Ms. Edwards

Please find below exhibits that may be used in the telephonic testimony to be given by Mr. Hessler on June 6th if my pending Second Motion to Deny and Dismiss does not prevail. I ask Staff Counsel to please provide exhibit copies to Mr. Hessler ahead of time so that he has them in front of him for his telephonic testimony. I also respectfully ask Staff Counsel to provide copies of the attached exhibits to other appropriate parties for purposes of the possible telephonic hearing. I would appreciate it if Staff Counsel will confirm distribution. Additionally I ask that the attached exhibits be marked ahead of time by Staff Counsel so that proper reference to an exhibit may be made. I have written below an exhibit description for each exhibit –unless Staff has other suggestions. I am by email providing Applicant's counsel with copies. This list is not intended as Intervenors' final exhibit list, but rather is provided because of the possible testimony of Mr. Hessler

Thanks much for your cooperation.

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Int. 5

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

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

Prepared Cooperatively By:

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

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

Rand Acoustics, Brunswick, ME
Principal: Robert Rand

Schomer and Associates, Inc., Champaign, IL
Principal: Dr. Paul Schomer

1.0_Introduction

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

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

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

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

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

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

2.0_Testing Objectives

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

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

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

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

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

Figure 2.1: *Aerial view showing sound survey locations*

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

3.0_Investgator Observations

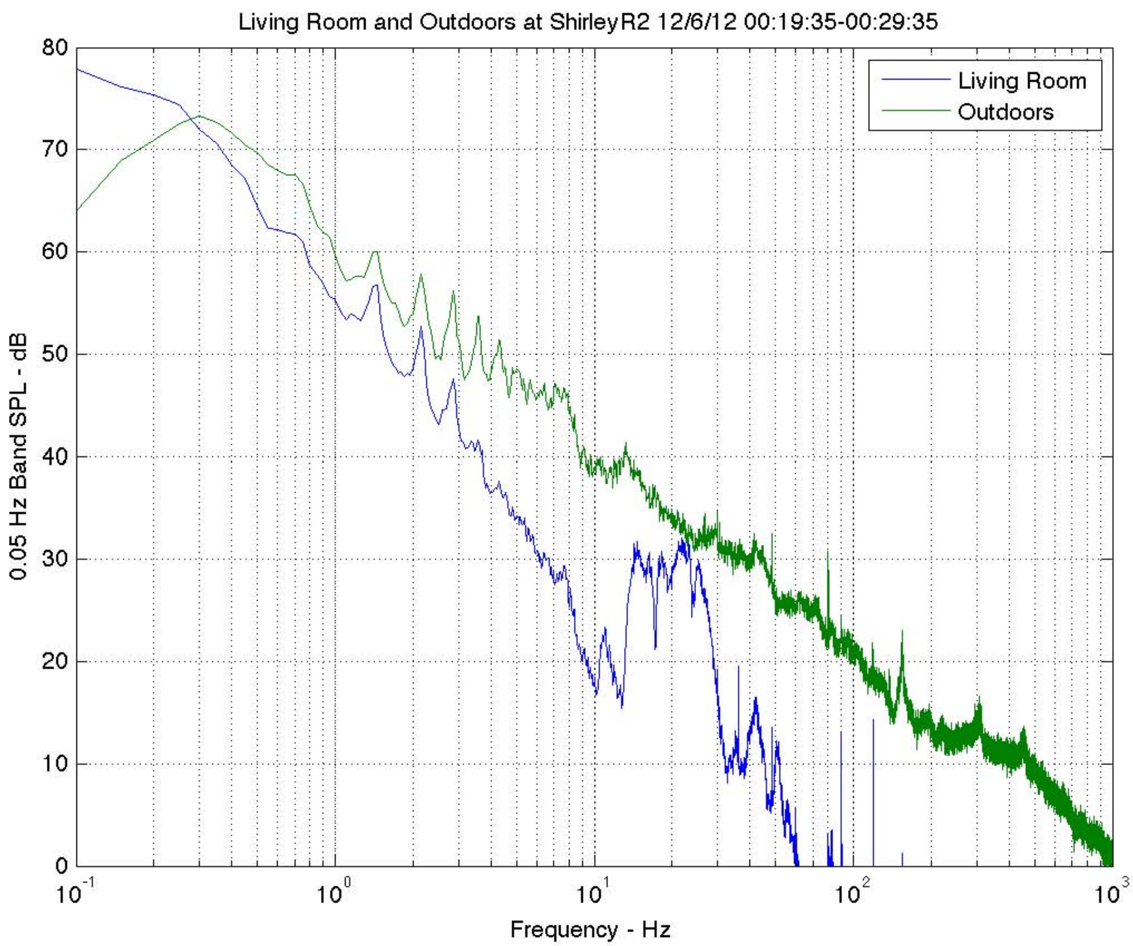
Observations from the five investigators are tabulated below: It should be noted the investigators had a relatively brief exposure compared to 24/7 occupation.

