MASSACHUSETTS STUDY ON WIND TURBINE ACOUSTICS

REPORT

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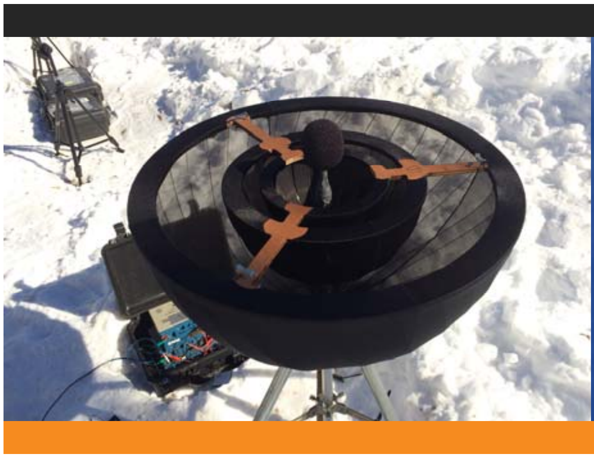

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MASSACHUSETTS CLEAN ENERGY CENTER AND
DEPARTMENT OF ENVIRONMENTAL PROTECTION

SUBMITTED BY:

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1.0 EXECUTIVE SUMMARY

In the fall of 2012, the Massachusetts Clean Energy Center (MassCEC), in partnership with the Massachusetts Department of Environmental Protection (MassDEP), launched the Research Study on Wind Turbine Acoustics (RSOWTA) to advance the understanding of wind turbine acoustics, taking into account the influence of variables such as turbine size, technology, wind speed, topography, and distance from the turbine. The study will provide a quantitative basis for testing noise evaluation and modeling methodologies and improve wind turbine siting and approval processes. This report describes the methods and findings of the RSOWTA.

In the fall of 2013, as a first step in the process of incorporating the latest research on wind turbine acoustics into policy and regulations, MassDEP formed a Wind Turbine Technical Advisory Group (WNTAG), made up of representatives with technical expertise in wind turbine acoustics and who offer a range of perspectives. The WNTAG provides technical advice to MassDEP on how best to craft effective regulatory and policy responses to wind turbine installations and to possible noise impacts. Members of the group are listed at the WNTAG website. To inform ongoing WNTAG discussions, two interim reports of preliminary RSOWTA findings were shared with the WNTAG:

- **Amplitude Modulation.** The first interim report (October 17, 2013) uses some of the data collected to evaluate the spectral and temporal characteristics of amplitude modulation with turbines operating and in ambient conditions. The report includes a discussion on how sound meter settings and sampling rates affect the levels reported for wind turbine and ambient sound.
- **Sound Modeling and Monitoring.** The second interim report (February 26, 2014) focuses on a comparison of sound levels from operating wind turbines with calculations from sound propagation models to help inform and synchronize the pre-construction estimates of wind turbine noise impacts with post-construction monitoring.

This final report provides additional information on the topics addressed in the interim reports and addresses the following additional topics: low frequency sound and infrasound, tonality, meteorological data, and standards analysis.

1.1 | INTRODUCTION AND KEY TERMS

Section 2 of this report provides an introduction covering the scope of the project and general background information; Section 3 provides a technical introduction to key acoustical terms and concepts used in the report.

1.2 | METHODOLOGY (SECTION 4)

Section 4 of this report details the general methodology of the study. The study involves collection and analysis of acoustical, meteorological and operational data from five operating wind-power facilities in Massachusetts and other New England states. Each of the five facilities fully cooperated with the study, allowing periodic shutdowns for background measurements, access to property, and provision of turbine operating data.

Sound level monitoring was conducted at these sites during the winter, spring, and summer of 2013, and winter of 2014. All of the sites were located in New England with terrain similar to that found in

Massachusetts. Four sites were relatively flat with either one or two operating wind turbines at 1.5 MW or greater, with hub heights at approximately 80 meters. One site was in a mountainous area that had multiple turbines along a ridge. In this case, the monitoring positions were situated toward the end of the turbine string. Long-term monitoring (approximately 14 days) was conducted at three to six locations at each site. Short-term attended monitoring (20 to 30 minutes during the day and night) was conducted at each of the long-term monitoring locations and at supplemental locations.

Acoustical data were collected using standard industry instrumentation and methodologies. Meteorological towers and LIDAR measurements were used to collect concurrent meteorological data. Acoustical sampling generally occurred at locations approximately 330, 660 and 990 meters downwind from the turbine under study. Sampling also occurred at one or two locations per site in the upwind and crosswind orientations, relative to the prevailing wind direction. Four sites had turbine operational data reported via their SCADA (supervisory control and data acquisition) system.

With the completion of the RSOWTA, approximately 145 million sound level data records were collected at 23 locations. Researchers collected more than 300 observed and calculated variables, including spectral sound levels in the audible and infrasound range, meteorological data from 1 meter to 200 meters in height, and turbine data.

Turbines were shut down 187 times, for 10 to 30 minutes at a time, to allow for direct comparisons between background and wind turbine sounds. This allowed researchers to evaluate the behavior of various sound level metrics and to assess their suitability for use in a potential regulatory standard.

Acoustical data were collected using “A”, “C”, and “Z” frequency weighting standards. A-weighted sound is the most commonly used metric in environmental noise regulation, because it represents what humans typically hear. Therefore, A-weighted acoustical data is the primary focus of this report. However, un-weighted frequency band data and other weightings are also presented.

1.3 | SOUND LEVEL METRICS AND FREQUENCY SPECTRA (SECTION 5)

Section 5 of the report describes and evaluates sound level metrics used to measure wind turbine sound and reports on the frequency spectra of wind turbines based on the long-term continuous sound monitoring data. The different metrics evaluated include sound level meter response times (fast, slow, impulse), averaging times (e.g., instantaneous, one-second, five-minute, one-hour), weightings (A, C, and Z), and statistical metrics (e.g., Leq, L_{90}, L_{50}, and L_{10}).

The goal in this section is to identify the most useful metrics for describing wind turbine sound. A particular focus is analysis of data around turbine shutdowns. By comparing turbine-on to turbine-off sound levels, and by looking at the variability of those levels across the turbine-on and turbine-off time periods, we can find those metrics that change the greatest between turbine-on and –off. A change indicates the presence of turbine sound. During the turbine-on measurement, a low variability in sound levels over time shows a lower influence of background noise. The combination of a noticeable change in sound level and low influence of background noise improves repeatability and predictability of wind turbine measurements.

The results of the analysis show that of the shutdowns at the flat sites, approximately 8% of the locations had discernible changes in the A-weighted sound level. Locations downwind relative to the prevailing wind direction had the most discernible shutdowns (18% at 330 meters) and upwind sites had the least discernible

(8% at 330 meters). Beyond 330 meters, none of the crosswind or upwind sites had discernible shutdowns. At the multi-turbine mountain site, all monitoring locations were approximately 660 meters away from the turbines. In all, 49% of these shutdowns were clearly discernible, with the most in the upwind and downwind locations.

In screening the data to focus evaluation on time periods around these discernible shutdowns, the key conclusions from this section include:

- The most predictable and stable metrics for wind turbine unattended monitoring tend to be the L_{min} and L_{90}, followed by the Leq, while the five-minute L_{90} of the A-weighted LFmax is about 2 dB lower than the Leq in the prevailing crosswind and downwind directions, but about the same in the upwind direction
- While the C- and Z-weighted sound levels are a good indicator of wind turbine sound, they would be poorly correlated with human audibility at the sound levels present around wind turbine sound. If low frequency sound is of interest for regulatory purposes, then 1/3-octave or 1/1-octave low-frequency limits would be more appropriate.
- The measured background sound is highly variable over time and location, even using the L90 metric. This points to difficulty in accurately predicting what the background level will be at any time in the future, and at every location around a wind project during pre-construction assessments.
- The relationship between wind speed and L_{90} ranges from 0.9 to 1.2 dB per meter/second depending on the site.
- The spectral shape of wind turbine noise is generally consistent among the different turbines measured in the study. Some turbines have unique signatures due to breakout noise from mechanical equipment in the nacelle, and others do not. The audible portion of the wind turbine sound spectrum, assessed by comparing the spectrum levels to the ISO-389-7 standard, ranges at the lower frequencies from about 50 to 80 Hz to the higher frequencies around 6,300 Hz to 8,000 Hz.

1.4 | SOUND PROPAGATION MODELING (SECTION 6)

Section 6 addresses the question of which factors influence the level of wind turbine sound at a receptor and the accuracy of engineering methods used to predict it.

The section begins with an assessment of how various turbine and meteorological factors effect measured sound levels, by comparing these parameters in a linear regression model.

This is followed by an evaluation of how well several sound propagation models predict measured sound levels during periods when wind turbine sounds are relatively prominent and the influence of background sounds is small. For each model, the influence of various parameters, such as wind speed and ground hardness, is evaluated. Key results and conclusions from this section include:

- The biggest drivers of A-weighted sound from wind turbines are wind speed, the number of turbines, and distance. These are also the factors used in the existing MassCEC preconstruction assessment methodology.
- Vertical wind speed, 30-second turbulence intensity, wind direction, standard deviation of wind direction, and veer each appear to have a smaller effect on sound levels at a specific location.

This does not mean that the turbine sound levels are the same regardless of the wind direction and turbulence intensity, for example, but that their impact is relatively small (generally less than 1 dB) compared to distance, the number of turbines, and the influence of wind speed on the sound emissions of the wind turbine.

- When implemented correctly, different modeling methods can provide reasonably accurate or conservative assessments of future sound levels, though variation in actual sound levels will always occur.
- The two main engineering prediction models evaluated here are the International Standards Organization (ISO) 9613 and European Harmonoise. The models using ISO 9613 with hard ground (G=0) and Harmonoise are the most conservative, with none of the monitored five-minute Leq sound levels exceeding the maximum modeled sound level.
- Researchers compared the modeling results with sound monitoring under various metrics and averaging times. Modeling was most conservative when comparing to L_{90} measured sound levels. When comparing to the measured five-minute Leq, the ISO 9613 model with mixed ground and a 2 dB penalty (G=0.5 plus 2 dB) showed the greatest precision for receivers at 330 meters downwind. Longer averaging times (15 minutes and one hour) increased the modeling precision. Over all flat locations, ISO 9613 modeling with hard ground (G=0) was the most precise.
- Modeled comparisons with L_{max} were not made because there was no way to subtract background from L_{max} during unattended modeling. However, we expect less precision and a greater likelihood of the monitored L_{max} sound levels exceeding the modeled sound levels compared with the other tested metrics.
- If turbine shutdowns are used for compliance monitoring, turbine-on monitoring should commence at least two to three minutes after the turbine-startup to allow the blade pitch to optimize to the wind speed and avoid artificially high sound levels created by the monitoring protocol. This is especially important when monitoring under moderate or high wind conditions because wind turbines do not normally re-start under those conditions; rather they would already be operating.
- After removing the higher sound levels relating to startup, the flat site and mountainous multi-turbine sites yielded similar modeling accuracy and precision. No difference in modeling protocol are recommended for flat and mountain sites.
- Factors that reduce model accuracy include:
  (1) Modeling shorter time periods;
  (2) Modeling specific meteorological conditions;
  (3) Modeling that includes the prediction of or dependence on background sound levels.

1.5 | AMPLITUDE MODULATION (SECTION 7)

Amplitude modulation is a recurring periodic change in sound levels over time. Amplitude modulated sound from a wind turbine is typically broadband, where the modulated sound comes from interactions of the blade with the atmosphere, turbulence, directionality of the broadband sound of the blades, or tower interaction with the wake of the blade. In this section, the study explores questions related to the best way to measure amplitude modulation in the presence of background sound, the frequency with which it occurs and its causes.

It is useful to quantify the amplitude modulation depth, or the difference in level between the maximum and minimum sound level in one cycle, as higher modulation depths can be more annoying to people. The researchers evaluated modulation depth using data collected at rates of between 50 ms and 125 ms, depending on location. Since these wind turbines had a blade passes every 1.2 to 2.0 seconds, depending on wind speed, this logging rate allowed a clear identification of modulated patterns when present.

The section starts by introducing new methods for isolating amplitude modulated sound from other sounds. It includes a number of graphs and figures that identify amplitude modulation and address possible causes. Key results and conclusions from this section include:

- The technique of calculating a spectrogram from A-weighted sound levels and one-third octave band levels is very effective in finding the signature of amplitude-modulated wind turbine noise, even when the levels produced by the wind turbines are quite low and comparable to the background noise.
- This new technique is effective at isolating frequency-specific amplitude modulated sounds from background. Our analysis of data at three monitoring locations showed clear differences in modulation depth between background and turbine sounds. We found amplitude-modulated sounds in the mid-frequency range of about 250 Hz to 2 kHz, but did not find notable amplitude modulation in infrasonic, low, and high frequencies.
- For the flat sites, 91% of the modulation is of 2 dB or less. At the mountain site, 88% of the modulation is of 2 dB or less. Going higher in modulation depth, for the flat sites, 99.87% of the modulation is of 4.5 dB or less. At the mountain site, 99.996% is of 4.5 dB or less. Higher modulation events do occur, but they are rare. Of the 105,907 10-second readings, fewer than 300 had modulation depths of 4 dB or greater.
- While larger modulation events over 4.5 dB can and do occur on the flat locations, these events occur less than 0.13% of the time. They are less common at the mountainous site (0.004%) likely because the multiple turbines at this site turn asynchronously which tends to cancel out modulation events
- For short-duration amplitude modulation events (10-second averages), the measured sound level, wind speed, and distance to turbine appear to have the greatest impact on modulation. Modulation depth is reduced with an increase in masking background sounds.

1.6 | LOW-FREQUENCY SOUND AND INFRASOUND (SECTION 8)

The standard definition of Infrasound is sound of a frequency that is below the range of human hearing at nominal levels, generally below 20 Hz. Most measurements from this study included infrasonic frequencies down to approximately 6 to 12.5 Hz. Researchers expanded infrasound measurements down to 0.4 Hz, discussed in this section, at two locations with different topology. Researchers collected simultaneous outdoor and indoor measurements at both locations to evaluate the extent of transmission of infrasound through buildings. Researchers used specialized equipment, described in the text, to measure this infrasound.

The intent of the infrasound monitoring was to identify the spectral shape of the wind turbines in the infrasonic range, and to compare the measured levels to both the background levels when the turbines were shut off and to ISO 7196 and other audibility metrics. In addition, by correlating the infrasound levels to concurrent metrological conditions, the factors that contribute to wind turbine and background infrasound were estimated.

Key results and conclusions from this section include:

- Wind turbines increase infrasound levels, especially at higher wind speeds. However, the resulting levels are, at the least, 25 dB below ISO 7196 audible perception thresholds, and the difference between measured infrasound levels and the audibility threshold increases as frequency decreases.
- The only time infrasound was close to the ISO 7196 audibility threshold with the turbine on was when the study team was present at the site, where their activity created the infrasound.
- The outside-to-inside noise reduction was measured as the difference in sound level from outside the house to inside of it while the turbines were on. The flat site showed a small increase in sound in the house compared with the outside below 1.6 Hz; whereas, the mountain site showed a small increase between 2.5 and 8 Hz. these increases may be due to structural resonances induced either by wind or sound. At frequencies above this, through 25 Hz, the noise reduction is less than 15 dB.
- Above 25 Hz, the noise reduction varied from 8 to 20 dB. This latter higher frequency attenuation is lower than that cited in the literature. This may be due to particularities of construction (see text) and/or the fact that the sound levels inside and outside the homes are too low at these frequencies to give accurate outside-to-inside differences.

1.7 | TONALITY (SECTION 9)

A pure tone is one where specific frequencies of sound can be readily observed. Detection of tones is important as tonal sound is more annoying than sound with no obvious tones (broadband). Section 9 resolves questions relating to the types of procedures that can be used to assess tonality, and how often the turbines were considered tonal using those methods.

The tonal noise evaluation was conducted using the data around shutdowns where there was a discernible difference in the A-weighted sound levels between turbine-on and turbine-off. Analyses were done on 1/1 and 1/3-octave band sound levels. Methodologies using narrow band frequency spectra were discussed but not evaluated.

The following summarize the key results and conclusions:

- Tonality is best determined as a function of frequency, as this corresponds to the behavior of human hearing. Tonality procedures using 1 to 2 Hz bandwidths (i.e. narrowband) are best at assessing the existence of pure tones, followed by 1/3-octave bands and then 1/1 octave bands. However, narrowband analyses require specialized equipment and training.
- For regulatory use, balancing accuracy with ability to implement the method in the field, the 1/3-octave band method of ANSI S12.9 Part 4 is recommended.
- Using this method, none of the locations around the discernible shutdowns exhibited tonal sounds from the wind turbines.

1.8 | METEOROLOGICAL DATA (SECTION 10)

Section 10 describes meteorological data collected at the turbine sites, including the relationship between variables such as wind speed and wind shear. Key conclusions from this section include:

- The research found that wind shear decreased with wind speed and increased during nighttime, which is typical for sites in the northeastern U.S.
- Modeling is less precise at lower wind speeds. This may be due, in part, to certain meteorological effects. For example, wind shear and turbulence tend to be higher at lower wind speeds. Wind speed dispersion (standard deviation) is higher at lower wind speeds, which would affect the variability in measured sound levels. When measuring the Leq over a five-minute period, if the wind speed varies considerably, the Leq will be more heavily influenced by events occurring at the higher wind speeds than the median wind speed.
- Comparison of measured and extrapolated wind speed for 80 meters above ground using data from the 10-meter meteorological tower, 80-meter LIDAR, and nacelle anemometer shows the greatest wind speed using LIDAR, and high variability using extrapolations from the 10-meter anemometer. Differences between the nacelle and LIDAR average wind speed ranged from 0.3 m/s to 1.1 m/s. This is not unusual, and points out the greater reliability of direct LIDAR measurement.

1.9 | STANDARDS ANALYSIS (SECTION 11)

Section 11 discusses questions related to the implementation of regulatory sound metrics, focusing on short-term attended monitoring.

The study suggests four criteria to evaluate the appropriateness of a sound metric for use in regulation: relevance, repeatability, predictability and ease of implementation. The use of attended monitoring to ensure that measurements are not contaminated by sound sources other than wind turbines is discussed. Seven possible metrics with which to measure sound levels of wind turbines during operation are analyzed. The report does not endorse a particular metric for use in regulation.

At each location, sound levels were measured for 15 to 30 minutes during a daytime and nighttime session. At the same time, an attendant, using a custom-programmed tablet computer, recorded their observation on the relative level (high/medium/low) of the different types of sound they observed over time. In this way, we could determine whether and when wind turbine sound was dominant, and what the sound levels were during these periods. Seven metrics were evaluated using combinations of averaging times (5 to 15 minutes), metrics (L_{Smax}, L_{90} of one-second L_{Fmax}, and Leq), and adjustments (for wind speed and for background sound level). Averages and standard deviations of sound levels during the turbine-on and turbine-off period were compared. Generally, lower standard deviations were favored, but consideration was given to the predictability of the metric when doing pre-construction modeling.

Some of the key findings are as follows:

- Metrics using the L_{max} for wind turbine sound had the greatest difference between background sound and wind turbine sound. Metrics using the L_{90}, including the L_{90} of the $L_{Fmax\ (1\text{-}sec)}$ tended to have the lowest difference between the background and wind turbine sound level. Metrics using the Leq metric were between the two.

- Metrics using the L_{max} had the highest standard deviation, while the $Leq_{(5\ min)}$ and L_{90} of $L_{Fmax\ (1\text{-}sec)}$ had the lowest. A high standard deviation indicates lower predictability and lower repeatability.
- The background-adjusted Leq appears to be a good method to measure wind turbine sound relative to background sound. It is predictable using modeling, and background sound influences can be taken into account.
- Analyses of the measured background L_{90} shows significant spatial and temporal variability. This makes pre-construction compliance assessments more difficult when the noise standard is based on the difference between concurrent background and source sound levels. To help remedy this, the background L_{90} can be measured during pre-construction permitting, and then fixed for the lifetime of the project. This removes a measure of uncertainty from pre-construction noise studies.

1.10 | AVALIABILITY OF DATA

The raw data are available by contacting RSG. Requests must be in writing and include the research purpose for the data. Only legitimate research needs will be considered. If requests are approved, the requester must provide a hard drive to RSG. The data are not available online. To cover time and expenses involved in providing data, a fee will be charged for each request. While site names and other metadata will be removed to hide the identity of the sites, the requester will be required to sign a non-disclosure agreement requiring that site and location identifying information not be released, to the extent that it can be ascertained.

Audio files are available for research use. Requests must follow the same format as above. A separate fee will be a charged for these files based on the number of hours of audio to be released, to allow for the screening and removal of personal conversations that may have been inadvertently recorded.

1.11 | HOW TO CITE THIS REPORT

The body of work included in this report was performed by RSG and funded by MassCEC – a public agency of the Commonwealth of Massachusetts. The report should be cited in the following manner: RSG et al, "Massachusetts Study on Wind Turbine Acoustics," Massachusetts Clean Energy Center and Massachusetts Department of Environmental Protection, 2016. Permission is not required to copy portions of this report so long as it is correctly cited.

1.12 | EPILOGUE

A wide variety of analyses and interpretations can be applied to the data and results presented in this report, and to the raw data. The authors acknowledge that this report does not identify and describe all possible implications of the data that have been collected. For example, this study does not attempt to draw conclusions from the large amount of data wherein it was difficult to discern changes in sound levels between turbine-on and turbine-off conditions and did not analyze sound level data outside of the turbine shutdown periods. Analysis and interpretation of such data may shed useful light about the way wind turbine sounds are experienced. The RSG, MassCEC and MassDEP team invites interested parties to apply their expertise to the data to further advance the understanding of wind turbine acoustics.

2.0 INTRODUCTION

Regulation of wind turbine sound in the U.S. is done on a state by state, county by county, and town by town basis. Given the complicated nature of the subject, there has been no consensus on such basic issues as standard levels, sound level metrics, averaging times, pre-construction methodologies (with the exception of modeling standards), post-construction monitoring methods, and methods to reduce or eliminate the influence of background sounds.

The overall goal of the research project described in this report is to advance our understanding of both the characteristics and foundations of wind turbine sound to help inform the public and improve the wind turbine siting and approvals processes. Ideally, these analyses will help siting and regulatory authorities to create predictable and consistent approaches regarding pre-construction prediction techniques and post-construction compliance monitoring.

The research project involves analysis of multiple parameters of sound, turbine operation, and meteorology collected at fixed distances from a variety of operating wind facilities.

The data were gathered at operating commercial wind energy projects in Massachusetts and northern New England. The study was fortunate to find five wind turbine operators who not only allowed access to turbine operational data and study sites, but also in many cases provided transportation to analysis sites, conducted turbine shutdowns at their own expense, and varied turbine operating parameters for short-term experiments. Because of the sensitive nature of wind turbine noise, the names and exact locations of the wind turbine sites are kept confidential.

During the course of this project, approximately 145 million sound level data records were collected at 24 locations. We have over 300 observed and calculated variables, including spectral sound levels in the audible and infrasound range, meteorological data from 1 meter to 200 meters in height, and turbine operational data. Turbines were shut down 187 times for 10 to 30 minutes at a time, supporting direct comparisons between background and wind turbine sounds.

The avenues of research for this study include:

- **Sound levels and metrics** – In what ways can we measure wind turbine sound, using commonly available equipment? How stable and consistent are different sound level metrics for measuring wind turbine sound? How does the background sound affect sound level metrics when measuring wind turbines? What meteorological parameters affect the generation and propagation of wind turbine sound?
- **Sound propagation modeling** – What are the commonly available methods to model wind turbine sound? How do these methods compare to actual sound measured sound levels? How do these methods compare using different averaging times? Are these methods useful for measuring sound generated at different wind speeds? Are sound model biases the same when measuring mountain versus flat sites? Does the receiver height make a difference?
- **Amplitude modulation** – What is the nature and extent of amplitude modulation as it relates to wind turbines? How can amplitude modulation be measured in the presence of background sound? How much amplitude modulation is present and what are its causes?
- **Low frequency sound and infrasound** – What is the spectral shape of wind turbine noise and how does it change over time and between wind turbines? How is infrasound measured? How do

measured wind turbine infrasound levels compare to the standards for human sensitivity? Do structures attenuate infrasound? What turbine operational and meteorological factors have an effect on infrasound levels?

- **Tonality** – What are the commonly accepted ways of measuring tonality? How practical are these methods for use in regulatory standards? How often do the turbines measured for this project exhibit tonal noise under these methods?
- **Standards analysis** – What are some approaches to noise regulation from wind turbines? How do sound levels change when conducting attended versus unattended sound monitoring? What are the most stable metrics for use in attended versus unattended sound monitoring? How do sound level metrics change when averaging time is changed? How different are turbine-on to turbine-off metrics for the shutdowns monitored? What happens when we use some of these metrics as regulatory limits?

We understand that in such a large set of data, there are many avenues of research that could be conducted. As a result, the MassCEC and MassDEP will make this data available to other researchers after the project is complete.[1]

This study is the final report of the Massachusetts Research Study on Wind Turbine Acoustics sponsored by the Massachusetts Clean Energy Center (MassCEC) and Massachusetts Department of Environmental Protection (MassDEP).

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[1] The database will have site names and identifying details removed to preserve the confidentiality of the sites.

3.0 TERMS USED IN THIS REPORT

Section 2 of the Preliminary Interim Report for WNTAG (October 17, 2013) defines terms used in that report. We will not repeat definitions, but will include here additional definitions and terms commonly used in this report.

Absolute Standard – a regulatory standard based on absolute limits, such as “no greater than 45 dBA”.

Accuracy A measure of how close an estimate is to the true value.

Ambient noise – The ANSI S1.1 definition is the “all-encompassing sound at a given place, usually a composite of sounds from many sources near and far.” The MassDEP definition is the L_{90} of the background noise (see “nth percentile” and “background sound level”.

Amplitude Modulation – with respect to wind turbine sound, a regular pattern of increasing and decreasing sound with a period roughly equal to the blade passage frequency (generally less than one-second). Qualitatively, this is sometimes described as “swishing”, “thumping”, or “churning.”

Atmospheric Stability – A condition related to the tendency of air in the atmosphere to move vertically. Unstable atmospheres, such as where the ground is heated, have greater vertical movement of air, and are potentially more turbulent. Stable air, such as under a nighttime temperature inversion, resists the vertical movement of air. Neutral stability, such as on a cloudy day or night, is typically characterized by a normal change in temperature with height (where the actual temperature lapse rate is the same as the dry adiabatic lapse rate of 1°C per 100 meters of lift). Stability classes used to describe atmospheric stability are described in Section 6.

Attended Monitoring – sound monitoring where a person is present to record their qualitative observations of the sound along with the sound level. A sound monitor may automatically record sound levels while the attendant is making observations, or the attendant can record both sound levels and observations at the same time.

Audible For the purposes of this report, able to be heard by ontologically normal healthy young adults (18 to 25 years), according to ISO 389-7 (see Figure 1). For infrasound, audibility is defined in this report according to the 90-dBG curve of ISO 7196 (Figure 74).

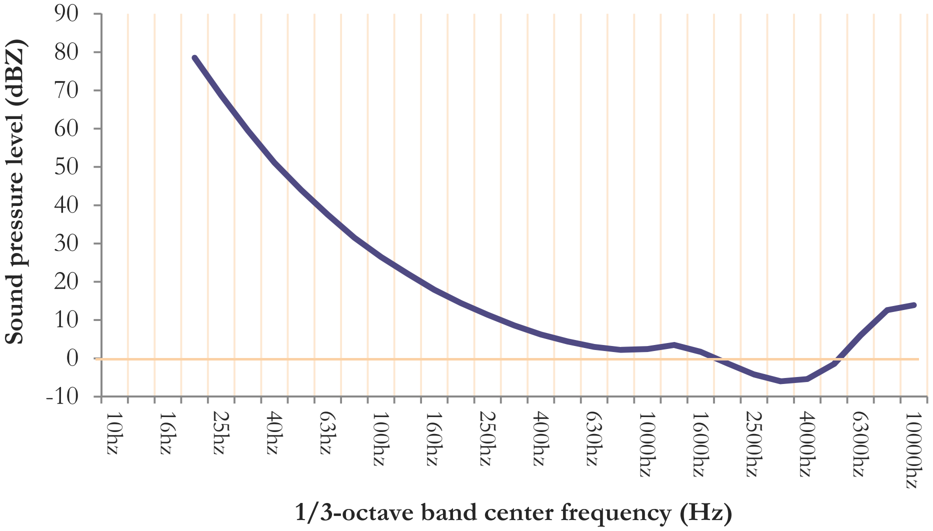

FIGURE 1: ISO 387-7 AUDIBILITY CURVE IN A FREE FIELD

Background Sound Level – the sound level in absence of the source of interest. In this case, it is the level measured either before a wind turbine becomes operational or when an installed turbine is not operating.

Broadband Sound – Sound with a broad spectral distribution, with no tones, such as white noise, static, and airflow.

Confidence Interval – a reliability measure provided for an estimated value or parameter.

Energetic Adding – The addition of two decibel levels. Since a decibel is 10 times the logarithm of a value, the energetic addition would be:

$$Lp = 10log_{10}\left(10^{Lp1}/_{10} + 10^{Lp2}/_{10}\right)$$

Where Lp is the total level, and Lp1 and Lp2 are the levels to be added.

Frequency In acoustics, the number of times in a second one cycle of a waveform passes a fixed space. The perceived pitch of a sound is proportional to its frequency. The relationship between wavelength and frequency is dependent on the speed of sound.

$$f = \frac{c}{\lambda}$$

where λ is wavelength, c is the speed of sound, and f is frequency. The typical hearing range for young healthy individuals is roughly between frequencies of 20 Hz (1 Hertz is one cycle per second) and 20,000 Hz (also designated as 20 kHz, where 1 kHz is one thousand cycles per second).

Discernible Shutdown – When the turbine shuts down as part of this test procedure, it is “discernible” if we see a distinct change in A-weighted sound levels when the level is plotted over time. This distinction is qualitative, and relies on seeing distinct changes in the L_{90} between turbine-off and turbine-on periods. (See also “Fair Shutdown” and “Indiscernible Shutdown”.) More information is provided in Section 5.

Fair Shutdown When the turbine shuts down as part of this test procedure, it is “fair” if we see a distinct change in C- or Z-weighted sound levels when the level is plotted over time, but we do not see a distinct change in the A-weighted level. (See also “Discernible Shutdown” and “Indiscernible Shutdown”.)

G The proportion of ground that is considered porous, as defined under ISO 9613-2. For example, G = 1 represents all porous ground, G = 0 represents all hard ground, and G = 0.5 represents half-porous and half-hard ground.

hh:mm:ss Hours:Minutes:Seconds, For example, 20:10:01 would be 8:10 PM plus one second.

Hybrid Standard – A regulatory standard that combines a relative standard with absolute minimum and/or maximum limits, such as “10 dB over background L_{90}, with no less than 36 dBA and no more than 45 dBA”.

IEC 61400-11 The International Electrotechnical Commission standard, “Wind turbines – Part 11: Acoustic noise measurement techniques.” This is the industry standard for measuring the sound power, uncertainty, and tonality from wind turbines. The measurement procedures defined in this standard are different in some respects from those that would be adopted for noise assessment in community noise studies.

Impulse Response – See L_{AI}.

Indiscernible Shutdown – When a turbine is shutdown, it is indiscernible if no change in plotted sound level, including A-, C-, and Z- weighted levels, can be observed. This is a qualitative distinction. (See also “Discernible Shutdown” and “Fair Shutdown”.)

Inferential Statistics – a branch of statistics aimed at drawing conclusions from sampled data.

Infrasound Sound that is of such low frequency that it is not readily audible by humans at nominal levels – generally considered to be below 20 Hz (Figure 2)

ISO 9613 The International Standards Organization Standard ISO 9613, “Acoustics – Attenuation of sound during propagation outdoors”. The standard is used to predict how sound propagates outdoors. It is currently the standard used by most noise control engineers in the U.S. to predict wind turbine sound levels in communities. Part 1 of the standard estimates atmospheric attenuation, and Part 2 uses the results from Part 1 with sound emissions from the source and propagation path factors to estimate sound levels at some distance from the source.

L_{90} of the L_{90} – For a series of L_{90} measurements, the L_{90} that is exceeded 90 percent of the time. Unless otherwise specified, this report calculates the first L_{90} by taking the 10th percentile of a time-series of measurements, generally five minutes long, of logged one-second Leqs. These five-minute L_{90}s are then collated into wind speed bins, for example, and the 10th percentile of the L_{90}s in each wind speed bin is calculated. The result is the “L_{90} of the L_{90}” for that wind speed bin.

L_{90} $L_{F\,max}$ The one-second L_F (fast response level- L_F defined below) maximum sound level exceeded 90 percent of the time in a period.

L_{90} $L_{S\,max}$ The one-second L_S (slow response level – L_S defined below) maximum sound level exceeded 90 percent of the time in a period.

L_A or A-weighted level - A weighting of the sound spectrum used to mimic the human response to loudness at lower sound levels. An A-weighted sound level – both sound pressure and sound power level – is reported in decibels as dBA (or dB(A)). The various weighting schemes are shown in Figure 2.

L_{Ai} The "insect" A- weighted response. L_{Ai} is used to filter out biogenic sounds, by eliminating all sounds at and above the 1,600 Hz 1/3-octave band. (Schomer & Hessler, 2010) (see Figure 2).

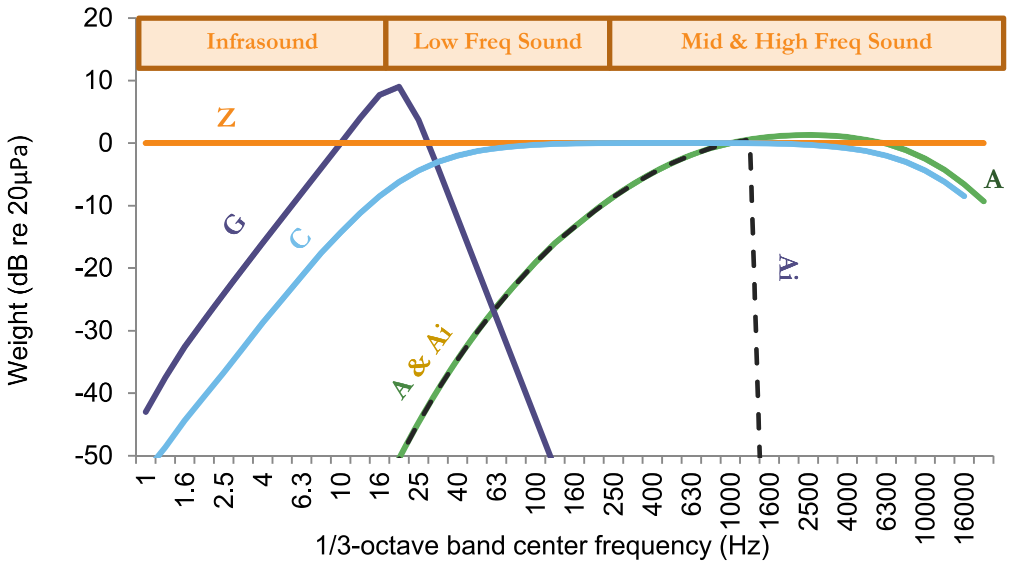

FIGURE 2: SOUND WEIGHTING SCHEMES

L_F Fast-response sound level, where the exponential response time is set to 125 ms. A sound level meter set to Fast-response is relatively faster to respond to rapidly changing sound levels, such as amplitude modulation close to a typical wind turbine. For example, it is used in the Maine DEP wind turbine regulations to assess "short duration repetitive sounds", i.e. amplitude modulation depth. It can be expressed as an instantaneous level, in a percentile, or in a statistic such as a one-second L_{Fmax}, for example. (See "sound level meter response")

$L_{Fmax\ (1\text{-}sec)}$ The A-weighted, fast-response maximum sound level, as measured over a one-second period, in decibels.

L_I The impulse response sound level, in decibels. (See "sound level meter response").

L_C	The C-weighted sound level. This weighting was developed to represent the human response to high-energy sounds. It is relatively flat in the audible range (see Figure 2).
L_{Ci}	The C-weighted sound level filtered to eliminate sound above 1,250 Hz.
Leq	Equivalent average sound level. The average of the mean square sound *pressure* over an entire monitoring period and expressed as a decibel: $Leq_T = 10 * log_{10}\left(\frac{1}{T}\int_{\theta}^{T} p_A^2(t)dt \Big/ p_{ref}^2\right)$ where p_A^2 is the squared instantaneous weighted sound pressure signal, as a function of elapsed time t, p_{ref} is the reference pressure of 20 μPa, and T is the stated time interval. The reference pressure of 20 μPa is used for all measurements in this document. The monitoring period, T, can be for any defined length of time. It could be one second ($Leq_{1\text{-sec}}$), one hour ($Leq_{(1)}$), or 24 hours ($Leq_{(24)}$). Because Leq is a logarithmic function of the average pressure, loud and infrequent sounds have a greater effect on the resulting Leq than quieter and more frequent sounds. The Leq is the most commonly used metric in environmental sound regulations for wind turbines, including IEC 61400-11 test procedures for wind turbines.
L_G	The G-weighted sound level. This is a weighting relative to the perception and annoyance of infrasound (see Figure 2).
L_n	See “n^{th} percentile”
Lp	See “Sound Pressure Level”
L_S	Slow response sound level, where the exponential response time is set to 1.0 second. This is a relatively slower response time to Fast and results in a longer rise and fall time in the displayed sound level. The five-second instantaneous A-weighted L_S is the metric currently used by MassDEP for compliance monitoring. L_S is often used in local sound regulations as it tends to filter short-term contamination by responding more slowly to rapidly changing sound levels, and is easier to read on a sound level meter display. (See “sound level meter response”)
Lw	See “Sound Power Level”
L_Z	The Z-weighted sound level has zero weighting; un-weighted. The units are dBZ or dB(Z). This is sometimes seen elsewhere as dB, dB(L) (linear), or dB(F) (flat).
LIDAR	Light Detection and Ranging system, used to remotely quantify wind speed and direction at various ranges.
Location	A specific monitoring location within a Site.

Logarithmic Addition – see “Energetic adding”.

Low Frequency Sound – Sound with frequency content between 20 Hz and 200 Hz.

Measured	An observed quantity. In this report, we differentiate between measured values, for example, those that are logged by a sound level meter, and modeled values, such as those that are predicted by a sound propagation model.
m/s	Meters per second, a standard unit measuring wind speed.
ms	Milliseconds; one thousandth of a second
nth Percentile	In statistics, the value which represents the highest nth percent of a series of values. For example, in 100 measurements sorted from high to low, the 10th percentile would be the 90th measurement down from the top. That is, 10 percent of the observations fall below that value. In acoustics, the nth percentile level is the level exceeded n percent of the time, which is the opposite of the statistical definition. Thus the acoustic L_{90} represents the statistical 10th percentile level. In this document, if we use “*n*th percentile” it will refer to the statistical definition, and if we use “L*n*”, it refers to the acoustical definition. L_{50} is the median sound level.
Octave bands	An octave is a band of frequencies whose lower frequency limit is one half of its upper frequency limit. An octave-band is identified by its center frequency. As an example, the 500 Hz octave band is the range which includes frequencies between 360 Hz and 720 Hz. An octave higher would be twice this. That is, it would be centered at 1,000 Hz with a range between 720 and 1,440 Hz. The range of human hearing is divided into 10 standardized octave-bands: 31.5 Hz, 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, 8 kHz, and 16 kHz. For analyses that require even further frequency detail, each octave-band divided into equal parts, such as 1/3-octave-bands.
p	A measure of statistical significance. “p” is the probability that the relationship you have observed in the sample data is due to random chance alone. That is, it is the probability that there is no relationship. A very small p-value means that it is extremely unlikely that this relationship is not real. Researchers often use cut-offs of 0.01 to 0.10 as a measure to determine what is “statistically significant.” In this report, a p-value less than 0.05 will be reported as significant.
Precision	The repeatability of measuring the same value if conditions stay the same.
R-squared, R^2	A statistical measure which represents the proportion of the variance in a variable explained by other independent variables. R-squared varies from 0 (no relation between the variables) to 1 (perfect correlation between the variables).

Relative standard – A regulatory standard based on some number of decibels above a background level. For example, “10 dB above the background L_{90}”.

rms	Root mean squared. The square root of the arithmetic mean of the squares of a set of values.
Site	The entire area of a wind turbine project and its surroundings.

Sound [Pressure] Level – the sound pressure level as measured in decibels:

$$\text{Lp (in dB)} = 10log_{10}\left(\frac{p}{p_{ref}}\right)^2$$

where p is the sound pressure in Pascals and p_{ref} is the reference sound pressure of 20 μPa. All sound pressure levels shown in this document use this p_{ref}.

Sound level meter response – The rate at which a sound level meter display can change related to a change in actual sound level. Sound levels vary over time. In fact, the variation is so fast, that one would not be reliably able to read the level on a sound level meter. For that reason, the displayed sound level is damped in time, to make it readable.

There are three standard time responses available on most sound level meters: Slow, Fast, and Impulse (see "Ls", "Lf", and" Li", respectively). Fast response has a time constant of 125 ms. This response is similar to the response of the human ear. The Slow response has a time constant of 1 second. This is often used in environmental noise measurement because its slow rise and fall time eliminates very short spikes in noise that are not related to the measurement. The Impulse response has a very fast rise time of 35 ms and a slow decay time of 1.5 seconds. It is rarely used in environmental noise measurements, but can be used with other metrics to evaluate the impulsivity of a sound event.

Fast, slow, and impulse sound levels cannot be averaged over time, since they are not representative of the actual sound level over time. They are simply applied to the actual sound level to slow the meter reading. A true energy average can be calculated using the Leq metric, which is independent of the sound level meter response setting (see "Leq").

Sound Power Level – The level of sound power (sound generation) of a source, independent of environmental factors, measured in decibels:

$$\text{Lw (in dB)} = 10log_{10}\left(\frac{w}{w_{ref}}\right)^2$$

where w is the sound power measured in Watts and w_{ref} is the reference sound power of 10^{-12} Watts. A simple way of thinking about the difference between sound pressure and sound power is by the analogy of a light bulb: the sound pressure is similar to the lumens of light measured in a certain place under specific conditions, while the sound power would be equivalent to the wattage rating of the bulb, which does not change.

Sound Speed Profile – The change of the speed of sound as a function of height above ground. Within about 200 meters of the ground, the sound speed profile is most affected by the vector wind speed (combining wind speed and direction) by height and the temperature profile. Sound travels faster in warmer air.

Spectrum The components of a sound broken down in to individual frequencies.

Standard Deviation – A measure of the variability or dispersion of a given value in a population. Standard deviation can be estimated from a subset (sample) of a given population.

Standard Error –The standard deviation of the estimated statistic's sampling distribution. If the statistic is a mean, it is a measure of the precision of the estimate of the mean. For example, if one calculated many means from a population, the standard error would be the standard deviation of the means. Thus, it is a measure of how close the actual mean is to your estimate. Standard Error is estimated by dividing the sample standard deviation by the square root of the sample size.

Statistical Bias – The tendency to under- or over-estimate the true value, i.e., a directional error. A bias may be intentional or unintentional. An example of an intentional bias is adding to sound modeling results to increase the likelihood that the true level of sound does not exceed the modeled level.

Temperature Lapse Rate – The rate at which temperature decreases with increasing height above ground.

Tonal Sound - Sound where narrow frequency band(s) are pronounced, such as in alarms, sirens, squeals, and horns.

Trend Line The best fit line through a series of points on a graph, such as through a regression or least squares approach. The trend line can be straight (linear) or based on a curve, such as logarithmic, exponential, or polynomial. The trend line shows the estimated relationship between an independent and dependent variable, such as the relationship between wind speed and sound level. (See also R-squared)

Turbine-off Sound Level – the background sound level when a wind turbine is shut down.

Turbine-on Sound Level (modeled or measured) – the sound level that includes both background sound and turbine-generated sound.

Turbine [Only] Sound Level – the estimated sound level due to a wind turbine alone. It can be either modeled from the sound power profile of the particular wind turbine and propagation characteristics, or estimated by subtracting background sound from measured Turbine-on sound level. The Turbine [only] sound level does not include any background sound.

Turbulence Intensity – The standard deviation of the wind speed divided by the mean wind speed, over a defined period. The IEC 61400-1 turbulence model uses a period of 10-minutes over which to calculate the mean and standard deviation. However, other lengths of time can be used for different purposes.

Unattended monitoring – Sound monitoring where a sound level meter and associated equipment is left unattended for some length of time. Data are post-processed to filter out events not associated with the target source. Sound recordings may be taken along with the logged sound levels to aid in identification of different sources of sound.

Wind Shear The change in wind speed with height. Higher shear represents higher wind speeds aloft compared with closer to the ground.

Wind Shear Exponent – A quantification of the vertical wind shear between two levels of the atmospheric boundary layer. Derived from the wind shear power law, the function of the vertical wind speed profile is expressed as,

$$\alpha = \frac{ln\frac{v}{v_0}}{ln\frac{z - dh}{zh_0 - d}}$$

where:

α is the wind shear power law exponent;
v and v_0 are the wind speeds at heights z and z_0, above ground level respectively;

d represents the displacement height above ground level to account for the decoupling of the winds throughout the tree canopy. For simplicity throughout this analysis, the displacement height is assumed to be zero for all sites.

Wind Veer The change of wind direction with height. In this report, wind veer is calculated as the difference between wind directions measured at 80 meters and at 40 meters.

4.0 GENERAL METHODOLOGY

Sound level monitoring was conducted at five sites during the winter, spring, and summer of 2013, and winter of 2014. Long-term monitoring was conducted at three to six locations at each site. Short-term monitoring was conducted around the same locations plus some auxiliary locations.

In this report, we use the word "site" to refer to the entire area around a wind turbine project. We use "location" to represent a specific locale within that site. If we use a city as an analogy, a "site" could be Boston, and a "location" could be 63 Franklin Street.

4.1 | WIND TURBINE SITES

All sites were located in either Massachusetts or elsewhere in New England with terrain that is similar to that found in Massachusetts. Some sites had been the sources of noise complaints at some point in the past. All sites had wind turbines with hub heights of approximately 80 meters and an electrical output capacity of 1.5 MW or greater. Four sites were relatively flat and within five kilometers (3.1 miles) of the ocean. One site was in a mountainous area that had multiple turbines along a ridge. In this case, the monitoring positions were situated toward one end of the turbine array.

As part of our agreement with some of the wind turbine operators, the site names have been kept confidential. We have taken several measures in order to accomplish this, including referring to each site by a randomly assigned code. In each chapter, the sites discussed are assigned a unique identifier specific to that chapter, e.g., Site 1A and Site 1B in Chapter 1, Site 2A and Site 2B in Chapter 2, and so on. In this way, each distinct site within the specific topics covered in the report can be treated independently. The mountainous site will always be identifiable because it was the only site with such surrounding terrain, and this geography may be important to the measurements and their interpretation. We ask that if the reader is able to identify a particular site, that they respect the operator's wishes and keep that information confidential. In addition, the data in this report should not be used to infer or interpret whether or not a study project complies with the MassDEP noise regulation. See Table 1 for a summary of these sites.

TABLE 1: SITE DESCRIPTION SUMMARY

# of Turbines	Topography	Terrain	Foliage and Ground Cover	Average Temp (C)	# Long Term Locations	# Short Term Locations	# Infrasound Locations	Monitoring Duration (days)
1	Coastal	Flat	Grass, Marsh, Dense Forest	1.9	6	7	0	26
1	Inland Coastal	Flat	Grass, Bushes, Dense Forest	3.9	5	6	2	15
2	Inland Coastal	Flat	Grass, Bushes, Dense Forest	7.9	5	9	0	16
1	Coastal	Flat	Grass, Sand, Thin Forest	20.3	4	2	0	16
>2	Inland Mountainous	Mountainous	Grass, Dense Forest	-6.9	4	2	2	15

4.2 | LONG-TERM SOUND MONITORING

EQUIPMENT

At each of the primary and auxiliary monitoring locations, sound level data were collected using ANSI/IEC Type 1 sound level meters, each logging 1/3-octave band equivalent sound pressure levels at intervals ranging from 50 milliseconds to one second. Depending on the capabilities of the meters, fast- and slow-response sound levels (L_F and L_S, respectively) were also logged. Impulse-response sound levels (L_{AI}) were also recorded at many locations, but we do not report these levels, as this exponential time weighting is rarely used for environmental noise.

Audio was recorded at each location either using an audio recording function on the sound level meters or audio recorders with audio output from the sound level meters. At each site, all sound level meters' internal clocks were synchronized manually, and then an impulse sound was generated and recorded to allow for better time-synchronization during post-processing. All sound level meters were calibrated before and after each monitoring period, and approximately once per week during monitor checkups.

Microphones were mounted on one-meter tall wooden stakes or tripods and covered with 7- inch ACO-Pacific or similar weather-resistant windscreens. At each of the monitoring locations, an anemometer, set at microphone height, was used to measure wind speed. One of the microphone-height anemometer loggers was also equipped with a temperature gauge at each site.

METEOROLOGY

A 10-meter meteorological tower was installed at each site to gather wind speed, wind direction, and temperature. The tower was equipped with NRG equipment (#40C anemometer, #200P wind vane, #110S temperature sensor) and recorded the following:

- 10m Met Anem (m/s) – the average wind speed at 10 meters. This is a 10-minute average of 3-second samples.
- 10m Met Anem SD (m/s) – the standard deviation of wind speed at 10 meters. This statistic applies to 10 minutes of 3-second samples.
- 10m Met Anem Max (m/s) – the 3-second maximum wind speed for each 10-minute period at 10 meters.
- 10m Met Anem Min (m/s) – the 3-second minimum wind speed for each 10-minute period at 10 meters.
- Direction B (degrees True North) – the average wind direction at 10 meters. This is a 10-minute average of 3-second samples.
- Direction B SD (deg True North) – the standard deviation of wind directions at 10 meters. This statistic applies to 10 minutes of 3-second samples.
- Direction B Max (deg True North) – the direction of the 3-second maximum wind speed at 10 meters for each 10-minute period.
- Direction B Min (deg True North) – the direction of the 3-second minimum wind speed at 10 meters for each 10-minute period.
- Temperature (deg C) – the average temperature at 10 meters. This is a 10-minute average of 3-second samples.
- Temperature SD (deg C) – the standard deviation of temperatures at 10 meters. This statistic applies to 10 minutes of 3-second samples.
- Temperature Max (deg C) - the 3-second maximum temperature at 10 meters for each 10-minute period.
- Temperature Min (deg C) - the 3-second minimum temperature at 10 meters for each 10-minute period.

WindCube LIDAR equipment manufactured by NRG and Leosphere, was installed in conjunction with the met-tower. This system provided wind speeds and directions at a series of altitudes ranging from 40 meters to 200 meters above ground level, and temperature 1 meter above the ground. The data fields collected by the LIDAR included:

10-minute LIDAR data:

- Ext Temp (deg C) – the 10-minute average ambient temperature recorded from a pole mounted temperature sensor at the LIDAR location mounted at 1.2 m above ground level (agl).
- Pressure (hPa) - the 10-minute average barometric pressure recorded from a pole mounted pressure sensor at the LIDAR location mounted at 1.2 m feet agl.
- Rel Humidity (%) - the 10-minute average relative humidity recorded from a pole mounted relative humidity sensor at the LIDAR location mounted at 1.2 m feet agl.
- XXm Wind Speed (m/s) - 10-minute average wind speed recorded at XX meter height by the LIDAR. This is an average of one-second samples within that 10-minute period.
- XXm Wind Speed Dispersion (m/s) - 10-minute standard deviation of one-second wind speeds recorded at XX-meter height by the LIDAR.

- XXm Wind Speed Min (m/s) - minimum one-second wind speed recorded at XX-meter height by the LIDAR in a 10-minute period.
- XXm Wind Speed Max (m/s) - maximum one-second wind speed recorded at XX-meter height by the LIDAR in a 10-minute period.
- XXm Wind Direction (deg True North) - 10-minute average of one-second wind direction samples recorded at XX-meter height by the LIDAR.
- XXm Z-wind (m/s) - 10-minute average of one-second vertical wind speed samples recorded at XX-meter height by the LIDAR. Positive vertical wind speed values represent downward wind flow.
- XXm Z-wind Dispersion (m/s) – the 10-minute standard deviation of one-second vertical wind speed samples recorded at XX-meter height by the LIDAR
- XXm Data Availability (%) – A measure of the quality of data. As not all laser emissions hit sufficient particles in the air to record a return (or the beam is obstructed by heavy precipitation), the Data Availability is proportional to the percentage of successful samples of one-second data. Periods with >=5% Data Availability are considered to have sufficient samples to provide representative statistics. Periods with <5% Data Availability are not considered to have sufficient samples and have been screened out.

One-second LIDAR data:

- Position – The LIDAR emits approximately 1 beam per second, rotating across the cardinal directions and vertical. The position data point provides what direction is being sampled during that second.
- Temperature (deg C) –the internal temperature of the LIDAR and is for diagnostic/performance monitoring purposes.
- XXm Wind Speed (m/s) – the horizontal one-second average wind speed at XX meters agl.
- XXm Wind Direction (deg True North) - The one-second direction of the wind speed at XX meters agl.
- XXm X-wind (m/s) - The x vector component of the one-second wind speed at XX meters agl.
- XXm Y-wind (m/s) - The y vector component of the one-second wind speed at XX meters agl.
- XXm-Z-wind (m/s) - The z (vertical) component of the one-second wind speed vector at XX meters agl. Positive vertical wind speed represent downward wind flow.

The meteorological towers and LIDAR were set up within approximately 100 meters and upwind of one of the turbine(s) with respect to the prevailing wind direction.

At each long-term monitoring location, a MicroDAQ HOBO anemometer was set up to measure wind speed. The anemometer height was the same as the microphone height. Wind speed and any other supplemental data were logged every 10 seconds.

Additional information on meteorological data is provided in Section 10.

TURBINE OPERATIONAL DATA

Four sites had turbine operational data reported via their SCADA (supervisory control and data acquisition) system. Since there were different turbine types at each site, the SCADA systems differed. SCADA data was acquired at intervals ranging from one second to 10-minutes. All SCADA systems captured real power production, wind speed and wind direction at the nacelle. In addition, the systems reported some of the following: temperature, wind speed turbulence, nacelle orientation towards the wind, yaw error, blade pitch, reactive power, and blade rotation rate in rpm. Temperature data at some of the turbines appears to have been affected by heat emanating from the nacelle. As a result, SCADA temperature data were not used.

For the one site that did not have SCADA, corresponding information was developed using detailed shutdown logs, LIDAR data, and wind speed-to-turbine power relationships published by the turbine manufacturer.

DATA COLLECTION

At each site, three sound level monitors were placed downwind (based on predominant wind direction) at approximately 330 meters, 660 meters and 990 meters from the turbine(s). One monitor was also placed upwind at approximately 330 meter, and one or two monitors were installed at crosswind locations at approximately 330 and 660 meters.

At least 14 days of sound level data were recorded at each site. Each monitor was checked approximately every week to refresh batteries and download the previous week's data. For the five sites analyzed in this report, approximately 145 million sound level records were logged.

4.3 | SHORT-TERM SOUND MONITORING

Attended short-term monitoring was conducted in 20- to 30-minute periods at a logging interval of 125 milliseconds or finer. Using Nexus 7 tablet computers, the audible events during this interval were logged and time-stamped for later comparison with sound level data. Attended monitoring was conducted at each long-term location and some additional short-term locations during both daytime and nighttime periods near to times when the project turbine or turbines were manually shut down for background sound level measurements. For multiple-turbine sites, at least three of the closest turbines were shut down to obtain background measurements.

Examples of some sounds that were logged during attended listening include wind turbine sound, wind turbine amplitude modulation, traffic noise, aircraft overflights, wind-induced foliage sound, and animals, among others. The full list is shown in Figure 97. At one location, due to equipment issues, attended listening was performed after measurements were completed using audio recordings.

At each short-term location, sound level data were collected using ANSI/IEC Type 1 sound level meters logging 1/3-octave band sound levels. Some monitors also logged A-, C-, and Z-weighted L_F, L_S, and/or L_I depending on their capability.

In order to reduce potential sound created by attendants themselves, the microphones were placed at a distance of 10 to 20 feet from the attendee and connected to the sound level meters by extension cables.

4.4 | STATISTICAL EVALUATIONS

Statistical testing is used throughout this report. This section presents a short primer on some of the statistical techniques and parameters used in this study.

CONFIDENCE INTERVALS

When evaluating any summary statistic based on sampled data, such as an arithmetic mean, the resulting value is an *estimate* of the true population value and we can compute the resulting confidence in that estimate. For continuous variables, such as sound pressure levels, the estimate's accuracy relies on two other quantifiable parameters. The first is the sample size, or *n*, as is commonly referenced in statistical equations. For the discussion here, *n* is the number of measurements used in the calculation of a summary statistic. It can also be the number of summary statistics used to calculate another summary statistic. The second is the standard deviation of the underlying data used to calculate the statistic. Standard deviations measure spread, or variability, in sampled values.

As mentioned, when calculating averages or standard deviations, the results are estimates and those estimates can have high degrees of uncertainty.

To clarify, the following equation defines the calculation of the mean and standard deviation, respectively:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \text{ and } \sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

Where

σ (sigma) is the standard deviation of all x

$\bar{x}$ is the estimated mean value of all x

x_i is the i^{th} value of x

n is the sample size.

For a population that has a normal distribution (as in a bell curve), about 95 percent of the population is within two standard deviations of the mean.

The standard error differs from the standard deviation, in that it describes the precision of the mean rather than the population as a whole. Our confidence that the mean we calculate would not vary if we repeated the study increases with the sample size. The standard error is thus defined as:

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}}$$

Where

σ is the standard deviation of the sample;

$\sigma_{\bar{x}}$ is the standard error of the mean of $\bar{x}$;

n is the sample size (or number of observations used in calculating the mean).

The confidence interval is an estimate of the likely values of the mean if the analysis were to be repeated. In this report, we use the 95 percent confidence interval, which means that there is a 95 percent probability that the true mean falls within the defined range.[2] The upper and lower confidence interval range for an estimate of a mean is calculated as:

$$\bar{x} \pm t_{\alpha/2} * \sigma_{\bar{x}}$$

Where

t is the critical value from the student's t distribution at $\alpha/2$

α is the Type I error rate (typically 5%).

For a large enough sample size, the value of *t* for a 95% confidence interval is 1.96.

We can see that datasets with very few observations (*i*.e. *n*) will have larger standard errors. Since confidence intervals are computed directly from standard errors, the resulting confidence intervals will naturally get wider with fewer observations.

The minimum sample size required for a desired statistical precision can be pre-determined, but it will depend on the standard deviation of the values collected during monitoring. The more sound levels vary during monitoring, the larger the sample size must be to estimate summary statistics within the desired confidence intervals.

INFERENTIAL STATISTICS – THE NULL HYPOTHESIS

Inferential statistical procedures can be used to explicitly test for differences between groups (or monitoring periods, for example). The general framework establishes a null hypothesis (H_o) and an alternative hypothesis (H_1). The statistical test can provide information on whether to accept or reject the null hypothesis.

Here is one example of how to frame the hypothesis:

H_o: *The* L_{90} *sound pressure level with turbines active is less than 10 dB above the background* L_{90}.

H_1: *The* L_{90} *sound pressure level with turbines active is greater than or equal to 10 dB above the background* L_{90}.

Here we specify that any sound level differences less than 10 dB are not important. Naturally, we can arrange the test any way that meets the policy guidelines, so this is only for illustration.

The result of an inferential statistical test is usually presented as a probability or p-value. When a statistical effect is observed, the p-value from the test quantifies the likelihood of observing such an effect even if no relationship exists. Many scientists require that a sample meet $p <= 0.05$ (or 5%) to be considered statistically significant, but lower or higher p-values can be set as thresholds, depending on the application. Taking the above example, assume we observe a sound level increase of 12 dB with turbines active, and that a p-value of 0.01 has been set as the threshold of statistical significance. Under these assumptions, the probability that the turbines had no effect on the 12 dB rise in sound levels is only 1%, or extremely unlikely. We therefore reject the null hypothesis and accept the alternative hypothesis.

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[2] Note that the 95 percent confidence interval does not mean that 95 percent of the population falls within that interval, but that there is a 95% probability that the mean of the population falls within that interval.

LINEAR REGRESSION MODELING

Linear regression is a statistical technique used to model the relationship between a dependent variable and a set of independent variables (sometimes referred to as predictor variables). With linear regression, the dependent variable is written mathematically as a linear function of the independent variables and set of estimated parameters or coefficients that describe the relationships in the model. For example, you might hypothesize that sound power level is linearly related to wind speed and wind shear. The linear regression model in this case would look like:

$$Sound\ power\ level = \beta_1 * Wind\ Speed + \beta_2 * Wind\ Shear + \beta_3$$

The values β_1, β_2, and β_3 would be estimated. It should be noted that β_3 is a constant in the model. As with the sample mean, standard errors can be calculated and provide insight into the precision of the coefficient estimates. Other statistics are produced like the R^2 which provides an indication of the percent of variance in the dependent variable explained by the model.

The most common approach to estimating the parameters of a linear regression model is to use an ordinary least squares approach. With ordinary least squares, the model identifies the coefficients that minimize the difference between the model prediction and the observed values.

STRUCTURAL EQUATION MODELING

Structural equation modeling (SEM) is an advanced modeling technique that allows the analyst to test specific structural relationships between multiple dependent variables and independent variables simultaneously. This is referred to as the models structure and example can be found in Figure 3 below. As with linear regression, SEM produces a set of coefficients that describe the influence that the variables have on the modeled outcomes. One of the main benefits of SEM in this report's context is its ability to account for measurement error (error in the measurement of the observed values) directly within the modeling structure.

In this model, sound power level, sound speed profile and sound pressure level are treated as latent (or unobserved) variables (the circles) with causal relationships (the arrows) between sound power level and sound speed profile and the resulting sound pressure level. In the structure, a number of environmental independent variables (in the rectangles) influence the latent variables.

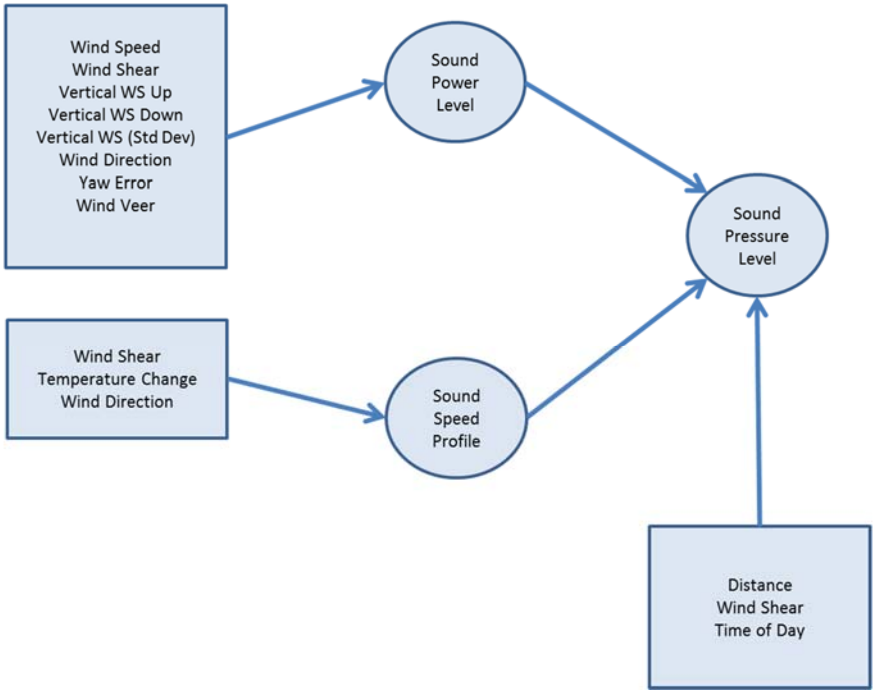

FIGURE 3: DEPENDENCIES OF VARIABLES IN A STRUCTURAL EQUATION MODEL FOR MEASURED SOUND LEVELS FROM WIND TURBINES

5.0 CONTINUOUS SOUND MONITORING, METRICS, AND SPECTRUM

One of the purposes of this study is to evaluate ways to measure wind turbine sound. When one asks, "What is the sound level from a wind turbine," there are many valid and correct responses depending on what aspect of turbine sound one is interested in, how long one measures, what instrumentation settings are used, whether one wants a single level encompassing all frequencies, or a set of levels at specific frequencies, etc. In this Section, data gathered during long-term continuous sound monitoring around wind turbine shutdowns are analyzed using a diverse set of sound level metrics, weightings, and spectra to help characterize wind turbine sound.

In this section, we discuss "sound levels" and "metrics". That is, we evaluate how wind turbine sound, in the presence of background sound, appears under different sound level meter response times (fast, slow, impulse), averaging times (e.g., instantaneous, one-second, five-minute, one-hour), weightings (A, C, Z, and G), statistical metrics (e.g., Leq, L_{90}, L_{10}), and individual frequency bands.

Many combinations of sound levels and metrics have been used in wind turbine regulations throughout the world. For example, the wind turbine noise regulation in Maine uses the arithmetic average of 12 consecutive 10-minute A-weighted Leqs. Huron County in Michigan used an LA10 measured over an hour, and the Vermont Public Service Board has used a maximum one-hour Leq measured over two weeks (rolling Leq every 10-minutes) for each of four seasons, and Z-weighted 1/3-octave band sound levels are used for tonality assessment. The Netherlands use the Lden metric, which is an equivalent average that adds a penalty of 5 dB for sounds emitted during the evening and 10 dB during the night. The state of Oregon uses the L_{50} and L_{10} statistics. In the state of Illinois, standards are based on unweighted octave bands with a tonal penalty based on 1/3-octave bands.

5.1 | OVERVIEW OF SOUND LEVEL METRICS

Modern sound level meters are commonly capable of logging one-second equivalent average and exponential time weighted (fast/slow response) sound levels. As a result, we will focus on these metrics for use in compliance monitoring, in combination with averaging time and frequency weighting. We address the following:

- **Equivalent average sound level (Leq)** – Equivalent continuous average sound levels are the most commonly used metric in environmental sound regulations for wind turbines, including IEC 61400-11 test procedures for determining sound emissions from wind turbines.
- **Slow response sound level (L_S)** – The A-weighted five-second instantaneous L_S (i.e., the instantaneous L_S logged once every five seconds) is a metric currently used by MassDEP for compliance monitoring of wind projects. L_S is often used in local sound regulations, as it tends to filter out very brief sound events by responding more slowly to rapidly changing sound levels. In this section of the report, we expand the consideration of L_S, by using a series of consecutive one-second $L_{S\,max}$ values and then taking averages or percentiles of these measurements over defined time periods.
- **Fast response sound level (L_F)** – L_F responds faster to rapidly changing sound levels, such as amplitude modulation close to a typical wind turbine. For example, the A-weighted L_F is used in the Maine DEP wind turbine regulations to assess "short duration repetitive sounds", i.e.

amplitude modulation depth. It can be reported as either an instantaneous level or a statistic, including those calculated as average or percentile of one-second L_{Fmax} readings, for example. Consider the 10-second sample of amplitude-modulated sound shown in Figure 4, which was collected 260 meters from a single turbine as part of this study. The modulation frequency is about 0.8 cycles per second (0.8 Hz) or equivalent to a three-bladed turbine operating at 16 rpm. The modulation frequency is correlated to the rate at which each blade passes a point of rotation. Audio recordings confirmed that the wind turbine is audible.

