annoyance to both, acoustical characteristics and visual setting, while a differential carryover effect was observed for the latter only. Thus, the association of noise annoyance with acoustical characteristics can (usually) be reliably assessed by counterbalancing, eliminating simple order effects. The presentation order of visual stimuli, in contrast, needs more attention and should be explicitly accounted for in experimental designs (Nonyane & Theobald, 2007). The strength of the current study is the full control to separate the "primary" effects (Table 1) from simple order and differential carryover effects. To our knowledge, available studies from literature on audio-visual effects of environmental noise on annoyance did not explicitly investigate the latter effects to date. Whether and to what degree differential carryover effects affected their results thus cannot be answered.

In conclusion, audio-visual characteristics were found to mutually affect noise annoyance. The sound pressure level and amplitude modulation increased annoyance, the presence of a visualized landscape decreased annoyance, and the visibility of a wind turbine increased annoyance. To obtain unbiased experimental results, however, the presentation order of audio-visual stimuli needs to be carefully considered in experimental studies as well as in participatory landscape planning. As the number of audio-visual studies is increasing and findings are thought to support landscape planning and design decisions, it is essential to give these topics more consideration in future studies.

Acknowledgments

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Appendix A. Supplementary material

Supplementary data (authors' questionnaire) associated with this article can be found, in the online version, at https://doi.org/10.1016/j.landurbplan.2019.01.014.

Appendix B. Results of the preliminary experiment

See Fig. B1.

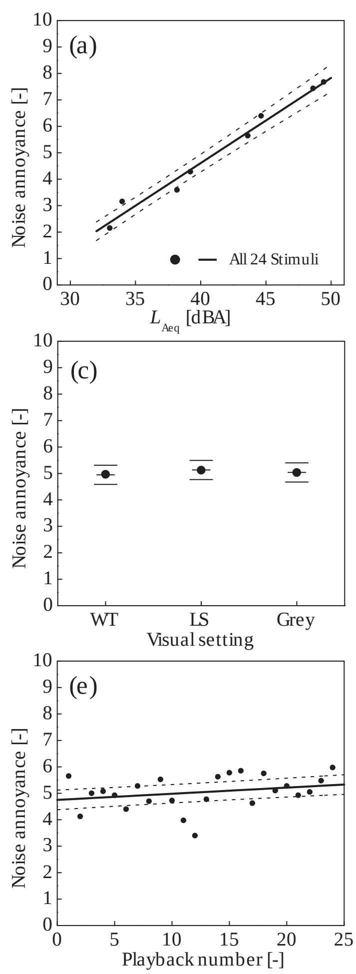

Fig. B1. Mean short-term noise annoyance as a function of (a) the equivalent continuous sound pressure level (L_{Aeq}) (pooled data of different situations of amplitude modulation (AM) and visual settings), (b) AM (without ("no") or with; pooled data of different L_{Aeq} and visual settings), (c) visual settings (landscape with wind turbine (WT), landscape only (LS) and grey; pooled data of different L_{Aeq} and AM), (d) attitude towards wind farms (mean of all ratings per participant, with values of 0 = very negative to 4 = very positive) according to Schäffer et al. (2016), and (e) playback number (mean of all ratings per playback number). Symbols represent observations, and lines the corresponding mixed-effects model with 95% confidence intervals, in (b) and (c) as horizontal lines. The annoyance ratings of (a)–(d) are shown at the mean playback number of all 24 stimuli. Note that an analogous statistical model was used here as for the main experiment (cf. Eq. (1) and Table C1), except that the visual setting was modelled simpler (3 categories only: WT, LS and grey), without accounting for differential carryover effects.

Appendix C. Linear mixed-effect model

See Table C1.

Table C1
Model coefficients with 95% confidence intervals (CI) and probability values (p) of the linear mixed-effects model for the annoyance ratings. The parameters symbols are explained in Eq. (1) in Section 3.4.

Parameter	Symbol	Coefficient	95% CI	p
Intercept	μ	−7.4373	[−10.0772; −4.7973]	< 0.001
L_{Aeq}	β	0.3322	[0.2930; 0.3713]	< 0.001
AM	$\tau_{AM,i=with}$	0.5703	[0.4201; 0.7205]	< 0.001
	$\tau_{AM,i=no}$	0[a]		
Visual setting (current; first)	$\tau_{vis,j=WT;none}$	0.6773	[−0.3008; 1.6554]	0.17
	$\tau_{vis,j=WT;LS}$	−0.2270	[−0.6274; 0.1733]	0.27
	$\tau_{vis,j=WT;Grey}$	1.0733	[0.0454; 2.1012]	0.04
	$\tau_{vis,j=LS;none}$	0[a]		
	$\tau_{vis,j=LS;WT}$	0.9265	[−0.0761; 1.929]	0.07
	$\tau_{vis,j=LS;Grey}$	1.5532	[0.5208; 2.5856]	< 0.01
	$\tau_{vis,j=Grey;none}$	1.2232	[0.2164; 2.2301]	0.02
	$\tau_{vis,j=Grey;WT}$	0.6999	[−0.3027; 1.7025]	0.17
	$\tau_{vis,j=Grey;LS}$	−0.1369	[−0.5438; 0.2700]	0.51
Playback number	γ	0.0255	[0.0065; 0.0444]	< 0.01
Attitude towards wind farms	δ	−0.8647	[−1.5207; −0.2086]	0.01
Random intercept	u_{0k}^2	27.3095	[16.891; 44.1541]	< 0.001
Random slope	u_{1k}^2	0.0143	[0.0088; 0.0232]	< 0.001
Residual	ε^2_{ijk}	1.4951	[1.3656; 1.6369]	< 0.001

[a] Redundant coefficients are set to zero.

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EXHIBIT
12

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Prevalence of wind farm amplitude modulation at long-range residential locations

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ABSTRACT

The presence of amplitude modulation (AM) in wind farm noise has been shown to result in increased annoyance. Therefore, it is important to determine how often this characteristic is present at residential locations near a wind farm. This study investigates the prevalence and characteristics of wind farm AM at 9 different residences located near a South Australian wind farm that has been the subject of complaints from local residents. It is shown that an audible indoor low-frequency tone was amplitude modulated at the blade-pass frequency for 20% of the time up to a distance of 2.4 km. The audible AM occurred for a similar percentage of time between wind farm percentage power capacities of 40 and 85%, indicating that it is important that AM analysis is not restricted to high power output conditions only. Although the number of AM events is shown to reduce with distance, audible indoor AM still occurred for 16% of the time at a distance of 3.5 km. At distances of 7.6 and 8.8 km, audible AM was only detected on one occasion. At night-time, audible AM occurred indoors at residences located as far as 3.5 km from the wind farm for up to 22% of the time.

1. Introduction

The rapid global expansion of wind energy has been associated with widespread complaints regarding annoyance, sleep disturbance and adverse health effects from people who have been exposed to wind turbine noise [1]. Therefore, to ensure that residents living near wind farms are not subjected to excessive noise-related disturbance, it is important to identify potentially disturbing wind farm noise components. Moreover, suitable methods for quantifying these components are required. Acceptable threshold levels also need to be defined to determine the prevalence of potential noise disturbance.

Several researchers have shown that amplitude modulation (AM) of wind farm noise contributes to annoyance [2–5]. Despite this finding, many regulations and guidelines concerning wind farm noise do not include penalties for this characteristic, possibly due to the ongoing debate as to what constitutes a reasonable penalty [6]. As discussed by Perkins et al. [7], the exposure-response to wind turbine AM noise is influenced by several factors including AM depth, noise level, duration/consistency of AM, time of occurrence and noise sensitivity of the individual.

Several methods have been developed to determine the AM depth of wind farm noise based on analysis in the time-domain, frequency-domain and a combination of both [8]. Recently the AM Working Group (AMWG), on behalf of the UK

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Institute of Acoustics, conducted an extensive review of existing methods for AM detection and quantification [8]. Following this review and a period of consultation, the group developed a method referred to as the IOA 'reference method' [9], which incorporates concepts developed by other research groups including Fukushima et al. [10] and Renewable UK [2] into a hybrid (time- and frequency-domain based) method. The main advantages of this method are that it can be automated, allowing analysis over long time periods, and it is robust to background noise contamination, reducing the instances of false positives.

This study investigates the suitability of the IOA 'reference method' for detecting low-frequency AM of a tone that is generated by wind turbines. The motivation for this analysis is to investigate the prevalence of a low-frequency 'thumping' or 'rumbling' noise that has been mentioned in complaints from residents. In fact, during a study by the South Australian Environmental Protection Agency in 2013, at least 14 (out of 15) residents living at various distances up to 8 km complained of 'thumping' and/or 'rumbling'. Their responses were documented in noise diaries that were collected over several weeks and these were provided to our research group. Since the IOA 'reference method' has been validated using broadband noise [2,11], which is representative of wind farm noise at distances less than 1 km from a wind farm, some modifications are proposed to extend its applicability to tonal AM measured at larger distances. These include changes to the analysis bandwidth, reduction in the prominence factor representing 'valid AM', assessment of the tonal audibility and reduction in the AM depth for cases when the tonal audibility is less than 0 dB at AM 'troughs'. The modified algorithm is then applied to outdoor and indoor data measured at 9 residences over a total of approximately 64 days of continuous recording to investigate the prevalence of AM and the associated AM depth. Relationships between AM and distance from the wind farm, AM and wind farm operating conditions and AM and time of day are also explored.

2. Measurement set-up

Outdoor measurements were carried out for a total of approximately 64 days at 9 different residences located between 1 and 9 km from the nearest wind turbine of a South Australian wind farm, which at the time of measurements was made up of 37 operational turbines, each with a rated power of 3 MW. The wind farm is positioned along the top of a ridge and the wind turbine hub height relative to the residences varies between 85 and 240 m. The wind turbine and residence locations are shown in Fig. 1. Time series data were acquired both outdoors and indoors using National Instruments 9234 (at 10240 Hz sampling rate) and Bruel and Kajer LAN-XI Type 3050 (at 8192 Hz sampling rate) data acquisition systems, respectively. The outdoor microphone was a G.R.A.S type 40AZ with a 26CG preamplifier, which has a noise floor of 16 dB(A) and a flat frequency response down to 0.5 Hz. The outdoor microphone was mounted at a height of 1.5 m and protected using a spherical secondary windscreen with a diameter of 450 mm. Details of the construction of this windscreen are provided in Hansen et al. [12]. The outdoor microphone was typically positioned at least 20 m away from the residence and at least 10 m from surrounding vegetation to minimise façade reflections and wind-induced vegetation noise, respectively. A typical outdoor measurement set-up is shown in Fig. 2. The indoor microphone was a B&K type 4955, which has a noise floor of 6.5 dB(A) and a flat frequency response down to 6 Hz. The indoor microphone used in the analysis was mounted on a mini tripod and positioned approximately 100 mm from a room corner, at the intersection between two walls and the floor. Two other indoor microphones were mounted at heights of 1.5 m

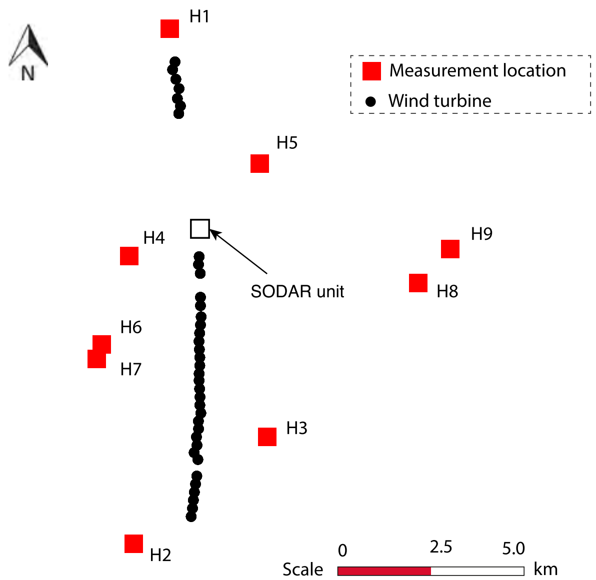

Fig. 1. Scaled diagram showing position of residences relative to the wind farm.

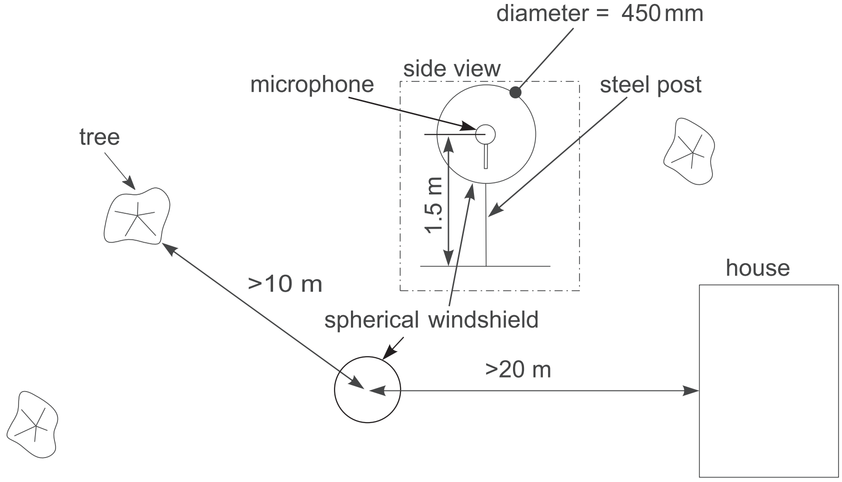

Fig. 2. Schematic showing a typical outdoor measurement set-up.

Table 1
Number of 10-min samples measured outdoors and indoors at each residence.

Residence	H1	H2	H3	H4	H5	H6	H7	H8	H9
Distance (km)	1.3	2.3	2.4	2.5	3.3	3.4	3.5	7.6	8.8
Outdoors	833	700	471	1548	1087	640	1659	999	848
Indoors	834	803	860	1561	1091	640	1344	989	850

and positioned randomly within the room. At all residences, the indoor measurements were taken in a room that faced as closely as possible towards the wind farm and the windows were closed. A total of 8716 and 8972 10-min samples of outdoor and indoor data, respectively, were analysed in this study. The number of 10-min samples taken outdoors and indoors at each residence is shown in Table 1.

Hub-height wind speed data for the nearest wind turbine to each residence were available from the wind farm operator for all residences except H5, for which the hub height data were measured using a Fulcrum 3D SODAR. The SODAR was located on the same ridge-top as the wind turbines, as shown in Fig. 1. The resolution of this device is ±0.01 m/s, according to the manufacturer. Power output data for the wind farm were obtained from the Australian Energy Market Operator website [13] in 5-min averages. These data pertain to the entire wind farm and data for each individual wind turbine were not available.

3. Analysis techniques

3.1. AM detection and quantification method

Several methods have been developed for detecting and quantifying AM and they can be divided into 3 categories: time-domain [10], frequency-domain [4] and 'hybrid' methods [9], the latter of which involves analysis in both the time and frequency domains. A comprehensive review of these methods can be found in Refs. [8,14]. In this study, the IOA 'reference method' [9], a hybrid method, has been used for detecting and quantifying AM. However, to ensure reliable detection of the low-frequency tonal AM that is characteristic of the wind farm noise analysed in this study, several modifications were required, which are as follows:

1. The bandwidth of analysis was limited to a single 1/3-octave band containing AM with the highest associated AM depth.
2. The prominence factor described in the IOA 'reference method' was reduced to 3. This means that the spectral peak at the BPF did not need to be as high above the noise floor of the power spectrum to be considered as wind farm AM.
3. The audibility of the tone was assessed based on the sound pressure level (SPL) in the 50 Hz 1/3-octave band and masking noise in the first critical band (20–120 Hz).
   (a) The normal hearing threshold curve specified in ISO 389-7 [15] was used to determine if the SPL in the 50 Hz 1/3-octave band was sufficiently high to be potentially audible.
   (b) For cases identified in (a), the tonal audibility was assessed using the method outlined in the IEC 61400-11 standard [16]. Note that this standard does not explicitly state that the tone should be above the hearing threshold. However, this is an important consideration for low level tones, and thus audibility was also evaluated using ISO 389-7 [15].

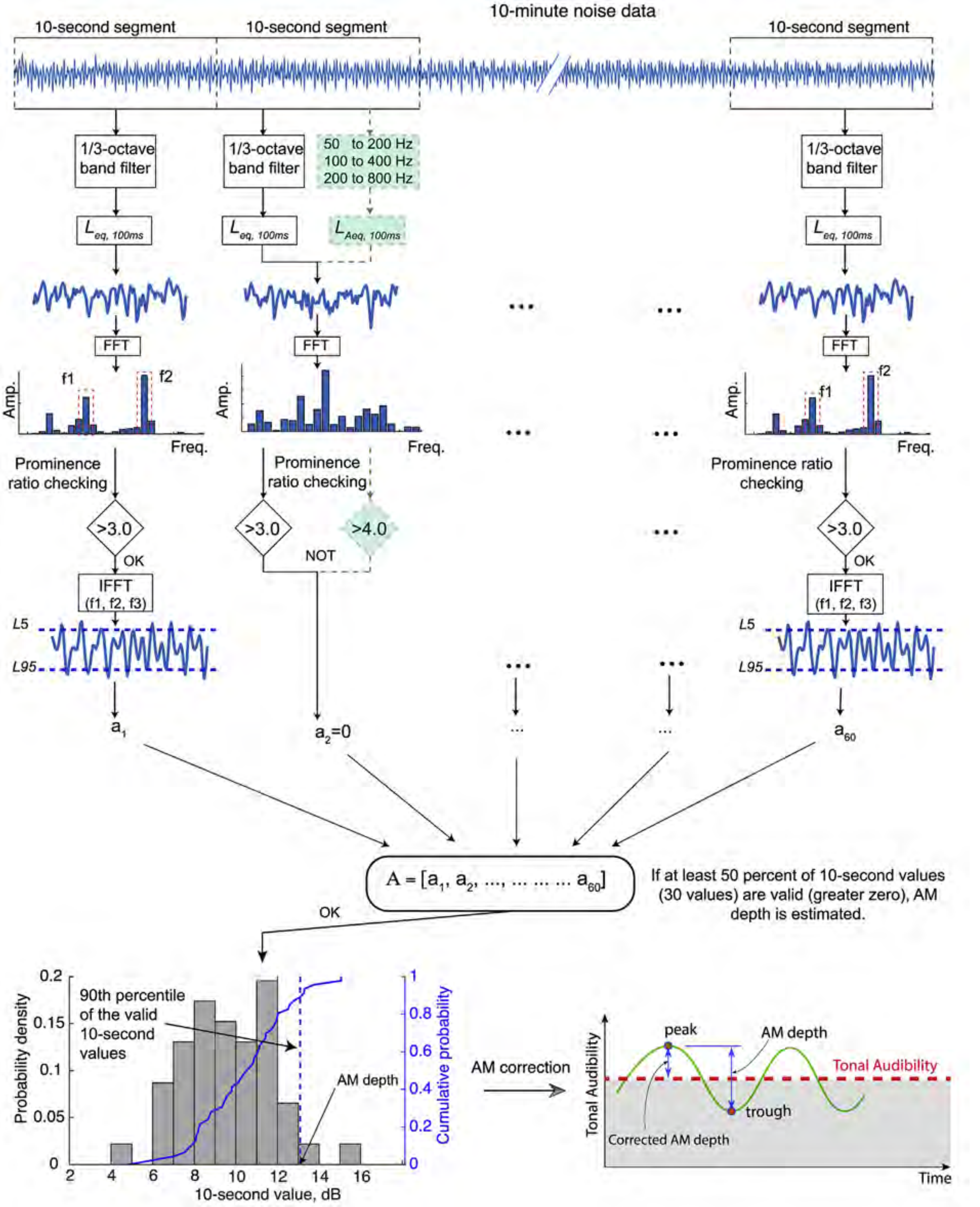

Fig. 3. A summary of the steps for determining and quantifying AM based on the IOA 'reference method' that has been modified to suit analysis of AM of a low-frequency tone. The Inverse Fast Fourier Transform (IFFT) is calculated using the fundamental and first two harmonics. The values in the box shaded green with dashed grey outline are the original values used in the IOA 'reference method'. The modifications are applied for all 10-s segments. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. If the AM troughs, as pictured in the bottom-right of Fig. 3, were not expected to be audible based on the calculated tonal audibility, the AM depth was reduced. For instance, if the tonal audibility was 0 dB and the AM depth was 6 dB, the reduced AM depth would be 3 dB. This is referred to as the 'AM correction' hereafter.

For the specific wind farm and receiver distances analysed in this study, narrowband analysis revealed that the most significant AM occurs at approximately 46 Hz [17]. Therefore, due to the tonal nature of the AM, the analysis bandwidth was reduced to the 50 Hz 1/3-octave band. Although Bass et al. [9] suggest an analysis bandwidth of 50 Hz–200 Hz, it is highlighted that this bandwidth precludes the audible tone and that even if the lower bound were extended to 40 Hz, the AM depth would be much lower. This is expected for the tonal AM analysed in this study but the approach may not be valid for broadband AM such as 'swish'. In fact, it is recommended that before deciding on the analysis bandwidth, it is important to identify the frequency range in which AM occurs. To ensure that the AM depth is not underestimated, it is important to choose a bandwidth that results in the highest AM depth. In this analysis, a narrow bandwidth of 2 Hz, centred on the tone, was also investigated but it was found that the AM depth was close to that obtained using 1/3-octave bands. Moreover, use of 1/3-octave bands is required by the New Zealand standard for wind farm noise measurement [18] and has been used by other researchers [19,20] for AM analysis.

The prominence ratio was reduced from 4 to 3 based on a systematic analysis, which is described in Section 3.2. Fig. 3 shows a summary of the steps for determining and quantifying AM based on the IOA 'reference method' with the modifications discussed above.

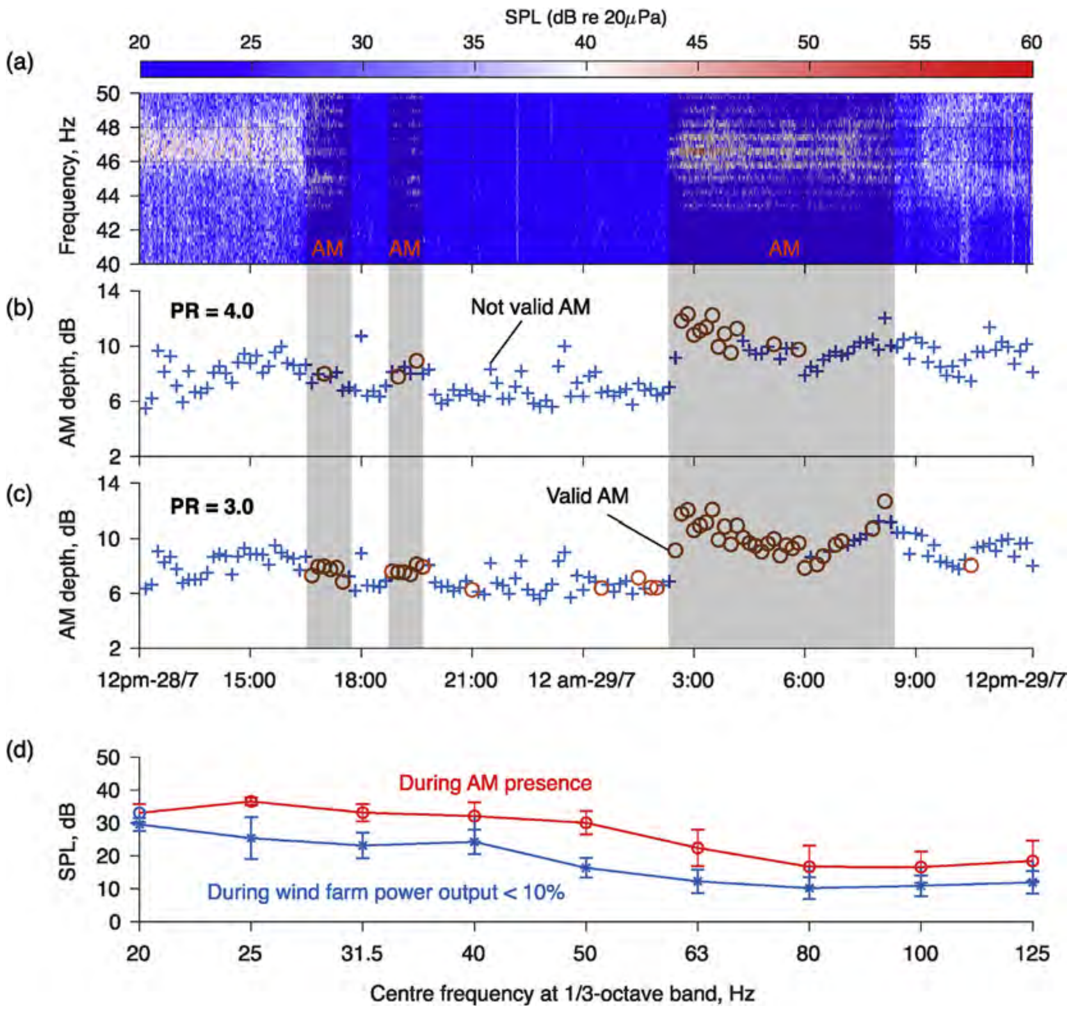

Fig. 4. The effect of prominence ratio on the result of AM detection for measurements at H5. (a) Spectrogram showing the presence of AM, as determined by a human scorer, shaded in grey. The AM is characterised by horizontal bands of relatively high SPL spaced at the BPF. (b), (c) Results of AM detection corresponding to prominence ratios of 4.0 and 3.0, respectively. The red and blue markers show AM depth for 10-min data points that are considered valid and not valid, respectively using the IOA 'reference method' [9]. (d) Mean and standard deviation of 1/3-octave spectra corresponding to data containing wind farm AM (red) as shaded in (a–c), and the period with negligible wind farm noise (blue), as indicated by the low-level signal without AM in the centre of (a–c). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Validation of AM detection algorithm

To show a visual representation of the accuracy of the IOA 'reference method' with prominence ratios of 3 and 4, comparison is made to a spectrogram plot in Fig. 4. These data were measured at H5 over 24 h, during which there were some periods with AM present and other periods with AM absent. The plot was constructed using a Hamming window, frequency resolution of 0.1 Hz, time resolution of 5 s and 50% overlap. As shown in Fig. 4(a), use of a spectrogram plot is an effective method of identifying AM of a tone, which is visible as horizontal lines in the spectrum spaced vertically at the blade pass frequency (BPF) of 0.8 Hz. The disadvantage of this approach is that it requires significant computational resources and a human for visual data interpretation. Hence, it was used in this study as a validation tool only. The results of applying the IOA 'reference method' with modifications are shown in Fig. 4(b) and (c). Here the AM depth is plotted against time, and 10-min periods with and without AM are shown using red circles and blue plus signs, respectively. Fig. 4(d) shows that the SPL of low-frequency noise is much higher during periods containing wind farm AM compared to periods when the ambient noise is dominant.

Comparison between Fig. 4(a) and (b) indicates that the prominence ratio of 4 that is recommended by Bass et al. [9] fails to detect many occurrences of AM. On the other hand, selection of a more conservative prominence ratio of 3 results in a better correlation between the AM visible in Fig. 4(a) and the 10-min periods identified as containing AM in Fig. 4(c). The rate of detection of true and false positives for various prominence ratios is discussed in more detail below.

To further refine the selection of the prominence ratio for the entire data set, a Receiver Operating Curve (ROC) analysis was carried out using the methodology outlined by Fawcett [21]. The aim of the ROC analysis was to systematically examine true versus false positive and negative detection rates at each possible prominence ratio to find the optimal prominence ratio cut-off that simultaneously maximised both true positive (sensitivity) and true negative (specificity) detection. This is done by comparing the algorithm output to a 'gold standard' which in this case is the human-scored presence of AM. To construct the 'gold standard' data set, 96 10-min periods (equivalent to 16 h of continuous measurement) were randomly selected from each of the 9 data sets. These data were plotted in spectrograms with the same criteria used to plot Fig. 4(a). One investigator (PN) manually reviewed and classified each of the resulting 864 spectrogram segments into those containing ($N = 200$) versus not containing ($N = 664$) visually discernible AM for at least 50% of the time, as consistent with the IOA 'reference method'. The IOA 'reference method' was then employed to detect AM, using prominence ratios between 2.5 and 4.5, with steps of 0.25, and the resulting ROC curve is shown in Fig. 5(a). The standard IOA 'reference method' and prominence ratio cut-off of 4 showed high specificity (0.99) but poor sensitivity (0.09) for detecting 'gold standard' classified AM events compared to a prominence ratio of 3; which achieved a more reasonable balance of lower specificity (0.82) and higher sensitivity (0.62). A prominence ratio of 3 is closest to the top-left corner (0,1) of the ROC which represents an ideal classifier and so provides the best compromise between true and false positive rates [22]. The total area under the ROC curve (AUC) is 0.783 (95% confidence interval 0.751 to 0.815), which indicates that the IOA 'reference method' is a reasonably good discriminator of AM, but could potentially be improved. Fig. 5(b) shows an alternative method for measuring algorithm performance using the number of true and false positives for each value of the prominence ratio investigated. For each prominence ratio, the vector containing a binary

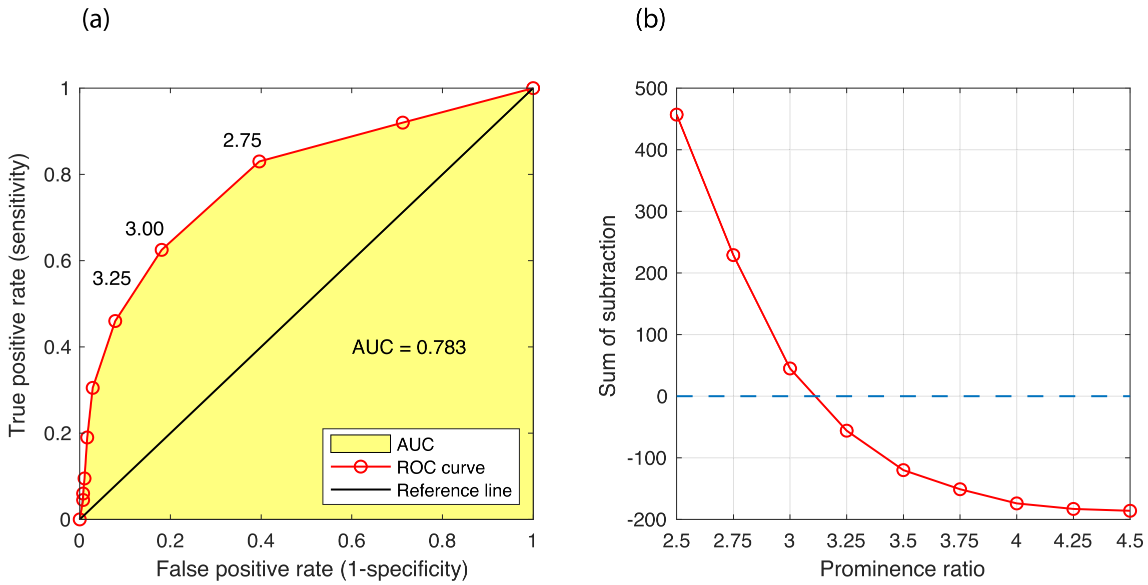

Fig. 5. Selection of the most suitable prominence ratio. (a) ROC curve analysis and (b) Sum of subtraction method.

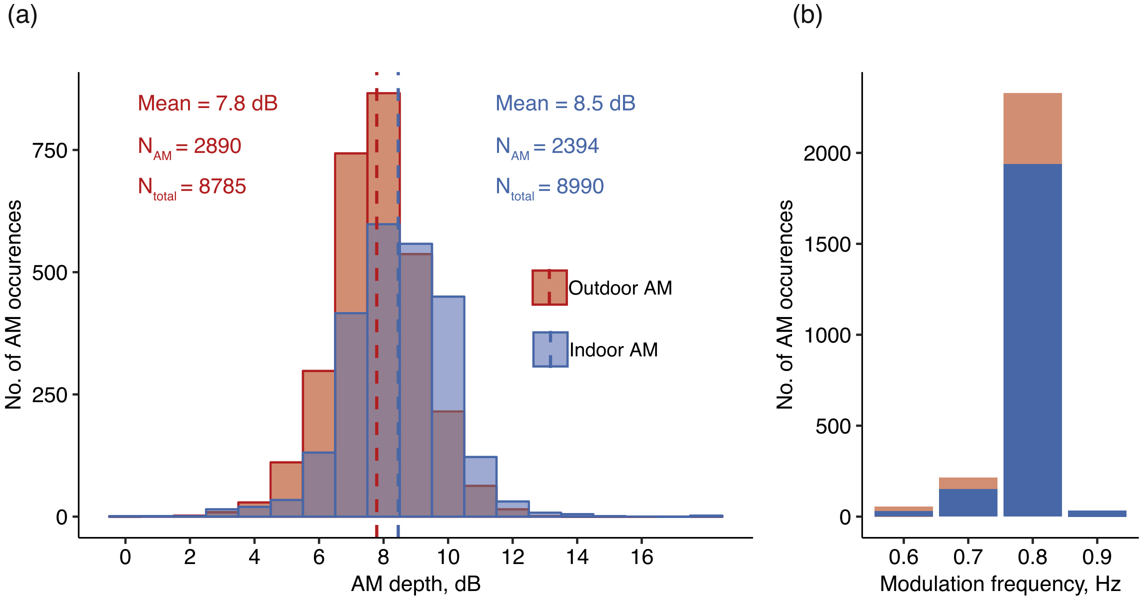

Fig. 6. AM analysis of outdoor (red) and indoor (blue) noise measured at 9 different residences located near a wind farm. The overlap between outdoor/indoor AM data is shown in purple. The 'AM correction' has not been applied. (a) Histogram of AM depth. (b) Histogram of modulation frequency. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

outcome for the presence/absence of AM from the 'gold standard' data set is subtracted from the corresponding vector obtained using the IOA 'reference method'. All elements in the resulting vector are summed and the entire process is labelled 'sum of subtraction' in Fig. 5(b). The results show that at low prominence ratios, there is a high rate of false positives whereas at high prominence ratios, there is a high rate of false negatives (i.e. non-detection of AM). The curve asymptotes near a value of −200 as this corresponds to the number of AM events in the 'gold standard' data set and thus indicates that few AM events were detected using high prominence ratios. The point closest to the blue dashed line, which reflects maximum true positives and true negatives, corresponds to a prominence ratio of 3, which is in agreement with the ROC analysis. Hence, a prominence ratio of 3 was selected for this study. Use of a higher cut-off, such as 3.5, could be used to reduce the false positive rate to more confidently 'rule-in' the presence of AM (i.e. higher specificity), but also increases the chances of missing AM (i.e. lower sensitivity). Similarly, use of a lower cut-off, such as 2.5, could be used to more confidently ensure that AM is not missed (i.e. higher sensitivity), but at the expense of falsely detecting AM in some cases (i.e. lower specificity). Ultimately AM classification methods need to both reliably detect the most annoying features of AM when AM is present, and reliably rule out AM when it is absent.

4. Results

4.1. Prevalence of AM

The results of applying the modified AM algorithm without the 'AM correction' for audibility to outdoor and indoor data measured at 9 different residences located near a wind farm are shown in Fig. 6. In Fig. 6(a), the number of AM events is plotted against the AM depth. It is evident that the mean AM depth for indoor noise was higher than that for outdoor noise. The reason for this is that the background noise in the 50 Hz 1/3-octave band was higher indoors, resulting in less AM events being detected, and thus a shift in the mean value. Given that the AM occurs in the 50 Hz 1/3-octave band, where the equal loudness contours are closer together than for mid-frequency noise, the fluctuation in loudness as a result of AM would be greater and hence potentially more annoying. On the other hand, to obtain a more realistic prediction of annoyance, the 'AM correction' should be applied, as outlined in Section 4.2. Fig. 6(b) shows that the modulation frequency was consistently 0.8 Hz, which corresponds to the expected blade-pass frequency when the wind turbines are operating at their nominal speed of 16.1 rpm [23].

4.2. Prevalence of audible AM

To determine which data points required an 'AM correction' to more accurately reflect the perception of AM depth, the tonal audibility was assessed as described in Section 3.1. Results of this assessment are shown in Fig. 7(a) and it can be seen that the tone was potentially audible both outdoors and indoors. In fact, the tone would have been audible in more cases than reflected in Fig. 7(a) since the tonal audibility assessment is based on mean values and therefore the peak audibility of an AM tone is higher.

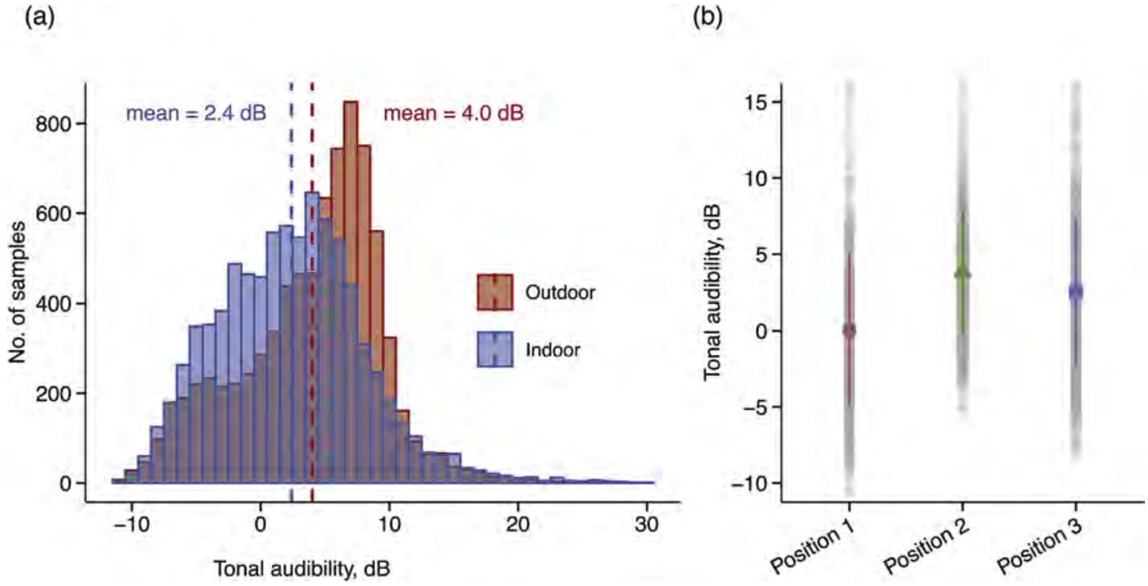

Fig. 7. (a) Histogram of tonal audibility measured outdoors (red) and indoors (blue) using the corner microphone. (b) Tonal audibility measured at 2 random locations within a room (Positions 1&2) and in the corner location (Position 3). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The mean tonal audibility outdoors and indoors was 4 dB(A) and 2.8 dB(A), respectively. As the histogram for the outdoor data is negatively-skewed, the mode was much higher at 7 dB(A). The lower tonal audibility indoors may be the result of higher indoor masking noise.

An unexpected result was obtained when comparing the tonal audibility at various positions around the room for H5. It was found that the mean tonal audibility was highest at randomly chosen 'Position 2' in Fig. 7(b), where the microphone was mounted near the centre of the room at a height of 1.5 m. At the corner 'Position 3' in Fig. 7, the mean tonal audibility was slightly lower and therefore the results shown in Fig. 7(a) may not reflect worst case conditions. The reason that the tonal audibility is not necessarily highest in the corner is that the corner is an anti-node for all room response modes and therefore the masking noise in the critical band containing the tone would have been higher as well. At another randomly chosen location near the centre of the room at a height of 1.5 m, the mean tonal audibility was shown to be lower than the other two positions and therefore for consistency, the corner position was used in the tonal audibility assessment. However, these results indicate that it

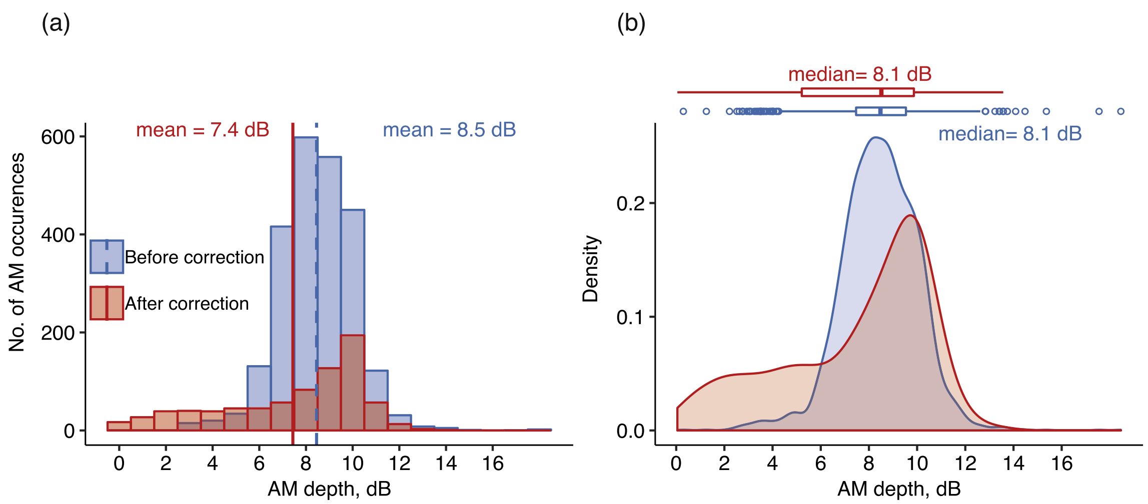

Fig. 8. Indoor noise measurements taken at 9 different locations near a wind farm before and after the 'AM correction' (blue and red, respectively). (a) Histograms of AM depth. (b) Probability Density Function of AM depth. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

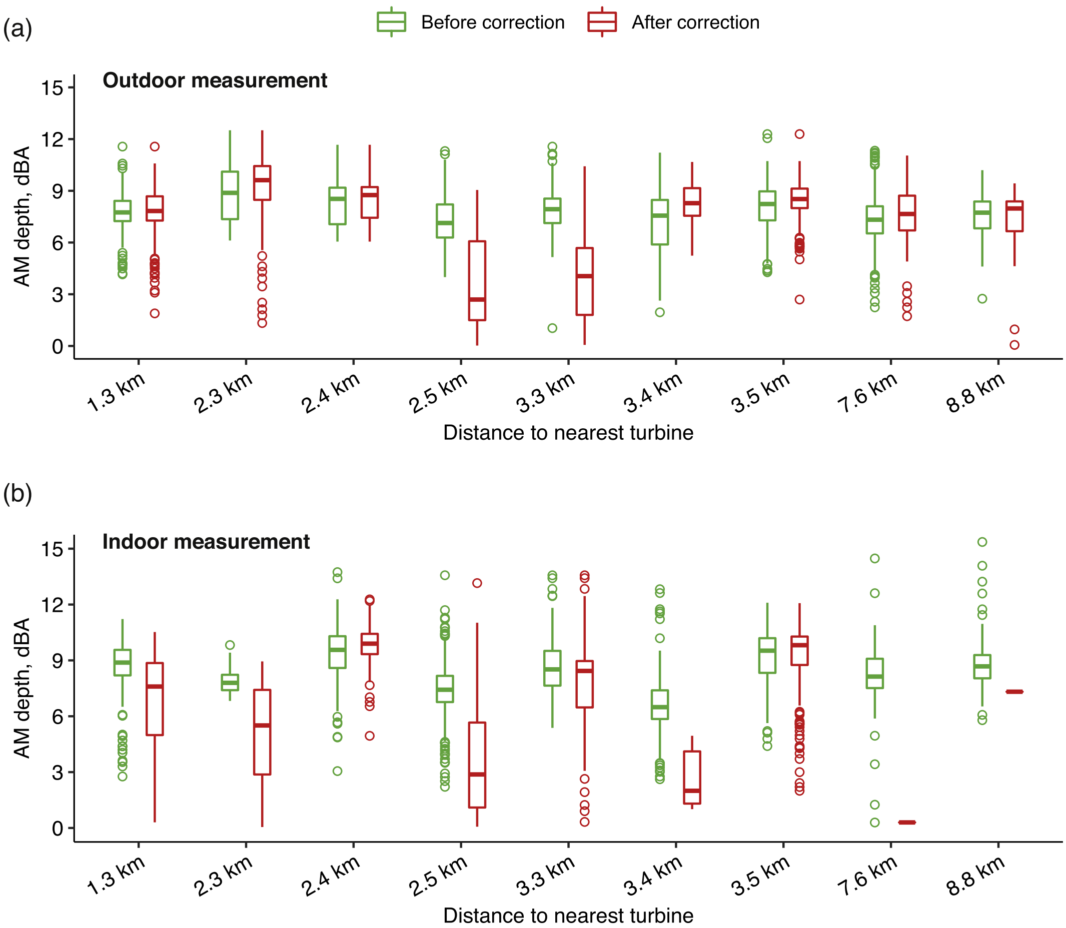

Fig. 9. Relationship between AM depth and distance from the wind farm before (green) and after 'AM correction' (red). (a) Outdoor measurement, (b) Indoor measurement. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

could be advantageous to involve the resident when selecting measurement positions when a tone is involved, since the corner position may not represent the worst case in this situation.