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

4.0_Conclusions

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

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



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

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

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

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

5.0_Recommendations

5.1_General

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

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

5.2_For the Highlands Project

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

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

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

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

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

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

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

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

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

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

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

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

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

5.3_For the Shirley Project

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

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

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

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

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

Bruce Walker

George F. Hessler Jr.

David M. Hessler

Robert Rand

Paul Schomer

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

APPENDIX A
by
CHANNEL ISLANDS ACOUSTICS

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Low Frequency Acoustic Measurements at Shirley Wind Park

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

OVERVIEW

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

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

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

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

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

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

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

TERMINOLOGY

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

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

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

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

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

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

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

MEASUREMENT SYSTEM and DATA ACQUISITION

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

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

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

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

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

Table 3. Summary Test Log

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

DATA ANALYSIS

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

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

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

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

RESULTS EXAMPLES

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

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

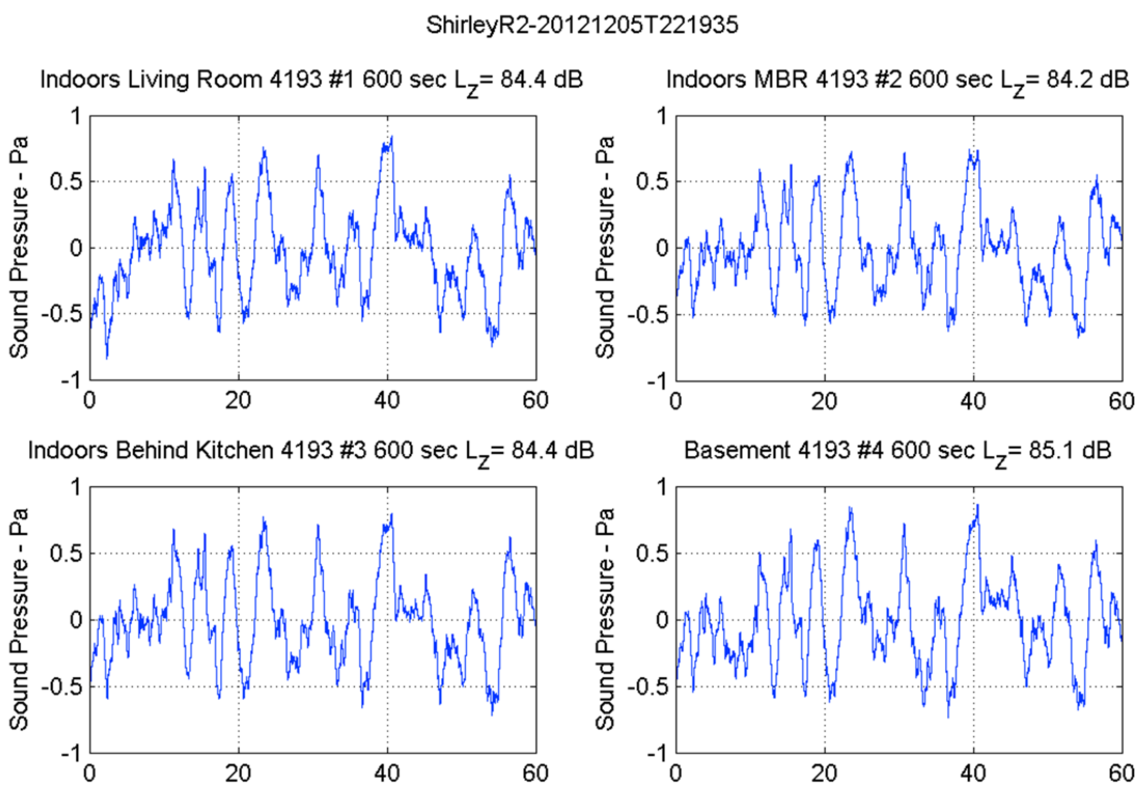

Figure 2. First Minute of Raw Data Collected at R2 On Dec 6 Starting 00:19:35. Note very low frequency fluctuations are nearly equal at four locations.