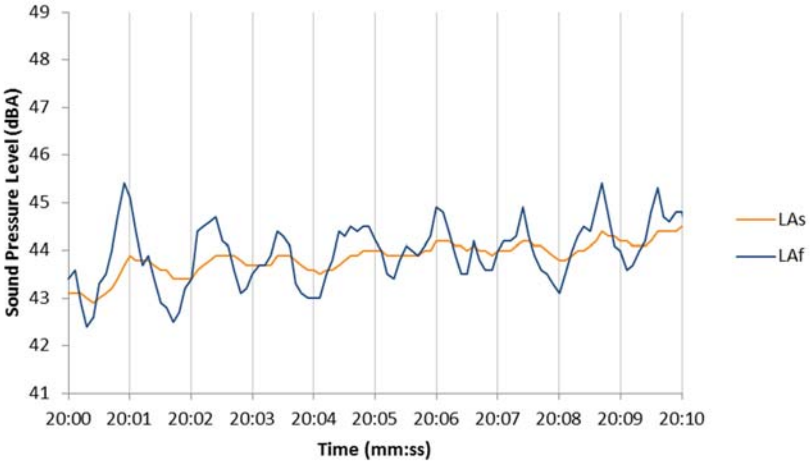

FIGURE 4: 10-SECOND SAMPLE OF WIND TURBINE AMPLITUDE MODULATED SOUND 260 METERS CROSSWIND SHOWING SLOW- AND FAST-RESPONSE SOUND LEVELS AT 100 MS DATA COLLECTION FREQUENCY

Each second's worth of sound level data can be summarized using an equivalent average, arithmetic average, minimum, maximum, or percentiles. Following the example from Figure 4, Figure 5 shows one-second A-weighted Leq and one-second maximum A-weighted L_S and L_F sound levels.

These one-second metrics can then be further summarized into longer-term statistics. Figure 6 shows the 10-second Leq and the tenth percentile of the one-second L_{Smax} and L_{Fmax} readings (i.e., L_{90} based on one-second L_{Smax} and L_{Fmax} readings). These terms are defined in Section 3.

In comparison, a sample of background sound (sources other than the wind turbine) for an adjacent period is shown in Figure 7. In this sample, the signal is not amplitude modulated, but varies slowly over 10-seconds. The L_{90} of the one-second L_{Fmax} levels is now closer to the lowest of the levels during this period, while the Leq is higher. The L_{90} of the one-second L_{Fmax} (and L_{Smax}) filters the varying portion of the sound and is representative of the base level of the background sound. At the same time, the L_{90} of the one-second L_{Fmax} of the wind turbine sound is representative of the higher amplitude modulated sound, while filtering out unusual events.

Thus, in an ideal situation of constant background sound, the difference between the background L_{90} and turbine-on L_{90}, both calculated using the L_{90} of the one-second L_{Fmax}, would be the difference between the crest of the turbine amplitude modulation and background L_{90}.

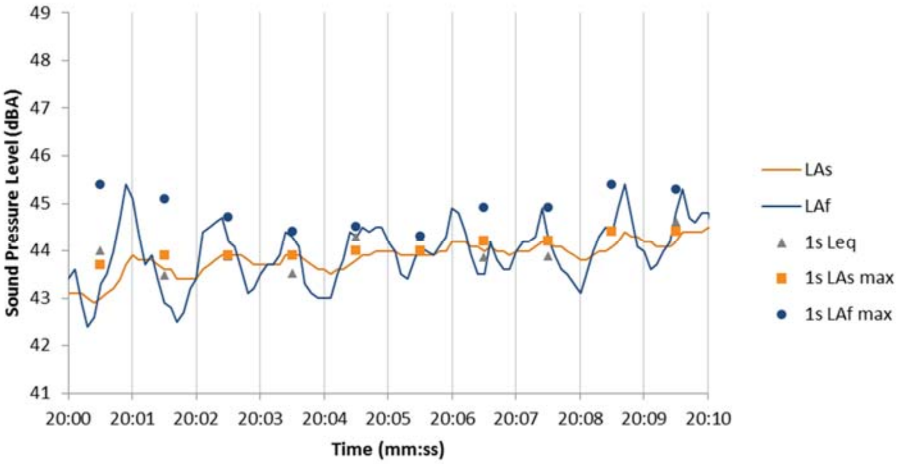

FIGURE 5: SAME SAMPLE AS FIGURE 4, WITH ONE SECOND LEVELS

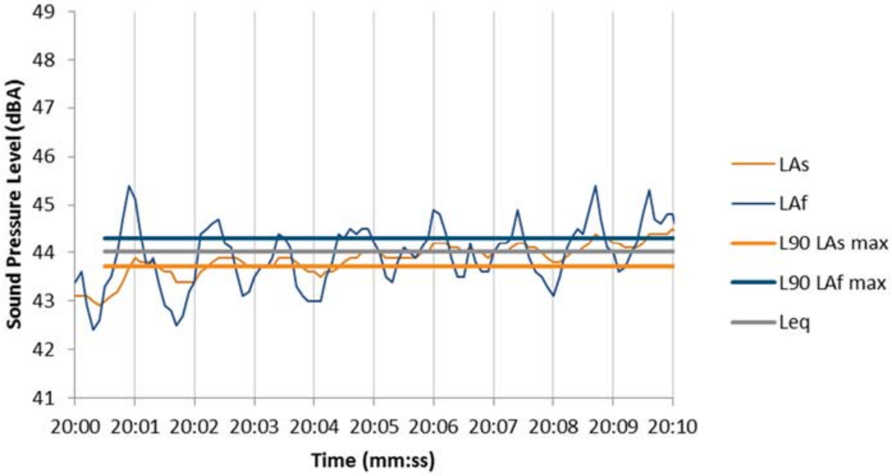

FIGURE 6: SAME AS FIGURE 5, SHOWING OVERALL METRICS

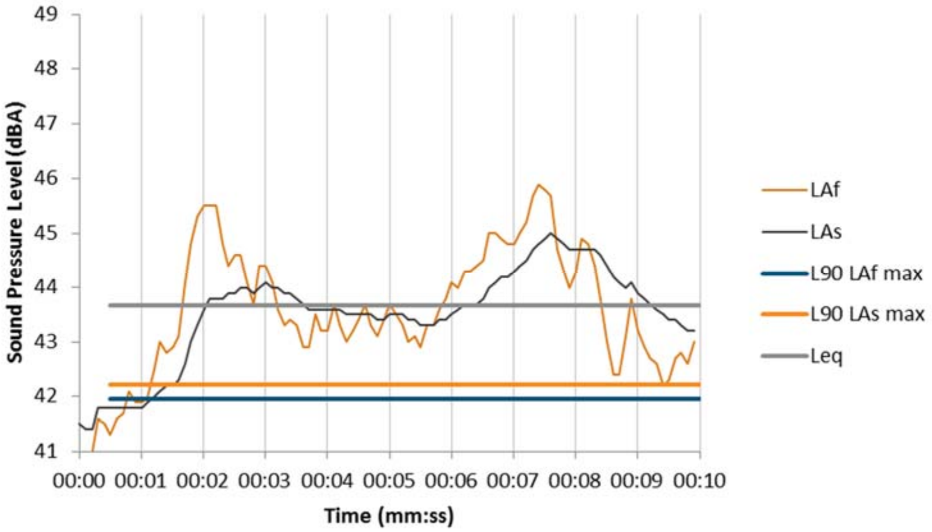

FIGURE 7: OVERALL METRICS FOR A 10-SECOND SAMPLE OF BACKGROUND SOUND

Using the Leq to measure wind turbine sound tends to yield repeatable and predictable results. Leq is the standard used by turbine manufacturers to determine sound power level. It more heavily weights higher sound levels over time, so it would reflect the increases in sound level over a period better than the L_{90}. Subtracting the background sound level from an Leq is also straightforward.

However, if one would like to take into consideration the crest of the amplitude modulation, then the L_{90} (10th percentile) of a series of one-second L_{Fmax} readings is an option we will further consider. As shown in Figure 5, the L_{90} of the one-second L_{Fmax} weights the higher sound levels from the amplitude-modulated crests, but as the maximum level of the crests move up and down over time, this metric would represent the lowest 10th percentile of those crests. In any case, the metric may still include much of the wind turbine sound that is below the crest.

One important advantage of using the L_{90} metric is that it is consistent with the current MassDEP practice of using L_{90} during background measurements. By using the same metric, when one compares the L_{90} from background sound to the L_{90} when the turbine is operating, there is greater confidence that the difference in sound level is due to the additional sound from the wind turbines alone. Using the same L_{Fmax} metric also accounts for the amplitude modulation of the wind turbine. The L_{90} tends to filter out extraneous noise from short-term, non-wind-turbine events. Finally, it allows for a greater statistical confidence in the resulting measurement. It is important to keep in mind that, since the L_{90} represents the lower, more constant sound levels during a given period, it will not include 90 percent of higher wind turbine sound crests and/or contaminating background sound.

The Leq, on the other hand, has the advantage that it is an energy average. There are two benefits to this. The first is that one-second average sound levels can be further averaged together to yield true five-minute (or any other period) averages. As a result, one can subtract turbine-off Leqs from turbine-on Leqs to get accurate turbine-only Leqs. This cannot be done using statistical sound levels like L_{90} and L_{max}. The second advantages is that it gives greater weights the higher sound levels during the given averaging period, which is similar to human reaction to sound. A drawback of using the Leq metric is that higher background sounds can more easily contaminate it as compared to the L_{90} metric.

Section 5.3 contains a more detailed comparison of these metrics using the data collected in this study.

5.2 | METHODOLOGY FOR PROCESSING DATA

LONG-TERM SOUND LEVEL DATA PROCESSING

The levels and metrics analyses focus on the long-term data.

In this section, all levels were standardized to one-second. For example, if data were logged at 0.1 second intervals, the ten samples in each second would be combined into one-second metrics, such as Leq, L_{max}, L_{min}, etc. where appropriate. Sound level data were then synchronized in time with their respective meteorological and turbine operational data in periods that spanned the period from one hour before each turbine shutdown until one hour after the turbine restarted. Over the course of this study, a total of 187 shutdown measurements were successfully completed across the five sites.

The data for each shutdown at each location was graphed and manually reviewed. If the turbine shutdown was not clearly indicated by a coincident drop in the A-weighted sound level, then that period was set aside. We primarily looked at the differences in the L_{90} between turbine-on and turbine-off, as other metrics were more sensitive to background sound contamination.

Of the 187 shutdowns, 43 (23%) showed clear and discernible differences in A-weighted levels between the background and turbine-on conditions. These were labeled as “Discernible” shutdowns. Another 23 (12%) showed differences in unweighted or C-weighted sound levels and small differences in the A-weighted sound level. These were labeled as “Fair” shutdowns. Any shutdowns that did not meet either of these criteria were labeled as “Indiscernible” shutdowns.

For each Discernible shutdown, a more detailed analysis was conducted. The one-second sound levels were processed into five-minute levels before, during, and after each shutdown. Descriptive statistics, including arithmetic averages and standard deviations, were computed.

GRAPHING AND SCREENING SOUND LEVELS AROUND SHUTDOWNS

Sound levels and statistics around each of the 43 Discernible shutdowns at 24 measurement locations are provided in Appendix B. Table 2 and Table 3 summarize these shutdowns.

TABLE 2: PERCENT SHUTDOWNS INDISCERNIBLE, FAIR, AND DISCERNIBLE, BY DISTANCE AND RELATIVE DIRECTION TO THE PREVAILING WIND – FLAT SITES

Relative Location	Distance (m)	Indiscernible	Fair	Discernible
Downwind	330	57%	25%	18%
	660	88%	5%	7%
	990	90%	6%	3%
Crosswind	330	68%	20%	12%
	660	84%	16%	0%
	990	N/A	N/A	N/A
Upwind	330	68%	23%	8%
	660	100%	0%	0%
	990	N/A	N/A	N/A
Total	N/A	76%	16%	8%

TABLE 3: PERCENT SHUTDOWNS INDISCERNIBLE, FAIR, AND DISCERNIBLE BY DISTANCE AND RELATIVE DIRECTION TO THE PREVAILING WIND – MOUNTAINOUS SITE

Relative Location	Distance (m)	Indiscernible	Fair	Discernible
Downwind	330	N/A	N/A	N/A
	660	22%	28%	50%
	990	N/A	N/A	N/A
Crosswind	330	N/A	N/A	N/A
	660	89%	0%	11%
	990	N/A	N/A	N/A
Upwind	330	N/A	N/A	N/A
	660	25%	14%	61%
	990	N/A	N/A	N/A
Total	N/A	32%	19%	49%

A specific analysis chart was created for each shutdown. An example of such a chart is shown in Figure 8. It has two major components. The upper portion consists of graphs of the one-second and five-minute time histories of unweighted, A-weighted, and C-weighted sound levels. The lower portion consists of a table showing the numeric values of the plotted metrics and supplemental metrics. The arrows in the figure demonstrate the links between the graphical data and the tabulated data.

The tabulated data are broken up into different sections; each section is assigned a color that is related to its content. Orange, gray, and green are used to signify the unweighted, C-weighted, and A-weighted sound pressure levels, respectively. The pink sections are wind statistics, the blue are the 80-meter height relative wind direction, and the yellow are the turbine power as a percentage of maximum project output. The intensity of each color varies with the value of the metric, where: darker colors represent higher values.

Also plotted but not shown in Appendix B, are graphics of the five-minute unweighted 1/3-octave band sound levels for the same shutdowns (see Figure 9). These plots aid in identification of wind turbine tonality.

Each processed shutdown includes a summary table of the overall sound level metrics. Table 4 lists these metrics for the shutdown event shown in Figure 8. Metrics for the turbine-on and turbine-off period, including minima, maxima, percentiles, and equivalent averages. The standard deviation is included for each metric. The last column in the table is the difference in sound level between the turbine-on and turbine-off periods.

In general, the better metrics for measuring turbine sound would be those with a relatively low standard deviation and greater difference between turbine-on and turbine-off conditions (using the same metric). Since wind turbine sound for each five-minute period tends to change relatively slowly, smaller standard deviations are to be expected while a turbine is operating. When background noise contaminates a measurement, sound levels tend to rise and fall more frequently. For example, car passbys, airplane overflights, and barking dogs will create spikes in the data, especially when residual background sound (L_{90}) is low. This volatility in level results in higher standard deviation when comparing one period to the next.

As noted above, a good metric also shows a greater difference between turbine-on and turbine-off levels. When measuring wind turbines in the presence of background sound, one has greater confidence that that the prevailing sound is due to the wind turbine if the sound levels decline significantly when the turbines are turned off and return to previous, higher levels when the turbine is turned on. A metric that does not behave in this way for a given location is potentially contaminated with higher levels of background sound. An example case is one where the L_{90} decreases from 40 dB to 35 dB at shutdown, while the Leq decreases from 43 dB to 41 dB. One can report with confidence that the wind turbine is responsible for the decline in the L_{90}. However, with only a two 2 dB difference in the Leq, there is only a small confidence that the difference is due to the wind turbine.[3]

Table 5 is created for shutdowns where fast and/or slow response sound levels are available. It is used to evaluate special metrics, such as the L_{90} of the A-weighted L_{Fmax}. Minimum, maximum, and statistical levels of these metrics are shown.

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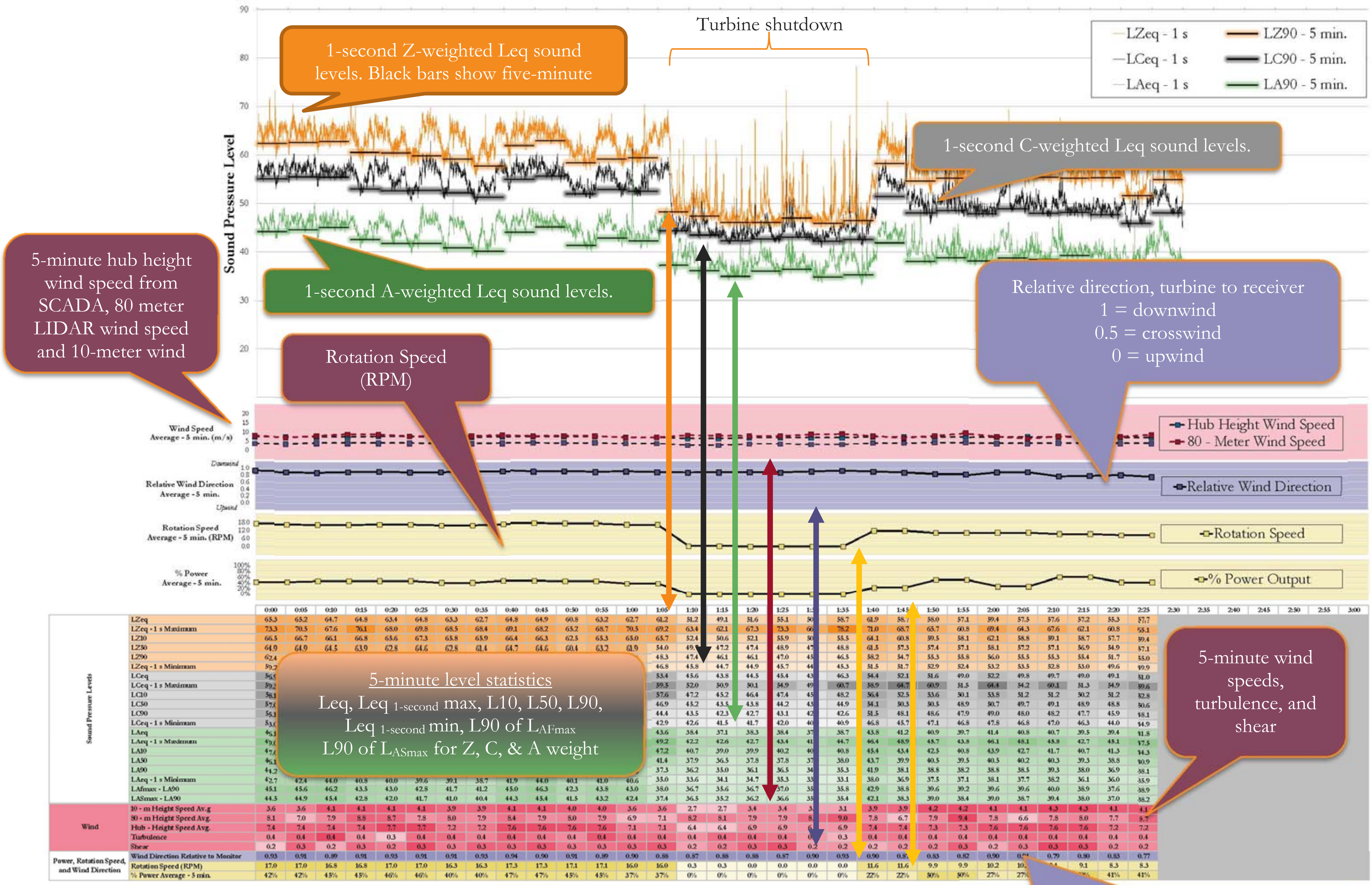
[3] The ANSI S12.18 standard, "Procedures for Outdoor Measurement of Sound Pressure Level," is frequently used as the basis for environmental sound measurements. It states, "if the increase in sound pressure level in any given band, with the sound source operating, compared to the background sound pressure level is 3 decibels or less, the sound pressure level due to the sound source is equal to or less than the background sound pressure level, and the two contributions cannot be properly separated with the measuring techniques described in this standard."



1-second Z-weighted Leq sound levels. Black bars show five-minute

1-second C-weighted Leq sound levels.

5-minute hub height wind speed from SCADA, 80 meter LIDAR wind speed and 10-meter wind

1-second A-weighted Leq sound levels.

Rotation Speed (RPM)

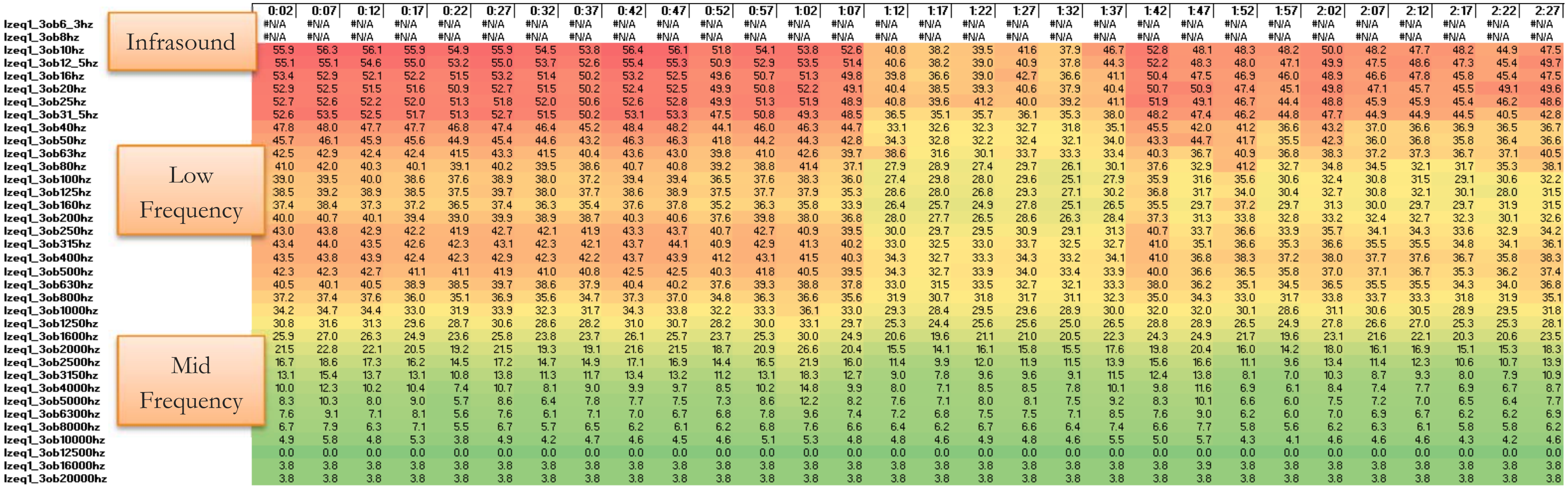
Relative direction, turbine to receiver
1 = downwind
0.5 = crosswind
0 = upwind

5-minute level statistics
Leq, Leq $_{\text{1-second}}$ max, L10, L50, L90,
Leq $_{\text{1-second}}$ min, L90 of L_{AFmax}
L90 of L_{ASmax} for Z, C, & A weight

5-minute wind speeds, turbulence, and shear

FIGURE 8: SHUTDOWN ANALYSIS: EXAMPLE OF A CLEAR SHUTDOWN AND DESCRIPTIVE STATISTICS

Relative wind direction, Turbine power (as a percent of maximum), and Turbine Rotation Speed (RPM)



	0:02	0:07	0:12	0:17	0:22	0:27	0:32	0:37	0:42	0:47	0:52	0:57	1:02	1:07	1:12	1:17	1:22	1:27	1:32	1:37	1:42	1:47	1:52	1:57	2:02	2:07	2:12	2:17	2:22	2:27
lzeq1_3ob6_3hz	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
lzeq1_3ob8hz	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
lzeq1_3ob10hz	55.9	56.3	56.1	55.9	54.9	55.9	54.5	53.8	56.4	56.1	51.8	54.1	53.8	52.6	40.8	38.2	39.5	41.6	37.9	46.7	52.8	48.1	48.3	48.2	50.0	48.2	47.7	48.2	44.9	47.5
lzeq1_3ob12_5hz	55.1	55.1	54.6	55.0	53.2	55.0	53.7	52.6	55.4	55.3	50.9	52.9	53.5	51.4	40.6	38.2	39.0	40.9	37.8	44.3	52.2	48.3	48.0	47.1	49.9	47.5	48.6	47.3	45.4	49.7
lzeq1_3ob16hz	53.4	52.9	52.1	52.2	51.5	53.2	51.4	50.2	53.2	52.5	49.6	50.7	51.3	49.8	39.8	36.6	39.0	42.7	36.6	41.1	50.4	47.5	46.9	46.0	48.9	46.6	47.8	45.8	45.4	47.5
lzeq1_3ob20hz	52.9	52.5	51.5	51.6	50.9	52.7	51.5	50.2	52.4	52.5	49.9	50.8	52.2	49.1	40.4	38.5	39.3	40.6	37.9	40.4	50.7	50.9	47.4	45.1	49.8	47.1	45.7	45.5	49.1	49.6
lzeq1_3ob25hz	52.7	52.6	52.2	52.0	51.3	51.8	52.0	50.6	52.6	52.8	49.9	51.3	51.9	48.9	40.8	39.6	41.2	40.0	39.2	41.1	51.9	49.1	46.7	44.4	48.8	45.9	45.9	45.4	46.2	48.6
lzeq1_3ob31_5hz	52.6	53.5	52.5	51.7	51.3	52.7	51.5	50.2	53.1	53.3	47.5	50.8	49.3	48.5	36.5	35.1	35.7	36.1	35.3	38.0	48.2	47.4	46.2	44.8	47.7	44.9	44.9	44.5	40.5	42.8
lzeq1_3ob40hz	47.8	48.0	47.7	47.7	46.8	47.4	46.4	45.2	48.4	48.2	44.1	46.0	46.3	44.7	33.1	32.6	32.3	32.7	31.8	35.1	45.5	42.0	41.2	36.6	43.2	37.0	36.6	36.9	36.5	36.7
lzeq1_3ob50hz	45.7	46.1	45.9	45.6	44.9	45.4	44.6	43.2	46.3	46.3	41.8	44.2	44.3	42.8	34.3	32.8	32.2	32.4	32.1	34.0	43.3	44.7	41.7	35.5	42.3	36.0	36.8	35.8	36.4	36.6
lzeq1_3ob63hz	42.5	42.9	42.4	42.4	41.5	43.3	41.5	40.4	43.6	43.0	39.8	41.0	42.6	39.7	38.6	31.6	30.1	33.7	33.3	33.4	40.3	36.7	40.9	36.8	38.3	37.2	37.3	36.7	37.1	40.5
lzeq1_3ob80hz	41.0	42.0	40.3	40.1	39.1	40.2	39.5	38.6	40.7	40.8	39.2	38.8	41.4	37.1	27.9	28.9	27.4	29.7	26.1	30.1	37.6	32.9	41.2	32.7	34.8	34.5	32.1	31.7	35.3	38.1
lzeq1_3ob100hz	39.0	39.5	40.0	38.6	37.6	38.9	38.0	37.2	39.4	39.4	36.5	37.6	38.3	36.0	27.4	29.8	28.0	29.6	25.1	27.9	35.9	31.6	35.6	30.6	32.4	30.8	31.5	29.1	30.6	32.2
lzeq1_3ob125hz	38.5	39.2	38.9	38.5	37.5	39.7	38.0	37.7	38.6	38.9	37.5	37.7	37.9	35.3	28.6	28.0	26.8	29.3	27.1	30.2	36.8	31.7	34.0	30.4	32.7	30.8	32.1	30.1	28.0	31.5
lzeq1_3ob160hz	37.4	38.4	37.3	37.2	36.5	37.4	36.3	35.4	37.6	37.8	35.2	36.3	35.8	33.9	26.4	25.7	24.9	27.8	25.1	26.5	35.5	29.7	37.2	29.7	31.3	30.0	29.7	29.7	31.9	31.5
lzeq1_3ob200hz	40.0	40.7	40.1	39.4	39.0	39.9	38.9	38.7	40.3	40.6	37.6	39.8	38.0	36.8	28.0	27.7	26.5	28.6	26.3	28.4	37.3	31.3	33.8	32.8	33.2	32.4	32.7	32.3	30.1	32.6
lzeq1_3ob250hz	43.0	43.8	42.9	42.2	41.9	42.7	42.1	41.9	43.3	43.7	40.7	42.7	40.9	39.5	30.0	29.7	29.5	30.9	29.1	31.3	40.7	33.7	36.6	33.9	35.7	34.1	34.3	33.6	32.9	34.2
lzeq1_3ob315hz	43.4	44.0	43.5	42.6	42.3	43.1	42.3	42.1	43.7	44.1	40.9	42.9	41.3	40.2	33.0	32.5	33.0	33.7	32.5	32.7	41.0	35.1	36.6	35.3	36.6	35.5	35.5	34.8	34.1	36.1
lzeq1_3ob400hz	43.5	43.8	43.9	42.4	42.3	42.9	42.3	42.2	43.7	43.9	41.2	43.1	41.5	40.3	34.3	32.7	33.3	34.3	33.2	34.1	41.0	36.8	38.3	37.2	38.0	37.7	37.6	36.7	35.8	38.3
lzeq1_3ob500hz	42.3	42.3	42.7	41.1	41.1	41.9	41.0	40.8	42.5	42.5	40.3	41.8	40.5	39.5	34.3	32.7	33.9	34.0	33.4	33.9	40.0	36.6	36.5	35.8	37.0	37.1	36.7	35.3	36.2	37.4
lzeq1_3ob630hz	40.5	40.1	40.5	38.9	38.5	39.7	38.6	37.9	40.4	40.2	37.6	39.3	38.8	37.8	33.0	31.5	33.5	32.7	32.1	33.3	38.0	36.2	35.1	34.5	36.5	35.5	35.5	34.3	34.0	36.8
lzeq1_3ob800hz	37.2	37.4	37.6	36.0	35.1	36.9	35.6	34.7	37.3	37.0	34.8	36.3	36.6	35.6	31.9	30.7	31.8	31.7	31.1	32.3	35.0	34.3	33.0	31.7	33.8	33.7	33.3	31.8	31.9	35.1
lzeq1_3ob1000hz	34.2	34.7	34.4	33.0	31.9	33.9	32.3	31.7	34.3	33.8	32.2	33.3	36.1	33.0	29.3	28.4	29.5	29.6	28.9	30.0	32.0	32.0	30.1	28.6	31.1	30.6	30.5	28.9	29.5	31.8
lzeq1_3ob1250hz	30.8	31.6	31.3	29.6	28.7	30.6	28.6	28.2	31.0	30.7	28.2	30.0	33.1	29.7	25.3	24.4	25.6	25.6	25.0	26.5	28.8	28.9	26.5	24.9	27.8	26.6	27.0	25.3	25.3	28.1
lzeq1_3ob1600hz	25.9	27.0	26.3	24.9	23.6	25.8	23.8	23.7	26.1	25.7	23.7	25.3	30.0	24.9	20.6	19.6	21.1	21.0	20.5	22.3	24.3	24.9	21.7	19.6	23.1	21.6	22.1	20.3	20.6	23.5
lzeq1_3ob2000hz	21.5	22.8	22.1	20.5	19.2	21.5	19.3	19.1	21.6	21.5	18.7	20.9	26.6	20.4	15.5	14.1	16.1	15.8	15.5	17.6	19.8	20.4	16.0	14.2	18.0	16.1	16.9	15.1	15.3	18.3
lzeq1_3ob2500hz	16.7	18.6	17.3	16.2	14.5	17.2	14.7	14.9	17.1	16.9	14.4	16.5	21.9	16.0	11.4	9.9	12.0	11.9	11.5	13.9	15.6	16.6	11.1	9.6	13.4	11.4	12.3	10.6	10.7	13.9
lzeq1_3ob3150hz	13.1	15.4	13.7	13.1	10.8	13.8	11.3	11.7	13.4	13.2	11.2	13.1	18.3	12.7	9.0	7.8	9.6	9.6	9.1	11.5	12.4	13.8	8.1	7.0	10.3	8.7	9.3	8.0	7.9	10.9
lzeq1_3ob4000hz	10.0	12.3	10.2	10.4	7.4	10.7	8.1	9.0	9.9	9.7	8.5	10.2	14.8	9.9	8.0	7.1	8.5	8.5	7.8	10.1	9.8	11.6	6.9	6.1	8.4	7.4	7.7	6.9	6.7	8.7
lzeq1_3ob5000hz	8.3	10.3	8.0	9.0	5.7	8.6	6.4	7.8	7.7	7.5	7.3	8.6	12.2	8.2	7.6	7.1	8.0	8.1	7.5	9.2	8.3	10.1	6.6	6.0	7.5	7.2	7.0	6.5	6.4	7.7
lzeq1_3ob6300hz	7.6	9.1	7.1	8.1	5.6	7.6	6.1	7.1	7.0	6.7	6.8	7.8	9.6	7.4	7.2	6.8	7.5	7.5	7.1	8.5	7.6	9.0	6.2	6.0	7.0	6.9	6.7	6.2	6.2	6.9
lzeq1_3ob8000hz	6.7	7.9	6.3	7.1	5.5	6.7	5.7	6.5	6.2	6.1	6.2	6.8	7.6	6.6	6.4	6.2	6.7	6.6	6.4	7.4	6.6	7.7	5.8	5.6	6.2	6.3	6.1	5.8	5.8	6.2
lzeq1_3ob10000hz	4.9	5.8	4.8	5.3	3.8	4.9	4.2	4.7	4.6	4.5	4.6	5.1	5.3	4.8	4.8	4.6	4.9	4.8	4.6	5.5	5.0	5.7	4.3	4.1	4.6	4.6	4.6	4.3	4.2	4.6
lzeq1_3ob12500hz	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
lzeq1_3ob16000hz	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.9	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8
lzeq1_3ob20000hz	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8

FIGURE 9: SHUTDOWN ANALYSIS: GRAPHIC OF 1/3-OCTAVE BAND LEVELS AROUND THE SAME SHUTDOWN IN FIGURE 8

1/3-octave bands from 6.3 Hz to 20,000 Hz from top to bottom, time from left to right, redder colors are higher values

TABLE 4: SHUTDOWN ANALYSIS: EXAMPLE OF FIVE-MINUTE SOUND LEVEL METRICS AROUND A SHUTDOWN EVENT SHOWN IN FIGURE 8 (IN DECIBELS)

Level	5 min. Metric	Turbine On	St Dev	Turbine Off	St Dev	Level Difference
LZeq	Lmin	55.3	3.8	45.5	0.7	9.8
	L90	57.9	3.9	46.8	0.9	11.1
	L50	60.5	4.1	49.0	2.4	11.4
	L10	63.1	3.6	54.5	5.4	8.6
	Lmax	68.4	4.1	67.0	3.7	1.3
	Leq	61.4	3.2	53.0	4.1	8.3
LCeq	Lmin	49.3	3.4	41.9	0.7	7.4
	L90	51.0	3.4	43.0	0.8	8.0
	L50	53.1	3.5	44.5	1.2	8.6
	L10	55.2	3.3	48.2	4.3	7.0
	Lmax	59.1	3.4	52.9	3.4	6.3
	Leq	53.5	3.3	46.1	3.4	7.5
LAeq	Lmin	39.3	2.6	34.4	0.6	4.9
	L90	40.9	2.7	36.0	0.8	4.9
	L50	42.9	2.8	38.1	1.6	4.9
	L10	45.0	2.6	41.2	2.7	3.8
	Lmax	48.0	2.8	43.7	2.5	4.3
	Leq	43.3	2.6	38.9	2.1	4.4
LAf max	Lmin	39.9	2.7	34.9	0.7	5.0
	L90	41.8	2.8	36.6	0.9	5.2
	L50	44.0	2.9	38.7	1.7	5.3
	L10	46.4	2.8	42.1	3.1	4.3
	Lmax	49.7	2.9	44.6	2.9	5.1
LAs max	Lmin	39.6	2.7	34.6	0.6	5.0
	L90	41.1	2.8	36.2	0.8	4.9
	L50	43.1	2.8	38.2	1.6	4.9
	L10	45.1	2.6	41.3	2.8	3.8
	Lmax	47.6	2.9	43.3	2.5	4.3

TABLE 5: SHUTDOWN ANALYSIS: SPECIAL A-WEIGHTED FIVE-MINUTE FAST- AND SLOW-RESPONSE SOUND LEVEL STATISTICS AROUND THE SHUTDOWN EVENT SHOWN IN FIGURE 8

	0:00	0:05	0:10	0:15	0:20	0:25	0:30	0:35	0:40	0:45	0:50
Lafmx - 1 s Maximum	**51.8**	**50.7**	**50.9**	**49.7**	**50.5**	**53.4**	**52.1**	**51.9**	**51.8**	**50.4**	**47.9**
Lafmx10	**49.3**	**49.3**	**49.5**	**48.1**	**48.3**	**49.3**	**48.2**	**48.5**	**49.6**	**48.8**	**46.5**
Lafmx50	**47.1**	**47.6**	**47.6**	**45.9**	**45.6**	**47.0**	**45.8**	**44.6**	**47.4**	**47.4**	**44.6**
Lafmx90	**45.1**	**45.6**	**46.2**	**43.5**	**43.0**	**42.8**	**41.7**	**41.2**	**45.0**	**46.3**	**42.3**
Lafmx - 1 s Minimum	**43.1**	**43.4**	**44.9**	**41.4**	**40.5**	**40.2**	**40.1**	**39.3**	**42.5**	**44.6**	**41.0**
Lasmx - 1 s Maximum	**49.0**	**49.9**	**48.8**	**48.1**	**48.3**	**49.7**	**49.7**	**48.7**	**49.0**	**48.4**	**46.8**
Lasmx10	**47.8**	**47.6**	**47.8**	**46.8**	**46.7**	**47.8**	**46.8**	**47.3**	**47.9**	**47.3**	**45.5**
Lasmx50	**46.1**	**46.5**	**46.3**	**45.0**	**44.3**	**46.1**	**44.9**	**43.5**	**46.4**	**46.3**	**43.8**
Lasmx90	**44.5**	**44.9**	**45.4**	**42.8**	**42.0**	**41.7**	**41.0**	**40.4**	**44.3**	**45.4**	**41.5**
Lasmx - 1 s Minimum	**42.8**	**42.7**	**44.3**	**41.1**	**40.3**	**40.0**	**39.6**	**38.9**	**42.1**	**44.4**	**40.8**

5.3 | SOUND LEVELS SPANNING TURBINE SHUTDOWNS

Measurement locations at each site were classified as upwind, downwind, or crosswind relative to the prevailing wind direction. An upwind location would be where the prevailing wind direction is from a particular measurement location toward the wind turbine(s). A crosswind location is one where the prevailing wind is at an angle of 90 degrees, either to the right or to the left of the wind turbine. A downwind location has the prevailing wind blowing from the turbine(s) toward the location. While this classification looks at the prevailing wind direction, Section 6 of this report analyzes the sound level using the actual compass wind direction during each 30-second period.

Next, all of the five-minute sound levels within one hour of the start or end of a Discernible shutdown[4] were averaged. The results for all flat sites are shown in Figure 10. The figure shows five tables that represent, from top to bottom, the upwind locations at 330 meters, the crosswind locations at 330 meters (left and right of the turbine are not distinguished), and the downwind locations at 330 meters, 660 meters, and 990 meters. Additional locations at further distances, both upwind and crosswind, were measured, but the shutdowns were not discernible there. The data in each table of the Figure are colored from red through yellow to green, indicating a scale from the highest to the lowest levels, respectively.

The first column in each table of Figure 10 is the turbine-on sound level. Since the C-weighted levels will almost always be greater than the A-weighted levels, the top of the table, where the C-levels are shown, will be a darker red (higher levels). Within each level (LCeq, LAeq, L_{AFmax}, L_{ASmax}) the shading will generally go from dark green to dark red, from top to bottom, since the metrics are going from a minimum to a maximum. The exception is for the LCeq and LAeq, where the last row is the five-minute Leq, which is lower than the Lmax. The second column shows the standard deviation of the turbine-on sound levels. Higher values indicate a greater variance in the five-minute sound levels while the turbine is on. Since five-minute wind turbine sound metrics are usually consistent, a larger standard deviation is generally indicative of variation due to other sounds in the background.

The metrics listed in the fifth and sixth columns in each table are similar to the third and fourth columns, but they apply during the turbine-off period. Where there is a great deal of background noise contamination, we would expect the turbine-on and turbine-off columns to be similar. The last column in each table lists the differences in sound level between the turbine-on and turbine-off conditions; the greater the difference, the more effective that metric is at indicating changes due to turbine operations.

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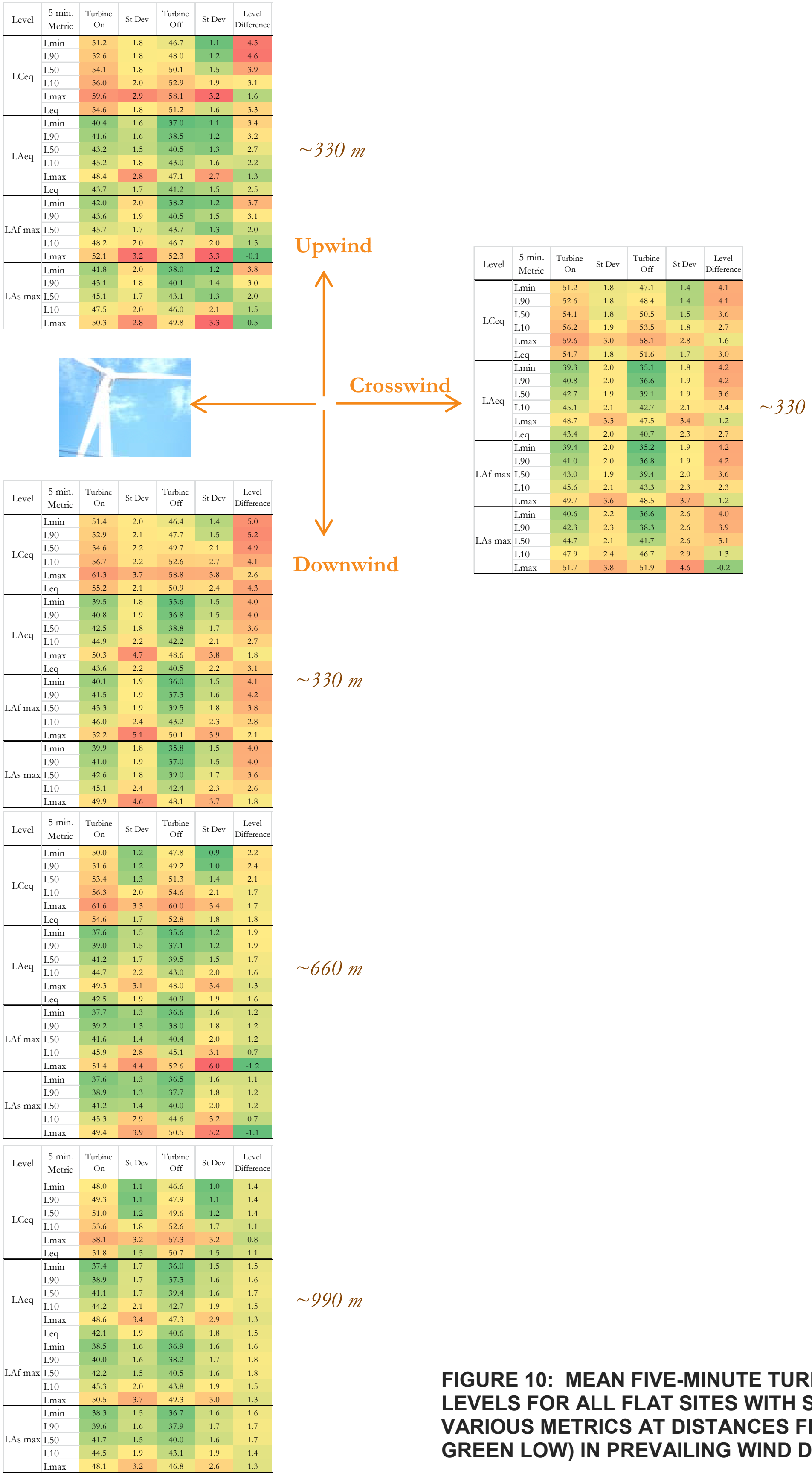
[4] A "Discernible" shutdown is one where at least one measurement location shows a clear drop in A-weighted sound level during the shutdown period. If one location is good, then all locations are analyzed for that shutdown.



Upwind, ~330 m

Level	5 min. Metric	Turbine On	St Dev	Turbine Off	St Dev	Level Difference
LCeq	Lmin	51.2	1.8	46.7	1.1	4.5
	L90	52.6	1.8	48.0	1.2	4.6
	L50	54.1	1.8	50.1	1.5	3.9
	L10	56.0	2.0	52.9	1.9	3.1
	Lmax	59.6	2.9	58.1	3.2	1.6
	Leq	54.6	1.8	51.2	1.6	3.3
LAeq	Lmin	40.4	1.6	37.0	1.1	3.4
	L90	41.6	1.6	38.5	1.2	3.2
	L50	43.2	1.5	40.5	1.3	2.7
	L10	45.2	1.8	43.0	1.6	2.2
	Lmax	48.4	2.8	47.1	2.7	1.3
	Leq	43.7	1.7	41.2	1.5	2.5
LAf max	Lmin	42.0	2.0	38.2	1.2	3.7
	L90	43.6	1.9	40.5	1.5	3.1
	L50	45.7	1.7	43.7	1.3	2.0
	L10	48.2	2.0	46.7	2.0	1.5
	Lmax	52.1	3.2	52.3	3.3	-0.1
LAs max	Lmin	41.8	2.0	38.0	1.2	3.8
	L90	43.1	1.8	40.1	1.4	3.0
	L50	45.1	1.7	43.1	1.3	2.0
	L10	47.5	2.0	46.0	2.1	1.5
	Lmax	50.3	2.8	49.8	3.3	0.5

Crosswind, ~330

Level	5 min. Metric	Turbine On	St Dev	Turbine Off	St Dev	Level Difference
LCeq	Lmin	51.2	1.8	47.1	1.4	4.1
	L90	52.6	1.8	48.4	1.4	4.1
	L50	54.1	1.8	50.5	1.5	3.6
	L10	56.2	1.9	53.5	1.8	2.7
	Lmax	59.6	3.0	58.1	2.8	1.6
	Leq	54.7	1.8	51.6	1.7	3.0
LAeq	Lmin	39.3	2.0	35.1	1.8	4.2
	L90	40.8	2.0	36.6	1.9	4.2
	L50	42.7	1.9	39.1	1.9	3.6
	L10	45.1	2.1	42.7	2.1	2.4
	Lmax	48.7	3.3	47.5	3.4	1.2
	Leq	43.4	2.0	40.7	2.3	2.7
LAf max	Lmin	39.4	2.0	35.2	1.9	4.2
	L90	41.0	2.0	36.8	1.9	4.2
	L50	43.0	1.9	39.4	2.0	3.6
	L10	45.6	2.1	43.3	2.3	2.3
	Lmax	49.7	3.6	48.5	3.7	1.2
LAs max	Lmin	40.6	2.2	36.6	2.6	4.0
	L90	42.3	2.3	38.3	2.6	3.9
	L50	44.7	2.1	41.7	2.6	3.1
	L10	47.9	2.4	46.7	2.9	1.3
	Lmax	51.7	3.8	51.9	4.6	-0.2

Downwind, ~330 m

Level	5 min. Metric	Turbine On	St Dev	Turbine Off	St Dev	Level Difference
LCeq	Lmin	51.4	2.0	46.4	1.4	5.0
	L90	52.9	2.1	47.7	1.5	5.2
	L50	54.6	2.2	49.7	2.1	4.9
	L10	56.7	2.2	52.6	2.7	4.1
	Lmax	61.3	3.7	58.8	3.8	2.6
	Leq	55.2	2.1	50.9	2.4	4.3
LAeq	Lmin	39.5	1.8	35.6	1.5	4.0
	L90	40.8	1.9	36.8	1.5	4.0
	L50	42.5	1.8	38.8	1.7	3.6
	L10	44.9	2.2	42.2	2.1	2.7
	Lmax	50.3	4.7	48.6	3.8	1.8
	Leq	43.6	2.2	40.5	2.2	3.1
LAf max	Lmin	40.1	1.9	36.0	1.5	4.1
	L90	41.5	1.9	37.3	1.6	4.2
	L50	43.3	1.9	39.5	1.8	3.8
	L10	46.0	2.4	43.2	2.3	2.8
	Lmax	52.2	5.1	50.1	3.9	2.1
LAs max	Lmin	39.9	1.8	35.8	1.5	4.0
	L90	41.0	1.9	37.0	1.5	4.0
	L50	42.6	1.8	39.0	1.7	3.6
	L10	45.1	2.4	42.4	2.3	2.6
	Lmax	49.9	4.6	48.1	3.7	1.8

Downwind, ~660 m

Level	5 min. Metric	Turbine On	St Dev	Turbine Off	St Dev	Level Difference
LCeq	Lmin	50.0	1.2	47.8	0.9	2.2
	L90	51.6	1.2	49.2	1.0	2.4
	L50	53.4	1.3	51.3	1.4	2.1
	L10	56.3	2.0	54.6	2.1	1.7
	Lmax	61.6	3.3	60.0	3.4	1.7
	Leq	54.6	1.7	52.8	1.8	1.8
LAeq	Lmin	37.6	1.5	35.6	1.2	1.9
	L90	39.0	1.5	37.1	1.2	1.9
	L50	41.2	1.7	39.5	1.5	1.7
	L10	44.7	2.2	43.0	2.0	1.6
	Lmax	49.3	3.1	48.0	3.4	1.3
	Leq	42.5	1.9	40.9	1.9	1.6
LAf max	Lmin	37.7	1.3	36.6	1.6	1.2
	L90	39.2	1.3	38.0	1.8	1.2
	L50	41.6	1.4	40.4	2.0	1.2
	L10	45.9	2.8	45.1	3.1	0.7
	Lmax	51.4	4.4	52.6	6.0	-1.2
LAs max	Lmin	37.6	1.3	36.5	1.6	1.1
	L90	38.9	1.3	37.7	1.8	1.2
	L50	41.2	1.4	40.0	2.0	1.2
	L10	45.3	2.9	44.6	3.2	0.7
	Lmax	49.4	3.9	50.5	5.2	-1.1

Downwind, ~990 m

Level	5 min. Metric	Turbine On	St Dev	Turbine Off	St Dev	Level Difference
LCeq	Lmin	48.0	1.1	46.6	1.0	1.4
	L90	49.3	1.1	47.9	1.1	1.4
	L50	51.0	1.2	49.6	1.2	1.4
	L10	53.6	1.8	52.6	1.7	1.1
	Lmax	58.1	3.2	57.3	3.2	0.8
	Leq	51.8	1.5	50.7	1.5	1.1
LAeq	Lmin	37.4	1.7	36.0	1.5	1.5
	L90	38.9	1.7	37.3	1.6	1.6
	L50	41.1	1.7	39.4	1.6	1.7
	L10	44.2	2.1	42.7	1.9	1.5
	Lmax	48.6	3.4	47.3	2.9	1.3
	Leq	42.1	1.9	40.6	1.8	1.5
LAf max	Lmin	38.5	1.6	36.9	1.6	1.6
	L90	40.0	1.6	38.2	1.7	1.8
	L50	42.2	1.5	40.5	1.6	1.8
	L10	45.3	2.0	43.8	1.9	1.5
	Lmax	50.5	3.7	49.3	3.0	1.3
LAs max	Lmin	38.3	1.5	36.7	1.6	1.6
	L90	39.6	1.6	37.9	1.7	1.7
	L50	41.7	1.5	40.0	1.6	1.7
	L10	44.5	1.9	43.1	1.9	1.4
	Lmax	48.1	3.2	46.8	2.6	1.3

FIGURE 10: MEAN FIVE-MINUTE TURBINE-ON AND TURBINE-OFF LEVELS FOR ALL FLAT SITES WITH STANDARD DEVIATIONS FOR VARIOUS METRICS AT DISTANCES FROM WIND TURBINE(S) (RED HIGH, GREEN LOW) IN PREVAILING WIND DIRECTIONS (IN DECIBELS)

COMPARISON OF THE SOUND LEVEL METRICS

In reviewing all locations, those at distances of 660 meters and 990 meters consistently demonstrate relatively low sound level differences between the turbine-on and turbine-off conditions. At 330 meters downwind, the average difference in the A-weighted L_{90} of the Leq is 4.0 dB. This drops to 1.9 dB at 660 meters and 1.6 dB at 990 meters. The 330-meter upwind and crosswind differences in this metric are 3.2 dB and 4.2 dB, respectively. Note again that these are relative to *prevailing* wind direction, not instantaneous wind direction.

For each position relative to the turbine and for each weighting category (L_{Ceq}, L_{Aeq}, etc.), there is a consistent increase in the level difference (between turbine-on and turbine-off for the same metric) moving from the loudest statistics, like L_{max} to the quietest statistics, like L_{min}. From the greatest to the least sound level difference, the metrics are ordered L_{min} L_{10}, L_{eq}, L_{50}, L_{90}, and L_{max}. For example, using metrics based on the $LAeq_{(1\text{-}sec)}$ for the 330-meters downwind positions (Figure 10), the greatest difference between turbine-on and turbine-off is 4.0 dB for the L_{min} and, in order of decreasing difference, L_{90} (4.0 dB), L_{50} (3.6 dB), Leq (3.1 dB), L_{10} (2.7 dB), and L_{max} (1.8 dB).

The standard deviations for the metrics generally follow a consistent pattern. The lowest standard deviations occur with the quietest statistics and highest standard deviations occur with the louder statistics. Examining the metrics from the same 330-meter downwind locations as above, the standard deviations (with the turbine on) are 1.8 dB (L_{min}), 1.9 dB (L_{90}), 1.8 dB (L_{50}), 2.2 dB (Leq), 2.2 dB (L_{10}), and 4.7 dB (L_{max}).

These patterns in standard deviations are the same for both the turbine-on and turbine-off conditions. That is, higher sound level statistics will have more variance than lower sound level statistics. This higher variance is most likely due to naturally occurring background sounds (see Section 5.2).

DIFFERENCES BETWEEN WEIGHTINGS

Among the metrics used in this report, statistics derived from $LCeq_{(1\text{-}sec)}$ show the greatest differences in level between turbine-on and turbine-off for each of the 330-meter upwind, 330-meter downwind, and 660-meter downwind locations. For the remaining locations, the LCeq, LAeq, L_{AFmax} and L_{ASmax} all have similar level differences within the groups. The reasons why this trend is relevant are discussed further in Section 5.6.

SENSITIVITY OF METRICS

At the 330-meter downwind locations, statistics based on the A-weighted $L_{Fmax\ (1\text{-}sec)}$ are slightly more sensitive to turbine operation than those based on the $Leq_{(1\text{-}sec)}$. That is, the difference between the turbine-on and turbine-off L_{90} of the $L_{Fmax(1\text{-}sec)}$ is 4.2 dB compared with 4.0 dB for the Leq. The turbine-on standard deviation for each metric is about the same, as shown in Table 6.

TABLE 6: COMPARISON BETWEEN THE A-WEIGHTED L_{90} BASED ON $Leq_{(1\text{-SEC})}$ AND L_{Fmax} AT 330 METERS DOWNWIND FOR ALL FLAT SITES, ALL DISCERNIBLE SHUTDOWNS

PARAMETER	L_{90} OF Leq (1-SEC)	L_{90} OF L_{FMAX} (1-SEC)
Turbine-on level	40.8 dBA	41.5 dBA
Turbine-on st. dev.	1.9 dB	1.9 dB
Background level	36.8 dBA	37.3 dBA
Background st. dev.	1.5 dB	1.6 dB
Turbine-on minus background	4.0 dB	4.2 dB

5.4 | RELATIONSHIP OF WIND SPEED TO BACKGROUND L_{90}

MEASUREMENT OF BACKGROUND L_{90}

Five-minute L_{90}s were measured during turbine shutdowns to assess residual background sound levels, totaling 827 five-minute periods among the four sites.

For comparison purposes, one site (arbitrarily named Site 5A) was selected which had less noise contamination: the closest highway was between 0.5 and 1 mile (0.8 to 1.6 km) away from each measurement location. Site 5A was relatively flat had five long-term monitoring locations, including upwind, downwind, and crosswind. The measurement locations were all lightly forested, with most trees bare of leaves during the time of year the monitoring took place.

We only used background L_{90}s during periods when the turbines would otherwise have been operating and when there was no precipitation. It would not be appropriate to include in our analysis L_{90}s for very low wind speeds when the wind turbines would not operate. These periods are not relevant to this wind turbine sound analysis.

The background L_{90}s were collated by time of day. The three locations shown in Figure 11 are all at wind turbine Site 5A, but they were positioned as much as 1.6 miles (2.1 km) apart.

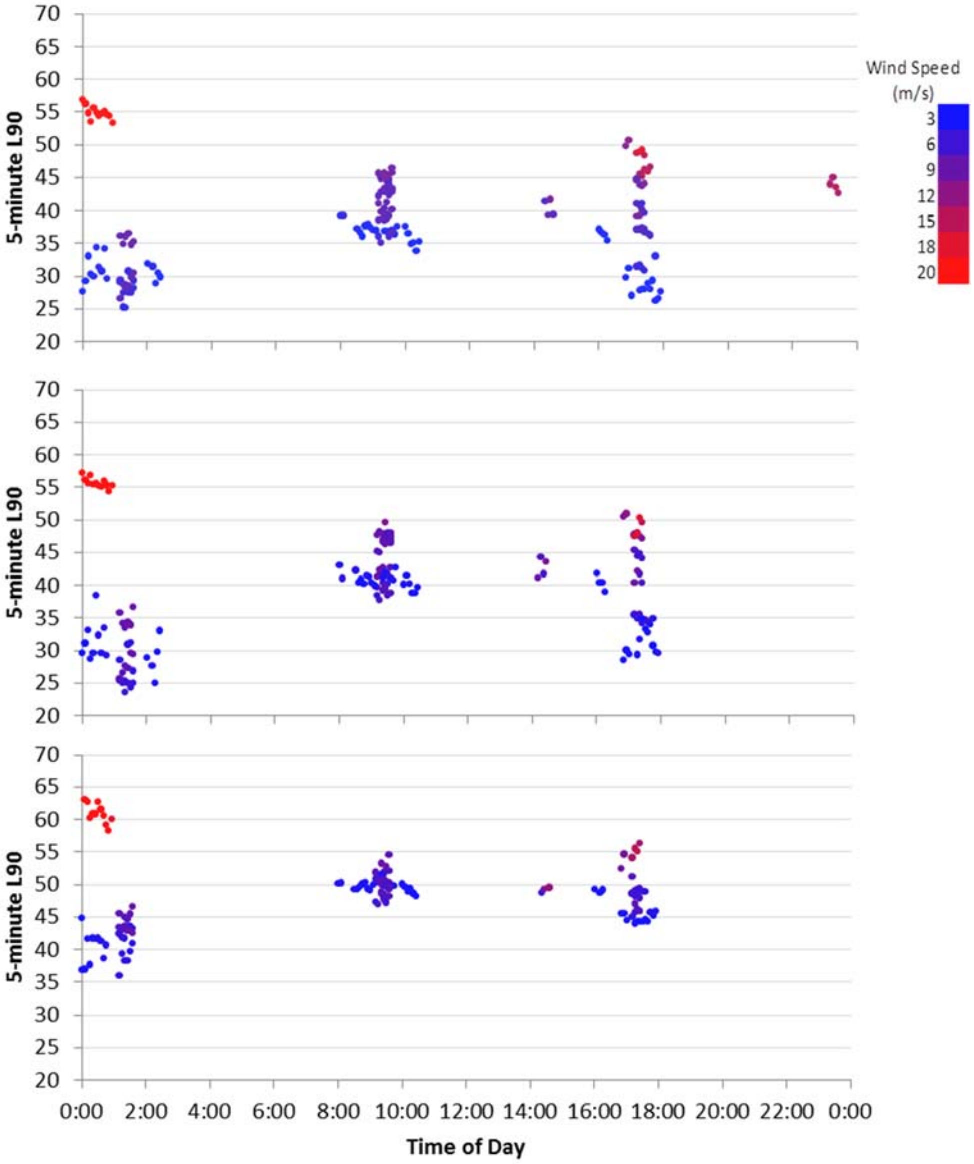


FIGURE 11: BACKGROUND L_{90} VS TIME OF DAY FOR THREE LOCATIONS AT DIFFERENT DISTANCES FROM SITE 5A TURBINE(S)

As shown, the L_{90} within a given time period tends to vary. Just after midnight, the variation is about 30 dB, with the highest outliers resulting from high winds. During midday, the variation is smaller, from 7 to 15 dB, and in the evening, the variation is 12 to 25 dB. Given the relative remoteness of the site, much of the variation in background sound levels within any one time period is likely due to wind and other natural factors.

EFFECT OF WIND ON L_{90}

As noted above, the L_{90} can vary over time. In more remote areas, the most likely factor creating this variance is wind. For the site analyzed above, the effect of wind speed on background sound level was evaluated.

The influence of wind speed is shown by the coloration of the dots in Figure 11, ranging from blue (3 m/s wind speed) to red (20 m/s wind speed) measured at 80 meters. The very high wind speeds correlate with higher sound levels. The mid-range speeds (from 3 m/s to 9 m/s) are less correlated with sound level, depending on the location and time of day. For example, in the middle location of Figure 11, the evening sound levels increase with increasing wind speed, but the early morning sound levels for those wind speeds between 3 and 9 m/s are scattered from 23 dBA to 38 dBA.

The higher nighttime variation may be due to the greater variance in wind shear that occurs at night. The chart in Figure 12 shows Site 5A's wind shear exponent vs. wind speed at 80 meters. The wind shear exponent is a logarithmic function of the vertical wind speed profile,

$$\alpha = \frac{ln\frac{v}{v_0}}{ln\frac{h}{h_0}}$$

where:

α is the wind speed exponent
v and v_0 are the wind speeds at heights h and h_0, respectively.

The greater the wind shear exponent, the greater difference there is between the wind speed aloft and that nearer to the ground. As Figure 12 shows, there is greater variability in nighttime wind shear compared to the daytime, and there is greater variability at lower wind speeds. Thus, we would expect that the background sound level, if it were based on wind speed near the microphone alone, would also show greater variability at night and during lower hub height wind speeds.

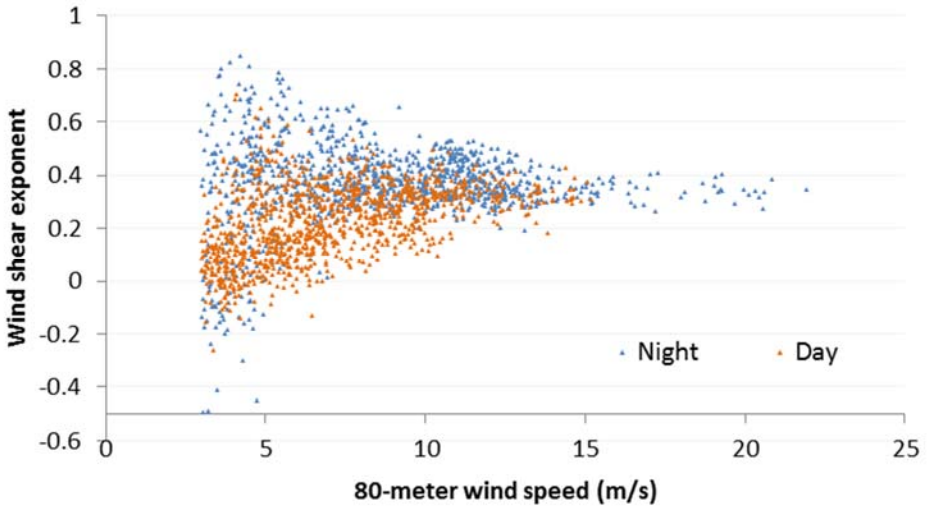


FIGURE 12: WIND SHEAR FROM 120 M TO 40 M FOR SITE 5A [5]

Linear regressions of background L_{90} as a function of 80-meter wind speed were applied for each of the five locations. The regression uses a "t-test" and "F-test" to determine the probability that the dependent variable,

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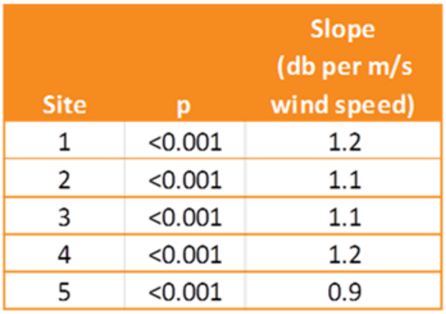
[5] Measurements where wind speeds at 80 meters are below 3 m/s are excluded

in this case the L_{90}, is correlated to the independent variable, wind speed, due to chance alone. A low coefficient of correlation, or p-value, would indicate a low probability that random chance explains the correlation, and thus the two are more likely to be correlated. In this case, for each location, the L_{90} was significantly correlated to 80-meter wind speed with p-values (both F and t-tests) of less than 0.001 (Table 7). On average, there was a 1.1 dB increase in background L_{90} for every 1 m/s increase in 80-meter wind speed.

TABLE 7: LINEAR REGRESSION RESULTS OF FIVE-MINUTE L_{90} AS A FUNCTION OF 80-METER WIND SPEED



Site	p	Slope (db per m/s wind speed)
1	<0.001	1.2
2	<0.001	1.1
3	<0.001	1.1
4	<0.001	1.2
5	<0.001	0.9

While there is a direct and significant relationship of increasing L_{90} with wind speed, there is still a relatively wide variance of L_{90} within each integer wind speed, or wind speed bin. While a trend line or regression analysis can be used to determine the average relationship of hub-height wind speed to sound level, there will always be a variation of sound level within any given wind speed bin due to atmospheric effects such as wind shear, turbulence, and influence from nearby background sources (highways, homes, and water, for example).

5.5 | SOUND SPECTRUM FROM WIND TURBINES

Sound levels for a wind turbine can be expressed using overall metrics, like the Leq and L_{90} as discussed above, or divided into partitions of the complete frequency spectrum. That is, the sound from a wind turbine can be shown as a function of frequency. Doing so can be helpful in assessing effects that are frequency specific, such as tonality or sound-induced vibration and rattle in lightweight structures.

Using the same shutdowns and associated data sets discussed in Section 5.2, five-minute Leqs were calculated for each 1/3-octave band from the one-second data. The data were then screened to include only the closest locations at each site (upwind, downwind, and/or crosswind), and for which the turbine shutdown was discernible. This included the relevant 330-meter locations at the flat sites and the 660-meter locations at the mountainous multi-turbine site.

To determine the turbine-only sound levels, the turbine-off levels were logarithmically subtracted from the turbine-on levels. The results are shown in Figure 13. Each line shows the arithmetic average of all turbine-only $Leq_{(5\text{-min})}$ values for all the shutdowns at a particular measurement location. Figure 14 shows the average spectrum across all the locations, and the standard deviation in each band.

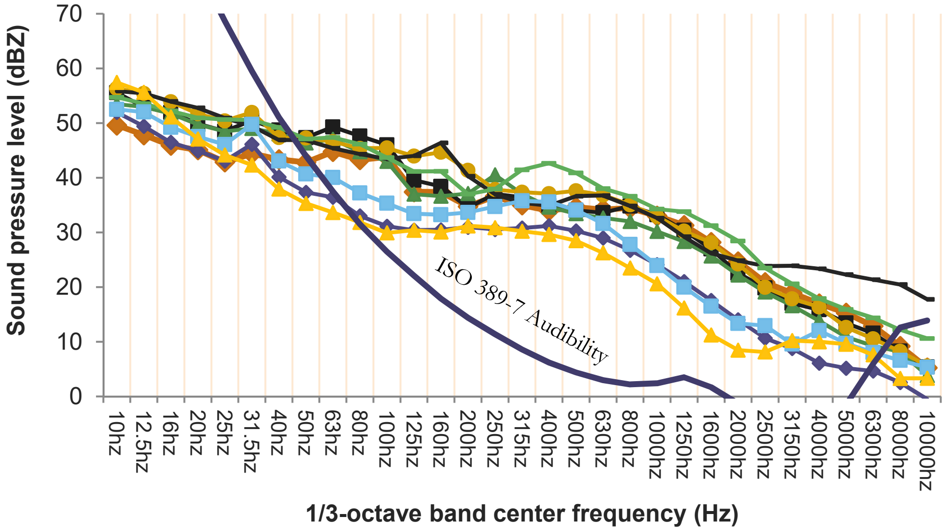


FIGURE 13: MEAN OF 1/3-OCTAVE BAND Leq$_{5\text{-MIN}}$ BY LOCATION

Only 330-meter flat site measurement locations and the 660-meter mountainous site measurement location are shown, and only those locations that had at least one discernible shutdown.