The results obtained after applying the 'AM correction' to the indoor data are shown in Fig. 8(a) and (b). It is evident that the 'AM correction' is necessary for a large number of data points, resulting in a reduction in the mean AM depth from 8.5 dB to 7.4 dB. This indicates that the tonal audibility at 46 Hz was often less than 0 dB, as shown in Fig. 7(a). The overall number of AM events is also much lower, indicating that a large proportion of detected AM events were entirely below the hearing threshold. Fig. 8(b) shows that the median AM depth is the same before and after correction but that the mode is higher after correction. Also, the distribution shape changes significantly and becomes negatively-skewed, which is expected as the 'AM correction' involves a subtraction only. Similar trends were observed for the outdoor data and thus the results are not presented here.

4.3. Relationship between distance from the wind farm and AM

Fig. 9(a) and (b) show uncorrected and corrected AM depth as a function of distance from the nearest wind turbine for data measured outdoors and indoors, respectively. There is no clear relationship between the AM depth and distance for both outdoor and indoor data before the 'AM correction' is applied. This is anticipated as the difference between the peak and trough SPL remains constant. Also, our previous analyses [17] have shown that the wind turbine signal is as high as 15 dB above ambient noise levels in the 50 Hz 1/3-octave band at a distance of 8.8 km from the nearest wind turbine, suggesting that masking in this frequency range may only occur during periods of low wind farm power output. In these cases, it is possible that the AM would not be detected as valid due to relatively high ambient levels. Differences in the AM depth measured at the various residences can be explained by differences in the positioning of the residences with respect to the wind farm. This affects the distance between the residence and the wind turbines other than the closest one. Also, the number of wind turbines that are orientated in a given direction with respect to the residence varies with both wind direction and residence position.

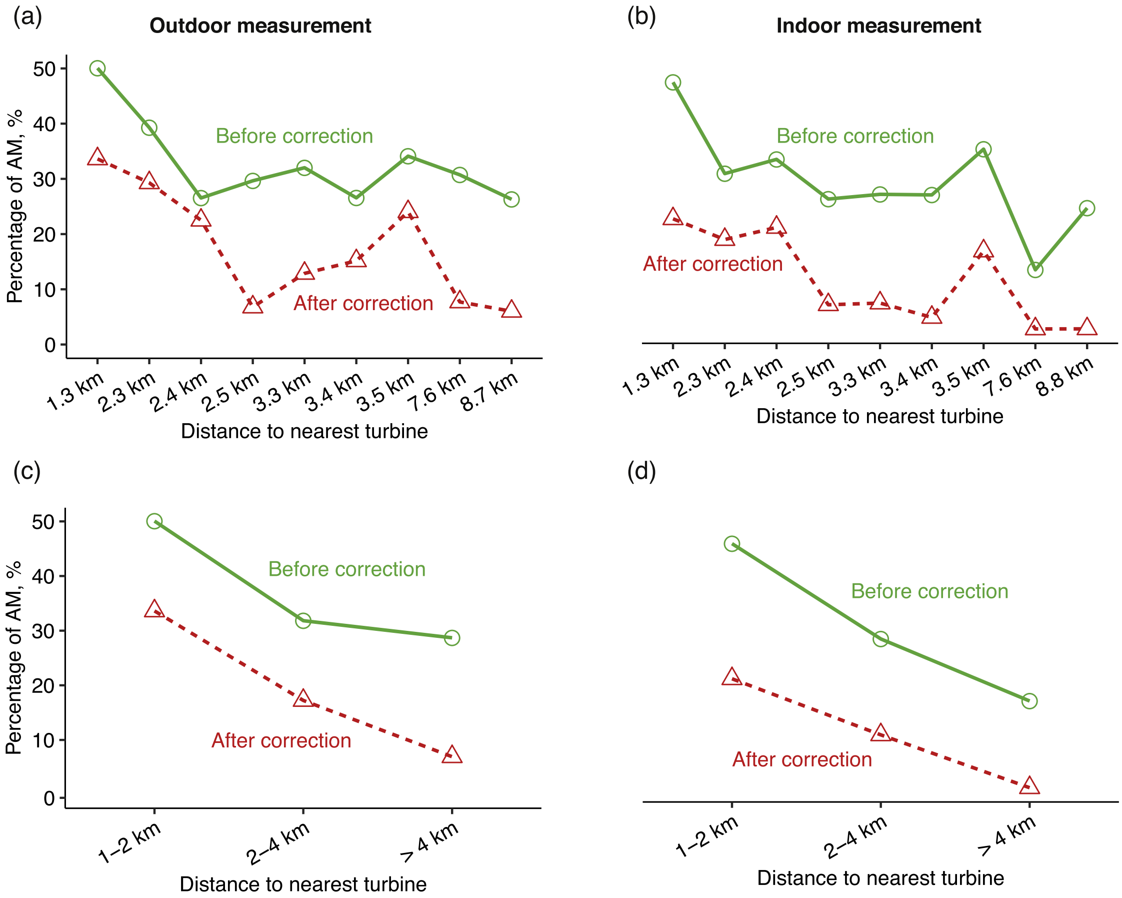

Fig. 10. Outdoor and indoor noise measurements taken at 9 different locations near a wind farm. (a, b) Relationship between the percentage of time that AM was present and the distance from the wind farm. (c, d) Relationship between percentage of time that AM was present and distance from the wind farm, where the results have been combined into three distance bins of 2 km width.

The AM depth is expected to reduce with distance when the ‘AM correction’ is applied, since tonal noise at 46 Hz is less likely to be audible at larger distances from the wind farm. However, this relationship is not evident in Fig. 9(a) and (b). The reason for this is that audibility of wind farm noise is dependent on the wind turbine power output and this was not the same during the measurements taken at each residence. In fact, the reduced tonal audibility and lower AM depth after ‘AM correction’ at 2.5 and 3.3 km in Fig. 9(a) may indicate that worst-case conditions, in terms of AM depth and audibility, were not captured at these residences. It is interesting to note that although the number of AM events is lower at 8.8 km relative to 1.3 km, the AM depth is similar outdoors both before and after the ‘AM correction’, as shown in 9(a). For the indoor data, there was only one instance of audible AM at 8.8 km but the associated AM depth was also similar to that measured at 1.3 km. The variation in the AM depth with distance for the indoor data after ‘AM correction’ shown in 9(b) can be attributed to differences in housing construction and orientation of the room relative to the wind farm. These factors affect the indoor SPL and hence audibility.

The large number of outliers, shown by the green and red open circles, in Fig. 9(a) and (b) is attributed to meteorological effects such as changes in wind direction, atmospheric stability and atmospheric turbulence. However, the number of outliers is small (10%) compared to the total number of data points, from all locations, that were used for the averages. Fewer outliers are associated with the red data points as the ‘AM correction’ reduces the overall number of AM events, however, the actual percentage of outliers remains the same.

Fig. 10(a) and (b) provide insight into the percentage of time that AM occurred at each residence both outdoors and indoors. These numbers should be interpreted with caution due to differences unrelated to distance such as: size of the data set, position of the residence with respect to the wind farm, worst case atmospheric conditions for wind farm AM not captured, housing construction, room orientation relative to the wind farm and room size. The latter three characteristics are only relevant when considering the results after ‘AM correction’. Valid AM was detected less often indoors, which may be related to background noise, as some of the residences (but not the measurement room) were occupied during the measurement period.

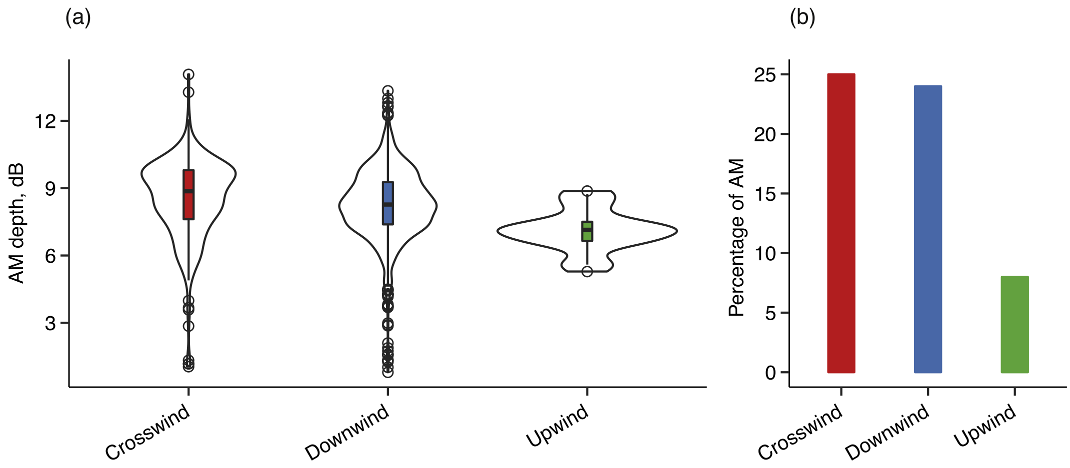

Fig. 11. Indoor noise measurements taken at 9 different locations near a wind farm. (a) Bean plot of AM depth against hub-height wind direction. (b) Percentage of time that AM was present during various hub-height wind directions.

Fig. 10(a) and (b) indicate that tonal AM was present outdoors between 25 and 50% of the time and indoors between 14 and 46% of the time. Applying the 'AM correction' results in fewer AM events, however, the tonal AM is shown to be audible outdoors and indoors up to distances of 3.5 km for as much as 24 and 16% of the time, respectively. At distances of 7.6 and 8.8 km, it is expected that the tonal AM would generally not be audible for a person with hearing in the normal range. The tonal AM could be audible at these distances for a small proportion of the population that have sensitive hearing (i.e. 2.5% of the population have a hearing threshold that is 10–12 dB less than the ISO 389-7 [15] threshold curve [14]). The results at 2.5 and 3.5 km are not considered representative for the reasons discussed in the paragraphs above. Therefore, to further investigate the relationship between percentage of AM and distance, Fig. 10(c) and (d) were plotted. To reduce the variance between measurement locations in this figure, the data have been categorised into three groups; 1–2, 2–4 and > 4 km. A clear trend of reducing AM with distance is apparent from these figures both before and after the 'AM correction'. In fact, it is shown that the occurrence of AM may be reduced by a factor of two after a distance of 2 km. A lower AM detection rate at distances greater than 2 km may be associated with a reduced signal-to-noise ratio, particularly during periods of low wind farm power output.

4.4. Wind farm operating conditions and AM

Fig. 11(a) provides insight into the relationship between AM depth and hub-height wind direction for the indoor data without 'AM correction'. It can be seen that the mean AM depth is similar for crosswind and downwind conditions but slightly lower for upwind conditions. Also, the distribution shapes vary such that there are more AM events with a higher AM depth under crosswind conditions. Fig. 11(b) indicates that the percentage of time that AM was present during each wind direction is similar for downwind and crosswind directions but much lower for the upwind direction. For the entire data set, crosswind, downwind and upwind conditions occurred 17%, 80% and 3% of the time, respectively. For the results shown in Fig. 11, the wind direction is defined based on the line joining the nearest wind turbine to the receiver with a margin of ±45°. This is an approximation as wind turbines adjacent to the nearest wind turbine are orientated differently for a given wind direction. On the other hand, since the wind farm layout is approximately linear in the North-South direction and most of the residences are located to the East and West of the wind turbines, the direction categories are usually applicable to the adjacent wind turbines as well.

The relationship between wind farm power output, hub-height wind speed and the presence of AM indoors is presented in Fig. 12(a) and (b). In these figures, the grey and green bars correspond to periods of no AM and valid AM, respectively. The line plot indicates the percentage of time that AM was present for the entire measurement period. As shown in Fig. 12(a), a large number of measurements were taken when the wind farm was operating at a percentage power capacity of <5% as there were several periods during which the wind speed was less than the cut-in wind speed of 3.5 m/s [23].

Fig. 12(a) and (b) indicate that the highest number of AM events is associated with a wind farm percentage power capacity and hub-height wind speed of approximately 40% and 10 m/s, respectively. After applying the 'AM correction', the peak in the percentage of time that AM was present is less distinct and it is more useful to consider a range of operating conditions. Referring to the dashed line in Fig. 12(a) and (b), it can be seen that audible tonal AM was present indoors for at least 20% of the time when the hub-height wind speed at the nearest wind turbine was between 11 and 14 m/s and the percentage power capacity was between 40 and 85%.This indicates that AM is more likely to be detected when the wind turbines are operating below their maximum rated power. It is unclear if this is a source characteristic or an environmental effect, as the background

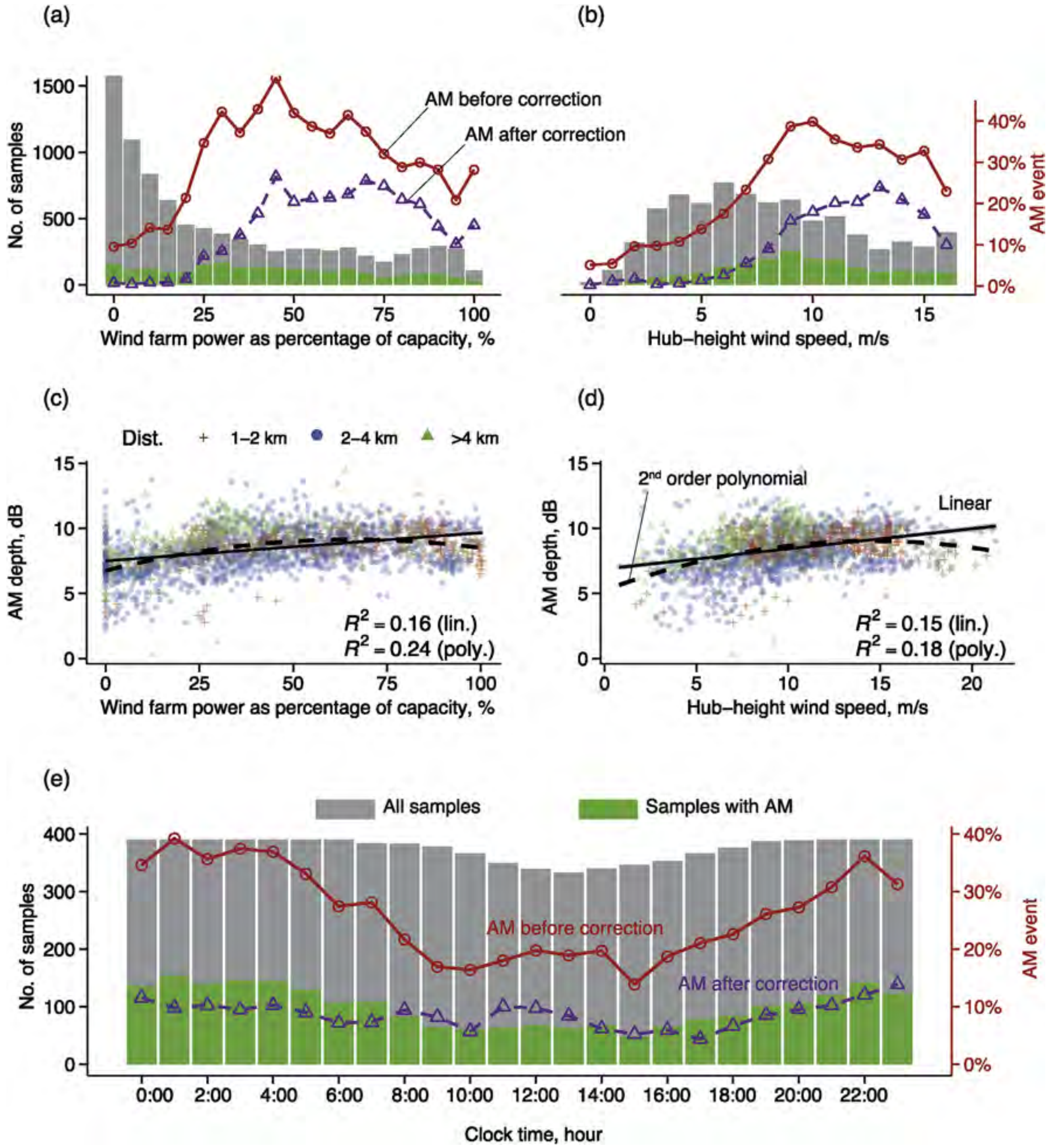

Fig. 12. Indoor noise measurements taken at 9 different locations near a wind farm. (a) Number of AM events and percentage of time that AM was present before and after 'AM correction' against wind farm percentage power capacity, (b) Number of AM events and percentage of time that AM was present before and after 'AM correction' against hub-height wind speed, (c) AM depth against wind farm percentage power capacity, where the data has been separated into 2 km-wide distance bins and the regression fits applied to all data, (d) AM depth against hub-height wind speed, where the data has been separated into 2 km-wide distance bins and the regression fits applied to all data, (e) Number and percentage of time that AM was present as a function of time of day.

noise may also be higher due to wind noise at the receiver when the wind farm is operating at higher power capacities. This could result in non-detection of AM, even though it may be present.

In Fig. 12(c) and (d), the AM depth without the correction for audibility is plotted against the percentage power capacity and wind speed at hub height, respectively. There is a poor correlation between the AM depth and percentage power capacity as well as hub-height wind speed, as indicated by the low R^2 values obtained for both linear and second order polynomial regression fits. However, according to the second order polynomial regression fit, which has a higher R^2 value, there is a general trend that the AM depth increases slightly up to a percentage power capacity and wind speed at hub height of 70% and 15 m/s, respectively, after which it decreases slightly. Limited improvement in the correlation between AM depth and percentage power capacity as well as hub-height wind speed is obtained when the data are separated into 2 km-wide distance bins. This is indicated by the large scatter in the data points for each distance bin shown in Fig. 12(c) and (d). Hence, the large variation in AM depth for the various power capacities and wind speeds at hub height is most likely attributable predominantly to meteorological effects. Detection of valid AM at a power output of 0% can be explained by the 18% false positive rate using a prominence ratio of 3, as shown in Fig. 5(a).

Fig. 12(e) shows that tonal AM occurs much more frequently during the night-time, particularly between 10pm and 5am. In fact, compared to daytime hours from 9am to 5pm, there are twice as many AM events during the night-time. This is in agreement with the findings of Van den Berg [24] and supports the idea that AM is more likely to occur during stable conditions, which occur more often at night-time. A larger proportion of AM events that occurred during the daytime were audible compared to the night-time. A possible explanation is that inaudible AM events are less likely to be detected during the daytime when the background noise level is higher. Approximately 10% of the total measurement time at night-time contained audible AM. However, at residences located up to 3.5 km from the wind farm, audible AM occurred for as much as 22% of the measurement time at night-time.

5. Conclusions

Low-frequency tonal AM with a modulation frequency consistent with the expected blade-pass frequency, has been measured between 1 and 9 km from a wind farm. The mean AM depth was 8.5 dB for noise measured indoors, slightly higher than the mean of 7.8 dB which was measured outdoors. On the other hand, when the tonal audibility was taken into account, the mean AM depth reduced to 7.4 dB for noise measured indoors and there was a similar reduction for the outdoor data.

Despite the relatively low noise levels, it was found that the tonal AM could be audible both outdoors and indoors up to distances of 3.5 km from the nearest turbine in the wind farm. The tonal audibility was higher outdoors than indoors, possibly due to higher indoor masking noise relative to the tonal noise. The indoor tonal audibility was dependent on the microphone location and the highest tonal audibility was not measured in the corner. This is because both the tonal level and masking noise are higher in the corner position since it is an anti-node for all room response modes. The relatively higher masking noise at the corner location can therefore give rise to a relatively lower tonal audibility.

There was no clear relationship between the AM depth and distance from the wind farm before the ‘AM correction’ for audibility was applied. This is expected, as AM depth is not affected by distance, and masking of the wind farm noise by ambient noise in the 50 Hz 1/3-octave band can be negligible, even at distances as far as 8.8 km from the nearest wind turbine. Due to differences in the power output that occurred during the measurement period at each residence, it was not possible to draw conclusions about the relationship between AM depth and distance from the wind farm after ‘AM correction’. However, for the outdoor data, it was observed that the AM depth after correction was similar at the various distances. The percentage of time that AM was present was shown to reduce significantly with distance from the wind farm both before and after the ‘AM correction’. This observation is consistent with noise attenuation during propagation, which results in a decrease in the wind farm noise level and hence, a reduction in tonal audibility and valid AM. Tonal AM was shown to be audible outdoors and indoors up to distances of 3.5 km for as much as 24 and 16% of the time, respectively. At distances of 7.6 and 8.8 km, the results indicate that the tonal AM would generally not be audible for a person with hearing in the normal range.

The percentage of occurrence and AM depth were both found to be higher during downwind and crosswind conditions. However, under crosswind conditions, the AM depth was higher for a larger number of AM events. The AM occurred most often when the wind farm percentage power capacity was approximately 40% both before and after the ‘AM correction’ was applied to account for the tonal audibility. Audible tonal AM was shown to be present indoors for at least 20% of the time for the entire data set when the hub-height wind speed at the nearest wind turbine was between 11 and 14 m/s and the percentage power capacity was between 40 and 85%.

Tonal AM occurred most often at night-time, during the hours between 10pm and 5am. Approximately 10% of the total measurement time at night-time contained audible AM. At residences located up to 3.5 km from the wind farm, audible AM occurred for as much as 22% of the time at night. This has important implications for possible sleep disruption from wind farm AM, particularly as ambient noise levels in rural South Australia can be as low as 15 and 5 dBA, outdoors and indoors, respectively. Further research is needed to determine the prevalence of AM on an annual basis. Further work is also needed to quantify the annoyance and sleep disturbance potential of this type of tonal AM.

Acknowledgements

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EXHIBIT
13

dBF Associates, Inc.
3129 Tiger Run Court, Suite 202
Carlsbad, CA 92010
619-609-0712

December 16, 2019

Backcountry Against Dumps, Inc.
% Donna Tisdale
P.O. Box 1275
Boulevard, CA 91905

Re: Wind Turbine Infrasound and Low-Frequency Noise Survey in Boulevard, CA

Ms. Tisdale:

At your request, dBF Associates, Inc. (dBFA) conducted an acoustical survey to document infrasound and low-frequency noise (ILFN) generated by the existing wind turbines (WTs) in the Boulevard area of unincorporated San Diego County, California.

There are currently two wind farms in the Boulevard area: Kumeyaay with (25) 2-megawatt WTs and Tule with (57) 2.3-megawatt WTs. To the east is the Ocotillo wind farm with (112) 2.3-megawatt WTs. To the southeast in Mexico is the Energia Sierra Juarez (ESJ) wind farm with (47) 3.3-megawatt WTs.

Noise recordings obtained on Friday, August 16, 2019 conclusively document the presence of ILFN, at homes up to approximately 6 miles away, generated by the WTs at the Kumeyaay and Tule facilities.

During the noise recordings, amplitude modulated (AM) noise was observed in the field. Analysis of the noise recordings also indicates excessive AM noise generated by the existing WTs.

MEASUREMENT LOCATIONS

Outdoor and indoor noise recordings were made at three residences in the Boulevard area, during daytime, evening, and nighttime periods of the day. Refer to Table 1 for details.

Table 1. Measurement Locations

Residence	Address	Location	Distance to Closest WT	Measurement Start Times
Tisdale	1250 Tierra Real Lane	32.622245, -116.348327	5.7 miles (Kumeyaay)	12:12 PM 6:58 PM 10:23 PM
Morrison	2920 Ribbonwood Road	32.709943, -116.297129	1.46 miles (Tule)	1:40 PM 8:14 PM 11:16 PM
Guy	2975 Ribbonwood Road	32.718458, -116.290017	4,430 feet (Tule)	2:44 PM 9:25 PM 11:58 PM

NOISE RECORDING METHODOLOGY

All noise recordings were made with Brüel and Kjær (B&K) type-4193 ½-inch pressure field microphones, which are specifically designed for infrasound and low frequency (below 40 cycles per second [Hz]) measurements, and provide a linear response from 0.07 Hz to 20,000 Hz. A B&K type-UC-0211 adapter was used to couple the microphones to a B&K type-2639 preamplifier, providing a linear frequency response down to 0.1 Hz for the microphone / adaptor / preamplifier system. All recordings were calibrated with B&K type-4230 calibrators, which are checked and adjusted every 6 months with a B&K type-4220 pistonphone in the Wilson Ihrig laboratory in Emeryville, California. The Wilson Ihrig pistonphone itself is calibrated annually with a signal traceable to the National Institute of Standards and Technology.

Inside each residence, a microphone was mounted on a tripod at 4.5 feet above the floor, in the middle of the living room or a bedroom; the microphone was oriented vertically and covered with a 3-inch diameter wind screen.

A second microphone was set up outside of each residence. In some cases, a third microphone was set up in another location outside of the residence. Following International Electrotechnical Commission (IEC) Standard 61400-11, the outside microphone was rested horizontally (i.e., flush mounted) on a ½-inch-thick plywood "ground board" that is 1 meter in diameter. The microphone was oriented in the direction of the nearest visible wind turbine and the ground board was placed in a flat location between the residence and the wind turbines.

Also following IEC 61400-11, wind effects on the outdoor microphone were reduced using both a hemispherical 7-inch-diameter primary windscreen placed directly over the microphone, and a hemispherical 20-inch-diameter secondary windscreen placed over the primary windscreen and mounted on the ground board. The microphone and primary windscreen were placed under the center of the secondary windscreen.

The primary windscreen was cut from a spherical, ACO-Pacific foam windscreen with a density of 80 pores per inch (ppi). The secondary windscreen was constructed by WIA using a wire frame covered with ½ inch open wire mesh. A one-inch-thick layer of open cell foam with a density of 30 ppi was attached to the wire mesh.

Both microphones used at the residences were powered by B&K type-2804 power supplies. Indoor and outdoor noise signals were recorded simultaneously to allow for correlation of indoor and outdoor sound levels during subsequent analysis.

All noise samples were recorded with a RION DA21 digital recorder, which provides a linear frequency response (i.e., ±0.1% or less) to a lower frequency limit of essentially 0.1 Hz when used in the "AC mode" (which was used). Twenty-minute (nominal) noise recordings were made at each location. All measurement data reported herein are based on analyses conducted in the Wilson Ihrig laboratory.

Noise Measurements in Presence of Wind

Some atmospheric pressure fluctuations are oscillatory in nature, whereas others are not. An example of a non-oscillatory pressure fluctuation is a change in barometric pressure – a change that occurs over a much longer time scale (e.g., hours) than the fluctuations being measured in this study. Wind and, in particular, gusts of wind cause another form of non-oscillatory pressure fluctuation, though it occurs on a much shorter time scale (e.g., a fraction of a second). Local wind can cause a pressure change affecting the human ear similar to the pressure change that occurs in an airplane as it ascends or descends during takeoff and landing, but this pressure change is not sound.

Sound, in contrast to non-oscillatory fluctuations, consists of regular oscillatory pressure fluctuations in the air due to traveling waves. Sound waves can propagate over long distances depending on many factors. In the case of noise generated by machinery, the pressure fluctuations can be highly periodic in nature (i.e., regular oscillations). Sound that is characterized by discrete frequencies is referred to as being tonal. Although wind can generate sound due to turbulence around objects (e.g., trees, buildings), this sound is generally random in nature, lacks periodicity and is usually not in the infrasound range of frequencies.

However, the sound measurements we were interested in for this study (i.e., periodic wind turbine-generated ILFN) can be greatly impacted by non-oscillatory pressure fluctuations and extraneous noise caused by, for example, wind turbulence due to steady wind and particularly during gusts. The microphones used in these measurements are highly sensitive instruments, with pressure sensor diaphragms that will respond to any rapid enough pressure change in the air regardless of the cause. To minimize spurious (i.e. unrelated to the noise source being measured) noise and "pseudo sound" artifacts caused by wind gusts and other pressure fluctuations not associated with the wind turbine-generated noise itself, we employed special procedures. The main sources of spurious noise and the procedures we used to minimize its impact are discussed more fully below.

Noise Artifacts due to Turbulence at the Microphone

The most commonly-encountered source of noise artifacts in outdoor noise measurements is the turbulence caused by wind blowing over the microphone. To minimize this effect of wind when conducting environmental noise measurements outdoors, it is standard practice to use a windscreen, the size of which is usually selected based on the magnitude of the wind encountered. The higher the wind speed, generally the larger the windscreen required to minimize noise artifacts caused by air turbulence at the microphone.

The windscreen used must be porous enough so as not to significantly diminish the pressure fluctuations associated with the noise being measured, which is to say that the windscreen must be acoustically transparent. As indicated above, the measurements reported herein followed procedures on windscreen design and usage as recommended by IEC 64100-11 to ensure accurate measurements.

Noise Artifacts due to Air Gusts

There is another – and more problematic – source of wind-based noise artifacts. This one is caused by non-oscillatory pressure fluctuations associated with wind gusts as well as the pressure associated with the air flow in a steady wind. Air gusts can have an effect on a microphone signal in two ways. Outdoors, the microphone diaphragm will respond to the direct change in pressure associated with air flow; whereas indoors, the microphone will respond to the indirect change in pressure associated with wind and particularly gusts of wind that pressurize the interior of the building. These wind effects induce noise artifacts that appear in the electrical signal generated by the microphone that is in the ILFN frequency range. This pseudo noise can, in turn, affect the spectral analysis of the recorded data. This form of pseudo noise (i.e., pressure changes due to air flow) is not substantially reduced by the use of a windscreen or even multiple windscreens regardless of their size.

As discussed more fully in the Method of Analysis of Recorded Data section below, the sound recordings in this study were analyzed using a fast Fourier transform (FFT) technique to resolve low frequency and infrasound data. The primary range of interest in these measurements was in frequencies between 0.1 and 40 Hz. An FFT analysis produces a constant bandwidth (B). A 400-line FFT was used in the analysis, which means the bandwidth was B = 0.1 Hz. This allows resolution of frequency components to fractions of one Hz. When using a very narrow bandwidth (e.g., 0.1 Hz), the time required for filtering is long in order to obtain adequate frequency resolution. The FFT analysis time T required for a specific bandwidth B is given by: T = 1/B. For a 0.1 Hz bandwidth, the time required is 10 seconds. At this time scale, the effects of air pressure changes due to air movement tend to linger in the filtering process as discussed in the Method of Analysis of Recorded Data section below.

To reduce the wind gust-induced noise artifacts that manifest in the data with such long filtering times, both physical means during recording and analytical post-recording methods can be employed to minimize this spurious noise. The most effective pre-measurement technique is to dig a hole in the ground and put the microphone into it. If two pits and microphones are used, then a cross-spectral analysis is also possible. In this study, however, it was impractical and, in some cases, impossible to dig microphone pits at the measurement locations. We thus relied on post-measurement analytical methods to filter out the pseudo noise as much as possible.

Each of the two most effective analytical techniques takes advantage of the fact that wind turbines and other large rotating machinery with blades (e.g., building ventilation fans and helicopters) produce very regular, oscillatory pressure fluctuations that are highly deterministic, whereas pressure changes due to air movement associated with local wind gusts are essentially random in nature. The sound produced by wind turbines is tonal in nature, meaning that it has a spectrum with discrete frequencies that, in this case, are interrelated (i.e., harmonics of the blade passage frequency). This difference between the random wind noise and the wind turbine noise provides a means to minimize the latter in the signal processing of the recorded data. It has been posited that it is the tonal nature of wind turbine infrasound that may have some influence on residents in the vicinity of large wind turbines.

The noise artifacts associated with pressure changes at the microphone due to local wind gusts can be minimized in two ways when analyzing the recorded signal. The first technique is to average the noise measurements over a longer time period. This tends to reduce the effect of pseudo noise associated with random air pressure transients during wind gusts, but does not affect the very regular, periodic pressure fluctuations generated by wind turbines.

When averaging over time is not sufficient, a second technique can be used to further minimize the effect of random pressure fluctuations associated with local wind. This second technique uses “coherent output power,” a cross-spectral process. Both time averaging and coherent output power are discussed below under the method of analysis of recorded data.

WIND TURBINE OPERATION DURING MEASUREMENTS

The blade passage frequency (BPF) is the rate at which a WT blade passes in front of its tower. The formula for BPF is:

$$\text{BPF} = (\text{Turbine rpm} / 60 \text{ seconds per minute}) \times \text{Number of blades}$$

Associated with the BPF are harmonics, which are integer multiples of the BPF. In this study, we typically observed up to five discrete harmonics in the measurement data. The majority of the WTs at Kumeyaay and Tule were observed to be operating during the recordings. The BPFs observed for Kumeyaay Wind and Tule Wind were 0.84 Hz and 0.71 Hz, respectively.

METEOROLOGICAL DATA

Weather Underground is a source for local weather data including wind speed and direction, temperature, precipitation, and atmospheric pressure. The closest weather monitoring station to Boulevard is approximately 12 miles away in Campo. Weather Underground data are archived by MesoWest from which we obtained meteorological data for the period of noise recordings. Average wind speeds ranged from 4 mph to a high of 18 mph. Daytime and evening wind was predominately from the west-southwest, southwest, or south-southwest; nighttime wind was from the north-northeast.

METHOD OF ANALYSIS OF RECORDED DATA

The recordings were subsequently analyzed in the Wilson Ihrig laboratory with a Larson Davis type-2900 2-channel FFT analyzer. Each recorded sample was first viewed in digital strip chart format to visually locate periods of lower local wind gusts to minimize low- frequency wind pressure transient effects on the data. The FFT analyzer was set for 40-Hz bandwidth, with 400-lines, resulting in 0.1-Hz resolution. Linear averaging was used. A Hanning window was used during a one- to two-minute, low-wind period to obtain an "energy average" with maximum sampling overlap. The results were stored for each sample, including autospectra, coherence, and coherent output power for both channels of data at the residential locations (i.e., indoors and outdoors). Autospectra were also obtained for the reference locations.

Autospectra and Coherent Output Power

One of the strengths of the indoor-outdoor sampling procedure is that it made possible the use of what is called the "coherent output power" to minimize the effect of the low-frequency wind pressure transients caused by local wind gusts.

Coherent output power is based on use of the coherence between two signals to weight the spectra of one of the signals based on coherent frequency components common to the two simultaneously recorded signals. Where, as here, the wind turbine-generated noise remains at fairly consistent frequencies over the recording periods, the effects on the recorded signal of the essentially random, non-oscillatory pressure fluctuations caused by wind gusts should be reduced using this analysis procedure. The result is sometimes referred to as the coherent output spectrum.

Sound Level Corrections Due to Use of Ground Board

Placing an outdoor microphone on a ground board, as was done in this study, results in higher sound pressure levels (up to 3 dB greater) for frequencies in the range of 50 to 20,000 Hz when compared to those measured at 4.5 to 5.5 feet above the ground, a standard height used to make environmental noise measurements as indicated in ANSI S12.9-2013/Part 3. Consequently, corrections to the sound level data at frequencies greater than 50 Hz obtained using a ground board would be required.

However, for frequencies less than 50 Hz, the sound pressure level at the ground surface is essentially the same as that at a height of 5 feet. This is because a microphone on a tripod 5 feet above the ground is at a height less than one-fourth the wavelength of the sound at this frequency and there is little difference at frequencies less than 50 Hz between the sound field at ground level and the sound field at 5 feet above the ground.

Because the data presented herein are in the ILFN range with frequencies less than 40 Hz, no corrections to the sound level data are necessary, even though the measurements were made with a ground board. Similarly, because AM describes relative differences in sound level, no corrections are necessary.

ILFN Data

There are four wind turbine facilities with a combined total of 241 WTs within 11 miles of the residences at which recordings were made. Each of the current WT facilities has an array of WTs made by a different manufacturer or installed with a different WT model. Consequently, the WTs at each facility have different rotational speeds. It was not practical to simultaneously observe all the WTs at the four facilities, and the rotational speeds of individual WTs vary from one another and change over time depending on local wind conditions. Furthermore, the WTs at Kumeyaay Wind and Tule Wind operate at rotational speeds that are not too dissimilar (i.e., about 16 and 14 rpm, respectively). These factors make linkage of ILFN at certain frequencies with a specific wind turbine facility somewhat challenging.

It is clear from the discussion above that well-defined spectral peaks at frequencies less than 10 Hz are generally mechanically-generated infrasound, and at frequencies less 5 Hz the infrasound is obviously generated by WTs. Note that in general for large, industrial wind turbines the highest operational speed is 20 rpm, which corresponds to a BPF of 1.0 Hz for a turbine with three blades.

Consequently, peaks below 1.0 Hz are clearly BPFs of various WTs, and peaks that are multiples of a BPF between the frequencies of 1.0 Hz and 10 Hz are consequently harmonics of BPF, although harmonics that appear in the spectral data are typically limited to about 5 Hz.

The coherent output power spectra measured inside residences are shown in the attached plots. It is apparent from the data plots that there are reoccurring spectral peaks at specific frequencies less than 5 Hz. Not all the peaks occur for all the residences, due to differences in distance, orientation of WT blade to the residence, possible shielding by intervening terrain, atmospheric conditions; however, where they are present, they are present regardless of time of day or location, which is a clear indication of infrasound generated by WTs.

Table 2 lists the highest measured indoor sound pressure levels, and the frequency of those peak sound pressure levels.

Table 2. Measured Sound Levels

Residence	Measurement Period	Highest Sound Pressure Level; Dominant Frequency	Rotor Rotational Component
Tisdale	Daytime Evening Nighttime	44 dB at 0.88 Hz 49 dB at 2.54 Hz 47 dB at 1.66 Hz	Kumeyaay BPF Kumeyaay 2nd Harmonic Kumeyaay 1st Harmonic
Morrison	Daytime Evening Nighttime	52 dB at 0.59 Hz 48 dB at 0.78 Hz 57 dB at 1.66 Hz	Ocotillo BPF Tule BPF Kumeyaay 1st Harmonic
Guy	Daytime Evening Nighttime	64 dB at 0.88 Hz 60 dB at 1.47 Hz 63 dB at 2.54 Hz	Kumeyaay BPF Tule 1st Harmonic Kumeyaay 2nd Harmonic

AMPLITUDE MODULATION

Several area residents have commented on what they characterize as a “whooshing” sound from WTs. This sound was pronounced at the Guy residence, the closest measurement to the Tule WTs. An analysis of the Guy residence recordings clearly indicates amplitude modulation (AM). AM is the fluctuation of sound, in this case air flow turbulence noise generated at the WT blades’ trailing edge, modulated (changing sound level) at the frequency of the BPF.

A sample of recorded noise from the Guy residence was analyzed, as shown in the attached plot. At 250 Hz, the AM ranges from 3 to 10 dB, with the typical variation from 5 to 6 dBA.

CONCLUSIONS

It is clear from the measured noise data that there is significant wind turbine-generated ILFN and AM from the Kumeyaay and Tule Wind facilities affecting homes up to approximately 6 miles away. This conclusion is coherent with the conclusions of the 2014 and 2019 Wilson Ihrig studies.

Sincerely,

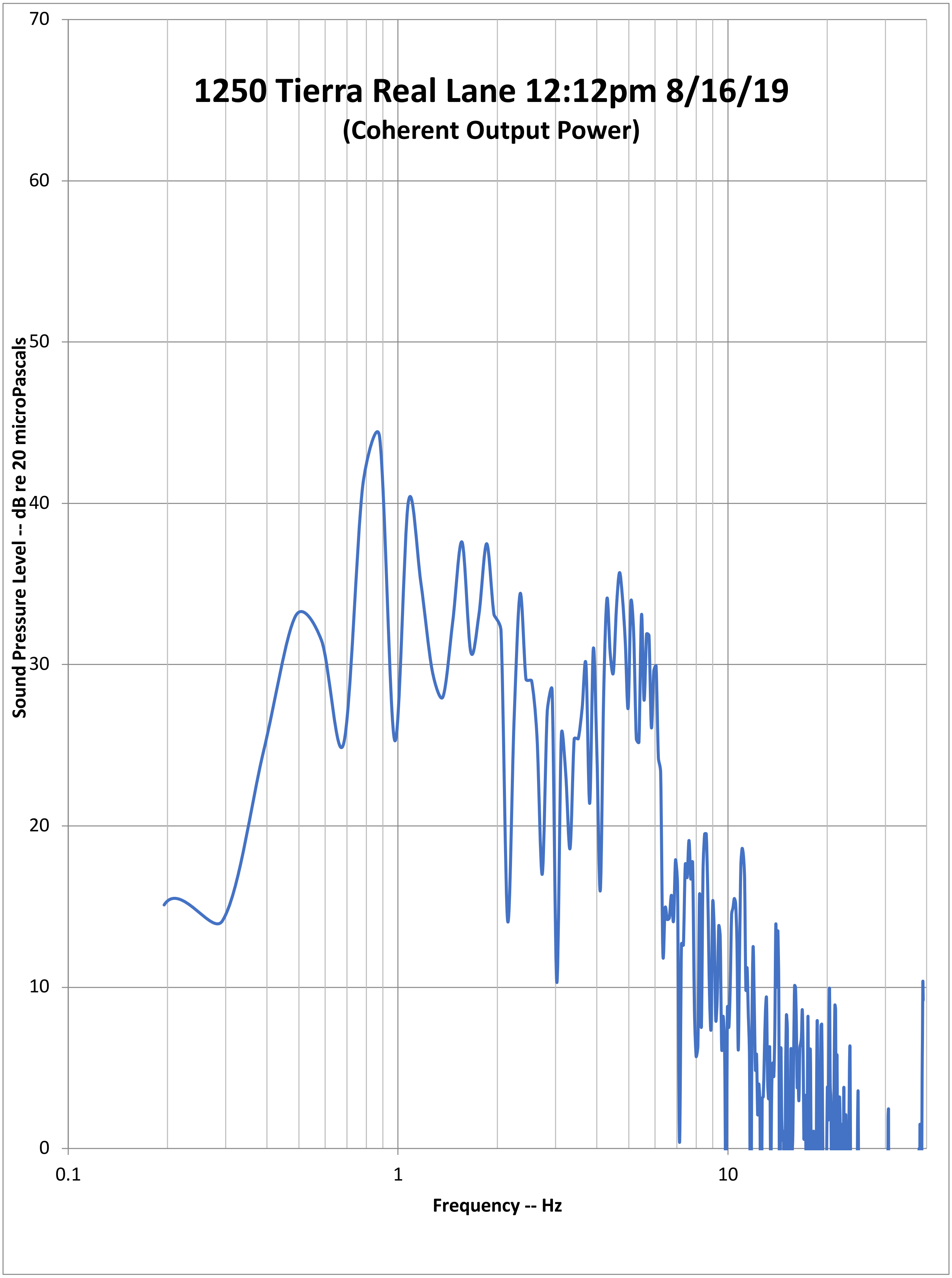
dBF ASSOCIATES, INC.