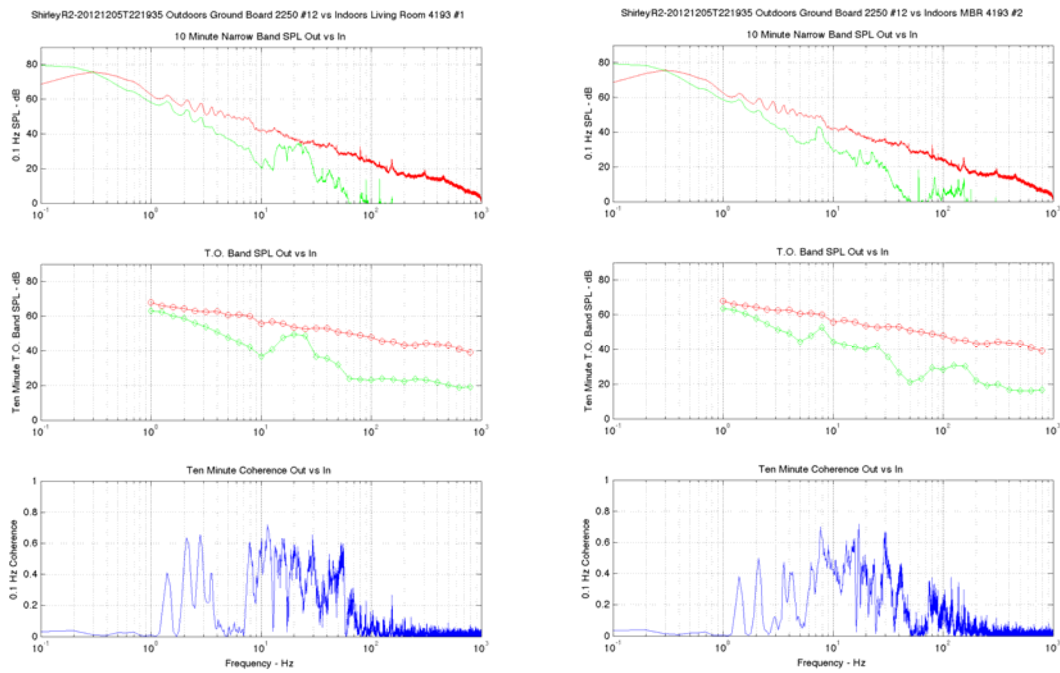

Figure 3. Low Frequency (0.1-1,000 Hz) Spectra and Coherence from Two Rooms in R2 measured 12/6/12 starting 00:19:35 showing differences in detail and well correlated low-order blade-pass harmonics. Red curve is measured outdoors between turbines and home.