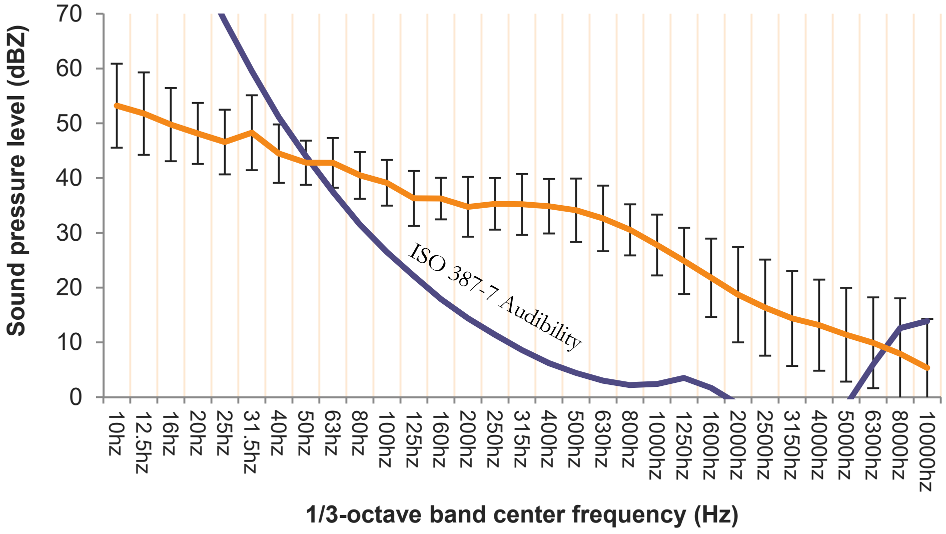


FIGURE 14: 1/3-OCTAVE BAND TURBINE-ONLY MEAN AND STANDARD DEVIATION OF ALL SITES FROM FIGURE 13

There are differences in the overall sound levels at each location. However, without additional context, these differences have little meaning as the turbines were operating at different loads (wind speeds) and wind directions, and the locations vary slightly in distance from the turbines.

Plotted along with the spectral sound levels in Figure 14 is the ISO 389-7 audibility curve, which is based on the median from tests of healthy 18 to 25 year old subjects (see "Audible" in Section 3). The figure shows that wind turbine sound becomes audible in the frequency range from 50 Hz to 80 Hz through 6,300 Hz. At

20 Hz, the highest of these curves is 16 dB below the audibility threshold. The mean of the standard deviations among all locations in the 20 Hz band is 5.6 dB, making it unlikely that sound would exceed the audibility threshold at that frequency and below.

The shapes of the frequency spectra measured at the locations are very similar to one another, decreasing at about -3 dB per octave. Some mechanical sound from the nacelles of the turbines is apparent in some of the curves, showing bumps at 31.5 Hz, 63 Hz, and 160 Hz, depending on the site. None of these are considered tonal sounds (see Section 9), but can serve as markers for wind turbine sound, depending on the turbine model.

5.6 | CONTINUOUS MONITORING METRICS DISCUSSION

We start with the assumption that the ideal sound metric for use in regulation would be one that (1) yields consistent results in the presence of varying levels of background sound, (2) can be reliably predicted using engineering models, and (3) reflects the way people hear and react to sound. While this is discussed in more detail in Section 11.3, we point out that this would, in part, reveal itself in a single metric that is the most sensitive to turbine shutdowns. That is, the metric would changes the most when a turbine is shut and would be relatively insensitive to varying background noise. This would be manifested in lower variability of the metric across time periods having similar conditions.

DISCUSSION OF C- AND Z-WEIGHTED SOUND LEVELS

For analysis of unattended monitoring data conducted in this section of the report, the C- and Z- weighted L_{min} and L_{90}s show the greatest change from turbine-on to turbine-off. That is, even when the A-weighted sound levels do not show discernible change, the C- and Z-weighted sound levels may show discernible change. This is because, as shown in the spectral data from Figure 14, the wind turbines have a relatively larger portion of their emitted acoustical energy in the low-frequency and infrasonic range. Only about 2 to 3 percent of the sound energy from the wind turbines measured in this study is audible.[6] The remainder is sub-audible low-frequency and infrasonic sound. Natural phenomenon such as wind and waves can generate similar spectral shapes. As a result, when one measures sound from wind turbines using the C- and Z-weightings, which do not discount low frequency sound to the extent that the A-weighting does (see Figure 2), the resulting sound levels show greater differences between background and turbine operations.

As an example, for a typical wind turbine sound, more than half of the acoustical energy that makes up the C-weighted sound level is below 50 Hz, the lower level of audibility from Figure 13. Therefore, it is more difficult to relate the level of C-weighted and Z-weighted sound to human perception.[7] Two sounds may be perceived as exactly alike, but there could be significant variations in the C-weighted sound level depending on the content of inaudible sound in each. This is not to say that low-frequency sound is not important, but that low frequency content is best quantified by directly measuring 1/3-octave band sound levels, rather than through a single-number C-weighted or Z-weighted sound level.

Many noise control engineers use the ratio of the C- to A-weighted level to get a sense for the proportion of low frequency sound in a signal. The larger the ratio, the larger is the low frequency sound content. However,

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[6] Based on the audible and infrasound spectra measured in this study. See Section 8 for more information about infrasound levels.

[7] However, for high-energy sounds, like blasts, where much of the low-frequency sound is perceptible, the C-weighting is related to human loudness response.

the ratio cannot indicate whether there is a problem due to low frequency sound, as higher ratios can result from mostly inaudible/imperceptible content. In addition, if both the C-weighted and A-weighted sound levels are relatively low, a larger difference between them does not necessarily indicate any issue with the sound's content.

Because C- and Z-weighted levels are mostly influenced by sound that is not audible (when measuring wind turbines), and because there are more informative ways to quantify low-frequency sound content, we do not recommend using C- or Z-weighted sound levels for regulation of wind turbine noise.

DISCUSSION OF A-WEIGHTED SOUND METRICS

The A-weighted sound value is the most commonly used metric in environmental noise regulation. We believe this to be due, in part, to the fact that it is designed to mimic the human response to loudness at lower sound levels. Assuming audibility is the minimum requirement for annoyance and activity interference, the A-weighted sound level is relevant for use in noise regulations.

This Section establishes which metric results in the greatest observable change when the turbines are shut down and restarted. At locations within 660 meters, the L_{min} and L_{90} show the greatest change. These parameters are less sensitive to short-duration events in the background. At 990 meters, there is so much background sound relative to the wind turbine sound that there is very little difference between the metrics.

The next best metrics for demonstrating changes to the A-weighted sound levels resulting from wind turbines around shutdowns, after the L_{min} and L_{90}, are the L_{50} followed by the Leq.

Comparing five-minute metrics based on one-second Leq, L_{Fmax} and L_{Smax}, there is generally little difference between Leq and L_{Fmax}. The L_{Smax} generally has a smaller level difference between turbine-on and turbine-off. This is likely because the slow response setting is less responsive to wind turbine amplitude modulation.

With respect to the variability of the parameters from one five-minute period to the next, improved predictability comes from lower standard deviations when the wind turbine is on. The L_{max} metric has the highest standard deviations. There is little difference in standard deviation among the L_{min}, L_{90}, L_{50}, and Leq metrics. The highest standard deviations tend to occur in the prevailing crosswind direction.

In light of these findings, the most predictable and stable metrics for wind turbine unattended monitoring tend to be the L_{min} and L_{90}, while the least predictable and stable are the L_{10} and L_{max}.

If the structure of a regulatory standard is a comparison of the measured wind turbine sound level to the background L_{90}, then one may choose both how to calculate the background L_{90}, and to what metric it should be compared. By collecting one-second sound levels, the L_{90} of any period (e.g. five minutes) can be calculated from the statistical distributions of the A-weighted $L_{F(1\text{-sec})}$, $L_{S(1\text{-sec})}$, $L_{Fmax(1\text{-sec})}$, $Leq_{(1\text{-sec})}$, etc. As shown in Table 6, when calculating turbine-on sound levels using the L_{90} of the $L_{Fmax(1\text{-sec})}$, we get a 0.7 dB higher level than when using the $Leq_{(1\text{-sec})}$. When calculating background using the L_{90} of the $L_{Fmax(1\text{-sec})}$, we get a 0.5 dB higher level than when using the $Leq_{(1\text{-sec})}$. The difference between the two methods of calculating L_{90} is insignificant.

When looking among the metrics in Figure 10, the five-minute L_{90} of the A-weighted L_{Fmax} is about 2 dB lower than the $Leq_{(5\text{-min})}$ in the prevailing crosswind and downwind directions, but about the same in the upwind direction.

SOUND SPECTRUM

The spectral shape of wind turbine noise is generally consistent among the different turbines measured in the study. Some turbines do have unique signatures due to rotational frequencies of components of the gearbox and other mechanical equipment in the nacelle. These signatures can be used to identify wind turbines. However, these nacelle sounds are often inaudible or undiscernible at a distance and are evident only when analyzing the time history of the sound spectrum. Depending on the wind turbine and operating conditions, the lowest frequency for which the sound from the turbine is generally audible is in the one-third octave band with center frequencies of 50 to 80 Hz. (For comparison, 50 Hz is the 12th note (G-sharp-1) on an 88-key piano and 80 Hz is the 20th key (E-2).) At high frequencies, the wind turbine sound drops below audibility above about 6,300 Hz.

6.0 SOUND PROPAGATION MODELING

6.1 | INTRODUCTION TO SOUND PROPAGATION MODELING

Sound propagation modeling is a computational method that estimates sound levels from a source at distant receivers. By “propagation”, we mean the way sound travels over a path and the changes in sound levels and/or frequency characteristics along that path. For example, as one hears a vehicle from a distance, the sound may get louder or quieter due to the characteristics of the ever-changing atmosphere (wind, temperature, pressure, humidity) and terrain between the vehicle and you.

The amount of sound energy that arrives at some receiver at a distance from the source of sound depends on the strength of the source and various influences along the path between the source and receiver.

In this section, we will assess the ways in which various turbine and meteorological factors affect measured sound levels and evaluate the degree to which various modeled sound level metrics and averaging times are able to reproduce sound levels measured in the field during periods when wind turbine sounds are relatively prominent.

WIND TURBINE SOUND EMISSIONS

For regulatory purposes, the primary source of turbine sound power data is the wind turbine manufacturer. Manufacturers follow the International Electrotechnical Commission standard, IEC 61400-11, “Wind Turbines – Part 11: Acoustic noise measurement techniques”, to measure sound from wind turbines in a standardized way, or they may use their own proprietary models to estimate sound power for wind turbines that have not yet been built and/or tested.

The 2012 version of IEC 61400-11 requires the measurement of at least 100 seconds of A-weighted and 1/3-octave band equivalent average sound levels for each 0.5 m/s increment in wind speed. From these measurements, emitted equivalent average apparent sound power levels are calculated.[8]

In addition, the standard is used to measure the uncertainty around that sound power estimate, and tonal audibility based on narrowband measurements. Another standard is used for reporting the results of IEC 61400-11 tests: IEC 61400-14, “Declaration of apparent sound power level and tonality values.” Among the reporting requirements is an uncertainty factor “K”, which is added to the apparent sound power level. This uncertainty factor accounts for a five percent chance that an apparent sound power level measurement made according to the standard would exceed the declared value. K typically ranges from 1.5 to 2.0 dB.

Manufacturers may use the results from the IEC 61400-11 test and IEC 61400-14 reporting requirements to guarantee to a purchaser the sound emissions from their wind turbines. However, that guarantee may be lower or higher than the IEC 61400-11 tests results. For example, in a guarantee, a manufacturer may increase the declared sound level to account for meteorological conditions that may occur outside of the test conditions. Some manufacturers add the K uncertainty factor into their guarantee or they will report uncertainty. When using the manufacturer guarantee for as an input to modeling, the uncertainty factor is sometimes added (if is not included already), depending on how conservative of an estimate is desired. For

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[8] Sound power levels of other metrics, such as L_{max}, are generally not available, because this standard for wind turbine sound power is based on measurements of Leq.

example, a working group of British sound consultants recommend adding no uncertainty if modeling using hard ground (G = 0), while adding 2 dB of uncertainty to the apparent sound power for modeling using mixed hard and soft ground (G = 0.5).[9]

For wind turbines that control their response to differing wind speeds by mechanically pitching their blades (pitch-controlled), sound power will increase with wind speed up to about eight to 10 m/s, depending on the turbine. Above this wind speed, sound power will tend to either remain the same or decrease slightly with increasing wind speed, until the cut-off wind speed is reached. Above this cut-off wind speed, the turbine will shut down. An example of the sound power level versus wind speed for a turbine measured for this study is shown in Figure 15.

The reason that sound levels do not increase beyond eight to 10 m/s wind speed is that sound levels are generally directly proportional to blade tip speed, which is, in turn, proportional to rotor RPM. The rotor RPM reaches a maximum at eight to 10 m/s, corresponding with a gradual leveling of electrical power output.

For wind turbines that control their response to differing wind speeds by pitching their blades to stall (active stall-control), sound power will increase with wind speed up to the cut-off speed. No wind turbines of this type were measured in this study.

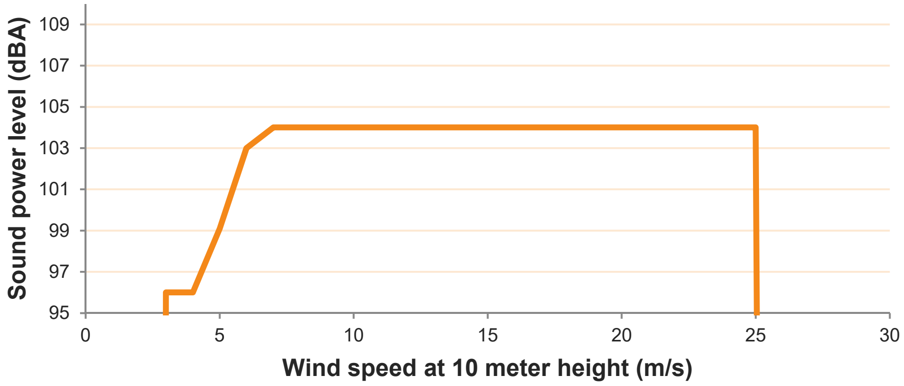

FIGURE 15: MANUFACTURER SOUND POWER BY WIND SPEED FOR A WIND TURBINE IN THIS STUDY

While wind speed is the primary driver of sound emissions from a wind turbine, sound emission may also be affected by other meteorological factors, such as wind turbulence, vertical wind speed, turbine yaw error (when the turbine is not facing directly into the wind), wind veer (change in wind direction by height), and wind shear.

SOUND PROPAGATION

Sound propagating from source to receiver is affected by the atmosphere and ground conditions. As sound propagates away from a source, the pressure wave diminishes in strength due to its spreading outward. Ideally, for a point source in free space, this diminishing due to spreading results in a decrease of 6 dB per

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[9] Bowdler et al., “Prediction and Assessment of Wind Turbine Noise: Agreement about Relevant Factors for Noise Assessment from Wind Energy Projects.”

doubling of distance. However, several conditions can alter this ideal decay rate with distance. These conditions include:

- Wind speed profile – the change in wind speed with height can refract sound upward or downward.
- Wind direction – wind direction can change the vector wind speed relative to the direction from source to receiver.
- Temperature profile – the change in temperature with height can refract sound upward or downward (sound travels faster in warmer temperatures).
- Sound speed profile – Since the wind speed profile, wind direction, and temperature profile all affect sound speed, we can calculate the sound speed profile. An example of the effect of increasing sound speed with height is shown in Figure 16.
- Turbulence – turbulence of the winds can disperse sound and break up refraction effects. For example, it could increase the level of sound in the shadow zone.
- Ground – The porosity and other characteristics of the ground will affect how much sound is absorbed and reflected. Reflections off the ground can result in increases or decreases in sound levels at different frequencies. This can result in either increasing or decreasing overall sound levels.
- Barriers – Structures that block a receiver's line of sight to the source of sound, including houses, berms, terrain that blocks the line of sight, will tend to reduce sound levels at the receiver. At the same time, however, atmospheric refraction and diffraction over the top of the obstacle will result in some sound reaching the receiver.
- Vegetation – Foliage that completely blocks the line of sight between source and receiver can attenuation sound propagation. Since most of the attenuation is at higher frequencies versus the lower frequency content of wind turbine sound, and the amount of vegetation between an elevated turbine and receiver near the ground is usually small, vegetation effects are usually ignored in models of wind turbine sound propagation.
- Atmospheric absorption – The atmosphere will absorb some sound. The amount of sound attenuation increases with higher frequencies. (This is why the low rolling of thunder can be heard much further away than the high "crack" of the lighting stroke.) Atmospheric absorption is mainly a function of temperature and relative humidity.
- Water – The surface of a body of water tends to act as a completely reflective surface. Sound propagating over large bodies of water diminishes at a rate closer to 3 dB per doubling of distance, rather than the ideal 6 dB.
- Source configuration – Line sources, or closely spaced point sources diminish at a rate of about 3 dB per doubling of distance. The sound waves they produce tend to spread out like a cylinder, rather than a sphere. At distances further than about length of the source divided by π (3.14), the sound attenuation transitions to that of spherical spreading.

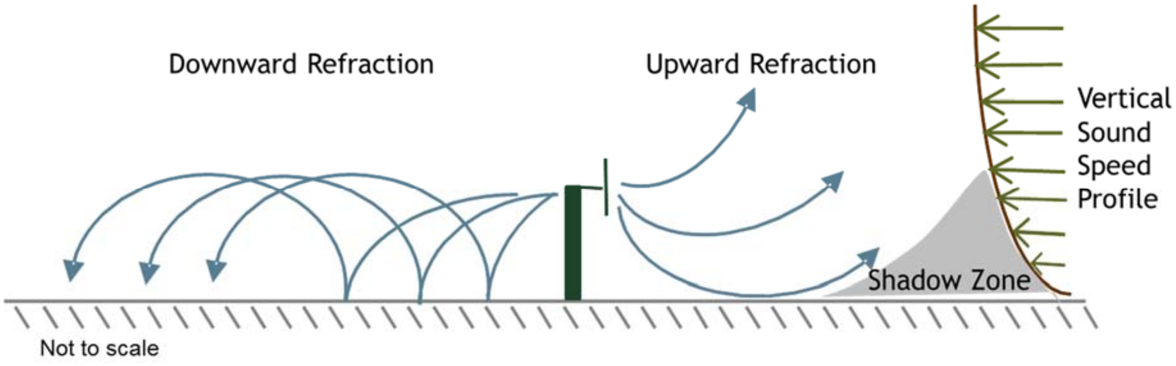

FIGURE 16: EXAMPLE OF SOUND REFRACTION DUE TO SOUND SPEED HEIGHT PROFILE

6.2 | DETAILED METHODOLOGY

SOUND MODELING

Sound propagation modeling for this study was conducted using the ISO 9613 and Harmonoise methodologies.

ISO 9613 is the current international standard for modeling sound propagation in the outdoors. It is used for modeling equivalent average sound levels (Leq) under well-developed moderate nighttime temperature inversions, or equivalently, downwind conditions. It is the required model under the current MassCEC acoustic study methodology.

Harmonoise is a sound propagation model that is in development in Europe. Harmonoise differs from ISO 9613-2 in that it is capable of modeling specific wind speeds, wind directions, and classes of atmospheric stability.

Modeling was conducted using the following steps:

1. Manufacturer sound power level data were obtained for each wind turbine model. The data obtained for all turbine models included the maximum A-weighted sound power level. Data for four of the turbines included frequency content and variation of sound level as a function of wind speed. Of these, all listed sound power level at the maximum wind speed, four listed sound power as a function of wind speed, and three had either measured or calculated sound powers by octave band. The sound power levels assigned to the models did not include any adjustment for uncertainty.
2. Terrain elevation data from MassGIS Digital Terrain Models (DTMs) were obtained for each site at three-meter intervals.
3. For the ISO 9613-2 spectral ground attenuation methodology, ground cover was a variable in the model, including hard ground (G=0.0), mixed ground (G=0.5), and porous ground (G=1.0). The ISO 9613-2's "alternative" non-spectral ground attenuation model was also used. According to that portion of the standard, non-spectral ground attenuation can be used when only the overall A-weighted sound level is of interest and the ground is mostly porous. All of the monitoring sites were over acoustically porous ground – either snow, grass, or forest.

4. Receivers (locations in the model at which sound levels were calculated) were placed at each of the monitoring locations at a height of one meter. Distances from the turbines to the receivers ranged from 260 meters to 1,100 meters.
5. Atmospheric variables were modeled at combinations of 10°C and 20°C with 50%, 70%, and 90% humidity.
6. Both ISO 9613-2 and Harmonoise modeling methods were implemented in Datakustik GmbH's Cadna/A™ computer program.
7. Both octave band and overall A-weighted sound levels were calculated for each model.

In using the Harmonoise model for this study, two atmospheric stability conditions were considered. The first was "S3", which was taken to represent the general meteorological conditions on all daytime and cloudy night measurements. The second was "S5" (stable), which was taken to represent the general meteorological conditions on clear nights. In this case, nighttime is defined as the period from one hour before sunset until one hour after sunrise. Wind directions were modeled to the nearest 45° increment. Ten-meter wind speeds were assigned one of four classes (or "bins"): W1 is 0 to 1 m/s, W2 is 1 to 3 m/s, W3 is 3 to 6 m/s and W4 is 6 to 10 m/s.

SOUND MONITORING

The sound modeling results were compared to monitored sound levels for select periods. The sound monitoring data were screened to include only those times when the background sound levels were relatively low. Only these screened results were compared to those from the acoustical propagation model. The approach was based on the procedure reported by Conny Larsson and Olof Ohlund of Uppsala University.[10]

1) Five-minute sound levels were used for comparison. (The Uppsala University procedure used 10-minutes)
2) All levels were A-weighted.
3) Samples were retained for periods that met all of the following criteria:
   a. L5 – L95 ≤ 4 dB: the sound is relatively stable;
   b. L1 – L95 ≤ 15 dB: there are no very loud single events;
   c. The overall Leq minus the sum of the Leq for frequencies at and below 800 Hz is less than or equal to 1.5 dB. In addition, the measured sound must exceed 23 dBA. (This assures that higher frequency sounds, generally related to biogenic activity, do not substantially contribute to the overall sound level and the overall level is not so low as to be significantly affected by slight changes in background sound.); and,
   d. The modeled sound level at a receiver of interest exceeds 30 dBA: the signal-to-noise ratio is sufficiently high.

To accomplish this, shutdowns were first filtered to include only those that had clearly observable changes resulting from the shutdown. If the shutdown met this test for at least one location, then all locations measured during that shutdown were included in the next steps.

The resulting five-minute sound levels were then filtered using the steps above. Overall, 332 five-minute periods met the filtering criteria.

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[10] Larsson, C., and Ohlund, O., "Sound from wind turbines during different weather conditions," Internoise 2013, 2013

The modeled sound level was then estimated from the five-minute average wind speed, and in the case of Harmonoise, wind direction and stability class. This approach does not account for amplitude modulation. Neither the manufacturer's guaranteed sound power levels nor the propagation models account for phenomena as short term as the blade pass or rotation period.

6.3 | MODELING RESULTS

We compared modeled to monitored sound levels of various metrics for the flat sites by distance from the turbine and relative position of monitoring locations (upwind, crosswind, or downwind of the wind turbine(s) relative to the prevailing wind direction). The monitored versus modeled levels for each five-minute or other period were plotted; an example of which is shown in Figure 17. The plotted points fell into one of several categories:

- If a point falls in the lower left quadrant (blue), the model has over-predicted the actual sound level. In Figure 17, the five points are all in this quadrant, indicating that in this case the model is conservative.
- If the point falls in the middle red quadrant, the model has under-predicted the actual sound level for the sound power at that particular wind speed, but has over-predicted relative to the maximum possible sound power level. That is, the model is conservative if the objective is to model for the maximum sound generation from the turbine, but is not conservative with respect to lower wind turbine rotational speeds.
- If the point falls in the bottom right quadrant (green), the monitored levels exceed the maximum modeled sound level. In this case, the model is not conservative.
- The blue line that goes across and down in Figure 17 is shown at 42 dBA, which is the maximum modeled sound level for this particular location. There may be several of these demarcating lines if results from more than one location is graphed on a single plot.
- The diagonal line going from the lower left to upper right denotes where the monitored sound level would be equal to the modeled sound level.
- For the flat sites in this section, a letter was assigned to monitoring location as a unique identifier. The assigned nomenclature remains consistent throughout this section, e.g., monitoring location "A" is the same in Figure 18 and Figure 19. The points and lines are color-coded.

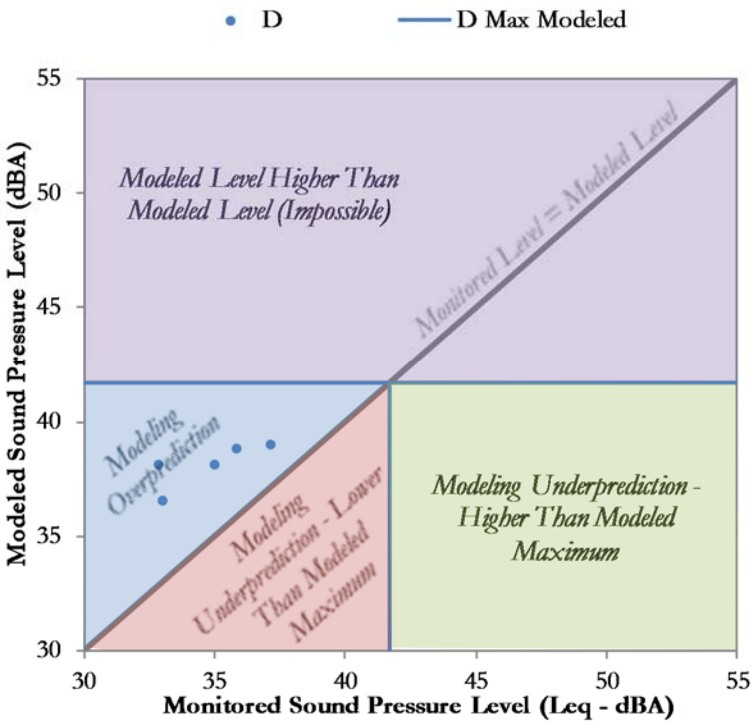


FIGURE 17: MODELING RESULTS EXAMPLE GRAPHIC

ISO 9613 WITH HARD GROUND (G=0)

The first set of results, showing the ISO 9613 model with hard ground (G=0), is shown in Figure 18. The 330-meter upwind locations are shown on the top of the figure, the 330-meter crosswind locations are shown in the right, and the 330- and 660-meter downwind locations are shown on the bottom. Note that the actual distances from the turbine(s) to the monitoring locations are rounded to the nearest 1/3 kilometer and are for all flat sites monitored in this study until otherwise mentioned.

There are no results for the 990-meter locations because turbine noise was diminished enough such that the signal to noise ratios were not sufficient to meet the criteria.

For the upwind location in Figure 18, the points fall on both sides of the diagonal line, indicating the model both under- and over-predicted actual sound levels. All points were below the maximum modeled sound levels. This indicates that modeling at wind speeds slower than the rated wind speed for the maximum sound power had the potential to under-predict actual levels, but modeling at the maximum sound power would over-predict actual levels. Modeling for the crosswind direction consistently over-predicted the monitored levels. For the downwind directions, the model consistently over-predicted the monitored sound levels, with one exception each at 330 meters and 660 meters. The exceptions are below the maximum modeled sound level.

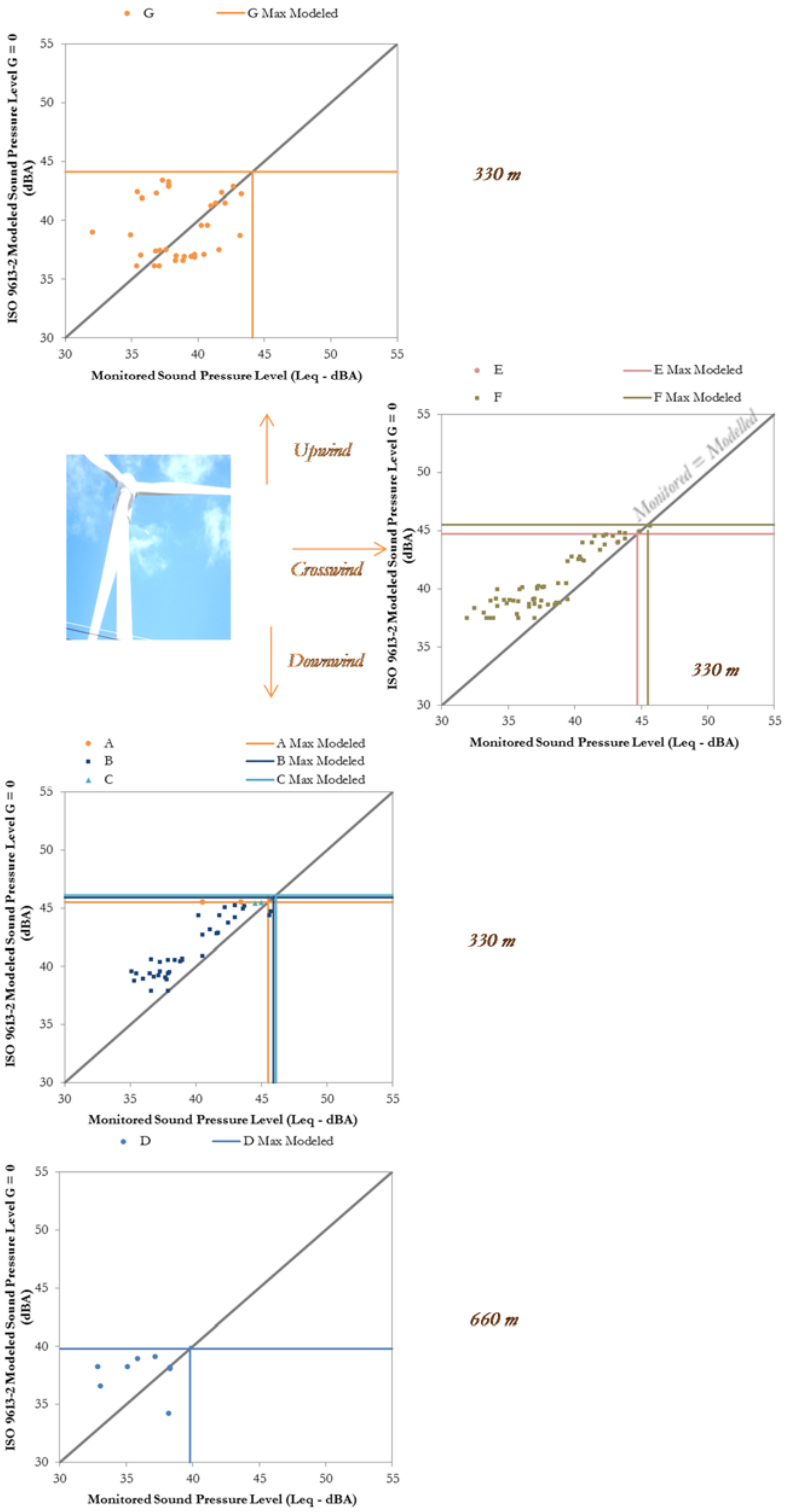


FIGURE 18: COMPARISON BETWEEN MONITORING RESULTS (FIVE-MINUTE LEQ) AND MODELING RESULTS (ISO 9613-2, G=0)

ISO 9613 WITH MIXED GROUND (G=0.5)

Figure 19 shows results for ISO 9613 model using mixed ground (half-hard, half porous, G=0.5). In the upwind direction, the modeled levels fall in each of the three quadrants. That is, there are under-predictions, over-predictions, and monitored levels that exceed the maximum modeled levels.

In the crosswind and downwind directions, the same pattern emerges. Deviations of as much as 4 dB occur from the modeled maximum sound levels.

ISO 9613 WITH MIXED GROUND (G=0.5) PLUS 2 dB

The results shown in Figure 20 indicate that adding 2 dB to the previous results makes the modeling more conservative, with most points clustered close to the diagonal line of equal sound levels. In the upwind direction, three monitored five-minute periods exceed the modeled levels by about 1 dB. In the crosswind direction, two monitored five-minute periods exceed the maximum modeled level by as much as 2 dB. Similar results appear downwind.

The ISO 9613 model with mixed ground plus 2 dB is the current MassCEC modeling method, except in locations where actual ground is harder than mixed ground, like over a body of water. In this case, hard ground (G=0) is used at that location. The MassCEC specifies 1.5-meter receptor heights while we modeled at 1.0 meters to be consistent with the actual microphone heights.

ISO 9613 WITH SOFT GROUND (G=1)

Figure 21 shows results for ISO 9613 modeling using soft ground (G=1). This condition resulted in the greatest under-prediction of sound levels by the model. In almost all cases, the monitored levels are higher than the modeled levels, and all locations have the monitored sound levels exceeding the maximum modeled.

ISO 9613 NON-SPECTRAL GROUND ATTENUATION

The ISO 9613-2 methodology allows for the use of a ground attenuation procedure that does not depend on the spectral characteristics of the sound. The standard allows this so long as the ground is relatively flat and mostly porous. The text of the ISO standard refers to this as the "alternative method for calculating A-weighted sound level": For this report, the phrase "non-spectral" ground attenuation is used.

The results of using non-spectral ground attenuation are shown in Figure 22. The modeled fit is approximately between the results for hard ground and mixed ground. Upwind, three points exceed the maximum modeled level. In the crosswind direction, the model over-predicted most of the measurements, with two points exceeding the maximum modeled sound level by about 1 dB. In the downwind direction, the model over-predicted most of the measurements at 330 meters, with none exceeding the maximum modeled sound level. At 660 meters, the scatter was greater, with three measurements that exceed the maximum modeled level by about 1 dB.

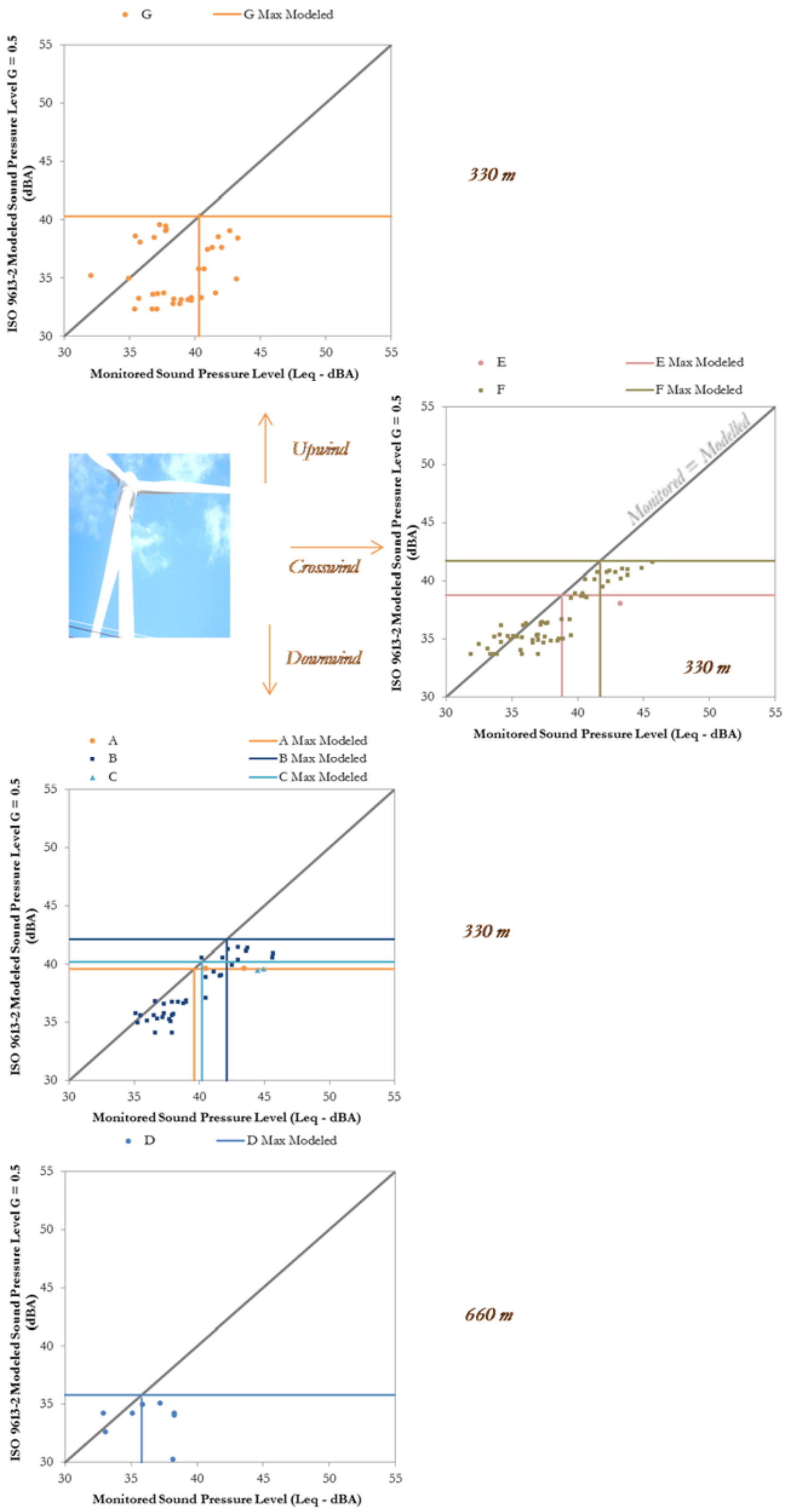


FIGURE 19: COMPARISON BETWEEN MONITORING RESULTS (FIVE-MINUTE LEQ) AND MODELING RESULTS (ISO 9613, G=0.5)

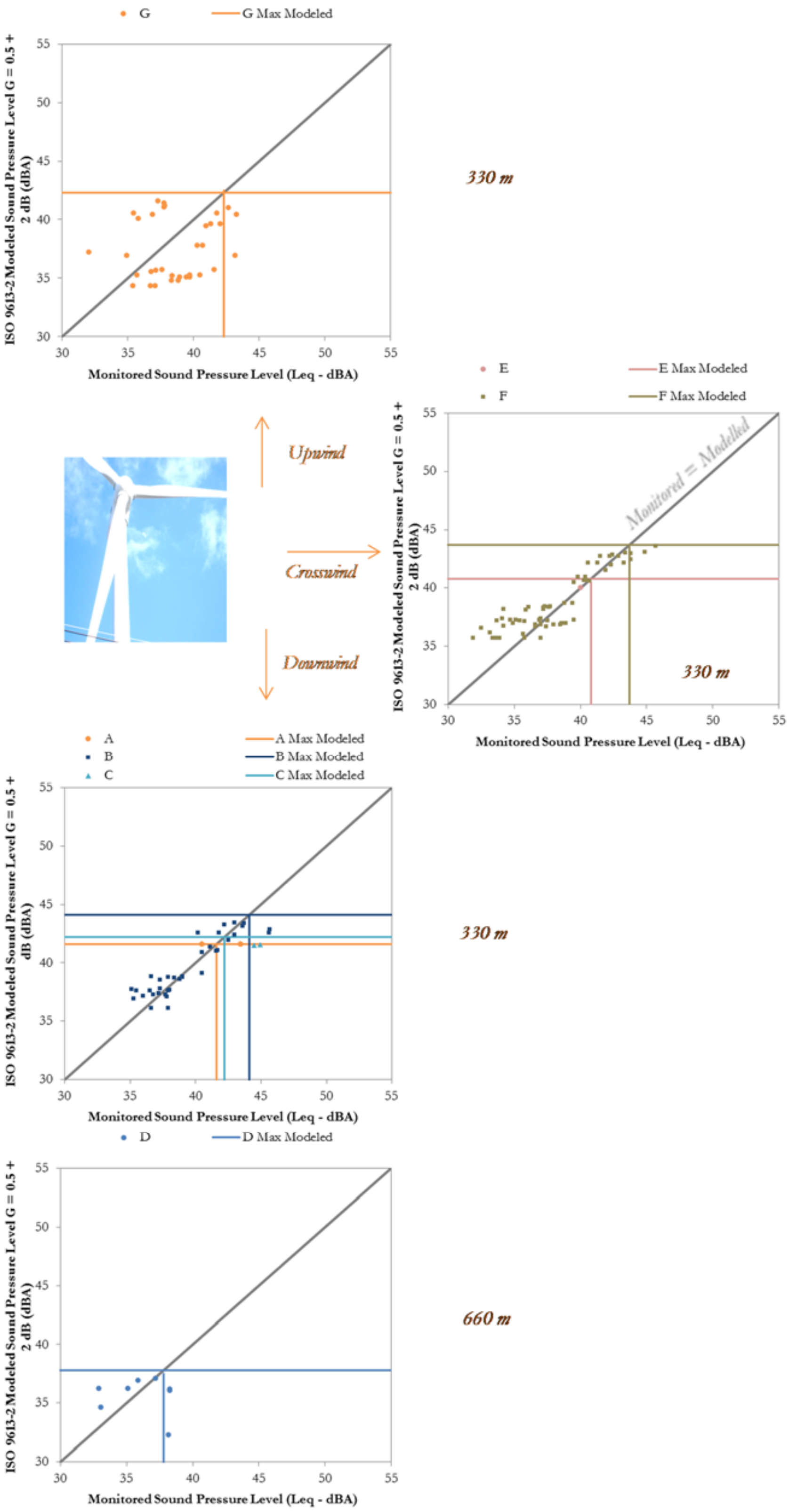


FIGURE 20: COMPARISON BETWEEN MONITORING RESULTS (FIVE-MINUTE LEQ) AND MODELING RESULTS (ISO 9613, G=0.5 + 2 DB)

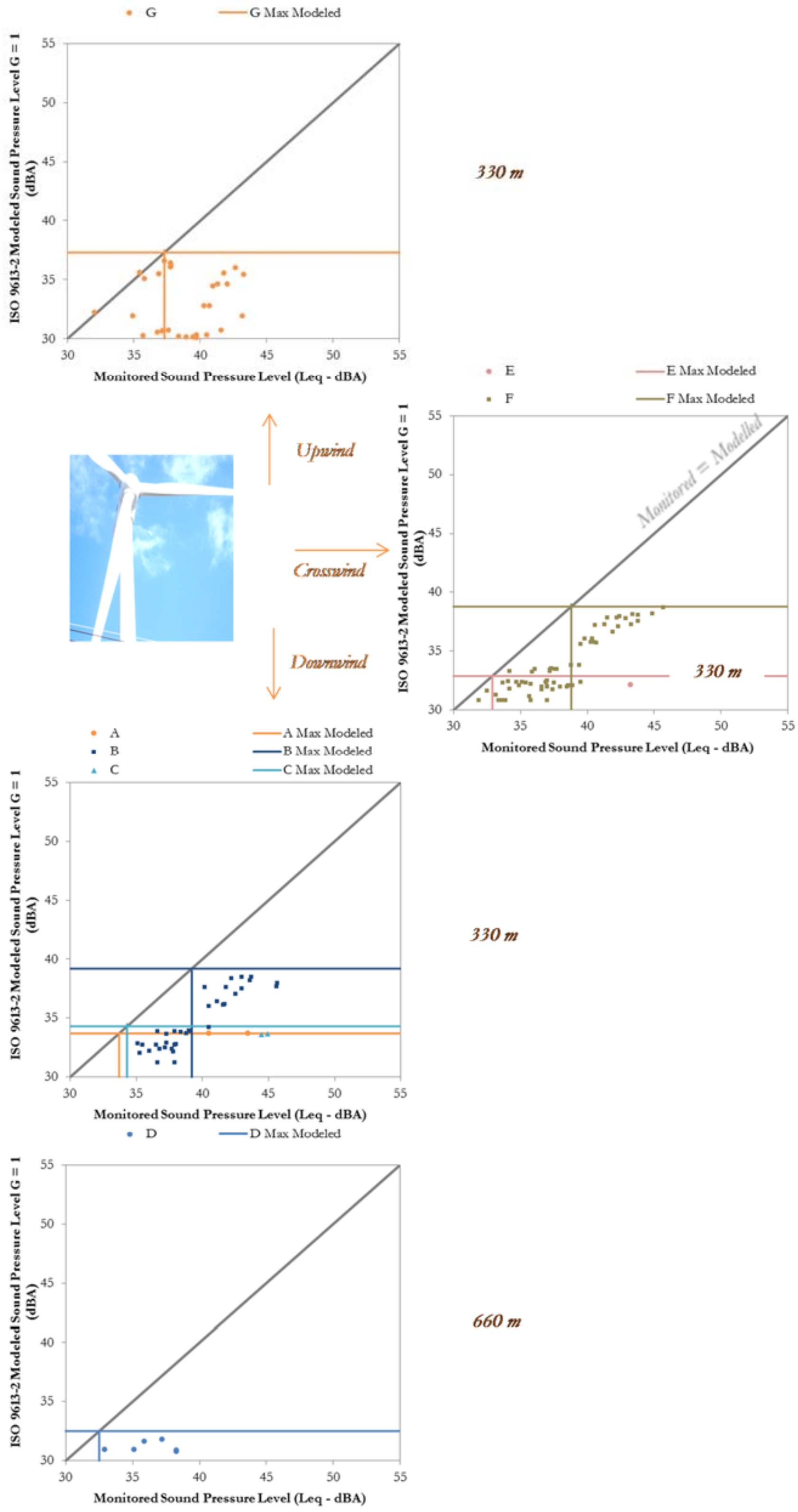


FIGURE 21: COMPARISON BETWEEN MONITORING RESULTS (FIVE-MINUTE LEQ) AND MODELING RESULTS (ISO 9613, G=1)

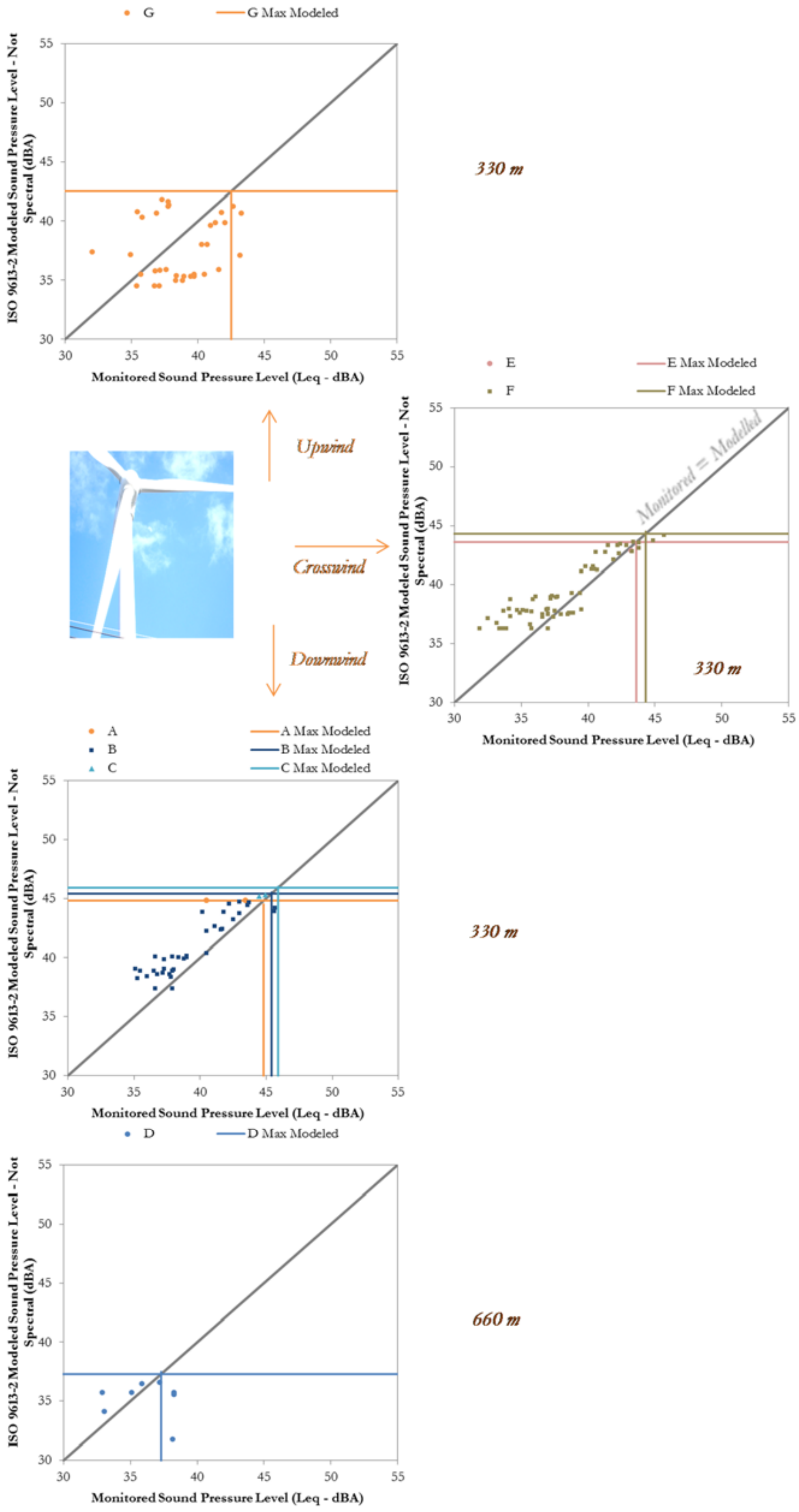


FIGURE 22: COMPARISON BETWEEN MONITORING RESULTS (FIVE-MINUTE LEQ) AND MODELING RESULTS (ISO 9613, NON-SPECTRAL GROUND ATTENUATION)

HARMONOISE

As noted above, the Harmonoise model can account for wind speed, wind direction, and atmospheric stability in predicting propagated sound levels. As a result, our modeling included the actual meteorological parameters observed during each five-minute period as input parameters to the model.

The results, shown in Figure 23, reveal that Harmonoise provided the most conservative predictions. The maximum modeled sound levels exceed monitored levels in all cases, and the sound levels modeled for time-matched meteorological conditions exceeded most of the monitored levels. The only exception was the upwind direction, where the comparisons show more scatter around the diagonal line.

MULTI-TURBINE MOUNTAIN SITE

One of the sites analyzed for this study was a multi-turbine project located on a mountain ridgeline. This site is reported separately, because the behavior of the turbines and the local meteorology can differ from those of the flat sites.

The comparison of modeled to monitored sound levels are shown in a different way in this Section. For each model, all three of the upwind, crosswind, and downwind comparisons are plotted in one chart. The upwind comparisons are plotted using green markers, the crosswind comparisons are plotted using red markers, and the downwind comparisons are plotted using blue markers.

Figure 24 shows the comparisons for the ISO 9613-2 model with the ground attenuation set to hard (G=0), mixed (G=0.5) and mixed (G=0.5) with 2 dB added to the results. For hard ground, the points are scattered around the diagonal, indicating some under- and over-prediction relative to specific wind speeds. However, none of the monitored five-minute periods exceeded the maximum modeled sound level.

For mixed ground (G=0.5), the maximum modeled sound levels were lower. Therefore, the corresponding lines shift down and to the left in the Figure, increasing the number of under-predicted points. With 2 dB added (bottom sub-figure), there was an improvement, but several points exceeded the maximum modeled sound level by as much as 2 dB. Many of these under-predicted periods occurred just after the turbine restarted after a shutdown.

Figure 25 shows the comparisons for the ISO 9613-2 model with porous ground (G=1) and non-spectral ground attenuation, and for the Harmonoise model at the mountainous locations. For porous ground (top sub-figure), the monitored sound levels were well above the modeled sound levels. For non-spectral ground attenuation, the comparisons were similar to the ISO 9616 model using mixed ground (G=0.5) with 2 dB added. The Harmonoise model predictions were the most conservative. While the comparisons show some scatter, none of the five-minute periods exceeded the maximum modeled sound level.

With respect to prevailing wind direction, the upwind location exhibited the most scatter, while the crosswind location indicated consistent over-prediction by the model. This is consistent with the results from the flat sites.

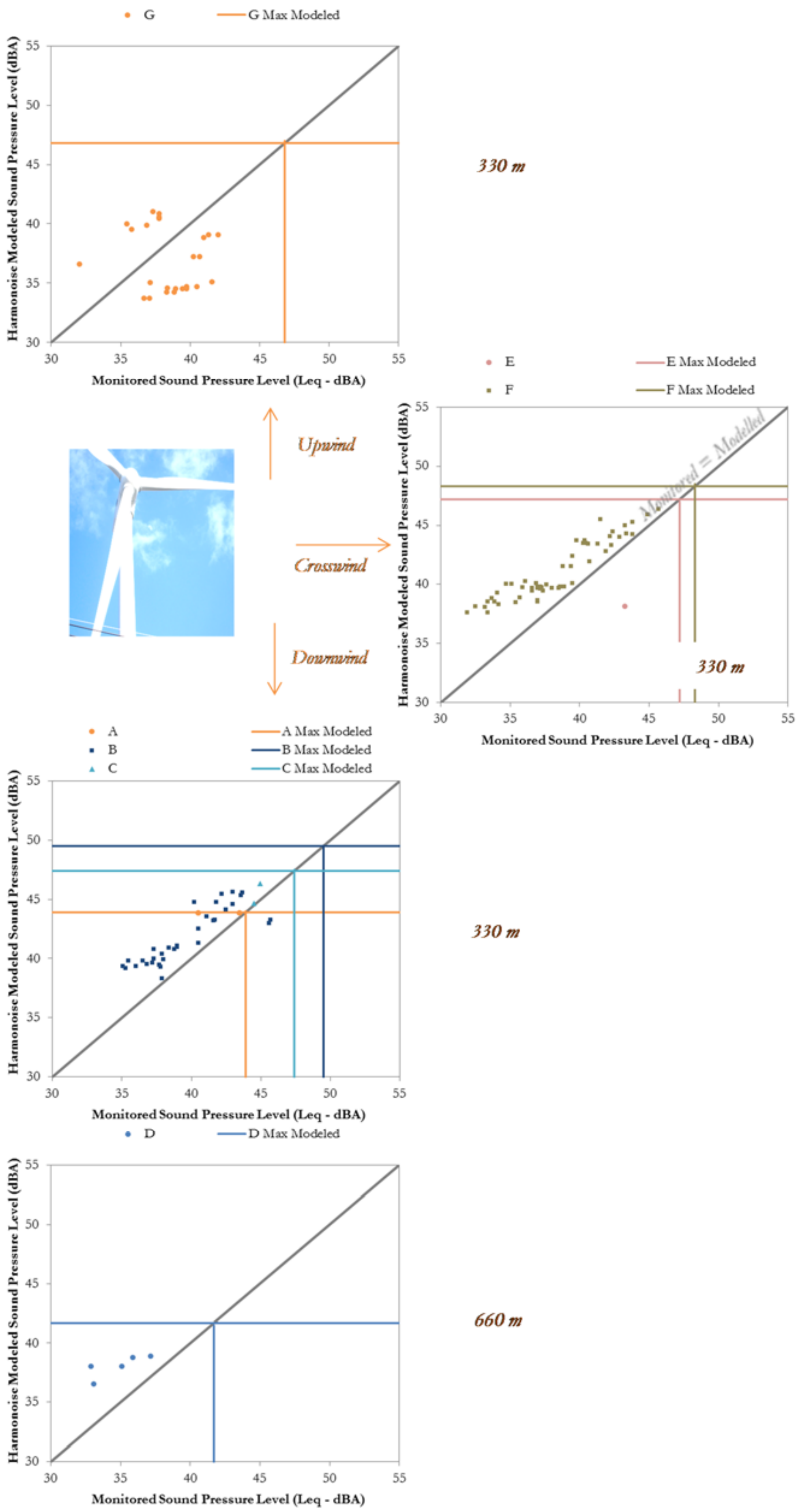
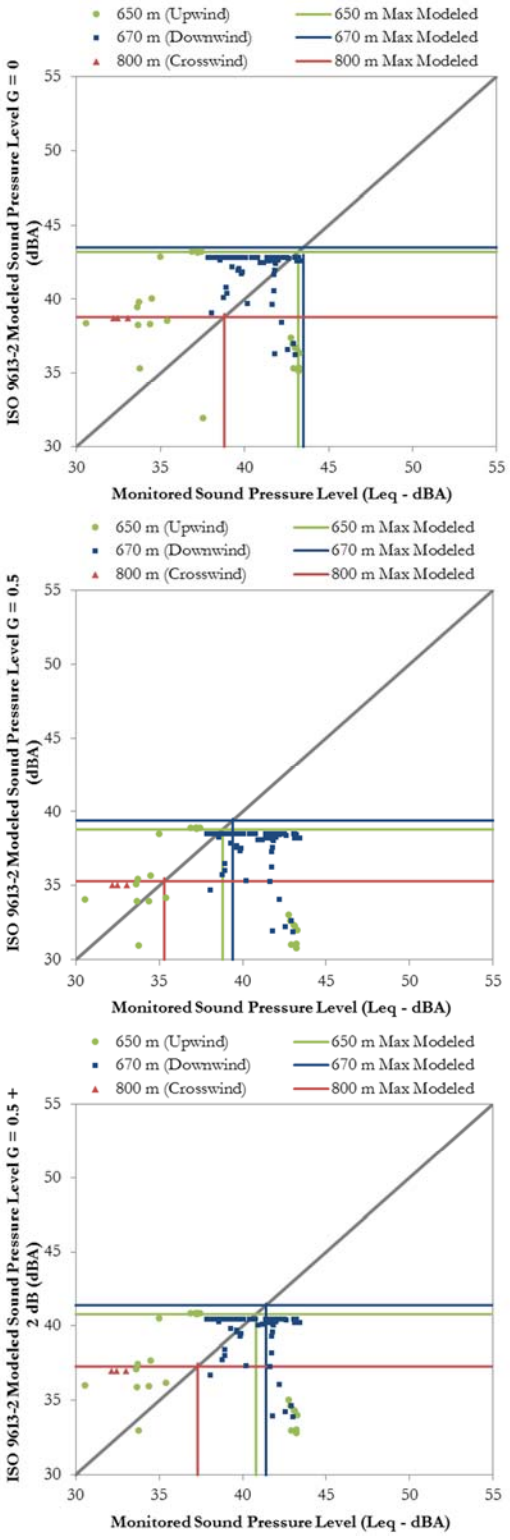


FIGURE 23: COMPARISON BETWEEN MONITORING RESULTS (FIVE-MINUTE LEQ) AND MODELING RESULTS (HARMONOISE)

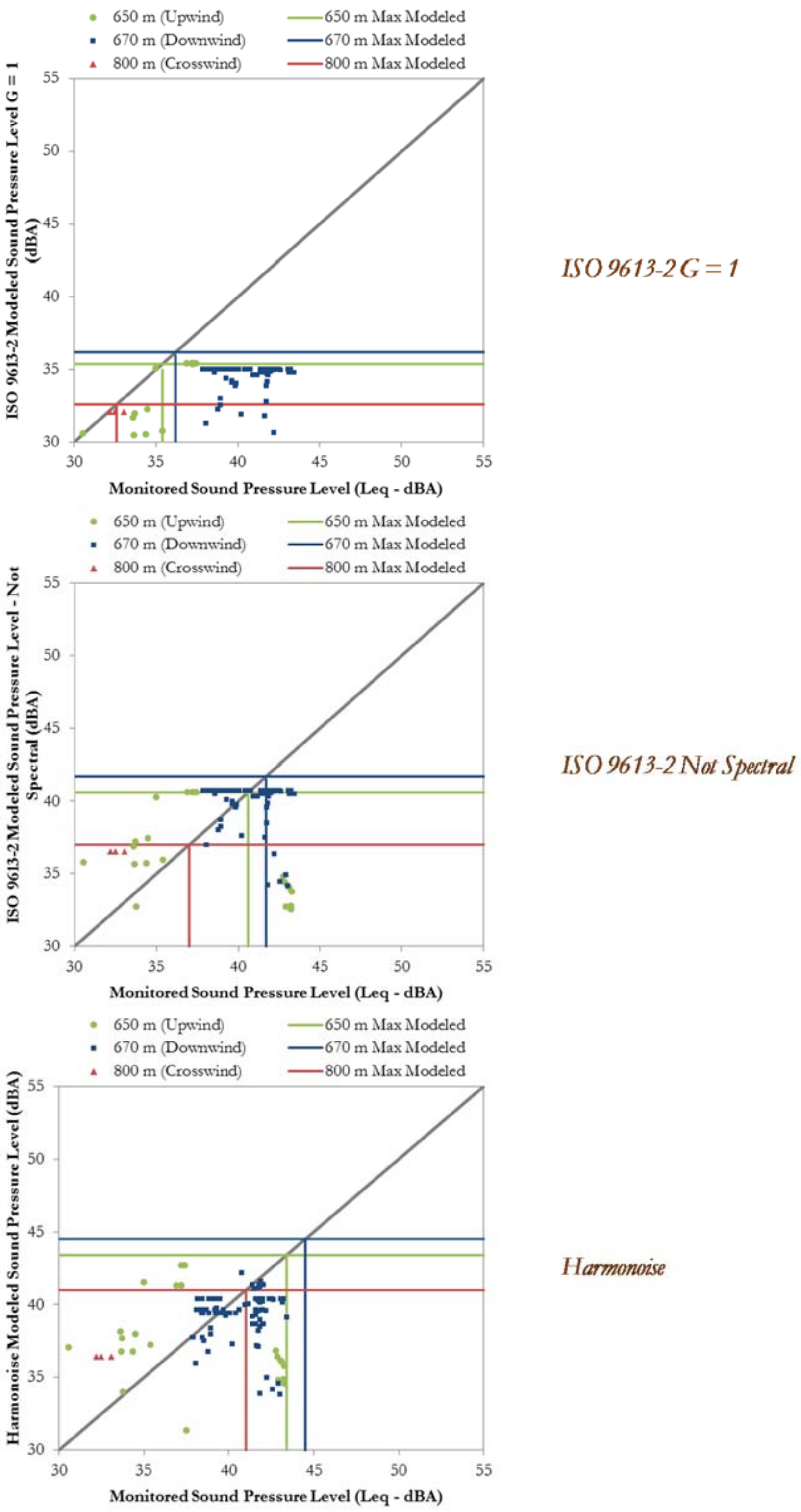


ISO 9613-2 G = 0

ISO 9613-2 G = 0.5

ISO 9613-2 G = 0.5 + 2 dB

FIGURE 24: COMPARISON BETWEEN MONITORING RESULTS (FIVE-MINUTE LEQ) AND MODELING RESULTS - MOUNTAINOUS LOCATIONS PART 1


ISO 9613-2 G = 1

ISO 9613-2 Not Spectral

Harmonoise

FIGURE 25: COMPARISON BETWEEN MONITORING RESULTS (FIVE-MINUTE LEQ) AND MODELING RESULTS - MOUNTAINOUS LOCATIONS PART 2

COMPARISON OF METRICS

The accuracy and precision of a model depends, in part, on the metric it is predicting. If, under normal circumstances, the metric of interest is unstable or varying with time, then the modeling will likely have less precision.

To evaluate this, we tested each of the locations above to compare the $Leq_{(five\text{-}minute)}$ measurements with $Leq_{(1\text{-}hour)}$ and $L_{90(five\text{-}minute)}$. Shown in Figure 26 are the results comparing monitored sound levels at the 330-meter downwind locations with the ISO 9613-2 model using mixed ground (G=0.5) plus 2 dB. For the five-minute L_{90}s, shown in the upper left subplot, the modeled levels tend to match the monitored levels. One monitored level is about 1 dB above the modeled level, and two monitored levels are a few tenths of a decibel above the modeled level. The five-minute Leq subplot in the upper right is the same as that presented in Figure 20. Computing the one-hour Leq resulted in a smaller data set, but the modeled and monitored levels clustered closely along the diagonal line with the exception of a single outlying measurement that exceeded the modeled level.

From these results, it can be concluded that the accuracy and precision of the model improves when compared with the L_{90} metric, and by extending the length of the equivalent averaging duration from five minutes to one hour.

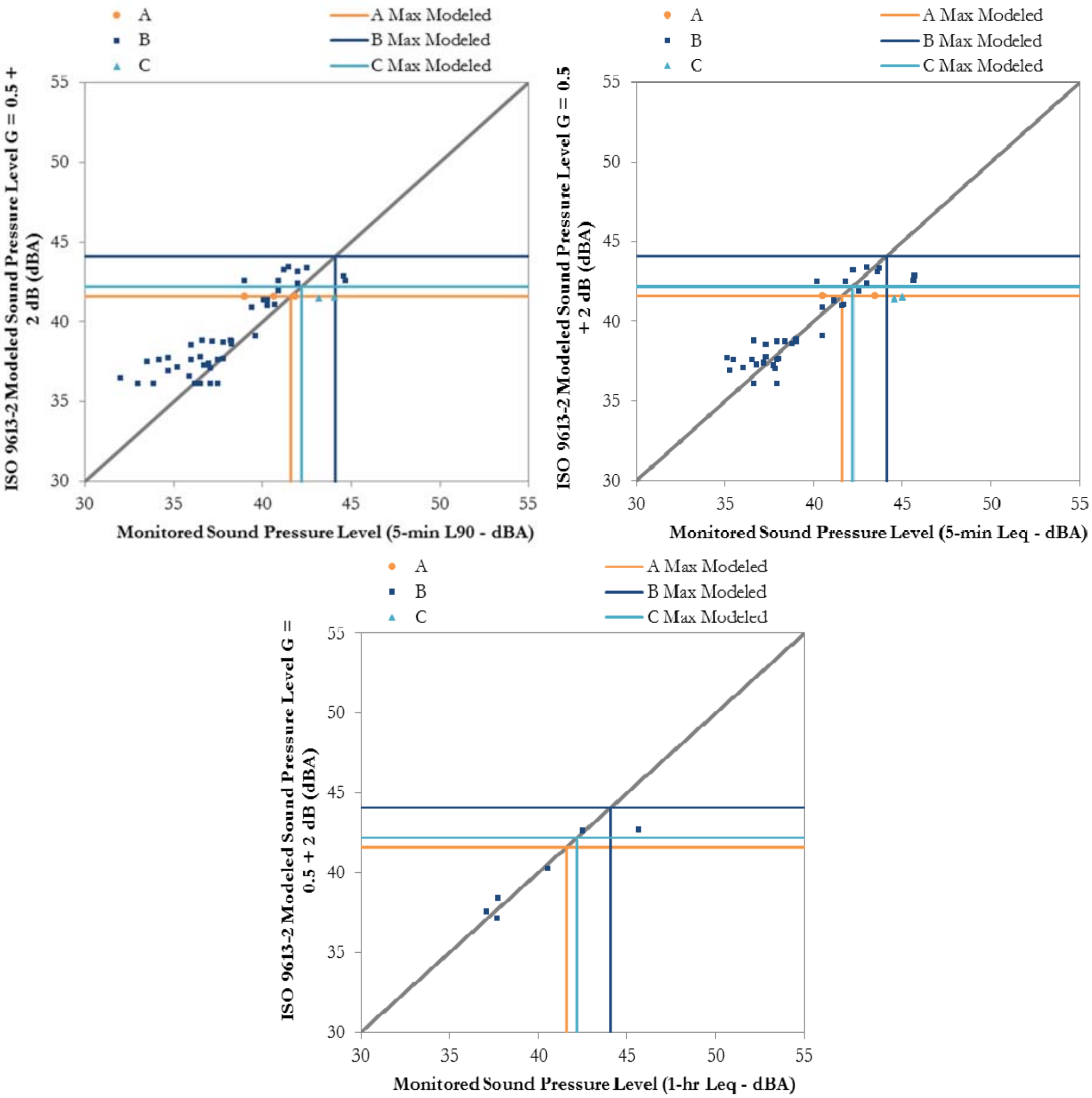


FIGURE 26: MODELING VS MONITORING AT 330 METERS DOWNWIND FOR VARIOUS METRICS

Clockwise from top, five-minute L_{90}*, five-minute Leq, one-hour Leq*

MODELING PRECISION

A model's *accuracy* is assessed by how well its predicted result matches the true value. In the results shown in the previous section, a perfectly accurate model would be one in which the points are all aligned around the 1:1 diagonal line (where the modeled values equal the monitored values). A model's *precision* is assessed by how repeatable and reproducible the results are. A model with high precision would be one in which the points all fall along a very straight diagonal line, whether or not that line matches the line of equal sound levels. It is desired to have both accuracy and precision. However, precision is more important, because we can make adjustments to make a precise model more accurate.