Steven Fiedler, INCE
Principal

References:

Wilson Ihrig. 2014. Kumeyaay and Octotillo Wind Turbine Facilities Noise Measurements. February 28.

Wilson Ihrig. 2019. Results of Ambient Noise Measurements of the Existing Kumeyaay Wind and Tule Wind Facilities in the Area of Boulevard and Jacumba Hot Springs Pertaining to the Proposed Torrey and Campo Wind Turbine Facilities. March 18.



1250 Tierra Real Lane 12:12pm 8/16/19
(Coherent Output Power)
Sound Pressure Level -- dB re 20 microPascals
Frequency -- Hz
70
60
50
40
30
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10
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1
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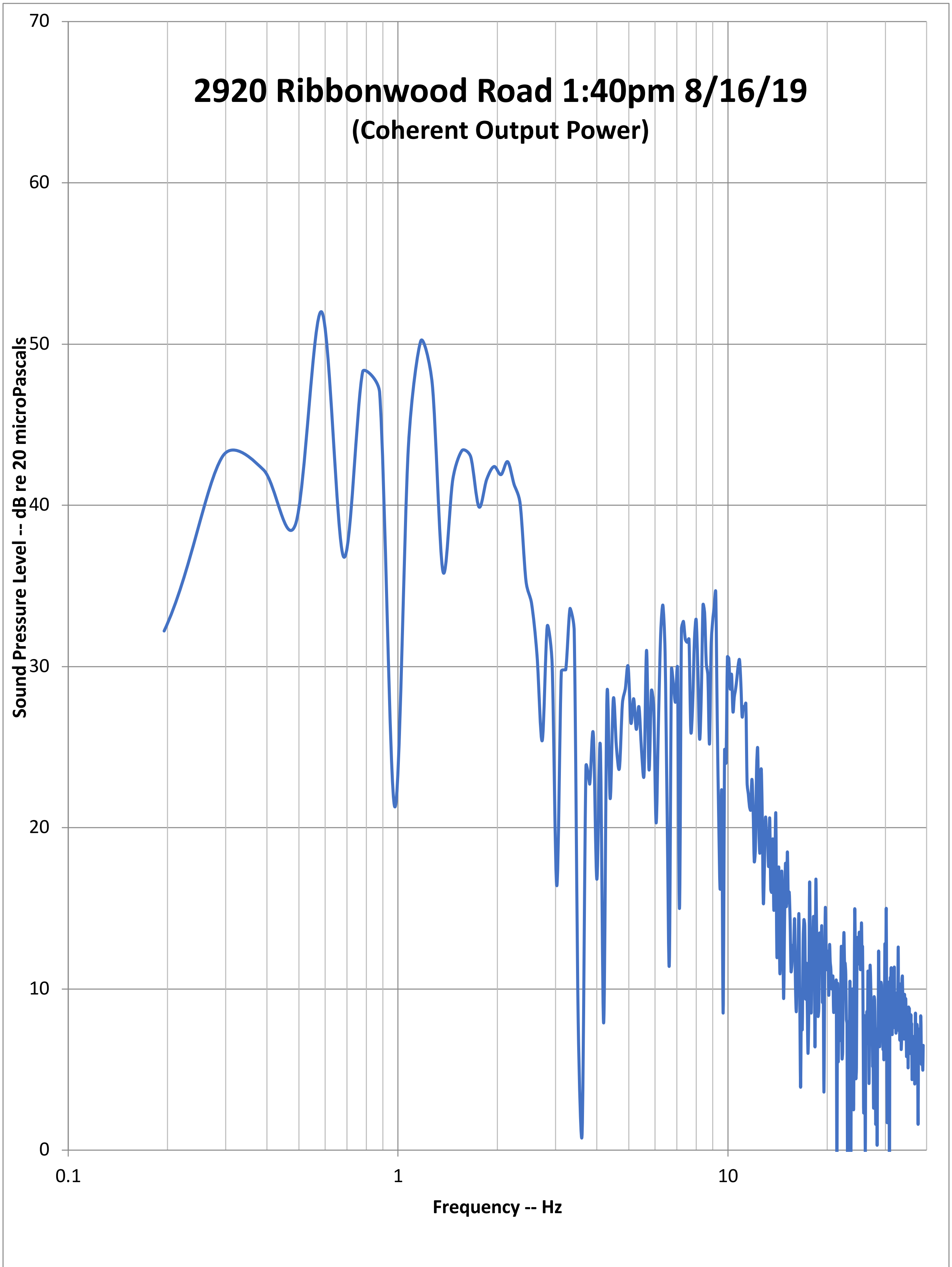

2920 Ribbonwood Road 1:40pm 8/16/19
(Coherent Output Power)
Sound Pressure Level -- dB re 20 microPascals
Frequency -- Hz
0
10
20
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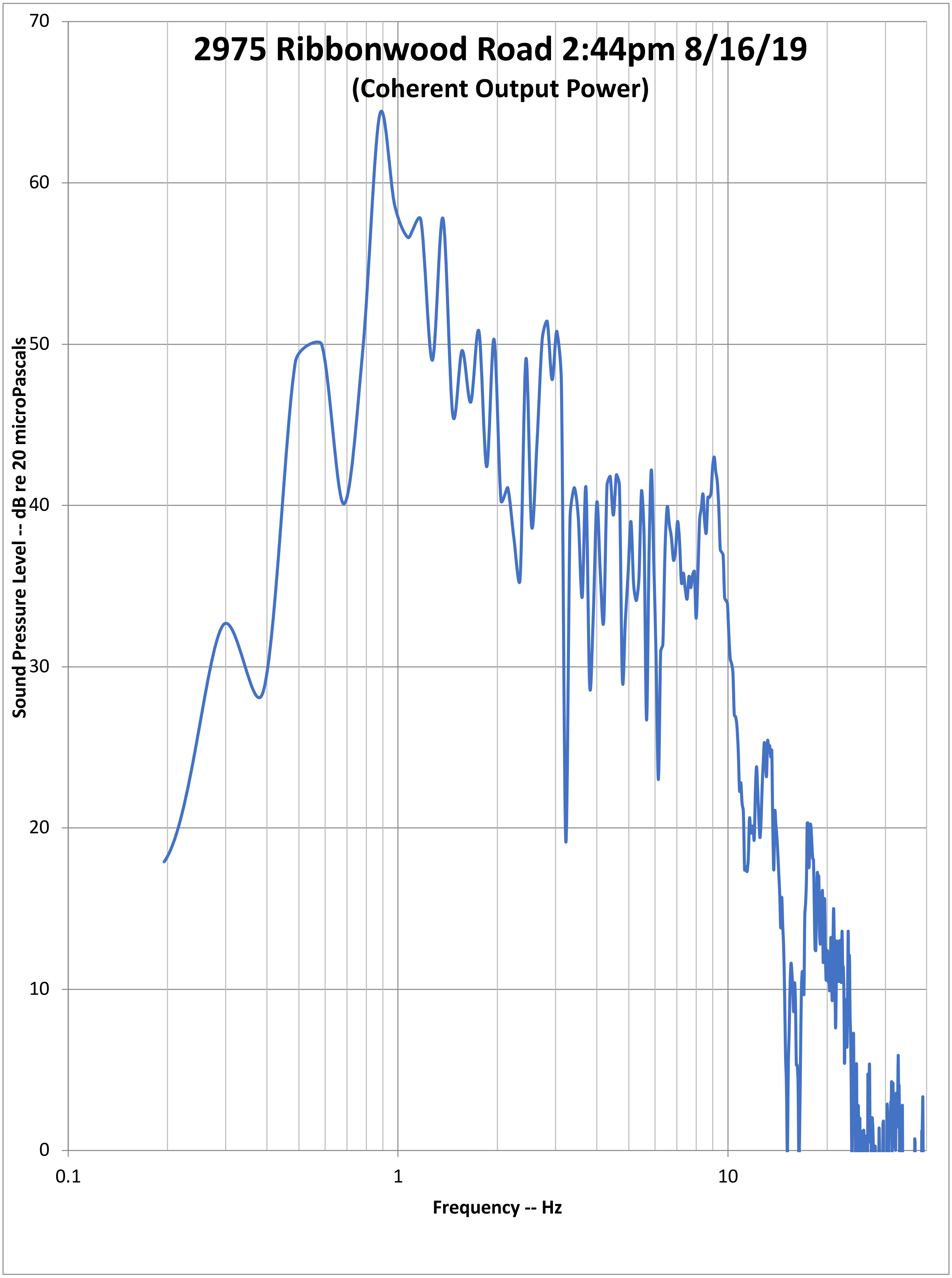
2975 Ribbonwood Road 2:44pm 8/16/19
(Coherent Output Power)
Sound Pressure Level -- dB re 20 microPascals
Frequency -- Hz
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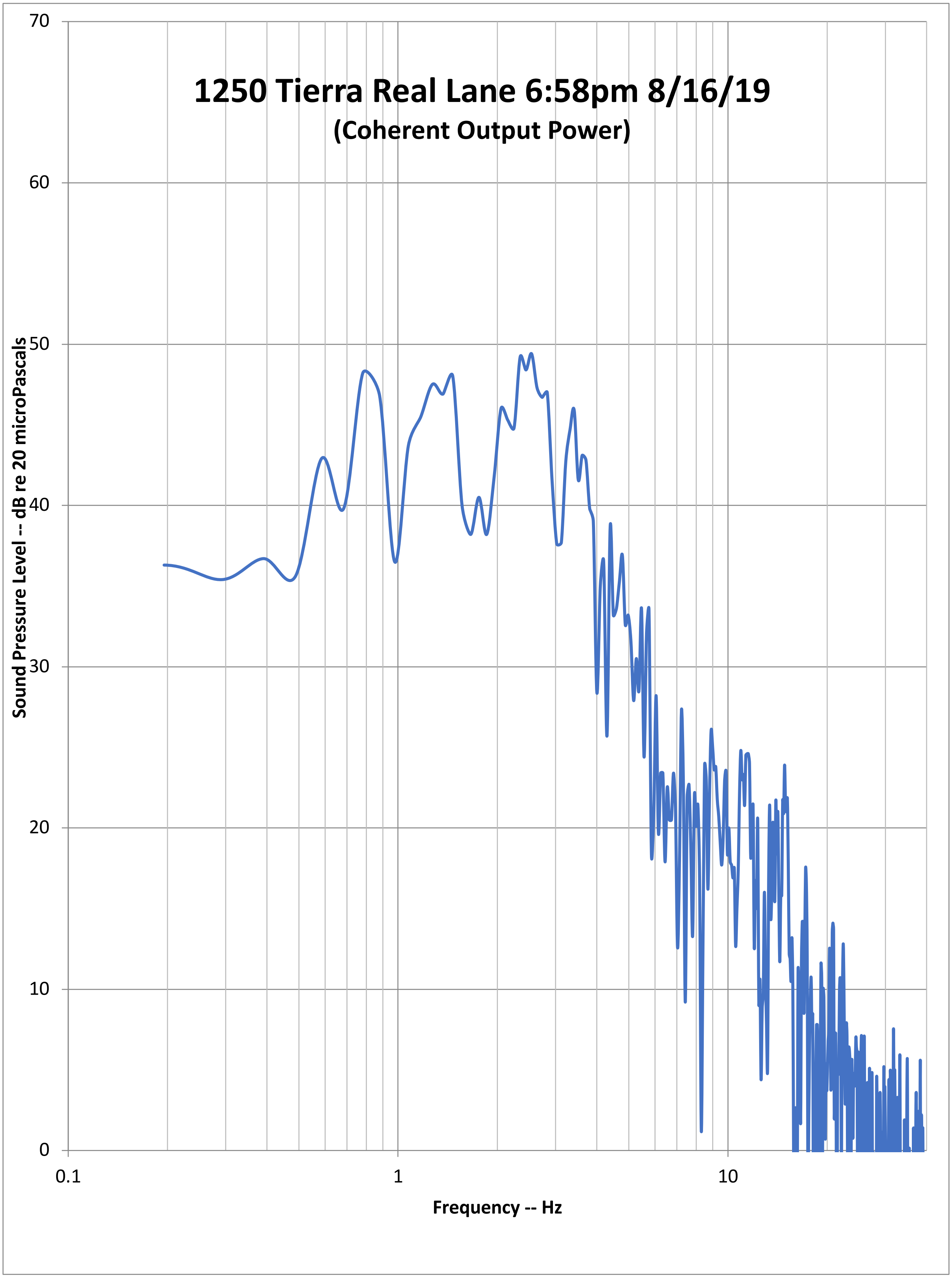

1250 Tierra Real Lane 6:58pm 8/16/19
(Coherent Output Power)
Sound Pressure Level -- dB re 20 microPascals
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0.1
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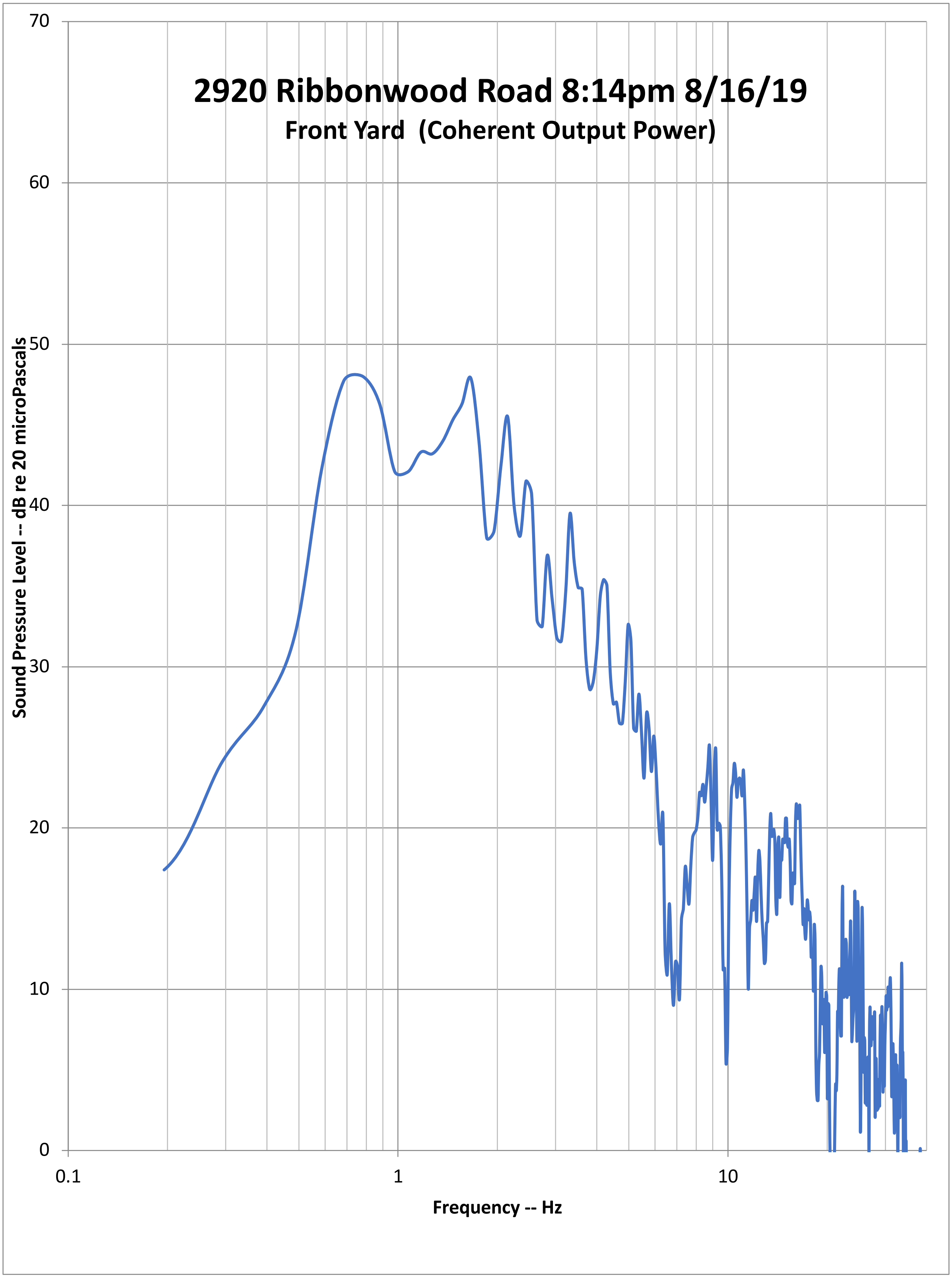
Frequency -- Hz


2920 Ribbonwood Road 8:14pm 8/16/19
Front Yard (Coherent Output Power)
Sound Pressure Level -- dB re 20 microPascals
Frequency -- Hz
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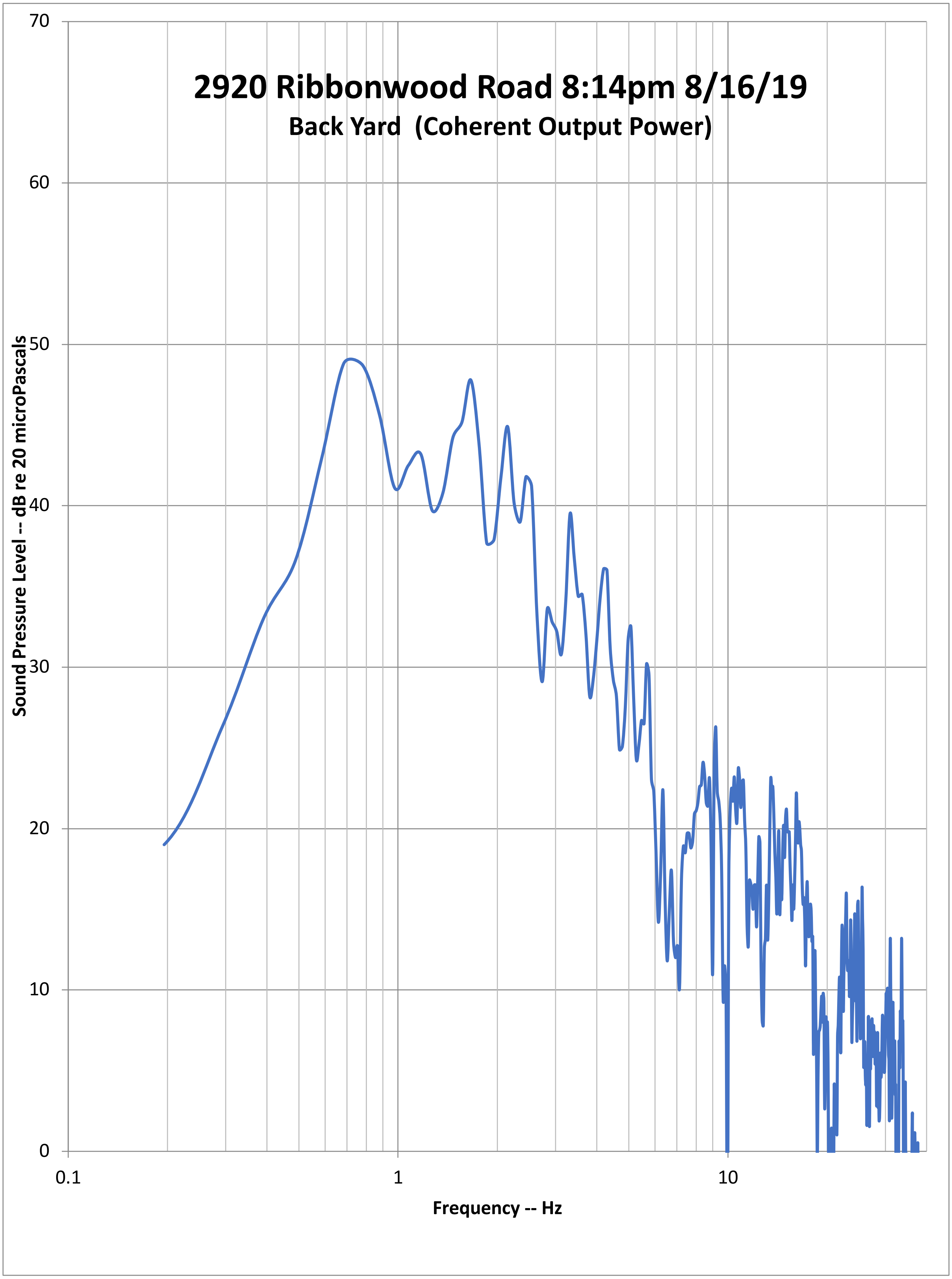

2920 Ribbonwood Road 8:14pm 8/16/19
Back Yard (Coherent Output Power)
Sound Pressure Level -- dB re 20 microPascals
Frequency -- Hz
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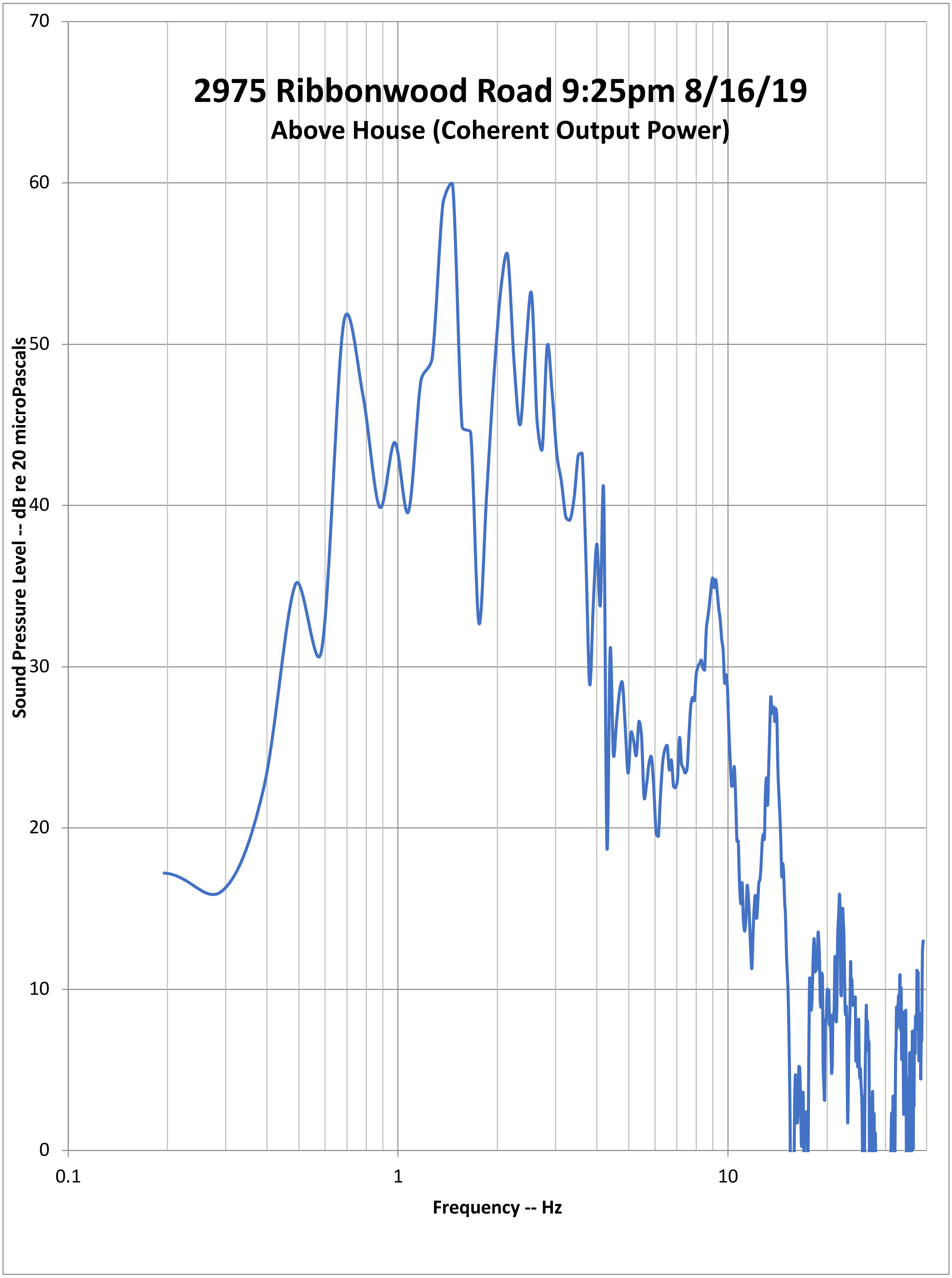
2975 Ribbonwood Road 9:25pm 8/16/19
Above House (Coherent Output Power)
Sound Pressure Level -- dB re 20 microPascals
Frequency -- Hz
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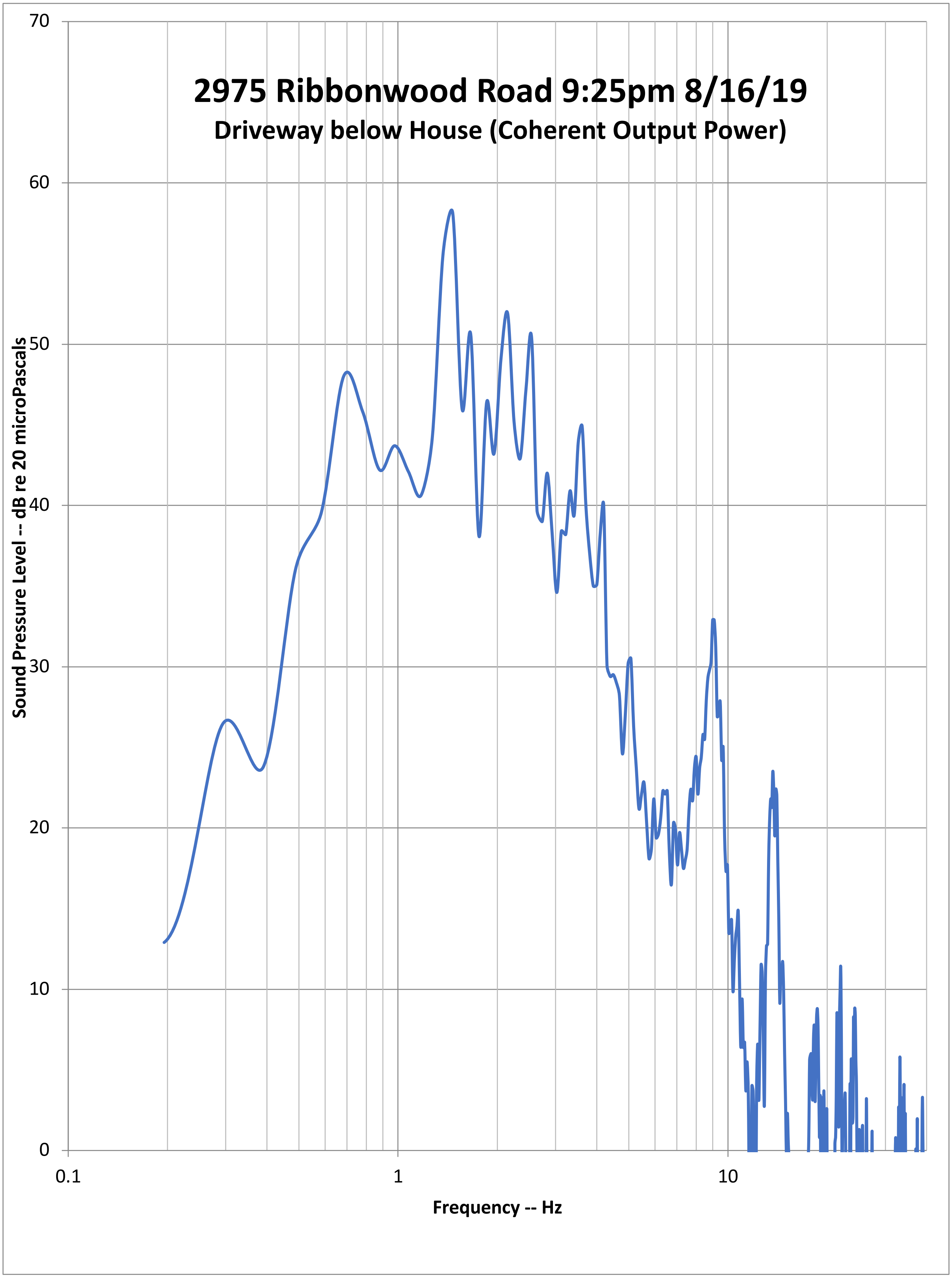
2975 Ribbonwood Road 9:25pm 8/16/19
Driveway below House (Coherent Output Power)
Sound Pressure Level -- dB re 20 microPascals
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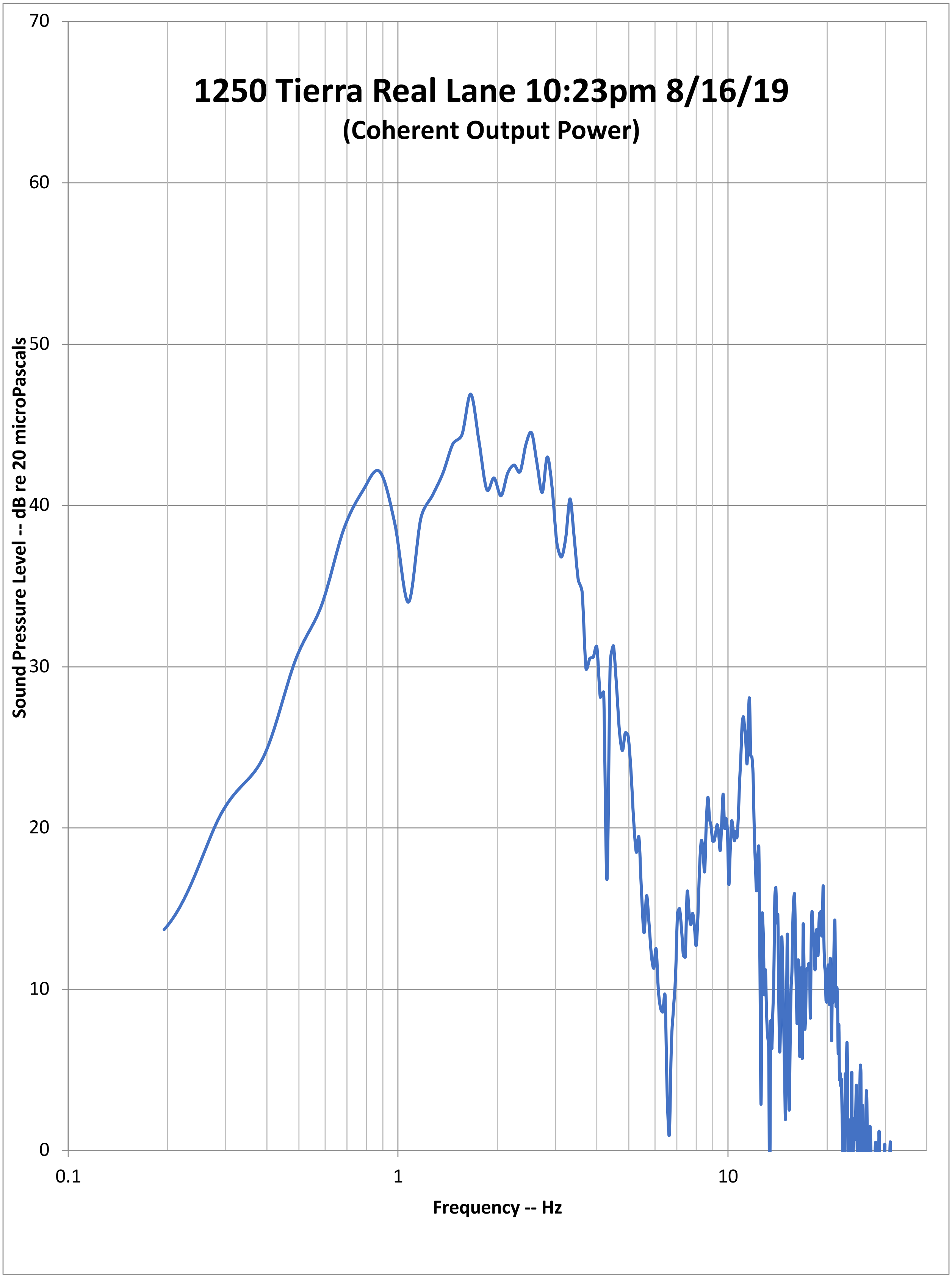
Frequency -- Hz


1250 Tierra Real Lane 10:23pm 8/16/19
(Coherent Output Power)
Sound Pressure Level -- dB re 20 microPascals
Frequency -- Hz
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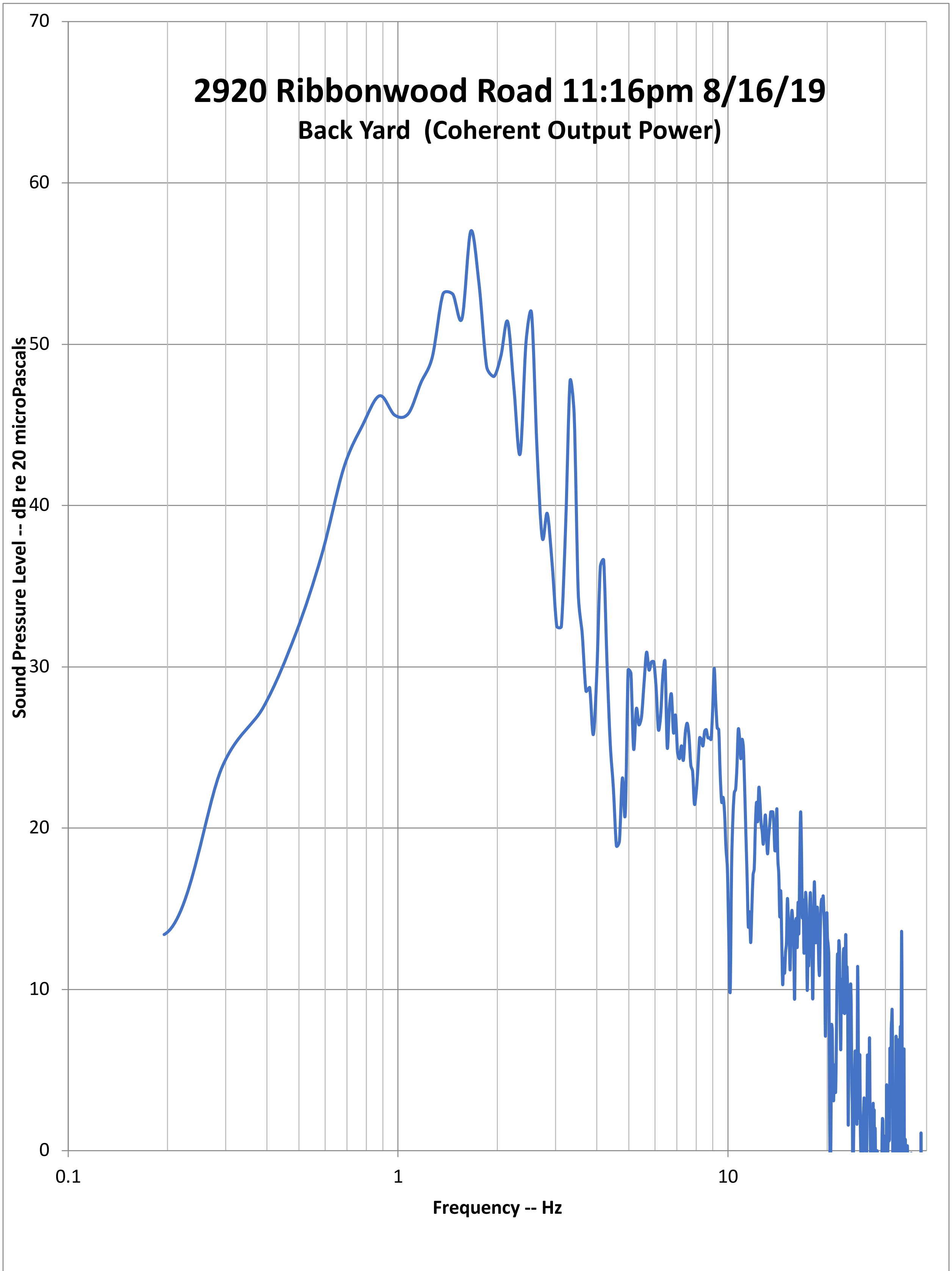

2920 Ribbonwood Road 11:16pm 8/16/19
Back Yard (Coherent Output Power)
Sound Pressure Level -- dB re 20 microPascals
Frequency -- Hz
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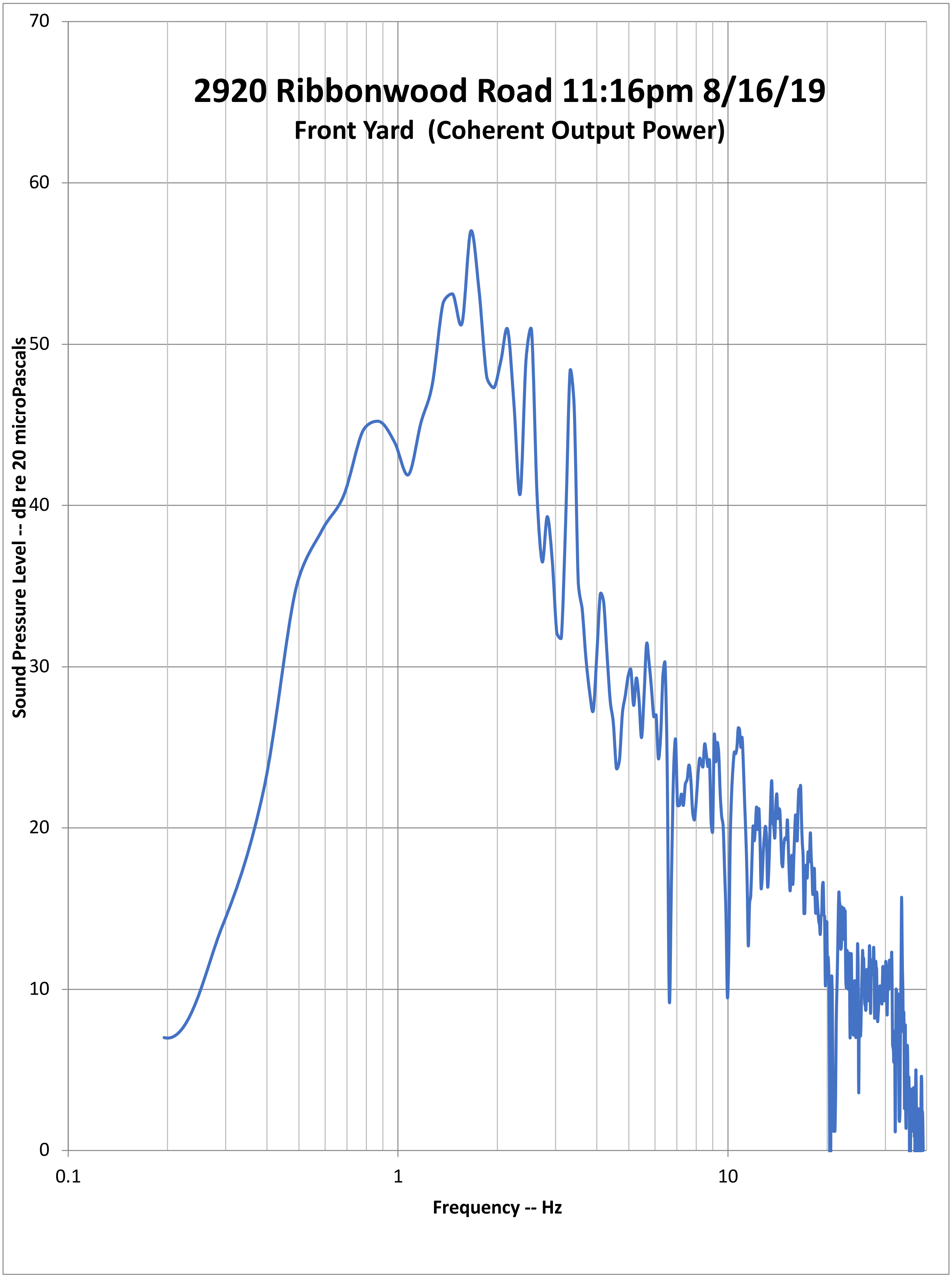
2920 Ribbonwood Road 11:16pm 8/16/19
Front Yard (Coherent Output Power)
Sound Pressure Level -- dB re 20 microPascals
Frequency -- Hz
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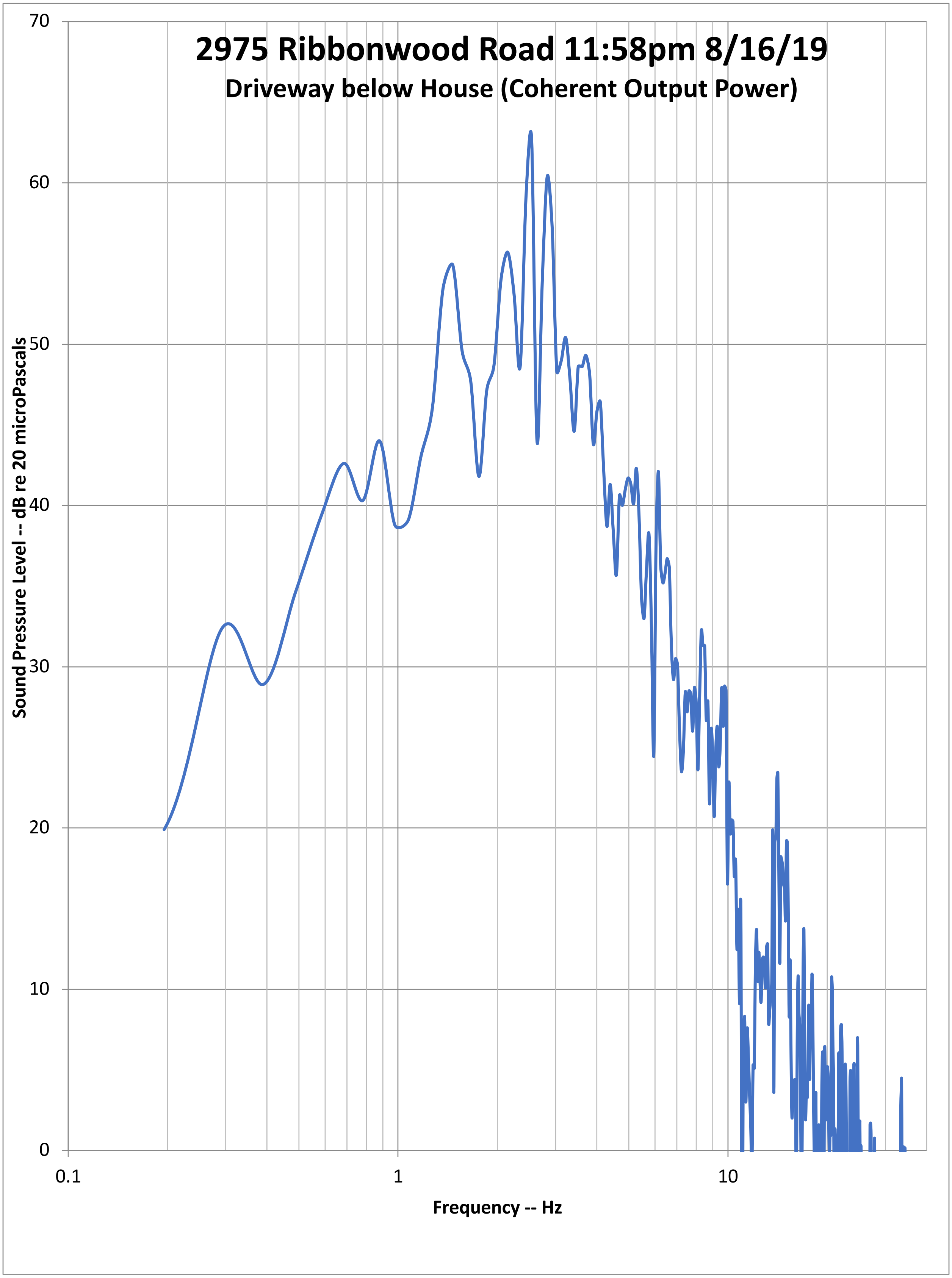
2975 Ribbonwood Road 11:58pm 8/16/19
Driveway below House (Coherent Output Power)
Sound Pressure Level -- dB re 20 microPascals
Frequency -- Hz
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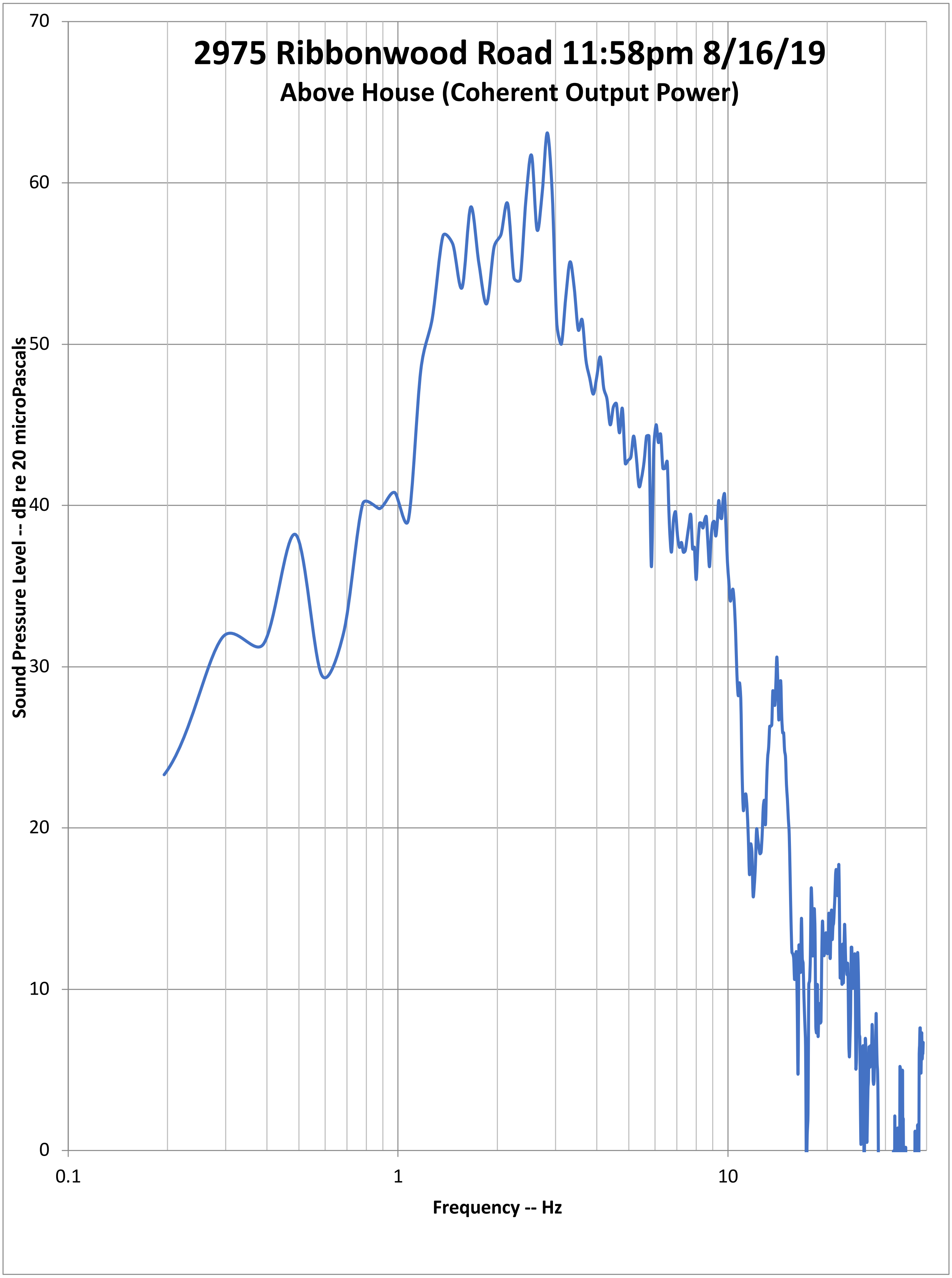
2975 Ribbonwood Road 11:58pm 8/16/19
Above House (Coherent Output Power)
Sound Pressure Level -- dB re 20 microPascals
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0.1
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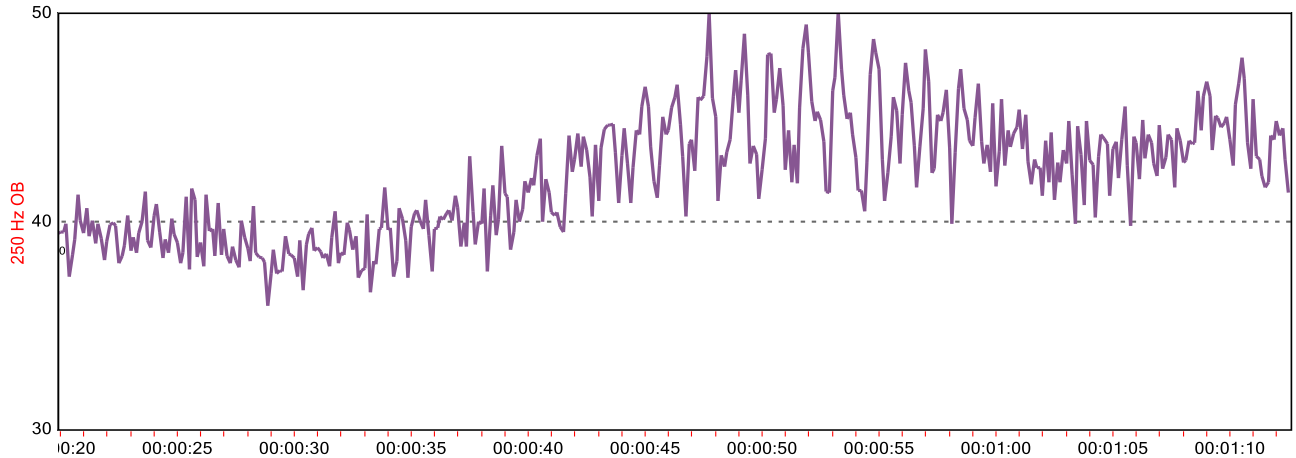

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Wind Turbine Noise and Sleep: Pilot Studies on the Influence of Noise Characteristics

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Abstract: The number of onshore wind turbines in Europe has greatly increased over recent years, a trend which can be expected to continue. However, the effects of wind turbine noise on long-term health outcomes for residents living near wind farms is largely unknown, although sleep disturbance may be a cause for particular concern. Presented here are two pilot studies with the aim of examining the acoustical properties of wind turbine noise that might be of special relevance regarding effects on sleep. In both pilots, six participants spent five consecutive nights in a sound environment laboratory. During three of the nights, participants were exposed to wind turbine noise with variations in sound pressure level, amplitude modulation strength and frequency, spectral content, turbine rotational frequency and beating behaviour. The impact of noise on sleep was measured using polysomnography and questionnaires. During nights with wind turbine noise there was more frequent awakening, less deep sleep, less continuous N2 sleep and increased subjective disturbance compared to control nights. The findings indicated that amplitude modulation strength, spectral frequency and the presence of strong beats might be of particular importance for adverse sleep effects. The findings will be used in the development of experimental exposures for use in future, larger studies.

Keywords: wind turbine noise; sleep disturbance; experimental study; amplitude modulation; polysomnography

1. Introduction

Wind is a renewable, sustainable source of power. Gross electricity consumption from wind energy in the European Union (EU) member states increased more than threefold between 2004 and 2014, a trend which can be expected to continue in order to fulfil EU climate goals for 2020 [1]. However, with the increase in wind power, more people will consequently live near wind turbines and are at risk of exposure to wind turbine noise (WTN).

According to the World Health Organization (WHO), an estimated 1.0–1.6 million healthy life years are lost each year due to environmental noise in Western Europe alone [2]. Sleep disturbance is the greatest contributor to this loss, accounting for approximately 900,000 years lost annually. Sleep is a physiological state necessary for maintaining mental and physical well-being [3]. Disturbed sleep can have a negative impact on many aspects of health and wellbeing, including impairment of attention [4], memory consolidation [5,6], neuroendocrine and metabolic functions [7,8], mood [9] and overall quality of life [10]. Night-time noise also affects autonomic functions [11,12], and epidemiological studies have demonstrated that long-term exposure to night-time environmental noise may increase the risk for developing cardiovascular disease [13,14].

While sleep disturbance by certain types of environmental noise has been relatively well investigated, particularly transportation noise from rail, air and road traffic [11], there is a relative lack of knowledge regarding the effects of WTN on sleep. Cross-sectional studies in communities with nearby wind farms have demonstrated that WTN causes both annoyance [15–19] and self-reported sleep disturbance [18,19] in a proportion of residents. A recent meta-analysis reported that self-reported high sleep disturbance increased with each A-weighted 10 dB increase in predicted outdoor nocturnal WTN (odds ratio = 1.60, 95% confidence interval: 0.86–2.94) [20]. However, this effect was not statistically significant, and the authors of the meta-analysis concluded that studies with objective measures of sleep and WTN were needed. The results of the meta-analysis were used by the WHO to conclude recently that public health recommendations could not be made for night-time WTN levels, since the quality of evidence was too low [21], assessed via the GRADE approach [22] adopted by the WHO. Low quality evidence in the GRADE approach can be interpreted as "further research being very likely to have an important impact on the certainty of the effect estimate and is likely to change the estimate" [21].

At present, effects of WTN have mainly been evaluated using subjective means, and only a few studies have investigated the physiologic response to WTN during sleep. Using wrist actigraphy, Michaud et al. measured sleep of individuals living 0.25–11.22 km from operational wind turbines to examine whether there was an association between objectively measured sleep disturbance and calculated outdoor WTN levels [23]. They found no consistent relationship between sleep disturbance and sound pressure level (SPL) averaged over one year. In another study, Jalali et al. measured sleep using polysomnography (PSG) in participants' homes, both pre- and post- wind turbine installation and operation [24]. They found no significant differences for any of the measured sleep variables. However, they also did not find any significant differences in SPLs measured in the bedrooms prior to- and after the wind turbines began operating.

Disturbance from noise depends not only on SPL but also on the characteristics of the noise [25]. The main source of noise from modern wind turbines is aerodynamic noise generated when air passes over the rotor blades [26]. Varying wind speed at different locations in the space swept by the rotor blades can lead to an amplitude modulated sound [27], which may be a possible source of disturbance as it is easily perceived and poorly masked by ambient background noise [15]. WTN is also unpredictable as it varies with wind speed and meteorological conditions [28]. Additionally, WTN is not necessarily attenuated during night-time; in fact, WTN levels may increase during stable atmospheric conditions which occur during the night to a greater extent than during daytime [29,30].

When dose-response curves for WTN levels and annoyance have been compared to previously established dose-response curves for other types of environmental noise (industrial and transportation noise), higher proportions of annoyed residents have been found for WTN at equal SPLs [17,31]. It is likely that several factors other than noise level contribute to response, including respondents' general attitude towards wind turbines and the experience of procedural fairness or injustice. Furthermore, one possible source of additional annoyance could be that certain characteristics of WTN are more disturbing [31] than those of other types of environmental noise. It is unclear at present whether such acoustical characteristics of WTN are also of relevance for noise-induced effects on sleep.

Because of the need for further research, we implemented a project named Wind Turbine Noise Effects on Sleep (WiTNES), the primary aim of which is a better understanding of causal links between WTN and sleep impairment. Within the project, a method was developed for synthesising WTN, allowing us to generate WTN with no background noise such as traffic, wildlife or meteorological phenomena, and also allowing for manipulation of different acoustical parameters of the noise [32]. Frequency-dependent outdoor to indoor attenuation curves for WTN level were also developed, allowing us to reproduce WTN spectra for indoor locations such as bedrooms, which is relevant for effects on sleep [33]. The present paper presents two pilot studies investigating the effect of wind turbine noise on physiologically measured sleep, conducted with the intention to guide the design and implementation of a larger-scale main study. Of primary interest was aiding the design of sound exposures for the main study. To our knowledge, these are the first studies investigating the effects of wind turbine noise on sleep under controlled laboratory conditions.

2. Methods

2.1. Experimental Design Overview

Two experimental studies were performed: Study A and Study B. Both studies used a within-subject design, with participants sleeping for five consecutive nights in a sound environment laboratory. Baseline sleep measured during a control night was compared to sleep measured during three nights where participants were exposed to WTN. These exposure nights involved variations of outdoor SPLs and frequency content due to outdoor-indoor filtering, simulating a bedroom with a window being slightly open or closed. Furthermore, within exposure nights there were variations in the acoustic characteristics of WTN.

2.2. Experimental Procedure

In order to make the study environment as ecologically valid as possible, the laboratory was outfitted to resemble a typical apartment, with further details and photographs available elsewhere [34]. It contained a combined kitchen and living area, three separate bedrooms and three lavatories. This allowed three individuals to participate concurrently during a given study period, sharing communal areas but sleeping privately. Each of the bedrooms was furnished with a single bed, a desk, a nightstand, chair and lamps. Low frequency noise (≤125 Hz) was introduced through eighty-eight loudspeakers (Sub-Bass modules, Mod. 4 × 10 in, Jbn Development AB, Örnsköldsvik, Sweden) mounted in the ceilings of the bedrooms. Higher frequencies (>125 Hz) were reproduced via two loudspeaker cabinets in the upper corners of the rooms (C115, frequency response 80–20,000 Hz, Martin Audio, High Wycombe, United Kingdom). Lights out was at 23:00 and an automated alarm in the bedrooms woke the participants at 07:00. To ensure there was sufficient time for PSG electrode placement (see below) and relaxation before going to bed, participants were required to arrive at the laboratory by 20:00 each evening. In order to allow participants to adapt to the unfamiliar environment and the PSG equipment used to measure sleep, the first night was a habituation night without exposure to WTN. Data from this night were not used in the analyses. The second night was an exposure-free control night used to measure baseline sleep. During nights 3–5, participants were exposed to WTN. The order of exposure nights was varied between study weeks, however there were only two study weeks in each of the studies and hence the order of nights was not perfectly counterbalanced. A low background noise (18 dB L_{Aeq}) simulating ventilation noise was played into the bedrooms throughout the study, as otherwise the background level was unnaturally low (≤13 dB L_{AEq}). Questionnaires were completed by study participants within 15 minutes of waking up. To avoid potential confounders that might affect sleep, participants were prohibited from daytime sleeping, caffeine consumption after 15:00 and alcohol consumption at any time during the studies.

2.3. Polysomnography

Sleep can be broadly classified into two states, rapid eye movement (REM) sleep and non-REM (NREM) sleep. NREM is further divided into three stages which are—in order of increasing depth—N1, N2 and N3 [35]. Different sleep stages have different characteristics in the electroencephalogram

(EEG), so we measured physiologic sleep using PSG. We recorded the surface EEG with derivations C3-A2, C4-A1, F3-A2, F4-A1, O1-A2 and O2-A1, electrooculogram and submental electromyogram. Additionally, the electrocardiogram was recorded with two torso electrodes, and pulse, blood oxygen saturation and plethysmogram were recorded using a finger pulse oximeter. Sampling and filter frequencies and placements of electrodes were in line with the American Academy of Sleep Medicine (AASM) guidelines [35]. All data were recorded offline onto an ambulatory PSG device (SOMNOscreen Plus, Somnomedics, Randersacker, Germany). Scoring of the PSG data was performed in line with AASM guidelines [35] by a single experienced sleep technologist who was blind to the study design. EEG arousals, which are abrupt changes in the EEG frequency and sometimes considered indicators of sleep fragmentation [36], were scored as per the American Sleep Disorders Association criteria [37]. Arousals lasting longer than 15 s were classed as awakenings.

Objective sleep variables of interest were sleep onset latency (SOL); total duration and maximum continuous time in stages wake (W), N1, N2, N3 and REM sleep; REM and N3 latency; sleep efficiency (SE); sleep period time (SPT): total sleep time (TST); wakefulness after sleep onset (WASO); timing of first and final awakenings; and the number and frequency of sleep stage changes (SSCs), arousals and awakenings. SOL was the time from lights out until the first non-wake epoch. REM and N3 latencies were the time from sleep onset until the first occurrence of REM or N3 respectively. SPT was the time from sleep onset until the final awakening. WASO was the time spent in W after sleep onset until the final awakening. TST was SPT minus WASO. SE was TST divided by time in bed (TIB, 480 min). SSCs were defined as transitioning from one sleep stage to a lighter stage. Transitions to W were not defined as SSCs but as awakenings. REM sleep was defined as the lightest sleep stage and hence no SSCs could occur from REM. Therefore, SSCs could occur from N3 to N2, N1 or REM, from N2 to N1 or REM and from N1 to REM.

2.4. Questionnaires

In laboratory studies, numerical scales with fixed end points and Likert scales have previously proved capable of detecting the effects of single nights of noise on morning tiredness and perceived sleep quality and depth [38,39], and have been correlated with certain objective sleep measures [40]. Subjective sleep quality was therefore assessed both using an eleven-point numerical scale (anchor points Very poor–Very good) and a five-category Likert scale (Very good; Good; Not particularly good; Poor; Very poor). Nocturnal restoration (anchor points Very tired–Very rested; Very tense–Very relaxed; Very irritated–Very glad) and self-assessed sleep (anchor points Easy to sleep–Difficult to sleep; Better sleep than usual–Worse sleep than usual; Slept deeply–Slept lightly; Never woke–Woke often) were assessed using eleven-point numerical scales.

Questions pertaining to noise-specific effects on sleep were adapted from recommendations for annoyance questions by the International Commission on the Biological Effects of Noise [41]. An eleven-point numerical scale was used to assess how much participants perceived that WTN disturbed their sleep (anchor points Not at all–Extremely) and four five-category Likert scales were used to investigate whether WTN caused poor sleep, wakeups, difficulties falling back to sleep and tiredness in the morning (Not at all, Slightly, Moderately, Very, Extremely). Also included on the questionnaire were items regarding perceived sleep latency, number of awakenings and whether participants found it difficult or easy to fall asleep following awakenings. The complete questionnaire is presented in the Supplemental Methods.

2.5. Noise Exposure: Study A

Following analysis of field measurements of WTN, three eight-hour night-time exposures of WTN were synthesised (hereafter termed Nights A1, A2 and A3) [32,33]. We varied the noise levels to correspond to different outdoor sound pressure levels in the three nights and used different outdoor-indoor filters to simulate the bedroom window being slightly open (window gap) or closed (Table 1). These resulting indoor noise spectra are given in Supplemental Figure S1. To allow investigation of differential effects of different WTN scenarios, eight periods with different sound character, each 400 s in duration, occurred in each hour of each night. Across the eight hours of the night, the ordering of these sound character periods was balanced in a Latin square so that any period would only follow and precede any other period once. Each hour ended with a 400 s period with no WTN. Based on analysis of existing sound characteristics of WTN [32], the noise scenarios differed in SPL, amplitude modulation (AM) strength (3–4 dB, 7–9 dB, 12–14 dB), rotational frequency of the turbine blades, AM frequency bands (low- or middle-frequency) and the presence or absence of strong beats (Table 2). AM is a rhythmic fluctuation in the noise level, and its calculation is described in detail elsewhere [32]. Beats are in this context defined as strong AM in the frequency range 400–2500 Hz. The spectrum for each sound character period is presented in Supplemental Figure S2.

Table 1. Simulated outdoor and indoor sound pressure levels and frequency filtering used in exposure Nights A1, A2 and A3 in Study A.

Exposure Night	$L_{AEq,8h,outdoor}$ (dB)	$L_{AEq,8h,indoor}$ (dB)	Filtering
Night A1	40	29.5	Window gap
Night A2	45	34.1	Window gap
Night A3	50	33.7	Window closed

Indoor levels were measured at the pillow position. $L_{AEq,8h,outdoor}$ = Outdoor A-weighted equivalent noise level over the 8 h night-time period. $L_{AEq,8h,indoor}$ = Indoor A-weighted equivalent noise level over the 8 h night-time period.

Table 2. Overview of the 400 s sound character periods within each hour in Study A.

Period	L_{AEq} Relative to 8-h Level (dB)	Rotational Frequency (rpm)	AM Strength	AM Frequency Band (Hz)	Beats
1	−2.5	15	7–9 dB	500–2000	No
2	-	15	7–9 dB	500–2000	No
3	+2.5	15	7–9 dB	500–2000	No
4	-	13	7–9 dB	80–315	No
5	-	17	12–14 dB	500–2000	Yes
6	-	14	3–4 dB	500–2000	No
7	-	15	12–14 dB	500–2000	No
8	-	18	12–14 dB	500–2000	Yes
9	No WTN				

Sound character was varied in level, turbine rotational frequency, amplitude modulation (AM) strength, AM frequency band and presence or absence of strong beats. Periods 1–8 were counterbalanced across the 8 night-time hours. Period 9 was always the final 400 s of each hour. L_{AEq} = A-weighted equivalent noise level.

2.6. Noise Exposure: Study B

In Study B the noise level, outdoor-indoor filtering and the frequency band of the amplitude modulation were varied between nights (Table 3). These resulting indoor noise spectra are given in Supplemental Figure S3. Within nights, there were variations in AM strength, rotational frequency and the presence or absence of beats. Unlike Study A, each factor had only two levels, giving a 2 × 2 × 2 factorial design, in order to allow comparison between specific sound characters (see Table 4). Each period was 400 s in duration and each hour ended with a WTN-free 400 s period. The periods were presented in a Latin square as described for Study A. The noise spectrum was kept the same for each sound character period, and is given in Supplemental Figure S4.

Table 3. Outdoor and indoor sound pressure levels, frequency filtering and AM frequency bands used in exposure Nights B1, B2 and B3 in Study B.

Exposure Night	$L_{AEq,8h,outdoor}$ (dB)	$L_{AEq,8h,indoor}$ (dB)	Filtering	AM Frequency Band (Hz)
Night B1	45	32.8	Window gap	160–500
Night B2	45	32.8	Window gap	80–315
Night B3	50	30.4	Window closed	80–315

Indoor levels were measured at the pillow position. $L_{AEq,8h,outdoor}$ = Outdoor A-weighted equivalent noise level over the 8 hour night-time period.

Table 4. Overview of the 400 s sound character periods within each hour in Study B.

Period	Rotational Frequency (rpm)	AM Strength	Beats
1	13	3–4 dB	No
2	17	3–4 dB	No
3	13	12–14 dB	No
4	17	12–14 dB	No
5	13	3–4 dB	Yes
6	17	3–4 dB	Yes
7	13	12–14 dB	Yes
8	17	12–14 dB	Yes
9	No WTN		

Sound character was varied in turbine rotational frequency, amplitude modulation (AM) strength, and presence or absence of strong beats. Periods 1–8 were counterbalanced across the 8 night-time hours. Period 9 was always the final 400 s of each hour.

2.7. Participants

For each of the two studies, six young, healthy participants were recruited via public advertising. Participants in study A (4 women, 2 men) had a mean age of 22.2 years, (standard deviation SD ± 1.3 years) and a mean body mass index (BMI) of 22.6 kgm^{-2} (SD ± 2.4 kgm^{-2}). Participants in study B (5 women, 1 man) had a mean age of 24.0 years (SD ± 2.3 years) and a mean BMI of 20.7 kgm^{-2} (SD ± 0.4 kgm^{-2}). Participants were screened prior to acceptance with the following exclusion criteria: any self-reported sleep-related disorders; sleeping patterns deviating from the intended sleeping hours in the study; tobacco or nicotine use; dependent on caffeine; regular medication affecting sleep; any self-reported hearing disorders including but not limited to hearing loss, tinnitus and hyperacusis. In order to avoid an increased risk of breathing problems or obstructive sleep apnoea among participants, they were required to have a BMI within the normal range (18.5–24.99 kg/m^{-2}). Before acceptance, participants had their hearing tested using pure tone audiometry between 125–8000 Hz to a screening level of 15 dB HL. All participants in both Study A and Study B were classed as being noise sensitive via a single item in the screening questionnaire. All subjects gave their informed consent for inclusion before they participated in the study, and were financially compensated for taking part in the studies. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Gothenburg Regional Ethical Review Board (Dnr 974-14).

2.8. Statistical Analysis

Statistical analyses were performed in SPSS 22 (IBM Corp., Armonk, NY, USA), employing non-parametric methods. Differences between nights were tested using Friedman tests (within-subject), and if a main effect was found then pairwise comparisons were performed using Wilcoxon signed-rank tests. As a pilot, the primary aim of Study A was not hypothesis testing, but rather to inform on the exposures to be used in future, larger studies [42]. Therefore, analyses were restricted to differences between-nights for PSG variables. In Study B, differences across nights for sound character periods 1–9 across nights were additionally analysed. Time in sleep stages N1, N2, N3 and REM were analysed as fractions of TST. To avoid overlooking any potentially relevant outcomes, a significance level of <0.1 was used, and corrections for multiple comparisons were abdicated. All results should therefore be interpreted with this consideration. Median and interquartile range (IQR) values are reported.

3. Results

3.1. Study A: Sleep Micro- and Macro-Structure

Mean values of each PSG variable in each study night are given in Supplemental Table S1. One female participant was excluded from analysis of absolute variables as she woke herself up early following two exposure nights. The ratio of events per hour of TST was analysed for cortical reactions:

SSCs, arousals, awakenings and combined EEG reactions (both arousals and awakenings together). There was a significant main effect of the frequency of awakenings (χ^2(df = 3) = 9.0, $p = 0.029$, Figure 1). Awakenings occurred more frequently during nights with indoor noise levels of 34 dB (window closed, Night A3) than in the control night ($p = 0.046$) and nights with 30 or 34 dB with the window slightly open, (Nights A1 and A2, $p = 0.028$ and $p = 0.028$ respectively).

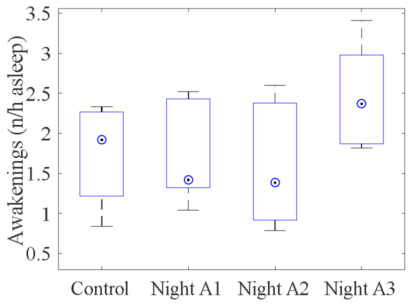

Figure 1. Frequency of awakenings per hour in Study A. Median (◉), interquartile range (boxes) and maximum/minimum values (whiskers).

There were no significant main effects between nights for the frequency of arousals, SSCs or combined EEG reactions, or for measures of sleep macrostructure SOL, N3 latency, WASO, time or maximum continuous time in stages W, N1, N2, N3 or REM.

3.2. Study A: Self-Reported Sleep

There was a significant main effect of perceived sleep disturbance by WTN (Table 5) where, relative to the control night, disturbance was greater in Night A2 ($p = 0.042$) and Night A3 ($p = 0.066$). There was also a significant difference in WTN causing tiredness in the morning, with post-hoc tests revealing that Night A3 caused more tiredness in the morning compared to the control night ($p = 0.059$). No significant main effects were found for any of the variables relating to sleep quality, nocturnal restoration, perceived sleep latency or number of recalled awakenings.

Table 5. Self-reported sleep variables where a main effect of night was found in Study A.

Sleep Measure	Median (IQR)				χ^2	*p*-Value
	Control	Night A1	Night A2	Night A3		
Sleep disturbance by WTN (0 = Not at all, 10 = Extremely)	0 (0–0.75)	0 (0–2.5)	1.5 (0.75–4)	2.5 (0–4.75)	7.227	0.065
WTN cause tiredness in the morning (Not at all = 1; Extremely = 5)	1 (1–1)	1 (1–2.25)	1 (1–2.25)	2 (1–2.25)	6.400	0.094

IQR = Interquartile range.

3.3. Study B: Sleep Micro- and Macro-Structure

3.3.1. Differences between Nights

Mean values of each PSG variable in each study night are given in Supplemental Table S2. There was a main effect on time spent in N3 (χ^2(df = 3) = 6.310, $p = 0.097$, Figure 2A), with a significant reduction in N3 sleep in exposure Night B2 compared to the control night ($p = 0.043$) and Night B3 ($p = 0.046$). There was a significant main effect of first awakening (χ^2(df = 3) = 9.400, $p = 0.024$, Figure 2B), with the first awakening occurring earlier in Night B2 compared to Night B1 ($p = 0.028$) and Night B3 ($p = 0.028$). There was a main effect of maximum continuous time in stage N2 ($N2_{max}$), (χ^2(df = 3) = 10.200, $p = 0.017$, Figure 2C), where $N2_{max}$ was shorter in Night B1 ($p = 0.027$) and Night B3 ($p = 0.027$) compared to the control night. Furthermore, $N2_{max}$ was shorter in Night B1 ($p = 0.046$) and Night B3 ($p = 0.028$) compared to Night B2. No significant main effects were found for SOL, REM or N3 latencies, total number of SSCs, WASO or SPT.

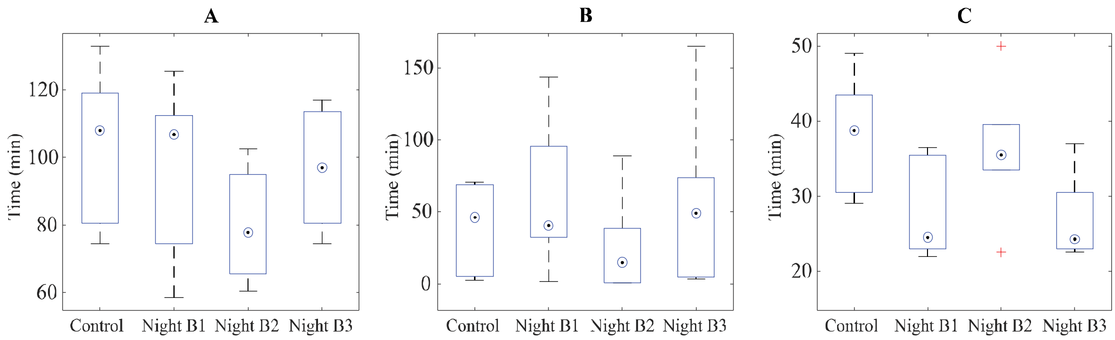

Figure 2. Median (◉), interquartile range (boxes) and maximum/minimum values (whiskers) for objective sleep parameters from Study B. (**A**). Total time in N3. (**B**). Time between sleep onset and first awakening. (**C**). Maximum continuous time in N2 sleep.

3.3.2. Effects of Sound Character Period between Experimental Nights

Main effects were found for percentage of N1 sleep in Period 6, percentage of N3 sleep in Period 4 and for time awake in Period 3 and 7 (Table 6). Participants spent more time awake in Period 7 in Night B1 (p = 0.042) and Night B3 (p = 0.026) compared to in the control night. However, post-hoc comparisons revealed no significant between-night differences for time awake in Period 3. The percentage of N1 sleep in Period 6 was higher in Night B2 compared to the control night (p = 0.028). There was a higher percentage of N1 sleep in Period 6 in Night B2 compared to the control night (p = 0.028). The percentage of N3 sleep in Period 4 was significantly lower in Night B2 compared to the control night (p = 0.046), Night B1 (p = 0.028) and Night B3 (p = 0.028).

Table 6. Objective sleep variables where a main effect of WTN sound character period was found in Study B.

Sleep Measure	Period	Median (IQR)				χ^2	p-Value
		Control	Night B1	Night B2	Night B3		
Time awake (min)	3 [a]	1 (0.50–1.63)	0.75 (0.50–1.25)	1.75 (0.75–5.13)	2 (0.88–2.88)	7.000	0.072
	7 [b]	0.75 (0.38–1.13)	1.75 * (1.50–2.0)	1.25 (0.50–2.75)	6.63 * (5.74–7.52)	8.509	0.037
N1 (%)	6 [c]	6.63 (5.74–7.52)	6.37 (0.71–13.84)	11.32 * (8.47–15.64)	4.69 (1.81–5.27)	11.400	0.010
N3 (%)	4 [d]	26.77 (21.24–29.41)	29.12 (13.60–33.02)	4.60 *,† (0–13.58)	27.22 (18.72–32.89)	10.900	0.014

[a] 13 rpm, strong AM, no beats; [b] 13 rpm, strong AM, beats; [c] 17 rpm, weak AM, beats; [d] 17 rpm, strong AM, no beats. Significant (p < 0.05) post-hoc differences to the control night are denoted *. Significant (p < 0.05) post-hoc differences to both Night B1 and Night B3 are denoted †. IQR = Interquartile range.

Cortical reaction frequencies (arousals, awakenings and SSCs) were calculated for similar sound character periods and analysed to examine whether any specific sound characteristic was of particular importance (Supplemental Figure S5). There were no significant main effects for arousals (p = 0.649), awakenings (p = 0.197) or SSCs (p = 0.191).

3.3.3. Study B: Self-Reported Sleep

Main effects between-nights were found for tiredness in the morning, tension in the morning, difficulties falling asleep, perceived sleep disturbance due to WTN. Furthermore, main effects were found for whether WTN caused poor sleep, awakenings difficulties falling asleep after awakenings or tiredness in the morning (Table 7).

Table 7. Self-reported sleep variables in Study B.

Sleep Measure	Median (IQR)				χ^2	p-Value
	Control	Night B1	Night B2	Night B3		
Sleep quality (Very good = 0, Very poor = 10)	3 (2.75–6.50)	4.5 (2–5.5)	4.5 (1–7.5)	6 (4.25–6.25)	0.911	ns
Verbal sleep quality (Very good = 1, Very poor = 5)	2 (2–2.25)	2 (1.75–4)	2 (1–2.75)	3 (2–3.25)	3.692	ns
Very rested (0)–Very tired (10)	2.5 (1.75–3.25)	5.5 * (1.75–6.25)	2.5 (1.5–6.75)	5.5 * (4–7)	9.367	0.025
Very relaxed (0)–Very tense (10)	3 (2.5–3.5)	4.5 (1–6)	3 (1–4.25)	5.5 *† (4.5–7)	8.625	0.035
Very glad (0)–Very irritated (10)	2 (0.75–4.75)	3.5 (1.75–7)	4 (1–4.5)	5.5 (3.75–6.25)	5.308	ns
Time to fall asleep (min)	15 (8.75–22.5)	27.5 (15.5–38.75)	15 (8.75–46.25)	25 (16.25–42.50)	3.808	ns
Estimated number of wakeups (n)	2 (2–3)	2 (2–4.25)	2.5 (1.75–4)	3 (1.75–3)	0.796	ns
Easy to sleep (0)–Difficult to sleep (10)	3 (0.75–4)	6 * (2.75–8)	2.5 (1–7.25)	6.5 * (4.25–8)	8.793	0.032
Slept better than usual (0)–Worse than usual (10)	5 (4.25–7.25)	6 (4.75–8.25)	5 (2.75–7.5)	7 (6–8.25)	3.982	ns
Deep sleep (0)–Light sleep (10)	3 (2.5–4.25)	6 (2–7.5)	3.5 (1.75–6.75)	6 (3–7.25)	3.911	ns
Never woke (0)–Woke often (10)	6.5 (5–7.25)	4 (2.75–9)	4 (3.25–5)	6 (2.75–7)	0.661	ns
Sleep disturbance by WTN (0 = Not at all, 10 = Extremely)	0 (0–0.25)	2.5 *† (2–7.25)	2.5* (1–4.5)	6 *‡† (3.5–6.25)	14.722	0.002
WTN cause poor sleep (Not at all = 1, Extremely = 5)	1 (1–1)	2 * (1–3.25)	2 (1–3)	3 * (2–3)	10.432	0.015
WTN cause awakenings (Not at all = 1, Extremely = 5)	1 (1–1.25)	1.5 (1–3.25)	1.5 * (1–2.25)	2.5 * (1.75–3.25)	9.250	0.026
WTN cause difficulties falling back to sleep (Not at all = 1, Extremely = 5)	1 (1–1)	2.5 * (1.75–4)	2 * (1.75–2)	3 * (1.75–3.25)	9.889	0.020
WTN cause tiredness in the morning (Not at all = 1, Extremely = 5)	1 (1–1.25)	2 * (2–4)	2 (1.75–3.25)	3 *† (2.75–4)	15.125	0.002

Sleep quality was coded such that the scales are in the same direction as for other items, i.e., a higher value indicates worse sleep. p-values relate to tests of main effects. ns = not significant ($\alpha = 0.1$). Significant ($p < 0.1$) post-hoc tests are denoted * (compared to control night); ‡ (compared to Night B1); † (compared to Night B2). IQR = Interquartile range.

Relative to the control, after Night B1 participants were more tired ($p = 0.063$), had greater difficulty falling asleep ($p = 0.072$) and were more disturbed by WTN ($p = 0.026$). In Night B1, WTN-induced poor sleep ($p = 0.066$), WTN-induced difficulty falling asleep after awakenings ($p = 0.041$) and WTN-induced tiredness ($p = 0.024$) were rated deleteriously compared to the control night. Additionally, perceived disturbance from WTN was greater in Night B1 than Night B2 ($p = 0.066$).

Relative to the control, participants in Night B2 were more disturbed by WTN ($p = 0.027$) and reported more WTN-induced awakenings ($p = 0.083$) and WTN-induced difficulty falling asleep after awakenings ($p = 0.025$).

Relative to the control, participants in Night B3 were more tired ($p = 0.026$), more tense ($p = 0.041$), had more difficulty falling asleep ($p = 0.027$) and were more disturbed by WTN ($p = 0.027$). Furthermore, they indicated more WTN-induced poor sleep ($p = 0.023$), more WTN-induced awakenings ($p = 0.038$), greater WTN-induced difficulty falling asleep after awakenings ($p = 0.039$) and increased WTN-induced tiredness in the morning ($p = 0.024$). Furthermore, tension ($p = 0.043$) and WTN-induced sleep disturbance ($p = 0.068$) were greater following Night B3 than Night B2. WTN-induced tiredness was higher following Night B3 than Night B1 ($p = 0.083$) and Night B2 ($p = 0.059$).

4. Discussion

Two studies investigating the effects of nocturnal wind turbine noise on physiologically measured sleep in a laboratory setting have been presented. They were intended to serve as pilot studies prior to a subsequent larger study, and they had the main objective of providing indications of specific sound character of WTN that may be of particular relevance for effects on sleep. Regarding an overall effect of WTN on sleep, there was some evidence that participants had more frequent awakenings, reduced amounts of N3 ("deep") sleep, reduced continuous N2 sleep, increased self-reported disturbance and WTN-induced morning tiredness in exposure nights with WTN compared to WTN-free nights.

Furthermore, there was limited evidence from Study B that wakefulness was adversely affected by strong amplitude modulation and lower rotational frequencies, N3 sleep seemed to be adversely affected by higher rotational frequency and strong amplitude modulation and N1 sleep increased with high rotational frequency and beating. However, the current analyses have not accounted for potential interaction effects between sound character periods and exposure night. For instance, it cannot be excluded that an interaction between the exposures used in exposure Night B2 in Study B (50 dB outdoor level with a closed window) and the sound characteristics of Period 4 (high RPM, strong AM, no beats) in the same night is responsible for the observed reduction in N3.

Awakenings occur spontaneously during sleep, but an increased awakening frequency can disrupt the biorhythm of sleep, causing sleep fragmentation and often resulting in an increase in wakefulness and stage N1 ("light") sleep with corresponding decreases in deep and REM sleep [38,43]. Deep sleep is believed to be important for nocturnal restoration [44], while N1 may be of little or no recuperative value [45]. Additionally, deep sleep is thought to be important for consolidation of declarative memory, while REM sleep may be important for more implicit memory processes, such as procedural memory [46,47]. While the current studies cannot and do not aim to say anything regarding potential after-effects of the observed changes, the observations of reduced N3, increased N1 and an increased wakefulness under certain sound characteristics of WTN warrants further research.

In Study A, physiologic sleep was generally most impacted during the night with 33.7 dB $L_{AEq,8h,indoor}$ closed window and in Study B by nights with low frequency band AM and 32.8 dB $L_{AEq,8h,indoor}$ slightly open window. Both cases represent experimental nights with the highest or close to highest SPL in the respective studies, although differences to the lowest WTN levels were at most 4 dB. This provides some small support for the level-dependence for WTN-induced sleep disturbance that has sometimes been seen previously in the field for self-reported measures [19]. In both Studies A and B there were however exposure nights with similarly high noise levels where no effects on sleep were seen, although there were also differences in the AM frequency band or spectral content of the noise due to outdoor-indoor filtering. A possible frequency dependency of WTN-induced effects on sleep should be considered in future work.

The studies are limited by both the low sample size, and the representativeness of the study population. The low sample size means that only large effect sizes were likely to be detected, even after relaxing the criterion for statistical significance. The participants, being young and healthy individuals with good normal sleep, are not representative of the typical population that may be exposed to WTN at home. However, considering that the aim was to evaluate whether WTN at these levels could have an impact on sleep and whether certain sound characteristics would have a higher impact, the generalisability to a larger population was not the primary concern. Nevertheless, sleep generally deteriorates with increasing age [48], and the prevalence of sleep-related disorders may be around 27% in field settings [49]. It is therefore plausible that the study population represent a particularly robust group, and any WTN-induced effects on sleep may be worse in the field.

The experimental WTN levels were above the recommended outdoor levels for Sweden [50], although within the recommended outdoor levels for many other countries [51]. The levels were selected to represent worst-case conditions that may occur under unfavourable weather conditions and to increase the likelihood of detecting any effects of WTN despite the low sample size. However, this also means that the findings should not be taken as clear evidence of sleep disturbance due to WTN. The studies were conducted with the aim of providing guidance in the implementation of a larger study, preliminary results of which are available elsewhere [52], and results should be treated accordingly.

5. Conclusions

There were some indications that WTN led to objective sleep disruption, reflected by an increased frequency of awakenings, a reduced proportion of deep sleep and reduced continuous N2 sleep. This corresponded with increased self-reported disturbance. However, there was a high degree of heterogeneity between the two studies presented, precluding firm conclusions regarding effects of WTN on sleep. Furthermore, there was some limited evidence from the second study that wakefulness increase with strong amplitude modulation and lower rotational frequency, the deepest sleep was adversely affected by higher rotational frequency and strong amplitude modulation, and light sleep increased with high rotational frequency and acoustic beating. These findings will be used in the development of noise exposures for a larger-scale sleep study that will implement more naturalistic WTN and use a more representative study population.