For example, in Figure 27, the small squares fall along the 1:1 line where the modeling results equal the monitored results. These are more accurate in that they are closer to the actual value. The triangles are further from the 1:1 line, but line up in a tight diagonal, making them more precise. It is relatively straightforward to make the precise triangular points more accurate by adding a constant of 5 dB to the modeled sound levels such that they line up on top of the 1:1 line.

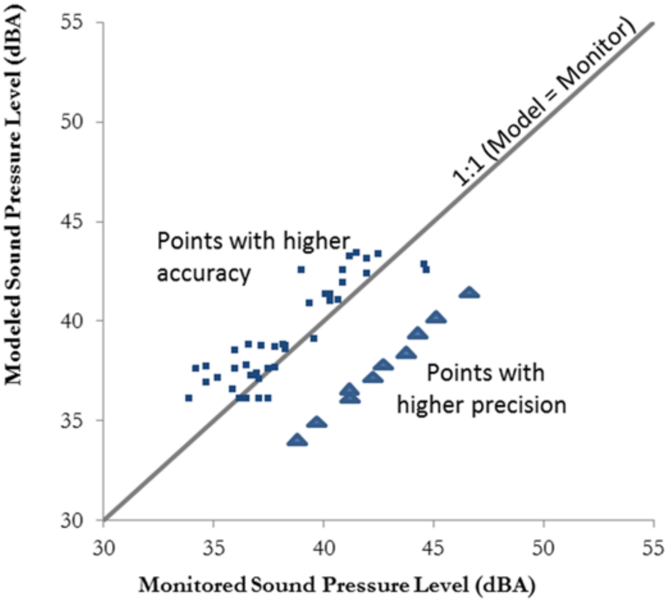


FIGURE 27: COMPARISON OF ACCURACY AND PRECISION (EXAMPLE)

To estimate precision from the modeled sound levels in this section, we conducted the following analysis:

1) The model vs monitored comparisons were separated into flat and mountainous sites.
2) The root mean squared error of the estimate was modeled. That is, for each point, the square of the difference between the modeled and monitored levels were calculated. This was summed for all the points. The root mean squared error is the square root of this sum.
3) A constant was added to all modeled levels in an attempt to reduce the root mean squared error.
4) Steps 2 and 3 were repeated until the lowest root mean squared error was obtained.

This methodology was implemented using an automated optimization routine.

The results of the precision analysis are shown in Table 8 for the flat sites and Table 9 for the mountainous site. For the flat sites, G=0 has the lowest root mean squared (RMS) error, followed by G=0.5. The adjustment constant is negative for G=0 and positive for G=0.5. For mountainous site, the root mean squared error is higher; with the most precise being the Harmonoise model, closely followed by the ISO 9613 models. The adjustment constants between the flat and mountainous sites are within 0.6 dB of each other, with the exception of the Harmonoise model which is -1.6 for flat sites and +0.8 for the mountain site.

TABLE 8: PRECISION OF MODELING FOR FLAT SITES

Modeling Parameters	RMS Error	Adjustment Constant
ISO 9613-2 G=0	2.2	-1.8
ISO 9613-2 G=0.5	2.3	2.1
ISO 9613-2 G=1	2.5	5.2
ISO 9613-2 NS	2.3	-0.7
Harmonoise	2.7	-1.6

TABLE 9: PRECISION OF MODELING FOR THE MOUNTAINOUS SITE

Modeling Parameters	RMS Error	Adjustment Constant
ISO 9613-2 G=0	3.4	-1.9
ISO 9613-2 G=0.5	3.4	2.4
ISO 9613-2 G=1	3.4	5.8
ISO 9613-2 NS	3.4	0.2
Harmonoise	3.2	0.8

6.4 | EFFECTS OF METEOROLOGICAL VARIABLES ON MEASURED SOUND LEVELS

To evaluate the influences various parameters had on wind turbine sound measured at our monitoring locations, we conducted a regression analysis of 11 million samples of one-second sound levels, and how they are affected by meteorological conditions and turbine operating parameters. The regression analysis took into account sound levels from all sites and all locations as long as data of sufficient quality were available.

REGRESSION PARAMETERS

The parameters used in analyzing sound levels included:

- **80-meter wind speed** – The 30-second trailing average of wind speed measured by LIDAR at 80 meters, in meters per second;
- **Turbulence intensity** – The 30-second standard deviation of 80-meter wind speed divided by the average 30-second 80-meter wind speed, as measured by LIDAR;
- **Sound speed profile low** – The difference in sound speed between 10 meters and 1 meter, based on the vector horizontal wind speed (wind shear) and temperature difference at those two heights, in meters per second; and,
- **Vertical wind speed up** – The positive wind speed moving upward, in meters per second, as measured by LIDAR. The LIDAR recorded winds moving downward as positive and winds moving upward as negative. For the regression analysis, these data were split into two components, vertical wind speed upward and downward; both were assigned positive numerical values. For example, if the

LIDAR measured a vertical wind speed of -2 m/s, which is upward wind, the "Vertical Wind Speed Up" variable was 2 m/s and the "Vertical Wind Speed Down" was 0 m/s;

- **Vertical wind speed down** – The positive wind speed moving downwards, in meters per second, as measured by LIDAR.
- **Wind direction** – The wind direction was divided into five categories: directly away from the receiver, diagonally away from the receiver, crosswind (perpendicular to the line between turbine and receiver), diagonally towards the receiver, or directly towards the receiver (Figure 28). Each of these was taken relative to the upwind (wind blowing from receiver to source) direction.

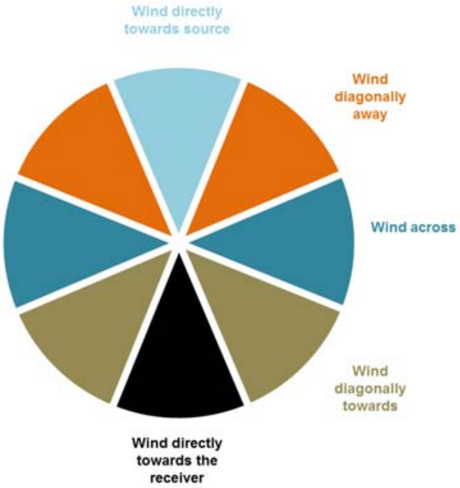


FIGURE 28: WIND DIRECTION SECTORS USED IN REGRESSIONS

- **Standard deviation of 80-meter wind direction** – The standard deviation of wind direction over 30 seconds, as measured by LIDAR, in degrees. Because wind direction is radial, special algorithms were used to adapt the data for statistical analysis. We used the "Yamartino" method, which has been shown to perform well.[11]
- **Absolute value of veer** – The absolute value of the difference in wind direction between 80 meters and 40 meters, in radians;
- **Log of the number of turbines** - 10 Log_{10} of the number of turbines near the receiver; and,
- **Log of the distance** - 20 Log_{10} of the distance, in meters, between the acoustic center of the turbines and the receiver.

STRUCTURAL EQUATION MODELS

Structural Equations Models were used to model the direct and indirect influence of the environmental variables on the sound speed profile, sound power level, and sound pressure level. Figure 29 maps the structure used for the model. In this structure, the sound power level, sound speed profile and sound pressure level were treated as latent variables (to account for possible measurement error of these variables).

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[11] Bruce Turner, D., 1986: Comparison of Three Methods for Calculating the Standard Deviation of the Wind Direction. J. Climate Appl. Meteor., 25, 703–707.

Sound power level and sound speed profile were taken as causal influences on the sound pressure level. Additionally, environmental variables were included and had direct effects on all three latent variables.

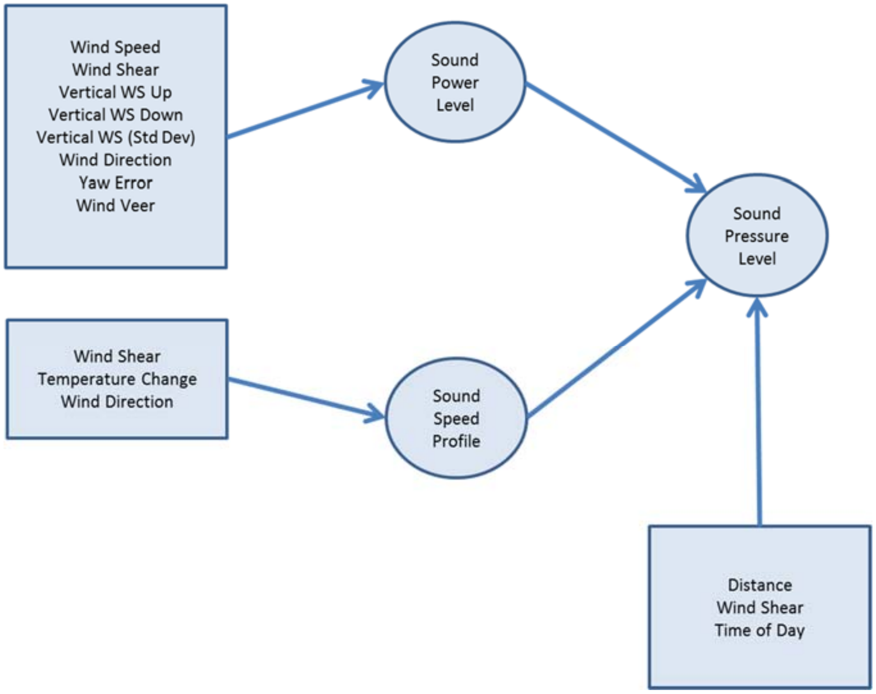

FIGURE 29: VARIABLE INTER-RELATIONSHIPS IN THE STRUCTURAL EQUATION MODEL

A-weighted and G-weighted sound pressure levels were evaluated with this model. The results of the A-weighted model is shown in Table 10. The results of the G-weighted model are found in Section 8.4.

The results of the A-weighted Structural Equation Model suggest that:

- Horizontal wind speed at 80 m, vertical wind speed up, the standard deviation of horizontal wind speed, and wind veer all have positive effect on the sound power level;
- Vertical wind speed down, the standard deviation of wind direction, the absolute yaw error, and the wind shear have a negative effect on sound power level
- Distance, wind shear, and sound speed profile have a negative effect on the A-weighted sound pressure level;
- The sound power level and time of day (day versus night) have a positive effect on the sound pressure level;
- Vertical temperature difference, wind direction, time of day (day versus night), and vertical wind speed up have a negative effect on the sound speed profile; and,
- Wind shear and vertical wind speed down have a positive effect on the sound speed profile.

TABLE 10: STRUCTURAL EQUATION MODEL RELATING METEOROLOGICAL VARIABLES TO A-WEIGHTED SOUND PRESSURE LEVELS

		Estimate	Standard Error	T-Value	Effect Size
Model for Sound Power Level	delta_lw	96.422	0.014	6743.5	N/A
	zeta_site_A	-0.681	0.013	-54.1	N/A
	zeta_site_B	-0.546	0.009	-60.8	N/A
	zeta_avg_80m_ws_30s.lw	0.950	0.002	586.7	16.11
	zeta_vert_windspeed_down.lw	0.537	0.010	56.2	2.49
	zeta_vert_windspeed_up.lw	-0.286	0.009	-32.9	-0.93
	zeta_sd_80m_v_ws_30s.lw	0.024	0.012	2.0	0.07
	zeta_sd_80m_wd_30s.lw	-0.007	0.001	-8.6	-0.65
	zeta_veer_40_120.lw	0.001	0.000	6.5	0.38
	zeta_abs_yaw_error.lw	-0.030	0.000	-81.3	-5.32
	zeta_shear_lw	-0.185	0.014	-13.1	-0.70
	lambda_lw	1.547	0.003	565.1	N/A
Model for Sound Pressure Level	delta_la	-57.442	0.454	-126.5	N/A
	zeta_distance.la	-0.381	0.003	-126.1	-4.01
	zeta_day1_night0_boolean.la	1.345	0.024	56.0	N/A
	zeta_shear_la	-1.808	0.047	-38.5	-6.89
	lambda_la	5.521	0.008	733.3	N/A
Model for Sound Speed Profile	delta_ss	0.215	0.017	12.4	N/A
	zeta_temp_lapse_low.ss	-49.733	0.206	-241.7	-14.54
	zeta_avg_80m_wd_30s.ss	-0.001	0.000	-13.2	-0.38
	zeta_day1_night0_boolean.ss	-0.090	0.017	-5.2	N/A
	zeta_vert_windspeed_down.ss	0.240	0.021	11.5	1.11
	zeta_vert_windspeed_up.ss	-0.241	0.018	-13.1	-0.78
	zeta_shear_ss	0.030	0.031	0.9	0.11
	lambda_ss	4.009	0.005	741.1	N/A
Cross Effects	beta_lw_la	1.107	0.004	262.9	27.68
	beta_ss_la	-0.469	0.006	-79.6	-10.71

Model Log-Likelihood	-2,481,243
Number of Observations	308,906

6.5 | MODELING DISCUSSION

The goal of sound modeling in the regulatory framework is generally to forecast turbine sound levels with the greatest accuracy under conditions specified in the respective standard. That is, the model need not estimate a particular sound level for every combination of variables, but rather focus on engineering estimates of sound under the conditions set out in the standard. There will also be a balance between the desire to lower the probability of a noise standard exceedance with impacts to the project design.

The variables having the greatest influence on A-weighted sound from wind turbines are wind speed, the number of turbines, and distance between turbines and receivers. These are also the most commonly used variables in wind turbine sound propagation modeling. The number of turbines and wind speed are used to determine wind turbine sound power output, and distance is used to determine the loss of sound energy from the spreading of the sound wave. The sound speed profile has the next largest effect. It is indirectly included in ISO 9613 modeling, which assumes a fixed set of meteorological conditions (i.e. sound speed profile) favorable to propagation. The Harmonoise model more explicitly accounts for the sound speed profile by using the wind speed, wind direction, and stability class as variables.

In light of this, the most precise modeling results, *when considering modeling by wind speed*, are with the ISO 9613 model with hard ground (G=0) for the flat sites and Harmonoise for the mountainous site (followed closely by the ISO models). Both ISO 9613 with hard ground and Harmonoise over-predict sound levels in almost all cases. ISO 9613 with hard ground over-predicts on average by 1.9 dB. When ignoring wind speed and comparing to the maximum modeled levels, the over-prediction is much larger. Harmonoise over-predicts receiver sound levels by an average of 0.4 dB.[12] ISO 9613 with mixed ground (G=0.5) plus 2 dB, currently the MassCEC preferred protocol, and non-spectral ground attenuation provide the best fit relative to the average difference between modeled and monitored sound level (accuracy).

As mentioned in the discussion of modeling methodology, the modeling done for this study does not include any uncertainty in the manufacturers' guaranteed sound power levels. For example, if the manufacturer of a particular turbine guarantees an apparent sound power level of 104 dBA with an uncertainty (K) of 2 dB, for the purposes of this study, the turbine was modeled with a sound power level of 104 dBA.

Depending on the regulatory standard, the modeling may further under-predict or over-predict sound levels. If the standard is based on an L_{90}, the actual sound levels will be about 1 dB lower, on average, and the modeled results will be that much more conservative. If the standard is based on an L_1 or L_{max}, for example, then the resulting turbine sound levels will be higher. The difference will depend on how the standard is formulated.

Typically, modeled levels using ISO 9613 with mixed ground (G=0.5) plus 2 dB results in similar sound levels to those for hard ground (G=0). In this case, the results are about 2 dB different. We believe that the reason for this is the 1.0-meter microphone and receiver height used in this study compared with the 1.5 or 4.0 meters typically used in regulatory modeling. The MassCEC methodology, for example, uses 1.5 meters. Microphones deployed for this study were set 1.0 meter above the ground in order to reduce the effect of wind on the measured levels.

To evaluate this further we sampled the modeling results at four receivers at various distances from one wind turbine, we found that raising the receiver height to 1.5 meters increased the modeled sound level under mixed ground by an average of 0.7 dB (Table 11). Raising it to 4 meters would increase the modeled level by 2.2 dB, making it about the same as hard ground. The modeled sound level is not affected by receiver height over hard ground.

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[12] This is the average over-prediction and is different from the adjustment constant from the previous two tables.

TABLE 11: EFFECT OF MODELED RECEIVER HEIGHT ON RESULTING SOUND LEVELS

Receiver ID	Sound Level (dBA)					
	H = 1m		H = 1.5m		H = 4m	
	G=0	G=0.5	G=0	G=0.5	G=0	G=0.5
1	44.4	40.4	44.4	41.1	44.5	42.6
2	43.5	39.4	43.5	40.1	43.5	41.7
3	38.8	35.4	38.8	35.9	38.8	37.3
4	44.4	40.3	44.4	41	44.4	42.6

We investigated several instances, where the monitored sound levels were consistently higher than the modeled levels. We found that they occurred just after the turbines restarted after a forced shutdown. An example of this was shown in Figure 8, where sound levels increased just after startup, then immediately fall to a lower steady-state sound level. Six additional examples of this phenomenon are shown in Figure 30. The first half of each chart shows sound levels with the turbines off, and the second half shows sound levels while the turbines are starting up and running. As indicated in each chart, the sound levels increase rapidly at startup, then decreases over a period of about one minute or more to a stabilized level. This is most likely not a common occurrence, because under normal operational circumstances, turbines are not stopped and started again while wind speeds are higher than the turbine's cut-in threshold. It may be that the blades are pitched on startup to match the actual wind speed, but the rotor requires some time to reach its proper speed, resulting in a short period during which the blade pitch is not correctly optimized. When blade pitch is not optimal, noise generation is increased. This increase in sound level goes away as the rotor speed matches the proper setting for the actual wind speed. As a result, the brief increase in operating sound level observed during this study is most likely an artificial construct of the test design and would not typically occur under normal conditions.

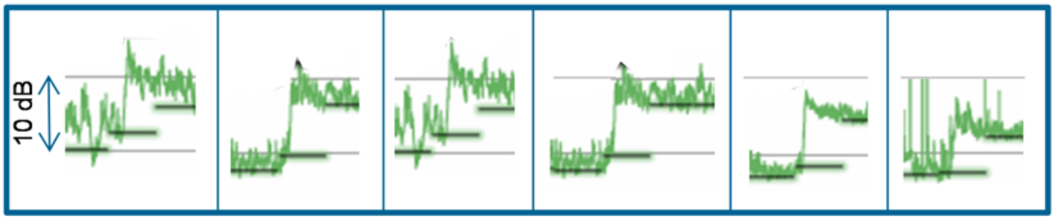

FIGURE 30: A-WEIGHTED SOUND LEVEL OVER TIME (GREEN) AT SIX TURBINE-STARTUPS

The green lines are one-second A-weighted Leqs. The darker horizontal lines show five-minute L_{90}*s.*

Based on these results, we can conclude:

- Turbulence, vertical wind speed, wind direction, standard deviation of wind direction, and veer each have a small effect on sound levels. The effect was generally less than 1 dB for each when measured at our receivers. These parameters are not included in regulatory models of sound emitted by wind turbine projects. It appears from this data, that since their effect is relatively small, site-specific differences in these parameters may not need to be considered in pre-construction sound modeling.

- The models using ISO 9613 with hard ground (G=0) and Harmonoise are the most conservative, with none of the monitored five-minute Leq sound levels exceeding the maximum modeled sound level.
  - Harmonoise tends to be the most conservative, and gives results two or more dB below the maximum modeled level.
  - ISO 9613 with hard ground (G=0) tends to be less conservative than Harmonoise, but still does not over-predict the maximum sound level.
- Comparing modeled sound levels with monitored five-minute L_{90} yields more predictable results than the five-minute Leq. The five-minute L_{90} is, on average, 1 dB lower than the Leq over all sites.
- The ISO 9613 model with hard ground (G=0), when applied to flat sites and Harmonoise model, when applied to the mountainous site, tend to have good correlation between modeled and monitored sound levels at wind speeds below that at the turbine's rated maximum sound power.
- At the one site upwind of the turbines (Location G), the results from all tested modeling protocols show a greater degree of scatter compared with the other wind directions.
- The ISO 9613 with mixed ground (G=0.5) plus 2 dB and ISO 9613 with non-spectral ground attenuation both yield the best fit to the monitored five-minute Leq sound levels.
- The ISO 9613 with mixed ground (G=0.5) plus 2 dB is the most precise at modeling the one-hour Leq.
- If a metric with an averaging time of less than one hour, or a metric other than L_{90}, is chosen as a standard, then an additional amount may be added to the ISO 9613-2 G=0.5 plus 2 dB results to make it more conservative.
- Modeling predictions are more difficult to validate at greater distances due to the reduced difference between the background and wind turbine sound levels. For single- or two-turbine sites, only seven five-minute periods met the validation protocol at 660 meters, and none met the validation protocol at 990 meters.
- If turbine shutdowns are used for compliance monitoring, turbine-on monitoring should commence at least two to three minutes after the turbine-startup. This delay will allow the blade pitch to optimize to the wind speed and avoid artificially high sound levels that occur while the turbine is spinning up.
- The results at the flat sites and mountain site were similar after removing the higher sound levels related to startup.
- No effort was made to manually screen for unusual noise events unrelated to the wind turbines. Therefore, if background levels were higher during the turbine-on periods, results computed for such periods would tend to over-estimate the contribution from the wind turbine.
- Comparisons were made between the precision and accuracy of different modeled metrics and averaging times. The five-minute L_{90} monitoring results had fewer exceedances of the maximum modeled sound level than the five-minute Leq. Under this scenario, ISO 9613 with mixed ground (G=0.5) plus 2 dB showed the greatest precision for receivers located 330 meters downwind of a turbine. The longer averaging time of one hour appears to increase the modeling precision, while use of the L_{90} results in lower monitored sound levels, thus making the modeled results more

conservative. Over all flat locations, ISO 9613 modeling with hard ground (G=0) was the most precise.

- L_{max} was not modeled, because there was no way to subtract the background sound level from L_{max} during unattended modeling. However, we would expect less precision and accuracy trying to model L_{max} because it is not included as a parameter in manufacturer's guaranteed sound power levels, is subject to short-term influences, and has a greater degree of variation over time.

It should be recognized that there are a great many factors that affect sound generation, propagation of that sound, and background sound levels. Some of these factors are outside the control of the wind turbine project developer, or they may change over time in an unpredictable manner. As a result, sound propagation modeling will always have some amount of inaccuracy. Modeling can be used to assess and minimize the probability of exceeding thresholds set in regulations, but it cannot be used to guarantee that an exceedance will never occur. Factors that that tend to decrease the accuracy of a given model include:

- Modeling shorter time periods;
- Modeling specific meteorological conditions; and,
- Modeling that includes estimates of or is dependent upon background sound levels.

7.0 AMPLITUDE MODULATION

7.1 | INTRODUCTION TO AMPLITUDE MODULATION

With respect to wind turbines, amplitude modulation is a recurring variation in the overall level of sound over time. The modulation sound is typically broadband, and it comes from interactions of the blade with the atmosphere, wind turbulence, directionality of the broadband sound of the blades, or tower interaction with the wake of the blade. As discussed in Section 8.0, this modulation is not infrasound; rather, it is variation in audible sound that is phase-locked (synchronized) to the passage of the turbine blades.

To illustrate the qualitative nature of the amplitude modulation, the 400 Hz, 500 Hz, and 630 Hz 1/3-octave band sound levels from a 15-second recording of wind-turbine sound, at a distance of about 300 meters from the turbine, is shown in Figure 31. Over the course of the 15 seconds, approximately 11 fluctuations of a weakly cyclical nature are distinguishable in each of the bands. The fundamental frequency associated with the modulations is roughly 11/15, or about 0.73 Hz. Although some regularity is evident in the modulations, there is also significant randomness in their levels from one cycle to the next. The fluctuations within one band are imperfectly correlated with the others. Hence, other than the fixed modulation frequency, the amplitude modulation appears as a random process.

To simplify description of the amplitude modulation, we might model it as a sinusoidal variation (Figure 32), although such a representation is an idealization. For consistency, the power in the sinusoidal representation should match that of the random process. This is done by matching the root-mean-square (rms) variations in the signals. (The rms value is defined as the square root of the mean of the square of the variations about the mean level.)

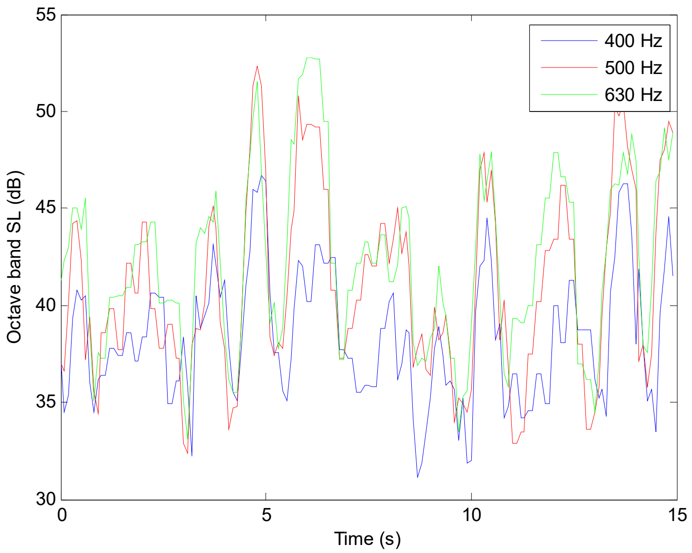

FIGURE 31: SAMPLE OF 15 SECONDS OF AMPLITUDE MODULATED WIND TURBINE SOUND FOR THREE ADJACENT 1/3-OCTAVE BANDS

The fundamental frequency of the modulations is usually coincident with the rotational speed of the turbine multiplied by the number of blades:

$$Modulation\ Fundamental\ Frequency = \frac{RPM \times Number\ of\ Blades}{60\ {}^{seconds}\!/_{minute}}$$

The rotor speed (RPM) varies according to the type of wind turbine and current operating conditions. For example, if a three-bladed turbine is turning at 17 rpm, the fundamental modulation frequency would be 0.85 Hz. The time it takes for a complete modulation cycle (the period) is 1/frequency. In this case, the cycle time would be about 1.17 seconds.

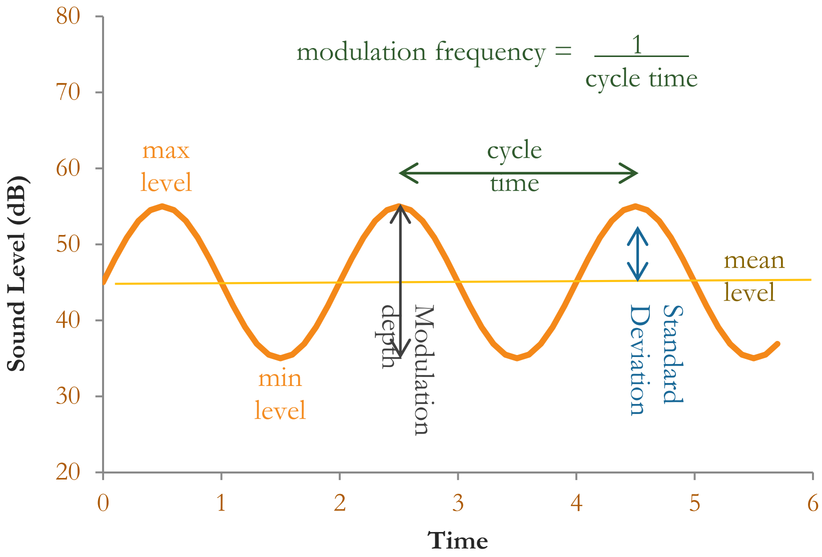

FIGURE 32: ILLUSTRATION OF TERMS USED TO DESCRIBE AMPLITUDE MODULATION

The greater the modulation in sound level, the greater the "modulation depth." For use in this report, the modulation depth is measured from the minimum sound level to the maximum sound level, or "crest-to-trough level", as illustrated in Figure 32 for a perfect sinusoidal signal. Half of this level is called the *amplitude* of the sine wave. For the perfect sine wave, the rms value defined above is equal to the modulation depth multiplied by the square root of two (1.414). The standard deviation is also approximately equal to the rms average level of the signal. This is important, as some of the methods used to quantify amplitude modulation of a signal use the rms of standard deviations.

Amplitude modulation from wind turbines is generally characterized either as "swishing," which is a broadband modulated sound, or as "thumping," which has a faster rise time and is composed of sound at lower frequencies. A "churning" sound has also been described, which is made up of broadband mid-frequency sound, but with a faster rise-and-fall rate.

7.2 | TECHNIQUES FOR MEASURING AMPLITUDE MODULATION

Our investigation into amplitude modulation required the logging of sound levels from the wind turbines at intervals of 50 ms, 100 ms, or 125 ms. These intervals are equivalent to sampling rates of 20, 10, or 8 samples per second, respectively. All millisecond logging recorded at least A-weighted slow response (L_{AS}), A-weighted fast response (L_{AF}), and unweighted 1/3-octave band equivalent average (Leq) sound levels. 1/3-octave bands ranged from 6.3 Hz to 20,000 Hz. The measurement methodology is the same as described in Section 4. Special infrasound wind screens were not used.

The simplest way to measure amplitude modulation is to calculate the minimum and maximum sound level within the time of a single rotation of the wind turbine blades. This technique was used in Section 4.3.1. of the first Interim Report[13] for this project. We found that this give a good first-order approximation of amplitude modulation, but it cannot distinguish between modulation synchronized with the wind turbine blade passage, or simply a short-duration variation in the background sound level. By simply assessing the minimum/maximum, an unrelated random variation in sound levels within a short period is counted as amplitude modulation, whereas in actuality it is not a component of the turbine noise. This is especially evident in the analysis of 1/3-octave band sound levels, which naturally vary considerably during any one second, especially at lower frequencies.

What is required to better evaluate amplitude modulation is a way to look at the time-varying characteristics of a sound to identify repeating patterns that are synchronized to the blade passage. For this purpose, a technique was developed that effectively isolates the wind turbine amplitude modulation. It is based on calculating short-time Fourier transforms of the 1/3-octave band and A-weighted sound levels. In other words, the time series is first filtered into 1/3-octave bands by the sound-level meter. These sound levels (not the raw sound) are then spectrally analyzed. This technique characterizes the frequency and depth of the amplitude modulation, and helps to isolate the part of the amplitude modulation that is related to the blade passage rate.

The amplitude modulation in the audible frequency range should be *independent* of the distance between the turbine and the listener, and the sound propagation conditions in the atmosphere. Except at very large amplitudes, characteristic of explosions and sonic booms, sound propagates essentially linearly in the atmosphere; that is, the attenuation of the sound is independent of the amplitude. Hence attenuation of the sound is the same at the minimum and maximum phases of the cycle shown in Figure 32. It is also important to understand that other linear atmospheric propagation effects, such as the impact of the atmospheric conditions (refraction, scattering, etc.), are likewise the same for both the minimum and maximum phases. For this reason, the amplitude modulation characteristics are best analyzed at a location near the turbine, where the signal for the turbine is loudest in comparison to the background noise.

The previous discussion should not be interpreted to mean that the amplitude modulation produced by the turbine is independent of atmospheric conditions or the receiver direction relative to the turbine and wind. Once sound has been produced by the turbine, the amplitude modulation of this sound is neither enhanced nor diminished by the atmosphere, regardless of the distance and direction of the propagation. However, in

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[13] RSG, Epsilon Associates, Northeast Wind, "Massachusetts Research Study on Wind Turbine Acoustics: Preliminary Interim Report for WNTAG," October, 2013.

the presence of a constant background sound, it will be diminished over distance as the turbine sound level becomes attenuated.

During the following discussion of amplitude modulation, we thus focus on several locations around wind turbines, which were selected because the noise from the wind turbine could be clearly identified above the background. The criteria for selecting particular intervals for detailed analysis were:

(1) The impact of the initial shutdown and subsequent restart could be clearly seen in the acoustic data, and were in agreement with the times recorded in the experiment logs;

(2) There were a minimal number of background "events" (such as car traffic); and

(3) Data from the LIDAR wind profiling system were available.

The strength or depth of the amplitude modulation was not used as a selection criterion per se. The first two selection criteria were found to be critical for identifying meaningful correlations between the amplitude modulation characteristics and potential causal variables (such as wind speed); otherwise, the scatterplots (to be described) were highly random and statistics of the acoustical observations did not clearly change when the turbine was operational.

SOUND LEVELS AROUND EXAMPLE LOCATIONS

In this section, we consider some representative samples of the data, which help to illustrate the various sources of background and wind turbine sound. All of the analyses discussed here are based on data logged by the sound-level meters,

Site 7A

We first consider some example data from a relatively flat site at a measurement location about 330 m east of a single wind turbine. The analyzed period began at around 22:15 and ended at 1:15 the next day. A strong wind (about 15 m/s at 80-m height) was blowing from the south; the microphone location was nominally crosswind from the turbine. A shutdown occurred from 21:10 to 21:40. For this analysis, the "turbine on" condition corresponds to the half hours before and after the shutdown. The "turbine off" condition corresponds to the half hour of the shutdown.

Figure 33 shows the A-weighted Leq with and without the turbine operating, along with the levels in one-third octave bands. The overall A-weighted level is about 6 dB higher when the wind turbine is operating. The same observation applies to the one-third octave bands over a broad range of frequencies, from about 8 Hz up to 500 Hz. At higher frequencies, the difference is somewhat less.

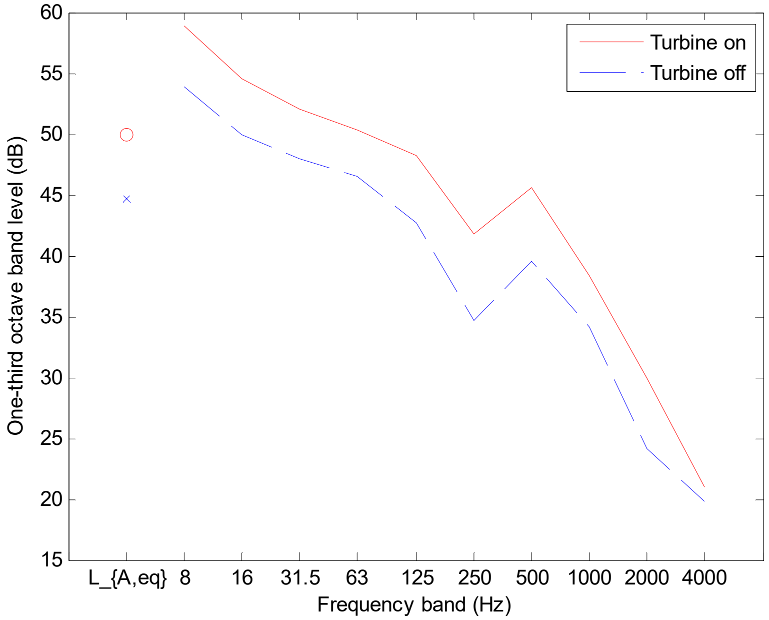

FIGURE 33: A-WEIGHTED SOUND LEVEL (LAeq) AND UNWEIGHTED ONE-THIRD OCTAVE BAND LEVELS AT SITE 7A (330 M) WITH AND WITHOUT THE TURBINE IN OPERATION

The red circle and blue x at the left of the plot represent the A-weighted sound level, with and without the turbine operating, respectively. The solid red line and dashed blue line represent the unweighted one-third octave band levels, with and without the turbine operating, respectively,

One of the ways we can view amplitude modulation is through a "spectrogram". A spectrogram is a three-dimensional graphic showing time on the horizontal axis, frequency on the vertical axis, and the level of the sound represented in a color scale. The recorded signals are separated into their respective frequency content by applying a Fourier transform to segments of the recorded signals, and averaging the transforms to determine the time-varying frequency content.

An example of time traces of sound levels and two spectrograms for the same time period is shown in Figure 34. The method used to calculate the spectrogram is described in more detail in the following subsection.

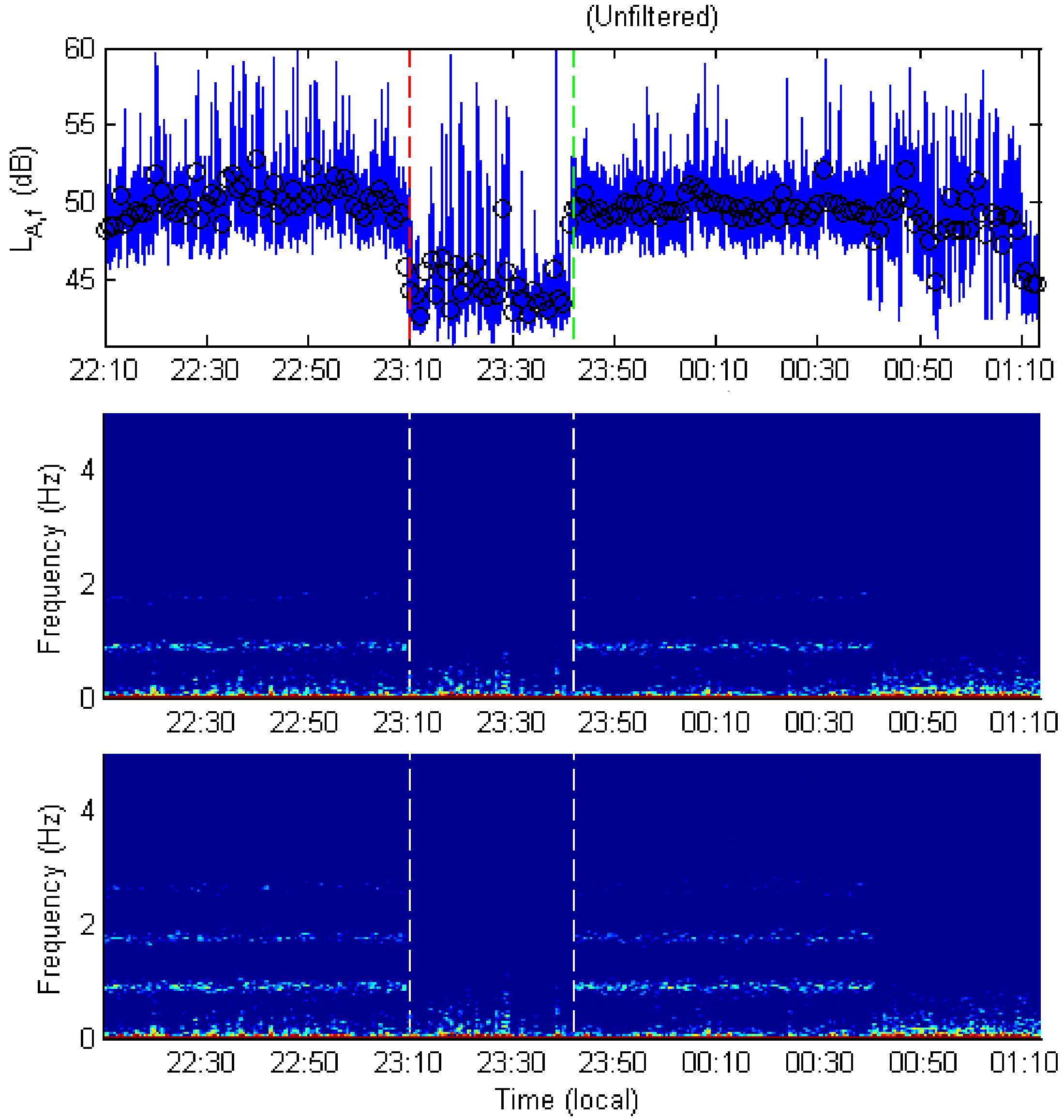

FIGURE 34: THREE TIME-SERIES VIEWS OF A SINGLE TURBINE SHUTDOWNTIME SERIES AT SITE 7A (330 M) AROUND A SINGLE TURBINE SHUTDOWN

The initial dashed vertical line indicates the beginning of the wind turbine shutdown interval; the following dashed vertical line indicates the restart of the turbine. Top: Fast-response overall A-weighted sound level; black circles indicate one-minute averages. Middle: Amplitude modulation spectrogram for the L_{AF} *during same period. The vertical axis is the frequency of the amplitude modulation of the* L_{AF}*. (Not to be confused with the actual frequency of the sound waves.) Bottom: Same as middle, except that the spectrogram of LAeq is shown.*

The top graph in the figure shows the overall A-weighted fast-response sound level, measured at 100 ms intervals, over time. The levels show scatter due to both turbine and background sounds. The shutdown in clearly seen starting at 23:10 and ending at 23:47. The middle chart is shows an amplitude modulation spectrogram of the L_{AF} for the same period, using the data from the top chart. A pronounced feature of the spectrograms is the approximately horizontal streak occurring at around 0.8 Hz and one multiple thereof.

Since these features disappear during the shutdown (as indicated by the dashed vertical lines in the figures), they are clearly a characteristic of the wind turbine noise. The dominant frequency indicates an amplitude modulation related to the rotation rate of the wind turbine.

Note that the spectrogram for L_{AF} exhibits little amplitude modulation above approximately 2 Hz. On the other hand, the first and second harmonics of the fundamental are evident in the spectrogram for LAeq shown in the bottom graph. Apparently, the damped response of the L_F setting on the sound level meter, although "fast," is not fast enough to capture fully the relatively weaker amplitude modulation above the fundamental frequency.

The following sequence of plots show the Leq for various 1/3-octave bands, along with the corresponding spectrograms. These help to clarify the mechanisms producing the sound and amplitude modulation in these data. Shown are results for the 1/3-octave bands centered at 8 Hz, 31.5 Hz, 125 Hz, 500 Hz, and 2 kHz. These were selected to illustrate the progression of spectral characteristics as the frequency is increased, which helps to motivate subsequent signal processing strategies.

Let us first consider the infrasound frequency behavior. In the 1/3-octave band centered at 8 Hz, shown in Figure 35, the Leq spectrogram exhibits substantial modulations in sound level with frequencies up to about 2 Hz. The spectrum is broadband and random. Close examination reveals a horizontal streak in the spectrogram at around 0.8 Hz, the characteristic period of the wind turbine amplitude modulation. Still, the spectrogram changes little during the shutdown.

In the 1/3-octave band centered at 31.5 Hz, shown in Figure 35, the randomly modulated noise still is present, but it appears to be somewhat weaker and has spread to higher modulation frequencies. These features are characteristic of wind noise (random turbulent pressure fluctuations due to the interaction of wind with the Earth's surface); this will be discussed further in connection with data from another location. No horizontal "streak" in the spectrogram associated with the wind turbine rotation rate is noticeable.

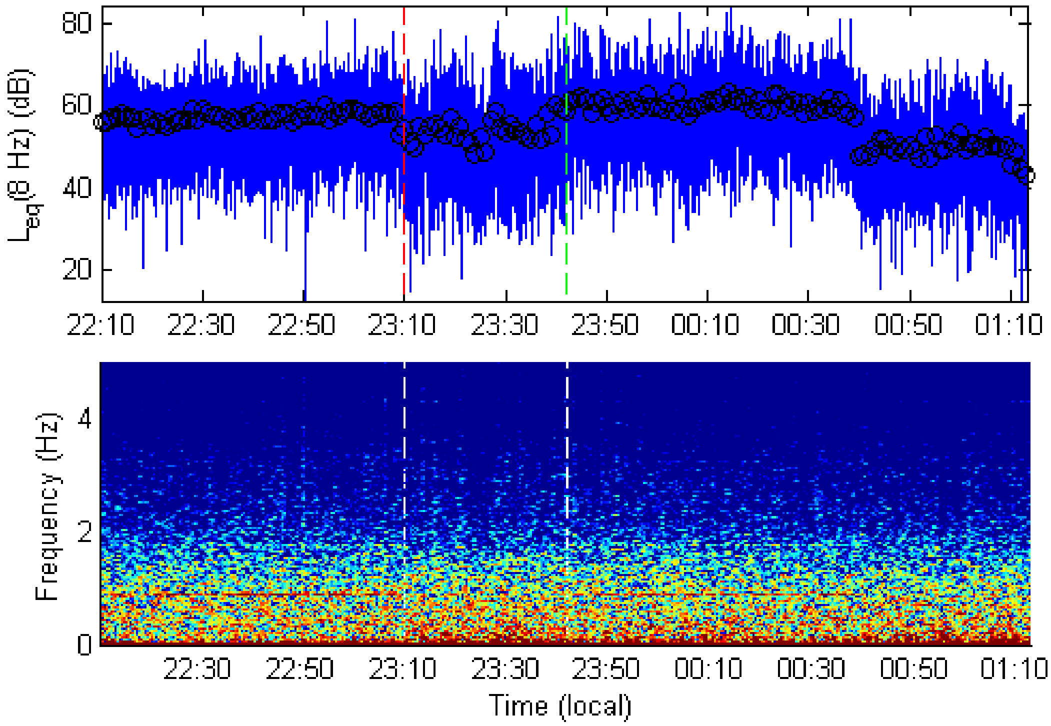

FIGURE 35: TIME SERIES (TOP) AND SPECTROGRAM (BOTTOM) FOR THE ONE-THIRD OCTAVE BAND Leq CENTERED ON 8 Hz AT SITE 7A (330 M)

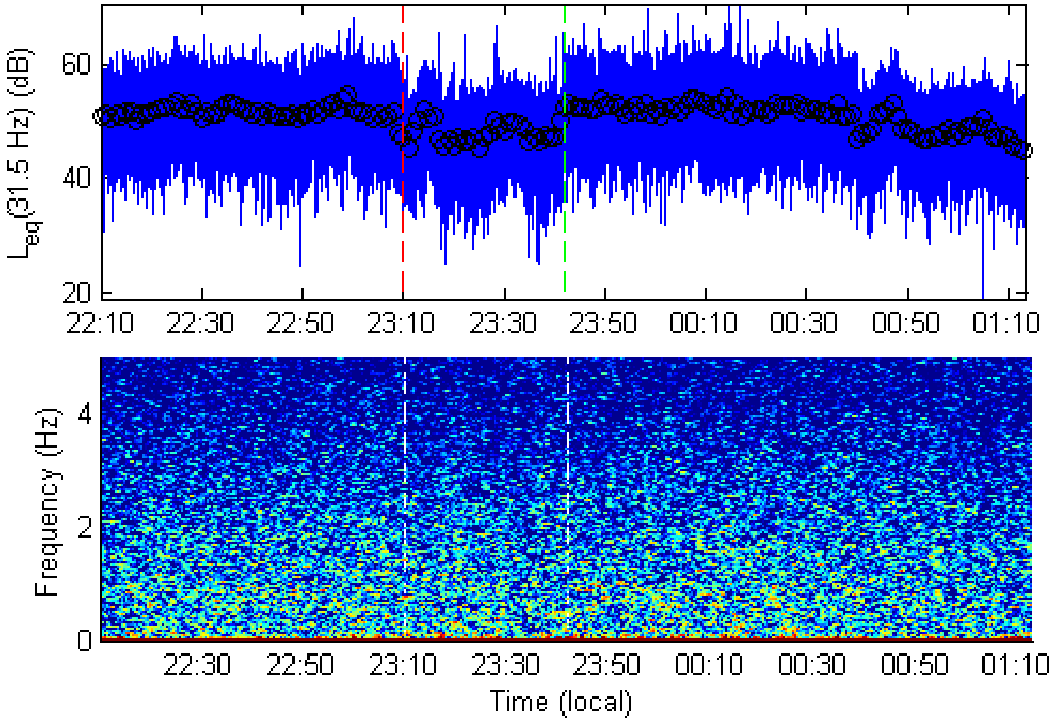

FIGURE 36: SAME AS PREVIOUS, BUT CENTERED ON 31.5 Hz

Figure 37, Figure 38, and Figure 39 show the 1/3-octave bands centered at 125 Hz, 500 Hz, and 2 kHz, respectively. In these bands, the time series indicate a clear decrease in sound level when the wind turbine is shut down, and the spectrogram clearly exhibits amplitude modulation characteristics from the wind turbine. Some evidence of wind noise is present in the 125 Hz spectrogram. This noise is less apparent in the 500 Hz band, leaving a very clear amplitude modulation signature. The amplitude modulation is still evident at 2 kHz, but has significantly weakened compared with the lower frequency bands. Intermittent environmental noise sources appear to prevail in this band.

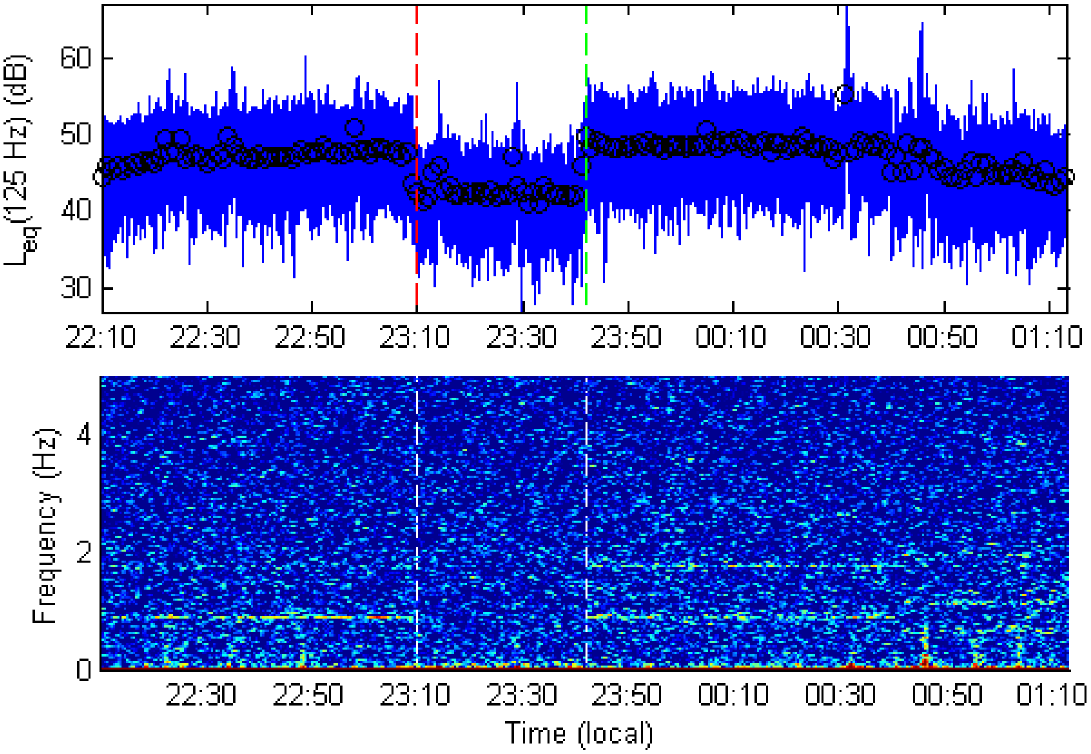

FIGURE 37: SAME AS PREVIOUS, BUT CENTERED ON 125 Hz

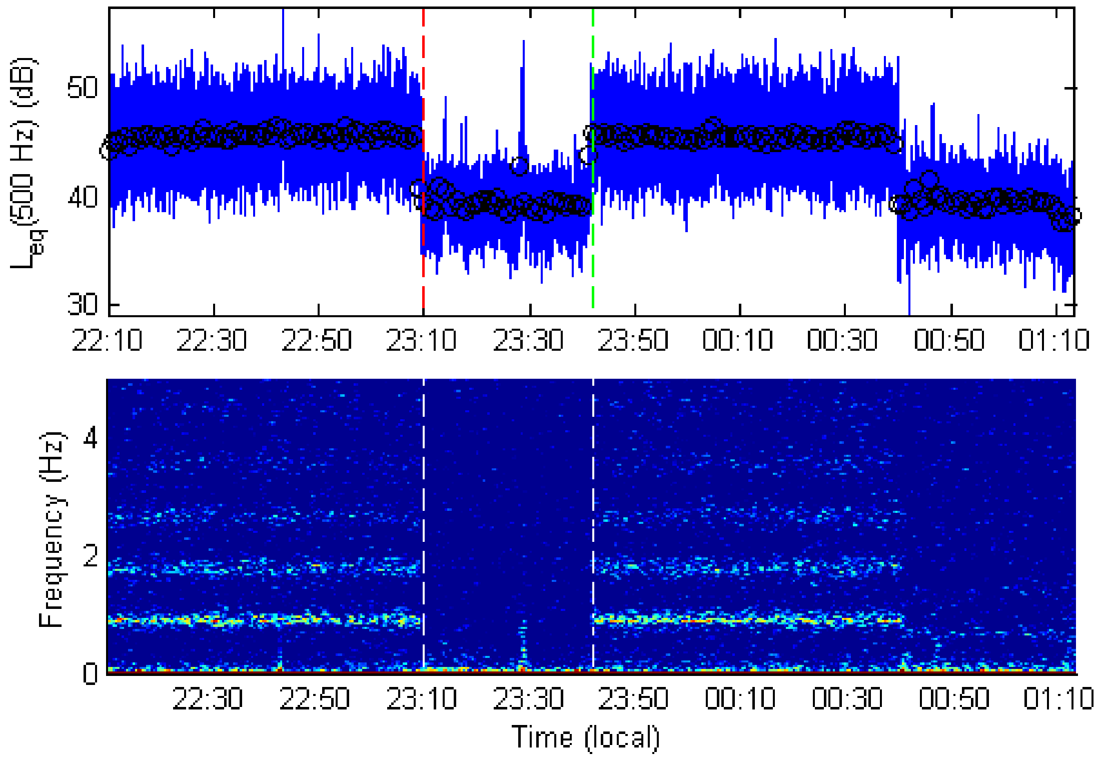

FIGURE 38: SAME AS PREVIOUS, BUT CENTERED ON 500 Hz

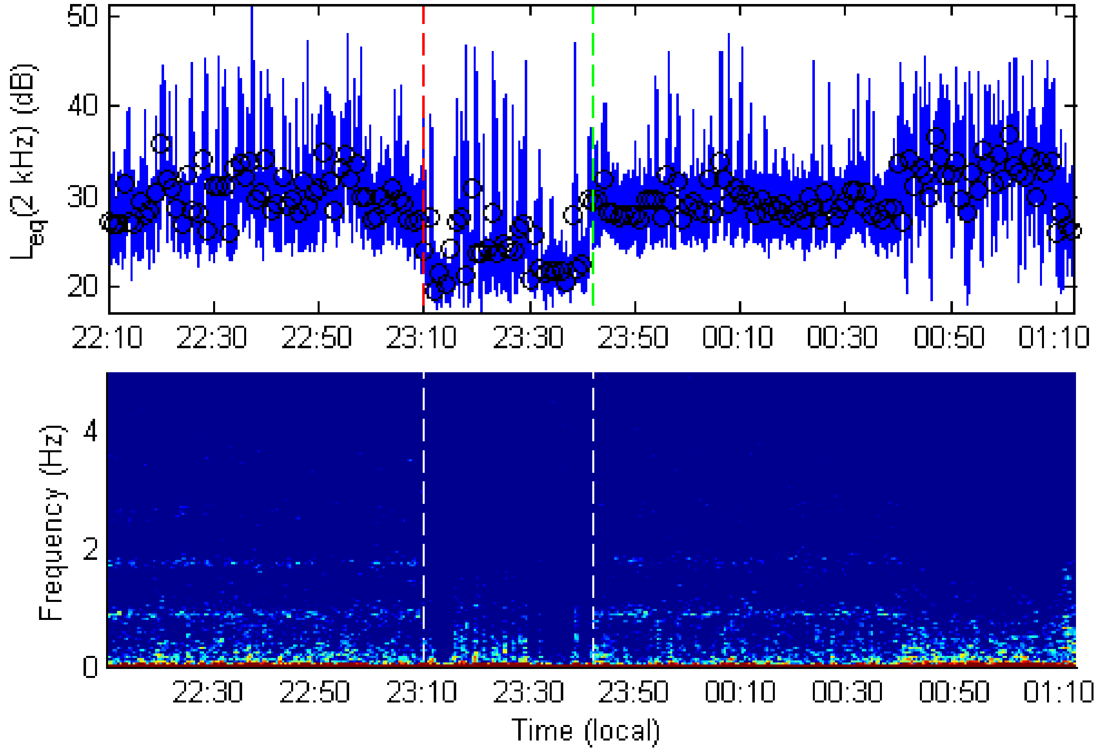

FIGURE 39: SAME AS PREVIOUS, BUT CENTERED ON 2 kHz

Site 7B

Next, we consider data recorded at a different flat site, Site 7B, about 330 meters upwind from a turbine. The analyzed interval starts at 20:50 and lasts for 2.5 hours, with a 20-minute shutdown period beginning at 21:50. During this time interval, a moderate wind (about 8 m/s at a height of 80 m) created an upwind condition at the measurement location.

The A-weighted equivalent sound level (Leq) and 1/3-octave band levels are shown in Figure 40. The wind turbine sound exceeds the background sound in the infrasonic range and at low frequencies, up to about 31.5 Hz. In the 8-Hz 1/3-octave band, the sound level with the turbine on is about 48 dB, and with it off, about 38 dB. However, in the A-weighted data, the turbine-on condition is only about 1 dB louder than the background. (The 8-Hz band contributes very little to the A-weighted level.). For the 1/3-octave bands from 63 Hz upward, there is little observed difference between the sound levels with and without the wind turbine in operation. An exception, although weak, occurs in the frequency range of 250 Hz to 500 Hz, for which levels are about 2 dB higher when the wind turbine is operating. In the high-frequency range, there is a strong peak around 4,000 Hz, which occurs regardless of the operating state. Hence, the acoustical impact of the turbine is evident only in the infrasonic and low frequency range, and in the mid-frequency range around 500 Hz, even though this location is relatively close to the turbine. This example helps to illustrate the challenge of obtaining a signal-to-noise ratio (SNR) sufficient for reliable extraction of the amplitude modulation characteristics.

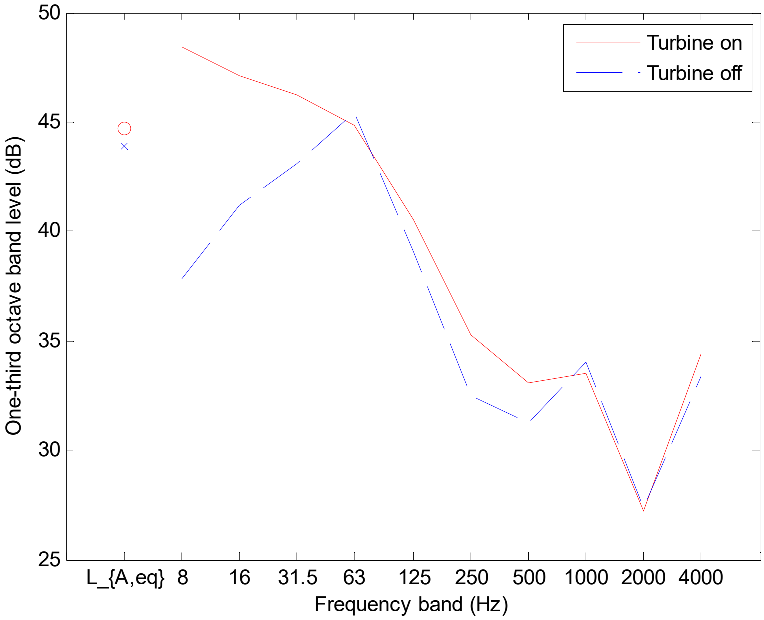

FIGURE 40: A-WEIGHTED SOUND LEVEL (LAeq) AND UNWEIGHTED ONE-THIRD OCTAVE BAND LEVELS AT SITE 7B (330 M) WITH AND WITHOUT THE TURBINE IN OPERATION

The red circle and blue x at the left of the plot represent the A-weighted sound level, with and without the turbine operating, respectively. The solid red line and dashed blue line represent the unweighted one-third octave band levels, with and without the turbine operating, respectively, The time series for the LAF, spectrogram for LAF, and spectrogram for Leq are shown in Figure 41. The spectrograms appear different from those for Site 7A. Specifically, there are elevated levels corresponding to modulations in the frequency range from 1 Hz to 3 Hz. These features could perhaps be confused with wind turbine amplitude modulation noise. However, since the blade rate of the wind turbine changes very slowly, this interpretation is unlikely. Also note that these features appear to be unaffected by the shutdown. Relatively short-term noise sound events, perhaps cars or airplanes, produce intermittent spikes in LAF and Leq. These events appear as vertical streaks in the spectrogram.

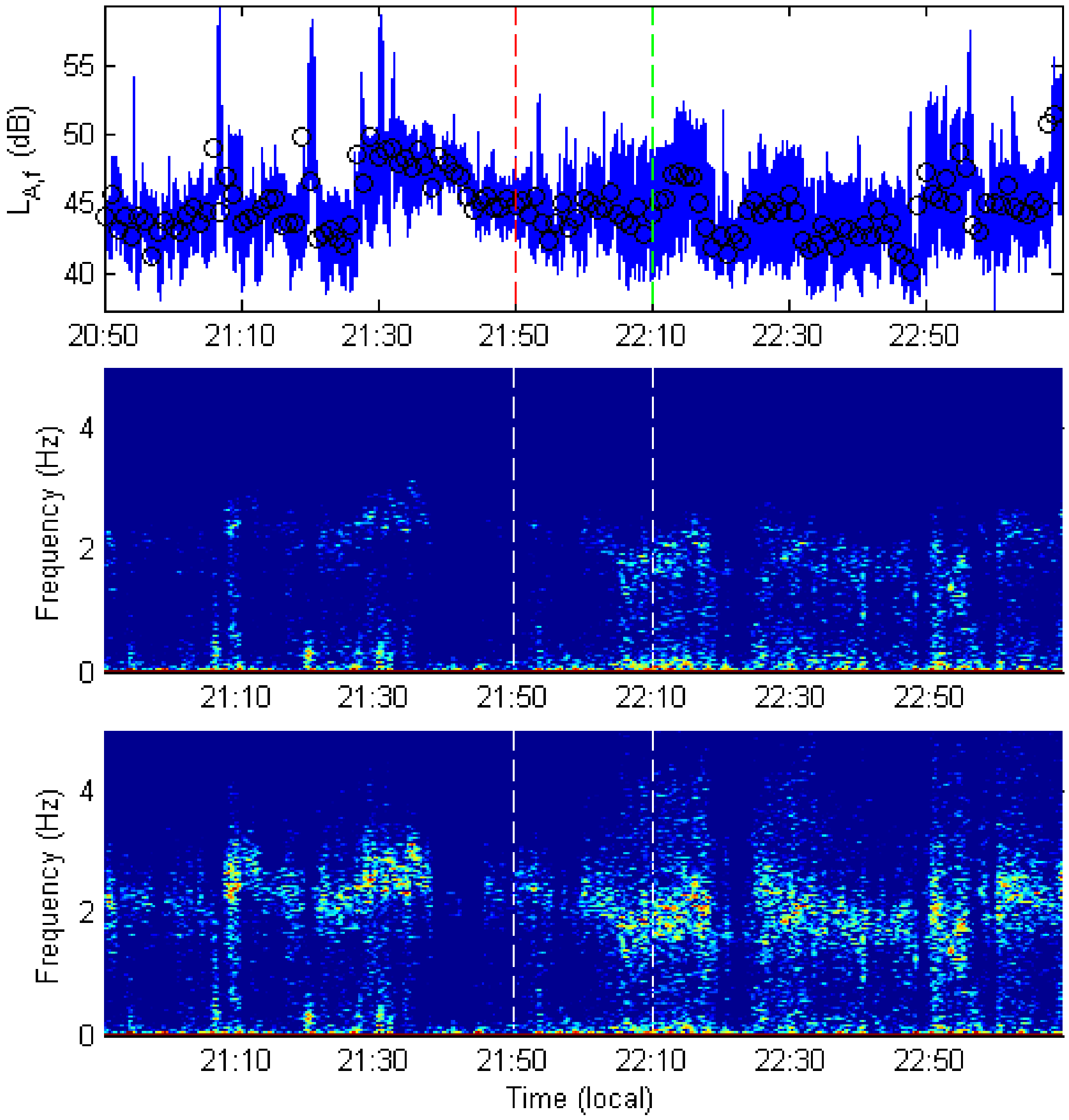

FIGURE 41: THREE TIME-SERIES VIEWS OF A SINGLE TURBINE SHUTDOWN AT SITE 7B (330 M)

Dashed vertical lines indicate the beginning and end of the interval of the wind turbine shutdown. Top: Fast-response overall A-weighted sound level; Middle: Amplitude modulation spectrogram for the LAF during same period. Bottom: Same as middle, except that the spectrogram of Leq is shown.

To help explain these patterns, we first consider the low-frequency behavior shown in Figure 42 through Figure 45. Up to about 16 Hz, the spectrograms exhibit substantial modulations in sound level. However, the spectrum is very broadband and random, and seems to roll off gradually with frequency, rather than exhibit any obvious spectral lines or streaks. This sound source is weaker at 63 Hz, and disappears altogether at 500 Hz (Figure 46), at which frequency the spectral lines characteristic of the wind turbine amplitude modulation can be seen. Still, it should be noted, in the time series, that the energy in the 1/3-octave bands from 6.3 Hz to 16 Hz does appear to depend on whether the wind turbine is operating. From the time-series graphs (the top portions of the charts), we can see a drop-off of about 5 dB when the wind turbine is shut down. We thus might conclude that infrasound and low-frequency sound from the wind turbine is indeed being measured, although it is difficult to discern from the background, that is, non-wind turbine, infrasonic and low-frequency noise. (Further discussion of infrasound can be found in Section 8).