Supplementary Materials: The following are available online at http://www.mdpi.com/1660-4601/15/11/2573/s1. Morning questionnaire. Figure S1: Indoor average spectra across the full 8-hour exposure period for each WTN night in Study A. Figure S2: Outdoor spectrum (40 dB $L_{AEq,8h}$) for each sound character period in Study A. Figure S3: Indoor average spectra across the full 8-hour exposure period for each WTN night in Study B. Figure S4: Outdoor spectrum (45 dB $L_{AEq,8h}$) for each sound character period in Study B. Table S1: Mean and standard deviation (SD) of sleep macro- and micro-structure data for each night in Study A. Table S2: Mean and standard deviation (SD) of sleep macro- and micro-structure data for each night in Study B. Figure S5: Median, interquartile range, maximum/minimum values and outliers for cortical reaction frequency across periods of different character WTN. A) Arousals. B) Awakenings. C) Sleep stage changes.

Author Contributions: K.P.W., M.G.S. and M.Ö. conceived the study. K.P.W., M.Ö., M.G.S. and E.P. designed the experiments. P.T., M.Ö. and J.F. developed the experimental noise exposures. M.G.S. performed the study. J.A.M. and M.G.S. analysed the data. J.A.M. and M.G.S. drafted the manuscript. All authors critically appraised and revised the manuscript.

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Glossary

AM	Amplitude modulation. A time-varying increase and decrease in sound pressure level, which can vary for different frequencies of the same sound signal
A-Weighting	Frequency weighting filter applied to a sound measurement to mimic the frequency-dependence of human hearing
dB	Decibel, relative to the threshold of human hearing (2×10^{-5} Pa)
EEG	Electroencephalogram
L_{AEq}	A-weighted equivalent continuous sound pressure level, expressed in decibels. Can be considered the "average" of a time-varying sound pressure level over a specified period
$L_{AEq,8h,indoor}$	A-weighted equivalent continuous indoor sound pressure level over 8 h
$L_{AEq,8h,outdoor}$	A-weighted equivalent continuous outdoor sound pressure level over 8 h
NREM	Non-rapid eye movement
PSG	Polysomnography
SSC	Sleep stage change
REM	Rapid eye movement
WHO	World Health Organization
WTN	Wind turbine noise

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EXHIBIT
15

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Impact of Long-Term Exposure to Wind Turbine Noise on Redemption of Sleep Medication and Antidepressants: A Nationwide Cohort Study

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Background: Noise from wind turbines (WTs) is associated with annoyance and, potentially, sleep disturbances.

Objectives: Our objective was to investigate whether long-term WT noise (WTN) exposure is associated with the redemption of prescriptions for sleep medication and antidepressants.

Methods: For all Danish dwellings within a radius of 20-WT heights and for 25% of randomly selected dwellings within a radius of 20-to 40-WT heights, we estimated nighttime outdoor and low-frequency (LF) indoor WTN, using information on WT type and simulated hourly wind. During follow-up from 1996 to 2013, 68,696 adults redeemed sleep medication and 82,373 redeemed antidepressants, from eligible populations of 583,968 and 584,891, respectively. We used Poisson regression with adjustment for individual and area-level covariates.

Results: Five-year mean outdoor nighttime WTN of $\geq$42 dB was associated with a hazard ratio (HR) = 1.14 [95% confidence interval (CI): 0.98, 1.33) for sleep medication and HR = 1.17 (95% CI: 1.01, 1.35) for antidepressants (compared with exposure to WTN of <24 dB). We found no overall association with indoor nighttime LF WTN. In age-stratified analyses, the association with outdoor nighttime WTN was strongest among persons $\geq$65 y of age, with HRs (95% CIs) for the highest exposure group ($\geq$42 dB) of 1.68 (1.27, 2.21) for sleep medication and 1.23 (0.90, 1.69) for antidepressants. For indoor nighttime LF WTN, the HRs (95% CIs) among persons $\geq$65 y of age exposed to $\geq$15 dB were 1.37 (0.81, 2.31) for sleep medication and 1.34 (0.80, 2.22) for antidepressants.

Conclusions: We observed high levels of outdoor WTN to be associated with redemption of sleep medication and antidepressants among the elderly, suggesting that WTN may potentially be associated with sleep and mental health. https://doi.org/10.1289/EHP3909

Introduction

Over the last several decades, wind power deployment has increased markedly worldwide, with a rise in the global cumulative wind capacity from 23 GW in 2001 to 487 GW in 2016 (GWEC 2017). In Denmark, wind power provides more than 40% of the national electricity consumption, which is the highest proportion worldwide. This has led to a growing number of persons being exposed to noise from wind turbines (WTs), followed by a rise in the number of persons complaining that WT noise (WTN) impacts their lives negatively through noise annoyance, disturbance of sleep, and other adverse health effects (Schmidt and Klokker 2014).

Epidemiological studies have consistently found that emission of noise from WTs is associated with annoyance (Guski et al. 2017; Hongisto et al. 2017; Michaud et al. 2016d). Exposure–response curves show that WTN is associated with a higher proportion of highly annoyed persons than traffic noise at comparable levels (Janssen et al. 2011; Michaud et al. 2016d). Potential explanations include that WTN, which depends on wind speed and direction, is less predictable for those exposed than other noise sources such as road traffic noise. In addition, onshore WTs are typically erected in rural areas, where people often expect silent surroundings and where the sound from WTs may be more noticeable than in urbanized areas. Furthermore, amplitude modulation gives WTN a rhythmic quality different from traffic noise, and it has been suggested that the characteristics of WTN relevant for annoyance may be better captured by metrics focusing on amplitude modulation or low-frequency (LF) noise, rather than the full spectrum A-weighted noise (Jeffery et al. 2014; Schäffer et al. 2016).

Studies have indicated that exposure to WTN is associated with the disturbance of sleep, and the potential mechanisms include a direct association with nighttime noise, disturbance of sleep through annoyance, or a combination of the two (Bakker et al. 2012). A meta-analysis from 2015 based on 1,039 persons from six cross-sectional studies using questionnaires to assess information on sleep disturbance, found that exposure to WTN increased the odds for self-reported sleeping problems (Onakpoya et al. 2015). The investigators, however, wrote that the results should be interpreted with caution due to large variations in the estimations of noise and self-reported sleep disturbance across the included studies. Since the meta-analysis in 2015, a Japanese study of 1,079 persons found that outdoor WTN levels >40 dB were associated with self-reported insomnia (Kageyama et al. 2016). Interestingly, a cross-sectional Canadian study of 1,238 persons found no associations between 1-y mean outdoor WTN and various measures of sleep, including both subjective self-reported information of sleep quality and use of sleep medication as well as objective measures of sleep (Michaud et al. 2016a, 2016b). Thus, it remains uncertain from which exposure levels and to what extent WTN disturbs sleep.

A few studies have investigated whether WTN is associated with mental health, which was mainly assessed as self-reported quality of life (Feder et al. 2015; Jalali et al. 2016; Onakpoya et al. 2015). While a systematic review from 2015 based on four cross-sectional studies concluded that living in areas with WTs might be associated with decreased quality of life (Onakpoya et al. 2015), a recent large Canadian study found no association (Feder

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et al. 2015). In addition, a study based on 31 participants with self-reported information on quality of life before and after installation of WTs, found a worsening in different components of quality of life such as the mental component score (Jalali et al. 2016). Last, the large Canadian study also investigated whether outdoor 1-y WTN noise was associated with self-reported anxiety or depression medication but found no association (Michaud et al. 2016b).

The existing studies on WTN and sleep and mental health are generally of cross-sectional design and rely on active participation and self-reported data. We aimed to investigate whether long-term residential exposure to WTN was associated with the redemption of prescriptions for sleep medication and antidepressants in a prospective, nationwide register-based cohort.

Methods

Study Base and Modeling of Noise

In Denmark, all WT owners are required to report the cadastral code and geographical coordinate of their WT(s) to the national Master Data Register of Wind Turbines. For WTs in operation at the time of data extraction, this register also included WT coordinates from the Danish Geodata Agency. In this register, we identified 7,860 WTs in operation at any time during the period 1980–2013. We then excluded 517 offshore WTs. In case of disagreement between the geographical information recorded in the register, the WT location was validated against historical topographic maps and aerial photographs. New coordinates were assigned to the 314 WTs that were incorrectly recorded in the register, and 87 WTs were excluded because no credible location could be established, leaving 7,256 WTs for noise modeling. For these WTs, we collected information on model, type, height, and operational settings (where relevant). Subsequently, each WT was classified into one of 99 noise spectra classes, with detailed information on the noise spectrum from 10–10,000 Hz in thirds of octaves for wind speeds from 4–25 m/s. The noise classes were determined from existing measurements of noise spectra for Danish WTs (Backalarz et al. 2016; Sondergaard and Backalarz 2015).

We estimated the hourly wind speed and direction at hub height for each WT location for the period 1982–2013. This was done using mesoscale model simulations performed with the Weather Research and Forecasting model (Hahmann et al. 2015; Peña and Hahmann 2017). For each WT location, the simulations also provided data on relative humidity and temperature at a height of 2 m and data on atmospheric stability, which were all used for noise modeling.

The modeling of WTN has been described in detail elsewhere (Backalarz et al. 2016). Briefly, we initially identified buildings eligible for detailed noise modeling, defined as all dwellings that could experience at least 24 dB outdoor noise or 5 dB indoor LF noise (10–160 Hz) under the (unrealistic) scenario that all WTs ever operational in Denmark were operating at the same time at 8 m/s wind speed, with downwind sound propagation in all directions. Subsequently, we performed a detailed modeling of noise exposure for the 553,066 buildings identified as eligible in the first step, calculating noise levels in one-third octave bands from 10–10,000 Hz with the Nord2000 noise propagation model (Kragh et al. 2001) and using the simulated hourly weather conditions as input variables. The Nord2000 model has been successfully validated for WTs (Sondergaard et al. 2009). For each dwelling, we modeled hourly noise contributions from all WTs within a 6-km radius. These modeled values were averaged over the nighttime period (2200–0700 hours), which we considered the most relevant time window because people are likely to be in their homes and asleep at that time. We calculated outdoor A-weighted sound pressure level (10–10,000 Hz)—a metric commonly used in health studies (Michaud et al. 2016c; Pedersen 2011)—and A-weighted indoor LF (10–160 Hz) sound pressure level because LF noise is less attenuated by distance and passage through typical building materials and has been proposed to be an important component of WTN in relation to health (Jeffery et al. 2014). We did not model WTN in detail for situations where the 24-dB outdoor noise and 5-dB indoor LF noise limit would not be exceeded even under the unrealistic scenario that all WTs ever operational in Denmark were operating at the same time at 8 m/s wind speed, with downwind sound propagation in all directions given that people living in these buildings would, regardless of exposure level, be categorized in the reference category.

The quality of the noise spectra available for different WT models differed, and these spectra were typically only described at certain wind speeds. We therefore determined a validity score that for each night and dwelling summed up information for all contributing WTs on the number of measurements used to determine the WTN spectra class and how closely the simulated meteorological conditions of each night resembled the conditions under which the relevant WTN spectra were measured.

In the calculation of indoor LF noise, we classified all dwellings into one of six sound insulation classes based on building characteristics listed in the Building and Housing register (Christensen 2011): "1½-story houses" (inhabitants presumed to sleep on second floor), "light façade" (e.g., wood), "aerated concrete" (as well as similar materials such as timber framing), "farm houses" (remaining buildings classified as farms in the registry), "brick buildings," and "unknown" (which were assigned the mean attenuation value of the five other classes). The frequency-specific attenuation values for these insulation classes have been presented previously by Backalarz et al. (2016).

Study Population

We found all Danish dwellings ever situated within a radius of 20-WT heights of a WT as well as a random selection of 25% of all dwellings situated 20-to 40-WT heights away. We excluded residential institutions, hospitals, and dwellings situated within 100 m of areas classified as a "town center" because the type of dwellings, traffic, and lifestyle in town centers may differ substantially from town center–type areas of the main study population. All inhabitants between 25 and 85 y of age and living at least 1 y in one of these dwellings determining eligibility for the study ("eligibility dwellings"), from 5 y before WT erection (from start of follow-up in 1996) until 2013, were subsequently found in the Danish Civil Registration System (Schmidt et al. 2014). This extended time frame ensured the inclusion of people living in exactly the same dwellings before erection (or after decommissioning) of a WT. Persons were included in the study population after living 1 y in an eligibility dwelling. Afterward, we obtained complete address histories from 5 y before study entry until 5 y after moving from the eligibility dwelling for all persons living at least 1 y in an eligibility dwelling. Persons with an incomplete address history for the 5 y preceding entry were excluded.

The study was approved by the Danish Data Protection Agency (J.nr: 2014-41-2,671). By Danish Law, ethical approval and informed consent are not required for studies based entirely on registries.

Covariates

We selected potential confounders *a priori*. From Statistics Denmark, we obtained data on age and sex, personal income (time-dependent), highest attained educational level (time-dependent), work-market affiliation (time-dependent), marital status (time-dependent), and areal-level ($10{,}000\,m^2$) mean household income. The type of dwelling was extracted from the Building and Housing Register (Christensen 2011). As proxies for local road traffic noise and air pollution, we identified for each dwelling the total daily distance driven by vehicles within a 500-m radius as well as the distance to the nearest road with an average daily traffic count of ≥5,000 vehicles (in 2005).

Redemption of Sleep Medication and Antidepressants

We collected information on redeemed prescriptions for sleep medication and antidepressants from the Danish National Prescription Registry, which contains data on all prescription drugs sold in Denmark since 1995 (Kildemoes et al. 2011). The register includes the date of dispensing as well as information on the name and type of drug prescribed according to the Anatomic Therapeutic Chemical (ATC) system (WHO Collaborating Centre for Drug Statistics Methodology 2012). The indication for prescribing was not available. We used these data to identify persons who redeemed prescriptions for orally administered sleep medication (ATC: N05CC-CF, N05CH except N05CD08or antidepressants [ATC: N06AA, AB, AF, AG, AX except N06AX12 and Yntreve® (from ATC group N06AX21)].

Because cases redeeming prescriptions upon start of the register in 1995 could have included prevalent cases from before the start of the register, we excluded all persons with a redeemed relevant prescription before 1996 or the start of the follow-up period.

Statistical Analyses

Log-linear Poisson regression analysis was used to calculate hazard ratios (HRs) for redemption of sleep medication or depression (as two separate outcomes) according to outdoor nighttime WTN (<24, 24 to <30, 30 to <36, 36 to <42, and ≥42 dB) or indoor nighttime LF WTN (<5, 5 to <10, 10 to <15, and ≥15 dB) exposure, calculated as running means over the preceding 1 and 5 y. The categorizations were determined *a priori*. At present, there are no standards regarding categorizations of WTN. After consulting acoustical experts we chose <24 dB outdoor and <5 dB indoor LF WTN as references because the acousticians evaluated that WTN in all likelihood would be inaudible below these levels. For outdoor WTN, the upper limit of 42 dB was chosen because this is the regulatory WTN limit in Denmark (at a wind speed of 6 m/s) and, therefore, of interest from an administrative point of view, and the intermediate cut points chosen were 30 and 36 dB, which separated categories by 6 dB.

When calculating running means, we applied a value of −20 dB for situations in which noise had not been estimated (when wind conditions or the distance to WTs made WTN above 24 dB outdoor or 5 dB indoor impossible). We started follow-up after participants had been living 1 y in the recruitment dwelling, turned 25 y of age or 1 January 1996, whichever came last, and stopped at 31 December 2013, 85 y of age, disappearance, death, 5 y after moving from the eligibility dwelling, having no recorded address in Denmark for ≥8 d, or at date of fulfilling our case criteria, whichever came first.

We adjusted all analyses for sex, calendar year (1996–1999, 2000–2004, 2005–2009, and 2010–2013) and age (25–85 y of age, in 5-y categories). Furthermore, we adjusted for education (basic or high school, vocational, higher, and unknown), personal income (20 annual categories of equal size and unknown), marital status (married or registered partnership and other), work-market affiliation (employed, retired, and other), area-level average disposable income (20 categories of equal size and unknown), type of dwelling (farm, single-family detached house, and other), traffic load within a 500-m radius of the dwelling (first and second quartile and above median) and distance to the nearest road with >5,000 vehicles per day (<500 m, 500 to <1,000 m, 1,000 to <2,000 m and ≥2,000 m). Subjects were allowed to change between categories of covariates and exposure variables over time.

We investigated sex and age (above and below 65 y of age) as potential effect modifiers in the Poisson model by stratified analysis and by including an interaction term. Furthermore, we investigated associations between 5-y mean exposures and redemption of sleep medication and antidepressants in subpopulations for whom we hypothesized that a potential association between exposure and risk could be more conspicuous: living on a farm (potentially less variation in lifestyle and other exposures in this subpopulation, which may reduce the potential for residual confounding in this group, although it is important to note that this subpopulation may differ substantially from the study population); nearest WT with a total height of >35 m; high validity of noise estimate; dwelling far from major road (>2 km to the nearest road with >5,000 vehicles per day); and low tree coverage defined as less than 5% covered by forest, thicket, groves, single trees, or hedgerows within 500 m of the dwelling (because we assumed that vegetation beyond this distance would be nearly indiscernible from background noise). Data were analyzed using SAS (version 9.3; SAS Institute Inc.).

Results

We identified 758,736 adults (25–84 y of age) living ≥1 y in one of the dwellings determining eligibility. We excluded persons who had emigrated ($n = 43{,}794$) or did not have a registered address in the address registry ($n = 1{,}573$) prior to entry, who had an unknown address for ≥8 consecutive days in the 5 y prior to entry ($n = 59{,}318$), or who lived in hospitals or institutions at study start of follow-up ($n = 1{,}586$). In addition, we excluded 26,700 persons who, before the start of the follow-up period, had redeemed both sleep medication and antidepressants. After exclusion of 41,797 people redeeming sleep medication before the start of follow-up, the final study population for the sleep medication analyses was 583,968 people of whom 68,696 had redeemed sleep medication during 4,974,043 person-years. The final study population for antidepressants analyses was 584,891 people (after exclusion of 40,874 people who had redeemed antidepressants before the start of follow-up) of whom 82,373 redeemed antidepressants during 4,986,327 person-years. The median age at first redemption was 56.9 y (5th–95th percentiles: 31.8–80.3) for sleep medication and 54.2 y (5th–95th percentiles: 29.9–81.3) for antidepressants.

The two populations for the study of redemption of sleep medication and antidepressants, respectively, were very similar with regard to characteristics at entry (Table 1). For both of these study populations, persons exposed to ≥36-dB outdoor nighttime WTN were at entry younger, more often working, more often living on farms and in areas with higher income, more often living far from a major road and with low traffic density, and more often living in a dwelling with low tree coverage as compared with persons exposed to <36 dB (Table 1). Furthermore, persons exposed to ≥42-dB outdoor nighttime WTN entered the study earlier, had slightly higher education levels, had higher personal incomes, and were more often married as compared with persons exposed to <42 dB. We found similar tendencies for indoor nighttime LF WTN as for outdoor nighttime WTN, although for this exposure, participants in both of the two high-exposure categories (10–15 and ≥15 dB) had higher educations and more often were never married (see Table S1). Furthermore, both of the two high-

Table 1. Characteristics of the populations for study of redemption of sleep medication and antidepressants, respectively, at start of follow-up according to residential A-weighted exposure to outdoor wind turbine noise calculated as mean exposure during the preceding year.

	Outdoor wind turbine noise		
Characteristics at entry	<36 dB Sleep/antidepressants ($n = 575{,}899/576{,}857$) (%)	36–42 dB Sleep/antidepressants ($n = 6{,}704/6{,}637$) (%)	≥42 dB Sleep/antidepressants ($n = 1{,}365/1{,}397$) (%)
Men	52/52	54/54	53/54
Age (y)			
<40	45/43	51/50	46/44
40–50	19/19	20/20	23/22
50–60	16/16	15/15	18/18
≥60	21/22	15/15	13/15
Year of entry			
1996–2000	55/57	56/57	73/74
2001–2005	14/14	19/20	17/17
2006–2010	20/20	16/15	7/7
2011–2013	10/9	9/8	3/3
Personal income			
Quartile 1 (low)	20/20	21/21	20/21
Quartile 2	24/23	25/24	22/22
Quartile 3	26/26	26/25	24/23
Quartile 4 (high)	25/25	22/23	28/28
Unknown	6/6	6/6	7/6
Highest attained education			
Basic or high school	35/35	36/36	37/37
Vocational	43/42	45/45	39/38
High	16/16	15/15	21/21
Unknown	6/7	4/4	3/4
Marital status			
Married	55/56	52/53	62/63
Divorced/widow(er)	14/14	12/12	11/11
Never married	31/30	36/36	27/26
Attachment to labor market			
Working	69/69	75/75	80/78
Retired	18/19	13/13	9/11
Other	13/13	12/12	11/11
Area-level income[a]			
Quartile 1 (low)	23/23	11/11	14/14
Quartile 2	28/28	28/28	21/21
Quartile 3	28/28	34/34	35/36
Quartile 4 (high)	19/19	20/20	24/23
Unknown	2/2	7/7	6/6
Type of dwelling			
Farm	13/13	40/40	40/41
Single-family detached house	62/62	51/51	51/50
Others	24/24	9/9	9/9
Distance to major road (m)[b]			
<500	35/35	17/17	18/18
500–2,000	27/27	26/26	25/25
≥2,000	37/37	57/57	58/57
Traffic load within 500 m (10^3 vehicles km/d)[c]			
<2.5	34/34	69/69	66/67
2.5–5.3	25/25	13/13	16/15
5.3–9.7	19/19	12/13	9/10
>9.7	22/23	6/6	8/8
Tree coverage (%)[c]			
<5	13/13	30/29	29/28
5–20	63/63	63/63	62/63
>20	24/24	7/7	9/9

[a]Average disposable household income among all households in a 100 × 100 m grid cell.
[b]Major road defined as ≥5,000 vehicles per day.
[c]In a 500-m radius around the dwelling.

exposure categories (10–15 and ≥15 dB) entered the study later than persons exposed to <10 dB.

We found that 78% of the sleep medication–study population and 79% of the antidepressant-study population at entry lived in dwellings with <24-dB outdoor nighttime WTN and that, for both study populations, 97% lived in dwellings with indoor nighttime LF WTN <5 dB (see Table S2). Of those exposed to WTN above 42 dB or 15 dB LF, the majority lived within 500 m of a WT, whereas in the reference population less than 10% lived <500 m from a WT. In addition, we found that people with outdoor nighttime WTN exposure of ≥42 dB more often had a shorter WT (<35 m) as the nearest WT, whereas people with indoor nighttime LF WTN of ≥10 dB more often had a higher WT (>70 m) as their nearest WT (see Table S2). We found high correlations for both outdoor and indoor WTN between 1- and 5-y mean exposures, whereas the correlations between indoor and outdoor WTN were lower (see Table S3).

In adjusted analyses, we found that persons exposed to 5-y mean outdoor nighttime WTN levels >42 dB had a 14% higher risk of redeeming sleep medication [HR = 1.14 (95% CI: 0.98,

Table 2. Associations between mean 1- and 5-y exposure to residential A-weighted outdoor wind turbine noise and redemption of prescriptions for sleep medication and antidepressants.

	Sleep medication			Antidepressants		
Outdoor wind turbine noise	Cases (*n*)	Crude HR (95% CI)[a]	Adjusted HR (95% CI)[b]	Cases (*n*)	Crude HR (95% CI)[a]	Adjusted HR (95% CI)[b]
1-y mean exposure (dB)						
<24	50,262	1 (Ref)	1 (Ref)	60,205	1 (Ref)	1 (Ref)
24–30	13,032	0.98 (0.96, 0.99)	1.01 (0.99, 1.03)	15,782	0.98 (0.96, 1.00)	1.00 (0.98, 1.02)
30–36	4,415	0.96 (0.93, 0.99)	1.04 (1.00, 1.07)	5,295	0.95 (0.93, 0.98)	1.01 (0.99, 1.04)
36–42	842	0.95 (0.89, 1.02)	1.05 (0.98, 1.13)	930	0.89 (0.84, 0.95)	0.99 (0.93, 1.05)
≥42	145	0.99 (0.84, 1.17)	1.08 (0.92, 1.28)	161	0.99 (0.85, 1.15)	1.12 (0.96, 1.31)
5-y mean exposure (dB)						
<24	50,559	1 (Ref)	1 (Ref)	60,315	1 (Ref)	1 (Ref)
24–30	13,021	1.00 (0.98, 1.02)	1.03 (1.01, 1.05)	15,958	1.01 (0.99, 1.02)	1.02 (1.00, 1.04)
30–36	4,133	0.97 (0.93, 1.00)	1.03 (1.00, 1.06)	5,016	0.96 (0.94, 0.99)	1.02 (0.99, 1.05)
36–42	814	0.98 (0.92, 1.05)	1.08 (1.00, 1.15)	899	0.92 (0.86, 0.98)	1.01 (0.95, 1.08)
≥42	169	1.06 (0.91, 1.23)	1.14 (0.98, 1.33)	185	1.05 (0.90, 1.21)	1.17 (1.01, 1.35)

Note: CI, confidence interval; HR, hazard ratio; Ref, reference.
[a]Adjusted for age, sex, and calendar-year.
[b]Adjusted for age, sex, calendar-year, personal income, education, marital status, work-market affiliation, area-level socioeconomic status, type of dwelling, traffic load in a 500-m radius, and distance to nearest major road.

1.33)] and a 17% higher risk of redeeming antidepressants [HR = 1.17 (95% CI: 1.01, 1.35)] when compared to persons exposed to <24 dB (Table 2). For antidepressants, similar, although weaker, tendencies were seen for 1-y mean exposures to outdoor nighttime WTN, with HRs for the ≥42-dB exposure group of 1.12 (0.96, 1.31). For sleep medication, risk estimates remained close to the null even at high exposure. In general, the unadjusted risk estimates were lower than the adjusted risk estimates, with no clear suggestions of increased risk. The most influential confounder was dwelling type. For indoor nighttime LF WTN, we found no association between 1- or 5-y exposure and risk of redeeming sleep medication or antidepressants (Table 3).

In analyses stratified by age, we found that outdoor nighttime WTN exposure among persons >65 y of age was associated with a higher risk of redeeming sleep medication, whereas for persons <65 y of age there was no association (Table 4). Furthermore, among persons >65 y of age, the association with outdoor nighttime WTN seemed to follow an exposure–response relationship, with HR = 1.22 (95% CI: 1.08, 1.38) in the 36–42 dB exposure group and HR = 1.68 (95% CI: 1.27, 2.21) in the ≥42 dB exposure group. Similar tendencies were seen for people redeeming antidepressants, with HR = 1.27 (95% CI: 1.13, 1.43) in the 36–42 dB exposure group and HR = 1.23 (95% CI: 1.09, 1.69) in the ≥42 dB exposure group among persons >65 y of age. There were also indications of a higher risk of redeeming antidepressants among persons <65 y of age in the highest outdoor WTN exposure group. When stratifying the indoor nighttime LF WTN analyses by age, we found similar tendencies as for outdoor nighttime WTN for both outcomes, with HRs among persons >65 y of age of 1.13 (95% CI: 0.97, 1.32) for 10–15 dB and 1.37 (95% CI: 0.81, 2.31) for ≥15 dB for redemption of sleep medication and of 1.09 (95% CI: 0.94, 1.26) for 10–15 dB and 1.34 (95% CI: 0.80, 2.22) for ≥15 dB for redemption of antidepressants (Table 5). We found no associations between indoor nighttime LF WTN and any of the two outcomes among persons <65 y of age.

In outdoor nighttime WTN analyses stratified by sex, we found for sleep medication that although the *p*-value for interaction was below 0.05, the HRs in the two highest exposure categories were almost identical, whereas for antidepressants, the association seemed to be confined to men (Table 4). For indoor nighttime LF WTN, we found no marked differences in risks between men and women for redeeming either sleep medication or antidepressants (Table 5). However, for indoor exposure, the number of cases exposed to ≥15 dB was small.

When investigating effects of outdoor nighttime WTN in different subpopulations, we found that among people living on farms or with low tree coverage, the increase in risk in the highest exposure group disappeared for both sleep medication and antidepressants (see Table S4). For the other subpopulations investigated, we found no consistent patterns when comparing results for sleep medication and antidepressants. For example, for highly exposed people living far from major roads, the HR for antidepressants = 1.25 (95% CI: 1.00, 1.55), whereas for sleep

Table 3. Associations between mean 1- and 5-y exposure to residential indoor low-frequency wind turbine noise and redemption of prescriptions for sleep medication and antidepressants.

	Sleep medication			Antidepressants		
Indoor low-frequency wind turbine noise	Cases (*n*)	Crude HR (95% CI)[a]	Adjusted HR (95% CI)[b]	Cases (*n*)	Crude HR (95% CI)[a]	Adjusted HR (95% CI)[b]
1-year mean exposure (dB)						
<5	64,617	1 (Ref)	1 (Ref)	77,360	1 (Ref)	1 (Ref)
5–10	3,299	0.94 (0.91, 0.98)	1.03 (0.99, 1.06)	4,073	0.93 (0.91, 0.96)	1.01 (0.98, 1.04)
10–15	726	0.96 (0.89, 1.03)	1.08 (1.00, 1.16)	882	0.92 (0.86, 0.98)	1.03 (0.97, 1.10)
≥15	54	0.93 (0.71, 1.22)	1.05 (0.81, 1.38)	58	0.82 (0.63, 1.06)	0.96 (0.74, 1.24)
5-y mean exposure (dB)						
<5	65,202	1 (Ref)	1 (Ref)	77,995	1 (Ref)	1 (Ref)
5–10	2,911	0.97 (0.93, 1.01)	1.05 (1.01, 1.09)	3,663	0.96 (0.93, 1.00)	1.04 (1.00, 1.07)
10–15	542	0.93 (0.86, 1.02)	1.04 (0.96, 1.14)	672	0.90 (0.84, 0.97)	1.01 (0.94, 1.10)
≥15	41	0.92 (0.68, 1.25)	1.03 (0.76, 1.40)	43	0.80 (0.59, 1.07)	0.94 (0.70, 1.27)

Note: CI, confidence interval; HR, hazard ratio; Ref, reference.
[a]Adjusted for age, sex, and calendar-year.
[b]Adjusted for age, sex, calendar-year, personal income, education, marital status, work-market affiliation, area-level socioeconomic status, type of dwelling, traffic load in a 500-m radius, and distance to nearest major road.

Table 4. Associations between 5-y exposure to outdoor wind turbine noise and redemption of sleep medication and antidepressants according to age and sex.

Subpopulations	Exposure categories (dB)	Sleep medication Cases (*n*)	Sleep medication Adjusted HR (95% CI)[a]	*p*-Value[b]	Antidepressants Cases (*n*)	Antidepressants Adjusted HR (95% CI)[a]	*p*-Value[b]
Age (y)				0.003			0.0001
<65	<24	33,895	1 (Ref)		41,630	1 (Ref)	
	24–30	8,691	1.03 (1.01, 1.05)		10,979	1.02 (1.00, 1.04)	
	30–36	2,833	1.02 (0.98, 1.06)		3,532	1.00 (0.96, 1.03)	
	36–42	550	1.02 (0.94, 1.11)		610	0.92 (0.85, 1.00)	
	≥42	118	1.00 (0.84, 1.20)		146	1.15 (0.98, 1.36)	
≥65	<24	16,664	1 (Ref)		18,685	1 (Ref)	
	24–30	4,330	1.03 (0.99, 1.06)		4,979	1.02 (0.98, 1.05)	
	30–36	1,300	1.06 (1.00, 1.12)		1,484	1.07 (1.01, 1.13)	
	36–42	264	1.22 (1.08, 1.38)		289	1.27 (1.13, 1.43)	
	≥42	51	1.68 (1.27, 2.21)		39	1.23 (0.90, 1.69)	
Sex				0.03			0.08
Men	<24	22,204	1 (Ref)		25,379	1 (Ref)	
	24–30	6,067	1.06 (1.03, 1.10)		7,047	1.04 (1.01, 1.06)	
	30–36	1,950	1.05 (1.00, 1.10)		2,274	1.03 (0.99, 1.08)	
	36–42	381	1.08 (0.97, 1.19)		423	1.06 (0.96, 1.16)	
	≥42	79	1.15 (0.92, 1.44)		97	1.39 (1.14, 1.69)	
Women	<24	28,355	1 (Ref)		34,936	1 (Ref)	
	24–30	6,954	1.00 (0.97, 1.03)		8,911	1.01 (0.98, 1.03)	
	30–36	2,183	1.01 (0.97, 1.06)		2,742	1.01 (0.97, 1.05)	
	36–42	433	1.08 (0.98, 1.19)		476	0.98 (0.89, 1.07)	
	≥42	90	1.14 (0.92, 1.40)		88	1.00 (0.81, 1.23)	

Note: CI, confidence interval; HR, hazard ratio; Ref, reference.
[a]Adjusted for age, sex, calendar-year, personal income, education, marital status, work-market affiliation, area-level socioeconomic status, type of dwelling, traffic load in a 500-m radius and distance to nearest major road.
[b]*p* for interaction.

medication, it remained unchanged. Among persons with high validity of the outdoor noise estimate, we found that the risk for redeeming antidepressants was slightly higher than in the overall analysis [HR = 1.25 (95% CI: 0.89, 1.74)], and for sleep medication, the risk estimate among persons exposed to 36–42 dB increased, whereas the risk in the highest exposure group disappeared [HR = 0.81 (95% CI: 0.52, 1.27); 19 cases; see Table S4]. With regard to indoor LF WTN in the same subpopulations, we found the lack of association for both outcomes to be consistent among people living on farms, whose nearest WT was ≥35 m, living far from a major road and with low tree coverage, whereas among people redeeming sleep medication/antidepressants after 2005, the estimate in the highest exposure group (≥15 dB) was increased [HR = 1.12 (95% CI: 0.79, 1.57); see Table S5]. There was a tendency toward a slight increase in risk for redeeming sleep medication in the highest exposure group among people with a high validity of the noise estimate [HR = 1.20 (95% CI: 0.75, 1.90)], whereas for redeeming antidepressants, the lack of an association remained [HR = 0.92 (95% CI: 0.57, 1.49)].

Discussion

We found that high levels of long-term nighttime exposure to outdoor WTN seemed associated with redemption of sleep medication and antidepressants in a large prospective study, whereas

Table 5. Associations between 5-y exposure to indoor low-frequency wind turbine noise and redemption of sleep medication and antidepressants according to age and sex.

Subpopulations	Exposure categories (dB)	Sleep medication Cases (*n*)	Sleep medication Adjusted HR (95% CI)[a]	*p*-Value[b]	Antidepressants Cases (*n*)	Antidepressants Adjusted HR (95% CI)[a]	*p*-Value[b]
Age (y)				0.40			0.06
<65	<5	43,617	1 (Ref)		53,739	1 (Ref)	
	5–10	2,062	1.05 (1.00, 1.09)		2,640	1.02 (0.98, 1.06)	
	10–15	381	1.01 (0.91, 1.12)		490	0.99 (0.90, 1.08)	
	≥15	27	0.91 (0.63, 1.33)		28	0.81 (0.56, 1.17)	
≥65	<5	21,585	1 (Ref)		24,256	1 (Ref)	
	5–10	849	1.06 (0.99, 1.13)		1,023	1.10 (1.03, 1.17)	
	10–15	161	1.13 (0.97, 1.32)		182	1.09 (0.94, 1.26)	
	≥15	14	1.37 (0.81, 2.31)		15	1.34 (0.80, 2.22)	
Sex				0.18			0.70
Men	<5	29,017	1 (Ref)		33,206	1 (Ref)	
	5–10	1,393	1.08 (1.02, 1.14)		1,687	1.06 (1.01, 1.11)	
	10–15	248	1.00 (0.88, 1.13)		306	1.00 (0.89, 1.12)	
	≥15	23	1.27 (0.84, 1.91)		21	1.04 (0.68, 1.60)	
Women	<5	36,185	1 (Ref)		44,789	1 (Ref)	
	5–10	1,518	1.02 (0.97, 1.08)		1,976	1.02 (0.98, 1.07)	
	10–15	294	1.09 (0.97, 1.22)		366	1.03 (0.93, 1.14)	
	≥15	18	0.83 (0.52, 1.32)		22	0.86 (0.57, 1.30)	

Note: CI, confidence interval; HR, hazard ratio; Ref, reference.
[a]Adjusted for age, sex, calendar-year, personal income, education, marital status, work-market affiliation, area-level socioeconomic status, type of dwelling, traffic load in a 500-m radius, and distance to nearest major road.
[b]*p* for interaction.

for long-term indoor nighttime LF WTN, no associations were found. We found the strongest associations between outdoor nighttime WTN and redemption of sleep medication and antidepressants among persons >65 y of age compared with those <65 y of age. In addition, for persons >65 y of age, high levels of indoor nighttime LF WTN seemed to be associated with redemption of sleep medication.

Our finding of an association between high exposure to outdoor nighttime WTN and redemption of sleep medication is in accordance with most (Kageyama et al. 2016; Onakpoya et al. 2015) but not all (Michaud et al. 2016a) studies on WTN and sleep problems (high exposure was generally defined as >40–41 dB in these studies). In support of our results on high outdoor nighttime WTN and depression, most (Jalali et al. 2016; Onakpoya et al. 2015) but not all (Feder et al. 2015) of the few studies investigating WTN and self-reported mental health indicated that living in areas with WTs could decrease the quality of life. Overall, this suggests that high levels of outdoor nighttime WTN is associated with sleep disturbance and depression, although it is important to note that most previous studies were cross-sectional (which hampers conclusions on causality), relied on active participation and self-reported data, and were based on much smaller study populations than the current study. That we see similar associations for both sleep and antidepressant medication for outdoor WTN strengthens the plausibility of both because it is well established that disturbed sleep and mental health problems, including depression, interact through a complex bidirectional relationship (Anderson and Bradley 2013; Lopresti et al. 2013). It is, however, noteworthy that we found no association between indoor nighttime LF WTN and redemption of sleep medication or antidepressants even though this exposure estimate likely better reflects exposure during sleep. In a recent study based on the current study population, we found indications that high levels of indoor LF WTN during the night may trigger cardiovascular events, whereas for outdoor nighttime WTN we found no association (Poulsen et al. 2018). A potential explanation is that outdoor WTN may be associated with a higher overall annoyance than indoor LF WTN given that people are disturbed during their outdoor activities during the day. However, further research is needed to elucidate this possibility, particularly because studies on both traffic and WT noise have indicated that the effect of annoyance on the association between noise exposure, sleep disturbance, and mental health is complex and as yet not fully understood (Bakker et al. 2012; Frei et al. 2014; Fyhri and Aasvang 2010; Héritier et al. 2014; WHO 2009).

We found stronger associations with WTN among the elderly, especially with regard to sleep medication, where the association seemed confined to persons >65 y of age, with a positive exposure–response relationship starting at relatively low WTN levels. Furthermore, for this age group, high levels of indoor nighttime LF WTN also seemed to be associated with the redemption of sleep medication. A potential explanation is that the elderly may be particularly susceptible to health effects from WTN given that a number of changes in sleep structure occur with age (Cooke and Ancoli-Israel 2011; Wolkove et al. 2007). Older people generally spend more time in the lighter stages of sleep (stage 1 and 2) and less time in deep sleep and REM sleep, which could lead to higher risk for awakenings due to nighttime WTN. Furthermore, the nocturnal sleep time of elderly is reduced and more fragmented, with an increased number of arousals and awakenings, and thus they are potentially more easily disturbed by noise, worry, and annoyance. In addition, one might speculate that persons >65 y of age are more likely to be retired from work and therefore at home during the daytime, which could potentially increase annoyance due to WTN and help explain the increased HRs observed for outdoor exposure.

For redemption of antidepressants, we observed similar trends as for sleep medication: The association with outdoor WTN during the night was stronger and started at lower levels among elderly compared with their younger counterparts, and there was a suggestion of an association with high levels of indoor nighttime LF WTN. As described above, there is a strong association between sleep and depression (Anderson and Bradley 2013; Lopresti et al. 2013), and the observed association between WTN and depression mainly among the elderly could be explained by a WTN-induced disturbance of sleep as well as a higher WTN-annoyance due to spending more time at home. In addition, depression in late life may present differently from depression in younger adults, with higher prevalence of, for example, sleep disturbance, loss of interest, and fatigue (Christensen et al. 1999; Fiske et al. 2009), and the incidence of diagnosed depression in later life is generally found to be lower than at younger ages (Büchtemann et al. 2012; Fiske et al. 2009).

Strengths of our study include the prospective nationwide design with access to residential moving history for the study period and the identification of a large number of cases through high-quality nationwide registers with high coverage and data quality (Kildemoes et al. 2011; Pottegård et al. 2017; Schmidt et al. 2014). We also had access to information on individual and area-level confounders though national registries with high coverage and validity (Baadsgaard and Quitzau 2011; Jensen and Rasmussen 2011; Petersson et al. 2011) as well as information on environmental confounders. Furthermore, we applied state-of-the art exposure models to estimate exposures to WTN using input data of high quality on hourly wind speed and direction at all WTs and detailed WTN spectra for all types of WTs, which allowed us to model noise during nighttime, which we found to be the most relevant time period. First, during the daytime, many people will be away from home, whereas during the nighttime, we expect the majority of the population to be at home, and second, for the sleeping medication outcome, this is the relevant time window, but for depression, nighttime exposure is also very relevant because we expect disturbance of sleep to be on the mechanistic pathway. In addition, by taking sound insulation characteristics of the types of dwelling into account, we estimated the potentially more biologically relevant indoor LF WTN, although we were only able to differentiate this into a few insulation categories. Other strengths include the modeling of WTN for all Danish dwellings potentially exposed to WTN and the inclusion of persons from the same geographical areas but with little or no WTN exposure.

The drugs used to define the outcomes in the current study are only available by prescription in Denmark and the redemption of these prescriptions is registered in an almost complete national register (Kildemoes et al. 2011). Furthermore, all Danes have access to free universal healthcare and subsidized drug costs. We therefore had an excellent sensitivity and specificity toward redemption of sleep and antidepressant medication. There are, however, some challenges associated with interpreting them as proxies for sleep or depressive disorders. A 2013 survey of 160,000 randomly selected Danes found the prevalence of sleep problems and "feeling depressed/unhappy" to be 41% and 29%, respectively. In the current study, 12% of the study population redeemed sleep medication and 14% redeemed antidepressants. This reflects that only people with more severe problems are likely to both contact a physician and to qualify for these drugs. Although we expect the lack of information on people with undiagnosed sleep problems and depression to be nondifferential with regard to exposure, it impairs sensitivity towards sleep disturbances or depressive conditions in general and our results, therefore, pertain most directly to more severe sleep or depressive conditions. Furthermore, our reliance on prescription data reduced specificity towards sleep and depressive conditions because some of the included drugs, particularly the antidepressants, also have other indications, primarily for anxiety-related conditions. Any bias resulting from this will depend on both the prevalence of these conditions among our cases and their association with WTN.

Due to the register-based nature of the study, we did not have access to potential lifestyle confounders, such as physical activity and alcohol consumption, and other factors that might affect the studied associations, such as orientation of the bedroom and hearing loss. This is a weakness of our study. We found that adjustment for individual and area-level socioeconomic variables generally tended to increase estimates in the highest exposure group. It is conspicuous that we found no association for either outcome when restricting analyses to people living on farms given that lifestyle and other exposures are expected to be more similar within this subpopulation as compared with the whole population. However, attitudes towards WTN and health behavior may also differ, which might contribute to the lack of association in this group. Another potential explanation is a healthy-worker bias, and in exploratory analyses restricted to farm dwellers >65 y of age, we found that exposure to ≥ 42 dB was associated with an increased risk for the use of sleep medication, whereas no association was observed for antidepressants.

Other limitations include the rather crude adjustment for local road traffic noise, using traffic load and distance to the nearest major road. However, residual confounding by traffic noise is unlikely to be a major problem in the current study because we obtained similar estimates among people living far from major roads as compared with the whole study population. In addition, there is inevitable uncertainty in the modeled noise exposure, particularly in indoor LF, where we had to rely on relatively crude data on building sound insulation. This uncertainty is likely to be nondifferential, influencing the estimates towards unity. To investigate this further, we used a validity score, which captured some of the features of uncertainty of the noise modeling. For outdoor WTN, we observed that for situations with high validity WTN, the risk estimates for antidepressants were largely unaffected, whereas for sleep medication, the estimate for 36–42 dB was elevated and for ≥ 42 dB, decreased. However, for sleeping medication, only 19 of the 169 cases exposed to ≥ 42 dB had a high validity score, resulting in high uncertainty for this subanalysis.

Conclusions

In conclusion, in a large nationwide population, we found suggestions of an association between exposure to high levels of outdoor nighttime WTN and increased risk of first-time redemption of sleep medication and antidepressants. This association was strongest among the elderly. We found no consistent associations for indoor nighttime LF WTN. Given that this was the first prospective study on this topic and that we had only a few cases for many of the groups, independent replication is desirable.

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EXHIBIT
16

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Re: Request of Backcountry Against Dumps and Donna Tisdale to Rescind or Revise the San Diego County Health and Human Services Agency's February 25, 2019 Public Health Position Statement on the Human Health Effects of Wind Turbines

Dear Honorable Commissioners, Mr. Wardlaw and Mr. Macchione:

On behalf of Backcountry Against Dumps and Donna Tisdale (collectively, "Backcountry"), we respectfully request that San Diego County (the "County") rescind the Health and Human Services Agency's February 25, 2019 Public Health Position Statement (the "Statement") on the Human Health Effects of Wind Turbines, or at the very least revise the Statement to (1) remove or correct (a) its erroneous conclusion that wind turbine noise is unlikely to affect human health and (b) its mistaken premise that there is a relevant distinction between direct and indirect impacts, (2) account for the additional evidence of health impacts described below, and (3) acknowledge the need for on-the-ground investigations of the health impacts of existing wind turbines in the County on neighboring residents, and conduct those long-overdue investigations and present their findings in the Public Health Position Statement.

I. The Statement's Conclusion That Wind Turbine Noise Is Not Likely to Affect Human Health and Its Implication That Indirect Effects Are Unimportant Must be Corrected

The Statement "conclude[s] that the available scientific evidence suggests that low-frequency noise and infrasound . . . are *not* likely to affect human health." Statement, p. 8 (original emphasis). But that conclusion is refuted by the body of the evidence reviewed in the Statement. For example, the Statement (p. 3) notes that a "growing body of research supports annoyance due to perceived wind turbine noise," and other wind turbine characteristics. It also states, citing five separate studies, that "low-frequency noise and infrasound from [wind turbines] cannot be ruled out as plausible causes of ***indirect*** health effects." Statement, p. 3 (original emphasis). Indeed, the Statement acknowledges that "annoyance has been statistically significantly associated with wind turbine noise." *Id*. at p. 6. And Dr. Wilma Wooten confirmed in her presentation before the Planning Commission on March 22, 2019 that annoyance from wind turbine noise is "well documented."

Unless annoyance is unrelated to health outcomes, the Statement's conclusion that wind turbine noise is unlikely to harm human health is thus, at best, unsupported. But annoyance *is* related to health outcomes. For example, the Statement (p. 3) discusses one "study by Bakker and colleagues [demonstrating] a clear correlation between annoyance and self-reported sleep disturbance." The Statement (p. 4) also explains that "headaches, tinnitus, disturbances of balance" and other symptoms are "a set of manifestations that can be caused by stress and loss of sleep, which can become *disabling*" (emphasis added). And, of course, annoyance can cause both stress and loss of sleep. "Annoyance, while not a *direct*, negative health impact, can be understood to result in *indirect* health impacts, such as irritability and sleep disturbance, which may, in turn, produce its own impacts on individual health (i.e. headaches, difficulties with concentration, dizziness, and changes in metabolism)." Statement, p. 8 (original emphasis). Dr. Wooten likewise confirmed in response to questions during the Planning Commission hearing on March 22, 2019 that indirect impacts from wind turbine noise "have been documented."

The Statement's conclusion that wind turbine noise is unlikely to affect human health is thus unsupported by the very evidence it reviews. Relatedly, the Statement's premise that there is a relevant distinction between direct and indirect impacts is false. At the very least, the Statement must be revised to remove or correct this erroneous conclusion and premise.

II. The Statement Fails to Discuss Key Recent Studies Demonstrating Wind Turbine Noise Health Impacts and the Presence of Infrasound and Amplitude Modulated Noise in and Around Boulevard-Area Residences

The Statement's conclusion that wind turbine noise is unlikely to affect human health is also refuted by numerous recent studies omitted from the Statement's review, including the six summarized below and attached hereto as exhibits.

The Statement (p. 10) asserts that the "major limitation of most of the studies referred to in [the] literature review is that they are literature reviews, mainly observational in nature, *or* rely on self-reporting as opposed to original scientific research" (original emphasis). But even assuming the Statement is correct about those studies' limitations, researchers are quickly filling the implied research gap with case-controlled laboratory studies and longitudinal studies. For example, a pair of recent pilot studies investigated the physiologically measured sleep effects of nocturnal wind turbine noise in a laboratory setting.[1] The results provided "evidence that participants had more frequent awakenings, reduced amounts of N3 ("deep") sleep, reduced continuous N2 sleep, increased self-reported disturbance and [wind turbine noise]-induced tiredness in exposure nights with [wind turbine noise] compared to [wind turbine noise]-free nights." **Exhibit 1** at 10. The increase in self-reported sleep disturbance also comports with numerous survey-based studies on the subject, including those cited in the Statement.

Morsing *et al.*'s (2018) results also comport with those of a cohort-based study in Denmark on the impacts on sleep and depression of long-term residential exposure to wind turbine noise.[2] Poulsen *et al.* (2019) found, based on their study of nearly 600,000 people during an approximately 20-year period, that "high levels of long-term nighttime exposure to outdoor" wind turbine noise (greater than or equal to 42 dBA) were "associated with redemption of sleep medication and antidepressants" (*i.e.* filling prescriptions for those medications), particularly amongst people aged 65 or older. **Exhibit 2** at 037005-6. The authors reported that their findings accord with most studies on the effects of wind turbine noise exposure on sleep and self-reported mental health. **Exhibit 2** at 037005-7.

But the audible noise level, like that measured with the A-weighted scale used in Poulsen *et al.*'s (2019) study, is only one aspect of wind turbine-generated noise. For example, a 2018 review of the scientific literature affirmed not only that "there is ample evidence demonstrating that a component of the sound energy produced by a [wind turbine] is in the low and infrasonic frequency range," but also that the literature presents a "strong prima facia case for neural transduction of low-frequency sound] and [infrasound]."[3] **Exhibit 3** at 2 (first quote), 6 (second quote).

Carlile *et al.* (2018) also noted that weighted noise measurements – like the A-weighted measurements typically done for audible noise impact analyses, and the C-weighted measurements required by San Diego County Zoning Code section 6952(f)(1) – "exclude crucial low frequencies" from wind turbines. **Exhibit 3** at 3. Poulsen *et al.* (2019) similarly noted studies "suggest[ing] that the characteristics of [wind turbine noise] relevant for annoyance may be better captured by metrics focusing on amplitude modulation or low-frequency (LF) noise,

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[1] Morsing, J.A., M.G. Smith, M. Ögren, P. Thorsson, E. Pedersen, J. Forssén, and K.P Waye, 2018, "Wind Turbine Noise and Sleep: Pilot Studies on the Influence of Noise Characteristics," *International Journal of Environmental Research and Public Health*, 15(2573) (attached hereto as **Exhibit 1**).
[2] Poulsen, A.H., O. Raaschou-Nielsen, A. Peña, A.N. Hahmann, R.B. Nordsborg, M. Ketzel, J. Brandt, and M. Sørensen, 2019, "Impact of Long-Term Exposure to Wind Turbine Noise on Redemption of Sleep Medication and Antidepressants: A Nationwide Cohort Study," *Environmental Health Perspectives*, 127(3) (attached hereto as **Exhibit 2**).
[3] Carlile, S., J.L. Davy, D. Hillman, and K. Burgemeister, 2018, "A Review of the Possible Perceptual and Physiological Effects of Wind Turbine Noise," *Trends in Hearing* 22:1-10 (attached hereto as **Exhibit 3**).

rather than the full spectrum A-weighted nose." **Exhibit 2** at 037005-1. That is one reason Backcountry commissioned a professional study by Wilson Ihrig on the wind turbine-generated infrasound, low-frequency noise and amplitude modulated noise in the Boulevard area.

Wilson Ihrig, a national noise, vibration and acoustical professional consulting firm, obtained noise recordings between November 13 and 17, 2018 in the Boulevard and Jacumba Hot Springs areas. The findings are documented in a 2019 report.[4] Among other things, the report and a predecessor 2014 report on earlier noise measurements "conclusively document the presence of [wind turbine] generated infrasound (IS) as measured at residential and other locations up to 8 miles from the wind turbines at the Kumeyaay and Tule [wind project] facilities," and up to 11 miles from the Ocotillo Wind Energy project. **Exhibit 4** at 1. The report also concludes that the 2018 noise recordings "indicate[] excessive amplitude modulated noise generated by the existing WTs." *Id*.

The Statement fails to discuss amplitude modulated noise *at all*, despite increasing academic and professional literature on the subject. For example, Pohl *et al.* (2018)[5] conducted a longitudinal study of wind turbine noise annoyance in Germany and found that a "cause for the WT noise annoyance might be the amplitude modulation (AM)." **Exhibit 5** at 126. Schäffer *et al*. (2019)[6] conducted a laboratory experiment with audio-visual simulations and likewise found that, even after accounting for visual impacts, amplitude modulation increased annoyance.

The Statement's conclusion that wind turbine noise is unlikely to affect human health is thus further unsupported by recent scientific studies that the Statement omits. At the very least, the Statement must be revised to remove or correct the erroneous conclusion and account for the additional scientific evidence summarized above.

III. The Statement Fails to Recognize the Need for Investigations of the Health Effects to Date on Residents Neighboring the Existing Wind Turbines in San Diego County

As Dr. Wooten recommended in her responses to questions at the March 22, 2019 hearing on the Statement, the County should conduct a health impact assessment of the effects of the existing wind turbines in the County (*e.g.* the Tule Wind turbines) on nearby residents. Wilson Ihrig's 2019 report should be used to guide – and be referenced in – the assessment. So too should the accounts of health impacts already reported by County residents living near wind turbines, including the residents who at the March 22 hearing bravely shared the harm they have suffered from the Boulevard-area turbines. The Statement should not be reissued until the assessment has been completed and its findings have been incorporated into the Statement.

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[4] The report is attached hereto as **Exhibit 4**.
[5] Pohl, J., J. Gabriel, and G. Hübner, 2018, "Understanding Stress Effects of Wind Turbine Noise – The Integrated Approach," *Energy Policy* 112:119-128, attached hereto as **Exhibit 5**.
[6] Schäffer, B., R. Pieren, U.W. Hayek, N. Biver, and A. Grêt-Regamey, 2019, "Influence of Visibility of Wind Farms on Noise Annoyance – A Laboratory Experiment with Audio-Visual Simulations," *Landscape and Urban Planning* 186:67-78, attached hereto as **Exhibit 6**.

IV. Conclusion

For each of the foregoing reasons, Backcountry respectfully requests that the County rescind, or at the very least revise, the County's February 25, 2019 Public Health Position Statement on the Human Health Effects of Wind Turbines.

Respectfully submitted,

Stephan C. Volker
Attorney for Backcountry Against Dumps
and Donna Tisdale

SCV:taf

Attachments:

Exhibit 1 – Morsing, J.A., M.G. Smith, M. Ögren, P. Thorsson, E. Pedersen, J. Forssén, and K.P Waye, 2018, "Wind Turbine Noise and Sleep: Pilot Studies on the Influence of Noise Characteristics," *International Journal of Environmental Research and Public Health*, 15(2573).

Exhibit 2 – Poulsen, A.H., O. Raaschou-Nielsen, A. Peña, A.N. Hahmann, R.B. Nordsborg, M. Ketzel, J. Brandt, and M. Sørensen, 2019, "Impact of Long-Term Exposure to Wind Turbine Noise on Redemption of Sleep Medication and Antidepressants: A Nationwide Cohort Study," *Environmental Health Perspectives*, 127(3).

Exhibit 3 – Carlile, S., J.L. Davy, D. Hillman, and K. Burgemeister, 2018, "A Review of the Possible Perceptual and Physiological Effects of Wind Turbine Noise," *Trends in Hearing* 22:1-10.

Exhibit 4 – Carman, R.A. and M.A. Amato (Wilson Ihrig), March 18, 2019, "Results of Ambient Noise Measurements of the Existing Kumeyaay Wind and Tule Wind Facilities in the Area of Boulevard and Jacumba Hot Springs Pertaining to the Proposed Torrey and Campo Wind Turbine Facilities."

Exhibit 5 – Pohl, J., J. Gabriel, and G. Hübner, 2018, "Understanding Stress Effects of Wind Turbine Noise – The Integrated Approach," *Energy Policy* 112:119-128.

Exhibit 6 – Schäffer, B., R. Pieren, U.W. Hayek, N. Biver, and A. Grêt-Regamey, 2019, "Influence of Visibility of Wind Farms on Noise Annoyance – A Laboratory Experiment with Audio-Visual Simulations," *Landscape and Urban Planning* 186:67-78.

EXHIBIT
17

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A Review of the Possible Perceptual and Physiological Effects of Wind Turbine Noise

Simon Carlile[1,2], John L. Davy[3,4], David Hillman[5], and Kym Burgemeister[6]

Abstract

This review considers the nature of the sound generated by wind turbines focusing on the low-frequency sound (LF) and infrasound (IS) to understand the usefulness of the sound measures where people work and sleep. A second focus concerns the evidence for mechanisms of physiological transduction of LF/IS or the evidence for somatic effects of LF/IS. While the current evidence does not conclusively demonstrate transduction, it does present a strong prima facia case. There are substantial outstanding questions relating to the measurement and propagation of LF and IS and its encoding by the central nervous system relevant to possible perceptual and physiological effects. A range of possible research areas are identified.

Keywords

auditory transduction, infrasound, low-frequency sound, wind turbine noise

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Introduction

In recent years, there has been growing debate about the effects of wind turbine noise (WTN) on human health. A number of reviews have recently been published (e.g., Knopper et al., 2014; McCunney et al., 2014; Schmidt & Klokker, 2014; Van Kamp & Van Den Berg, 2017), some under the auspice of different government bodies in Australia (National Health and Medical Research Council, 2015), Canada (Council of Canadian Academies, 2015), and France (Lepoutre et al., 2017), with some appearing in the indexed scientific literature (most recently the Health Canada study; D. Michaud, 2015; D. S. Michaud et al., 2016a, 2016b; D. S. Michaud, Keith, et al., 2016). Many of these studies have adopted an epidemiological approach including various meta-analyses of the existing research reports concerning the health effects of WTN. By contrast, the popular press portrays a largely polarized picture where the discourse often appears less informed and more opinionated than scientifically based.

There are clearly complex factors surrounding complaints about WTs that, apart from the health and safety concerns, include financial and other material factors and potential interactions with individuals' perceptions of devices themselves, including their appearance and the sounds they make. These factors are all potential contributors to the annoyance produced by WTs. Many of these concerns—sometimes referred to as nocebo effects—have been recently reviewed in the literature (Chapman & Crichton, 2017; C. H. Hansen, Doolan, & Hansen, 2017). There seems, however, to have been little discussion (or systematic review) of potential perceptual and physiological effects of WTN at the level of the individual. This provides the principal motivation for this review. This review does not consider the important question of whether WTN affects human health, given the reviews and debates referred to earlier, but focuses on two important foundational issues. The first section reviews recent research examining the nature of the sound generated by WTs with a particular focus on the low-frequency sound (LF) and infrasound

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(IS), together with the mechanisms of its generation, propagation, and measures of human exposure. The objective of this first part is to understand the accuracy and usefulness of measures of this sound pressure at locations where people work and sleep. The second issue for focus concerns whether there are plausible mechanisms of transduction of LF/IS or evidence for somatic effects of LF/IS. This is an important question as a key link in any argument attempting to relate WTN exposure to ill health is the extent to which that sound can have a somatic influence. In closing, some of the existing peer-reviewed research examining the perceptual effects of exposure to LF and IS in the laboratory setting is reviewed.

This review has been confined largely to the scientific literature represented by the relevant peer-reviewed articles in indexed journals.

WTN, LF, and IS

There are a range of potential sound generators produced by WTs which include mechanical generators (gearboxes, electrical generators, cooling systems, etc., in the WT nacelle) as well as interactions between the moving blades and the air, particularly where there are variations in flow, angle of incidence, and pressure.

Sound produced by rotating blades on modern upwind WTs (where the rotor is on the front of the nacelle when viewed from the direction that the wind is coming) results in part from an interaction between the airflow disturbed by the rotating blade interacting with the supporting tower (e.g., Jung, Cheung, Cheong, & Shin, 2008; Sugimoto, Koyama, Kurihara, & Watanabe, 2008; reviewed in detail Van den Berg, 2006; Zajamšek, Hansen, Doolan, & Hansen, 2016). The sound generated by this mechanism is tonal in nature with a fundamental frequency at the blade passing frequency (BPF) and a series of six or so harmonics (Figure 1; for further details, see Schomer, Erdreich, Pamidighantam, & Boyle, 2015, their Figures 2 and 3). The fundamental frequency is dependent on the rate of rotation and number of blades and for a modern WT, the sound energy produced by this mechanism is generally well below 20 Hz.

Other sources of sound include the aerodynamic noise generated by air flow across and leaving the trailing edge of the blades (trailing edge noise) and mechanical noise from the nacelle equipment. By contrast with BPF noise, the aerodynamic noise from the blades is broadband with a low-pass roll-off (~5 dB per octave > 1 kHz; Figure 2; Oerlemans, Sijtsma, & López, 2007, their Figures 5, 9, and 11). The center frequency (500–750 Hz, A-weighted) is related to the size and power generation capacity of the turbine with a downward shift of around 1/3 octave comparing 2.3 to 3.6 MW turbines to <2 MW turbines accompanied by a relative increase in the proportion of energy at low frequencies for larger turbines (Moller & Pedersen, 2011).

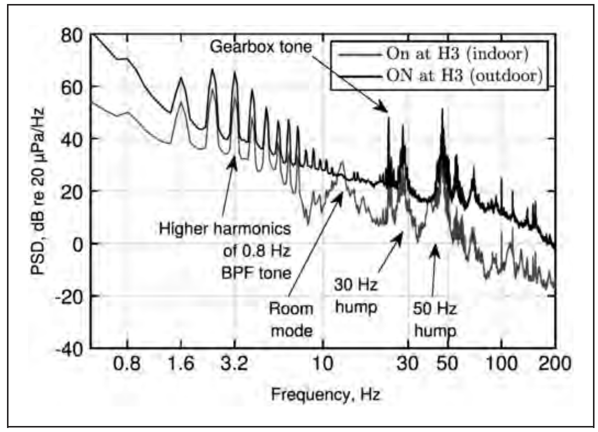

Figure 1. Comparison of indoor and outdoor spectral density recorded at an unoccupied dwelling approximately 3 km from a wind turbine. BPF = blade passing frequency; PSD = power spectral density.
Source: Reproduced with permission from Zajamsek et al. (2016), Figure 4.

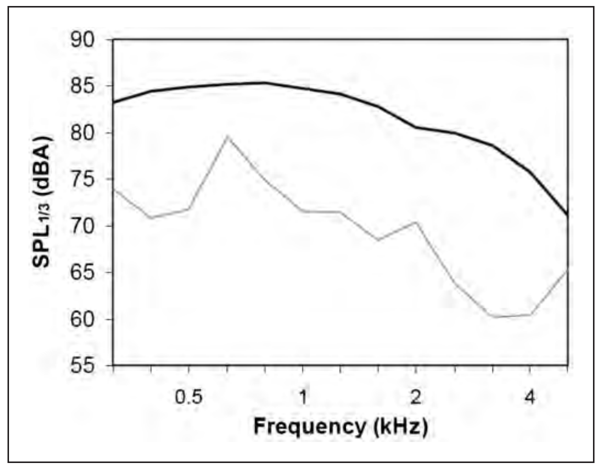

Figure 2. A-weighted average spectra of hub noise (thin line) and blade noise (thick line) recorded from a three-bladed pitch–controlled GAMESA G58 wind turbine (rotor diameter 58 m) using an acoustic array of 148 Panasonic WM-61 microphones 58 m upwind from the turbine.
Source: Reproduced with permission from Oerlemans et al. (2007).

In summary, from both a theoretical and an empirical standpoint, there is ample evidence demonstrating that a component of the sound energy produced by a WT is in the low and infrasonic frequency range. There are three other characteristics of LF that are relevant to understanding the measurements of sounds produced by WTs.

First, both modeling and measurement data have shown that the atmospheric boundary layer which extends from ground level to between 100 to thousands

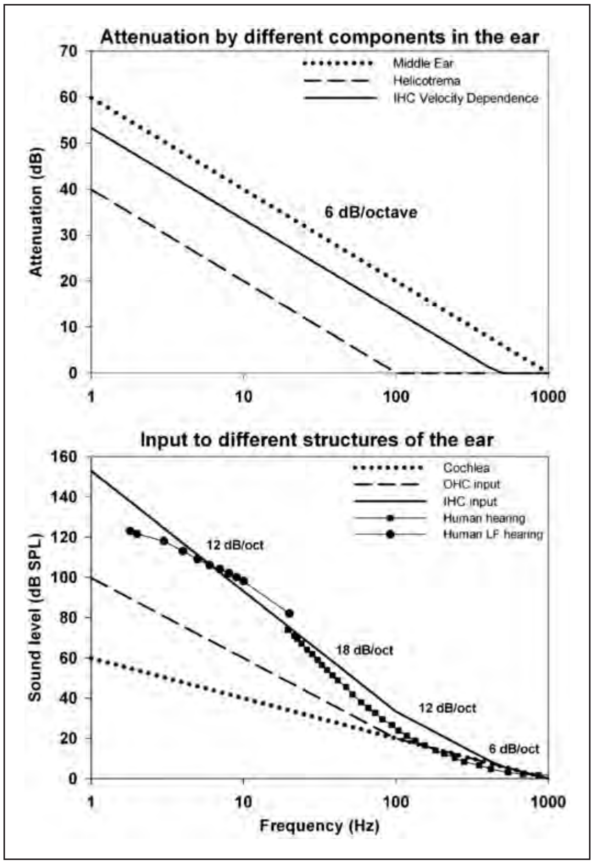

Figure 3. Upper panel: Estimated properties of high-pass filters associated with cochlear signal processing (based on Cheatham & Dallos, 2001). The curves show the low-frequency attenuation provided by the middle ear (6 dB/octave below 1000 Hz), the helicotrema (6 dB/octave below 100 Hz), and by the fluid coupling of the IHC resulting in the IHC dependence on stimulus velocity (6 dB/octave below 470 Hz). Lower panel: Combination of the three processes in the upper panel into threshold curves demonstrating: input to the cochlea (dotted) as a result of middle ear attenuation, input to the IHC as a result of additional filtering by the helicotrema, and input to the IHC as a result of their velocity dependence. Shown for comparison is the sensitivity of human hearing in the audible range (ISO226, 2003) and the sensitivity of humans to infrasound (Moller & Pedersen, 2004). The summed filter functions account for the steep (18 dB/octave) decrease in sensitivity below 100 Hz. OHC = outer hair cells; IHC = inner hair cells; LF = low-frequency sound.

Source: Reproduced with permission from Salt and Hullar (2010), Figure 3.

of meters can act as a low-frequency wave guide under a variety of common meteorological conditions (for review, see Marcillo, Arrowsmith, Blom, & Jones, 2015). With a stable boundary layer, which is common at night, LF radiation occurs as cylindrical waves and follows a two-dimensional decay model (−3 dB per doubling of distance) when measured downwind of a source (Zorumski & Willshire, 1989) in contrast to a three-dimensional decay model for higher frequency audible sound. Under such conditions, therefore, LF and IS levels decay more slowly with distance when compared with higher frequencies. Consistent with this, propagation of sound at the BPF from a 60-turbine wind farm has been recently measured using particularly sensitive equipment as far as 90 km from the source (Marcillo et al., 2015).

Second, IS and LF have wavelengths comparable with the dimensions of building structures such as homes which also allows for resonant interactions with those structures. Recent high-resolution data recorded inside and outside dwellings demonstrate such building cavity resonance in the 10 - to 20-Hz range (Pedersen, Møller, & Waye, 2007; Schomer et al., 2015; Zajamšek et al., 2016) along with other building resonances over a 2- to 80-Hz range. Third, sound attenuation provided by building walls is much less at low frequencies compared with higher frequency sounds (K. L. Hansen, Hansen, & Zajamšek, 2015; Thorsson et al., 2018) and very irregular because of the building resonances. These two observations indicate that exterior measures of LF and IS pressure are not necessarily good predictors of interior sound pressures as these are dependent on the particular characteristics of the structure.

Accurate measures of the sound pressure levels of LF and IS around WTs is complicated because of the very long wavelengths of sound at such low frequencies, and the high susceptibility of measurement microphones to atmospheric turbulence (i.e., wind noise). Special strategies such as very high performance wind-shields (Dauchez, Hayot, & Denis, 2016; K. Hansen, Zajamsek, & Hansen, 2014; Turnbull, Turner, & Walsh, 2012; Zajamšek et al., 2016) and the use of microphone arrays with sophisticated signal processing (Walker, 2013) are needed. There is a complex relationship between the wind speed and angle of incidence, atmospheric conditions, terrain, distance to the source and the number and distribution of sources, and the measurement of LF and IS (for an excellent review, see Van den Berg, 2006). External measures are complicated by wind noise and other interactions with the measuring instrument. The greater majority of measurements are external (rather than internal where the greatest disability is reported) and use A weighting which effectively filters out LF and IS frequencies. Even lower pass weightings (e.g., C weighting) exclude crucial low frequencies particularly at the BPF and first few harmonics. Measures made external to dwellings are not necessarily good predictors of dwelling interior pressures where people spend the majority of their time (particularly sleeping). In turn, internal measurements are also complicated, and often avoided by acousticians because of the influence of the room modes and occupational sources of noise, such as refrigerators and other household equipment. That there is a wide range of reported levels of LF and IS in and around wind farms should not be surprising, given the diversity of relevant factors (e.g., cf. Jung et al., 2008; Schomer et al., 2015; Sugimoto et al., 2008; Van den Berg, 2006). Given some of the physiological work reviewed later (particularly that relating to hydrops and basilar membrane biasing), use of a dosimetry approach to LF and IS exposure may prove a more appropriate measure for determining human exposure although this would require the development of new equipment and measurement techniques.

Sound Pressure Weighting Scales and WTN

The abovementioned considerations indicate that a complete understanding of sound energy emitted by WTs requires careful measurement and modeling approaches that are sensitive to the full range of possible sound frequencies. While the current practice of measuring and analyzing WTN using an A-weighted correction offers convenience and practicality, it will necessarily filter out much of the LF energy actually emitted by a WT. This approach appears to be motivated by practical measurement considerations and the assumption that, from the point of view of human perception, the auditory system sensitivity to sound level (loudness perception) is nonlinear and rolls off very sharply for frequencies below 1 kHz reaching −50 dB by 20 Hz (Keith et al., 2016; Yokoyama, Sakamoto, & Tachibana, 2014). These authors also argued that the A-weighted sound level of a wind farm is highly correlated with the sound levels of the LF and IS, and so A-weighted measures could act as a proxy for LF and IS levels. This supposition is, however, based on 1/3 octave C-weighted measures extending only to 16 Hz which is well above the BPF and it is not consistent with some recent data (e.g., Hansen, Walker, Zajamsek, & Hansen, 2015; Schomer et al., 2015). As reviewed earlier, there are also complicating factors relating to the potential difference in the propagation of IS and LF compared with the middle to high frequencies to which humans are sensitive. This suggests that, even if A-weighted measures are correlated with the total WT energy at a particular point in space, this may not provide an adequate indication of the relative sound levels at other distances from the source (see also Moller & Pedersen, 2011).

There is clearly a need for more research and development of methods to accurately measure and assess the level of exposure of individuals to LF and IS particularly in the built environment where individuals live and sleep. To be clear, in the first instance, this work needs to focus on the collection of high-quality scientific data to provide insights into the mechanisms and processes in play. While this may subsequently have implications for methods of making acoustic measurements in the field, the emphasis first needs to be on collecting high-quality scientific data to address the questions of sound propagation and human exposure.

Perceptual Sensitivity

Perceptual sensitivity to LF and IS has been studied for more than 80 years (reviewed in Moller & Pedersen, 2004), and although there is no international standard, the experimental data are in good agreement. Threshold rises sharply from 80 dB (SPL) at 20 Hz to around 124 dB SPL at 2 Hz and the perceptual effects also include vibration and the sensation of pressure at the ear drums. Consistent with these data, Yokoyama et al. (2014) showed that listeners were insensitive to resynthesized WTN in the laboratory at levels up to 56 dBA.

For a variety of biomechanical and other physiological reasons, the cochlea is known to be a highly nonlinear transducer. Given the relatively high sound levels required to achieve perceptual response to IS, the question arises as to whether this represents neural transduction at the fundamental frequency or sensitivity to nonlinear distortion products produced on the basilar membrane. While mechanisms of transduction are considered in more detail later, recent functional magnetic resonance imaging (fMRI) data (Dommes et al., 2009; Weichenberger et al., 2015) show auditory cortical activation to a 12-Hz tone at thresholds that are broadly consistent with those reviewed by Moller and Pederson (2004). This indicates that, regardless of whether IS is transduced as a fundamental or as a consequence of nonlinear distortion products, it does lead to activation of the auditory cortex providing a primary neural representation of these acoustic stimuli.

A more recent fMRI study (Weichenberger et al., 2017) took a different analytical approach using a regional homogeneity resting mode analysis and a relatively prolonged (200 s) 12-Hz stimulus. They report that subliminal sound levels (2 dB below measured threshold) also activated brain regions known to be involved in autonomic and emotional processing: In particular, the anterior cingulate cortex and amygdala—the latter is believed to be involved with stress and anxiety-related psychiatric disorders. The amygdala is also part of the nonleminiscal auditory pathway that mediates subcortical processing and has input to the reticular activating system, a key component regulating arousal and sleep (for discussion, see Weichenberger et al., 2017). This latter observation provides some explanation as to how subliminal IS stimulation could lead to arousal and potentially mediate sleep disturbances reported by some individuals.

Related to the question of individual differences, Moller and Pedersen (2004) make the observation that the dynamic range of the auditory system decreases significantly at low frequencies, demonstrated in the extreme compression of the equal loudness contours at 2 Hz (20–80 phon from 130 to 140 dB). This indicates that even small changes in pressure can result in very large changes in loudness perception. Likewise, small variations in threshold between individuals could produce significant differences in perceived loudness for the same pressure level stimulus. This would also result in differences in suprathreshold levels which, when taken in the context of the recent report of Weichenberger et al., could in turn explain some of the individual differences in reported physiological effects of WTN. A simple test of this prediction would be to measure the IS thresholds of individuals reporting physiological effects of exposure to WTN compared with those who report no effects under the same exposure conditions. If this proved to be discriminatory, then simple IS threshold measures would provide an indicator of likely susceptibility to WTN. Such measurements could involve perceptual impressions (Kuehler, Fedtke, & Hensel, 2015) or objective assessments such as fMRI (Weichenberger et al., 2017) or magnetoencephalogy (Bauer et al., 2013).

Physiological Transduction of LF and IS

Before considering the evidence for potential sensory or other transduction of LF and IS, it is useful to contextualize this discussion. As indicated in the Introduction section, a critical component in any argument attempting to link the sound level output from WTs (or any mechanical device) to ill health is the extent to which sound energy is able to influence the human body perceptually or somatically. If there is no influence, then it would be difficult to argue that reported health effects could be induced by sound or vibration. For instance, people in urban environments are exposed daily to significant qualities of low-level microwave radiation in the form of communications transmissions (radio, TV, cellular network, etc.) without any known effects of ill health (Valberg, Van Deventer, & Repacholi, 2007). This would likely be a consequence of the fact that, at these levels of exposure, microwave radiation is not an effective stimulus perceptually or somatically for the human body. By contrast, there is much debate and opinion as to whether the human nervous system is sensitive to the infrasonic and LF that is emitted by WTs. There are, unfortunately, very few peer-reviewed publications that consider the potential physiological mechanisms that might underlie sensory transduction of LF and IS. There is a much wider range of opinion pieces on the topic presented in a variety of formats (popular science magazines, newspaper articles, and self-published monographs and newsletters). Subsequently, we will consider principally reports or reviews in peer-reviewed scientific publications.

In a review in *Hearing Research*, Salt and Hullar (2010) outline a number of possible mechanisms by which the LF and IS could influence the function of the inner ear and lead to neural stimulation that may or may not be perceived as sound. These authors describe how, under normal physiological circumstances, the inner ear is remarkably insensitive to LF and IS. This results from the need to mechanically tune the sensory apparatus to sounds of greatest biological interest (in this case, from 100 Hz to a few kilohertz which is the range of human communication and of the inadvertent sounds of movement of predator or prey). Consequently, the anatomical structures of the cochlea would suffer significant damage in response to large mechanical displacements that would result from stimulation by even relatively low pressure LFs (for sounds of constant pressure, particle displacement is inversely proportional to frequency at +6 dB per octave).

There are three principal mechanisms providing this protective attenuation (see Figure 3; Salt & Hullar, 2010; for a very detailed review, see Dallos, 2012). First, the band-pass characteristics of the middle ear are roughly centered on 1 kHz and attenuate frequencies below that at 6 dB/octave. For a constant pressure, this inversely matches the increase in particle displacement so that for frequencies below 1 kHz, movement of the stapes and the amplitude of displacement input to the cochlea is constant. Second, low-frequency stimulation of the cochlea is reduced by the shunting of perilymph fluid between the chambers of the scala tympani and scala vestibuli through the helicotrema resulting in 6 dB/octave attenuation for frequencies less than 100 Hz. Third, the auditory transduction receptors, the inner hair cells (IHC) are sensitive to fluid velocity in the cochlea which results in a further attenuation of 6 dB octave below about 470 Hz. These three mechanisms add linearly to reduce stimulation of the IHC by 18 dB/octave between 100 Hz and 20 Hz.

Salt and Hullar (2010) make the important observation that as the outer hair cells (OHC) are sensitive to displacement (i.e., they are mechanically coupled and not fluid coupled to the tectorial membrane) which is constant for low frequencies, so even under physiologically normal conditions, at these low frequencies they should be stimulated at lower sound levels than the IHC. This prediction is borne out by the thresholds of endolymphatic potentials in the guinea pig cochlea to 5-Hz stimuli which represent strial current gated by OHC activity (Salt, Lichtenhan, Gill, & Hartsock, 2013). In contrast to the original estimates of OHC threshold (~40 dB lower than IHC at 5 Hz; Salt & Hullar, 2010), gain calculations in the later work suggest that the human apical cochlea could be similarly activated at around 55 dB to 65 dB SPL (corresponding to −38 to −28 dBA). This surprisingly high level of sensitivity of

OHCs to LF (when compared with IHC activation and perceptual threshold) is strongly supported by recent work examining the spontaneous otoacoustic emissions in humans (Drexl, Krause, Gürkov, & Wiegrebe, 2016; see also Drexl, Otto, et al., 2016; Jeanson, Wiegrebe, Gürkov, Krause, & Drexl, 2017; Kugler et al., 2014). It has been known for quite some time using human distortion product otoacoustic emissions (e.g., Hensel, Scholz, Hurttig, Mrowinski, & Janssen, 2007) as well as in vivo animal data (Patuzzi, Sellick, & Johnstone, 1984) that LF and IS do affect cochlear processing and that the cochlea aqueduct does pass IS frequencies into the inner ear (Traboulsi & Avan, 2007). The perceptual and other downstream consequences, however, are still not well studied. The more recent focus on the modulation of OHC activity is likely to provide important insights as to the physiological effects of IS and LF on cochlear processing. While the sensory role of OHCs are currently not well understood, they do carry sensory information via Type-II afferent fibers into the brain and probably play a role in signaling the off-set bias (and therefore operating point) of the basilar membrane and therefore also affect IHC transduction.

Before considering the effects of possible dysfunction of this system, it is worth summarizing the implications mentioned earlier. The healthy human ear significantly attenuates low-frequency input to the IHCs below around 100 Hz (~18 dB/octave). It is likely that at very low frequencies (<20 Hz), the OHCs are responding to stimuli at levels well below those producing activation of the IHCs. It is acoustic stimulation of the IHC which is the effective perceptual stimulus for hearing. Nonetheless, OHCs also have a sensory (afferent) input to the brain, although their stimulation is unlikely to lead to auditory perception per se. What is critical to emphasize at this juncture is that although the mechanisms outlined by Salt and Hullar (2010) are plausible and based on a large body of well-founded research, they do not by themselves constitute a demonstration of direct transduction of LF and IS by the inner ear. The effects of LF on OHC activity, however, could modulate transduction by the IHC, and such affects would likely be perceptible.

These data do provide, however, a strong prima facia case for neural transduction of LF and IS that needs to be properly examined at a functional and perceptual level in both animal and human models. Some critics of Salt and Hullar (2010) have argued that the level of LF and IS required to stimulate the OHCs is much greater than that recorded near wind farms. Given, however, the range of technical issues in making such acoustic measurements and the diversity of reported levels reviewed earlier, this claim is similarly limited by the available acoustic data. Furthermore, the recent work examining the guinea pig endocochlear potential (Salt et al., 2013) and human otoacoustic emissions (e.g., Drexl, Otto, et al., 2016; Kugler et al., 2014) indicate even greater levels of sensitivity of OHCs to LF when compared with the perceptual threshold mediated by IHC activity than first predicted. This suggests the need for a review of such conclusions.

Salt and Hullar (2010) also review the consequences of some pathologic conditions of the inner ear in terms of the potential to increase sensitivity to LF and IS. For instance, blockage or increased resistance of the helicotrema by a condition such as endolymphatic hydrops will reduce fluid shunting and reduce the attenuation for frequencies <100 Hz by up to 6 dB. Acute endolymphatic hydrops can be induced by exposure to low frequencies, although the relationship is complex and suggests that a dosimetry approach to exposure could be most informative. Hydrops would also lead to changes in the operating point of the basilar membrane resulting in a variety of changes in IHC sensory transduction including increased distortion. A further mechanism considered by Salt and Hullar is the increased fluid coupling of vestibular cells to sound input produced by changes in the input impedance of the vestibular system in conditions such as superior canal dehiscence (SCD), which can result in sound induced dizziness or vertigo, nausea, and nystagmus (Tullio phenomena).

Schomer et al. (2015) also examine potential physiological mechanisms that could mediate effects of LF and IS. They draw a link between the nauseogenic effects of low-frequency vestibular stimulation in seasickness and the potential vestibular stimulation by IS under normal listening conditions (as opposed to pathologic conditions of SCD). Using data collected by the U.S. Navy on nauseogenic effectiveness of low-frequency vestibular stimulation produced by whole body motion, they found significant overlap between the most effective nauseogenic frequencies and BPF of modern and larger WTs. Using a first-order model, they also demonstrate a better than order of magnitude equivalence between the force applied to the otoconia in the vestibular apparatus produced by whole body motion of 0.7 Hz at 5 m/s^2 peak and by IS of 0.7 Hz at 54 dB (SPL). Building on previous anatomical work (Uzun-Coruhlu, Curthoys, & Jones, 2007), Schomer et al. argue that pressure normal to the surface of the macular in the inner ear will provide an effective stimulus to the vestibular hair cells in the same way as the sheer motion between the otoconial membrane produced during linear acceleration of the head. While a plausible explanation, it is important to recognize that this suggestion is highly speculative and no data have yet been provided to support this latter assertion. Leventhall (2015) has also questioned this model although not in a peer-reviewed forum. Of note, however, the comparison with seasickness does add to the argument that a dosimetric approach to exposure may be more appropriate than measures of peak or root-mean-square sound pressure.

Perceptual Effects of Laboratory Exposure to LF and IS

A number of laboratory studies have directly exposed human listeners to IS and LF (e.g., Crichton, Dodd, Schmid, Gamble, & Petrie, 2014; Tonin, Brett, & Colagiuri, 2016) either directly recorded from WT (e.g., Yokoyama et al., 2014) or synthesized to reproduce key elements of these recordings (e.g., Tonin et al., 2016). A range of exposure symptoms have been reported but no systematic or significant effects of IS and LF have been demonstrated.

In general, sample sizes have been relatively small (e.g., $n = 2$, Hansen, Walker, et al., 2015; $n = 72$, Tonin et al., 2016) with studies likely to be statistically under powered (see Supplementary Material). Exposure times have been in the order of minutes to a few 10 s of minutes with a diversity of presentation levels above and below the IS/LF levels reported in the field.

Some free field stimulus playback systems have failed to deliver sound at the BPF and low-order harmonics frequencies (Yokoyama et al., 2014) while others have used headphone playback (Tonin et al., 2016). Many studies have not been blinded or double blinded, while others have been specifically designed to examine the effects of demand characteristics by manipulating expectancy (e.g., Crichton et al., 2014; Tonin et al., 2016). The latter studies have demonstrated, unsurprisingly, that manipulation of expectancy regarding the physiological effects of WT IS and LF has a moderate effect on the number and strength of symptoms reported by subjects regardless of the noise exposure conditions. Interestingly, Tonin et al. (2016) also report in their double-blind study that the presence of IS increased concern about health effects of WTN-expressed postexposure although subjects reported not hearing the IS stimulus.

In summary, there appears a prima facia case for the existence of sensory transduction of LF and IS and its representation in the nervous system. While a number of plausible mechanisms have been proposed, the actual mechanism of transduction has yet to be demonstrated. There are some laboratory-based studies examining the exposure to either recorded or simulated WTN, but the current data regarding potential perceptual or physiological are inconclusive.

General Summary and Conclusions

Although not an exhaustive survey of this literature, this review indicates that there are questions relating to the measurement and propagation of LF and IS and its encoding by the central nervous system (e.g., Dommes et al., 2009; Weichenberger et al., 2017) that are relevant to the possible perceptual and physiological effects of WTN but for which we do not have a good scientific understanding. There is much contention and opinion in these areas that, from a scientific perspective, are not well founded in the data, simply because there are little data available that effectively address these issues. This justifies a clear call to action for resources and support to promote high-quality scientific research in these areas.