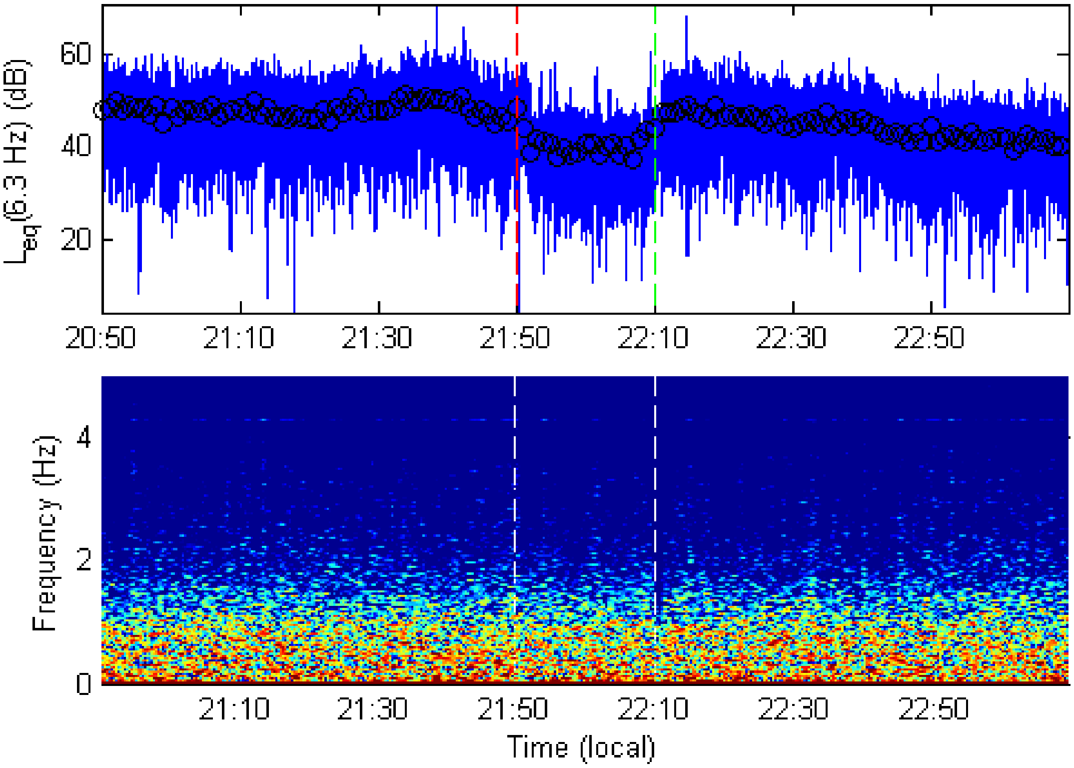

FIGURE 42: TIME SERIES (TOP) AND SPECTROGRAM (BOTTOM) FOR THE ONE-THIRD OCTAVE BAND CENTERED ON 6.3 Hz, SITE 7B (330 M)

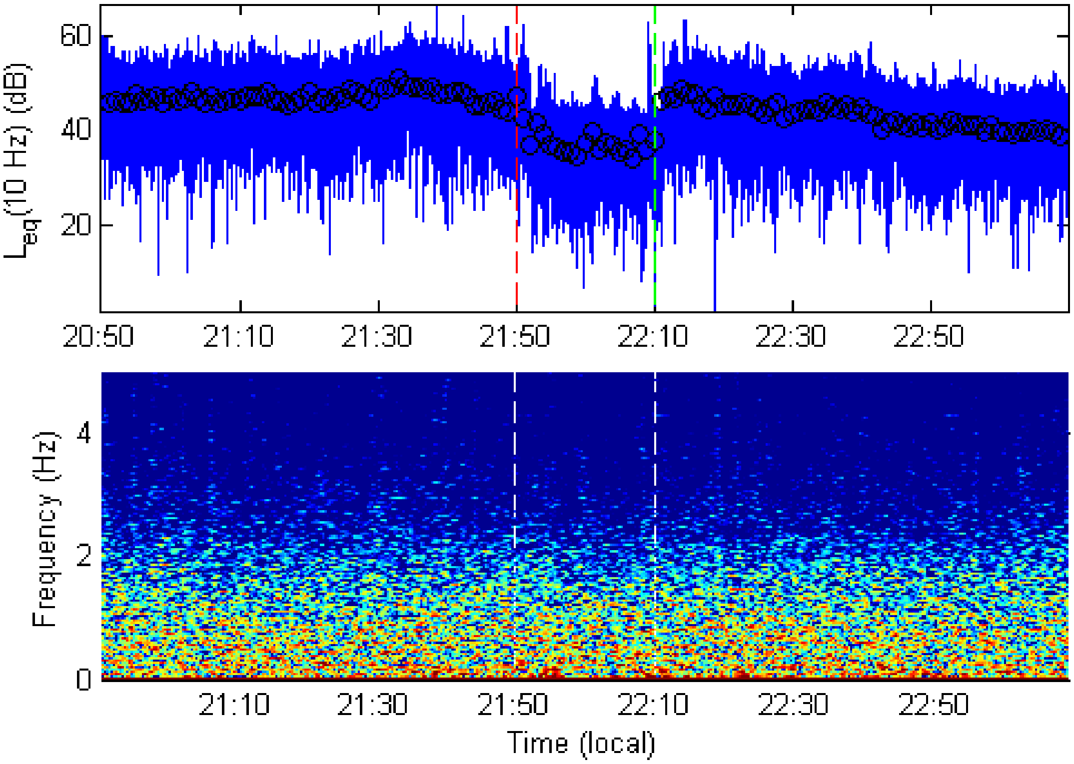

FIGURE 43: SAME AS PREVIOUS, EXCEPT FOR THE BAND CENTERED ON 10 Hz

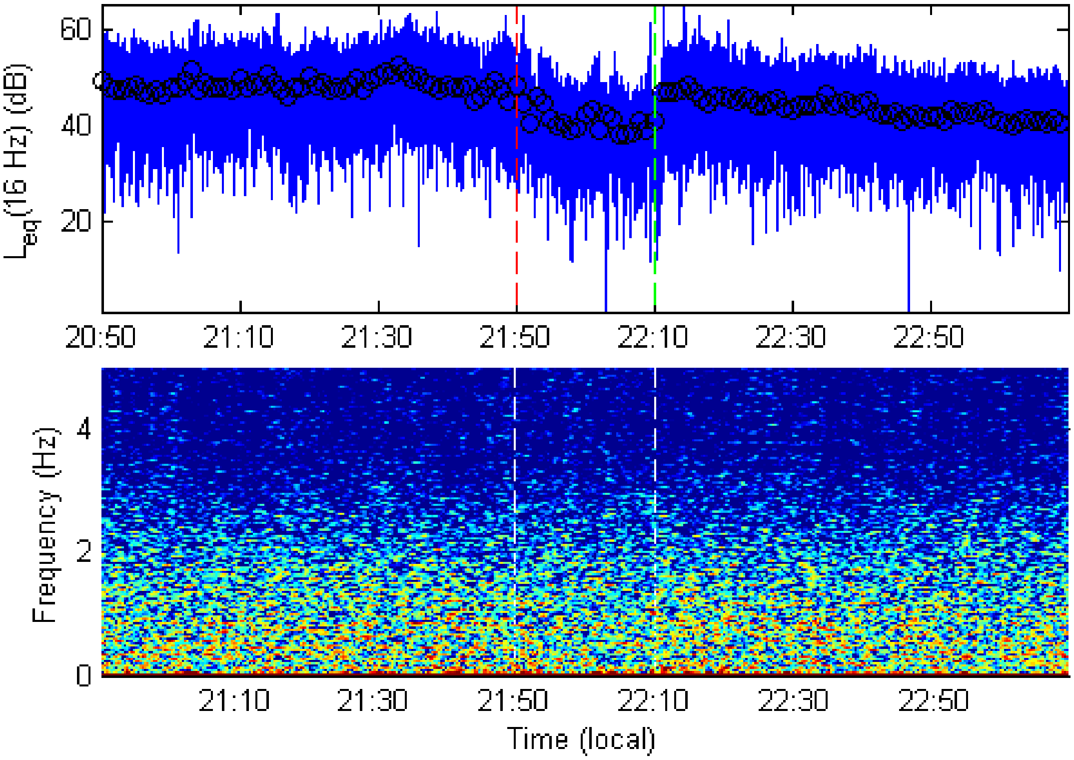

FIGURE 44 SAME AS PREVIOUS, EXCEPT FOR THE BAND CENTERED ON 16 Hz

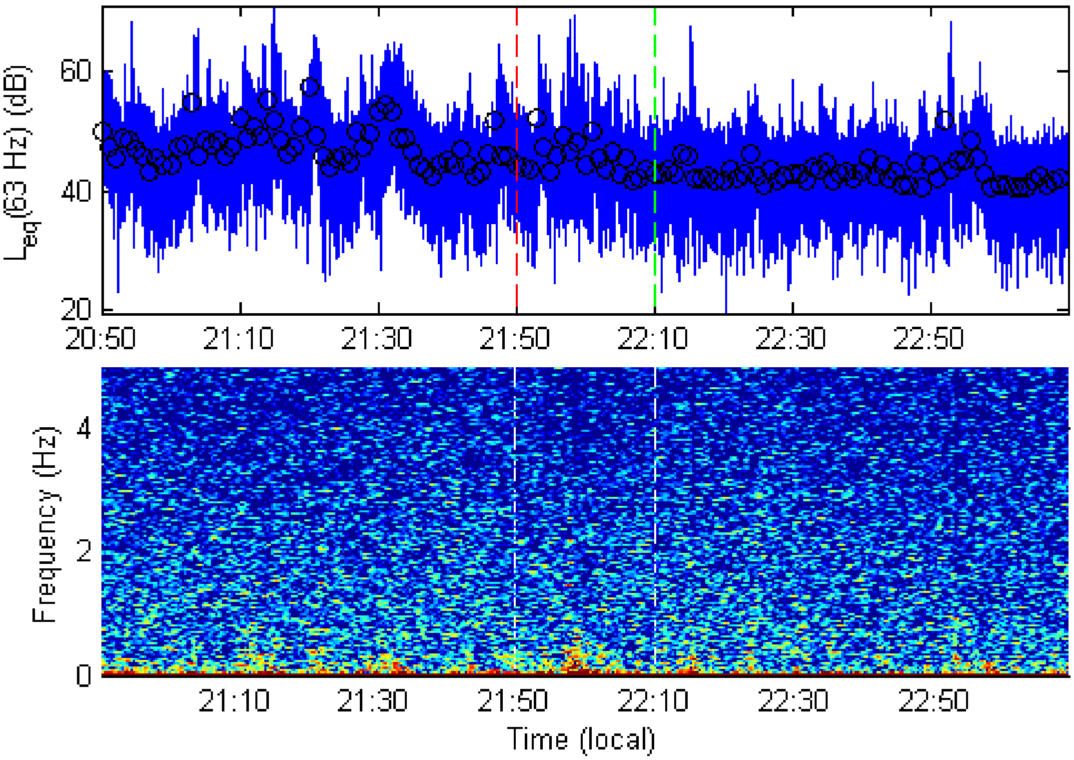

FIGURE 45: SAME AS PREVIOUS, EXCEPT FOR THE BAND CENTERED ON 63 Hz

The next three sets of figures show the sound levels and corresponding modulation spectrograms for the 1/3-octave bands at 500 Hz, 2 kHz, and 4 kHz for Site 7B at 330 meters. At 500 Hz (Figure 46), the wind turbine is most evident above the background noise, compared with the other frequencies. Its amplitude modulation characteristic is evident in the horizontal streaks in the spectrogram. This feature has all but disappeared at 2 kHz, however. Finally, when we examine the 4 kHz band, an amplitude modulation signature is found that resembles the pattern originally observed in the L_{AF} and Leq plots. This high-frequency background noise is possibly due to a chorus of crickets or other insects creating high-frequency, amplitude-modulated “chirping” sounds.

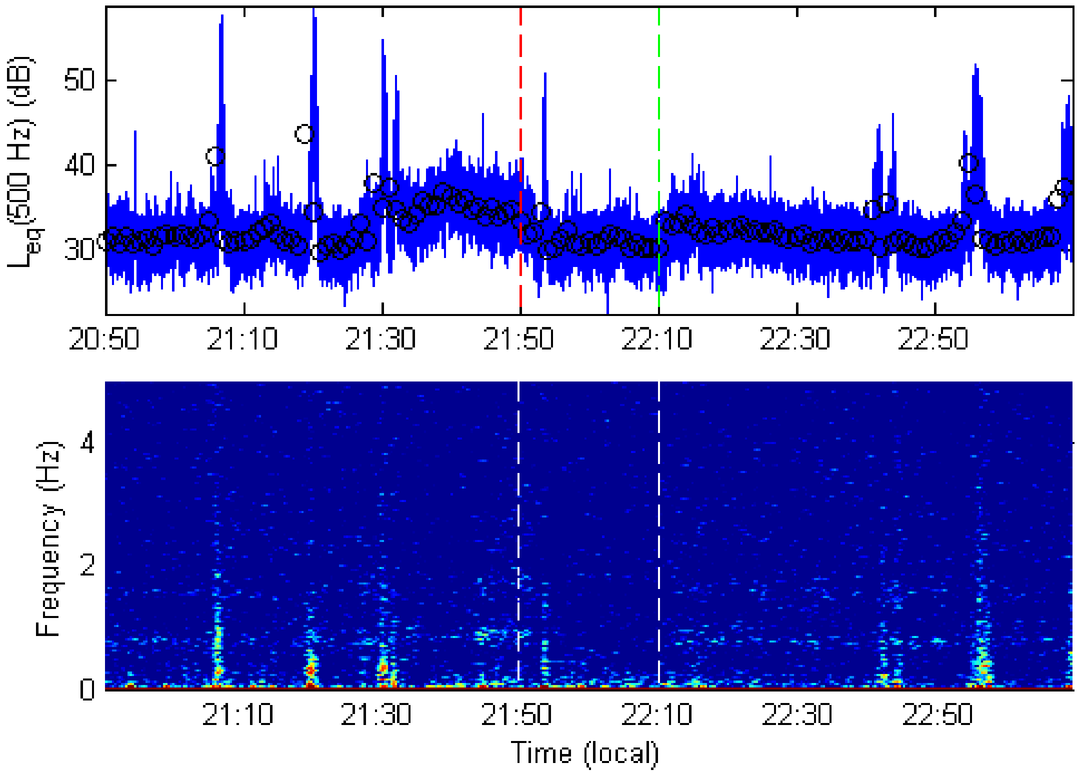

FIGURE 46: SAME AS PREVIOUS, EXCEPT FOR THE BAND CENTERED ON 500 Hz

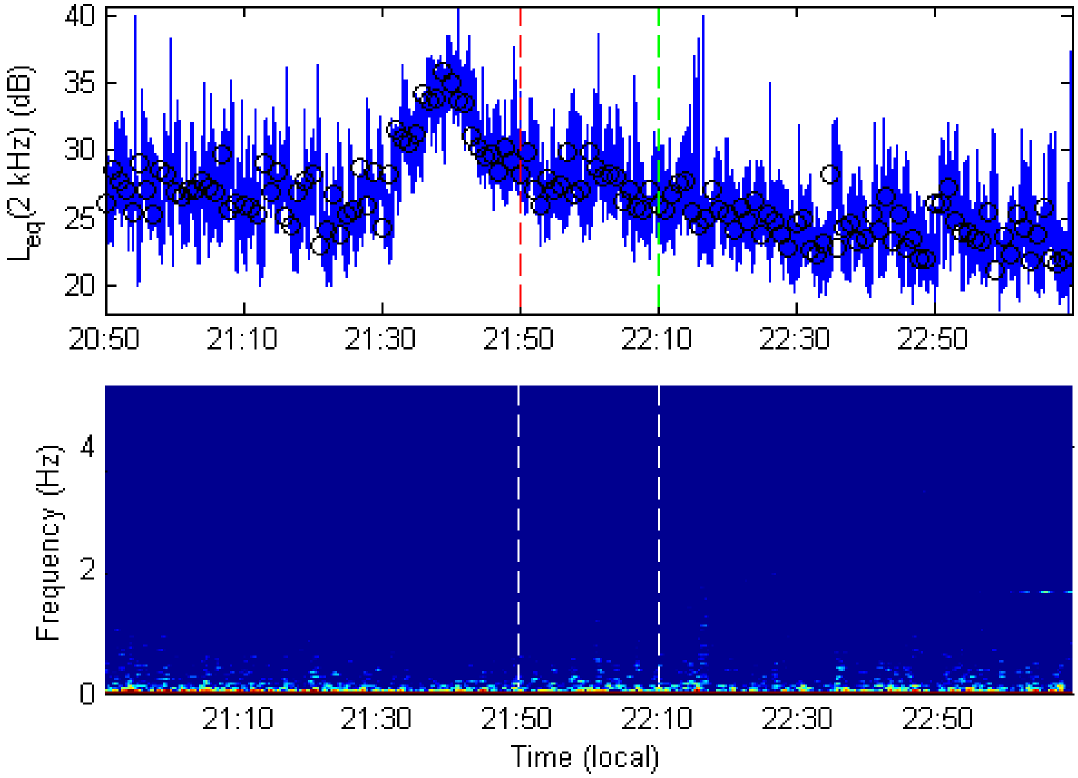

FIGURE 47: SAME AS PREVIOUS, EXCEPT FOR THE BAND CENTERED ON 2 kHz

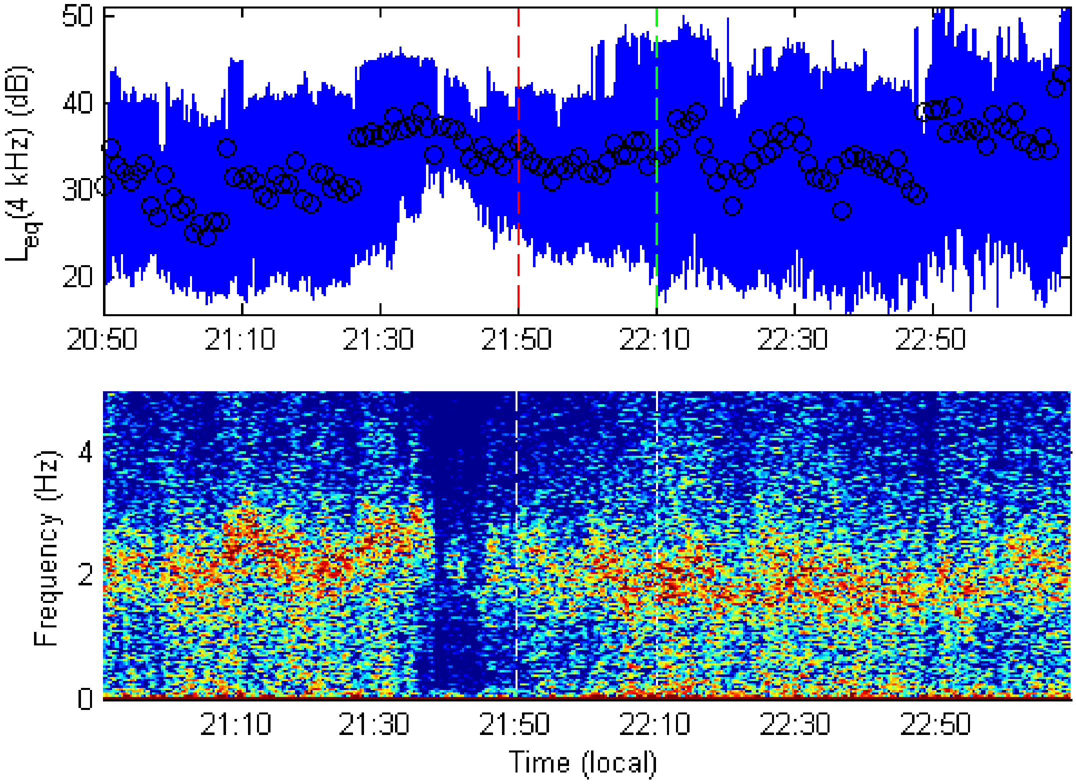

FIGURE 48: SAME AS PREVIOUS, EXCEPT FOR THE BAND CENTERED ON 4 kHz

METHOD FOR EXTRACTING AMPLITUDE MODULATION SIGNALS

This section describes how the amplitude-modulated signals from the previous section are detected and quantified.

The steps involved are:

Step 1: Obtain A-weighted overall sound levels and unweighted 1/3-octave band sound levels (fast-response) at logging intervals of 125 ms or faster.

The upper part of Figure 49 shows the fast-response A-weighted sound level for a 2.5-hour recording of wind-turbine sound at Site 7B, 660 meters crosswind of a single wind turbine. The vertical dashed red line indicates the (approximate) start time of the shutdown, and the vertical dashed green line indicates the re-starting of the turbine.

Step 2: Process the data using Fast Fourier Transforms (FFTs) of the measured sound levels to obtain the modulation frequencies.

The method for extracting the amplitude modulation is based on taking a Fourier spectrogram of the sound level meter data.[14]

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[14] The spectrogram was processed with FFTs of 1024 points, at the sample rate for the sound level meter of 0.1 seconds. This corresponds to windows of duration of 102.4 seconds. A 90% overlap was used in the processing.

The lower part of Figure 49 shows the part of the signal attributed to amplitude-modulated wind turbine sound, as extracted by the method that is explained below. Note that the processing method extracts the time-varying part of the signal – the mean is inherently zero. This methodology can be applied to any time series for a sound level, including A-weighted levels, and 1/3-octave band levels.

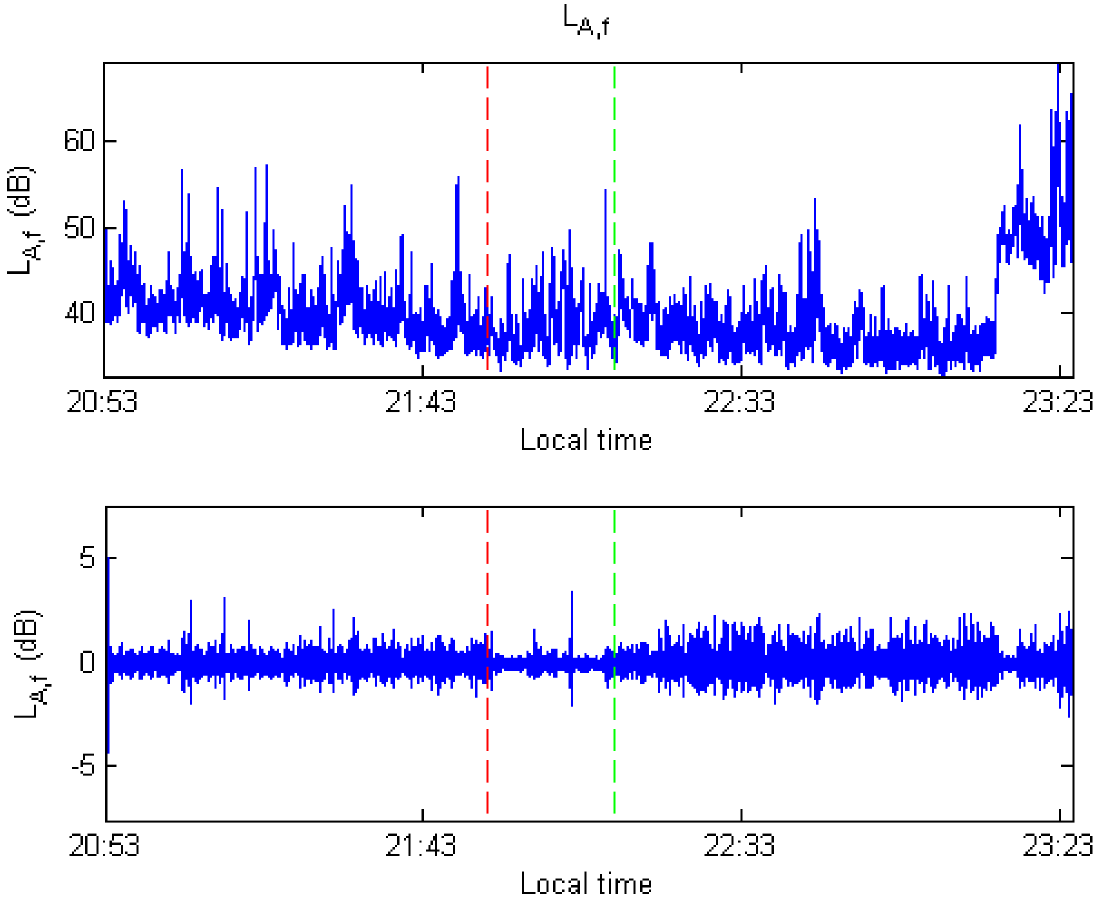

FIGURE 49. TOP: TIME SERIES FOR THE FAST-RESPONSE, A-WEIGHTED LEVEL ($L_{A,F}$) AT SITE 7B (660 M). BOTTOM: EXTRACTED AMPLITUDE MODULATION COMPONENT FOR THE $L_{A,F}$ SIGNAL AT TOP, WHICH IS PRIMARILY ATTRIBUTABLE TO THE WIND TURBINE

Step 3: Create a spectrogram of the time-sequence of individual modulation frequency spectra.

The result, for the L_{AF} data, is shown in the upper part Figure 50. Parts of the figure show a strong spectral (horizontal) streak at about 0.8 Hz. This is the amplitude modulation signature of the wind turbine sound. Note that the rotation rate of the wind turbine at this site was constant at this wind speed, so that the frequency of the amplitude modulation is very stable. A close examination of the figure also reveals the presence of a weak spectral line at 1.6 Hz, which is the first harmonic of the 0.8 Hz fundamental frequency. There is also significant energy at much lower frequencies; this part of the signal is attributable to the background environmental sound, since it persists even when the wind turbine is off. The vertically oriented features are individual noise events, such as passing automobiles.

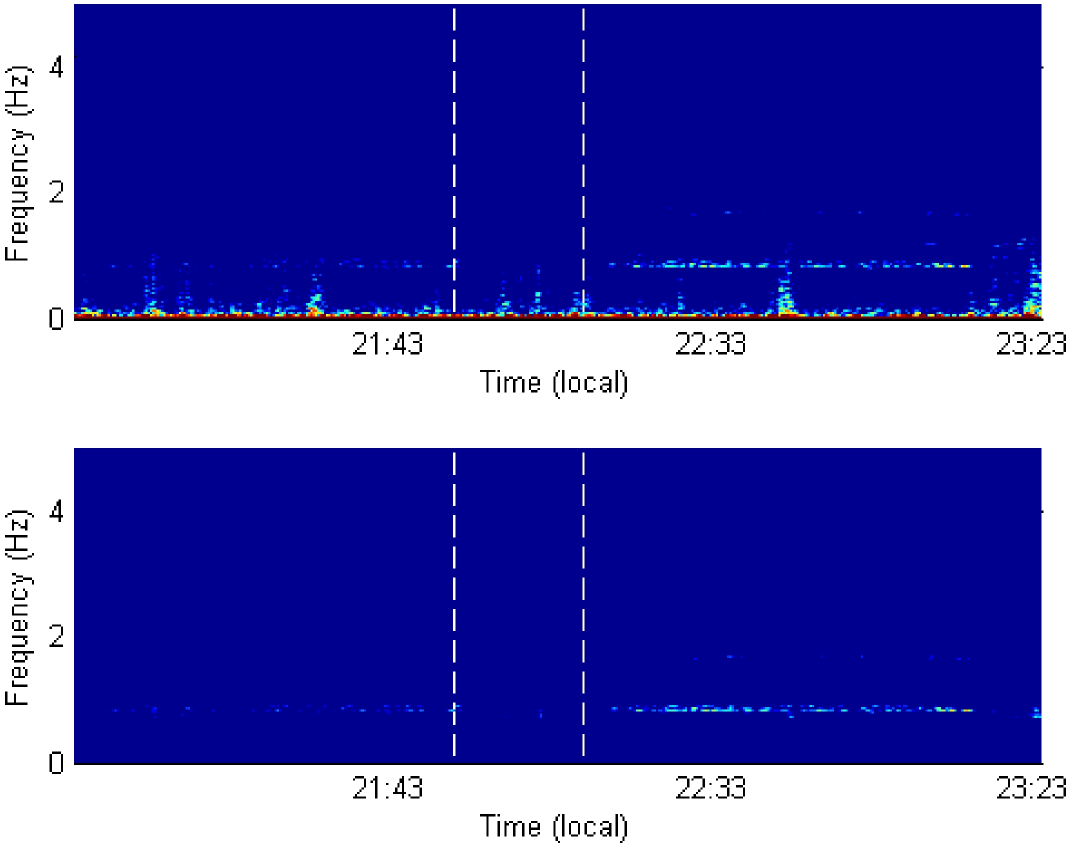

FIGURE 50: TOP - SPECTROGRAM OF THE L_{AF} TIME SERIES SHOWN IN THE PREVIOUS FIGURE. BOTTOM - SPECTROGRAM FOR THE EXTRACTED AMPLITUDE MODULATION COMPONENT FOR THE L_{AF} SIGNAL AT TOP, WHICH IS PRIMARILY ATTRIBUTABLE TO THE WIND TURBINE

Step 4: Filter out non-turbine amplitude modulated sounds.

Figure 50 shows the result of filtering out background noise. The upper part of the figure is the unfiltered sound, and the lower part of the figure is after application of a high-pass filter to isolate the wind turbine amplitude modulation noise.[15] The filter selects variability in the spectrogram occurring at modulation frequencies above approximately 0.5 Hz. This includes the fundamental frequency of 0.8 Hz, and the four harmonics above it: 1.6, 2.4, 3.2, and 4.8 Hz. Higher harmonics are unavailable, because the sampling rate for the sound level meter is 10 Hz, which corresponds to a Nyquist frequency (maximum processing frequency) of 5 Hz. Application of the high-pass filter effectively isolates the amplitude modulation from the wind turbine from the background noise, for which the modulations are typically below 0.5 Hz.

Step 5: Repeat the analysis for each 1/3-octave band.

The analysis is repeated for 1/3-octave bands centered at 16 Hz and 500 Hz in the following four figures. The 16 Hz analysis (Figure 51 and Figure 52) illustrates a frequency band for which the amplitude-modulated

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[15] The filter is an eighth-order digital high-pass filter with stopband frequency at 0.4 Hz, and passband frequency at 0.6 Hz.

sound is largely dominated by background noise sources. At this frequency, there is evidence of a decrease in sound level when the wind turbine is turned off. However, there is no appreciable change in the amplitude modulation when the wind turbine is turned off. This result indicates that the wind turbine is producing measurable infrasound; however, the infrasound does not modulate significantly. The levels observed when the wind turbine is not operational are likely due to wind noise.

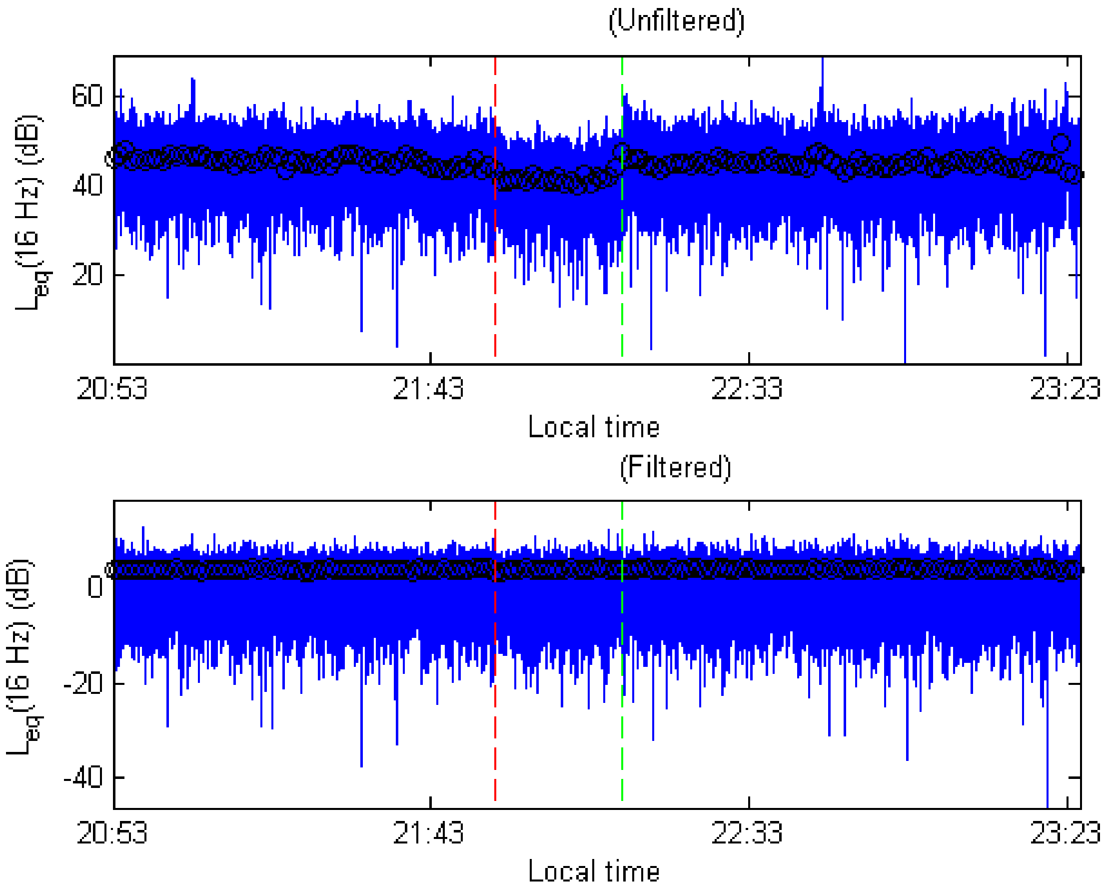

FIGURE 51: TOP - TIME SERIES FOR THE 16-Hz ONE-THIRD OCTAVE BAND LEVEL AT SITE 7B (660 M). BOTTOM - EXTRACTED AMPLITUDE MODULATION FOR THIS BAND

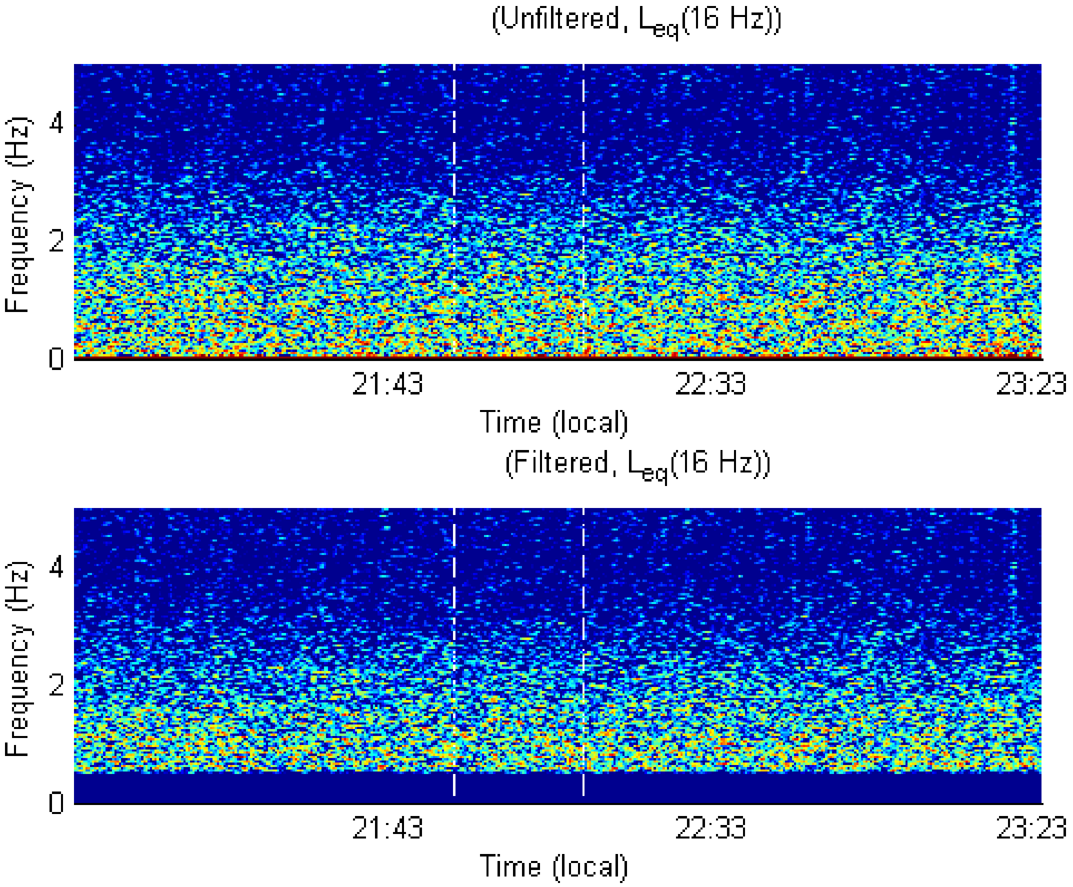

FIGURE 52: TOP - SPECTROGRAM 16-Hz ONE-THIRD OCTAVE BAND LEVEL SHOWN IN THE PREVIOUS FIGURE. BOTTOM - SPECTROGRAM OF THE HIGH-PASS FILTERED PART OF THE SIGNAL

The 500 Hz band (Figure 53 and Figure 54) is illustrative of a situation where the amplitude modulation is readily apparent with respect to the environmental background. In this band, the fundamental as well as several harmonics are evident. The amplitude modulation changes noticeably (Figure 54) between turbine-off and turbine-on. The high-pass filter clearly isolates the amplitude modulation attributable to the wind turbine.

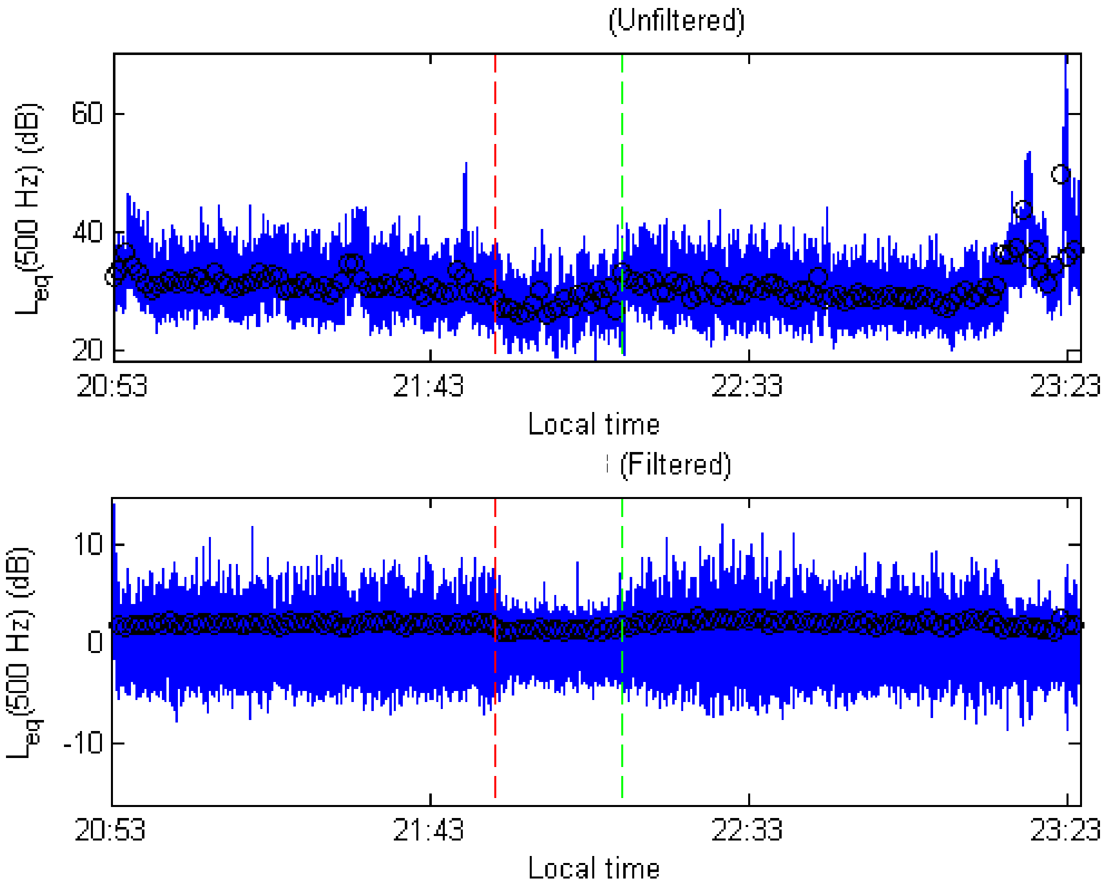

FIGURE 53: TOP - TIME SERIES FOR THE 500-Hz ONE-THIRD OCTAVE BAND LEVEL AT SITE 7B (660 M). BOTTOM - EXTRACTED AMPLITUDE MODULATION FOR THIS BAND

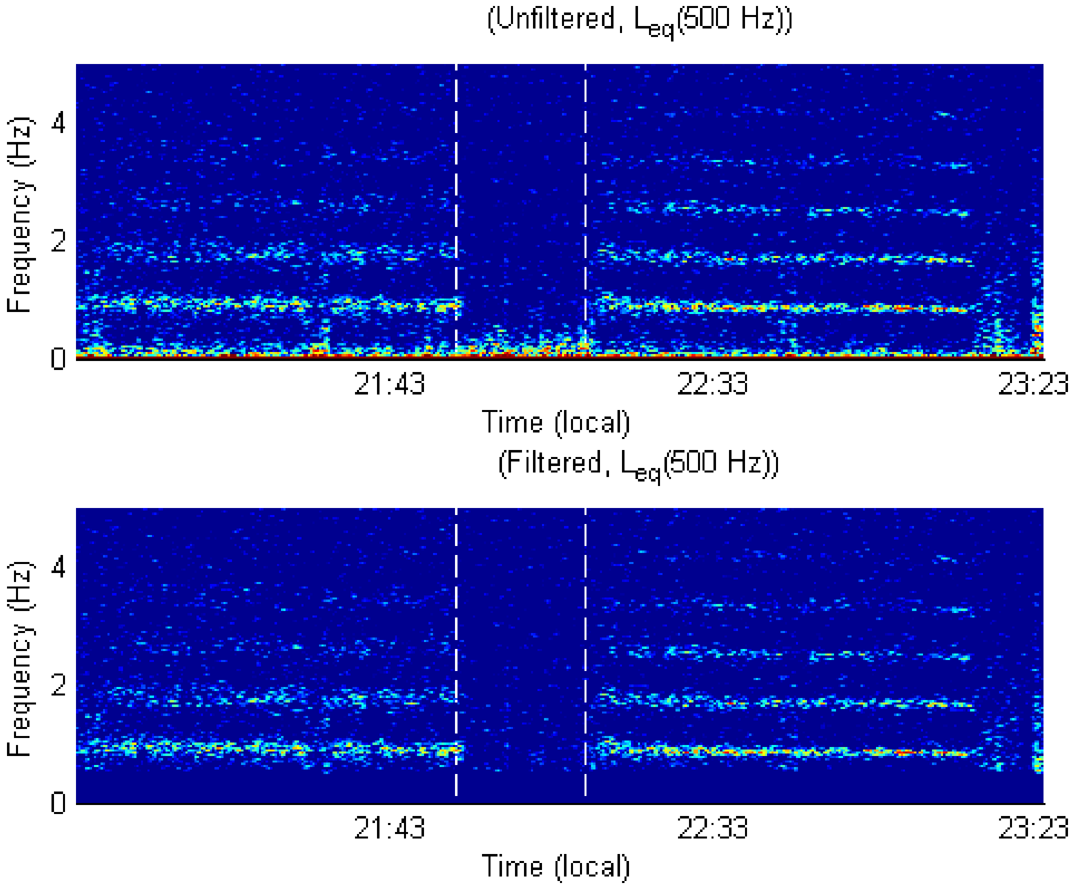

FIGURE 54: TOP - SPECTROGRAM 500-Hz ONE-THIRD OCTAVE BAND LEVEL SHOWN IN THE PREVIOUS FIGURE. BOTTOM - SPECTROGRAM OF THE HIGH-PASS FILTERED PART OF THE SIGNAL

7.3 | SWISHING VS. THUMPING

Amplitude-modulated sound from wind turbines modulation is often characterized either as “swishing” or “thumping”. The swishing sound is generally considered broadband mid-frequency sound with a gradual onset and decay, while the thumping sound is a lower frequency sound with a faster onset and decay.

Our investigation into amplitude modulation spanning each turbine shutdown found no instance of low-frequency modulation. As a result, we then evaluated attended monitoring data for those situations during which the attendant reported hearing “thumping” sound as opposed to normal modulation from the wind turbine(s).

Next, we consider an attended monitoring session that took place at Site 7A. At 330 meters upwind relative to the prevailing wind, amplitude modulation was reported at various intervals between 12:30 and 13:00, and thumping was reported from 12:32 to 12:37. At another attended monitoring location 660 meters upwind relative to the prevailing wind, amplitude modulation was reported on the same day at various intervals between 11:56 and 12:12. During this time, wind speed at 10 meters was 5 m/s, creating a nominally upwind condition at the monitoring locations. Figure 55 shows the spectrogram of the modulation at Site 7A (330 m) based on Leq. Data were unavailable at 660 m during this interval. The reduction of amplitude modulation during the curtailment from about 11:00 to 11:30 is evident. At around 12:30, at which time thumping was first reported, the amplitude modulation takes on a different appearance in the spectrogram. The dominant frequency of the amplitude modulation moves from about 0.8 Hz to 0.4 Hz. Activity also appears above 4 Hz. However, this activity mirrors that at lower frequencies, thus suggesting the occurrence of digital aliasing in the sound level data. Such aliasing would be caused by amplitude modulation that occurs more rapidly than can be resolved by the 10-Hz sampling rate of the sound level meter (in which case, only frequencies below 5 Hz are not aliased.) This observed change in the amplitude modulation may be the signature of thumping, as opposed to swishing, sound.

In listening to the recorded sound, the sound of the wind turbine was not necessarily of low frequency, but it had a more rapid onset and decay. The audible effect could be described as a "churning" sound. This sound may be due to yaw error, as the thumping reported at 12:32 was just prior to the nacelle changing position, and the thumping at 12:37 was during a short period of 20° yaw error. This data set could be used to investigate whether this occurred at times other than during this monitoring period.

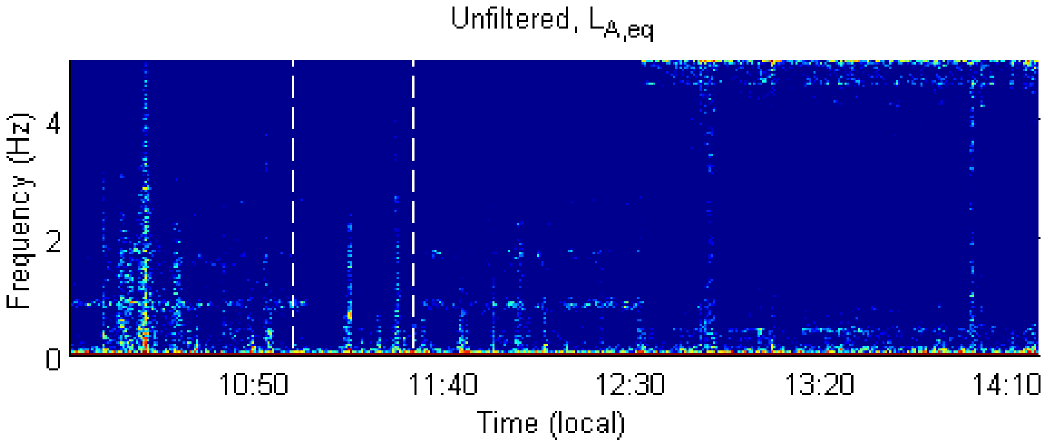

FIGURE 55: SPECTROGRAM SHOWING AMPLITUDE MODULATION AT SITE 7A (330 M)

7.4 | FREQUENCY DEPENDENCE OF AMPLITUDE MODULATION

In this section, we consider the frequency range over which amplitude modulation occurs. This is done by evaluating data from two of the study sites.

SITE 7A

Using monitored sound level data from Site 7A, Figure 56 was created by calculating the standard deviations of L_{Aeq} and the 1/3-octave band levels.[16] The "turbine off" condition corresponds to the shutdown; the "turbine on" condition corresponds to the one half hour interval immediately before and the one half hour interval immediately after the shutdown. The time series for the sound levels was then filtered to exclude modulation frequencies below 0.5 Hz, as described in Step 4 of the section "Method for extracting amplitude modulation signals", above. These results are shown in Figure 57. When the high-pass filter is applied, the

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[16] As described in Figure 32, the standard deviation of a perfect sinusoidal signal is equal to the half the modulation depth times the square root of two.

amplitude modulation for the turbine-off condition decreases from about 4 dB in the and low-frequency range to about 1 dB at 2 kHz. For the turbine-on condition, the amplitude modulation differs from the background only in the frequency range from 125 Hz to 2 kHz. In this frequency range, the increase in amplitude modulation, due to the operation of the turbine, varies from about 0.1 to 0.5 dB. This analysis illustrates the importance of isolating the amplitude variations attributable to the wind turbine from other sources of variation.

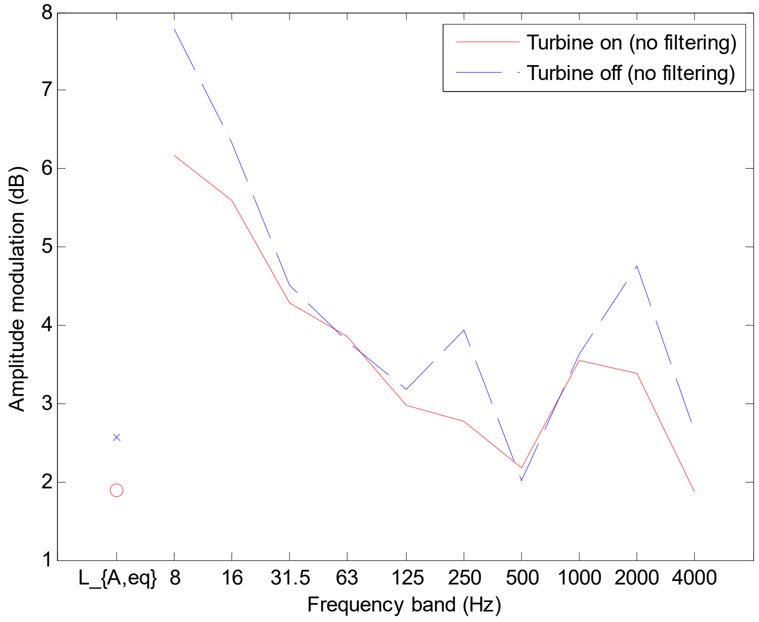

FIGURE 56: AMPLITUDE MODULATION DEPTH TIMES $\sqrt{2}$ FOR TURBINE-ON AND TURBINE-OFF CONDITIONS AT SITE 7A (330 M) AROUND ONE SHUTDOWN.

No high-pass filtering was performed to isolate the amplitude modulation from the wind turbine. The red circle and blue x at the left of the plot represent the A-weighted sound level, with and without the turbine operating, respectively. The solid red line and dashed blue line represent the unweighted one-third octave band levels, with and without the turbine operating, respectively,

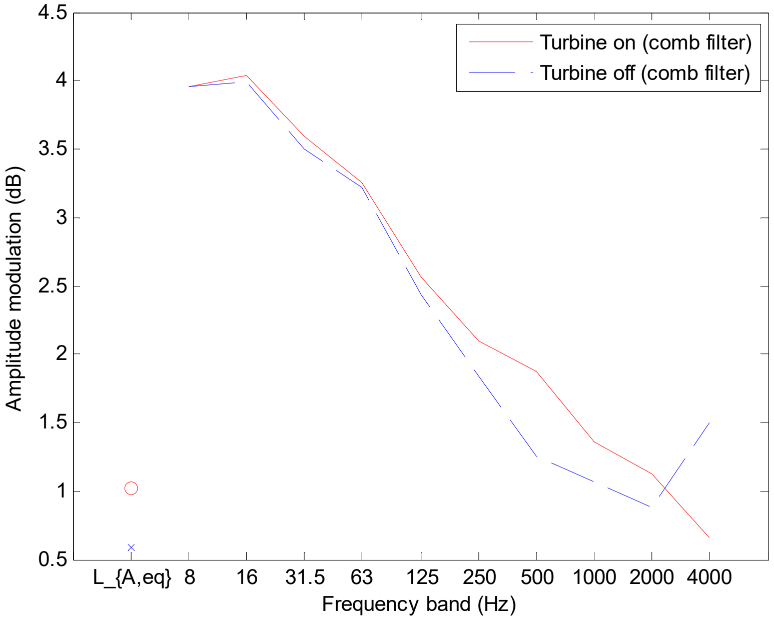

FIGURE 57: SAME AS FIGURE 56, EXCEPT THAT A HIGH-PASS FILTER WITH CUTOFF AT 0.5 Hz WAS FIRST APPLIED TO BETTER ISOLATE THE AMPLITUDE MODULATION FROM THE WIND TURBINE

SITE 7B

Using monitored sound level data from Site 7B during a single nighttime shutdown, the processing described above was conducted. The results are shown in Figure 58 (no filtering) and Figure 59 (filtered below 0.5 Hz). No systematic differences are apparent between the standard deviation with and without the wind turbine operational. This is not unexpected given that the wind turbine sound does not rise above the background for this observation period. For the filtered data, the amplitude modulation decreases from about 4 dB in the infrasonic range to about 1 dB at 2 kHz, much as with Site 7A. However, the amplitude modulation increases dramatically at 4 kHz, to over 5 dB, which is likely attributable to the aforementioned insect noise, since it is present whether the wind turbine is operating or not.

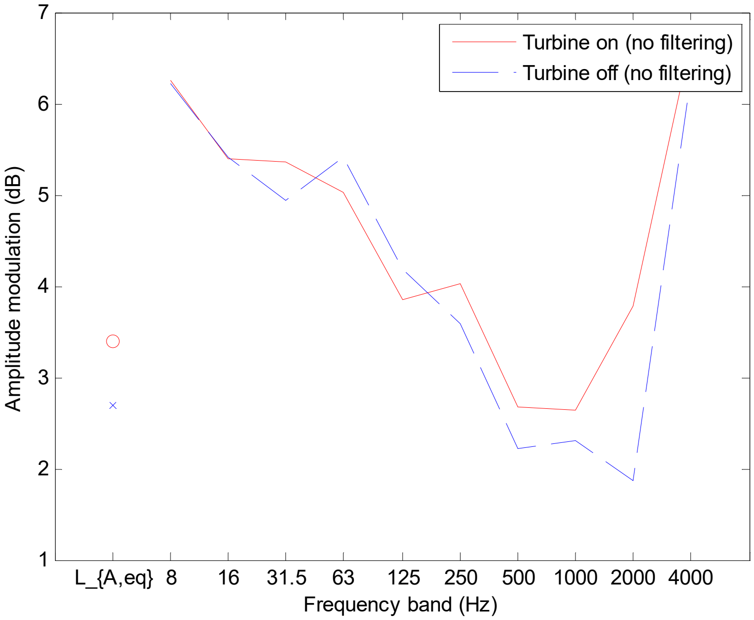

FIGURE 58: AMPLITUDE MODULATION TIMES $\sqrt{2}$ FOR TURBINE-ON AND TURBINE-OFF CONDITIONS AT SITE 7B (330 M) AROUND A SINGLE SHUTDOWN WITH RELATIVELY HIGH BACKGROUND NOISE

No high-pass filtering was performed to isolate the amplitude modulation from the wind turbine.

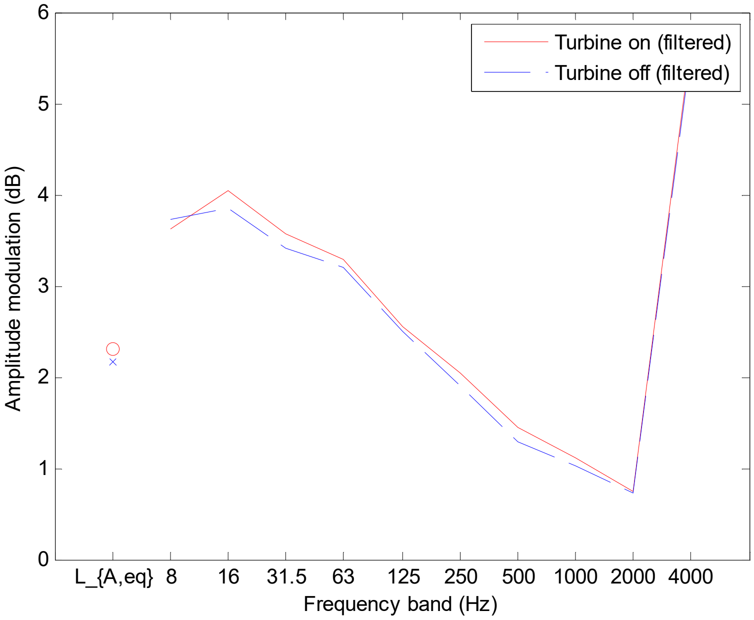

FIGURE 59: SAME AS FIGURE 58, EXCEPT THAT A HIGH-PASS FILTER WITH CUTOFF AT 0.5 Hz WAS FIRST APPLIED TO BETTER ISOLATE THE AMPLITUDE MODULATION FROM THE WIND TURBINE.

7.5 | DEPENDENCE OF THE SOUND LEVELS AND AMPLITUDE MODULATION ON METEOROLOGICAL PARAMETERS

In this section, we consider the dependence of sound levels and amplitude modulation on wind speed, direction, gradients, and turbulent intensity. Since previous sections have demonstrated that the 1/3-octave band levels at 500 Hz tend to most clearly exhibit the amplitude modulation characteristics, we will focus this analysis is on that band.

Wind data from the LIDAR system at 40 m and 50 m heights were processed into one-minute averages. These two heights were used, because they are the lowest two range gates available from the LIDAR. Shear (in this case, the vertical gradient of the horizontal wind speed) is calculated from the difference between the wind speeds at these two heights, divided by the height separation (10 meters). The vertical gradient of the wind direction (veer) is also calculated by taking the absolute value of the difference in the wind direction at the two heights and dividing by the height separation. The turbulence intensity is calculated as the standard deviation of the wind speed at 40 m, divided by the mean, for each one-minute interval.

In the figures in this section, red symbols denote results from periods during which the wind turbine was on and blue symbols denote results from periods during which it was off (shut down).

To identify and quantify the drivers of amplitude modulation, linear regressions were performed. Comparisons were made between the results for the turbine-on and turbine-off periods. For each regression, we calculate the residual sum-of-squares (R^2) as a measure of significance in the trend of the data. A value near $R^2=0$ indicates that there is no significant linear trend, whereas a value near $R^2=1$ indicates a perfect linear relationship between the quantities in question.

In the following, we have processed, combined, and analyzed data from many shutdowns at Sites 7A and 7B, both of which were close to the respective turbines. Only shutdowns for which LIDAR data were available were processed. Additionally, a third site (Site 7C) was analyzed using SCADA data reported by the wind turbine operator. Some quality control was also exercised to remove periods when the records were substantially corrupted by background noise events, or when there appeared to be shutdowns or restarts that were not in the curtailment log, as described in more detail in Section 7.2. The wind direction was normalized using the following formula:

Direction relative to downwind = (cos(*wind direction –direction of turbine to receiver)* + 1) / 2

This formula yields a value of 1.0 downwind (winds blowing from turbine to receiver), 0.5 crosswind, and 0.0 upwind relative to the wind turbine.

SITE 7A

Only the acoustic measurements at the closest stations (about 330 m and closer) were found to have sufficient signal-to-noise ratio to enable consistent identification of the wind-turbine noise.

The upwind measurement location at 330 m for Site 7A is considered first. The 500-Hz 1/3-octave band was selected for analysis because, as shown in the earlier examples, this is the band in which the amplitude modulation is most clearly attributable to the wind turbine.

Examining Figure 60, the strongest observed trend (as quantified with R^2) in the 500-Hz 1/3-octave band is an increase in sound level with increasing wind speed. There is a relatively weaker increase in sound level with increasing wind speed gradient (shear). However, this trend does not necessarily indicate a causal relationship between wind shear and sound level; it may simply result from the strong covariance between wind speed and shear.[17] That is, wind speed and wind shear are, between themselves, correlated. The turbulence intensity does not show any trend with respect to the sound level. There does appear to be some systematic dependence of sound level on the wind direction; however, this dependence is the same whether the wind turbine is operating or not. These results suggest that the amplitude modulation originates primarily from a mechanism that depends on the flow speed, such as wake turbulence from the turbine blades. Other mechanisms may also create amplitude modulation in particular cases, but they are not consistently dominant.

We next consider the amplitude modulation in the 500 Hz 1/3-octave band for the same data. The results are shown in Figure 61. The amplitude modulation is determined by filtering the variations as previously described, and then computing the rms variation as described earlier in this section. The amplitude modulation depth (as characterized by the rms variation) is consistently in the range of about 1.5 dB to 3 dB. Higher values are likely outliers caused by traffic and other short-term sources of background noise. When the wind turbine is operational, there is a significant positive correlation between the amplitude modulation and the wind speed. This curve is well approximated by the equation

$$\text{amplitude modulation (in dB)} = 1 + 0.135 * WS$$

where WS is the wind speed in m/s, averaged over one minute. Hence, for example, the amplitude modulation is predicted to be 2.4 dB at a wind speed of 10 m/s. There are no significant dependencies of the amplitude modulation on wind speed, direction, shear, or turbulent intensity. The amplitude modulation is increased by about 0.5 dB over the background, on average, when the turbine is operating.

Lastly, we consider data from a second measurement location at the same site, which was approximately 330 m from the turbine in the crosswind direction. Although not as many suitable datasets were available for this location (with reasonably high signal-to-noise ratio and available LIDAR data), it is helpful in confirming the general behavior observed at the upwind location considered in Figure 60 and Figure 61. Scatterplots of the 500-Hz 1/3-octave band sound levels, and the amplitude modulation in this band, vs. wind speed and direction, are shown in Figure 62 and Figure 63, respectively. As with the upwind site, the sound level increases with wind speed, regardless of whether the turbine is operating. However, the amplitude modulation increases with wind speed only when the turbine is operating.

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[17] A correlation analysis such as this cannot determine cause and effect, but the higher correlation with respect to the wind speed *suggests* that it has a more direct impact on the sound level than does the wind shear.

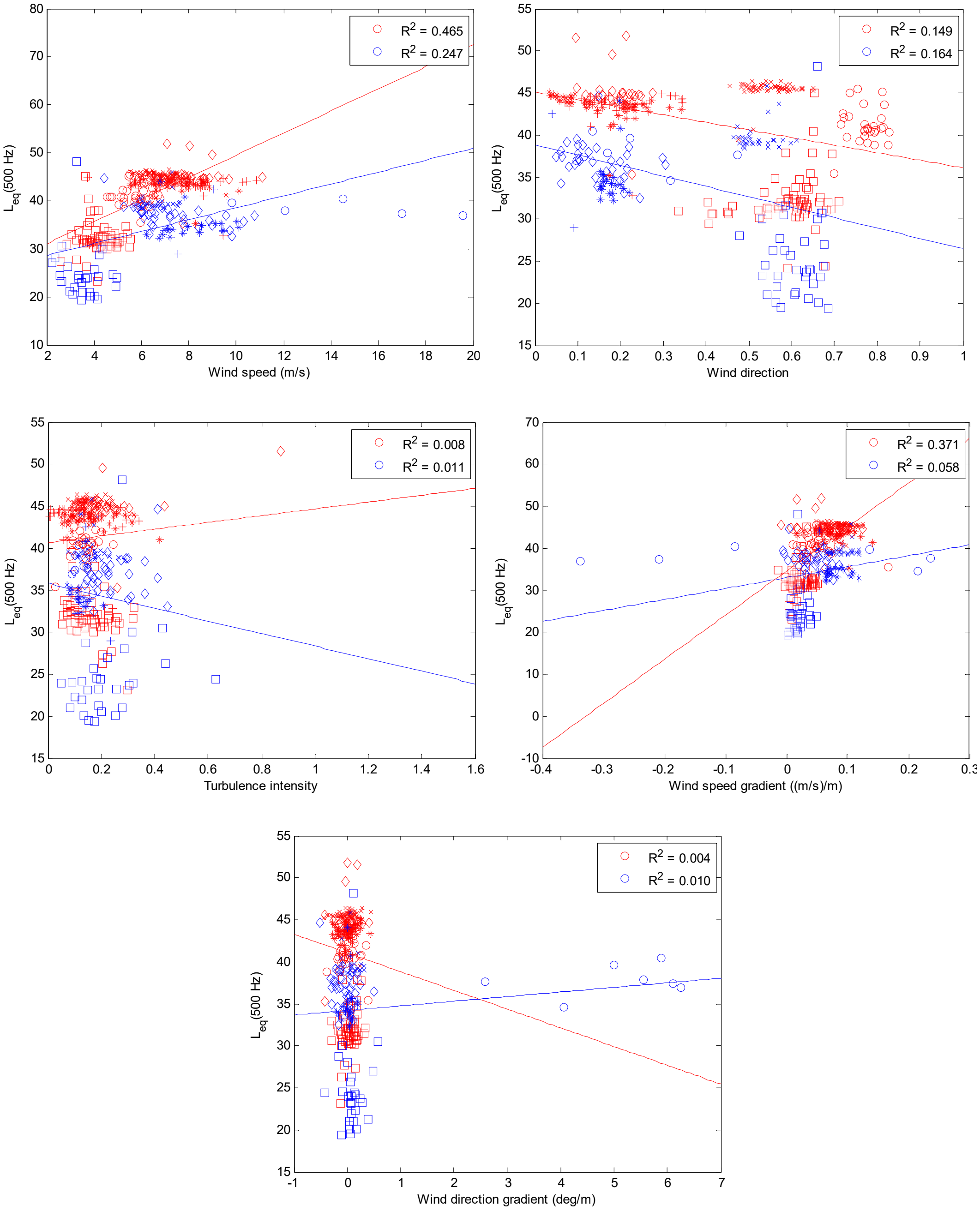

FIGURE 60: DEPENDENCE OF THE 500 Hz ONE-THIRD OCTAVE BAND LEVEL ON WIND CONDITIONS, AT SITE 7A (UPWIND 330M) ALL SHUTDOWNS

*Red symbols are for the turbine on condition; blue symbols are turbine off. The six different symbol types (squares, diamonds, circles, x's, *'s, and plus signs) represent six different shutdowns at Site 7A meeting the quality control criteria mentioned in the text. Shown are scatterplots for wind speed, wind direction, turbulence intensity, wind speed gradient (shear), and wind direction gradient (veer). The wind direction (upper left) is normalized to a range between 0 and 1, as described in the text.*

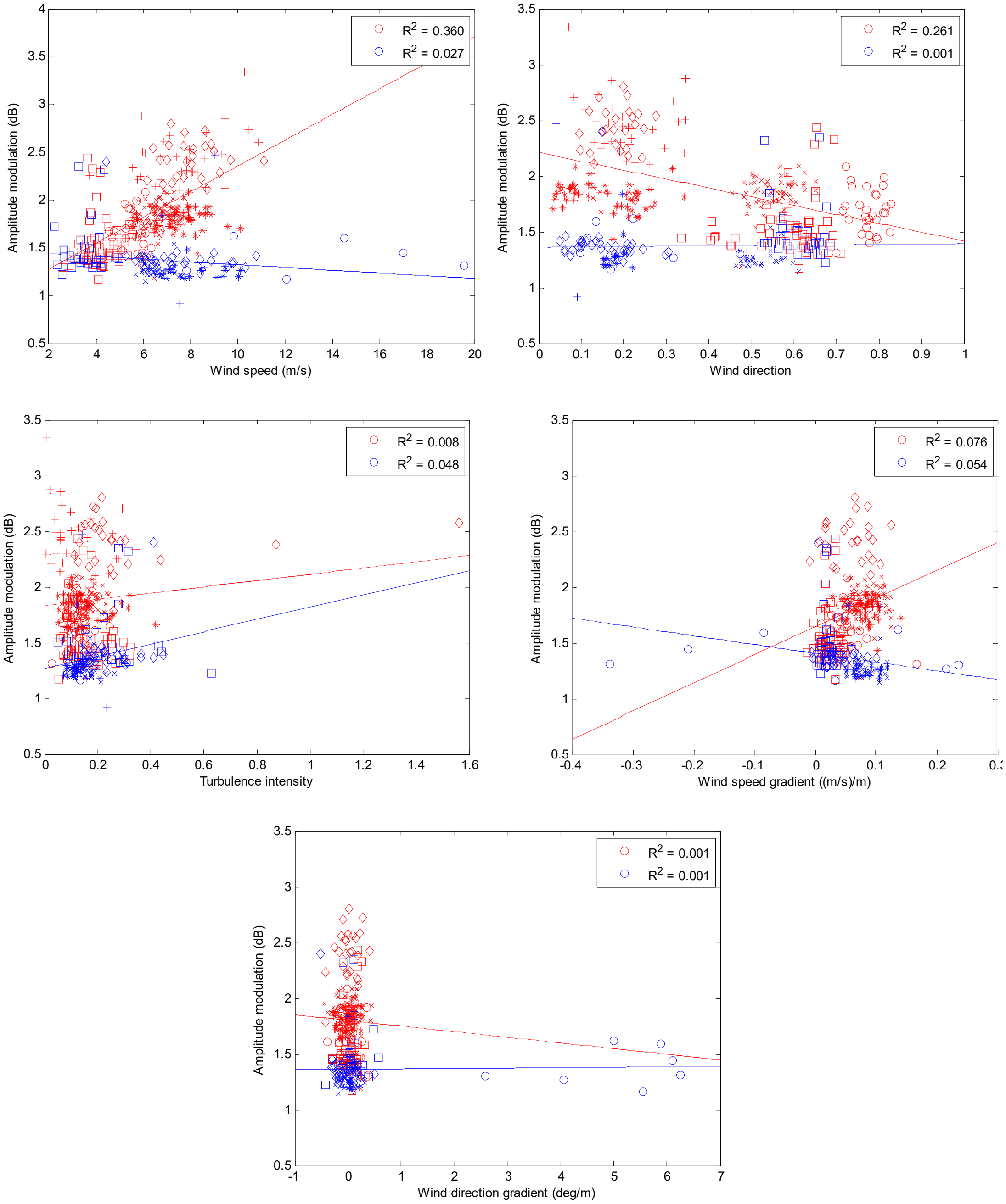

FIGURE 61. DEPENDENCE OF THE AMPLITUDE MODULATION DEPTH ON WIND CONDITIONS, AT SITE 7A (UPWIND 330M) ALL SHUTDOWNS

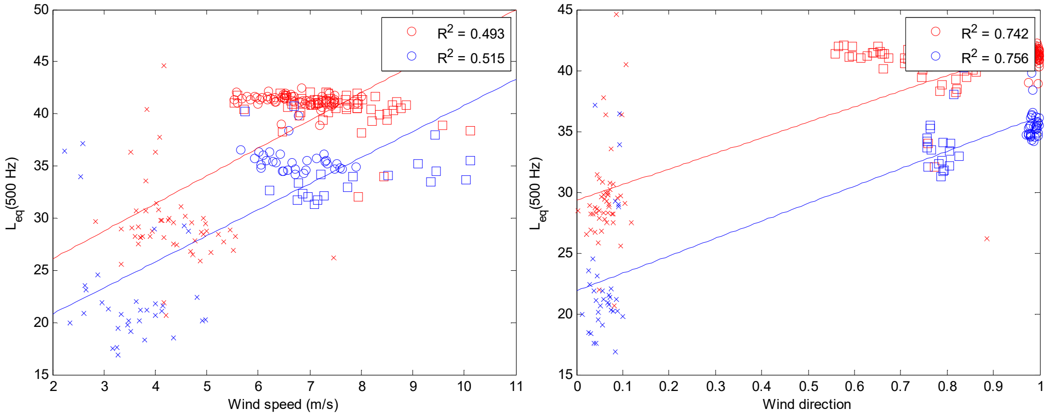

FIGURE 62: DEPENDENCE OF THE 500-HZ ONE-THIRD OCTAVE BAND LEVEL ON WIND CONDITIONS, AT SITE 7A (CROSSWIND 330 M)

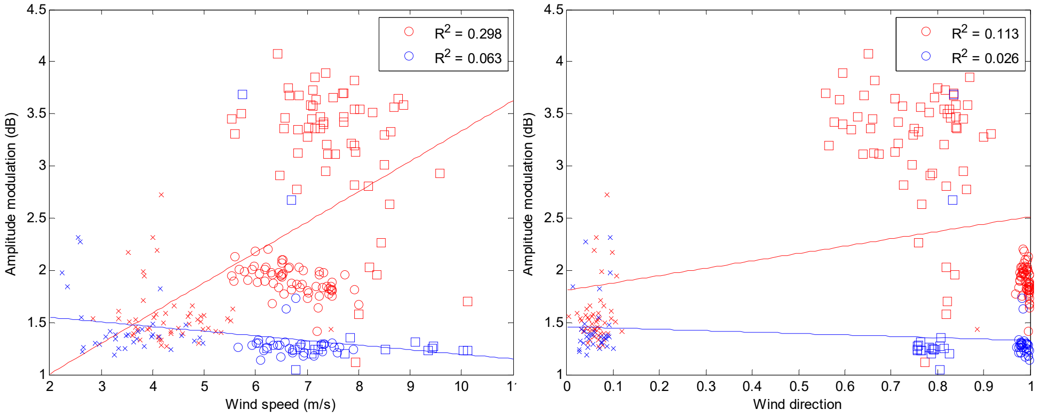

FIGURE 63: DEPENDENCE OF AMPLITUDE MODULATION DEPTH ON WIND CONDITIONS, AT SITE 7A (CROSSWIND 330 M)

Red symbols are for the turbine on condition; blue symbols are turbine off. The different symbols represent different shutdowns.