Some of the research questions that arise from this review include the need for the following:

1. A more complete characterization and modeling of the sound generated by individual WTs and the large aggregations that comprise the modern windfarm. Such research needs to consider the spectrum from the BPF to its higher harmonics and incorporate the different propagation models that apply to different frequency ranges along with the effects of terrain, atmospheric conditions, and other potential modifiers of the sound.
2. The development of a more complete understanding of the interactions between WTN and the built structures in which people live and sleep. Such research needs to consider the different modes of excitation including substrate vibration, cavity resonances (including Helmholtz resonance and the interconnection of rooms), and differential building material sound insulation. New methods need to be developed for accurately and effectively measuring acute and chronic exposure (dosimetry) and for managing wind and other interference in the measurements.
3. Structural and aeronautic engineering research to discover ways to minimize the BPF generation and other potentially annoying sound sources.
4. Research to directly examine the effects of IS on the cochlea and vestibular apparatus. Although different theories have been advanced as to how IS and LF might be transduced and excite the central nervous system, there are little direct data demonstrating whether and how this occurs.
5. Research to better understand the neural connectivity of the putative transducers in the inner ear and an understanding of the consequences of their possible activation by IS and LF, notwithstanding the recent brain imaging data demonstrating differential activation of different brain structures (including the auditory cortex) by IS.
6. Research to better characterize the physiology of individuals who report susceptibility to WTN with a focus on whether these individuals represent a statistical tail of a normally distributed population or display other dysfunction or pathology that mediates susceptibility (e.g., SCD or lymphatic hydrops). In particular, an examination is required of the

hypothesis that small individual differences in threshold sensitivity to IS could underlie the differential activation of the anterior cingulate cortex and amygdala at subliminal sound levels.

This is not intended to be an exhaustive list of possible research areas. A research initiative to encourage and develop a very wide diversity of proposals is warranted as it is from the depth, capacity, and ingenuity of the researchers that work in these areas that the insights and the most effective research questions will come.

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EXHIBIT
18

Life Cycle Greenhouse Gas Emissions of Utility-Scale Wind Power

Systematic Review and Harmonization

Stacey L. Dolan and Garvin A. Heath

Keywords:

greenhouse gas emissions
industrial ecology
life cycle assessment
meta-analysis
renewable energy
wind energy

Supporting information is available on the *JIE* Web site

Summary

A systematic review and harmonization of life cycle assessment (LCA) literature of utility-scale wind power systems was performed to determine the causes of and, where possible, reduce variability in estimates of life cycle greenhouse gas (GHG) emissions. Screening of approximately 240 LCAs of onshore and offshore systems yielded 72 references meeting minimum thresholds for quality, transparency, and relevance. Of those, 49 references provided 126 estimates of life cycle GHG emissions.

Published estimates ranged from 1.7 to 81 grams CO_2-equivalent per kilowatt-hour (g CO_2-eq/kWh), with median and interquartile range (IQR) both at 12 g CO_2-eq/kWh. After adjusting the published estimates to use consistent gross system boundaries and values for several important system parameters, the total range was reduced by 47% to 3.0 to 45 g CO_2-eq/kWh and the IQR was reduced by 14% to 10 g CO_2-eq/kWh, while the median remained relatively constant (11 g CO_2-eq/kWh). Harmonization of capacity factor resulted in the largest reduction in variability in life cycle GHG emission estimates.

This study concludes that the large number of previously published life cycle GHG emission estimates of wind power systems and their tight distribution suggest that new process-based LCAs of similar wind turbine technologies are unlikely to differ greatly. However, additional consequential LCAs would enhance the understanding of true life cycle GHG emissions of wind power (e.g., changes to other generators' operations when wind electricity is added to the grid), although even those are unlikely to fundamentally change the comparison of wind to other electricity generation sources.

Introduction

Electricity generation accounted for approximately 40% of energy-related carbon dioxide (CO_2) emissions in the United States in 2008 (EIA 2009). Interest in technologies powered by renewable energy sources such as the wind and sun has grown partly because of the potential to reduce greenhouse gas (GHG) emissions from the power sector. However, due to GHG emissions produced during equipment manufacture, transportation, on-site construction, maintenance, and decommissioning, wind and solar technologies are not GHG emission-free. Life cycle assessment (LCA) is particularly well suited for comparing conventional power generation systems to renewables because it accounts for GHG emissions across the full life cycle of each technology, and therefore helps to inform decision makers of the attributable environmental impacts of energy technologies.

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Hundreds of LCAs have been published on various solitary wind turbines and wind farms over the past several decades, as well as two articles reviewing the wind power LCA literature (Lenzen and Munksgaard 2002; Varun et al. 2009) and one meta-analysis, which focuses on energy return on investment (Kubiszewski et al. 2010). Lenzen and Munksgaard (2002) investigated the effects capacity factor, lifetime, power rating, method, scope, country of manufacture, and vintage have on energy and CO_2 emission intensities of 72 previously published analyses of wind turbines taken from 32 LCAs. They also performed a multivariate regression normalizing the capacity factor to 25% and lifetime to 20 years, resulting in a decrease in the range of energy intensities from almost two orders of magnitude to one.

In contrast, objectives of the present meta-analysis include identifying, explaining, and, where possible, reducing variability in estimates of life cycle GHG emissions through a meta-analytical process called "harmonization." The purpose of this analysis and its umbrella project, the LCA Harmonization Project, which examines other electricity generation technologies such as coal and natural gas, is to inform decision making and future analyses that rely on such estimates. (Articles from the LCA Harmonization Project appearing in this special issue on meta-analysis of LCAs perform similar analysis on crystalline silicon photovoltaic [Hsu et al. 2012], thin film photovoltaic [Kim et al. 2012], coal [Whitaker et al. 2012], concentrating solar power [Burkhardt et al. 2012], and nuclear [Warner and Heath 2012].)[1]

Variability exists in estimates of life cycle GHG emissions even between studies performed on the same technology. Differences can be attributed to several factors, including specifics of the particular model, configuration and operating conditions of the system studied, methodological decisions and assumptions made by those conducting the study, variability in data sources, and LCA approach (e.g., consequential or attributional, process chain or economic input-output). To better understand the extent to which some of these sources of variability affect the overall results of a study, the present research systematically reviews previously published wind power LCAs and harmonizes their GHG emission estimates by establishing more consistent methods and assumptions, including characteristics of system performance, system boundaries, and global warming potentials (GWPs) of the individual GHG species.

Methods

An exhaustive literature search of the English-language literature was performed to compile a database of published wind LCAs. Studies were initially screened out if they did not meet the following criteria: published as a scholarly journal article, trade journal article greater than three published pages in length, conference proceeding greater than five double-spaced pages in length, books or chapters, theses, dissertations, or reports; were published after 1980; were written in English; and evaluated electricity as an end product. This preliminary screen reduced the number of references from 237 to 175. The database was structured to record certain defining characteristics of each study, such as whether it is an empirical or theoretical study. Specific study information extracted included publication year, reference type, onshore or offshore technology, vertical- or horizontal-axis turbines, utility-scale or distributed generation, manufacturer, tower type, publication date, which GHG species were inventoried, and vintage of the GWPs used. Several quantitative system parameters were also recorded, such as capacity, capacity factor, lifetime, and lifetime power output.

An LCA's system boundary is the choice of the researcher, so there may be considerable differences in scope across studies. To allow for comparison of studies in a common framework, our research defines the wind power life cycle as comprising three generalized life cycle phases illustrated in figure 1 and described below:

One-time upstream emissions, which includes emissions resulting from raw materials extraction, materials manufacturing, component manufacturing, transportation from the manufacturing facility to the construction site, and on-site construction.

Ongoing emissions during the turbine's operating phase, which includes emissions from maintenance activities such as replacement of worn parts and lubricating oils, and transportation to and from the turbines during servicing.

One-time downstream emissions, which includes emissions resulting from turbine and site decommissioning, disassembly, transportation to the waste site, and ultimate disposal and/or recycling of the turbines and other site materials.

Transmission and distribution (T&D) of electricity is sometimes included within the scope of LCAs, either through accounting for construction of the infrastructure or the loss of generated electricity in delivery to the consumer, or both.

Screening of the Literature

After the preliminary screen, a quality screen consistent with the general principles of the umbrella LCA Harmonization Project was applied to each estimate of life cycle GHG emissions, as many references produced more than one estimate because they evaluated multiple scenarios. Although a reference wasn't necessarily eliminated if only one of its estimates was screened out, most screening criteria applied to the reference as a whole; the results of screening are therefore reported at the level of the reference.

The pool of references was reduced from 175 to 72 upon applying the following minimum screening criteria:

1. LCA method:
   a. Employed a currently accepted LCA method (e.g., following guideline 14040 from the International Organization for Standardization [ISO 2006a, 2006b]).
   b. Included the upstream life cycle stage, as this stage is known to be the largest contributor to total GHG emissions for wind power systems.

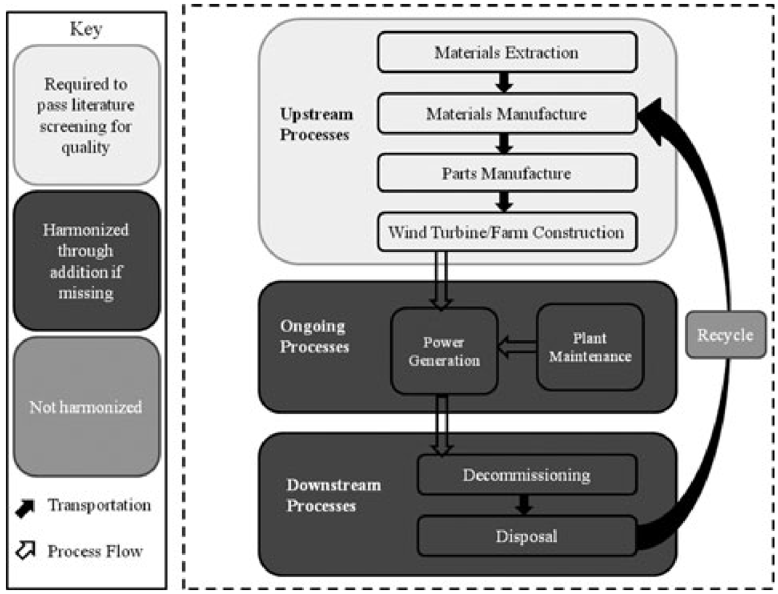

Figure 1 Process flow diagram illustrating the life cycle stages of wind power systems. Inclusion of at least one or more upstream life cycle stage was required for passing the screening process. Transportation between life cycle stages was not harmonized.

2. Transparency and completeness of reporting:
   a. Reported a reasonably descriptive method (e.g., scope and boundaries of study) and set of assumptions (e.g., capacity factor, system lifetime, recycling in end-of-life scenario).
   b. Cited primary or secondary data sources used for the analysis.
   c. Described, numerically where possible, characteristics of the wind power system studied (e.g., turbine model, capacity, site description or location, wind class, single turbine, or wind farm).
   d. Reported the name of software or database, if used, (e.g., SimaPro, Ecoinvent) as well as input parameters for the modeling (e.g., a material requirements list).
3. Relevance of the evaluated technology to modern, utility-scale wind power systems:
   a. Excluded wooden, steel, and aluminum rotor blades.
   b. Excluded non-three-bladed turbines.
   c. Excluded vertical-axis turbines.
   d. Excluded turbines with a rated capacity of less than 150 kilowatts (kW).

All estimates passing the above screening criteria were categorized as onshore, offshore, or a mix of the two, and are listed in table 1 along with important characteristics of the study and technology evaluated.

Harmonization Process

For the LCA Harmonization Project as a whole, two levels of harmonization were devised. The more resource-intensive level was envisioned as a process similar to that employed by Farrell and colleagues (2006) to harmonize the results of LCAs of ethanol. In that process, a subset of the available literature estimates of life cycle GHG emissions was carefully disaggregated. This process produced a detailed meta-model based on factors such as adjusted parameter estimates, realigned system boundaries within each life cycle phase, and a review of all data sources. A less-intensive and therefore grosser approach is more appropriate for the harmonization of a large set of literature estimates of life cycle GHG emissions. The less-intensive approach was chosen as the appropriate level of harmonization for wind power LCAs. The decision-making process for the level of harmonization is discussed in the supporting information available on the Journal's Web site.

This less-intensive harmonization process was performed by proportional adjustment of the published estimates of life cycle GHG emissions in grams CO_2-equivalent per kilowatt-hour (g CO_2-eq/kWh) to consistent values of two influential performance characteristics (capacity factor, system lifetime) and then, by addition or subtraction, to a consistent system boundary at the level of major life cycle stage.[2] GWPs were also harmonized where possible.

In keeping with the less-intensive harmonization approach, estimates were not audited for accuracy; published GHG emission estimates were taken at face value and converted to consistent units prior to being harmonized. Additionally, no exogenous assumptions were employed; if a reference did not report the information required for harmonization or conversion to the common functional unit, no assumptions were made. In those cases, that particular step of harmonization was not applied to that specific published GHG emission estimate, or the estimate wasn't included for harmonization, respectively. For instance, several estimates reported on a damages basis (e.g.,

Table 1 Studies and technologies that passed the screening criteria and produced an estimate of life cycle greenhouse gas (GHG) emissions, including key harmonization parameters

Author	*Year*	*Technology type*	*Turbine capacity (MW)*	*Lifetime (years)*	*Capacity factor (%)*	*Wind farm name, location*	*Study type*	*Notes*
Ardente et al.	2008	Onshore	0.66	20	19%	Italy (Sicily)	Empirical	
Berry et al.	1998	Onshore	0.3	—	31%	Penryddlan and Llidiartywaun, Wales	Empirical	
Chataignere and Le Boulch	2003	Onshore	0.6	20	29%		Theoretical	(1) Vestas 600 kW turbine
Chataignere and Le Boulch	2003	Onshore	2.5	20	34%		Theoretical	(1) Nordex 2.5 MW turbine
Chataignere and Le Boulch	2003	Offshore	2.5	20	46%		Theoretical	(50) Nordex 2.5 MW turbines, cassion
Chataignere and Le Boulch	2003	Offshore	2.5	20	46%		Theoretical	(100) Nordex 2.5 MW turbines
Chataignere and Le Boulch	2003	Offshore	2.5	20	46%		Theoretical	(50) Nordex 2.5 MW turbines, monopile
Chataignere and Le Boulch	2003	Onshore	1.5	20	29%		Theoretical	(1) Enercon 1.5 MW turbine
Crawford	2009	Onshore	3	20	33%		Theoretical	
Crawford	2009	Onshore	0.85	20	34%		Theoretical	
Dolan	2007	Offshore	1.8	20	30%	U.S. (Florida)	Theoretical	
Dones et al.	2005	Onshore	0.8	20/40	20%	Germany	Empirical	Turbine parts assume different lifetimes
Dones et al.	2005	Offshore	2	20	30%	Middelgrunden, Germany	Empirical	
Dones et al.	2007	Onshore	0.8	20/40	20%	Europe	Empirical	Turbine parts assume different lifetimes
Dones et al.	2007	Offshore	2	20	30%	Europe	Empirical	
Dones et al.	2007	Onshore	0.8	20/40	14%	Mont Crosin, Switzerland	Empirical	Turbine parts assume different lifetimes
DONG Energy	2008	Offshore	2	20	46%	Horns Rev, North Sea	Empirical	
Enel SpA	2004	Onshore	0.66	20	18%	Sclafani Bagni, Italy	Empirical	
European Commission	1995	Onshore	0.4	20	30%	Delabole, Penryddlan and Llidiartywaun, UK	Empirical	
Frischknecht	1998	Onshore	0.15	20	9.0%	Switzerland	Empirical	
Hartmann	1997	Onshore	1	20	19%		Theoretical	Process chain analysis
Hartmann	1997	Onshore	1	20	19%		Theoretical	EIO analysis
Hondo	2005	Onshore	0.4	50	20%	Japan	Theoretical	
Hondo	2005	Onshore	0.4	30	20%	Japan	Theoretical	
Hondo	2005	Onshore	0.3	50	20%	Japan	Theoretical	
Hondo	2005	Onshore	0.4	20	20%	Japan	Theoretical	
Hondo	2005	Onshore	0.3	30	20%	Japan	Theoretical	
Hondo	2005	Onshore	0.3	20	20%	Japan	Theoretical	
Hondo	2005	Onshore	0.4	10	20%	Japan	Theoretical	

(*Continued*)

Table 1 *(Continued)*

Author	Year	Technology type	Turbine capacity (MW)	Lifetime (years)	Capacity factor (%)	Wind farm name, location	Study type	Notes
Hondo	2005	Onshore	0.3	10	20%	Japan	Theoretical	
Jacobson	2009	Onshore	5	30	43%		Theoretical	
Jacobson	2009	Onshore	5	20	43%		Theoretical	
Jacobson	2009	Onshore	5	30	29%		Theoretical	
Jacobson	2009	Onshore	5	20	29%		Theoretical	
Jungbluth et al.	2005	Onshore	0.8	20/40	20%	Europe	Theoretical	Turbine parts assume different lifetimes
Jungbluth et al.	2005	Offshore	2	20	30%	Middelgrunden, Baltic Sea	Theoretical	
Khan et al.	2005	Onshore	0.5	20	—	Canada (Newfoundland)	Theoretical	
Krewitt et al.	1997	Onshore	0.25	20	25%	Northfriesland, Germany	Empirical	1990 technology vintage
Kuemmel and Sørensen[a]	1997	Mix	1.3	25	29%	Denmark	Theoretical	
Kuemmel and Sørensen	1997	Onshore	0.4	20	23%	Denmark	Theoretical	
Lee and Tzeng[b]	2008	Onshore	0.6–1.75	20	33%	Mailiao, Jhongtun and Chunfong, Taiwan	Empirical	
Lenzen and Wachsmann	2004	Onshore	0.6	20	68%	Manufactured and operated in Brazil	Theoretical	Recycled steel, coastal, 44 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	71%	Manufactured and operated in Brazil	Theoretical	Recycled steel, coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	55%	Manufactured and operated in Brazil	Theoretical	Recycled steel, near-coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	68%	Manufactured and operated in Brazil	Theoretical	Coastal, 44 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	71%	Manufactured and operated in Brazil	Theoretical	Coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	55%	Manufactured and operated in Brazil	Theoretical	Near-coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	42%	Manufactured and operated in Brazil	Theoretical	Recycled steel, inland, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	46%	Manufactured and operated in Brazil	Theoretical	Recycled steel, inland 65 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	42%	Manufactured and operated in Brazil	Theoretical	Inland, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	46%	Manufactured and operated in Brazil	Theoretical	Inland, 65 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	68%	Manufactured in Brazil and Germany, operated in Brazil	Theoretical	Coastal, 44 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	71%	Manufactured in Brazil and Germany, operated in Brazil	Theoretical	Coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	55%	Manufactured in Brazil and Germany, operated in Brazil	Theoretical	Near-coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	46%	Manufactured in Brazil and Germany, operated in Brazil	Theoretical	Inland, 65 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	42%	Manufactured in Brazil and Germany, operated in Brazil	Theoretical	Inland, 55 m hub height

(Continued)

Table 1 *(Continued)*

Author	*Year*	*Technology type*	*Turbine capacity (MW)*	*Lifetime (years)*	*Capacity factor (%)*	*Wind farm name, location*	*Study type*	*Notes*
Lenzen and Wachsmann	2004	Onshore	0.6	20	68%	Manufactured in Germany, operated in Brazil	Theoretical	Coastal, 44 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	71%	Manufactured in Germany, operated in Brazil	Theoretical	Coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	55%	Manufactured in Germany, operated in Brazil	Theoretical	Near-coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	46%	Manufactured in Germany, operated in Brazil	Theoretical	Inland, 65 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	42%	Manufactured in Germany, operated in Brazil	Theoretical	Inland, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	25%	Manufactured and operated in Germany	Theoretical	Coastal, 44 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	26%	Manufactured and operated in Germany	Theoretical	Coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	20%	Manufactured and operated in Germany	Theoretical	Near-coastal, 55 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	17%	Manufactured and operated in Germany	Theoretical	Inland, 65 m hub height
Lenzen and Wachsmann	2004	Onshore	0.6	20	15%	Manufactured and operated in Germany	Theoretical	Inland, 55 m hub height
Liberman and LaPuma[c]	2003	Onshore	0.75–1.3	Various	—	U.S. (Arkansas)	Empirical	
Martínez et al.	2009	Onshore	2	20	23%	Munilla, Spain	Empirical	
Martínez et al.	2009	Onshore	2	20	23%	Munilla, Spain	Empirical	
Martínez et al.	2009	Onshore	2	20	23%	Munilla, Spain	Empirical	
McCulloch et al.	2000	Onshore	0.6	25	20%		Theoretical	
Nadal	1995	Onshore	0.225	20	20%		Theoretical	
Pacca and Horvath	2002	Onshore	0.6	20	24%		Theoretical	
Pacca	2003	Onshore	0.6	40	24%	U.S. (Southern Utah)	Theoretical	
Pacca	2003	Onshore	0.6	30	24%	U.S. (Southern Utah)	Theoretical	
Pacca	2003	Onshore	0.6	20	24%	U.S. (Southern Utah)	Theoretical	
Pacca	2003	Onshore	0.6	10	24%	U.S. (Southern Utah)	Theoretical	
Pehnt	2006	Offshore	2.5	—	—	Germany	Theoretical	2010 technology vintage
Pehnt	2006	Onshore	1.5	—	—	Germany	Theoretical	2010 technology vintage
Pehnt et al.	2008	Offshore	5	—	—	North Sea	Theoretical	
Proops et al.	1996	Onshore	6.6	20	29%	UK	Theoretical	Used 1989 EIO tables
Proops et al.	1996	Onshore	6.6	20	29%	UK	Theoretical	Used 1989 EIO tables
Proops et al.	1996	Onshore	6.6	20	29%	UK	Theoretical	Used 1989 EIO tables
Rule et al.	2009	Onshore	1.65	100	39%	Te Apiti, New Zealand	Empirical	
Rydh et al.	2004	Onshore	0.225	30	26%	Gronhogen, Sweden	Empirical	End-of-life scenario: renovation
Rydh et al.	2004	Onshore	2	20	35%	Gronhogen, Sweden	Empirical	End-of-life scenario: replacement
Rydh et al.	2004	Onshore	0.225	20	26%	Gronhogen, Sweden	Empirical	End-of-life scenario: relocation

(*Continued*)

Table 1 *(Continued)*

Author	*Year*	*Technology type*	*Turbine capacity (MW)*	*Lifetime (years)*	*Capacity factor (%)*	*Wind farm name, location*	*Study type*	*Notes*
Rydh et al.	2004	Onshore	0.225	20	26%	Gronhogen, Sweden	Empirical	End-of-life scenario: recycling
Schleisner	2000	Onshore	0.5	20	25%	Tuno Knob, Denmark	Empirical	
Schleisner	2000	Offshore	0.5	20	29%	Fjaldene, Denmark	Empirical	
SECDA	1994	Onshore	0.3	40	24%	Canada (Saskatchewan)	Theoretical	
Spitzley and Keoleian	2004	Onshore	0.5	30	36%	Western U.S.	Theoretical	Ridge site, class 6 winds
Spitzley and Keoleian	2004	Onshore	0.5	30	26%	Western U.S.	Theoretical	Plains site, class 4 winds
Tremeac and Meunier	2009	Onshore	4.5	20	30%	Southern France	Theoretical	Transport by train
Tremeac and Meunier	2009	Onshore	4.5	20	30%	Southern France	Theoretical	Transport by truck
Tremeac and Meunier	2009	Onshore	4.5	20	30%	Southern France	Theoretical	Doubling transport distance
Uchiyama	1996	Onshore	0.4		20%	Japan	Theoretical	Micon 400/100 kW two-speed turbine
Uchiyama	1996	Onshore	0.3		20%	Japan	Theoretical	Mitsubishi 300 kW turbine
van de Vate	1996	Onshore	0.3	20	23%		Theoretical	
Vattenfall[d]	2003	Onshore	0.225–1.75	25	21%	Various wind farms, Sweden	Empirical	
Vattenfall[e]	2010	Mix	0.6–3	20	29%	Denmark, UK, Poland, Sweden, Germany	Empirical	Does not include T&D grid
Vattenfall[e]	2010	Mix	0.6–3	20	29%	Denmark, UK, Poland, Sweden, Germany	Empirical	Includes T&D grid
Vestas Wind Systems	2006a	Onshore	1.65	20	41%		Theoretical	
Vestas Wind Systems	2006b	Onshore	3	20	54%		Theoretical	
Vestas Wind Systems	2006b	Offshore	3	20	54%		Theoretical	
Voorspools et al.	2000	Onshore	0.6	20	34%	Belgium (coastal)	Theoretical	EIO analysis
Voorspools et al.[f]	2000	Onshore	0.15–1.5	20	34%	Belgium (coastal)	Theoretical	Process chain analysis
Voorspools et al.	2000	Onshore	0.6	20	11%	Belgium (inland)	Theoretical	EIO analysis
Voorspools et al.[f]	2000	Onshore	0.15–1.5	20	11%	Belgium (inland)	Theoretical	Process chain analysis
Waters et al.	1997	Onshore	0.15	25	23%	Baix Ebre, Spain	Empirical	
WEC	2004	Onshore	0.23	—	35%	Greece	Theoretical	
WEC	2004	Onshore	0.6	—	23%	Finland	Theoretical	
WEC	2004	Onshore	0.6	—	21%	Australia	Theoretical	
WEC	2004	Onshore	0.5	—	25%	Denmark	Theoretical	
WEC	2004	Offshore	0.5	—	29%	Denmark	Theoretical	
Weinzettel et al.	2009	Deep offshore	5	20	53%		Theoretical	With end-of-life scenario
Weinzettel et al.	2009	Deep offshore	5	20	53%		Theoretical	Without end-of-life scenario
Weinzettel et al.	2009	Offshore	2	20	30%		Theoretical	Ecoinvent database process
White	2006	Onshore	0.3425	25	26%	Buffalo Ridge, U.S. (SW Minnesota)	Empirical	Update to 1998 publication estimate
White	2006	Onshore	0.75	30	29%	Buffalo Ridge, U.S. (SW Minnesota)	Empirical	Update to 1998 publication estimate
White	2006	Onshore	0.6	20	20%	Glenmore, U.S. (Wisconsin)	Empirical	Update to 1998 publication estimate

(Continued)

Table 1 *(Continued)*

Author	*Year*	*Technology type*	*Turbine capacity (MW)*	*Lifetime (years)*	*Capacity factor (%)*	*Wind farm name, location*	*Study type*	*Notes*
White and Kulcinski	1998	Onshore	0.75	30	35%	Buffalo Ridge, U.S. (SW Minnesota)	Empirical	Zond Z-46 turbines
White and Kulcinski	1998	Onshore	0.3425	25	24%	Buffalo Ridge, U.S. (SW Minnesota)	Empirical	Kenetech KVS-33 turbines
White and Kulcinski	1998	Onshore	0.6	20	31%	Glenmore, U.S. (Wisconsin)	Empirical	Tacke 600e turbines
White and Kulcinski	2000	Onshore	0.3425	25	24%	Buffalo Ridge, U.S. (SW Minnesota)	Empirical	Update to 1998 publication estimate
Wibberly	2001	Onshore	0.6	30	21%	Crookwell, Australia	Empirical	

Notes: One meter (m, SI) ≈ 3.28 feet (ft); MW = megawatts; kW = kilowatts.

[a]This data point represents a mix of 1 megawatt (MW) onshore and 3 MW offshore turbines. Therefore a mean capacity of 2 MW listed here was assumed for plotting in figure 2. Because the proportion of onshore to offshore turbines in the mix is unknown, this estimate could not be harmonized by capacity factor.

[b]This data point represents a mix of (4) 660 kilowatt (kW), (4) 600 kW, and (2) 1.75 MW turbines. Therefore the average was assumed for plotting purposes in figure 2. A weighted average was also used for capacity factor to allow harmonization by this parameter.

[c]This data point represents a mix of various turbines for which only the capacity range of 750 kW to 1.3 MW was reported; therefore a mean capacity of 1.025 MW was assumed to include this data point in the scatter plots in figure 2.

[d]The capacity listed represents a weighted average of (1) 225 kW, (2) 500 kW, (7) 600 kW, and (1) 1.75 MW turbines. The capacity factor also represents a weighted average based on the reported power outputs of the 11 turbines.

[e]The capacity listed represents a weighted average of the mix of (7) 600 kW, (4) 850 kW, (10) 1.5 MW, (63) 2.0 MW, (50) 2.3 MW, and (30) 3 MW turbines. The capacity factor is also an average weighted by the reported capacity factors of the groups of turbines.

[f]This data point represents a range of turbine capacities for which only the endpoints of the range were given. Therefore the mean of the endpoints was assumed as the capacity to include this point in the scatter plots in figure 2.

milliperson-equivalents/kWh) could not be back-calculated to the common functional unit and thus were not retained. Only nonduplicative estimates were included; however, any estimate that adapted previous work in a way that resulted in an estimate different from the original was accepted. Only the latest publication from authors who published the exact same estimates in multiple papers was retained for further analysis. Finally, GHG emission estimates had to be reported numerically (not just graphically) for inclusion.

Harmonization Parameters

Life cycle GHG emission estimates for wind power systems are calculated as follows:

$$\frac{CO_2 + \left(CH_4 * 25\frac{\text{g } CO_2\text{−eq}}{\text{g } CH_4}\right) + \left(N_2O * 298\frac{\text{g } CO_2\text{−eq}}{N_2O}\right)}{\textit{Capacity factor} * 8760\frac{\text{hours}}{\text{year}} * \textit{Lifetime} * \textit{Nameplate capacity}}.$$

This equation allows for clear identification of the potential magnitude for adjustment that each of the harmonization parameters has in the life cycle GHG emission estimates. The numerator represents the total emissions over the life cycle, while the denominator represents the lifetime power output of the system. The GWP harmonization step adjusts two of the values in the summation in the numerator; however, the CO_2 portion of the emission estimates remains unchanged. Both the capacity factor and system lifetime harmonization steps scale the denominator in its entirety, and therefore have a larger potential than GWP harmonization to adjust the life cycle GHG emission estimates. The system boundary harmonization step adds additional emissions onto the numerator to account for life cycle stages that were not included in the scope of the original analysis. Thus this harmonization step has a potential for adjustment of the life cycle GHG emission estimates similar to that of the GWP harmonization step.

Statistical Assessment

Central tendency and variability in life cycle GHG emission estimates passing our screens are described using several statistical metrics. The key statistical metric chosen to characterize central tendency is the median value. The arithmetic mean is also reported but, due to the slight positive skew of the dataset, the median is preferred. Variability is discussed mainly in terms of interquartile range (IQR = 75th percentile − 25th percentile), which represents the spread of the middle 50% of estimates. Total range is also a key metric for expressing variability, as IQR only summarizes variability in the central half of the estimates. Standard deviation, as well as minimum and maximum values, is also reported. For each harmonization step, changes in central tendency and variability are compared with published estimates to describe the impact of the harmonization step. Decreases in measures of variability indicate effective harmonization in terms of a tightened IQR or range of life cycle GHG emissions from the evaluated technology.

These statistics are meant to summarize the current state of LCA literature of utility-scale wind power technologies. Although the studies and estimates that we selected were reasonably large in number and high quality, the available studies might not cover all possible cases of manufacture, deployment, or use. Thus the range exhibited in this article may not represent the true minimum, maximum, or central tendency for wind power GHG emissions, the current state of the technology as deployed or anticipated, or the inclusivity of all relevant contributions with regard to the depth and breadth across the supply chain. For example, the difference in results generated using process chain compared to hybrid economic input-output methods indicates that system boundary truncations can have significant impacts (Suh et al. 2004). In this respect, the upper end of the range exhibited in this article may be closer to the true life cycle GHG emissions than those estimates at the lower end.

The distribution of our results also cannot be considered a distribution of likelihood for actual life cycle GHG emissions for current or future applications of the technology. The precision and range of results are improved with the large sample size evaluated here, but sample limitations impact the accuracy of the results compared to the "true" life cycle GHG emission range and central tendency of wind power under all potential conditions. Confidence in the results for onshore wind is higher than for offshore owing to the larger sample size.

Finally, the impact on variability reduction of harmonizing a particular parameter is an indicator of the influence that parameter exerts on life cycle GHG emissions for wind, but is not a formal sensitivity analysis.

Harmonization of Global Warming Potentials

Per the screening criteria, the pool of articles ranged in publication year from 1980 to 2010, with several updates to GWPs published by the Intergovernmental Panel on Climate Change (IPCC) during this time. Therefore, because various GWPs were utilized in the literature, wherever mass emissions of individual GHGs were reported the GHG emission estimates were updated to reflect the most recent 100-year time horizon GWPs published by the IPCC (Forster et al. 2007) of 25 g CO_2-eq/g methane (CH_4) and 298 g CO_2-eq/g nitrous oxide (N_2O).

Harmonization of Operating Lifetime

Life cycle GHG emission estimates were also harmonized by assumed operating lifetime of the wind turbine and its components. Reported lifetimes ranged from 10 to 100 years, 20 years being the most commonly cited. Since 20 years is also a common design life for modern turbines (Vestas Wind Systems 2006a, 2006b), all GHG emission estimates were harmonized to a 20-year life span by proportionally scaling the lifetime power output while holding the life cycle emissions estimate constant. This assumes that emissions resulting from maintenance are not changed when a different lifetime is assumed. Operational maintenance, however, was the life cycle stage with the least coverage in the literature, and because its emissions are small relative to the other life cycle stages, any errors resulting from this assumption are likely small in magnitude. Several publications (Dones et al. 2005, 2007; Jungbluth et al. 2005; Rule et al. 2009) assumed lifetimes longer than 20 years and included a certain amount of parts replacement after the 20-year point, but did not separately report the emissions resulting from the refurbishing process. These estimates could not be harmonized by lifetime because the emissions from parts replacement could not be subtracted out. It is worth noting that different wind turbines or farms will have different lifetimes in practice. These depend on various factors—the length of the operating contract with the utility company, the lease on the land where the turbine is sited, parts failure and replacement with new turbines instead of repowering—and it is the nature of LCAs to be context specific. However, harmonization of assumed lifetime was nonetheless performed to demonstrate the effect that system lifetime has on wind power's life cycle GHG emissions, and to assess the degree to which harmonizing by this parameter tightens the range of estimates.

Harmonization of Capacity Factor

For wind power, capacity factor is the ratio of actual electricity generated to the maximum potential electricity generation (nameplate capacity multiplied by 8,760 hours per year). For a given wind resource, turbines operating at a higher capacity factor produce more electrical output than those with lower capacity factors by operating for longer periods of time over the course of the year.

In practice, different wind farms will operate at different capacity factors for several reasons, for instance, the specific wind conditions experienced at the site and the frequency and duration of maintenance. However, the purpose of harmonizing the GHG emission estimates is not to suggest that all LCAs of wind turbines or farms should assume a consistent nominal capacity factor, but to observe how large a role differences in assumed capacity factor play in the variability of published GHG emission estimates. The mean assumed capacity factor for onshore turbines in the pool of literature passing the quality and relevance screens was, after rounding, 30%, while the mean assumed capacity factor for offshore wind turbines was 40%. The latest survey of deployed turbines (Wiser and Bolinger 2010) suggests that the capacity-weighted average in 2009 is very close to these literature averages. Therefore GHG emission estimates that assumed alternative capacity factors were adjusted to these values. Modern turbines deployed in high wind class zones can reach 35% for onshore turbines and 45% for offshore turbines. In 2008, capacity-weighted average capacity factors for onshore wind reached 34%, owing to 2008 being a better wind resource year and having less curtailment than 2009. An additional contributing factor to the reduction in average capacity factor from 2008 to 2009 is the recent trend of wind installations in lower-quality wind resource areas because of transmission and other siting constraints (Wiser and Bolinger 2010). The effect of the higher capacity factor benchmarks on life cycle GHG emission estimates is provided in the supporting information on the Web.

Harmonization of System Boundary

The quality screen required that studies include an estimate for upstream GHG emissions because wind turbine operation has no direct combustion emissions. To improve consistency and reduce sources of variability, the median estimate of GHG emissions for operational or downstream life cycle phases from studies that included those phases were added to studies whose scope did not include one or both of those phases. When testing the effect of harmonization by system boundary independently, the median was calculated using published GHG emission estimates; when performed cumulatively with the other harmonization steps, the GHG emission estimates for studies that included these life cycle phases were harmonized by the other parameters first, and then the median of those harmonized estimates (per phase) was calculated. The rationale for employing these methods is further described in the supporting information on the Web.

Cumulative Harmonization of All Parameters

The last harmonization step was to harmonize by GWP, lifetime, capacity factor, and system boundary consecutively. As some harmonization steps may counteract previous ones, this represents the final results of the complete harmonization process.

Results

Summary of the Published Literature

The 126 estimates from 49 studies of wind power life cycle GHG emissions display a median of 12 g CO_2-eq/kWh, IQR of 12 g CO_2-eq/kWh, and a range of 79 g CO_2-eq/kWh. The IQR shows that the central 50% of the estimates lie within only 12 g CO_2-eq/kWh of each other, which is a relatively tight range when compared to the magnitude of other power technologies such as coal, for which life cycle GHG emission estimates are on the scale of 1,000 g CO_2-eq/kWh (Whitaker et al. 2012).

While the onshore studies are far greater in number than the offshore studies and have a larger total range of values, the IQR for the onshore group is only 13 g CO_2-eq/kWh, ranging from 7.3 to 20 g CO_2-eq/kWh. The published offshore studies are even tighter, with a smaller total range, and the central 50% of estimates within less than 5 g CO_2-eq/kWh of each other, lying in the range of 9.4 to 14 g CO_2-eq/kWh.

Cumulative installed wind capacity in the United States gradually grew from nearly zero in the early 1980s to roughly 3,000 megawatts (MW) by the year 2000, followed by exponential growth over the past decade to more than 35,000 MW in 2009.[3] The average turbine size in 1999 was 0.71 MW and the average price of wind energy was $65/megawatt-hour (MWh) expressed in 2009 U.S. dollars.[4] In 2009 the average turbine size had more than doubled to 1.74 MW while the average price had reduced to $45/MWh (Wiser and Bolinger 2010). These trends suggest that considerable learning has taken place in the industry. One might expect the increasing scale and industrial learning to reduce materials usage, which could reduce embodied GHG emissions. Figure 2 explores these potential trends, but neither is found, suggesting that with regard to GHG emissions, wind power has been stable over time and scale. This constancy may not remain into the future, but given the already low life cycle GHG emissions, even if relative reductions were to be achieved, they might not appreciably affect the magnitude.

Harmonization Results

The harmonization process was performed in a stepwise fashion, illustrated in figures 3 and 4 for onshore and offshore wind, respectively. In both figures, frame (a) displays the published estimates and frames (b) through (e) display the results of applying each harmonization step independently. Frame (f) is the final result of harmonizing by all factors cumulatively. Estimates are displayed in an ordinal ranking (from lowest to highest) that remains constant through all frames such that the effect of harmonization can be seen in the vertical translation of a given point. If a point remains in the same position after a given step, either the value of the harmonization parameter in the publication was already the same as the benchmark value chosen for harmonization, or the value for the harmonization parameter was not reported so harmonization of the estimate could not be performed.

Table 2 reports summary statistics for the onshore, offshore, and total pool of estimates passing the screens for each harmonization step. Life cycle GHG emission estimates that could not be harmonized in any given harmonization step due to missing data remain unchanged in the harmonization plots and the calculation of summary statistics from published values so that all of the summary statistics for each harmonization step are based on the same number of estimates ($n = 126$ for all values, $n = 107$ for onshore, and $n = 16$ for offshore). The three life cycle GHG emission estimates that were reported for an aggregated mix of both onshore and offshore technologies (Kuemmel and Sørensen 1997; Vattenfall 2010) were included in the harmonization process and the summary statistics for all technology types only. The individual GHG emission estimates from each publication for each harmonization step are also reported numerically in table S3 of the supporting information on the Web.

Harmonization of Global Warming Potentials

Only six estimates were harmonized in this step because most references do not report both the GWPs used and mass emissions of individual GHGs. All adjustments were less than 1 g CO_2-eq/kWh, resulting in an insignificant (less than 1%) change in variability and central tendency as a result of this harmonization step (figures 3b and 4b).

Harmonization of System Lifetime

Of the 126 estimates evaluated, 107 report system lifetimes; 80 were already at the benchmark value selected for harmonization, that is, 20 years. Therefore the effect of this harmonization step was relatively small, with a 2% increase in the median value, an 11% increase in the IQR, and a less than 1% reduction in total range (figures 3c and 4c).

Harmonization of Capacity Factor

Of the 126 GHG emission estimates in the pool, 118 report capacity factors. Because the assumed capacity factors of the literature vary considerably more than the assumed lifetimes, harmonizing by capacity factor reduced variability significantly

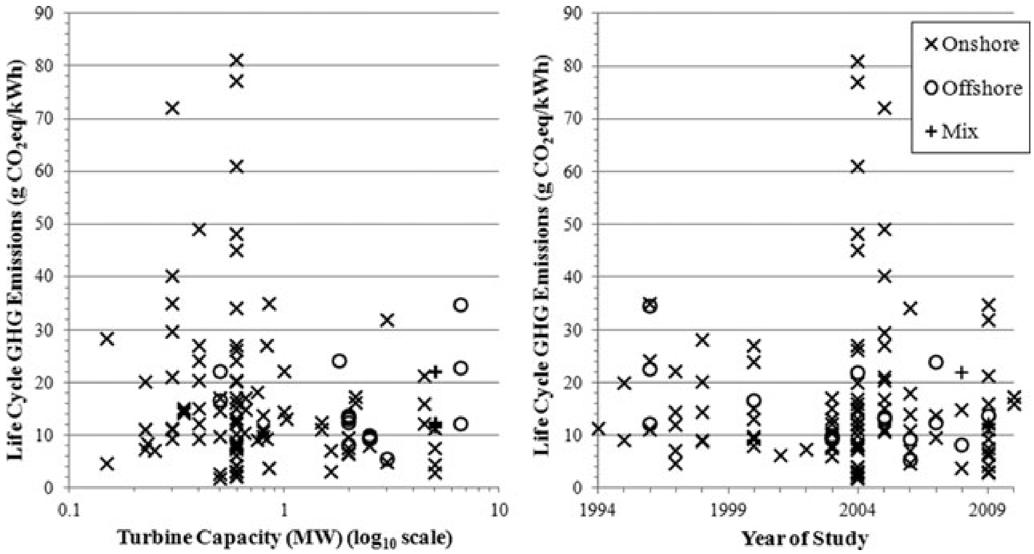

Figure 2 Published life cycle greenhouse gas (GHG) emissions of utility-scale wind power technologies by rated capacity (left) and year of study (right) for estimates that pass screening.

more. This harmonization step reduced the IQR by 14% and the total range by 42%. Figures 3d and 4d display that, on average, low-end GHG emission estimates increased while high-end estimates decreased as a result of this harmonization step. These results suggest that the value chosen for capacity factor in wind power LCAs significantly influences resulting estimates of life cycle GHG emissions.

Harmonization of System Boundary

Sixty-seven estimates of life cycle GHG emissions from 24 references disaggregated GHG emissions into life cycle phases. However, the system boundary for only 22 of those 67 estimates included all three previously defined life cycle stages: upstream, ongoing, and downstream. For the remaining 45 estimates, the median values for the missing life cycle stages, reported in table S2 in the supporting information on the Web, were added. Two sets of median add-on values were used, one for onshore and one for offshore technologies.

Harmonizing for system boundary logically resulted in an increase in the median estimate for both onshore and offshore studies, as add-on values were applied. Harmonization by system boundary did not, however, reduce the variability in life cycle GHG emission estimates. The IQR remained constant and the total range increased by 2.1%. Plots of this harmonization step (figures 3e and 4e) illustrate the small vertical translation of the individual estimates that were harmonized ($n = 45$), only two of which were offshore estimates. The majority of the life cycle GHG emission estimates remained constant because they either did not report disaggregated emissions or because, although disaggregated GHG emissions were reported, they already accounted for all three life cycle stages.

Cumulative Harmonization of All Parameters

Harmonizing for GWPs, system lifetime, capacity factor, and system boundary resulted in a significantly tighter distribution than the published GHG emission estimates for wind power systems (figures 3f and 4f). The published GHG emission estimates ranged from 1.7 to 81 g CO_2-eq/kWh, whereas harmonized estimates comprised a much smaller range of 3.0 to 45 g CO_2-eq/kWh, a decrease of 47% in the total spread of the data. The IQR decreased from 12 to 10 g CO_2-eq/kWh, a 14% reduction. The central tendency remained fairly constant through the harmonization process, with the median value decreasing from 12 to 11 g CO_2-eq/kWh. The change in IQR being considerably less than the change in total range implies that the lowest and highest 25% of the GHG emission estimates were more affected by the harmonization process than the middle 50% of the estimates. Harmonization of capacity factors resulted in a 42% reduction in total range, compared to the 47% reduction resulting from cumulative harmonization of all parameters. This effect implies that variability in assumed capacity factor is the largest contributor—of the harmonization parameters investigated—to variability in published estimates of life cycle GHG emissions of wind power systems.

These findings suggest that the harmonization process, through systematically adjusting estimates to reflect a consistent set of several important parameters, increased the precision of life cycle GHG emission estimates in the literature while having little effect on published central tendency. Figure 5 provides a side-by-side comparison of the published data and the harmonized data, which demonstrates the central tendency and variability of the data.

Overlay plots presenting the progression from published estimates to harmonized estimates showing each successive

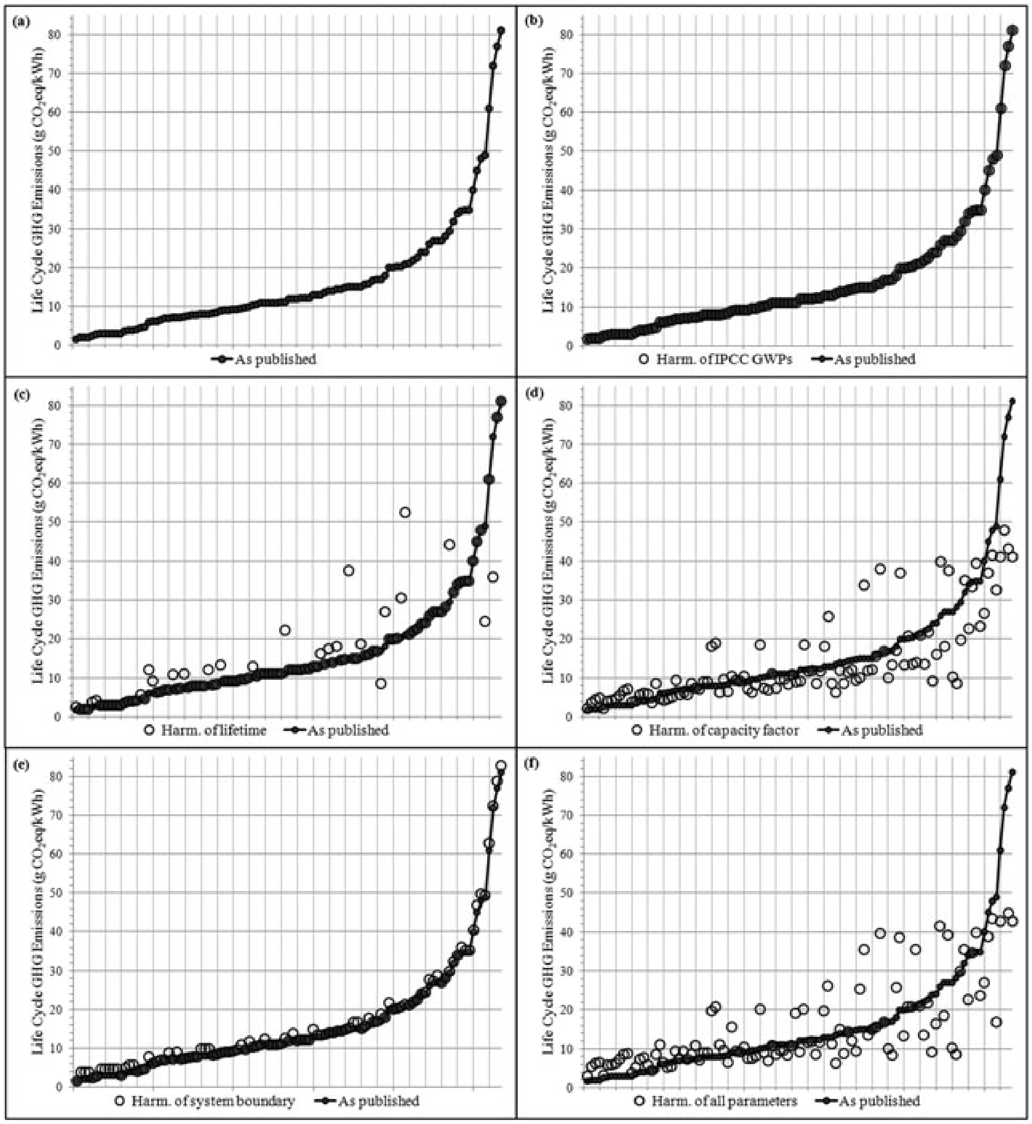

Figure 3 Life cycle greenhouse gas (GHG) emission estimates for onshore wind power from literature passing the screening criteria, ordinally ranked from smallest to largest published value. Frame descriptions: (a) published GHG emission estimates, (b) harmonization of global warming potentials to the most recently published values (Forster et al. 2007), (c) harmonization of operating lifetime to 20 years, (d) harmonization of capacity factor to 30%, (e) harmonization of system boundary to include the ongoing and downstream life cycle stages, and (f) cumulative harmonization of all parameters.

harmonization step (building upon the prior step) are given for onshore and offshore wind on a common set of axes in figures S1 and S2, respectively, in the supporting information on the Web.

Discussion

Comparing Onshore and Offshore

Based on the available literature, the range and IQR for onshore is considerably larger than for offshore, which may reflect the difference in the number of references or might reflect a true wider variability for this class of wind power technologies from range of siting circumstances, turbine size, turbine/wind farm design, and other factors. However, the median life cycle GHG emission estimates for onshore and offshore technology types are both 12 g CO_2-eq/kWh, as published, and 11 g CO_2-eq/kWh after harmonization. This similarity, combined with the tight distribution for both technology types in an absolute sense, suggests that the two technology types may not have significantly different life cycle GHG emissions. However, it should be remembered that these summary statistics reflect the technologies as they are represented in the

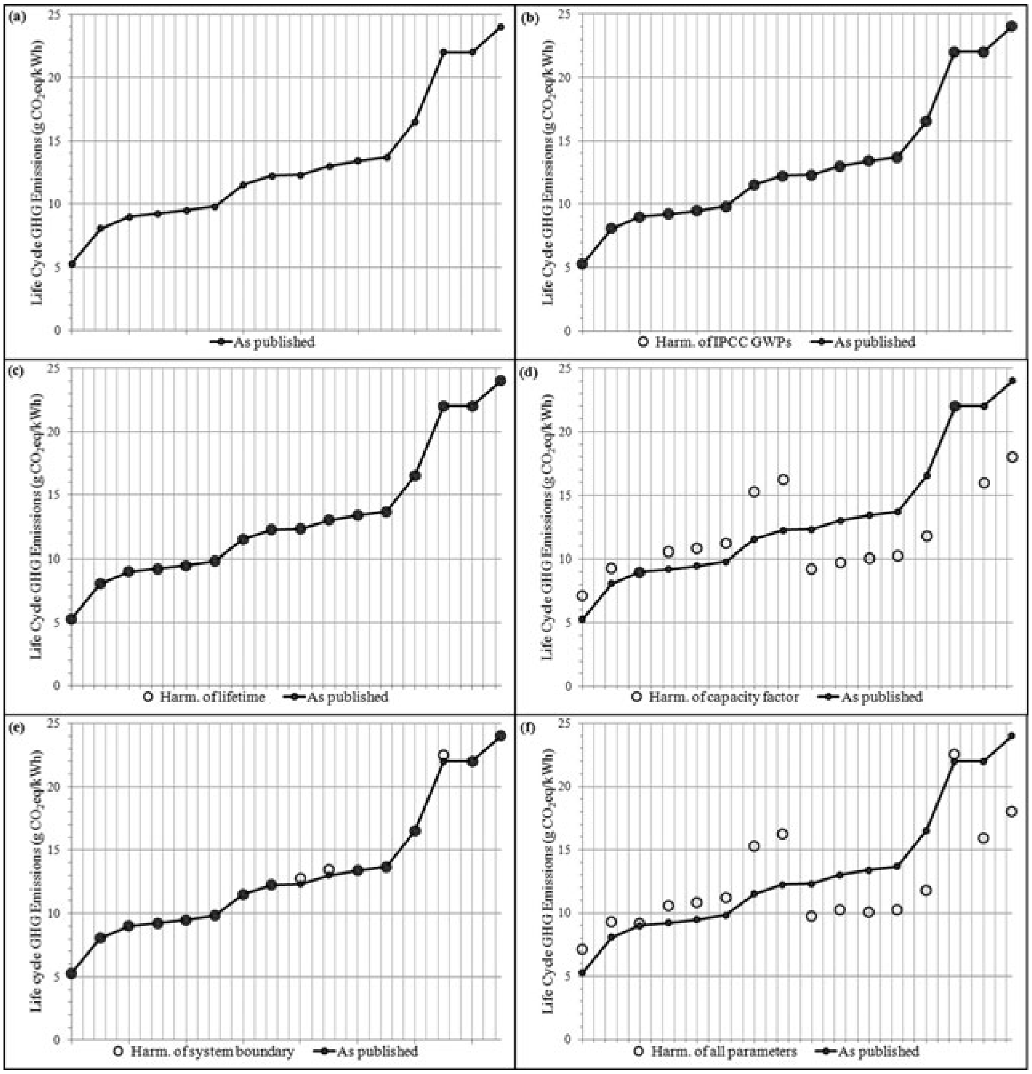

Figure 4 Life cycle greenhouse gas (GHG) emission estimates for offshore wind power from literature passing the screening criteria, ordinally ranked from smallest to largest published value. Frame descriptions: (a) published GHG emission estimates, (b) harmonization of global warming potentials to the most recently published values (Forster et al. 2007), (c) harmonization of operating lifetime to 20 years, (d) harmonization of capacity factor to 40%, (e) harmonization of system boundary to include the ongoing and downstream life cycle stages, and (f) cumulative harmonization of all parameters.

literature and perhaps not the true distribution of deployed technologies.

Limitations of this Analysis

Focus on Life Cycle Greenhouse Gas Emissions

The broad goal of the current phase of the LCA Harmonization Project is to clarify estimates of life cycle GHG emissions and better inform decision making and future analyses, where such estimates would be useful. However, to provide a more comprehensive perspective of the environmental and social impacts of power-generating technologies, other parameters, such as human health impacts, water consumption, and jobs created, should also be assessed.

Pooling Empirical and Theoretical Data

Some practitioners only consider empirical LCAs valid for current technologies because of the potential for modeled estimates to differ from measurements of the same parameter (e.g., Kubiszewski et al. 2010). Table 1 characterizes each study as either empirical or theoretical on balance, despite this characteristic being a continuum rather than a dichotomous choice. (In truth, almost all LCAs have some modeled estimates because empirical data are not always available for every process in the life cycle.) LCAs based on both types of data were included in this analysis. Including studies that are based, at least in important aspects, on parameters not empirically grounded could contribute some additional uncertainty to the results. However, given the similarity of results for GHG emission

Table 2 Summary statistics for each harmonization step, grouping the two system boundary harmonization steps (addition of ongoing and downstream life cycle stages) into one

Statistical measure	*As-published life cycle GHG (g CO_2-eq/kWh)*	*Harmonized by GWPs (g CO_2-eq/kWh)*	*Harmonized by lifetime (g CO_2-eq/kWh)*	*Harmonized by capacity factor (g CO_2-eq/kWh)*	*Harmonized by system boundary (g CO_2-eq/kWh)*	*Harmonized by all (g CO_2-eq/kWh)*
All values						
Mean	16	16	16	14	16	15
SD	14	14	13	10	14	10
Minimum	1.7	1.7	2.0	2.1	1.7	3.0
25th percentile	7.9	7.9	8.1	7.2	8.1	8.5
Median	12	12	12	10	12	11
75th percentile	20	20	21	17	20	18
Maximum	81	81	81	48	83	45
IQR	12	12	13	10	11.6	10
Range (maximum–minimum)	79	79	79	46	81	42
Change in mean (%)[a]	n/a	<1%	3.3%	−12%	3.4%	−5.6%
Change in SD (%)[a]	n/a	<1%	−5.6%	−27%	<1%	−28%
Change in median (%)[a]	n/a	0%	2.0%	−15%	1.5%	−10%
Change in IQR (%)[a]	n/a	0%	11%	−14%	0%	−14%
Change in range (%)[a]	n/a	<1%	<−1%	−42%	2.1%	−47%
Count of estimates[b]	126	6	109	118	82	126
Count of references[b]	49	3	42	44	26	49
Onshore						
Mean	16	16	17	14	17	15
SD	15	15	14	11	15	11
Minimum	1.7	1.7	2.0	2.1	1.7	3.0
25th percentile	7.4	7.4	7.9	7.0	7.9	8.4
Median	12	12	13	9.8	12	11
75th percentile	20	20	22	18	21	20
Maximum	81	81	81	48	83	45
IQR	13	13	14	11	13	11
Range (maximum–minimum)	79	79	79	46	81	42
Change in mean (%)[a]	n/a	<1%	3.5%	−13%	3.8%	−5.7%
Change in SD (%)[a]	n/a	<1%	−5.8%	−27%	<1%	−29%
Change in median (%)[a]	n/a	0%	4.6%	−18%	1.2%	−9.4%
Change in IQR (%)[a]	n/a	0%	12%	−13%	0%	−10%
Change in range (%)[a]	n/a	<1%	<−1%	−42%	2.1%	−47%
Count of estimates[b]	107	5	93	104	74	107
Count of references[b]	44	3	35	41	22	44
Offshore						
Mean	13	13	13	12	13	12
SD	5.2	5.2	5.2	3.9	5.3	3.9
Minimum	5.3	5.3	5.3	7.2	5.3	7.2
25th percentile	9.4	9.4	9.4	9.6	9.4	10
Median	12	12	12	11	13	11
75th percentile	14	14	14	15	14	15
Maximum	24	24	24	22	24	23
IQR	5.0	5.0	5.0	5.8	5.0	5.5
Range (maximum–minimum)	19	19	19	15	19	15
Change in mean (%)[a]	n/a	<1%	<−1%	−7.2%	<1%	−6.4%
Change in SD (%)[a]	n/a	<1%	<1%	−25%	1.2%	−24%
Change in median (%)[a]	n/a	0%	0%	−13%	2.0%	−13%
Change in IQR (%)[a]	n/a	0%	0%	17%	0%	10%
Change in range (%)[a]	n/a	0%	0%	−21%	0%	−18%
Count of estimates[b]	16	1	16	14	8	16
Count of references[b]	12	1	11	10	6	12

Notes: Statistics are reported to two significant digits with the exceptions of changes that are less than 1%, or if there is no change 0% is reported. GHG = greenhouse gas; g CO_2-eq/kWh = grams carbon dioxide equivalent per kilowatt-hour; GWP = global warming potential; SD = standard deviation; IQR = interquartile range.

[a]Percent change statistics were calculated with all references in the category (all values, onshore, or offshore) whether harmonized or not.

[b]Counts of estimates and references for each harmonization step only include the estimates that were harmonized for that step. The counts for the "harmonized by all" column include estimates that were harmonized by at least one parameter.

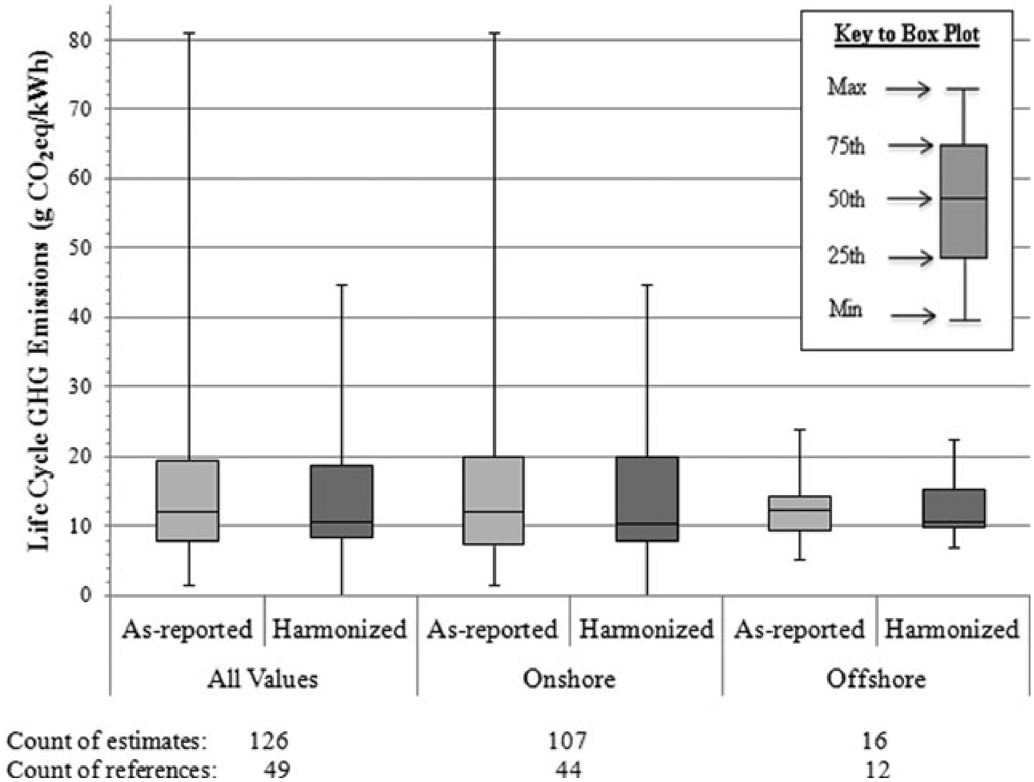

Figure 5 Side-by-side comparison of central tendency and spread of published greenhouse gas (GHG) emission estimates passing our screening criteria and the corresponding harmonized estimates.

estimates of wind power systems between studies characterized as empirical and theoretical, any additional uncertainty from combining the two types of studies is likely insignificant.

Remaining Dimensions of Inconsistency

The light level of harmonization performed for life cycle GHG emission estimates for wind power technologies included harmonizing system boundaries at the level of major life cycle phase, GWPs, system lifetimes, and capacity factors for the pool of estimates that passed the screening criteria. This extent of harmonization was deemed sufficient for reducing variability in published life cycle GHG emission estimates of wind power systems, as the published estimates already comprise a relatively tight dataset. However, additional dimensions of inconsistency across studies are known. Harmonization along these dimensions could potentially further reduce the variability in published estimates. Remaining parameters not harmonized here include upstream electricity mix used in the manufacturing processes (which determines the GHG emission intensity of input electricity); a more detailed system boundary harmonization to account for each individual subprocess that comprises the more general upstream, ongoing, and downstream life cycle stages used in this analysis; harmonization to either include or exclude transmission and distribution infrastructure for all estimates so that individual turbines can more accurately be compared to wind farms; and wind power class. Transmission and distribution losses (typically 5% to 10% of generated electricity) are also excluded, which could increase life cycle GHG emissions by a similar magnitude if the functional unit is chosen as delivered electricity rather than the more common generated electricity. Another effect of harmonization by additional parameters could be to alter the central tendency of life cycle GHG emission estimates, for instance, as has been shown in Lenzen and Wachsmann (2004) and Pehnt (2006) regarding changes to the GHG intensity of background energy systems.

Accuracy of the Central Tendency of Literature Estimates to True Life Cycle Greenhouse Gas Emissions

The literature collected consists solely of attributional LCAs, which evaluate the technology in isolation, with few exceptions such as Pehnt (2006). Consequential LCAs consider impacts to other systems caused by the studied technology. Potential consequential effects not covered in the reviewed literature include changes in consumption owing to changes in the retail price of electricity from the addition of wind power; lowering the GHG intensity of the electrical grid, which reduces embodied GHG emissions of industrial products, including newly manufactured wind turbines; GHG emissions caused by changes in land use to accommodate wind farms; and the combustion-based technologies in the electrical grid having to respond to accommodate the intermittency and nondispatchable nature of wind power. The thermal efficiency of fossil-based power plants is reduced when operated at fluctuating and suboptimal loads to supplement wind power, which may degrade, to a certain extent, the GHG benefits resulting from the addition of wind to the grid. A study conducted by Pehnt and colleagues (2008) reports that a moderate level of wind penetration (12%) would result in efficiency penalties of 3% to 8%, depending on the type of conventional power plant considered. Gross and colleagues (2006) report similar results, with efficiency penalties ranging from nearly 0% to 7% for up to 20% wind penetration. Pehnt and colleagues (2008) conclude that the results of adding offshore wind power in Germany on the background power systems maintaining a level supply to the grid and providing enough reserve capacity amount to adding between 20 and 80 g CO_2-eq/kWh to the life cycle GHG emissions profile of wind power, depending on the various conditions of the energy economy that determine the grid's composition. Thus, considering consequential effects on the background energy system can be significant relative to the attributional life cycle GHG emissions of wind power, as well as for the comparison of wind to other renewable electricity generation technologies (which themselves should be considered on a consequential basis), but should not fundamentally alter the comparison to fossil fuel-based technologies.

Some consequential effects of wind power systems listed above could improve the life cycle GHG emissions profile while others increase it, and all are dependent on specific circumstances of the systems in which wind power is embedded. Thus the answer could change depending on how the question is asked. Therefore the estimates found through this meta-analysis aren't necessarily any more accurate than the underlying LCA literature regarding true (and complete) life cycle GHG emissions, although, for many purposes, knowing the GHG emissions of this technology in isolation, which this study clarifies, could be desirable.

Clustering Bias

This study analyzed 126 distinct life cycle GHG emission estimates of wind power systems. However, these 126 estimates were generated from only 49 different studies and were produced by only 42 different primary authors (not accounting for additional overlap in authors where primary authors were also coauthors of other studies). Thus, there is potential bias in the results of this meta-analysis from clustering, such as multiple scenarios produced within the same study or multiple studies published by the same author(s). In both of these cases, estimates are more likely to be similar to one another than to the rest of the pool of estimates due to commonalities in methods, assumptions, the particular system studied, and data sources. The extent to which these two types of data clustering could cause bias in the results was not quantitatively accounted for or examined. Each of the 126 estimates was treated as independent throughout the analysis. As a result, large clusters within the dataset have potentially caused the summary statistics to be somewhat skewed in their direction. The cluster with the greatest potential to cause bias, due to the largest number of estimates produced from just one study (Lenzen and Wachsmann 2004), generated 25 GHG emission estimates that ranged from 2 to 81 g CO_2-eq/kWh. Given the breadth and even distribution of the range of estimates from this reference, author-based clustering from this study likely does not significantly skew the distribution of results found from harmonization. Other potential clusters in the dataset are considerably smaller in the number of estimates and thus would appear to present a small risk of potential bias.

There is also a third type of clustering bias inherent to LCAs, which is overlap in data sources. LCAs of any one type of system or product that employ common databases or software packages are more likely to have similar results than those using different data sources. The pool of publications that passed the screening criteria contains articles that used common data sources, for example, the Ecoinvent database. One might be able to quantitatively assess the influence of clustering by data source by defining a hierarchical influence tree for each article, statistically evaluating the extent of correlation and then perhaps using the correlation metric to weight the calculation of means. However, because of the large number of data sources for any given LCA, questions of cut-off in modeling data source influence, the subjective nature of assigning a quantitative measure of influence to each source, and other issues such an analysis were beyond the scope of this study. Nevertheless, given the tight distribution of published results, any bias in the distribution is not likely consequential when considering contexts of decision making and comparisons to other electricity generation technologies.

Sample Sizes

Another limitation of this analysis is the relatively small number of offshore wind studies compared to the much larger pool of onshore studies. There were only 12 publications producing 16 life cycle GHG emission estimates for offshore turbines that passed the screens for quality. With such a small dataset, summary statistics can easily be skewed by one or two outlying values. However, the published offshore GHG emission estimates fell within such a tight range that an outlier estimate causing biased results was not a serious concern. Additionally, only one study passing our screens considered deep offshore wind (Weinzettel et al. 2009), so this is a technology for which additional LCA studies are required to be able to assess with any amount of confidence how its life cycle GHG emission profile compares to onshore and shallow offshore wind technologies.

Conclusions

Life cycle GHG emissions of wind-powered electricity generation published since 1980 range from 1.7 to 81 g CO_2-eq/kWh. Although this is already a tight range, upon harmonizing the data to a consistent set of GWPs, system lifetime, capacity factors, and gross system boundary, the range of life cycle GHG emission estimates was reduced by 47%, to 3.0 to 45 g CO_2-eq/kWh. The first and third quartiles stayed relatively constant through the harmonization process, revealing that the middle 50% of the data did not change nearly as much as the lowest 25% and highest 25% of the estimates. The parameter found to have the greatest effect on reducing variability is capacity factor.

The extensive overlap in the distributions of estimates for onshore and offshore technologies suggests that their life cycle GHG emissions may not be notably different. An exception to this may be deep offshore wind technology, for which the literature provided only one estimate. Therefore, with deep offshore wind being a nascent technology on which there is sparse LCA literature to date, as well as a technology that may have considerably different material requirements due to design differences, this may be an area where life cycle GHG emissions of wind power systems have the potential to significantly differ from previously published studies and warrants further investigation.

The harmonization process decreased the variability and increased the precision of the previously published estimates by systematically aligning common system parameters across studies to a consistent set of values. However, improved precision does not imply improved accuracy. There are many consequential effects of deployment of wind power not typically considered in the majority of wind LCAs, which are attributional in nature, and these effects could increase or decrease previously published estimates of life cycle GHG emissions. Another issue is truncation error often inherent in process-based LCAs, which form the majority of LCAs considered in this article. In this respect, the upper end of the range exhibited in this article may be closer to the true life cycle GHG emissions than those estimates at the lower end.

This study ultimately concludes that, given the large number of previously published life cycle GHG emission estimates of wind power systems and their narrow distribution, it is unlikely that new process-based LCAs of similar wind turbine technologies will greatly differ. Additional consequential LCAs would enhance understanding of the true life cycle GHG emissions of wind power, although even those are unlikely to fundamentally change the comparison of wind to other electricity generation sources.

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Notes

1. Results from the whole LCA Harmonization project, including this article, can be visualized and downloaded at http://openei.org/apps/LCA.
2. One gram (g) = 10^{-3} kilograms (kg, SI) ≈ 0.035 ounces (oz). One kilowatt-hour (kWh) ≈ 3.6×10^6 joules (J, SI) ≈ 3.412×10^3 British thermal units (BTU). Carbon dioxide equivalent (CO_2-eq) is a measure for describing the climate-forcing strength of a quantity of greenhouse gases using the functionally equivalent amount of carbon dioxide as the reference.
3. One megawatt (MW) = 10^6 watts (W, SI) = 1 megajoule/second (MJ/s) ≈ 56.91×10^3 British thermal units (BTU)/minute.
4. One megawatt-hour (MWh) ≈ 3.6×10^9 joules (J, SI) ≈ 3.412×10^6 British thermal units (BTU).

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About the Authors

Stacey Dolan was an analyst at the National Renewable Energy Laboratory (NREL) in Golden, Colorado, USA, during the time of this research. **Garvin Heath** is a senior scientist at NREL.

Supporting Information

Additional supporting information may be found in the online version of this article:

Supporting Information S1: The supporting information provides further detail on the screening process, GHG emissions by life cycle and harmonization stage, and rationale for the system boundary harmonization approach.

Please note: Wiley-Blackwell is not responsible for the content or functionality of any supporting information supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

EXHIBIT
19

SNYDERGEOLOGIC

February 1, 2021

Backcountry Against Dumps
c/o Donna Tisdale
PO Box 1275
Boulevard, CA 91905-0375

Re: Groundwater Impacts of the Campo Wind Project with Boulder Brush Facilities in Eastern San Diego County

Dear Ms. Tisdale,

Snyder Geologic was retained by Backcountry Against Dumps ("Backcountry") to provide an independent technical review of the impacts of the Campo Wind Project and associated Boulder Brush facilities (collectively, the "Project") on groundwater. This included (1) reviewing the Draft ("DEIS") and Final Environmental Impact Statements ("FEIS") for the Project, which were prepared by Dudek and published by the United States Bureau of Indian Affairs ("BIA"), and (2) conducting site investigations in the areas surrounding the Project site. My review and conclusions are presented below, as well as in my July 5, 2019 report on the DEIS and my March 9, 2020 report on the FEIS, which were respectively submitted to the Bureau of Indian Affairs as attachments to the July 8, 2019 and March 11, 2020 comment letters of the Law Offices of Stephan C. Volker on behalf of Backcountry. In summary, I conclude that the Project presents significant hydrological risks and impacts that were not acknowledged in the environmental review documents for the Project.

BACKGROUND AND SUMMARY

I am the Principal of Snyder Geologic, Inc., a groundwater and environmental services consulting firm headquartered in La Jolla and specializing in investigating, analyzing and resolving complex issues involving geology, hydrology and hydrogeology. I am a California-registered Professional Geologist and Certified Hydrogeologist with 26 years of experience managing and providing technical oversight of environmental due diligence, site characterization, remediation, storm water monitoring, and resource development and protection services. I am also a California Qualified Storm Water Pollution Prevention Plan (SWPPP) Developer /Practitioner.

I have knowledge of groundwater conditions in the rural areas of eastern San Diego County based on 10 years of investigations into those conditions on behalf of numerous clients. As part of my review of the Project, I examined groundwater records from many independent sources documenting groundwater conditions in the vicinity of the Project as well as investigations conducted by other reputable geologists and hydrogeologists in connection with public and agency reviews of other major projects, including several solar and wind energy projects, that have been proposed or built in the East County area. I also reviewed the Groundwater Resource Evaluation ("GRE") prepared by Dudek which became Appendix F of the DEIS, along with the pertinent portions of the DEIS that related in any way to groundwater conditions in the Project Area and the Project's impacts on them. After completing my analysis I prepared a report dated July 5, 2019 which I transmitted to Backcountry for submission to BIA and other agencies to inform their review of the Project. My report found significant errors and omissions in the GRE, many of which tended to understate the Project's likely impacts on groundwater resources, in several cases to a significant degree.

Based on my findings and my subsequent review of the FEIS, I conclude that the GRE, DEIS and FEIS are incomplete and understate the Project's groundwater impacts, and that the Project is likely to cause significant adverse impacts on groundwater resources in the vicinity of the Project, and thereby harm surrounding residential and other existing and permissible groundwater uses.

ANALYSIS

The GRE prepared by Dudek as Appendix F to the DEIS understates the Project's likely impacts on groundwater resources in five principal respects. I discuss each of these errors below.

The GRE understates existing groundwater demand.

The GRE's first principal error is that it understates the existing groundwater demand in the Project Area. The GRE states that current demand on the groundwater basin is 6% of the groundwater in storage, or about 185.4 acre-feet per year (AFY). GRE, pp. 15-17, 26. However, this estimate is based on two mistaken assumptions, and each of them likely understates the actual or potential groundwater consumption.

The GRE's first mistaken assumption is that it assumes that existing residential demand for groundwater is 0.5 AFY per residential property. While this consumption rate may represent a common water use for a typical American family on a standard-sized lot in an urban area, it grossly underestimates the actual present and potential future water use for many of the landowners in the Project Area, for three reasons. First, many of their properties are much larger than a standard-sized lot, as they may range from several acres to over 100 acres in size. Second, many of these properties have agricultural uses, including both farming and grazing, that have a much greater demand for groundwater than a standard suburban household. Third, the area is semiarid, ranging from 10.8 to 17.0 inches of rain per year, and thus it has a greater need for summer irrigation than the average American residential use.

The GRE's second mistaken assumption is that historic use limits future demand. Many of the properties in the area have been underutilized in the past, and will increase their groundwater use in the future as population in the area continues to grow and vacant lots are built upon. For each of these reasons, actual residential demand for groundwater is growing, and it is already much greater than the GRE assumes.

The GRE understates the Project's groundwater demand.

The GRE's second principal error is that it understates the Project's groundwater demand in the first year by averaging groundwater demand over a 5-year period. Construction of the Project will take an estimated 14 months, and require an estimated 123 acre-feet of water on the Campo Reservation, and an additional 50 acre-feet of water off the Reservation during construction of the Boulder Brush facilities, for a total of 173 acre feet. GRE, p. 17. Operation is estimated to consume about 0.25 acre-feet per year. GRE, p. 17. But in assessing the severity of the Project's impacts on groundwater, the GRE averaged the estimated 173 acre-feet of water use during the 14-month construction phase over a 5-year period, and therefore concluded that the Project's "groundwater drawdown at off-site wells is within the limits set by the County of San Diego Standards of Significance." GRE, pp. 27-28.

Averaging the Project's groundwater pumping over 5 years understates the impact of the Project's impact on groundwater during the construction phase. For example, according to the GRE, the estimated drawdown after one year is up to 31 feet (depending on which of three alternate water impact scenarios is selected), which is more than 50 percent greater than the largest projected drawdown by the GRE – 19 feet – if the construction-phase water use is averaged over 5 years. GRE, p. 28. The GRE ignores the short-term impact of the very significant drawdown during the first 14 months on landowners whose wells might be rendered inoperable during the 14-month construction period. Also, the impacts of this initial drawdown would not end after 14 months. Instead, they would continue for many months and potentially years thereafter, depending on rainfall and competing uses for the groundwater during this time.

The GRE omits or misapplies principles of hydrogeological analysis

The GRE's third principal error is that it understates the Project's impacts on groundwater by omitting disclosure of key variables or misapplying key principles of hydrogeological analysis. I provide four examples. The first concerns Dudek's calculation of the drawdown experienced in off-site wells during pumping for previous energy projects. Dudek made this calculation to estimate the Project's likely drawdown impacts. To perform this calculation, Dudek had to select a pumping rate – variable "Q" in its drawdown formula. GRE, p. 27. However, Dudek never disclosed the value assigned to this critical variable anywhere in its GRE. As a result, it is impossible to independently verify the validity of Dudek's calculation of the drawdown for all three of its calculated scenarios–Tierra del Sol, Border Patrol Well 2, and Border Patrol Well 3. Dudek's failure to disclose this omitted pumping rate raises the possibility that it used a rate that would understate the impacts of pumping groundwater for the Project.

The second example concerns Dudek's application of the formula for determining the transmissivity (variable "T") of the groundwater basin as necessary to determine the likelihood and severity of drawdown and its impacts. In explaining this equation, Dudek provides a definition of "T" in *gallons per day per foot*. GRE, p. 28 and Table 4-2. However, Dudek presents the transmissivity for each of the three pumping scenarios in *square feet per day*. If Dudek actually used the formula stated in its GRE, then it would have to apply the definition stated in its formula in order to perform the calculation. Simply put, the definition of this variable must be the same in both the equation and in Dudek's application of the equation. Dudek's failure to apply the definition stated in its equation raises the possibility that it used a definition of transmissivity that understates the groundwater impacts of the Project.

The third example concerns Dudek's application of the variable known as storativity, or "S," in calculating the capacity of the water-bearing strata to store and deliver groundwater. Dudek calculated the storativity of the relevant groundwater sources for each of the three nearest off-site wells whose past drawdowns during pumping for large projects might best mimic the groundwater drawdowns caused by the Project–the Tierra del Sol Well, Border Patrol Well 2, and Border Patrol Well 3. For the Tierra del Sol Well, Dudek used a relatively high storativity value of 0.001. Use of a *higher* S value results in a *lower* predicted drawdown, as having greater storage volume means that a given rate of pumping causes less drawdown of the water table. Using this high S value resulted in a projected residual drawdown of 19 feet after 5 years, just one foot less than the criterion of 20 feet adopted by San Diego County in its Groundwater Ordinance and Guidelines for Determining Significance as the threshold for a significant impact on groundwater resources. GRE, p. 28 and Table 4-2. Dudek's selection of this high S value – resulting in a reduced drawdown projection – appears to be arbitrary. Given that the transmissivity for the Tierra del Sol Well was 75 percent *lower* than the transmissivities for the two Border Patrol wells, it would seem appropriate to select a storativity value that is also proportionately *lower* than the Border Patrol wells (i.e., 0.00012 to 0.00019). Had Dudek used the two storativity values from the Border Patrol wells (0.00074 and 0.00048), the resulting drawdowns after 5 years would be 21.89 and 26.25 feet, respectively. Both of these calculated drawdowns exceed the County's significance threshold of 20 feet.

The fourth example is related to the third. In using a high S value in its calculation of the Project's groundwater impacts for the Tierra del Sol Well scenario, Dudek also overlooked its own calculation of the deep groundwater storage in the relevant basin. Dudek had calculated a groundwater storage value for the Project Area's fractured bedrock water-bearing zone of 0.0005. GRE, pp. 25-26 and Table 4-1 (note that "0.05%" is equivalent to 0.0005). Had Dudek used the storage value that Dudek itself had used in calculating the deep groundwater storage in the fractured bedrock basin, 0.0005, the drawdown after 5 years of the nearest off-site well under the Tierra del Sol Well scenario would have been 25.84 feet. This drawdown exceeds the County's threshold of significance by nearly six feet.

It appears from these facts that Dudek's selection of an S value for the Tierra del Sol Well scenario that was substantially higher than the S values used for the other two off-site well scenarios – and substantially higher than the S value Dudek had calculated for the deep groundwater-bearing fractured bedrock in this basin – had the foreseeable effect of reducing –

and thereby understating – the predicted drawdown for the Tierra del Sol Well scenario below the County's significance threshold. By doing so, Dudek understated the true, significant, impact of the Project on groundwater.

The GRE ignores the impact of past groundwater use by the ECO Substation Project

The GRE's fourth principal error is that its text ignores the impact on the Reservation's southern well field of past off-site groundwater use by the East County ("ECO") Substation Project. The Reservation's southern well field will presumably be the source of the Project's water. The ECO Substation Project was constructed in late 2013 several miles east of the Project Area. The impacts of its water use during construction are plainly relevant in determining the likely impact of the Project's construction water use on the Reservation's southern well field. The GRE mentions the ECO Substation Project only in passing, noting that its groundwater pumping used 36.44 acre-feet during its construction over a three and one-half month period from late July to early November, 2013. GRE, p. 16. But the GRE says nothing about this project's groundwater impacts on the Reservation's southern well field.

Instead, the GRE completely ignores those impacts. Indeed, it leaves the reader with the impression that there have never been any such impacts. It states that the Reservation's southern well field has shown "no evidence of pumping or declines in groundwater levels observed during the period of January 2014 to August 2018 (Appendix A)." GRE, pp. 16-17. It omits any mention of the severe impacts of the ECO Substation Project's groundwater use on this well field that occurred *immediately prior* to this January 2014 to August 2018 period, from July 2013 to November 2013. This omission is questionable, since Dudek knew about those severe impacts which are shown in its own Appendix A to the GRE.

Unmentioned in its text, the GRE includes in its Appendix A several hydrographs showing water levels in four on-site wells (PG1, PD2, PD3 and PD4) in the Reservation's southern well field during the period when the ECO Substation Project was constructed in late 2013. GRE, Appendix A. One of the purposes of the EIS and its GRE is to evaluate the Project's potential impacts on groundwater. These hydrographs are highly relevant to this purpose. They show a substantial impact on the Reservation's groundwater levels. During construction of the ECO Substation Project, the water level in well PD1 dropped at least 200 feet, from an elevation of about 3,510 feet to an elevation of about 3,310 feet. GRE, Appendix A, Supply Well PD1, Hydrographs of Manual Soundings. During this same period, the water level in well PD2 dropped about 145 feet, from an elevation of about 3,475 feet to an elevation of about 3,330 feet. GRE, Appendix A, Supply Well PD2, Hydrographs of Manual Soundings. The water level in well PD3 dropped about 165 feet, from an elevation of about 3,455 to an elevation of about 3,290. GRE, Appendix A, Supply Well PD3, Hydrographs of Manual Soundings. The water level in well PD4 likewise dropped about 165 feet, from an elevation of about 3,485 feet to an elevation of about 3,320 feet. GRE, Appendix A, Supply Well PD4, Hydrographs of Manual Soundings.

The sharp drawdown which occurred in the Reservation's southern well field due to construction of the ECO Substation Project in late 2013 is informative. This impact should have been examined in detail in the GRE and the EIS. This dramatic drop in groundwater elevations shows that the groundwater basin that the Project will pump – a basin shared by hundreds of neighboring landowners in the rural communities of Campo, Live Oak Springs and Boulevard – is extremely vulnerable to even modest volumes of groundwater pumping. The ECO Substation Project drew just 36.44 acre-feet, over a three and one-half month period. Yet it caused the Reservation's southern well field to experience an extreme drop in water elevations, possibly extending below the reach of some of the Reservation's pumps.

The Project's construction water demands, by contrast, are far greater than those of the ECO Substation Project. They are projected to "last roughly 14 months and . . . require an estimated 123 acre-feet of water on the Campo Reservation." GRE, p. 17. This means that they could easily cause wells in these neighboring rural communities to go dry. And, since these communities have no other source of potable water, the potential impact on them from the Project's groundwater pumping would be extremely deleterious to their health, safety and wellbeing.

The GRE failed to examine the drawdown impacts of using on-site wells

The GRE's fifth principal error is that it failed to examine the drawdown impacts of using the closest, on-site wells for the Project. In fact, no wells were tested at all for this analysis. The GRE omitted any discussion of the impacts of using the 19 existing on-site wells on the Reservation that are available to Terra-Gen for the Project. GRE, pp. 19-20. These wells are located on the Reservation's southern well field, and are closer to the Project than any of the off-site wells that were considered. No reason was given for ignoring these obvious alternatives for supplying groundwater for the Project. Since it appears that use of these wells is feasible, the impacts of doing so should have been examined. As a consequence of Dudek's failure to consider the impact of using these wells, the impacts of using the Reservation's on-site wells to supply water for the Project are unknown.

If in fact the Reservation's southern well field is going to be used to supply water for the Project, then the GRE's failure to directly examine and calculate the Project's likely impacts on groundwater levels by disclosing, analyzing and reporting the southern well field's pertinent hydrological parameters, including well construction details, anticipated pumping rates, drawdown, and underlying hydrogeologic conditions, is not acceptable hydrogeologic practice. It is contrary to principles of hydrogeological analysis. Those principles require the hydrogeologist charged with evaluating the groundwater impacts of a project to conduct a thorough examination of the actual well field the Project will use. From a professional perspective, this unexplained omission does not meet the standard of care and is unacceptable.

PROFESSIONAL OPINION AND CONCLUSION

Based on the foregoing analysis, I have formed the professional opinion that the Project's DEIS and FEIS and their Appendix F, Groundwater Resource Evaluation (GRE), are incomplete and deficient in the numerous specific respects I have identified above. They fail to accurately and completely disclose, discuss and assess the Project's potential adverse impacts on groundwater and the surrounding landowners and residents who depend on that groundwater for their domestic, agricultural, commercial, industrial and recreational needs. It is my further professional opinion that the proposed construction and operation of the Project pose a significant and unacceptable risk to the groundwater resources of the Project Area and the surrounding lands, and to the neighboring communities that depend on this essential resource.

Respectfully submitted,
SNYDER GEOLOGIC, INC.

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