SITE 7B

We next examine data from an upwind monitoring location at Site 7B, which was 330 meters from the wind turbine, and processed in the same manner. For this monitoring location, 15 different shutdown periods passed the selection criteria described at the beginning of this section. Therefore, in Figure 64 and Figure 65, unlike Figure 60 through Figure 63, we do not attempt to plot each shutdown period with a separate symbol.

First, we consider the 500 Hz 1/3-octave band sound levels, as shown in Figure 64. There is no significant dependence of the sound level on the wind speed, unlike that found at Site 7A. There is also no significant dependence on the wind shear or the turbulence intensity. The strongest observed trend (as quantified with R^2) is with the wind direction; however, as noted for Site 7A, this dependence is the same whether the wind turbine is operating or not, so it cannot be attributed to the wind turbine alone.

Amplitude modulation depths for the 500-Hz band are plotted in Figure 65. The most significant trend, although weak ($R^2=0.22$), is on the wind speed gradient (shear). No other significant dependencies are observed. This suggests that a different mechanism (related to the wind shear) is the dominant cause of the amplitude modulation at this site. On average, the amplitude modulation at this site is only about 0.2 dB higher when the turbine is operating.

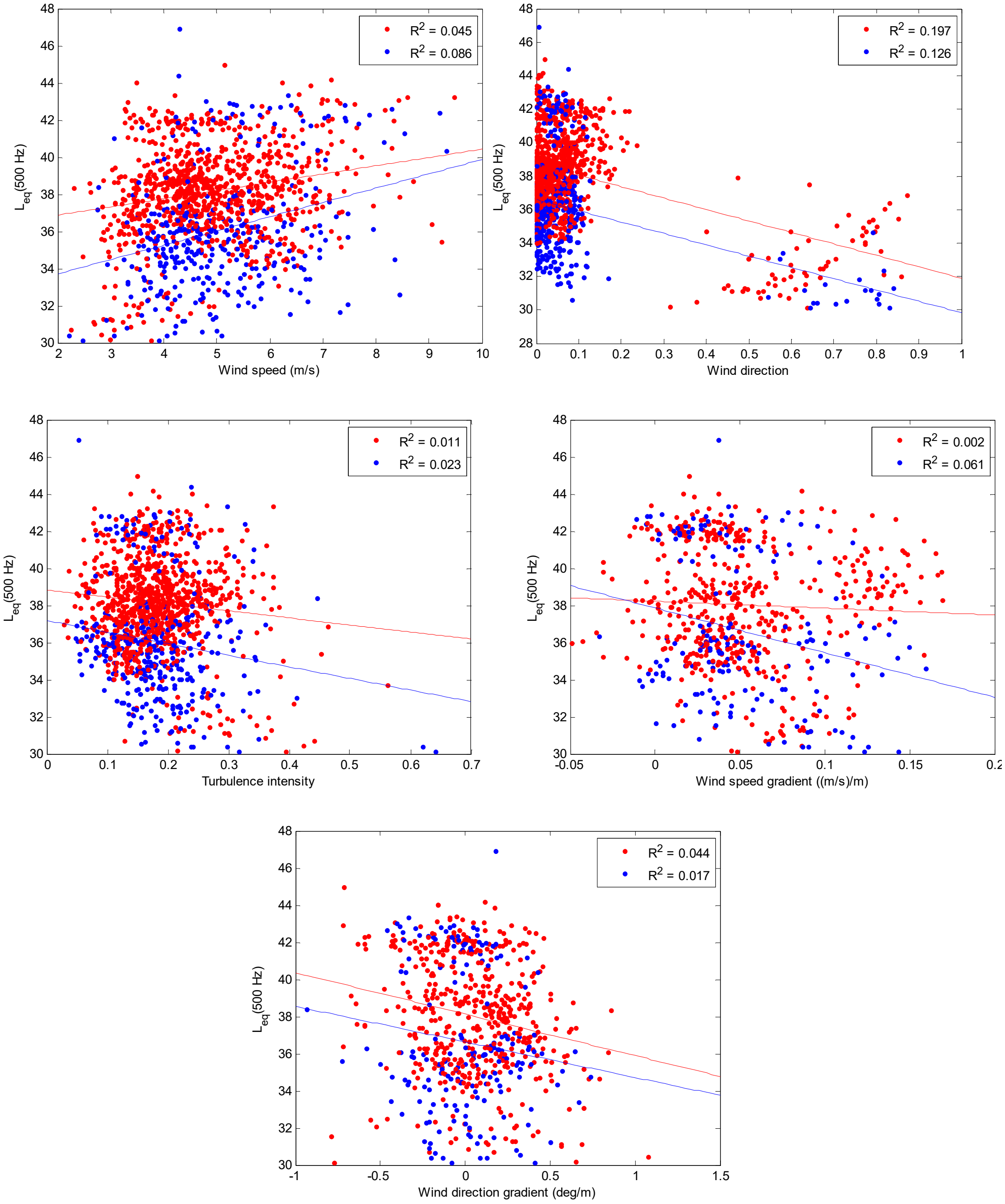

FIGURE 64. DEPENDENCE OF THE 500 HZ ONE-THIRD OCTAVE BAND LEVEL ON WIND CONDITIONS, FOR SITE 7B (330 M UPWIND)

Red symbols are for the turbine on condition; blue symbols are turbine off. The points are derived from 15 different shutdowns. Shown are scatterplots for wind speed, wind direction, turbulence intensity, wind speed gradient (shear), and wind direction gradient (veer). The wind direction (upper left) is normalized to a range between 0 and 1, as described in the text.

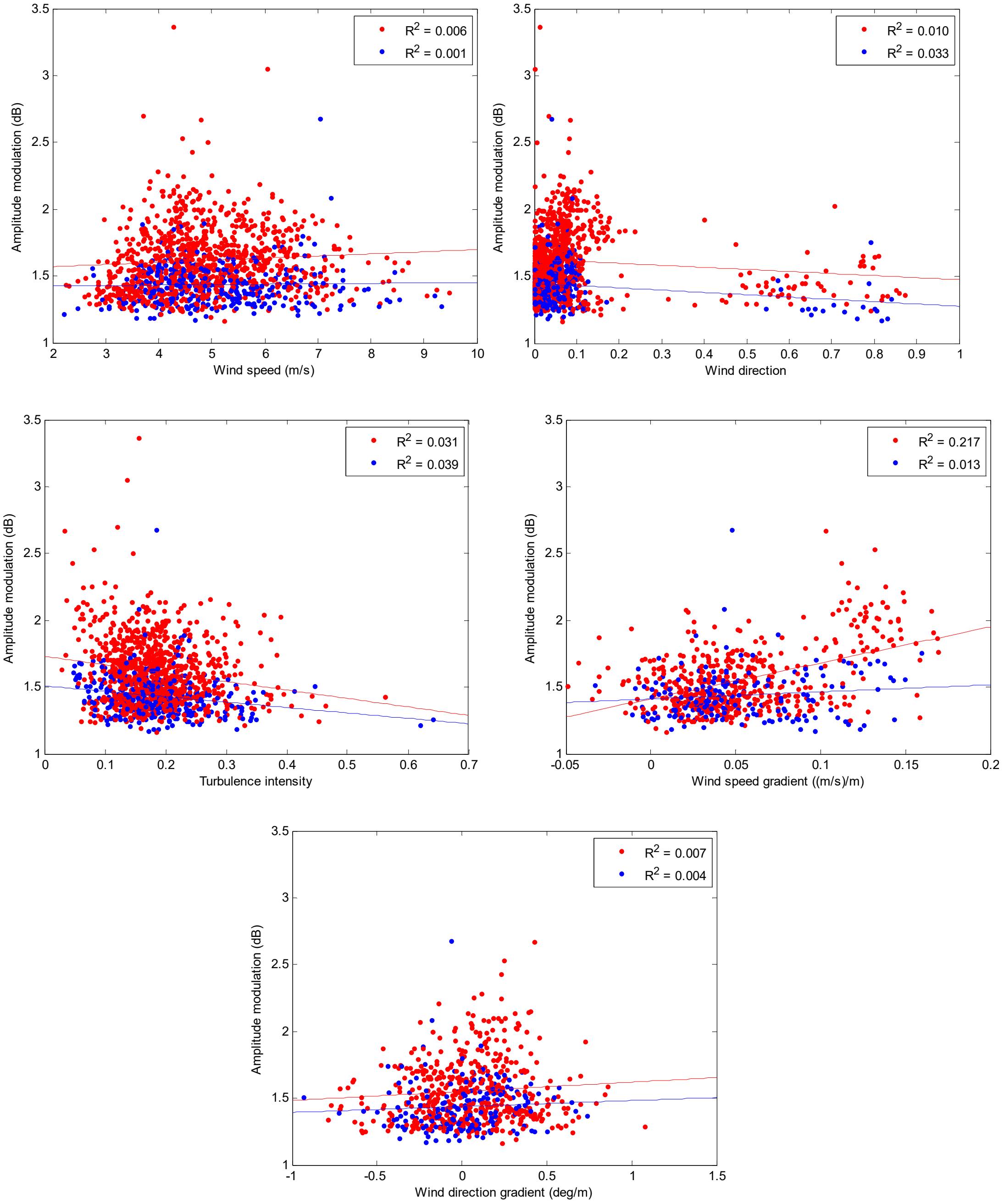

FIGURE 65. DEPENDENCE OF AMPLITUDE MODULATION DEPTH ON WIND CONDITIONS, FOR SITE 7B (330 M UPWIND).

SITE 7C (MOUNTAINOUS)

We perform an analysis similar to that described in the two previous at the mountainous site, Site 7C, except that we examine regressions with data from the SCADA system (turbine sensors) rather than with the LIDAR. The SCADA data (as with the LIDAR data previously) were processed into one-minute averages. Only the “turbine on” condition is considered, since there is no meaningful SCADA data, other than wind speed, when the turbine is off. The analyzed variables are hub rotation speed, absolute value of yaw error, and the wind speed at hub height.

Scatter plots and regressions for the sound level in the 500-Hz 1/3-octave band are shown in Figure 66. The strongest correlation is with the wind speed, as is consistent with results from Sites 7A and 7B. There is a weaker correlation with the turbine rotation speed; however, this may be due to the covariance between wind speed and rotation rate. Sound levels are not significantly correlated with yaw error.

Next, we consider the amplitude modulation results in the 500 Hz 1/3-octave band for Site 7C. These are shown in Figure 67. Although the correlations are somewhat weaker than was the case for the sound level itself, the general trends are the same.

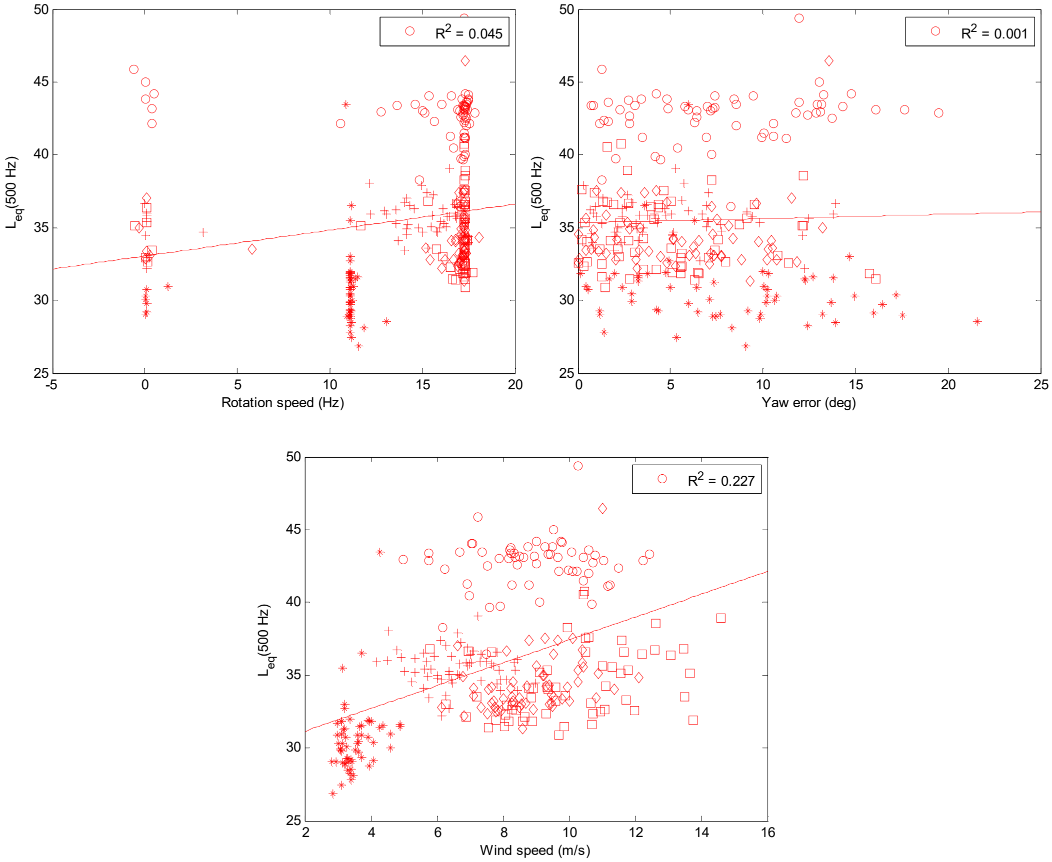

FIGURE 66: DEPENDENCE OF THE 500-HZ ONE-THIRD OCTAVE BAND LEVEL ON TURBINE OPERATIONAL DATA (SCADA), FOR SITE 7C (660 M DOWNWIND) OVER TWO DAYS

All data are for the turbine-on condition. Different symbols represent different shutdown tests. Shown are results for rotation speed, absolute value of the yaw error, and the wind speed at hub height.

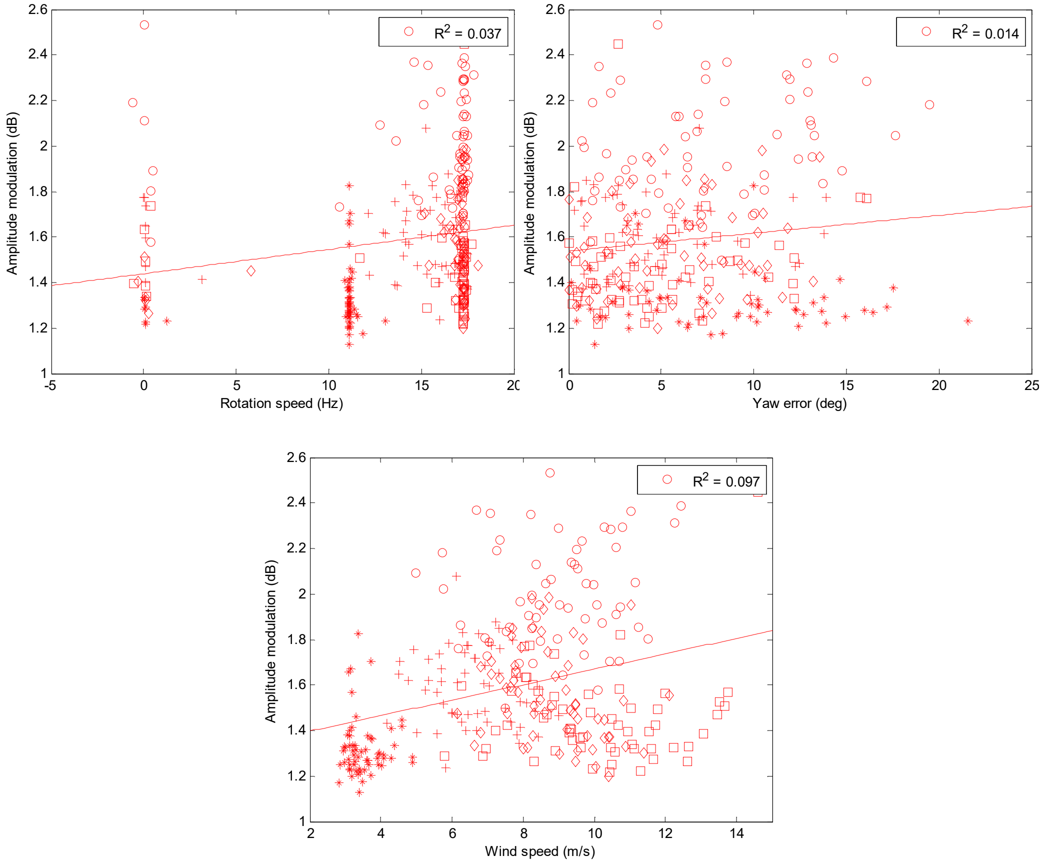

FIGURE 67: CORRELATION OF AMPLITUDE MODULATION WITH TURBINE OPERATIONAL PARAMETERS (SCADA DATA) AT SITE 7C (660 M DOWNWIND) OVER TWO DAYS

Going clockwise, Rotational speed, yaw error, and wind speed

7.6 | SHORT-DURATION AMPLITUDE MODULATION

In this section, we identify how often short-duration amplitude modulation occurs. To do this, we modify the techniques described in Section 7.2 to capture the frequency (in terms of "how often") and magnitude of amplitude modulation events.

To estimate the frequency distribution of amplitude modulation depth, we conducted a similar analysis of the data, but now using a shorter cut of the data: an FFT of every 10-seconds of data (with an approximate 20% overlap). This compares with the one-minute data periods analyzed in the previous portions of Section 7. The maximum FFT magnitude for modulation frequencies between 0.4 and 1.2 Hz was derived for each 10-second period for one hour before each shutdown, the duration of each shutdown, and one hour after each shutdown.

We used data for all three sites previously considered in this chapter; two flat sites and one mountainous site. For the flat sites, a total of four shutdowns were analyzed, representing the clearest turbine sounds at one or more of the locations in the site. For example, if one location at a given site showed a clear difference in A-weighted levels between the turbine-on and turbine-off periods, then all locations at that site would be analyzed for that shutdown.

For the mountainous site, one location, about 660 m downwind of the turbines, was used for the analysis. Nineteen of 20 shutdowns had discernible differences in sound levels between turbine-on and turbine-off. As a result, all of the shutdowns at this site were analyzed.

MODULATION OF A-WEIGHTED L_F

A comparison of modulation depth of fast-response A-weighted sound levels between sites and locations is shown in Figure 68. The chart shows turbine-off and turbine-on modulation depth, with a description of the rounded distance to each location and whether it was upwind, crosswind, or downwind. Turbine-off modulation depth represents the modulation present in the background sound level measurements.

Figure 68 shows that, on average, the least modulation occurs at Site 7B, with roughly the same amount of modulation in Site 7A and Site 7C (0.55 and 0.6 dB, respectively). The largest modulation depth occurred at a location about 330 m upwind, followed by a location 330 m crosswind, followed by 660 m downwind. Among the flat locations, the modulation depth decreased with increasing distance, with the lowest modulation depth observed downwind.

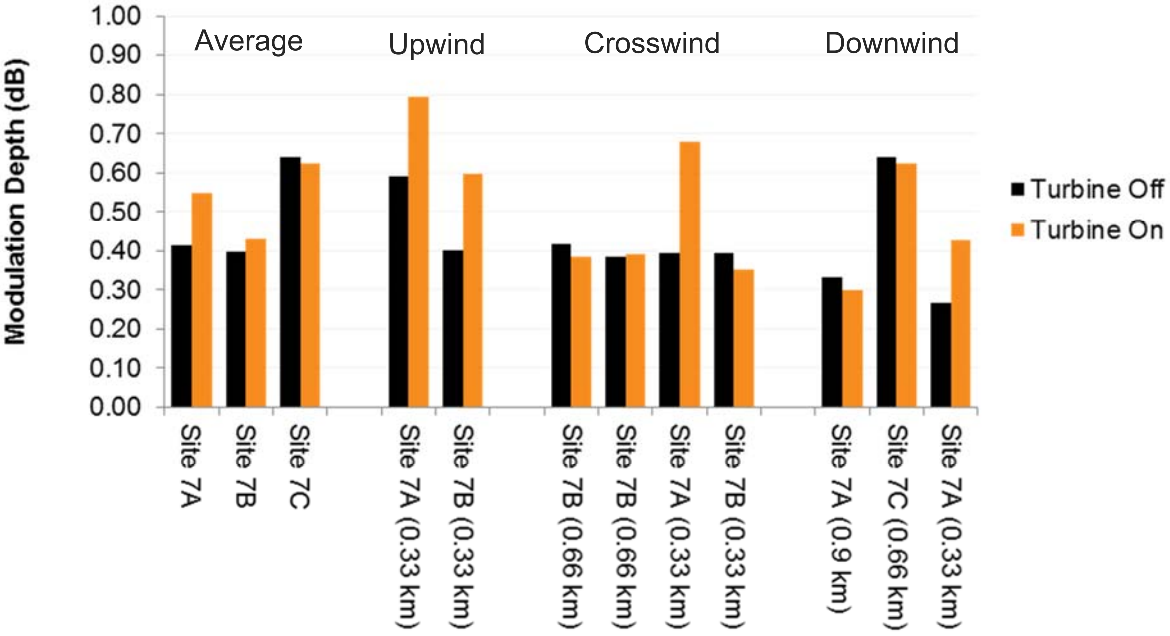

FIGURE 68: AVERAGE MODULATION DEPTH USING 10-SECOND FFTS OF A-WEIGHTED L_F

The distribution of modulation depths among the flat and mountain sites is shown in Figure 69. For the flat sites, 91% of the modulation has a depth of 2 dB or less. At the mountain site, 88% of the modulation has a depth of 2 dB or less. For the flat sites, 99.87% of the modulation has a depth of 4.5 dB or less, while at the mountain site, 99.996% of the modulation has a depth of 4.5 dB or less. Higher modulation events do occur, but they are rare. Of the 105,907 10-second periods that were analyzed, fewer than 300 had modulation depths of 4 dB or greater. The modulation depths reported in this analysis are those of the overall sound level: they differ from the longer-duration spectrograms discussed in Sections 7.2 through 7.5 which discussed modulation of sound levels within individual 1/3-octave bands.

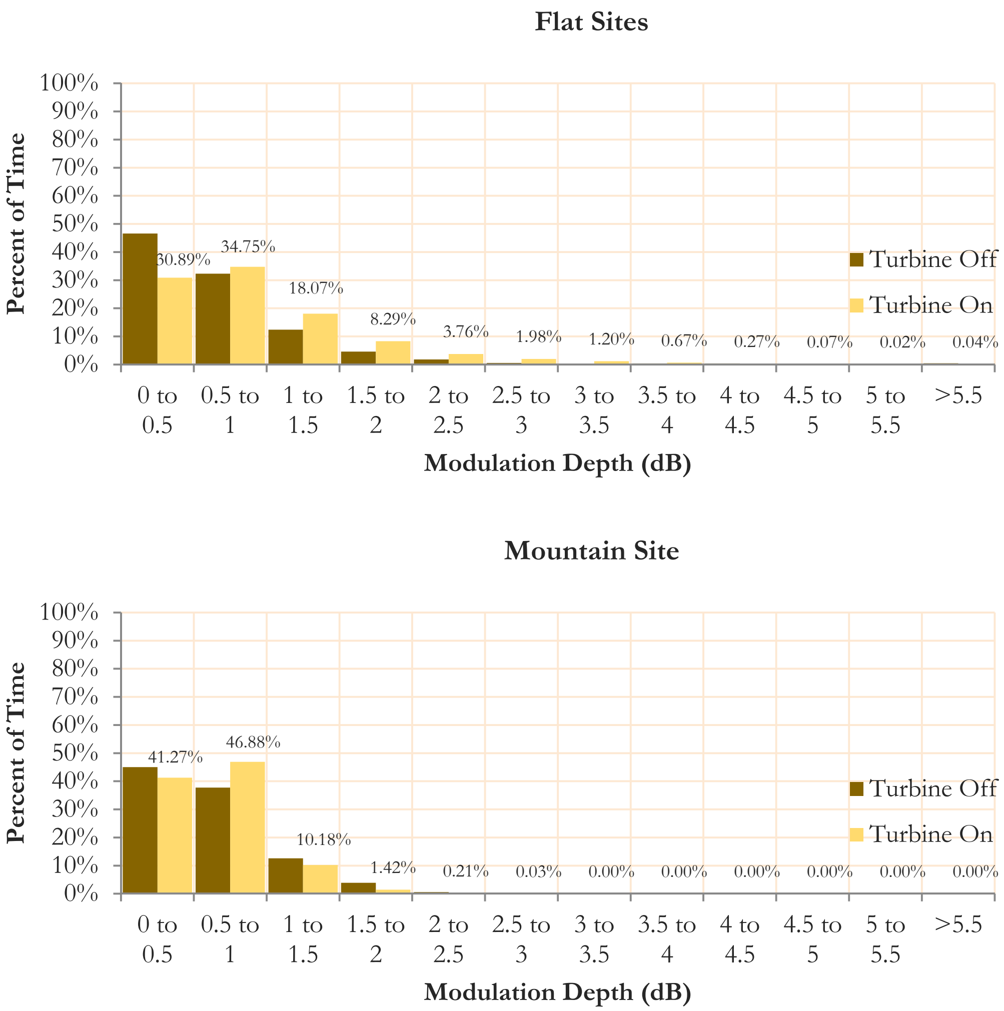

FIGURE 69: PERCENT OF TIME AMPLITUDE MODULATION DEPTHS OCCUR

Percentages above each bar are for the turbine-on scenario

MODULATION C-WEIGHTED L_F

Our analyses of amplitude modulation also included low-frequency sound. In this case, the fast-response “Ci”-weighted sound level was used as a proxy for low frequency sound. That is, frequencies above 1,250 Hz were removed from the data, and the remaining spectra, were C-weighted.

Figure 70 shows the sound levels and amplitude modulation depths for two shutdowns. In the first example shutdown, the sound levels decrease in both Ci weighting (top grey line) and A-weighting (orange line) during the shutdown. Both sound levels increase after the turbine is restarted. This can be compared to the bottom chart showing amplitude modulation during the same period. The A-weighted amplitude modulation (represented by the orange trace) decreases during the shutdown and increases after startup. However, the Ci-weighted amplitude modulation (represented by the grey trace) does not change, other than a brief period right after turbine startup.

In the second example shutdown, sound levels decrease during the shutdown itself, albeit less than in the first example. In this case, A-weighted amplitude modulation barely changes during the shutdown and the Ci-weighted level does not change.

A more detailed statistical analysis of A- and Ci-weighted amplitude modulation is presented in the next section on causation, Section 7.7.

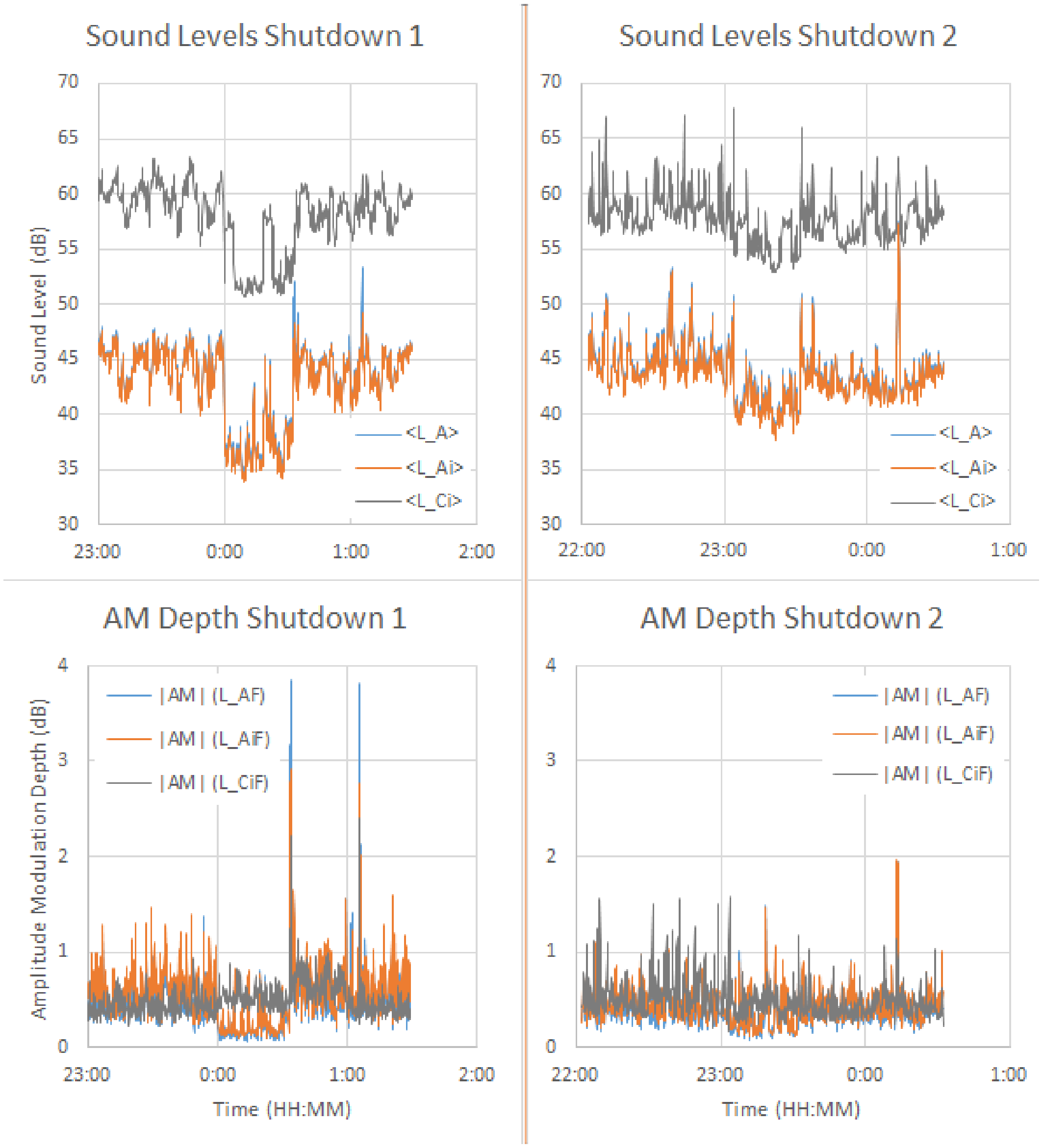

FIGURE 70: COMPARISON OF SOUND LEVELS (TOP) AND AMPLITUDE MODULATION DEPTH (BOTTOM) FOR TWO SHUTDOWNS

7.7 | CAUSES OF SHORT-DURATION AMPLITUDE MODULATION

To evaluate the causes of short-duration amplitude modulation, we conducted a regression analysis using concurrent meteorological and operational variables. A single site, Site 7B, with monitoring locations upwind, downwind, and crosswind was chosen such that a direct comparison can be made. Only shutdowns that showed discernible differences in A-weighted sound levels were selected for analysis.

The first regression tests modulation depth against both horizontal and vertical wind speed, yaw error, turbulence intensity, distance to the wind turbine, wind direction relative to upwind, and the measured sound pressure level. The regression results in an R^2 value of 0.23, meaning that 23% of the variation in amplitude modulation is explained by these variables. The results of the regression analysis are shown in Table 12, and the statistical contribution of each variable to the mean modulation depth is shown in Figure 71. As shown in Section 7.5, the overall measured sound level has the greatest impact on modulation depth. Assuming that these higher sound levels are caused by the wind turbine, higher sound levels would raise the turbine sound further above background levels, resulting in more distinct amplitude modulation.

TABLE 12: LINEAR REGRESSION MODEL OF 10-SECOND AMPLITUDE MODULATION - TURBINE ON

VARIABLE	COEFFICIENT LA(F)	P
Wind speed at 80 m	0.00557	0.001
Yaw Error	0.0029	<0.001
Upward vertical wind speed	-0.02365	0.097*
Downward vertical wind speed	-0.11841	<0.001
Turbulence intensity	-0.14376	<0.001
Distance to turbine (m)	-0.00022	<0.001
Wind direction relative to upwind – 45 degrees towards upwind	-0.0035	0.753*
Wind direction relative to upwind – Crosswind	0.1800	<0.001
Wind direction relative to upwind – 45 degrees towards upwind	3.50	<0.001
Wind direction relative to upwind – Downwind	5.89	<0.001
Sound level	0.02475	<0.001
Constant	-0.44724	<0.001

* - not statistically significant at the 95% level

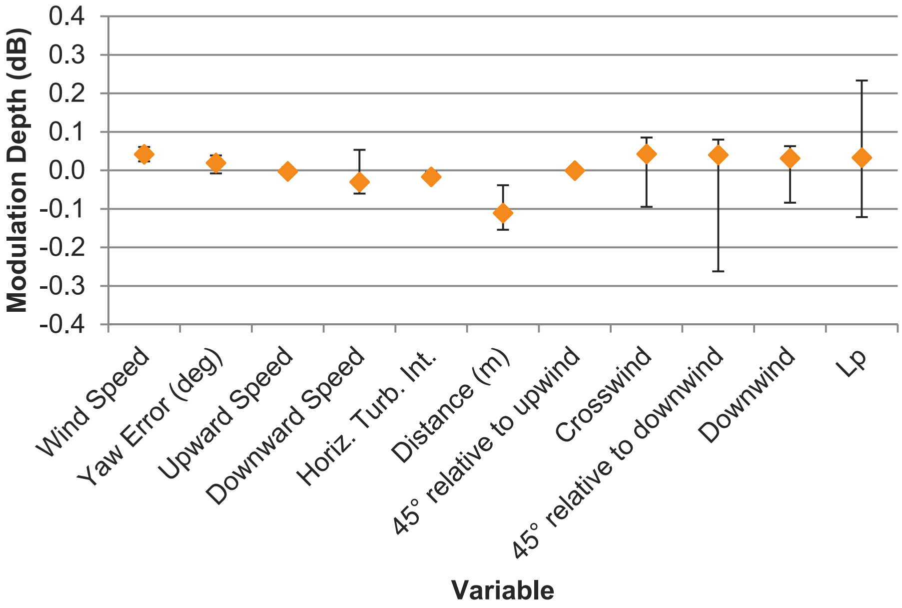

FIGURE 71: CONTIRIBUTION TO MEAN AMPLITUDE MODULATION WITH 5% TO 95% RANGE

Since sound pressure level itself does not cause amplitude modulation (instead, it affects the signal to noise ratio), we then ran a second model that excluded this variable (“Lp”). This model better reflects the contributions to amplitude modulation. These results are shown in Table 13 and Figure 72. In this case, the two largest contributors are wind speed, which increases amplitude modulation, and distance from the wind turbine, which reduces amplitude modulation. Both of these factors correlate to sound pressure level as well. That is, increasing wind speed increases sound emissions from the wind turbine, and increasing distance decreases sound level. It is therefore likely that these factors relate to the difference in sound level between the wind turbine-generated sound and the background sound.

Since amplitude modulation is strongly influenced by background sound, it would be impractical, prior to a project being constructed, to estimate the amplitude modulation depth due to a wind turbine at the distances of typical residential receivers.

TABLE 13: LINEAR REGRESSION MODEL OF10-SECOND AMPLITUDE MODULATION NOT INCLUDING SOUND PRESSURE LEVEL

VARIABLE	COEFFICIENT LA(F)	P
Wind speed at 80 m	0.0310	<0.001 / <0.001
Yaw Error	0.0029	<0.001 / <0.001
Upward vertical wind speed	0.0426	0.004 / <0.001
Downward vertical wind speed	-0.0602	<0.001 / <0.001
Turbulence intensity	--0.1106	<0.001 / <0.001
Distance to turbine (m)	-0.0004	<0.001 / <0.001
Wind direction relative to upwind – 45 degrees towards upwind	-0.0132	0.253* / <0.001
Wind direction relative to upwind – Crosswind	0.1382	<0.001 / <0.009
Wind direction relative to upwind – 45 degrees towards upwind	0.3329	<0.001 / 0.815*
Wind direction relative to upwind – Downwind	0.1050	<0.001 / <0.001
Mountain Site		
Constant	0.4355	<0.001 / <0.001

* - not statistically significant at the 95% level

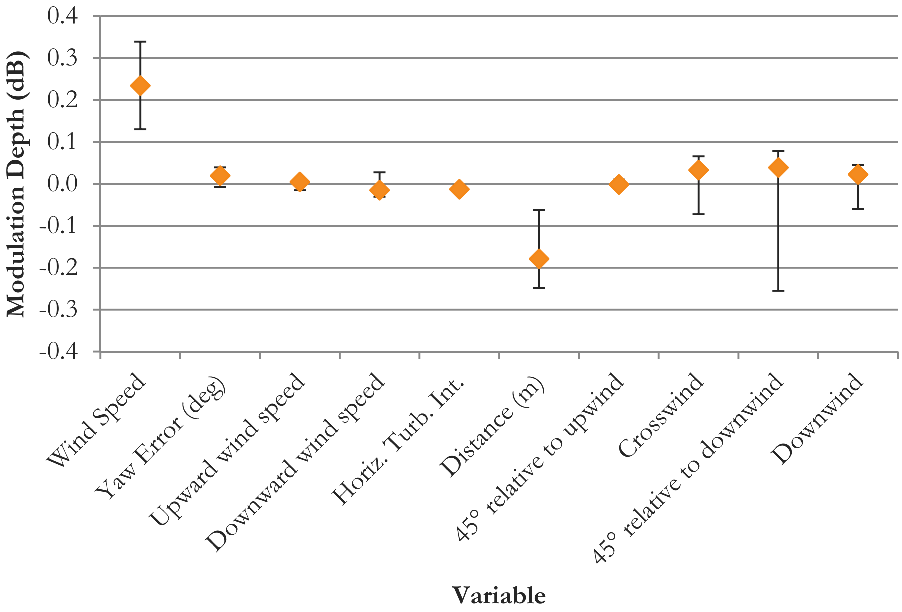

FIGURE 72: CONTIRIBUTION TO MEAN AMPLITUDE MODULATION WITH 5% TO 95% RANGE – EXCLUDING EFFECT OF SOUND PRESSURE LEVEL

7.8 | AMPLITUDE MODULATION DISCUSSION

The primary conclusions with respect to amplitude modulation are as follows:

- The data from the three locations analyzed for this study indicate that low-frequency sound and infrasound from the wind turbines are not modulated for the most part, and sounds in the frequency range from about 250 Hz to 2 kHz are amplitude-modulated.
- In addition to wind turbine sound, other environmental noises such as wind noise, traffic, and insects are also present and affect the measured amplitude modulation depth.
- The technique of calculating a spectrogram from A-weighted sound levels and one-third octave band levels, developed as part of this study, is very effective at revealing the signature of amplitude-modulated wind turbine sound, even when the levels produced by the wind turbines are quite low and comparable to the background sound levels.
- When the turbine is not operating, the amplitude modulation of the background sound is about 4 dB in the infrasonic range, decreasing to about 1 dB at 2 kHz. This modulation is from naturally occurring background sound and wind or "pseudo wind."[18] For the turbine-on condition, the amplitude modulation differs from that of the background sound only in the frequency range from about 125 Hz to 2 kHz. The maximum observed increase in modulation depth was at 500 Hz.
- The one-minute amplitude modulation depth has a significant dependence on wind speed at one of the flat locations, but not at the other we analyzed. For the first location, the standard deviation of the

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[18] When wind passes over a microphone, the rapid pressure fluctuations in the near field can be falsely be picked up as sound by a microphone. This is the same effect that occurs when someone blows onto a cell phone microphone – the sound heard on the other end of the phone is much greater than the sound of the moving air. Low frequencies are especially susceptible to wind-caused pseudo sound.

amplitude modulation is described approximately by the equation AM (in dB) = 1 + 0.135 * wind speed (m/s).

- Short-duration analysis, using overall A-weighted fast-response sound levels in 10-second blocks effectively captured amplitude modulation as distinct from randomly occurring changes in sound pressure levels.
- The measured sound level, wind speed, and distance to turbine have the greatest impact on modulation depth. The measured sound level has the greatest impact to the A-weighted amplitude modulation, most likely because higher turbine sound levels make the modulation more prominent above background.
- Wind turbulence, wind shear, and yaw error have a lesser, but statistically significant, effect on amplitude modulation depth compared to distance and sound level.
- Flat and mountainous sites have similar amplitude modulation levels, less than 2 dB. For the flat sites, 99.87% of the modulation has a depth of 4.5 dB or less. At the mountain site, 99.996% of the modulation has a depth of 4.5 dB or less. Brief periods of greater modulation depths do occur, but they are rare. With an occurrence rate of 0.13% at the flat locations, we would expect higher modulation to be short-lived, approximately 5 seconds every hour.

Overall, we conclude that while amplitude modulation is correlated with various meteorological parameters, prediction of the level of amplitude modulation at typical residential distances would not be reliable or practical. At these distance, local and regional background sounds have a significant impact on modulation depth. The analysis shows that larger modulation events (over 4.5 dB) can and do occur at the flat sites, but these events were observed less than 0.13% of the time. They were less common at the mountainous site (0.004%), likely because the multiple turbines at this site turn asynchronously, which tends to blur out modulation events.

Our analysis dealt only with those periods of time extending from one hour before to one hour after a turbine shutdown. However, a great deal of data were logged for this study between shutdowns; these data are available for further analysis. This is one area where future research can be directed.

8.0 INFRASOUND

8.1 | INTRODUCTION TO INFRASOUND

Infrasound is sound energy whose frequency content is lower than the nominal audio frequency range of human hearing. According to the definition from standard ANSI S1.1, infrasound is generally considered to be defined in the frequency range from 1 Hz to 20 Hz.[19]

Infrasound is generated by wind turbines due to the movement of their blades around the rotor plane. The fundamental frequency of this sound is the blade passage frequency. For example, if a three-blade turbine spins at 15 RPM, a blade passes a given point every 1.33 seconds. The fundamental blade passage frequency is then:

$$Freq = \frac{15\ {}^{rev}/_{min} \times 3\ blades}{60\ {}^{sec}/_{min}} = 0.75\ Hz$$

There are no moving parts within the nacelle that turn at a slower rate than this, so the lowest frequency sound generated by the turbine will have this fundamental frequency and its harmonics. In this example, the fundamental frequency is 0.75 Hz, and its harmonics include 1.5 Hz, 2.25 Hz, 3 Hz, 3.75 Hz, etc (corresponding to 2, 3, 4, and 5 times the fundamental frequency). Above the frequencies of these harmonics, infrasound, low-frequency sound, and audible sound from the wind turbine are generated by other mechanical and aerodynamic processes.

As with the use of A-weighting of measured sound level in order to mimic the human frequency response to low-level audible sound, G-weighting is designed to estimate perception and low-level annoyance of infrasound. G-weighting is defined by the ISO 7196:1995 standard. According to that standard, a G-weighted sound level of 100 dB is the normal threshold of perception and 90 dB "will not normally be significant for human perception." In this paper, we use the 90 dBG contour as a conservative estimate of the lowest threshold of perception for sensitive individuals.

8.2 | METHODOLOGY FOR ASSESSMENT OF INFRASOUND

The measurement of infrasound requires specialized equipment and techniques that are generally incompatible with measuring sound in the full audible spectrum. For example, microphones and processing electronics that are capable of measuring frequencies as low as the blade passage frequency (generally about 0.7 Hz) are not standard equipment on most sound level meters. In addition, sound level meters that can measure infrasound frequencies must be equipped with special infrasound wind screens (which tend to be quite large) or make use of other techniques to eliminate false infrasound readings created by airflow over the microphone. On the other hand, while appropriate for infrasound, these techniques are generally not suitable for measuring sound in the full audible spectrum.

In this study, a specialized infrasound system was used at a single location for each of two different sites – one flat and one mountainous.[20] The system included a Norsonic Nor140 sound level meter with an

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[19] American National Standards Institute, *ANSI/ASA S1.1-2013 Acoustical Terminology*.

[20] While most of the sound level meters used in this study measured infrasound, they were equipped with windscreens that were only appropriate for measuring audible spectrum sound.

infrasound package allowing it to measure 1/3-octave bands down to 0.5 Hz. The microphone was a model GRAS 40AN, which has a flat frequency response down to 0.5 Hz.

Since the cycle time of 0.5 Hz is 2.0 seconds, infrasound levels were integrated over ten-second periods as equivalent sound levels. This is consistent with ISO 7196, which recommends 10-second integration time for low infrasound frequencies, such as this. Each monitor logged 1/3-octave band sound levels from 0.4 Hz to 20,000 Hz.

At each location, an interior and exterior infrasound monitor were deployed. The exterior monitor was fitted with a 28-inch diameter spherical wind screen made by Sanchez Industrial Design (Figure 73). It consists of a three-inch diameter foam wind screen and three concentric layers of fabric wind screen at 9, 15, and 28-inch diameters.

Each exterior microphone was placed 1 meter off the ground.

The interior monitoring locations were within uninhabited homes. These monitors are identical to the exterior monitors, except they are fitted only with a three-inch wind screen. This is sufficient for indoors, as there was very little air movement. All windows remained closed throughout the infrasound testing periods.

FIGURE 73: CROSS SECTION OF INFRASOUND MONITOR

Two sites were measured. The first, Site 8A, was a flat site in eastern Massachusetts, within two miles of the Atlantic Ocean. The monitoring location was approximately 350 meters downwind of a single turbine. The exterior monitor was approximately 10 meters (33 feet) from the home. The interior monitor was in a room facing the wind turbine. The home was light wood-frame construction.

The second site, Site 8B, was a mountainous site with multiple ridgeline turbines. The monitoring location was approximately 650 meters from the nearest turbine and about 150 meters below the ground elevation of that turbine. The room in which the interior monitor was placed faced the wind turbines. The house was of light wood-framed construction. The interior face of the exterior wall was not covered in sheetrock and had exposed fiberglass insulation between the wall studs.

Because infrasound is so easily impacted by wind and other background sound, it is important to exclude background sound. Therefore, as in other portions of our analysis, data analysis focused on one hour before, during, and one hour after each shutdown. In this way, we can directly compare infrasound levels and more easily calculate turbine-only sound levels.

In all, we obtained 38,087 observations from the external infrasound monitors and 26,588 observations were obtained from the internal infrasound monitors.

8.3 | INFRASOUND LEVELS IN THE BACKGROUND AND FROM WIND TURBINES

We processed the infrasound records from the database, differentiating infrasound levels by wind speed and turbine operation (on or off). For each 1/3-octave band from 0.5 Hz and above, we then calculated the mean level with a 95% confidence interval. These results are shown in Figure 74 for Site 8A and Figure 75 for Site 8B.

In both figures, the exterior sound levels span the range of 1/3-octave bands from 0.5 Hz to 20 Hz. Sound levels are unweighted (dBZ). The Watanabe and Moller (1990) threshold of audibility is shown in blue, and the 90 dBG contour is shown in red. Combined, these are a conservative estimation of audibility along the entire infrasonic range. The arithmetic mean sound levels with the turbines off are shown with black markers; those with the turbines on are shown with orange markers. The 95% confidence intervals are shown as lines above and below each point; however, the intervals are so small, that they are difficult to see. The data are divided by ranges of wind speed. The top graph shows the results for 80-meter wind speeds of 3 to 6 m/s, the middle graph for 6 to 9 m/s, and the lower graph for wind speeds greater than 9 m/s.

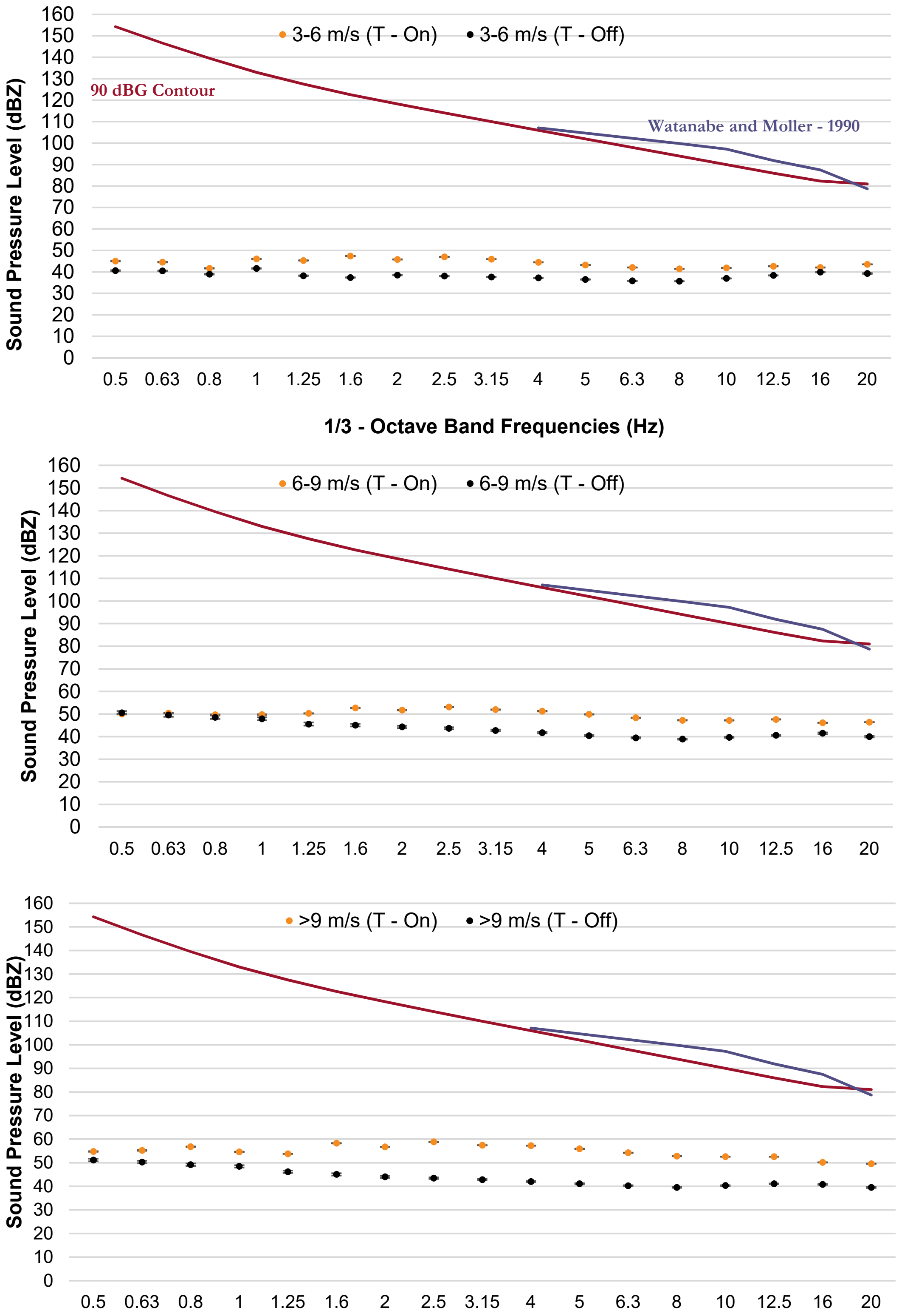

FIGURE 74: COMPARISON OF EXTERIOR TURBINE ON (Ton) AND TURBINE OFF (Toff) SOUND LEVELS WITH CONFIDENCE INTERVALS AT SITE 8A (FLAT SINGLE-TURBINE SITE) FOR THREE WIND SPEED RANGES AT 350 METERS

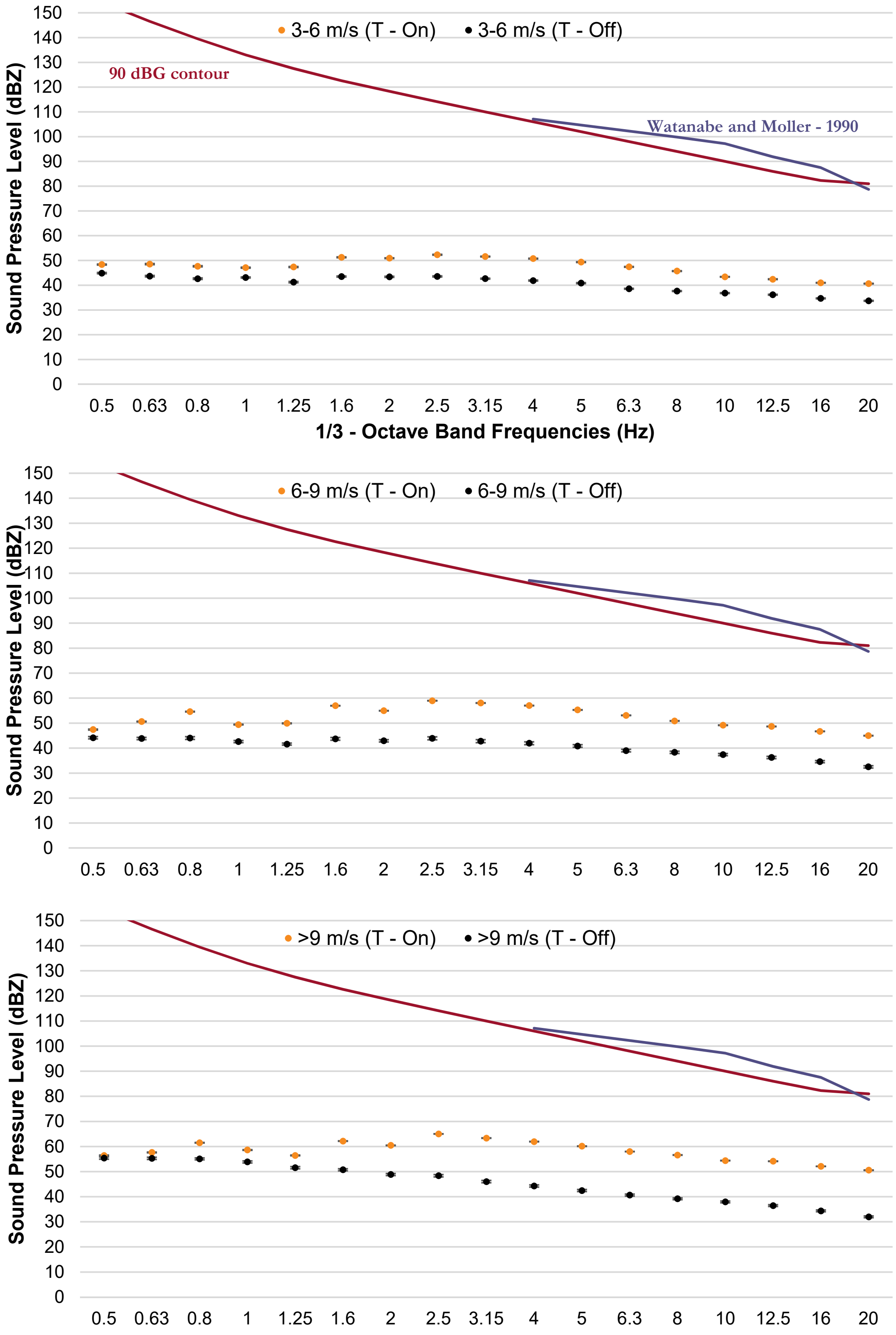

FIGURE 75: COMPARISON OF TURBINE ON (Ton) AND TURBINE OFF (Toff) SOUND LEVELS WITH CONFIDENCE INTERVALS AT SITE 8B (MOUNTAINOUS MULTI-TURBINE SITE) FOR THREE WIND SPEED RANGES AT 650 METERS

Figure 74 reveals several features of the results:

- Both the turbine-off and turbine-on infrasound levels are well below audible perception limits. At 20 Hz, the turbine-on sound level is 34 dB below the perception limit at wind speeds from 3 to 6 m/s. With higher wind speeds, higher than 9 m/s, the difference is 30 dB.
- With increasing frequency, the turbine-sound level either does not change, or decreases slightly. At wind speeds of 9 m/s, the change in sound level with frequency is greatest: the level at 0.5 Hz is 5.2 dB higher than it is at 20 Hz, resulting in a trend of approximately -0.9 dB per octave.
- For blade passage frequencies less than 1 Hz, turbine sound levels are about 80 dB below perception limits.
- Background sound levels measured by the infrasound monitors change little with increasing wind speed. This is one indication that the custom wind screen is effective at defeating pseudo-noise caused by wind. Note that wind speeds reported in this Section were measured at the turbine hub height and not at the monitoring location.
- Turbine-caused infrasound levels increase with wind speed. This trend becomes stronger as the wind speed increases from the 6 to 9 m/s range to above 9 m/s.

Figure 75 shows the same information as Figure 74, but for the multi-turbine ridgeline site, Site 8B. While the same trends appear in these data, we can make these additional observations and comparisons:

- The background infrasound levels at the ridgeline site are higher at the very low frequencies and lower at the higher frequencies when compared to the flat site.
- The 1/3-octave band sound levels at this site tend to have their highest values at 2.5 Hz for each wind speed category.
- The difference between the turbine-on sound level and the limit of audibility at 20 Hz is similar to the flat site, at about 30 dB for the >9 m/s wind speed category and 80 dB at the blade passage frequency.
- While the ridgeline infrasound monitor was about twice as far from the nearest turbine as that of the flat location, the ridgeline site has multiple turbines, and the flat site has only one turbine. As a result, the overall sound levels are similar. As a check, we modeled the overall A-weighted sound level at each location. At the flat site, the maximum modeled sound levels was 45 dBA compared with 43 dBA at the mountainous site. While modeling was not done for infrasound, we expect the results at each site would have been similar.

The results at the two sites show that wind turbines increase ambient infrasound levels, especially at higher wind speeds. However, the resulting levels are, at the least, 25 dB below ISO audible perception thresholds with very little variation, and that difference increases with decreasing frequency.

With respect to perception of loudness, the human ear is more sensitive to changes in levels at low frequencies than at high. For example, at 1,000 Hz, an increase of 10 dB is perceived a doubling of loudness. However, at 20 Hz, an increase of only 5 dB is perceived as a doubling of loudness. Therefore, once a sound is perceptible at low frequency, perceived loudness increases at a greater rate for each dB increase in sound pressure level. On the other hand, a decrease in sound pressure level at low frequencies decreases perceived loudness at a faster rate. As a result, a 25 dB difference at 20 Hz is approximately the same perceived loudness difference as a 50 dB difference would be at normal speech frequencies. However, since these infrasounds are inaudible, by definition, the perceived loudness does not change below the audibility limit. That is, there is no loudness to be perceived.

While the infrasound level within any 1/3-octave band is well below the audibility limits at individual frequencies, the wind turbine contributes sound to all of the infrasound 1/3-octave bands. Therefore, it is appropriate to consider infrasound as a combination of band levels using the G-weighted sound level. According to ISO 7196, the threshold of audibility for infrasound is between 90 dBG and 100 dBG.

Figure 76 shows how often we monitored different ranges of G-weighted sound levels when the turbines were on (orange) and off (black) at the flat site. As shown, the turbine-off levels were primarily between 50 and 55 dBG, while the turbine-on levels were between 55 to 70 dBG. No measurement exceeded 100 dBG and there was about one minute during which both turbine-off and -on levels ranged between 90 and 100 dBG. The number of these events are few – ten 10-second periods – and occur at a location that would have experienced vehicle passbys and other human activities. Half of these events (five of ten) occurred while the sites were visited by monitoring staff for installation, checkup, pickup, or attended monitoring. During the monitoring period, this residential location was uninhabited. However, during these short site visits, there would have been car door slams, car engine starts, and other high energy, low frequency events that would have raised the infrasound levels above 90 dBG, with no relation to wind turbine sound. The other five 10-second periods occurred during three separate occasions lasting no longer than 20 seconds each. In each of these cases, the elevated infrasound was due to airplane or helicopter overflights.

A similar pattern emerged in the data from the mountainous multi-turbine site in Figure 77. In this case, there were no instances of sound levels exceeding 85 dBG and an overall increase in 10 to 15 dB on the G-weighted scale when turbines were turned on. The larger increase compared to the flat site is primarily due to the lower background level at the mountainous site. The overall G-weighted sound levels are shown in Figure 77.

Table 14 lists statistical sound levels for both flat and mountainous sites. Despite the differences between the monitoring locations in terms of distance from the turbine(s) and number of turbines, the G-weighted sound levels are similar, with the median (L_{50}) sound levels at 61 dBG for the flat site and 63 dBG for the mountainous site.

Both sites indicate that, when using the G-weighting to combine infrasound 1/3-octave bands, the turbine infrasound is not typically perceptible using the ISO 7196 criteria. Factors that influence infrasound level are discussed in the next section, Section 8.4.

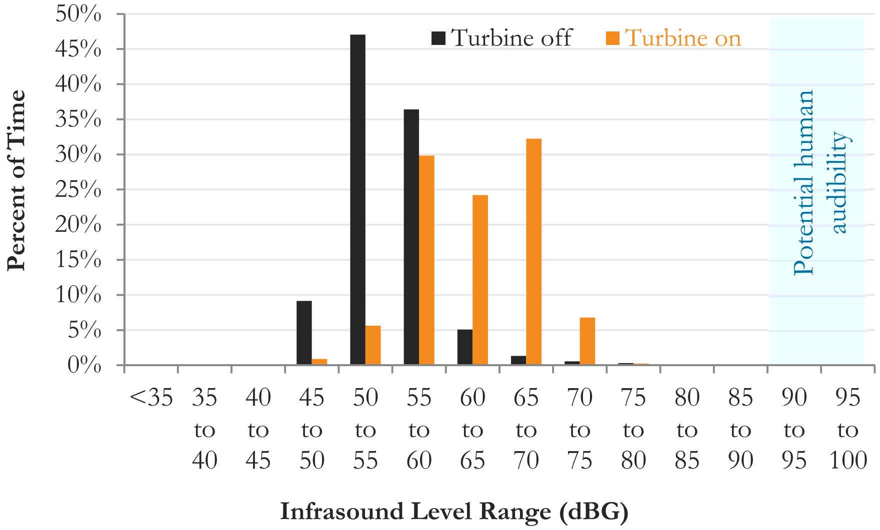

FIGURE 76: G-WEIGHTED SOUND LEVELS FOR TURBINE-OFF AND TURBINE-ON PERIODS AT SITE 8A (FLAT)

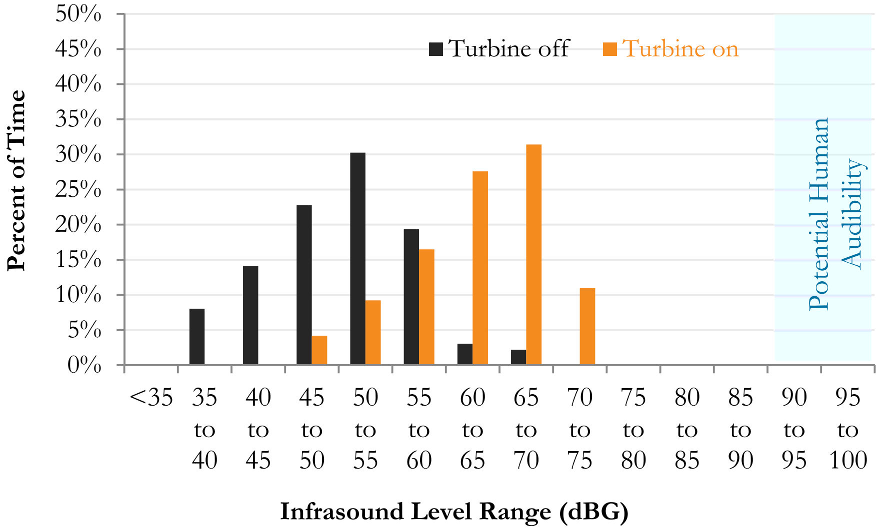

FIGURE 77: G-WEIGHTED SOUND LEVELS FOR TURBINE-OFF AND TURBINE-ON PERIODS AT SITE 8B (MOUNTAINOUS)

TABLE 14: OVERALL G-WEIGHTED TURBINE-ONLY SOUND LEVELS

	SITE 8A (350 M) FLAT SINGLE TURBINE	SITE 8B (650 M) MOUNTAINOUS MULTI TURBINE
L_{10}	69 dBG	70 dBG
L_{50}	61 dBG	62 dBG
L_{90}	53 dBG	48 dBG

8.4 | CAUSE AND EFFECT

During infrasound measurements, we also measured A-weighted sound levels, one-second wind speed and direction at 1.5 meters, 10 meters, and 10-meter increments between 40 and 200 meters. From these, we calculated factors such as wind shear and turbulence intensity (based on 80-meter LIDAR data).

For this analysis, G-weighted sound levels were averaged into 30-second periods to allow for a reliable estimate of turbulence.

Multivariate regression modeling was conducted using R statistical software. Model independent variables were examined univariately (one at a time) and in multivariate combinations. Partial correlations helped determine independent variables would be tested. Our team also investigated the presence and strength of variable interactions. In regression, variable interactions reveal if the impact that variable X has on variable Y depends on the values of a third extraneous variable, Z. This was modeled specifically by testing products of the independent variables (XZ), for example:

$$\hat{Y} = \beta_1 X + \beta_2 Z + \beta_3 XZ + \beta_0$$

Comparing the influence of these interaction terms against models that omitted them did not provide significant explanatory value, thus the terms ultimately were excluded from the regression analyses. Variables were tested assuming simple linear responses with a few exceptions. Relative wind direction was divided into five directions (shown in Figure 28). Reference-cell coded indicator variables were generated, with wind blowing *directly from the receiver to the source* acting as the reference group. Vertical wind speed was divided into two variables, one for each predominant flow (up or down) to allow the model to estimate effects of vertical wind direction independently.

We considered both the variable t-ratios and overall model F-statistic with versions of the fitted model. After each, an examination of model residuals and leverage plots were examined to determine if the basic assumptions for the linear model were still appropriate. Standardized beta coefficients provided further utility in evaluating each variable's relative importance in model fitting.

The results of the statistical tests are listed in Table 15. In all cases, except one shown with an asterisk, the relationships are statistically significant to a probability value less than 0.05.

BACKGROUND INFRASOUND

For the analysis of background sound, infrasound is tested as a function of 80-meter wind speed, turbulence intensity, wind direction, and wind shear. The R^2 value, shown in Table 15 below, is 0.78, indicating that these variables account for 78% of the variation in G-weighted sound levels. Wind speed has the greatest effect on sound levels. For every 1 m/s increase in wind speed, the G-weighted sound level increases by 1.45 dB. Interestingly, wind direction has an effect on background sound level, perhaps due to other contributing sources, like a distant highway in a certain direction.

The mountain site's background sound level is 11.5 dBG lower than that of the flat site, likely due to its more remote location. Turbulence also has a large effect on background G-weighted sound levels, but wind shear does not.

TURBINE-ON INFRASOUND

For the turbine-on periods, the effect of wind speed and turbulence intensity on infrasound are less than they are for background sound. For every 1 m/s increase in wind speed, the G-weighted sound level increases 0.82 dB, but there is also a coincident effect from turbine rpm – sound levels increase 0.12 dB for every 1 rpm increase in turbine speed. Compared with background, the coefficient for wind shear reverses its sign, meaning that increased wind shear decreases background levels but increases turbine-on levels. The effect is small – less than a decibel under most shear conditions. The receptor location relative to the turbine and the wind direction also have influence. The upwind direction increased the sound level, and the downwind decreased it by about 2 dB. The lowest level is under crosswind conditions (-4.7 dB). In this case, the mountain site adds 2.8 dB compared with the flat site. The R^2 results indicate that these variables account for 56% of the variation in G-weighted sound levels.

TABLE 15: LINEAR REGRESSION MODEL OF G-WEIGHTED SOUND LEVELS – TURBINE ON

VARIABLE	TURBINE OFF COEFFICIENT	TURBINE ON COEFFICIENT	P
Wind speed at 80 m	1.45	0.82	<0.000 / <0.000
Rpm	n/a	0.12	
Turbulence Intensity	6.58	5.51	0.001 / <0.000
Wind shear	-0.90	0.82	* / <0.016
Wind direction relative to upwind – 45 degrees towards upwind	3.60	-1.02	<0.000 / <0.016
Wind direction relative to upwind – Crosswind	6.26	--4.65	<0.000 / <0.000
Wind direction relative to upwind – 45 degrees towards upwind	3.09	--2.88	<0.000 / <0.000
Wind direction relative to upwind – Downwind	1.72	-1.98	0.033 / <0.000
Mountain Site Constant	-11.5	2.8	0.011 / <0.000
Constant	45.9	52.9	<0.000 / <0.000
Adjusted R-squared	0.7795	0.5566	
Standard error	3.783	2.373	
F Statistic	163.9	205.5	<0.000
Degrees of freedom	371	1457	

* - not statistically significant

Figure 78 is an illustration of the change of G-weighted sound level with wind speed. In this figure, the levels were adjusted to account for wind shear, wind turbulence, wind direction, and turbine operating mode (on or off). As shown, there is an increase in G-weighted sound levels as wind speed increases, which levels off at greater wind speeds. This curve is of a similar shape to the relationship of sound power with wind speed.

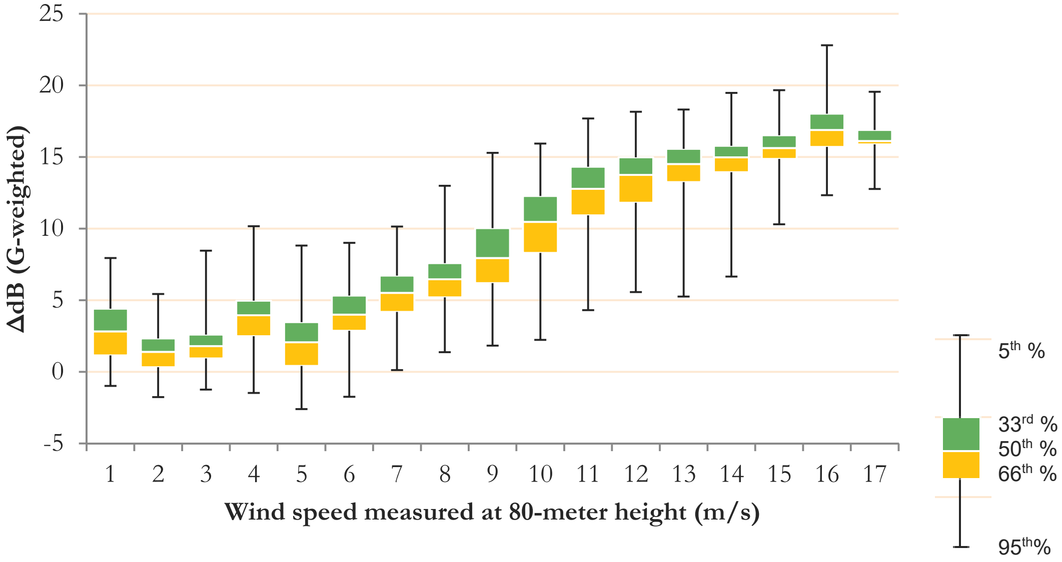

FIGURE 78: CHANGE IN G-WEIGHTED SOUND LEVEL AT SITE 8A BY WIND SPEED ADJUSTING FOR TURBINE OPERATING MODE, WIND SHEAR, TURBULENCE, AND DIRECTION

Box and whiskers chart shows the 5th, 33rd, 50th, 66th, and 95th percentiles.

In evaluating the regressions, we can see that there are interacting terms. For example, wind speed not only affects sound levels, but also turbine sound power. Wind speed also affects turbulence intensity and wind shear. To eliminate some of these interacting terms, we conducted a statistical analysis using Structural Equation Models (SEM). (The SEM method is discussed in more detail in Section 6.4). The results are listed in Table 16 for infrasound inside the structure and Table 17 for infrasound outside the structure.

TABLE 16: STRUCTURAL EQUATION MODEL RELATING METEROLOGICAL VARIABLES TO G-WEIGHTED SOUND PRESSURE LEVELS (INSIDE)

		Estimate	Standard Error	T-Value	Effect Size
Model for LW_DBA	delta_lw	99.438	0.127	785.5	N/A
	zeta_avg_80m_ws_30s.lw	0.508	0.011	45.4	7.97
	zeta_vert_windspeed_down.lw	0.456	0.093	4.9	0.96
	zeta_vert_windspeed_up.lw	-0.529	0.041	-12.8	-1.70
	zeta_sd_80m_v_ws_30s.lw	0.929	0.078	12.0	1.93
	zeta_sd_80m_wd_30s.lw	-0.029	0.004	-7.2	-2.70
	zeta_veer_40_120.lw	-0.003	0.001	-3.1	-0.92
	zeta_abs_yaw_error.lw	-0.065	0.002	-31.0	-6.73
	zeta_shear_lw	0.077	0.096	0.8	0.23
	lambda_lw	1.259	0.024	51.9	N/A
Model for LGEQ	delta_lg	-244.150	8.634	-28.3	N/A
	zeta_avg_80m_ws_30s.lg	-0.786	0.072	-10.9	-12.33
	zeta_day1_night0_boolean.lg	-2.725	0.223	-12.2	N/A
	zeta_shear_lg	-5.262	0.351	-15.0	-16.14
	lambda_lg	3.994	0.085	47.2	N/A
Model for Sound Speed Profile	delta_ss	1.945	0.093	20.8	N/A
	zeta_temp_lapse_low.ss	-56.879	1.545	-36.8	-9.48
	zeta_avg_80m_wd_30s.ss	0.032	0.000	68.4	11.52
	zeta_day1_night0_boolean.ss	-0.401	0.108	-3.7	N/A
	zeta_vert_windspeed_down.ss	-1.621	0.170	-9.6	-3.42
	zeta_vert_windspeed_up.ss	-1.169	0.080	-14.6	-3.75
	zeta_shear_ss	-0.247	0.169	-1.5	-0.76
	lambda_ss	2.364	0.033	72.5	N/A
Cross Effects	beta_lw_lg	2.973	0.088	33.6	62.45
	beta_ss_lg	0.262	0.027	9.8	6.09

Model Log-Likelihood	-25,594
Number of Observations	3,580

TABLE 17: STRUCTURAL EQUATION MODEL RELATING METEROLOGICAL VARIABLES TO G-WEIGHTED SOUND PRESSURE LEVELS (OUTSIDE)

		Estimate	Standard Error	T-Value	Effect Size
Model for LW_DBA	delta_lw	99.726	0.126	788.6	N/A
	zeta_site_mountain	-0.249	0.077	-3.2	N/A
	zeta_avg_80m_ws_30s.lw	0.513	0.011	48.1	8.04
	zeta_vert_windspeed_down.lw	0.448	0.090	5.0	0.95
	zeta_vert_windspeed_up.lw	-0.497	0.041	-12.0	-1.59
	zeta_sd_80m_v_ws_30s.lw	0.845	0.076	11.1	1.94
	zeta_sd_80m_wd_30s.lw	-0.030	0.004	-7.4	-2.82
	zeta_veer_40_120.lw	-0.002	0.001	-2.7	-0.83
	zeta_abs_yaw_error.lw	-0.064	0.002	-30.2	-6.60
	zeta_shear_lw	0.048	0.091	0.5	0.15
	lambda_lw	1.199	0.023	52.7	N/A
Model for LGEQ	delta_lg	-193.639	8.210	-23.6	N/A
	zeta_avg_80m_ws_30s.lg	-0.420	0.071	-5.9	-6.59
	zeta_day1_night0_boolean.lg	-3.568	0.202	-17.6	N/A
	zeta_shear_lg	-4.714	0.339	-13.9	-14.46
	lambda_lg	4.604	0.073	63.3	N/A
Model for Sound Speed Profile	delta_ss	2.012	0.101	19.9	N/A
	zeta_temp_lapse_low.ss	-50.499	1.219	-41.4	-15.71
	zeta_avg_80m_wd_30s.ss	0.024	0.000	55.0	8.51
	zeta_day1_night0_boolean.ss	0.708	0.109	6.5	N/A
	zeta_vert_windspeed_down.ss	-1.693	0.177	-9.6	-3.58
	zeta_vert_windspeed_up.ss	-1.278	0.084	-15.1	-4.10
	zeta_shear_ss	-1.553	0.176	-8.8	-4.76
	lambda_ss	2.681	0.034	79.2	N/A
Cross Effects	beta_lw_lg	2.513	0.084	29.8	50.97
	beta_ss_lg	0.307	0.025	12.2	4.39

Model Log-Likelihood	-29,646
Number of Observations	4,052

8.5 | BUILDING TRANSMISSION LOSS

The infrasound monitors, located both inside and outside a residence at both sites, operated simultaneously and were time-synchronized. As a result, we can compare the two to calculate the building transmission loss at low and infrasonic frequencies.

For each 10-second period, the noise reduction provided by the structure was calculated. The noise reduction is the outside sound level minus the inside sound level, by 1/3-octave band. Noise reduction was calculated for both the turbine-on and turbine-off conditions. This calculation requires the (reasonable) assumption that all of the measured sound was generated by a source outside of the home, and that no sound reached the indoor infrasound monitor without having passed through the facade of the structure. The results are shown in Figure 79 for the house at Site 8A and in Figure 80 for Site 8B.

Site 8A shows a small increase in sound level inside the house for frequencies below 1.6 Hz. From 0.5 Hz to 25 Hz, the noise reduction is less than 10 dB, and above 25 Hz, the noise reduction varies from 8 to 20 dB. The residence at the mountainous site exhibits similar behavior, with no appreciable attenuation for frequencies below 10 Hz. Overall, this house at the mountainous site provided less noise reduction compared to the flat site, by about 5 dB.

Increased sound levels inside the house are unlikely due to acoustic modes (resonances), given that the infrasound wavelengths are much greater than any room dimension. They are more likely due to wind exciting structural resonances, creating interior infrasound unrelated to the exterior sound.

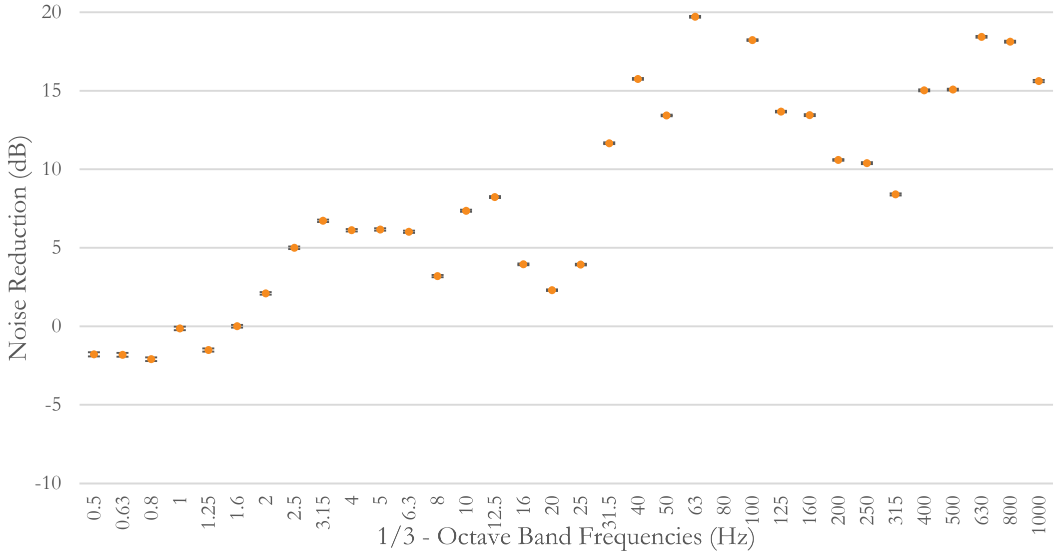

FIGURE 79: NOISE REDUCTION BY 1/3-OCTAVE BAND FOR THE HOUSE AT SITE 8B (FLAT)

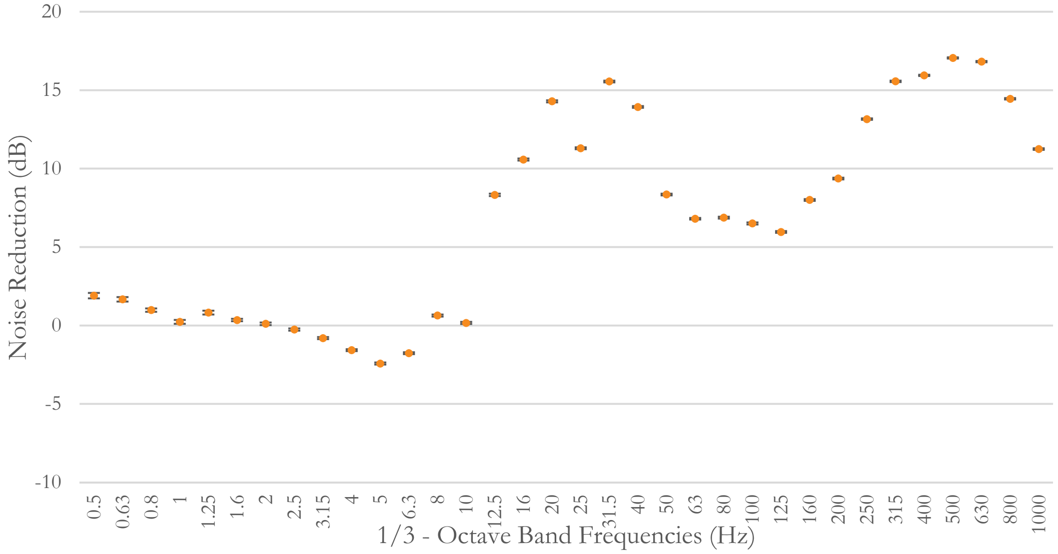

FIGURE 80: NOISE REDUCTION BY 1/3-OCTAVE BAND FOR THE HOUSE AT SITE 8B (MOUNTAINOUS)

At the audible frequencies, the noise reductions calculated for these homes are lower than those in the literature for homes in cold climates with closed windows. At the mountainous site, this may be explained by the lack of interior walls. Another explanation may be that the interior and exterior levels are so low, that any small amount of interior noise is likely to skew the results.

8.6 | INFRASOUND DISCUSSION

Much of the discussion of wind turbine-generated sound centers around the effects of infrasound and very low-frequency sound. However, few jurisdictions in the U.S. regulate sound of such low frequency. Illinois has an octave-band standard that extends down to 31.5 Hz (specifying a limit of as low as 63 dB at night). Connecticut limits infrasound to 100 dB at any time. Some European countries have set infrasound and low-frequency sound standards.

Wind turbine sound impact studies rarely address infrasound. It is thought that infrasound is generally well below audibility thresholds, which is supported by the results of this study. In addition, sound propagation modeling for wind turbine infrasound is hampered by a lack of manufacturer's data (infrasound testing is not required under IEC 61400-11 or -14) and lack of standardized modeling methodology. (Neither ISO 9613-2 nor Harmonoise are capable of modeling infrasound).

The infrasound results of this study should be considered of very high quality. Care was taken to use measurement equipment specifically intended for infrasound, including infrasound microphones and a custom-designed exterior windscreen. In addition, multiple wind turbine shutdowns allowed us to routinely assess background sound contributions to the overall sound level. Our simultaneous interior measurements reinforced the results, showing infrasound levels well below ISO audibility criteria.

The infrasound levels did not show a strong dependence on topography. The level of infrasound is primarily driven by wind speed for both background and turbine-on measurements. Our measurements of infrasound levels when the turbines are on show that it follows the relationship with wind speed as wind turbine sound power. Both measured infrasound and overall A-weighted sound power level off at higher wind speeds when the turbines are operating.

The structure of a residence can provide little relief from exterior infrasound. The lightweight residences tested for this study provided less than 6 dB of noise reduction at and below 12.5 Hz. The noise reduction results calculated for the homes at the higher audible frequencies are suspect, because the ambient sound levels both inside and outside each residence were so low.

Infrasound levels generated by the wind turbines in this study were well below ISO audibility limits – ranging from about 30 dB at 20 Hz to 80 dB at 1 Hz. Given these findings, and considering the lack of manufacturer's infrasound power data under current IEC standards, and the lack of commonly accepted propagation modeling methods for infrasound, it would be difficult to craft a regulation for wind turbine infrasound that meets the criteria of relevance, repeatability, and ease of implementation.

9.0 TONALITY

9.1 | INTRODUCTION TO TONALITY

Tones are individual sound frequencies in a spectrum that can be discerned from the rest of the sound in a given spectrum. Examples of tones include notes on musical instruments, a flying mosquito, and an emergency siren. Using these examples, tones can be pleasant, annoying, or alarming depending on the context.

In terms of noise, tones are generally considered more annoying than "broadband" sound. Broadband sounds include such sources as most fans, automobile traffic, and waves on the beach. Many noise regulations add decibel penalties for the presence of prominent tones. For example, many Vermont Public Service Board Certificates of Public Good for larger wind turbine projects do not allow any prominent pure tones. Maine's wind turbine regulations require a 5 dB penalty for prominent pure tones.[21] The ANSI S12.9 Part 5 land-use compatibility standard also adds a 5 dB penalty for the presence of a prominent tone.

There are many ways to determine that a sound spectrum includes a prominent tone. The most complex, but most accurate, method follows procedures similar to IEC 61400-11. This method is based on psychoacoustic principles concerning the ability of the ear to distinguish narrowband sounds of different frequencies. In particular, it recognizes the human ear's ability to distinguish individual tones within the range of speech frequencies, but its poor ability to detect them at low frequencies. However, the standard requires narrowband spectral sound measurements that are not typically available with sound level meters. Narrowband measurements require specialized equipment and software.

A commonly used method for assessing prominent tones is based on ANSI S12.9 Part 4. Similar to IEC 61400-11, it applies different criteria to low-frequency tones than for mid- and high-frequency tones. Tonality is assessed by comparing the level of each 1/3-octave band to the levels of its two adjacent bands. It is not as accurate as IEC 61400-11, especially where complex harmonics are involved, but the sound monitoring systems that are available to most noise control engineers are capable of providing the required banded levels.

A third method is used by MassDEP that involves full octave bands. Like ANSI 12.9 Part 4, this method also compares the level of each octave band to those of its neighbors, but it does not account for the reduction in the human ear's sensitivity to tonal sound at low frequency.

For this study, tonality of the measured wind turbine sound was evaluated according to the methods of ANSI S12.9 Part 4 and the current MassDEP Policy. Tonality using IEC 61400-11 was not evaluated.

All 1/1- and 1/3-octave band data in this section are unweighted, unless otherwise noted.

9.2 | CURRENT MASSDEP POLICY FOR ASSESSMENT OF TONALITY

Under current MassDEP policy, if the sound in question is evaluated by a listener who determines that a tone may be present, then the tonality of the sound is assessed using the following procedure:

1) Octave band levels are measured with source of interest turned on;
2) Octave band sound levels are measured with the source of interest off (background);

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[21] Maine is one of the few states that have sound regulations specific to wind turbines

3) The difference between the source sound level and the background sound level is calculated for each octave band;
4) If the difference level in any octave band is 3 dB higher than the differences from the two adjacent octave bands, then the sound is considered tonal.

To evaluate tonality under the current MassDEP policy, we first screened the data to identify discernible turbine shutdowns. If any location met this criteria for a given shutdown, than all locations at that site were evaluated for that shutdown.

The equivalent average sound level in each octave band between 31.5 Hz and 1,000 Hz was determined for the period of the turbine shutdown. In contrast to the turbine-on periods, where one-second data is used, this shutdown Leq is a single value representing the equivalent average over the entire shutdown period.

Levels were evaluated in one-second intervals for tonality during the one-hour period before the shutdown, during the shutdown, and during the one-hour period after the shutdown.

Figure 81 shows example results. At the bottom of the chart, the 1/1-octave band sound levels are shown for the $Leq_{(period)}$ turbine-off condition (black markers) and a single $Leq_{(1\text{-sec})}$ turbine-on condition sound level (orange markers). The difference between the two is shown as a blue horizontal line at each octave band. The tonal prominence, that is, the level above the adjacent octave band, if more than 3 dB (the black line) is shown as a yellow bar (tonality). In this example, there is a prominent discrete tone at 250 Hz under the procedure.

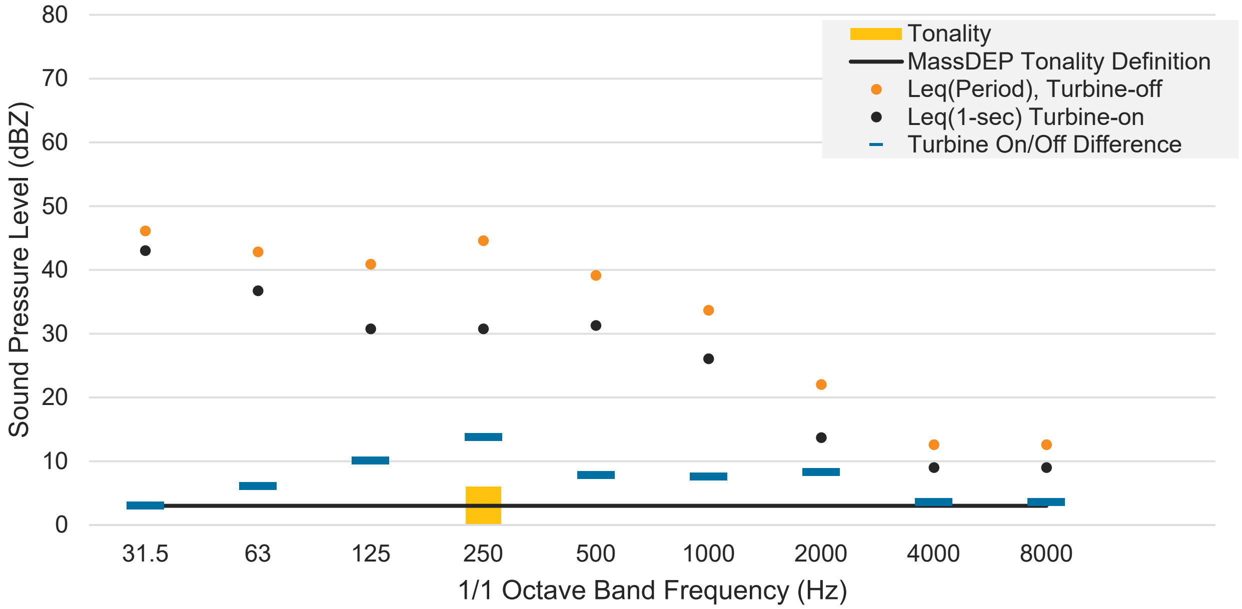

FIGURE 81: EXAMPLE TONALITY CHART UNDER MASSDEP METHOD

As noted above, we evaluated both turbine-on and turbine-off sounds for tonality for a total of 187 turbine shutdowns. The results are shown in Figure 82. Of the 187 shutdowns, 177 had at least one second of tonality for turbine-on and turbine-off. The percent time tonal was similar for turbine-off and turbine-on. The largest increase in calculated tonality occurred in the 125 Hz octave band, rising from 3.9% to 4.4%.

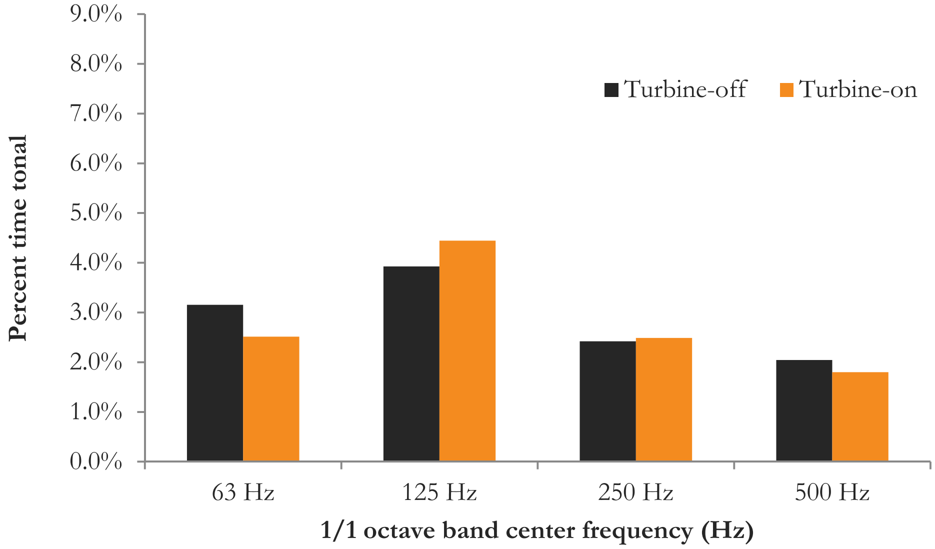

FIGURE 82: PERCENT TIME TONAL UNDER MASSDEP PROCEDURE FOR TURBINE-OFF AND TURBINE-ON RELATIVE TO BACKGROUND

Rather than evaluating the differences between the turbine-off and –on, as done above, we can simply look at spectral prominence with the measured levels. In this alternative method, we analyze 1/1-octave bands to identify any 3 dB prominence from both neighboring octave bands, independent of background sound. The results, shown in Figure 83, show lower tonality for the turbine-on than for turbine-off. Compared with the MassDEP procedure, there is an increase in tonality at 63 Hz and 500 Hz, and a decrease at 125 Hz and 250 Hz.

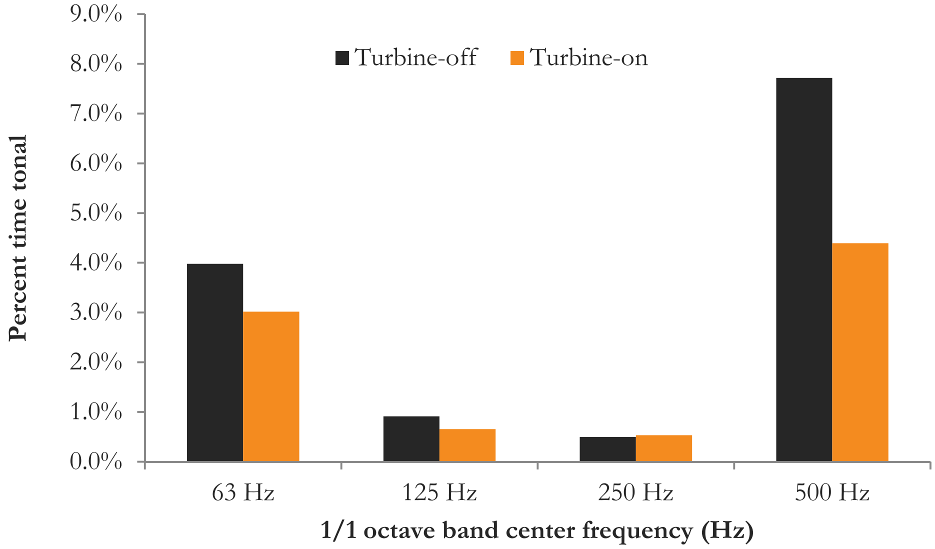

FIGURE 83: PERCENT TIME TONAL USING 3 DB PROMINANCE CRITERION OF MEASURED SOUND

9.3 | TONALITY UNDER ANSI S12.9 PART 4

Tonal sound is defined under ANSI 12.9 Part 4 using differences in adjacent 1/3-octave bands. For a tone to exist, one measures the difference in an unweighted 1/3-octave band with its two adjacent neighbors. If the sound level from that band exceeds the levels in the two adjacent bands by a certain amount, the sound is considered tonal. The standard suggests using 15 dB for bands between 25 and 125 Hz, 8 dB for 160 to 400 Hz, and 5 dB for 500 to 10,000 Hz.

Each second of the 187 discernable shutdowns were re-evaluated according to ANSI S12.9 Part 4. We limited our evaluation to the primary audible turbine frequencies ranging from 25 Hz to 1,000 Hz.

An example of the analysis is shown in Figure 84. The source data for this example is from the same period as Figure 81 showing the MassDEP procedure. The legend is the same, except that the sound levels shown are in 1/3-octave bands, and the ANSI S12.9 Part 4 tonality criteria, shown as a black line stepping down, is the tonality criteria. The step-down shows the increasing human sensitivity to tones as frequency increases.

As shown, the same 250 Hz prominence shows up as in Figure 81. However, in this case, the prominence is not considered tonal, because it does not exceed the criterion of 8 dB within this band. None of the 1/3-octave bands in this example are tonal.

Of the 187 shutdowns processed using this procedure, no tonality was found for turbine-off or turbine-on conditions.

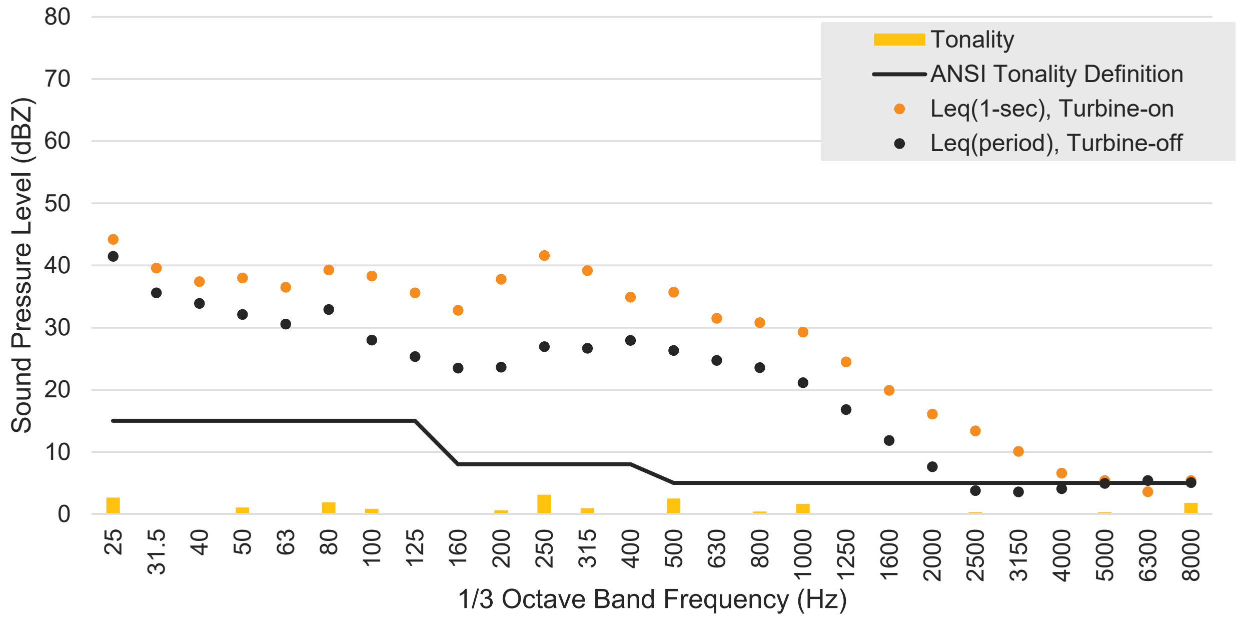

FIGURE 84: EXAMPLE TONAL EVALUATION USING ANSI S12.9 PART 4 FOR THE SAME PERIOD AS FIGURE 81

9.4 | TONALITY DISCUSSION

Tonal sound was evaluated using one-second data in and around 187 turbine shutdowns. The evaluation was limited to sound between 25 Hz and 1,000 Hz, the primary audible sound frequencies related to wind turbines.

The results showed that almost all shutdowns had one or more second of tonality under the MassDEP procedure during both turbine-off and turbine-on periods. On average, about 3% of the time analyzed was tonal – slightly lower with turbines off and higher with turbines on.

We attempted to resolve one issue with the current procedure, in that sounds that are not tonal can be considered tonal depending on how the background spectrum is shaped. We conducted another analysis evaluating tonality only using the observed sound level, that is, ignoring the background sound. The results showed relatively higher tonality when the turbines are off compared to when the turbines are on.

While the second method (not accounting for background) is better at addressing perceived tonality, it still ignores modern psychoacoustics practices that defines tonality using narrower spectral bands and considers the changing sensitivity of the human ear at different frequencies. In particular, the ear has less ability to distinguish tones at the lower frequencies, where most of the wind turbine sound occurs.[22]

These issues can be resolved by using narrowband methods similar to that described in IEC 61400-11. However, this method uses specialized equipment and software, which would be difficult for MassDEP enforcement staff to operate. A more practical alternative that is less accurate than IEC 61400-11, but more accurate in identifying tones than the current procedure, is found in ANSI S12.9 Part 4. This method uses 1/3-octave band prominence and a frequency-scaled criteria based on human hearing sensitivity. When applied to the one-second data from the 187 shutdowns in this study, no tonal sounds were identified.

In establishing tonality regulations, consideration should be given as to what averaging time to use. In our method, we used a one-second averaging time. However, it is likely that small tonality excursions can occur without creating undue annoyance from listeners. Consideration should be given to longer averaging time, for example, a five-minute Leq. Alternatively, tonal penalties couple be applied based on the number of observations per five-minute period. The Maine wind turbine regulations apply a 5 dB penalty if the 10-minute Leq is tonal according to the same criteria as ANSI S12.9 Part 4. The Illinois prominent discrete tone standard also follows ANSI S12.9 Part 4, and uses a 10-minute Leq for steady sounds and one-hour Leq for unsteady sounds.[23] The Connecticut noise regulations also define tonality based on the prominence of any 1/3-octave band, but use their own table of prominence level by frequency, which is similar, but not the same as ANSI S12.9 Part 4. Connecticut applies a 5 dB penalty for sound found to be tonal.

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[22] The low-frequency effect is evident in the bass line of much music, which more easily becomes “muddy” and indistinguishable to the listener.

[23] Illinois defines unsteady sounds as those having more than 3 dB variation when the sound level meter is set to slow response.

10.0 METEOROLOGICAL DATA

10.1 | SPECIFIC METHODOLOGY

Throughout this study, meteorological data were collected at each site in order to better understand how select atmospheric factors affect sound levels at receiver locations. Specific variables measured included rain, relative humidity, temperature, wind speed, and wind direction data at one- and ten-meter heights.

At each of the five sites, a 10-meter measurement station was collocated with an NRG WindCube v2 Light Detection and Ranging (LIDAR) system upwind of the wind turbine(s), based on the predominant wind direction. The LIDAR system collected 40 to 200 meter wind speed and direction data (at 10-meter intervals to 100 meters and 20-meter intervals to 200 meters). LIDAR data were logged every one-second and 10-minutes, depending on the variable. At four of the five sites, the meteorological data were supplemented with the SCADA data from the nacelle-mounted anemometry. Cloud cover used, in part, to calculate atmospheric stability, was obtained from the nearest National Weather Service Automated Surface Observation Station (ASOS) as reported by wunderground.com.

FIGURE 85: SOUND LEVEL METER IN BACKGROUND AND GROUND MET EQUIPMENT IN FOREGROUND

An example of a station set up on the ground is shown in Figure 85. This station is adjacent to a sound level meter, with wind direction and wind speed measured at 1 to 1.5 meters above ground. The LIDAR and 10-meter measurement station is shown in Figure 86.

As discussed in Sections 4, 6, 7, and 8, meteorological parameters affect both sound generation and propagation. For example, wind speed was shown to influence the radiated sound power of a turbine. Two calculable metrics related to wind speed are the turbulence intensity (how quickly the wind speed varies over a given period of time) and shear (the profile of wind speed with increasing height above the ground). The wind shear for this study was taken to be the wind speed gradient from 40 m elevation to 120 m elevation above ground.

An analysis of these metrics was conducted for one-second wind speeds binned in 1 m/s intervals from 1 to 16 m/s at 80 m elevation above ground using the LIDAR data from all sites. Means, standard deviations, and other statistical values were calculated for each site, and a comparison was made between flat and mountainous sites. Additionally, time-synchronized data for each record set were

FIGURE 86: 10-METER MET MAST ON LEFT WITH LIDAR ON RIGHT

used in order to calculate the average values for the hub-height wind speed using the 10-meter met tower, the LIDAR, and SCADA data sets. A range of wind profile exponents ($\alpha = [0.10, 0.60]$) were used to calculate a range of possible 80-meter wind speeds extrapolated from the 10-meter wind speed to provide a range of values based on commonly used coefficients.

The analysis of meteorological variables was conducted in order to better answer the following questions:

(1) What is the characteristic relationship between wind turbulence and wind shear for the sites?
(2) What is the characteristic relationship between turbulence intensity and shear with wind speed at the sites?
(3) How do these characteristics change depending on local topographic features?
(4) How do the hub height winds speeds measured at the turbine nacelle and by the LIDAR compare to those predicted by standard profiles extrapolated from wind speeds measured at 10 meters?

10.2 | WIND SPEED V. WIND TURBULENCE INTENSITY RESULTS

The following three charts plot 80-meter wind speed versus 80-meter turbulence intensity. These are "box and whiskers" charts showing the percentiles values for each wind speed, as in Figure 87.

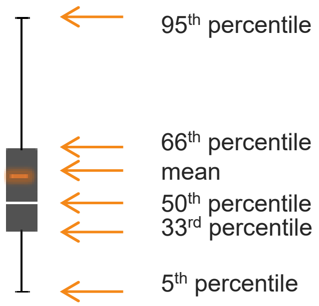

FIGURE 87: LEGEND KEY TO BOX AND WHISKERS CHARTS

Figure 88 is the combined results showing the relationship of wind speed to turbulence intensity at all sites. The mean and variation of the turbulence intensity decreases with increasing wind speed.

There is a similar trend for the mountainous site (Figure 89). There is a general decrease in the mean value of turbulence intensity as wind speed increases. However, the 5th percentile value in each wind speed bin decreases as well from a value of approximately 0.10 to approximately 0.05 at the 1 m/s to 16 m/s wind speed bins respectively.

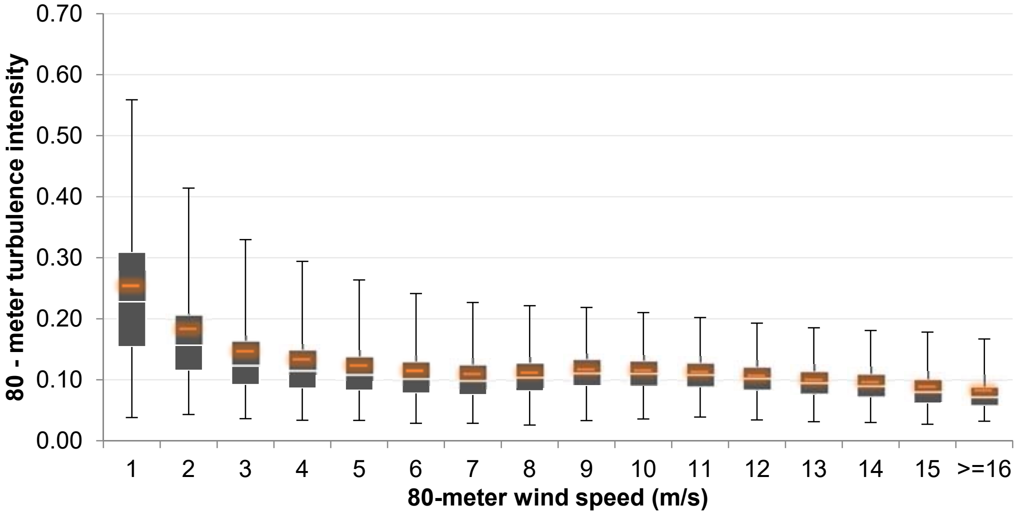

FIGURE 88: WIND SPEED V. TURBULENCE INTENSITY – ALL SITES

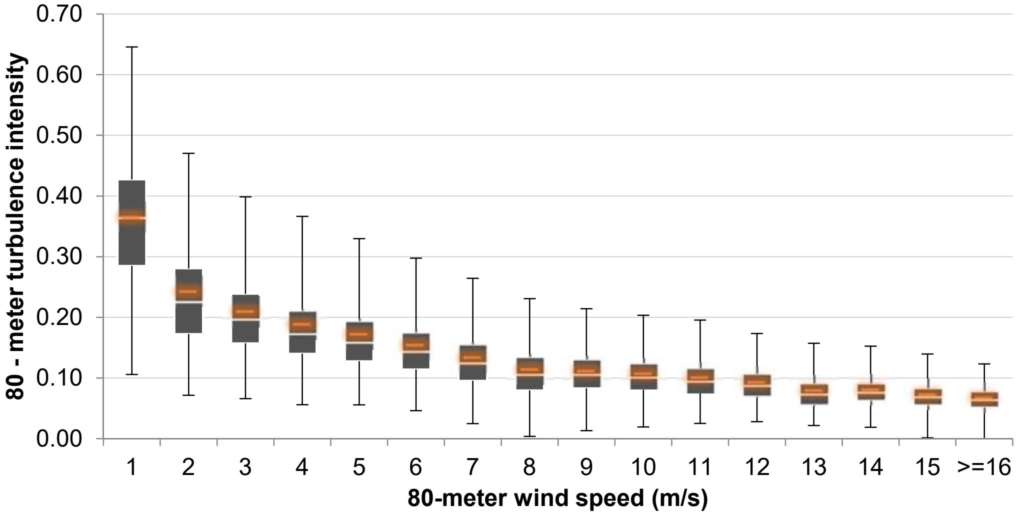

FIGURE 89: WIND SPEED VS. TURBULENCE INTENSITY – MOUNTAINOUS SITE

The trend of the flat site (Figure 90) is similar to that from the analysis considering all sites. Note that the conditions at the flat sites will dominate the trend for the all sites analysis since there were more flat sites included in the research study.

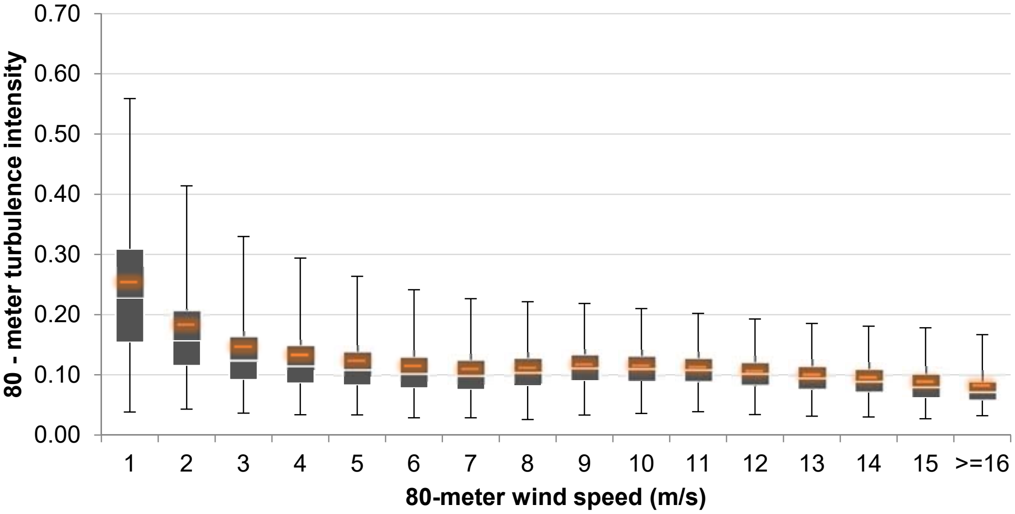

FIGURE 90: WIND SPEED VS. TURBULENCE INTENSITY – FLAT SITES

In comparing the flat sites to the mountainous site (Figure 91), some clear differences in the trends can be observed. The mountainous sites show a greater turbulence intensity value than the flat sites below the 8 m/s wind speed bin, a difference of approximately 0.10 at the 1 m/s wind speed bin to approximately 0.00 at the 8 m/s wind speed bin. For wind speeds above 8 m/s, the mean values of the turbulence intensity at the flat sites are greater than those of the mountainous sites by a maximum value of 0.025.

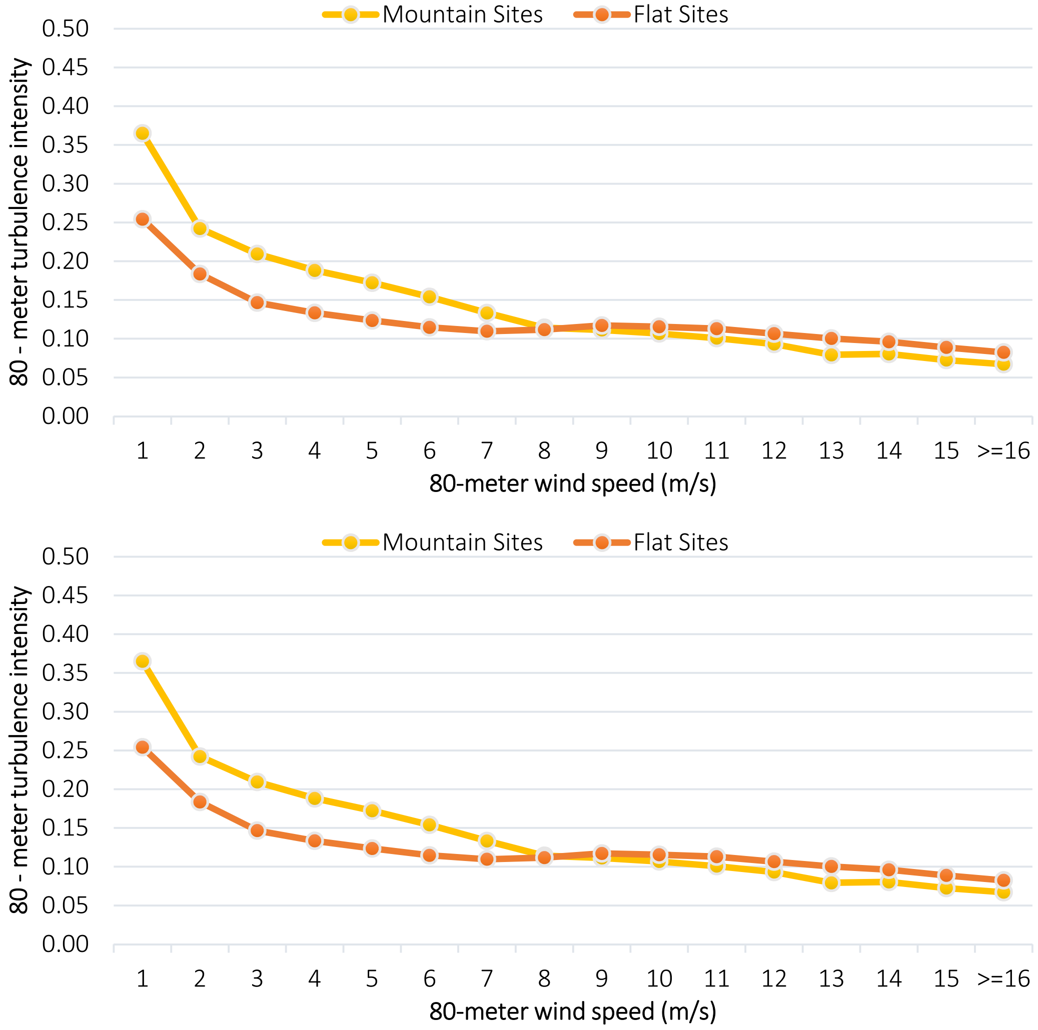

FIGURE 91: MOUNTAINOUS AND FLAT SITE COMPARISONS – TURBULENCE INTENSITY

10.3 | WIND SPEED V. WIND SHEAR

For this section, we use the wind shear power law exponent as defined here:

$$V_1 = V_0 \text{ x } \left\{\frac{(z_1 - d)}{(z_0 - d)}\right\}^{\alpha}$$

Where:

V_1 = wind speed at height Z_1

V_0 = wind speed at height $Z_{0[?]}$

d = displacement height above effective ground level. For simplicity in this analysis, d = 0 for all calculations throughout this analysis.

α = wind shear power law exponent.

The following three charts plot 80-meter 40-meter-to-120-meter wind shear versus 80-meter wind speed, using 30-second averaging times. Figure 92 shows the results aggregated for all sites, Figure 93 shows the mountain site results and Figure 94 shows the combined flat sites' results.

For all sites, the wind shear increases with wind speed to about 8 m/s, then declines. The 95th and 5th percentile values converge on the mean as the wind speed increases. The deviations range from plus or minus 1.5 at the 1 m/s wind speed bin to approximately 0.25 at the 16 m/s wind speed bin.

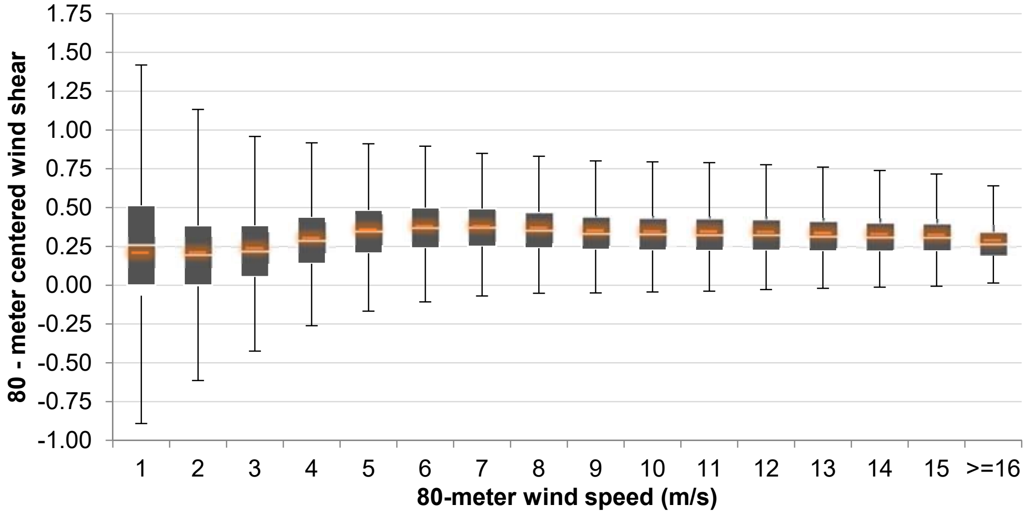

FIGURE 92: WIND SPEED V. WIND SHEAR – ALL SITES

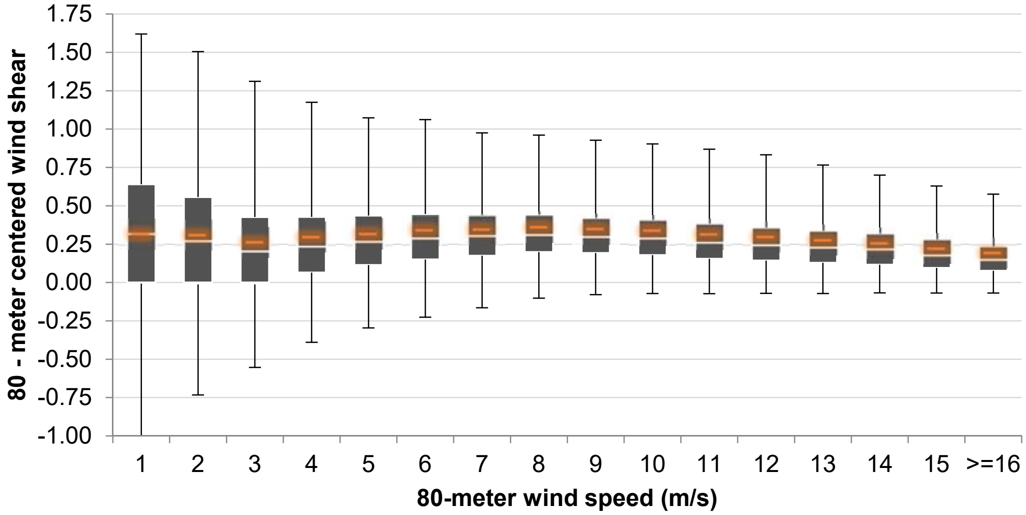

FIGURE 93: WIND SPEED V. WIND SHEAR – MOUNTAINOUS SITES

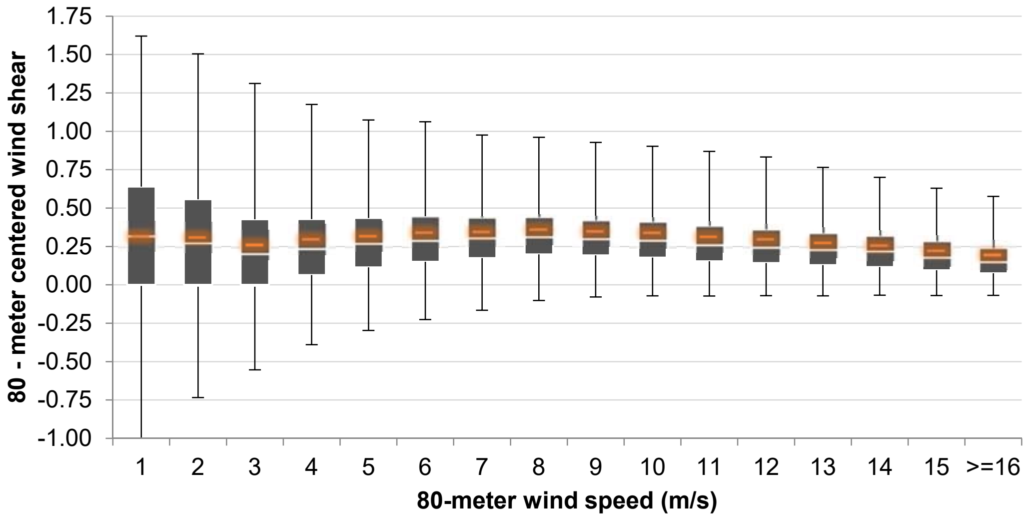

FIGURE 94: WIND SPEED V. WIND SHEAR – FLAT SITES

In comparing the flat sites to the mountainous sites, the behavior of the wind shear is similar (Figure 95). The largest differences between these two terrain types is below the 3 m/s wind speed bin, and above the 9 m/s wind speed bin. The maximum differences in the mean values reach approximately 0.10 at the 1 m/s and 16 m/s wind speed bins.

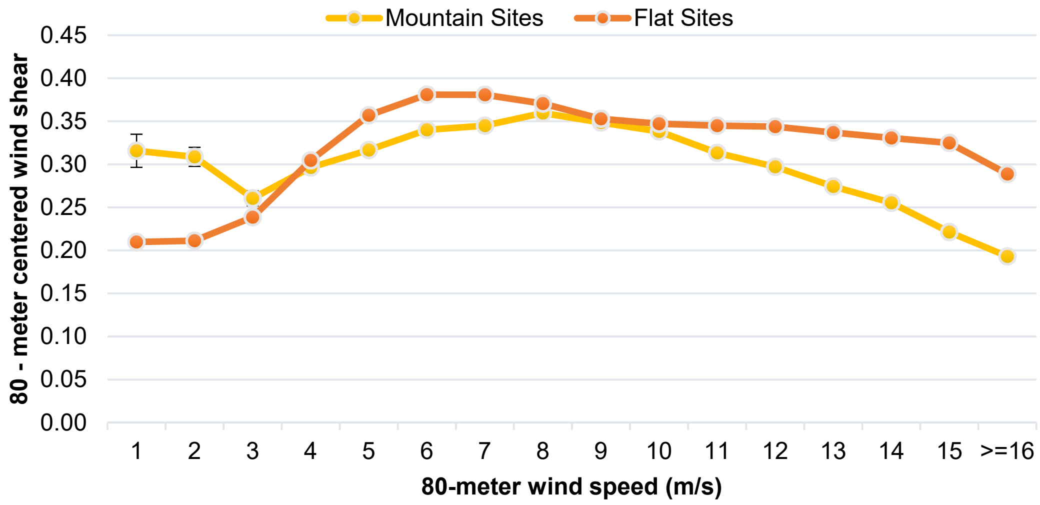

FIGURE 95: MOUNTAINOUS AND FLAT SITE COMPARISONS – WIND SHEAR

We did find a difference between wind shear during the night and day (Figure 96). In general, daytime wind shear is lower than nighttime, and the variability of nighttime wind shear tends to be greater. Thus, we would expect that the background sound level, assuming it is based on wind speed near the microphone alone, would also show greater variability at night and while hub height wind speeds are lower.

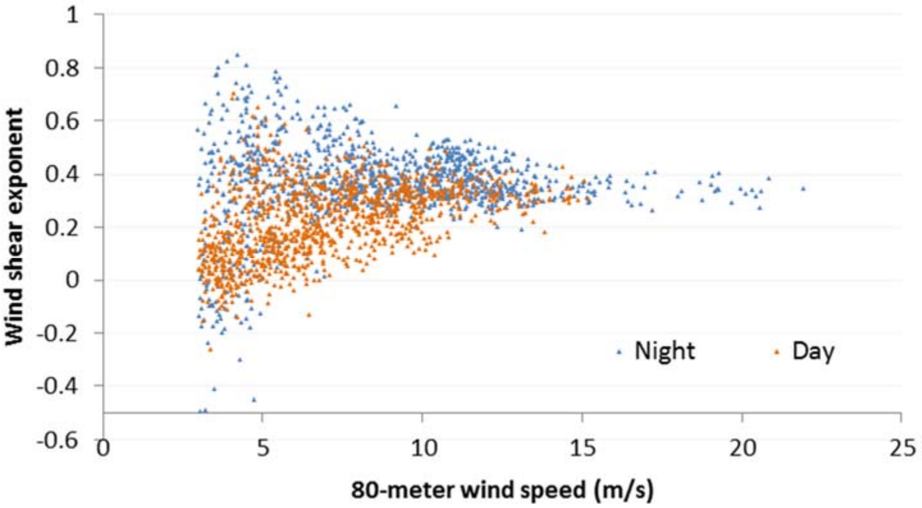

FIGURE 96: 40 TO 120 METER WIND SHEAR AS A FUNCTION OF WIND SPEED FOR FLAT SITES BY DAYTIME/NIGHTTIME

10.4 | COMPARING HUB-HEIGHT WIND SPEED MEASUREMENT AND PREDICTION TECHNIQUES

About seven million time-synchronized records were averaged across four sites[24] in order to determine the average hub-height wind speeds based on the 10 meter met tower, LIDAR, and SCADA data. See Table 18 below for a comparison of the values. The hub-height wind speed was estimated using a range of shear coefficients from 0.1 to 0.6. Using this method, the predicted 80-meter wind speed data covers a range of 1.36 to 6.45 m/s. This illustrates the difficulty of estimating hub-height wind speed without knowing the hour-by-hour shear profile.

The nacelle anemometer wind speed averaged 6.77 m/s, which is 0.32 m/s greater than the maximum predicted value from the ten-meter wind speed data. The highest wind speed was recorded using LIDAR. This average wind speed was 7.37 m/s, 0.6 m/s greater than the mean average wind speed calculated from the nacelle anemometer.

This trend is the same for each site with the exception of Mountain Site D. This may be because Site D is a multi-turbine site, and the wind speed reported here is the average of the three closest wind turbines. As such, wind speeds may be different at each turbine.

In general, the hub-height value as predicted by the 10-meter wind speed is the lowest and most variable, followed by the nacelle anemometer and the 80-meter wind speed from the LIDAR data.

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[24] The fifth site did not have available SCADA.

TABLE 18: AVERAGE 80-METER WIND SPEED (M/S) BASED ON DIFFERENT COLLECTION AND PREDICTION METHODS

	Site Type	10-Meter Met Tower Anemometer ($0.1<\alpha<0.6$)	Nacelle Anemometer	LIDAR (80 meters)
All Sites	**All**	**1.36 to 6.45**	**6.8**	**7.4**
Site 10A	Flat	1.35 to 6.42	5.6	6.7
Site 10B	Flat	1.30 to 5.42	6.1	7.1
Site 10C	Flat	1.36 to 6.74	7.2	7.5
Site 10D	Mountainous	0.98 to 3.60	8.2	7.7

10.5 | METEOROLOGICAL DATA DISCUSSION

We found that the meteorological conditions and relationships all sites were relatively normal conditions for their respective topographic areas.

The highest turbulence intensity occurs at the lowest winds speeds. Above the cut-in wind speed of 3 to 5 m/s, there is very little change in the mean turbulence intensity, with the exception of a drop in the 95th percentile values. That is, as wind speed at hub height increases, turbulence intensity becomes more stable. The mountain and flat sites had similar mean turbulence intensity values above 7 m/s. However, at wind speeds at and below 7 m/s, turbulence intensity was higher at the mountain site. At 5 m/s, this difference is about 0.04 and declines with increasing wind speed.

Wind shear has a similar pattern of decreasing variability as wind speed increases. After a cut-in speed of 5 m/s, the wind shear decreases. The flat sites have shown greater shear at lower wind speeds than the sampled mountain site, while the reverse is true above 9 m/s.

To the extent wind shear and turbulence affect sound levels, the impact would tend to occur at lower wind speeds before the wind turbine reaches maximum sound output – generally around 9 m/s. This may help to explain why the modeling predictions tend to be less accurate at lower wind speeds.

The last part of this analysis compared hub height wind speeds using three methods – estimates based on a 10-meter anemometer, and assumed wind shear coefficients, the nacelle anemometer as reported through the SCADA system, and 80-meter LIDAR wind speed. Estimates using the 10-meter met tower were generally inaccurate due to the variability in wind shear, especially at lower wind speeds. At 5 m/s, the range in wind shear coefficient was -0.2 to +0.8. Predications at higher wind speeds would be more accurate, since wind shear tends to stabilize under these conditions.

Nacelle-mounted anemometry can be unreliable as a proxy for the ambient wind speed. In addition to being biased from the extraction of the kinetic energy on the rotor plane, nacelle anemometry is also influenced from the distortion in the wind as it is deflected around the nacelle. This phenomenon occurs even during periods when the wind turbine is offline. This shows in the greater wind speed measured by LIDAR, which was always situated upwind of the turbine, relative to the prevailing wind direction (although not always upwind of the actual wind direction). Differences at the flat sites ranged from 0.3 m/s to 1.1 m/s, with an average of 0.6 m/s. Individual SCADA systems may or may not make adjustments for this, potentially accounting for differences between sites.

The multi-turbine mountain site nacelle anemometers tended to measure 0.5 m/s higher wind speeds than LIDAR. However, this may be due to the variability in wind speeds at the three closest wind turbines over which the nacelle anemometer wind speeds were averaged.

11.0 STANDARDS ANALYSIS

In defining a sound metric for regulation, four requirements should be considered.

1) Relevance – The sound metric should have some relevance to impacts on humans or wildlife and not be set arbitrarily.
2) Repeatability – The metric should have a relatively low standard deviation among samples taken under similar conditions.
3) Predictability – The metric should be able to be predicted (i.e. modeled) with a high level of confidence or reliability.
4) Ease of implementation – Ideally, the metric should be able to be measured without specialized sound monitoring equipment by a trained enforcement officer. Some metrics can only be measured or calculated by an experienced noise control engineer.

To assess sound levels on these bases, we must first evaluate how different metrics behave. In this section, we introduce “attended monitoring,” where an observer is present to write down what sources are audible at what times. The advantage of attended monitoring is that sound sources can be more easily identified such that contaminating sounds can be filtered out of the measurement. The main disadvantage is that the monitoring periods are limited to relatively short durations.

11.1 | ATTENDED MONITORING METHODOLOGY

Attended listening involves a person logging the types of sound heard at each moment of time throughout the period of measurement. As noted above, short-term events that are not part of the source of interest can be marked and later removed from the sound measurements. However, this manual process is practical only for limited time periods and may not coincide with typical or target conditions in the area.

As part of this research project, the project team conducted attended listening and sound monitoring for 20 to 90 minutes during 44 visits at 23 locations around five wind projects. During the attended listening, an adjacent sound level meter logged 50-millisecond to one-second sound levels. The attendants used a custom-programmed Nexus 7 tablet computer. By selecting an icon corresponding to what was heard at any moment, the attendant creates a time-stamped record of that events. After the first site was monitored, we added a feature such that the observer would also enter how loud the event seemed on a relative scale (low, medium, or high). The tablet also logged its GPS coordinates and allowed the recording of audio on demand. The audio can include voice annotations or recordings of the ambient sound. A picture of the tablet screen is shown in Figure 97.

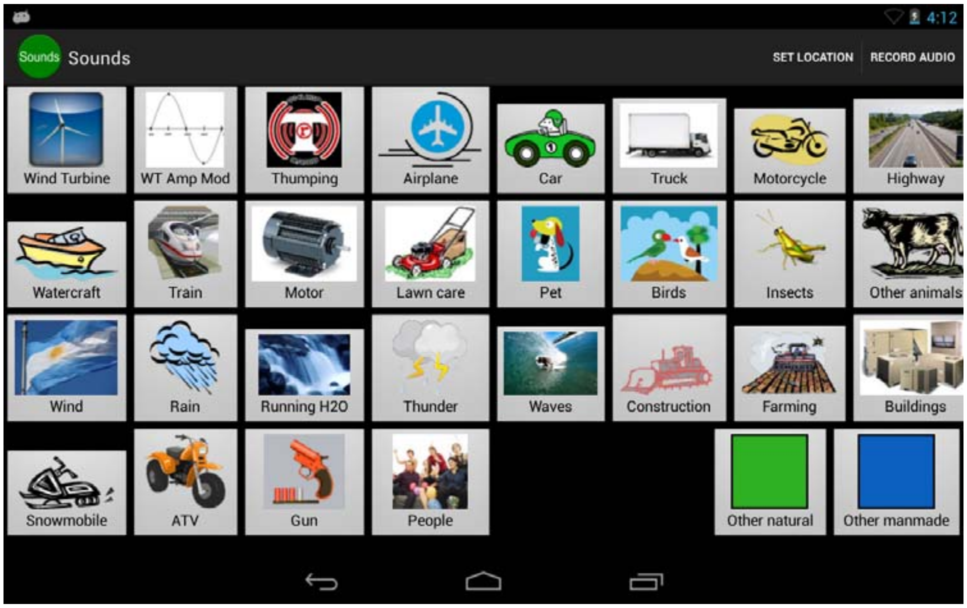

FIGURE 97: ATTENDED LISTENING TABLET SCREEN SHOT

Observations were made during both the daytime and nighttime, and mostly coincided with adjacent periods of turbine shutdowns.

With the collected data for each location, we evaluated the events that occurred in one-second intervals, totaling about 26 hours of observations. We then evaluated data during times with clean wind turbine sound. These were periods during which the attendant recorded that only wind turbine, wind turbine amplitude modulation, or wind turbine thumping could be heard, or that these were well above any contaminating sound sources such as highways, and there were no other short-term sound sources, such as vehicle passbys or wind gusts.

11.2 | SHORT-TERM STANDARDS ANALYSIS

The purpose of the short-term standards analysis is to compare different methods for attended wind turbine monitoring among those that could be used by the MassDEP for regulatory purposes. A pragmatic approach was taken to balance simplicity of execution, equipment required, and ease of analysis. Seven methods were chosen for comparisons.

DESCRIPTIONS OF THE METHODS

In the following section, we analyze seven ways to measure A-weighted sound levels during turbine operation and during background such that a reliable indicator of turbine sound is obtained. The methods are relatively straightforward to implement and use metrics common to most mid- to high-end commercial sound level meters. Each of these methods uses maximum, average, or 90th percentile sound levels during the turbine-dominant and turbine-off conditions.

The disadvantage to some of these following methods are that some do not effectively take into account anomalous sound during turbine-dominant time periods. The issue with calling a period of time "turbine-dominant" is that this is a relative metric because it varies based on the individual and how they perceive sound. RSG went a step further by quantifying this perception, discussed in the next section, in order to refine the process, but even still, it is hard to account for the human variable.

Method 1: $L_{Smax\ (5\text{-}min)}$

The L_{Smax} method is based, in part, on a monitoring process used by MassDEP in response to complaints on several wind projects. In this analysis, this method considers the maximum A-weighted L_S sound pressure level during a five-minute monitoring interval in which the wind turbine is considered the dominant source of sound. In a regulation that compares the background to the turbine sound level, the background would be calculated as the L_{90} of the L_S sound level of the entire duration of a period during which the wind turbine is shutdown. The difference between the turbine-on and background sound level is $\Delta L_{Method\ 1}$

$$\Delta L_{Method\ 1} = L_{Smax\ (5-min) Tdom} - L_S 90_{Toff}$$

Where *Tdom* is the period where wind turbine sound is the dominant[25] source of sound and *Toff* is the period of background sound when the turbines are turned off.

Method 2: L_{90} $L_{Fmax(1\text{-}sec)}$

This method considers the L_{90} of the $L_{Fmax\ (1\text{-}sec)}$ sound pressure level during a five-minute monitoring interval in which the wind turbine is considered to be the dominant source of sound (see Section 5.1 for a further description of L_{90} $L_{Fmax(1\text{-}sec)}$). This is compared to the L_{90} of the $L_{Fmax(1\text{-}sec)}$ sound level of the entire duration in which the wind turbine is shutdown. The difference between the turbine-on and background is $\Delta L_{Method\ 2}$.

$$\Delta L_{Method\ 2} = L90_{(5-\mathrm{min})}\ of\ L_{Fmax\ (1-sec)\ Tdom} - L90_{(5-\mathrm{min})}\ of\ L_{Fmax\ (1-sec)\ Toff}$$

Method 3: $Leq_{(5\text{-}min)}$

This method considers the five-minute continuously integrated sound level, Leq, when the wind turbine is considered to be the dominant source of sound. This is compared to the L_{90} of the $Leq_{(1\text{-}sec)}$ when the turbine is shut down. The difference between the turbine–on and background is $\Delta L_{Method\ 3}$.

$$\Delta L_{Method\ 3} = Leq_{(5-min)\ Tdom} - L90_{(5-min)}\ of\ Leq_{(1-sec)\ Toff}$$

Method 4: Adjusted $Leq_{(5\text{-}min)}$

For wind turbine sound, this method uses five-minute continuously integrated sound level, Leq, as above. Since the Leq can be influenced by short-duration wind gusts and other background sounds (as it is biased towards the louder sounds in a sample), we remove the background sound from it by subtracting the background Leq. This is a very common way to calculate the turbine-only Leq and is used in several noise standards, including IEC 61400-11, "Wind turbine acoustic noise measurement techniques." This is then logarithmically added to the background L_{90} to represent what the wind turbine sound would be absent the

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[25] For the purposes of analysis, wind turbine dominance was defined as:

1. When all turbine-related noises were between barely audible and dominantly audible while all other sounds were not perceptible, or
2. When at least one of the turbine related sounds was audible or dominant while all other sounds were barely audible or non-existent, and no continuous sources (i.e., highway noises, waves, and wind) were perceptible.

increased background sound above the L_{90}. For determination of compliance, this is compared to the background L_{90} as $\Delta L_{Method\ 4}$.

$$\Delta L_{Method\ 4} = 10 * \log_{10}\left(10^{\frac{Leq\ Tdom}{10}} - 10^{\frac{Leq\ Toff}{10}} + 10^{\frac{L90\ Toff}{10}}\right) - L90_{Toff} \quad (5-\mathrm{min})$$

Method 5: Wind Adjusted L_{Smax}

If wind is the only significant driver of background sound, then the wind speeds measured at the same time as the L_{90} is reached, would be exceeded 90 percent of the time. Therefore, one of the challenges with Method 1 ($L_{Smax\ (5\text{-}min)}$) is that this concurrent L_{90} wind speed and thus L_{90} sound level are likely to be exceeded during most of the turbine-on measurement period. In this case, the background sound level during an L_{max} measurement is likely to be higher than the wind speed when the level of the L_{90} occurred.

In this "Wind-Adjusted" method, the turbine-on sound is taken as the maximum L_S sound pressure level during a five-minute monitoring interval, as in Method 1. This is compared to the 10th percentile L_S sound level (L_{90}) of the entire duration in which the wind turbine is shutdown plus a wind speed level adjustment. Based on a linear regression model from this study, the sound level will increase by approximately 1.15 dB every 1 m/s increase in wind speed at hub height (holding all else constant). This wind speed adjustment is then the difference between the wind speed at the $L_{Smax\ (1\text{-}sec)}$ when the project is operating and the average of the one-second wind speeds during the turbine off period where the measured sound level is equal to the background L_{90}.

$$\Delta L_{Method\ 5} = L_{Smax\ (5-\mathrm{min}\ )\ \mathrm{Tdom}} - (L90_{Toff} + 1.15\Delta ws)$$

$$\Delta ws = ws_{Tdom\ @\ \mathrm{max}} - \overline{ws}_{Toff\ @L90}$$

Note that for this method to be used, systems need to be in place to log wind speeds at, ideally, 1 to 10 second intervals.

Method 6: Leq of one-minute L_{90} of $L_{Fmax\ (1\text{-}sec)}$.

This method considers the integrated A-weighted sound level, Leq, during a five-minute monitoring interval in which the wind turbine is considered the dominant source of sound. In order to take into account the quickly varying nature of background sound in the environment, this five-minute equivalent sound level is the logarithmic average of five one-minute L_{90} of $L_{Fmax\ (1\text{-}sec)}$ sound levels with the turbines operating. This is compared to the background L_{90} of $L_{Fmax\ (1\text{-}sec)}$.

$$\Delta L_{Method\ 6} = 10\log_{10}\left(\frac{\sum_{0\ min.}^{5\ min.} 10^{\frac{L90\ of\ L_{Fmax\ (1-min)\ Tdom}}{10}}}{5}\right) - L90\ of\ L_{AFmax\ Toff}$$

Method 7: $Leq_{(15\ min)}$

This method considers the continuously integrated A-weighted sound level, Leq, during the entire monitoring duration in which the wind turbine is considered to be the dominant source of sound. For our attended monitoring sessions, this is usually 15 to 20 minutes. The background Leq is logarithmically subtracted from this value to calculate the turbine-only sound level. If the standard is to include background, it must then be added back in. So, the background L_{90} (measured, or if fixed by regulation or permit, then the fixed L_{90}) is logarithmically added to the turbine-only Leq. This is compared to the background L_{90}, as in the following equation.

$$\Delta L_{Method\ 7} = 10\log_{10}\left(10^{\frac{Leq\ Tdom}{10}} - 10^{\frac{Leq\ Toff}{10}} + 10^{\frac{L90\ Toff}{10}}\right) - L90_{Toff}$$

The difference over Method 4 ($Leq_{(5\text{-}min)}$) is that the longer integration time serves to provide more information, improve statistical confidence in the results, and improve modeling reliability.

ATTENDED MONITORING

When doing attended monitoring, the perceived loudness or dominance of a sound is assigned a rating of low, medium, or high (see Section 11.1) In order to determine turbine dominance, the non-turbine related noise was compared to the turbine related noise. An algorithm was used to filter out all periods in which the turbine-related sounds were not dominant. For example, if an observer recorded "low" for wind turbine sound and "low" for wind sound, the turbine would not be dominant. If an observer recorded "high" for wind turbine sound and "low" for wind, the turbine would be dominant.

In the graphics below, there is an example of a "discernible" shutdown, one in which we can clearly see the A-weighted sound level drop during the turbine-off period. The graphic on the top of the chart, above the words "Attended Monitoring," shows the types of sound recorded by the observer. The thickness of the line corresponds to "low", "medium", and "high". The top line shows where the algorithm determines whether the turbine is dominant. As shown in Figure 98, when the project is operating, there is more turbine-related noise than there is non-turbine related noise. That is, the light blue line in the middle, representing turbine sound, is thicker than the dark blue line below it, representing non-turbine sound. For much of this attended monitoring period, the noise is turbine-dominant and contains values that we can use to calculate the suggested metrics.

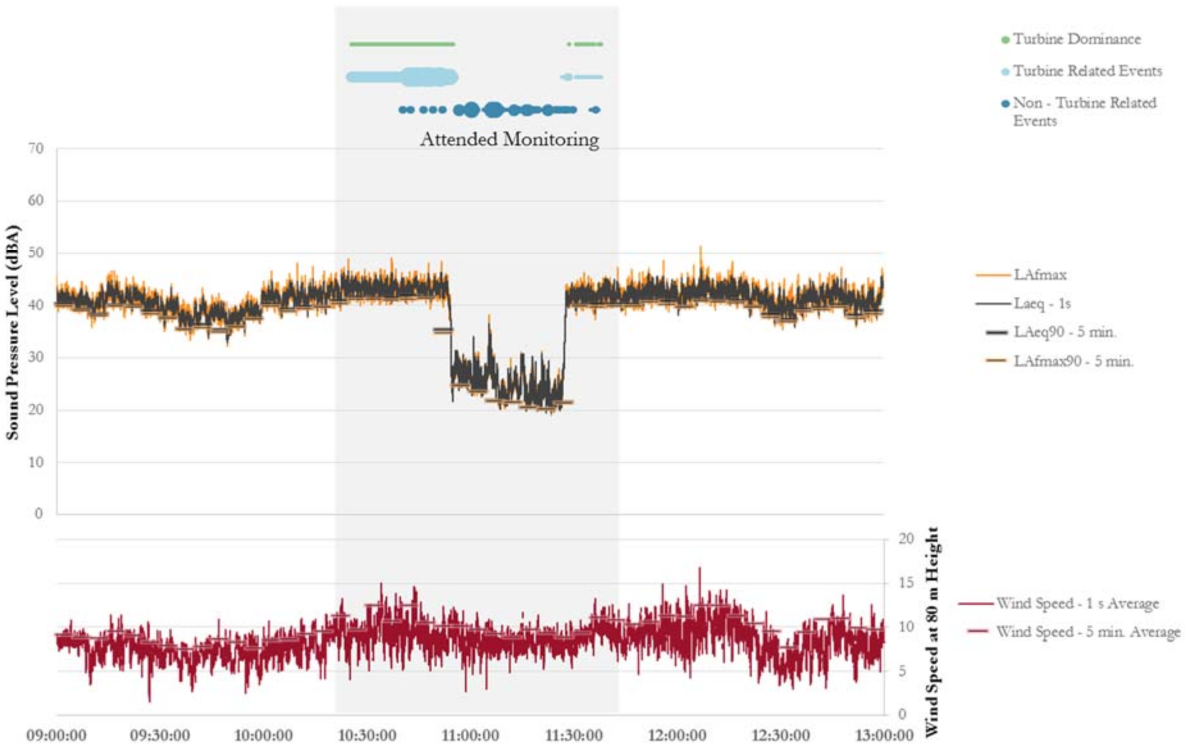

FIGURE 98: EXAMPLE OF ATTENDED MONITORING RESULTS FOR A “GOOD” SHUTDOWN

Shaded area from 10:20 to 11:40 is the period during which attended monitoring took place. The top part of the chart shows the attendant observations of turbine and non-turbine sounds. The thickness of the line represents “low”, “medium”, and “high” loudness or dominance. The green line on the top of the chart shows where the wind project is dominant above all other sources. The middle chart shows sound levels. The turbine shutdown is clearly seen in the middle of the figure. Wind speeds are shown on the bottom.

The second graphic below (Figure 99) shows an “indiscernible” shutdown, one in which we cannot clearly see a sound level change when the shutdown occurs. The observer data indicates turbine sound is audible, but it is dominated by other sources. Because of this, there is no time considered turbine-dominant. Consequently, the entire attended monitoring cannot be used to assess the level of wind turbine sound.

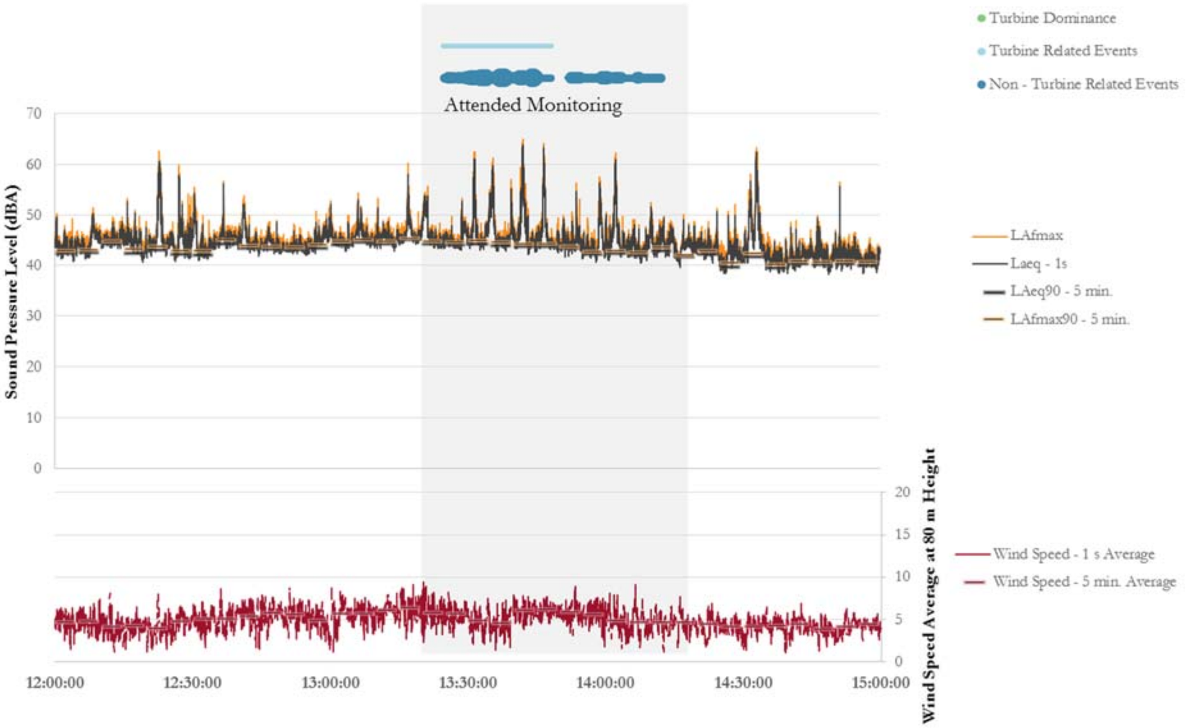

FIGURE 99: EXAMPLE OF ATTENDED MONITORING RESULTS FOR A “BAD” SHUTDOWN

The shutdown, which occurred from 13:50 to 14:10 is not readily apparent in the A-weighted sound levels shown. The turbine sound is never dominant.

CALCULATION OF SOUND METRICS USING ATTENDED MONITORING DATA

Of the 37 times we conducted attended monitoring, 13 were during periods when there was at least one second of turbine sound dominance. Of the five sites, two had no locations during which turbine sound was dominant at any place or time, based on attended listening.

The 13 remaining time periods were then processed to calculate the sound levels for each of the seven methods in the previous section. The results are tabulated in Table 19 and sorted and graphed in Figure 100.[26] Note that one value of 70 dBA that was marked as turbine dominant was removed from the data because, upon further review, it was found to be caused by an unidentified non-turbine related sound event.

Both methods using L_{Smax} show the greatest differences between the turbine-off and turbine-on sound levels and greatest standard deviation of those differences. Both methods using the L_{90} of the $L_{Fmax\ (1\text{-sec})}$ show the least change in sound levels. The three metrics using Leq are in the middle. The L_{90} of the $L_{Fmax\ (1\text{-sec})}$ (Method 2), $L_{eq(5\text{-min})}$, and $L_{eq(15\text{-min})}$ showed the greatest repeatability.

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[26] While some measurements showed that turbine sound resulted in an increase above background by 10 dB or more, none of these locations are subject to the MassDEP sound regulations (i.e., none of the monitoring locations are within privately owned residential properties.)

TABLE 19: COMPARISON OF SHORT-TERM SOUND METRICS WITH TURBINE ON AND OFF

Method 1: $L_{Smax\ (5\text{-}min)}$

	Turbine Dominant	Turbine Off	Difference (dB)
Average	48.1	31.7	16.4
Standard Deviation	6.2	6.6	7.5

Method 2: L_{90} $L_{Fmax(1\text{-}sec)}$

	Turbine Dominant	Turbine Off	Difference (dB)
Average	40.5	31.7	8.7
Standard Deviation	3.6	6.8	5.5

Method 3: $Leq_{(5\text{-}min)}$

	Turbine Dominant	Turbine Off	Difference (dB)
Average	43.0	31.0	12.0
Standard Deviation	3.0	6.5	5.8

Method 4: Adjusted $Leq_{(5\text{-}min)}$

	Turbine Dominant	Turbine Off	Difference (dB)
Average	39.9	28.7	11.2
Standard Deviation	4.6	6.5	7.5

Method 5: Wind Adjusted L_{Smax}

	Turbine Dominant	Turbine Off	Difference (dB)
Average	48.2	31.9	16.3
Standard Deviation	6.2	6.6	6.8

Method 6: Leq of one-minute L_{90} of $L_{Fmax\ (1\text{-}sec)}$

	Turbine Dominant	Turbine Off	Difference (dB)
Average	39.1	31.9	7.2
Standard Deviation	3.4	6.9	6.5

Method 7: $Leq_{(15\ min)}$

	Turbine Dominant	Turbine Off	Difference (dB)
Average	43.2	32.7	10.6
Standard Deviation	2.9	7.9	6.1

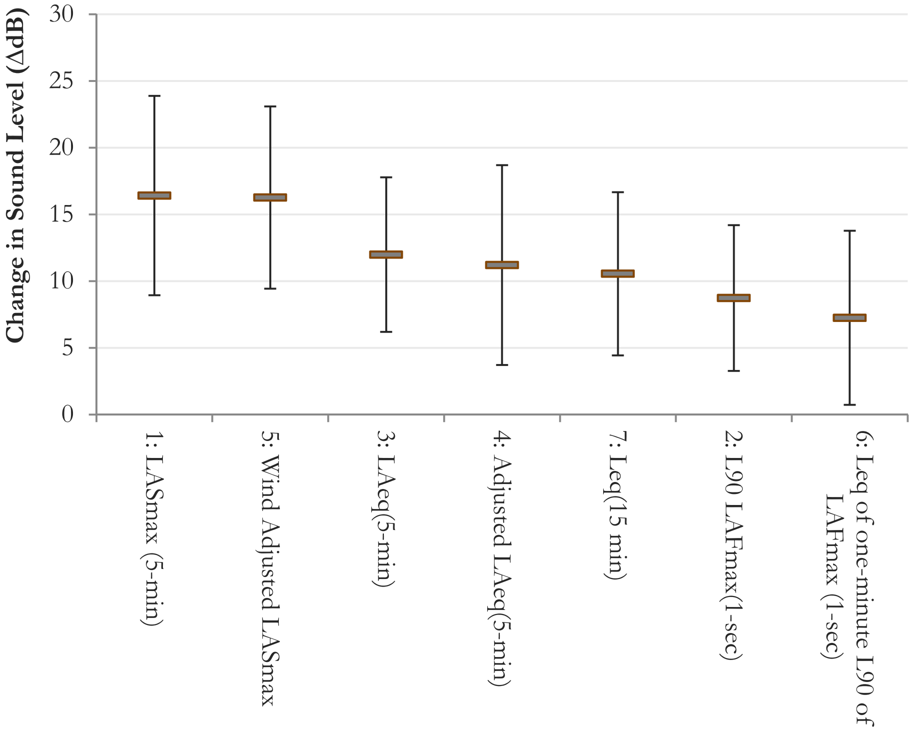

FIGURE 100: CHANGE IN SOUND LEVEL – TURBINE ON TO TURBINE OFF, WITH STANDARD DEVIATION ERROR BARS (DATA FROM TABLE 19)

Table 20 provides summary statistics for the 13 attended monitoring sessions analyzed above. Consistent with the above results, the Method 1 and Method 2 L_{max} criteria showed the greatest percentage of time when the sound difference in sound levels exceeded 10 dB, while the Method 2 and Method 6 L_{90} methods showed the least amount of time. The Leq methods (Methods 3, 4, and 5) were in the middle.

TABLE 20: SUMMARY STATISTICS FOR ATTENDED MONITORING METHODS

These data include only those shutdowns for which turbine sound was dominant at least part of the time

TOP Turbine on/ Turbine off sound levels **Bottom** Percentiles of sound level differences	Method 1: $L_{Smax\ (5\text{-}min)}$	Method 2: L90 $L_{Fmax(1\text{-}sec)}$	Method 3: $Leq_{(5\text{-}min)}$	Method 4: Adjusted $Leq_{(5\text{-}min)}$	Method 5: Wind Adjusted L_{Smax}	Method 6: Leq of 1-min L90 of $L_{Fmax\ (1\text{-}sec)}$	Method 7: $Leq_{(15\ min)}$
<0 dB	0%	2%	0%	3%	2%	14%	0%
0-5 dB	7%	28%	13%	19%	2%	24%	17%
5-10 dB	9%	36%	27%	26%	11%	32%	33%
>10 dB	84%	34%	60%	52%	85%	31%	50%
10th Percentile (dB)	7.7	2.2	3.3	3.1	8.1	-2.2	3.8
50th Percentile (dB)	16.2	7.5	12.3	13.4	16.2	6.9	10.9
90th Percentile (dB)	23.1	16.4	19.5	20.3	23.1	16.4	17.1

11.3 | SOUND METRICS DISCUSSION

As noted above, in defining a sound metric for regulation, we believe that there should be four requirements that ideally should be met.

1) Relevance,
2) Repeatability,
3) Predictability, and
4) Ease of implementation

RELEVANCE

Since the MassDEP would like to use the results of this study in a regulatory setting, a sound metric used in regulation should be related to the Massachusetts Code, which reads, in part:

Definitions (310 CMR 7.00) [27]

Noise is defined as "sound of sufficient intensity and/or duration as to cause a condition of air pollution."

Air pollution means "the presence in the ambient air space of one or more air contaminants or combinations thereof in such concentrations and of such duration as to: (a) cause a nuisance; (b) be injurious, or be on the basis of current information, potentially injurious to human health or animal life, to vegetation, or to property; or (c) unreasonably interfere with the comfortable enjoyment of life and property or the conduct of business."

In reviewing the sound metrics from Section 5.0, both C- and Z- weighted values show the clearest difference in levels between turbine-on and turbine-off periods. However, we do not know of any research that relates the relative difference in C- or Z-weighted sound between turbine-on and turbine-off to any of the requirements in 310 CMR 7.00. Assuming wind turbine sound levels are constant in the frequency range from 0.5 to 4 Hz and decrease by 3 dB per octave beyond that, and that wind turbines become audible/perceptible above 50 Hz (see Sections 5.6 and 8.3), then there is 35 times more sound energy at frequencies of sound that are inaudible than there is in the audible frequency range. As a result the C- and Z-weighted sound levels will not reflect the potential for impact listed in 310 CMR 7.00. That is to say, two sounds may have a very different level using C-weighting, but can sound to the human ear exactly the same - if that difference is due to sound at inaudible frequencies.

However, at levels below the audibility, low-frequency sounds can still have an impact. For example, the standard, ANSI 12.2, "Criteria for evaluating room noise", lists interior sound levels by octave bands from 16

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[27] The Commonwealth of Massachusetts Air Pollution Control Regulations 310 CMR 7.10 : Noise
(1) No person owning, leasing or controlling a source of sound shall willfully, negligently, or through failure to provide necessary equipment, service, or maintenance or to take necessary precautions cause, suffer, allow, or permit unnecessary emissions from said source of sound that may cause noise.
(2) 310 CMR 7.10(1) shall pertain to, but shall not be limited to, prolonged unattended sounding of burglar alarms, construction and demolition equipment which characteristically emit sound but which may be fitted and accommodated with equipment such as enclosures to suppress sound or may be operated in a manner so as to suppress sound, suppressible and preventable industrial and commercial sources of sound, and other man-made sounds that cause noise.
(3) 310 CMR 7.10(1) shall not apply to sounds emitted during and associated with:

1. parades, public gatherings, or sporting events, for which permits have been issued provided that said parades, public gatherings, or sporting events in one city or town do not cause noise in another city or town;
2. emergency police, fire, and ambulance vehicles;
3. police, fire, and civil and national defense activities;
4. domestic equipment such as lawn mowers and power saws between the hours of 7:00 A.M. and 9:00 P.M.

(4) 310 CMR 7.10(1) is subject to the enforcement provisions specified in 310 CMR 7.52.

Definitions (310 CMR 7.00)
Noise is defined as "sound of sufficient intensity and/or duration as to cause a condition of air pollution."

- *Air pollution* means "the presence in the ambient air space of one or more air contaminants or combinations thereof in such concentrations and of such duration as to: (a) cause a nuisance; (b) be injurious, or be on the basis of current information, potentially injurious to human health or animal life, to vegetation, or to property; or (c) unreasonably interfere with the comfortable enjoyment of life and property or the conduct of business."
- *Sound* means the phenomenon of alternative increases and decreases in the pressure of the atmosphere, caused by radiations having a frequency range of from 20 to 20,000 cycles per second, that elicits a physiologic response by the human sense of hearing.

Hz through 63 Hz that can cause "acoustically induced vibrations and rattles."[28] As a result, while protection from excessive low-frequency sound may be desirable, using C- or Z-weighting is not specific enough at the frequencies of interest. Rather, limits for sound levels at specific frequencies ranges or bands would be needed.

An alternative option for a single-number rating of low frequency sound is G-weighting. ISO 7196, which defines the G-weighting, states that 90 dBG "will not normally be significant for human perception." It also states that "some literature on annoyance from infrasound suggests that annoyance may be closely related to the direct perception." That is, if a person can perceive an infrasonic sound, they are also likely to be annoyed by it. As a result, the G-weighted sound level could be relevant in assessing human perception and annoyance of infrasound.

While that is the case, the data from this study show that the mean sound levels in the infrasonic frequencies from the studied wind turbines were more than 30 dB below ISO perceptibility thresholds. They were also below the ANSI S12.2 Table 6 criteria for sound-induced vibrations and rattles in structures.

The A-weighted sound level is the most commonly used metric for human response to sounds at these low and moderate levels typical of wind turbines. It is used by the U.S. Environmental Protection Agency, Federal Highway Administration, Department of Housing and Urban Development, and Federal Aviation Administration, for example, as well as the MassDEP. Studies of human annoyance from wind projects tend to focus on A-weighted sound levels. For these reasons, we have limited our detailed analysis of regulatory metrics to A-weighted sound levels.

REPEATABILITY

In measuring sound, repeatability is important so that other parties can confirm measurements. Repeatability also ensures a greater statistical confidence in the measurement. Greater numbers of samples, for example, should be more likely to converge on the true value. If the metric is based on short-lived outliers, the variability of repeated measurements will be high, and statistical confidence in the measurement results will be relatively low.

The standard deviation of multiple measurements is an indication of repeatability. The lower the standard deviation and the greater the number of samples, the higher is the statistical confidence in the results. For A-weighted sound metrics, the L_{min} and L_{90} sound levels tend to have the lowest standard deviations among repeated operating turbine measurements. This is, in part, due to the influence of intruding background sound. The sound from the turbine establishes a baseline sound level, which is affected by changes in background sound from both natural and manmade sources.

However, background sound is not the only source of variation in the measurement of wind turbine sound. Varying meteorological conditions can cause short-turn increases in amplitude modulation and sound levels. As we observed, for example, wind turbine start-ups in winds that are higher than the normal cut-in speed create short-term increases in sound levels that fall back to sustainable levels soon after.

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[28] The ANSI S12.2 Table 6 interior sound level criteria for moderately perceptible vibration and rattles is 65 dBZ for the 16 Hz and 31.5 Hz octave bands and 70 dBZ for the 63 Hz octave band. The sound levels measured in this study, as shown in Section 5.5 are below these criteria levels.

The attended and unattended L_{max} metrics yield the greatest standard deviations. The L_{max} is, by definition, an outlier. The level defining L_{max} may occur only in single one-second interval during any monitoring period, and it may not be repeatable or may be rarely repeatable. In addition, we found that even with attended monitoring, if it is not done with great care, other sounds may either be mistaken for wind turbine sound or short-term events (not related to wind turbine sound, but that set the level of the L_{max}) are not recorded.

The behavior of the Leq metrics generally falls in between those of the L_{max} and L_{90}/L_{min} metrics. For Leq, the difference between the turbine-on and background sound levels falls between those of the L_{90} and L_{max} metrics. The five-minute Leq has the lowest standard deviation, but it does not correct for background sound. If there exist higher levels of background sound, such as those found in the other 24 shutdowns not included in our analysis, then this metric would not be representative of wind turbine sound. While the adjusted Leq had a higher standard deviation, it does account for differences in background sound between the background L_{90} and background Leq, making it a more representative measure of how wind turbine sound affects the L_{90}. This, however is accounted by using similar metrics, such as the L_{90} of the $L_{Fmax(1\text{-}sec)}$.

Figure 101 illustrates the different behaviors of the five-minute metrics during a period with a clear turbine shutdown and amplitude-modulated turbine sound. The spiky orange line in the background is the 50-ms fast-response sound level. This metric can follow the true amplitude modulation of the sound. The black spiky lines behind that are the one-second Leqs. Various five-minute metrics are shown, including the Leq, L_{90} of one-second L_{Fmax} , L_{90} of one-second Leq, and the L_{90} of the L_F based on 50-millisecond measurements.

This graph is different from the 10-second sample shown in Figure 6, in that the sound level varies more over time. That is, the sound level from the turbine is not constant, but slowly varying. In this case, the five-minute Leq consistently exceeds the L_{90} of the $L_{Fmax\ (1\text{-}sec)}$. The L_{90} of the $L_{Fmax\ (1\text{-}sec)}$ did behave as expected, where it increased relative to the L_{90} of 50-ms samples as amplitude modulation increased just before the shutdown and around 23:45. The L_{90} of the $L_{Fmax\ (1\text{-}sec)}$ was 0.5 dB above the L_{90} of 50-ms samples during shutdown, and increased to 0.8 to 1.8 dB above the L_{90} of 50-ms samples when the turbine was on. The five-minute Leq was, in turn, 0.9 to 2.4 dB above the L_{90} of the $L_{Fmax\ (1\text{-}sec)}$ with the turbine on. The Leq thus responds well to short- and long-duration increases in amplitude modulation.

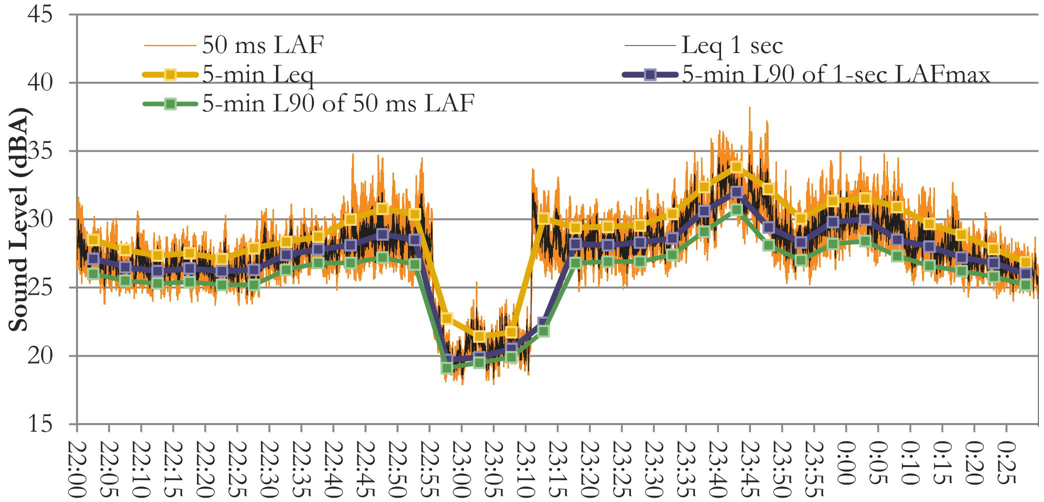

FIGURE 101: SOUND LEVELS AROUND CLEAR TURBINE SHUTDOWN AND VARIOUS METRICS TO SUMMARIZE THE DATA

Averaging time also affects repeatability. Generally, longer averaging times and more observations tend to reduce variability and improve repeatability. For example, if an L_{max} metric is used, the average of 60 one-minute L_{max} measurements results in more consistent outcomes than the average of four L_{max} measurements over a 20-minute period. This is because statistical confidence is gained with a greater number of observations, and the effect of any one outlier is reduced. A greater measurement time increases the likelihood of one observing a reasonable sample of operating modes and meteorological conditions that affect sound level.

PREDICTABILITY

Predictability is important in a sound metric. During the project design phase, it allows both the developer and the community a reasonable expectation of whether a project will comply with the noise standard. If a metric is not predictable, a project might be constructed that exceeds the standard. Alternately, the opposite effect may occur where developers or funding agencies must account for such large margins of error to avoid any possibility of an exceedance, such that projects cannot be permitted that otherwise would have met reasonable criteria.

The MassDEP noise regulation is currently enforced by comparing the A-weighted slow-response L_{90} during a turbine shutdown to a sound level when the turbines are operating. As a result, both the background L_{90} and the turbine sound level should be predictable to the extent possible.

With respect to the background sound level, this requires an estimate of the probability distribution of L_{90} values at every location where the Massachusetts regulations may be enforced and under every meteorological condition. It also requires knowing the contribution of all other background sources, such as transportation sources, insects, flowing water, and human activities, etc. Since compliance measurements can be made at any time, these parameters and their contribution to background levels are required to be known to some degree of accuracy in the course of a year.

With respect to the modeled sound level with the turbines operating, the value of its associated metric should be able to be estimated within a reasonable margin of error.

As shown in Section 5.4 (and Interim Report 2), the background L_{90} is a parameter that is difficult to predict with the precision required for pre-construction assessments. There are cases where tenths of decibels were significant with respect to either predicted or measured compliance. We would argue that the background L_{90} cannot be predicted with such accuracy, and, even if it could, at the time of pre-construction, background sound levels are not within the control of the developer. Further, background levels can change over time, such as through forest management practices, changes in traffic patterns, and stream flows resulting from weather extremes.

EASE OF IMPLEMENTATION

Different sound metrics will require different levels of sophistication with respect to measurement equipment and analysis difficulty. At one end, there may be metrics, such as L_{max}, L_{90}, and Leq, that can be read directly from sound level meters. A-, C-, and Z-weighted metrics, along with fast and slow response, are standard on most Type 1 and Type 2 sound level meters. Sound level meters used for enforcement should also have logging capability, to record relevant metrics. Whether an observer is present or not, we recommend one-second logging or faster intervals to allow for filtering out short-term background events without substantial data loss. Again, whether an observer is present or not, we also recommend recording audio during the compliance period to allow for event identification. We have found that even trained observers miss short-term events unrelated to turbine sound under certain situations.[29]

Among the metrics evaluated in this study, those that do not require significant post-processing include the simple L_{max}, Leq, and L_{90} over any averaging time. The L_{90} of the $L_{Fmax(1\text{-}sec)}$ requires processing of the logged one-second sound levels, but this is a relatively straightforward spreadsheet calculation. Similarly, Method 4, the background-adjusted Leq, is a simple spreadsheet or calculator calculation. The most time-consuming methodology and calculation is Method 5, which requires the recording of wind speed, preferably at 10-meters near the measurement site, and post-processing those data to determine the influence of wind on the measurements.

Any metric that involves infrasound or very low-frequency sound requires special instrumentation. Infrasound measurements are only available on more sophisticated sound level meters and recording equipment. In addition, special care needs to be taken to avoid wind-generated pseudo-sound – a particular problem with measuring sound at very low frequencies.[30]

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[29] In one case, air turbulence over the microphone created pseudo-sound logged by the sound level meter, but was not audible to the observer. This discovered afterwards when reviewing recordings of that event.

[30] For example, at 10 Hz, the wavelength of sound is about 100 feet. A seven-inch wind screen will not be particularly effective in screening air turbulence that can create a 10 Hz signal.

12.0 SUMMARY AND CONCLUSIONS

The Research Study on Wind Turbine Acoustics measured ambient sound levels, turbine operational conditions, and meteorological parameters at five wind turbine sites in Massachusetts and northern New England. The goal of the measurements was to advance our understanding of both the characteristics and foundations of wind turbine sound to help inform the public and improve the wind turbine siting and approvals processes.

At each wind turbine site, we monitored sound and metrological conditions for approximately two weeks. Sound monitoring used continuous logging sound level meters at upwind, downwind, and crosswind locations. In addition, at least one set of daytime and nighttime attended sound monitoring sessions were conducted to identify the characteristics of both turbine and background sound. Infrasound measurements were conducted inside and outside of a residential structure at two locations. Wind turbines were shut down 187 times for 10 to 30 minutes at a time to allow direct comparisons with background sound.

The study focused on providing data and analyses on the following issues:

- How the audible sound levels from wind turbines vary as a function of wind speed, topography, distance from the turbine and azimuth with respect to wind direction,
- How different sound level metrics that could be associated with community noise standards behave when measuring wind turbine and background sounds,
- Whether sounds from wind turbines have a specific spectral shape,
- What factors influence the sound level from wind turbines,
- How accurate are current methods for wind turbine sound modeling,
- How to identify and detect amplitude modulation in the presence of background sound,
- How much amplitude modulation is there and what are its causes,
- How much infrasound is produced by wind turbines,
- To what extent exterior infrasound and low-frequency sound are attenuated by a building,
- How methods to detect tonal sound from wind turbines compare,
- How various methods to evaluate wind turbine sound can be used in developing consistent compliance methodologies and sound standards.

Sound level metrics from unattended monitoring data

Sound level metrics were evaluated for use in regulatory settings by comparing their behavior when turbines are shut down and started up. Metrics that show larger changes during shutdowns would create higher confidence that those changes are due to wind turbine sound. Low variability between turbine-on periods would indicate the given metric is predictable and repeatable, and less influenced by background sound.

Sound level weighting schemes are used to create single-number sound metrics by weighting the frequency spectrum to mimic the human response to loudness. The C-weight was established to represent the human response to high-energy sounds such as blasts. It has a relatively flat response, meaning it does not readily discount low-frequency sound and, to some extent, infrasound. A-weighting was designed to closely match the human response to low- to moderate-level sounds. At these levels, the human ear has more difficulty detecting low-frequency sounds. Z-weighting is the absence of any weighting and is used to determine the total sound energy (both audible and inaudible). For this project, we evaluated A-, C-, and Z-weighted sound levels from wind turbines.

Our evaluation also included the processing of continuous sound level data from unattended monitoring into five-minute statistics, including the maximum and minimum values (L_{max} and L_{min}), equivalent averages (Leq), and percentiles (L_{10}, L_{50}, and L_{90}). Various ways to calculate the statistical levels were also evaluated, including use of one-second Leq's, fast-and slow-response levels (L_F and L_S), and fast- and slow-response maxima (L_{Fmax} and L_{Smax}).

Our key findings include:

1) The sound levels and accompanying operational and meteorological variables around 187 wind turbine shutdowns were first evaluated plotting the data for all locations for one-hour before, during, and one-hour after each shutdown. Of the 187 shutdowns, 43 (23%) had at least one monitoring location show discernible differences in A-weighted levels between the background and turbine-on conditions. Another 23 (12%) showed differences in C- and/or Z-weighted sound levels and small or no differences in the A-weighted sound level (labeled as "fair shutdowns").
2) As a percentage of the monitoring locations times the number of shutdowns, 13% had discernible changes in the A-weighted sound level during the shutdowns. These discernable shutdowns were primarily in the data from the closest locations to the wind turbines – approximately 330 meters downwind for the flat sites and at a majority of the mountainous multi-turbine locations.
3) Some metrics are more influenced by background sound than others. Those that are more influenced will tend to have a higher standard deviation over time and will exhibit a lower difference between turbine-on and turbine-off (background) measurements. From most influenced to least influenced, we found the metrics are the L_{max}, L_{10}, Leq, L_{50}, L_{90}, and L_{min}.
4) The standard way a sound level meter internally calculates an L_{90} is by calculating the 10th percentile of the fast- or slow-response sound level, generally at an internal sampling rate of more than 30 times per second. However, using this approach to measure wind turbine sound will weight the lower levels of the amplitude modulated blade swish sound over a defined period. To better capture the characteristics of amplitude-modulated sound, the L_{Fmax} (or Leq) can be measured every one second, which would capture the levels closer to the crest of each blade pass. The tenth percentile (L_{90}) of these on-second levels could then be calculated.
5) We found that during shutdown events, the C- and Z-weighted sound levels changed the most, indicating that they included a higher proportion of wind turbine sound. Despite this, our conclusion is that these weighting schemes should not be used for regulatory purposes since,
    a. Wind turbines have a larger portion of sound in the inaudible part of the spectra. Between 2% and 3% of the wind turbine sound energy we measured exceeded the audibility thresholds established in ISO standards 389-7 and 7196.
    b. Because of this, about 51% of the energy making up a C-weighted measurement of wind turbine sound is not audible. Thus, it is more difficult to relate the level of C-weighted sound to human perception and annoyance. Two sounds may be perceived as exactly alike, but there could be significant variations in the C-weighted sound level depending on the content of inaudible sound in each.
    c. While a comparison of C- to A-weighted sound levels may be an indication of low-frequency and infrasound content (whether inaudible or audible), a more useful metric is to evaluate directly the 1/3-octave band sound levels for the frequencies of interest.

   d. High C-weighted to A-weighted sound level ratios can also accompany very low sound levels, which are not indicative of problems with the sound content.

Wind turbine sound spectrum, low frequency sound, infrasound, and tonality

This study evaluated spectral sound levels for the purposes of determining whether infrasound was at or close to the ISO 7196 audibility threshold and at what point low-frequency sound tended to become audible. These results can be used to establish whether spectral analysis can help to identify turbine sound and to aid in identifying tonal sound, for example.

Infrasound was measured at an interior and exterior location at two sites. Customized equipment was used to capture infrasound levels around wind turbine shutdowns. Low frequency sound by 1/3-octave band was collected at all locations and all sites at logging intervals of 50 ms to 1 second.

Our key findings include:

1) Some wind turbine sounds have either inaudible or audible mechanical sounds from the nacelles at specific frequencies that can serve as markers. However, these markers did not show up at all turbines.
2) We evaluated methods to detect tonal sound, including those based on 1/1-octave bands, 1/3-octave bands, and narrow bands.
   a. Tonal assessment using full octave bands under the current MassDEP protocol show many measurements were identified as tonal for both turbine and background sounds. Because of the coarseness of the full octave band relative to 1/3-octaves and narrower bands and the constant tonality criteria across all frequencies, we found this approach to be unsuitable for evaluating the tonality of wind turbine sound. It should be noted that this evaluation was made using continuous sound monitoring data, so audible identification of tones and background sound, which are part of the MassDEP protocol, were not included.
   b. Improvements can be made to the current regulatory protocol in assessing tonality to take into account newer ANSI, IEC, and ISO standards, which reveal tonal sensitivity as a function of narrower frequency bands and the frequency of the sound. For example, ANSI 12.9 Part 4 tonality is based on 1/3-octave bands, and reflects the lower sensitivity humans have to low-frequency tones. This standard is the basis for Maine’s tonal sound regulations and recent wind turbine Certificates of Public Good in Vermont, for example. The IEC 61400-11 standard uses a narrowband tonality assessment based on more specific hearing sensitivity parameters.
   c. When 1/3-octave band data collected around discernable shutdowns were evaluated using the ANSI S12.9 Part 4 methodology, there were no periods in which wind turbine sounds were considered tonal.
   d. The IEC 61400-11 narrowband assessment method is an improvement over 1/3-octave band analyses. We did not conduct an analysis using this method since we did not collect narrowband frequency spectra as part of this project. In any event, narrowband tonality methods are not recommended in a screening assessment protocol due to the increased cost of equipment and expertise required. However, this method can used for refined analyses.
3) From the 1/3-octave band data around each wind turbine shutdown, we found that wind turbine sound exceeds the ISO 387-7 audibility curve (median hearing threshold for ontologically healthy

young adults) in the lower range from 50 to 80 Hz to an upper range of approximately 6,300 Hz. This is similar to the findings from other research studies.[31]

4) As frequency decreases, wind turbine sound levels increase about 3 dB per octave down to approximately 4 Hz, below which they level off or decline.
5) Infrasound levels inside and outside two homes in a flat area and mountainous area were collected and analyzed. For the two wind projects measured, infrasound levels were generally in the 55 to 70 dBG range. This is below the ISO 7196 perception limits of 90 to 100 dBG. However, there was a period of about one minute during one particular three-hour acoustical sample where infrasound reached between 90 and 100 dBG. The source was not identified, but it was likely due to human activity around the house. Mean wind turbine infrasound levels were about 30 dB below the ISO 7196 threshold at 20 Hz, and 80 dB below the threshold at 1 Hz.
6) Our comparison of simultaneous interior and exterior infrasound measurements shows that the structures provided less than 6 dB of transmission loss of infrasound below about 12.5 Hz.

Amplitude modulation

Sound level data were collected at selected locations at logging rates of between 50 ms and 125 ms – fast enough to capture the crests and troughs of an amplitude-modulated wind turbine sound. The study team investigated methods to detect amplitude-modulated sound in the presence of background sound, identify the spectral composition of amplitude-modulated sound, and to quantify modulation depth.

1) All wind turbines generated amplitude-modulated sound, but our ability to detect it was largely a function of distance and background sound (signal to noise ratio).
2) Methods were developed by the team to assess the modulation frequency and modulation depth using fast Fourier transform (FFT) spectral analyses of continuously recorded 50 to 125 millisecond sound level data.
    a. The method makes use of both large samples (200 to 400 seconds of data at a time) and small samples (10 seconds of data at a time). Using the large-sample method, amplitude modulation was able to be autonomously detected and quantified even with the presence of masking background sounds.
    b. Spectrograms were created showing the modulation strength by frequency. This made it possible to identify distinct patterns of amplitude modulation over time.
3) This technique of calculating a spectrogram from A-weighted sound levels and one-third octave band levels, developed as part of this study, is very effective in finding the signature of amplitude-modulated wind turbine noise, even when the levels produced by the wind turbines are quite low and comparable to the background noise.
4) Low-frequency modulation was not readily detected on a consistent basis in any of the samples. However, during attended monitoring, one attendant characterized a short period of wind turbine sound as "thumping". Upon investigation of this event, we found amplitude modulation, but not at low frequencies. Instead, the modulation was a mid-frequency sound with a rapid onset and decay time. Our qualitative description of this event is a "churning" sound as opposed to swishing or

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[31] For example, Hideki Tachibanaa, Hiroo Yanob, Akinori Fukushimac and Shinichi Sueokad, "Nationwide field measurements of wind turbine noise in Japan," Noise Control Engr. J. 62 (2), March-April 2014

thumping. This event was just prior to the nacelle changing direction where the yaw error was 20°. This may have been the cause of this event.

5) Amplitude modulation was strongest in the mid-frequencies around 500 Hz.
6) We evaluated 105,907 10-second samples around shutdowns where at least one of the locations shows a discernible change in A-weighted sound levels. Using a definition modulation depth as the difference in sound level from crest to trough, we were able to quantify the likelihood of modulations of different depths. For the flat sites, 91% of the modulation is of 2 dB or less. At the mountain site, 88% is of the modulation is of 2 dB or less. Going higher in modulation depth, for the flat sites, 99.87% of the modulation is of 4.5 dB or less. At the mountain site, 99.996% is of 4.5 dB or less. The lower amplitude modulation at the mountain site may be due to the larger number of turbines there. Multiple turbines tends to cancel out asynchronous modulated sound from any one turbine. Of the 105,907 10-second readings, fewer than 300 had modulation depths of 4 dB or greater.
7) In the absence of any background sound, modulation depth is not a function of distance, since the crests and troughs are attenuated at the same rate. However, our linear regression analysis of factors that could contribute to modulation depth found that distance and sound level have the greatest influence on modulation depth. Thus, masking background sound will significantly influence measured modulation. Taking these factors out, our regression analysis showed that amplitude modulation depth is most strongly correlated with wind speed. Yaw error, vertical wind speed, turbulence intensity, and relative wind direction also influence amplitude modulation depth, although to a lesser degree.
8) While we (and others) have shown that amplitude modulation is a function of various meteorological parameters, predicting the level of amplitude modulation at typical residential distances is not practical or reliable. At the distances of even the closest residences, local and regional background sounds can significantly mask modulation depth.

Wind turbine sound modeling

Sound modeling is used, in part, to assess the likelihood that a project will meet a given regulatory noise standard. There is a desire on behalf of all parties (community, regulators, investors, and project developers) to make these preconstruction estimates as precise and accurate as possible.

Given the large amount of simultaneous meteorological, operational, and sound level data we have collected for this study, we were able to model sound propagation as if the project were in the permitting stage, and then assess how close our estimates came to the actual measured sound levels.

Many variables, such as wind veer and turbulence intensity, are not directly modeled in typical preconstruction wind turbine noise study. With our data, we conducted regression analyses to assess whether these variables have a significant effect on sound levels and thus should be considered during permitting.

We found the following:

1) The regression analysis of A-weighted sound levels versus meteorological and operational parameters showed that sound level at a location is primarily affected by wind speed, RPM, and the number of turbines (which are the drivers for sound power) and distance.

   a. Not surprisingly, the results also showed that the sound speed profile also has an effect on downrange sound levels.[32] A sound speed profile that leads to downward refraction is assumed in the ISO 9613-2 model. The Harmonoise model allows one to specify wind speed, wind direction, and stability class, which are used to calculate specific sound speed profiles.
   b. Other factors were found to have a statistically significant relationship to measured sound level, but their effect was very small. Such factors include turbulence intensity, vertical wind speed, wind direction, standard deviation of wind direction, and wind direction veer.
   c. Based on this analysis, we find that no additional variables need to be considered to make reliable engineering estimates of wind turbine sound levels for pre-construction modeling.
2) Sound data around turbine shutdowns were screened to find periods where the A-weighted sound level clearly changed between turbine-on and turbine-off operating conditions. These periods were then further screened using a published protocol to eliminate periods where background sounds significantly influence the turbine-on sound levels. The goals was to find periods of wind turbine sound that were relatively unaffected by background sound. For each of these five-minute periods, sound level modeling was conducted to assess the predicted sound levels under the specific conditions during that five-minute period.
   a. The most conservative method (predicting higher results than were measured) was the Harmonoise model, followed by the ISO 9613-2 model using hard ground (G=0). The ISO 9613-2 model with mixed ground (G=0.5) with +2 dB added to the results was most precise and accurate at modeling the hourly Leq, as compared to individual five minute periods.
   b. The ISO 9613-2 model using hard ground (G=0) was the most precise modeling at the flat sites, while the Harmonoise model was most precise at modeling the mountainous multi-turbine site. In the latter case, the ISO and Harmonoise models had very similar precision.
   c. The models are most accurate when comparing to the highest wind turbine sound power, but less accurate at lower wind speeds. This may be due, in part, to the increased variance in measured sound levels during any one five minute period.
   d. When comparing the modeling results to various monitored sound metrics, the five-minute L_{90} and hourly Leq tend to be the most precise.
3) The greatest difference between modeled and monitored sound levels tended to occur during the startup of a wind turbine after a manual shutdown. As a result, if turbine shutdowns are used for regulatory testing, data within a few minutes before a shutdown and after a startup should be discarded.
4) The five-minute background L_{90}s were plotted by time and wind speed. While there was good average correlation of L_{90} by wind speed, the scatter was relatively large. This is an indicator that predicting background sound levels by time and place into the future may introduce additional uncertainty into regulatory compliance modeling (where the sound standard is based on the relative difference between the turbine sound level and some background sound level).

There are a great many factors that affect sound generation, background sound levels, and propagation, some of which are outside the control of the developer, or that change over time. As a result, sound

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[32] The sound speed profile is a function of relative wind direction, the change in wind speed by height, and the change in temperature by height.

propagation modeling will always have some amount of inaccuracy. Modeling can be used to assess and minimize the probability of a standards exceedance, but cannot be used to guarantee that an exceedance will not occur. Factors that lower accuracy/predictability include:

a. Modeling shorter time periods,
b. Modeling specific meteorological conditions, and
c. Modeling that includes background sound levels.

Meteorology

As part of this study, continuous meteorological data was collected via LIDAR, a 10-meter meteorological station, wind turbine anemometry at the nacelle, and ground stations near the sound monitors. In addition to using these data to find correlations with sound generation/propagation, they were analyzed to assess whether there was any difference in the behavior of meteorological variables in the flat coastal areas of Massachusetts and the mountainous New England terrain with what is known elsewhere.

We were able to confirm that these sites are not unique in that,

1) Turbulence intensity decreased with increasing wind speed.
2) The variability in turbulence intensity decreased with increasing wind speed.
3) Turbulence intensity was higher at the mountain site compared with the flat site, but only when wind speeds were below 8 m/s (as measured at 80 meters)
4) Wind shear decreases with increasing wind speed.
5) The variability in wind shear decreased with increasing wind speed.[33]
6) At lower wind speeds, the flat sites had higher shear than the mountain site, but the reverse was true at wind speeds above 9 m/s. During some periods, the turbines were upwind of the LIDAR, which may have affected these results.
7) Wind shear was more variable at night than during the day, especially at lower wind speeds. This has been shown by others to be due to the formation of nighttime inversions and/or decoupling of the near ground winds during strong nighttime radiational cooling periods.

While it is well known that the nacelle anemometers are affected by the passage of the upwind blades, we were able to quantify this for the turbines in our study. We found that SCADA-reported wind speeds that are 0.3 to 1.1 m/s lower than the upwind LIDAR measurements (averaged over all wind conditions, including when the LIDAR is downwind of the turbine). We also found that heat from the nacelle tended to increase the exterior temperature recorded by the SCADA system.

A comparison was also made between the LIDAR data and separate estimates of 80-meter wind speeds extrapolated from 10-meter data. We confirmed that this technique has a greater level of error and the results should be used for limited purposes and with caution given the high variability of wind shear, especially at lower wind speeds.

Standards analysis

One of the goals of this study was to evaluate various sound level metrics for use in a regulatory framework. We used the data from the attended short-term and unattended long-term monitoring to evaluate these metrics. For the short-term monitoring, a tablet device was programmed to allow an attendant to record their

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[33] Our analysis used 30-second wind shear calculations.

observations of the sources that contribute to background sound. The attendant recorded their observations on what sounds were present and, for four sites, also recorded the relative loudness of the sounds. In this way, we determined, to the nearest second, when turbine sound was dominant.

Of the 37 attended monitoring sessions conducted for this study, 13 were found to have at least some time in which the wind turbine(s) was (were) dominant. At the remainder of the locations, the wind turbine sound was never dominant, being masked by wind and other sounds.

Seven approaches to regulatory sound metrics were evaluated using this data (Section 11.2). We found that:

1) While the variability was moderate, the background-adjusted Leq appears to be a good method for measuring wind turbine sound relative to background sound. The Leq metric tends to take into account the variation in amplitude modulation over time better than the $L_{Fmax\ (1\text{-}sec)}$.
2) Measurement of background L_{90} shows that it is not readily predictable given the precision required in pre-construction assessments.
3) Metrics using the L_{90}, including the L_{90} of the $L_{Fmax\ (1\text{-}sec)}$ tended to have the lowest difference between the background and wind turbine sound level.
4) Metrics using the Leq had moderate variability during shutdowns relative to the other metrics.
5) A greater number of samples over a longer averaging time increases statistical confidence in the results.

These results can also be considered in the context of the conclusions from the evaluation of the unattended sound monitoring data.

1) The metrics of L_{min} and L_{90} show the greatest change in sound levels between turbine-on and turbine-off, using unattended data. These parameters also show the lowest variability. As a result, these tend to be the most consistent and stable for the purpose of assessing the contribution of wind turbine sound to the overall sound level.
2) Metrics using the L_{max} for wind turbine sound had the greatest difference between background sound and wind turbine sound. Methods used to adjust for increased wind speeds that contributed to the L_{max} had little effect. The L_{max} metrics also had the greatest standard deviation, making them difficult to predict.

In defining the core principles of a regulatory framework, approaches can be considered against the following criteria:

- Relevance – The sound metric should have some relevance to the sound's influence on humans or wildlife; it should not be set arbitrarily.
- Repeatability – the metric should have a relatively low standard deviation among samples taken under similar conditions, such that measurements taken under the same set of conditions yield the same results.
- Predictability – The metric should be able to be predicted (i.e. modeled) with a high level of reliability.
- Ease of implementation – Ideally, the metric should be able to be measured without specialized sound monitoring equipment by a skilled enforcement officer. Some metrics can only be measured or calculated by a trained noise control engineer.

Based on the results in this report, we have identified the following components that could be considered for use in pre- and post-construction sound monitoring procedures.

Preconstruction

- **Fixed background level** - Prediction of the background L_{90} for all locations for all times of the year now and into the future is unreliable and a source of uncertainty If a standard that is relative to background is chosen, consideration could be given to establishing the background sound level at the time of permitting to improve the confidence of all parties in whether the standard can be met. A minimum background level could be established to avoid an overly restrictive standard in rural areas.
- **Preconstruction monitoring** – To establish a fixed background sound level for use as the basis for a relative standard, monitor at representative locations around the project at distances not to exceed the predicted 35 dBA sound contour, for no less than two weeks, logging one-second Leq coincident with met tower or LIDAR wind speed measurements. The applicable L_{90} metric would be the average nighttime L_{90} of the monitoring locations, excluding outliers. The background level would be fixed and not vary with wind speed, but consideration could be made of eliminating periods when wind turbines would not have been in operation.
- **Modeling technique** – Assuming a four-meter measurement height above the ground, the ISO 9613 modelling with hard ground or ISO 9613 modelling with a mixed ground plus 2 dB is approximately equivalent. The sound power level input to the model would be those specified by the manufacturer with no adjustment other than what is explicitly stated above.
- **Measurement height** – Sound level measurements would be made at no less than 1.5 meters above ground to avoid excessive ground effects. To represent two-story homes, use 4 meters.

Metrics

- **A sound metric based on an A-weighted background-adjusted Leq (Method 7)**. For post-construction measurements, the background L_{90} would be compared to the background L_{90} energetically (i.e. logarithmically) added to the turbine-only Leq. The turbine-only Leq is the energetic difference between the turbine-on and background Leq.

$$\Delta L_{Method\ 7} = 10\log_{10}\left(10^{\frac{Leq\ Tdom}{10}} - 10^{\frac{LAeq\ Toff}{10}} + 10^{\frac{L90\ Toff}{10}}\right) - L90_{Toff}$$

  This does not have the lowest standard deviation among the methods, but accounts for changes in background sound between turbine-off and turbine-on, uses an Leq metric which is consistent with IEC 61400-11 manufacturer sound power measurement methodology, can easily be measured by sound level meters without substantial training and within the timeframe for short-term attended measurements, and can be modeled with a reasonable level of precision.
- **Amplitude modulation** – Consider a penalty for amplitude modulation (crest to trough) greater than 5 dB occurring more than 5% of the time, for example. Note this would require monitoring at intervals of 125 ms or faster and extensive post-processing.
- **Tonality** – Consider a penalty for tonal sound using the ANSI S12.9 Part 4 method based on five-minute or longer 1/3-octave band Leqs.
- **Low frequency sound/infrasound** – The results of this study show that wind turbine sound under 50 Hz are below ISO audibility limits. If a low-frequency sound standard is desired, then sound would be measured in the 31.5 Hz and 63 Hz octave bands, with limits based on commonly accepted

standards, such as ANSI S12.2 (interior 65 dBZ at 31.5 Hz and 70 dBZ at 63 Hz), adjusted for outside-to-inside sound transmission loss. Requiring the measurement of infrasound is not recommended, as doing so requires specialized equipment and expertise, and it is unlikely to result in levels above ISO perception limits.

Post-construction sound monitoring

- **Post-construction measurements** – Post-construction measurements would be made with continuous logging of $Leq_{(1\text{-sec})}$. Attendants would note sound events either through direct observations or via sound recordings. Event logging can be done using tablet software such as that developed here, or by other electronic methods for improved convenience and efficiency. Background sound would be filtered out to the extent possible. If low-frequency sound is included in a standard, then a wind screen with a minimum diameter of seven-inches should be used.
- **Long averaging time** - Longer averaging times and/or many iterations of shorter averaging times increase the statistical confidence in the results (compared to fewer and shorter). The total turbine-on monitoring time would be from between 15 minutes to one-hour.
- **Turbine shutdowns** - The turbines would be shut down for a short time (five to 15 minutes) such that the turbine-only sound level can be calculated. Large changes in background sound between the period of the background L_{90} and the turbine-on Leq (more than 1 m/s) would be documented.
- **Variation in wind speed from background to turbine-on** - If wind speed data are available, invalidate or make adjustments for turbine-on measurements that occur when wind speeds change by more than 1 meter per second from the time when the background L_{90} occurred.

Next Steps

This study has resulted in a large quantity of data around wind turbine operations. It is hoped that other researchers can use this data for their own studies. Some suggested topics include:

- Evaluating the characteristic of sound using the remaining data, not just limited to the times around the wind turbine shutdowns
- Quantifying differences between sites
- Evaluating sound level and amplitude modulation changes when one turbine was in the wake of another, and evaluate the effect on wind data when the met tower/LIDAR was downwind of the turbine.

Procedures for requesting use of the data are outlined in the appendix to this report.

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14.0 APPENDIX A: ACCESS TO DATA FROM THIS STUDY

The data for this project resides in a Microsoft SQL Server database. The database (without audio files) is over 200 GB. The database consists of individual tables for:

- SCADA data for each site
- Data from Cesva, Larson Davis, and Norsonic sound level meters (millisecond and one-second)
- Attended monitoring data
- LIDAR data (10-minute and one-second)
- 1-meter meteorological data
- 10-meter meteorological data
- Curtailment times
- X Y locations of equipment, with the acoustic center of the turbines as 0,0.

The start dates of the monitoring are arbitrarily set, but the time of day and date sequences are left intact. All data are time-synchronized.

Data will be made available through written request to RSG. Requests must state the research purpose for which the data will be used. Requests that are deemed to have no legitimate research purpose or are intended to identify and single out a specific site will be denied. Researchers may not distribute the data to other parties and must maintain confidentiality of the site names and locations, if for any reason they are able to discern this from the data.

If requests are approved, the requester must provide a hard drive to RSG. The data are not available online. To cover time and expenses involved in providing data, a fee will be charged for each request. While site names and other metadata will be removed to hide the identity of the sites, the requester will be required to sign a non-disclosure agreement requiring that site and location identifying information not be released, to the extent that it can be ascertained.

Audio files are available for research use. Requests must follow the same format as above. A separate fee will be a charged for these files based on the number of hours of audio to be released, to allow for the screening and removal of personal conversations that may have been inadvertently recorded. Audio files may be in wav or mp3 format, depending on how they were originally recorded.

15.0 APPENDIX B: DATA FOR PERIODS AROUND DISCERNIBLE SHUTDOWNS