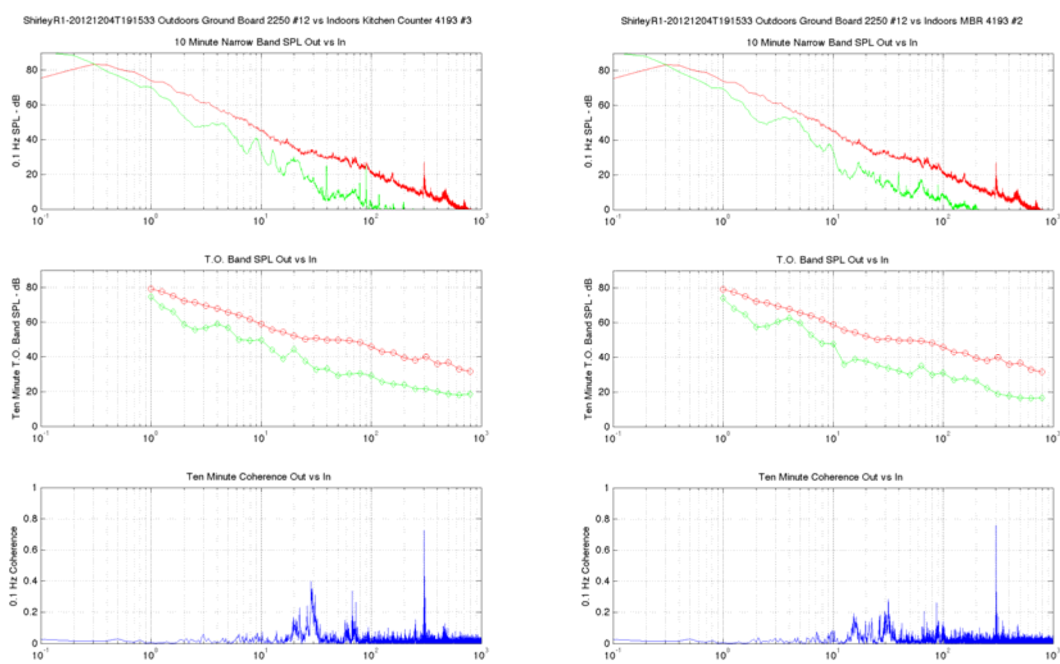

Figure 4. Low Frequency (0.1-1,000 Hz) Spectra and Coherence from Two Rooms in R1 measured 12/4/12 starting 21:15:33 showing differences in detail and poorly correlated low-order blade-pass harmonics. Red curve is measured outdoors between turbines and home.

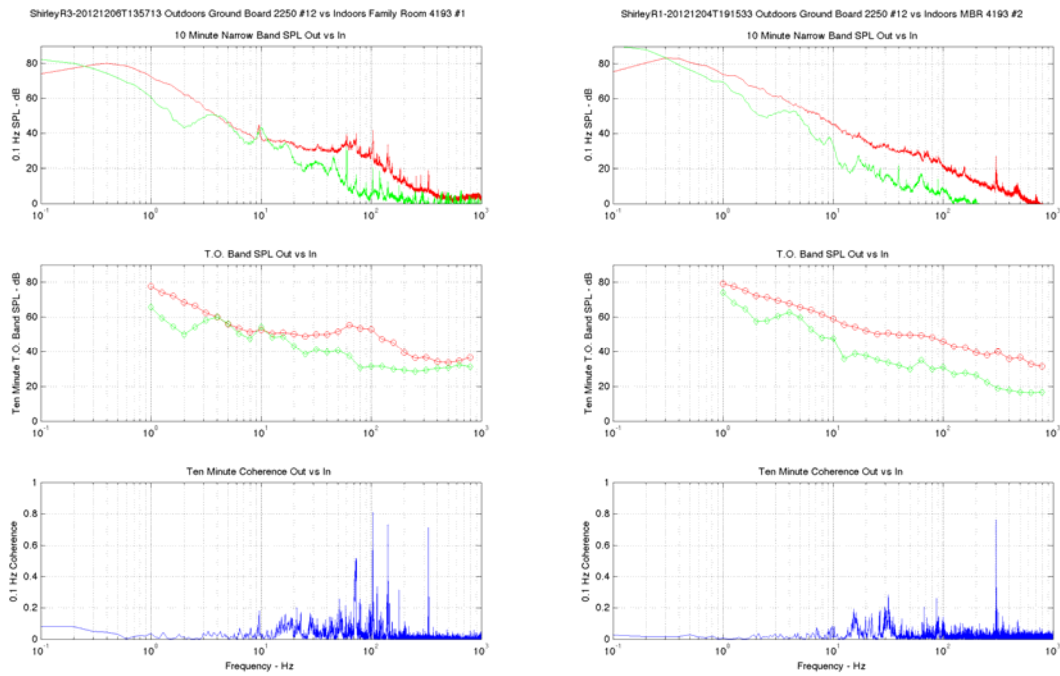

Figure 5. Low Frequency (0.1-1,000 Hz) Spectra and Coherence from Two Rooms in R3 measured 12/6/12 starting 15:57:13 showing differences in detail, poorly correlated low-order blade-pass harmonics and well correlated tones from passing vehicle exhausts. Red curve is measured outdoors between turbines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

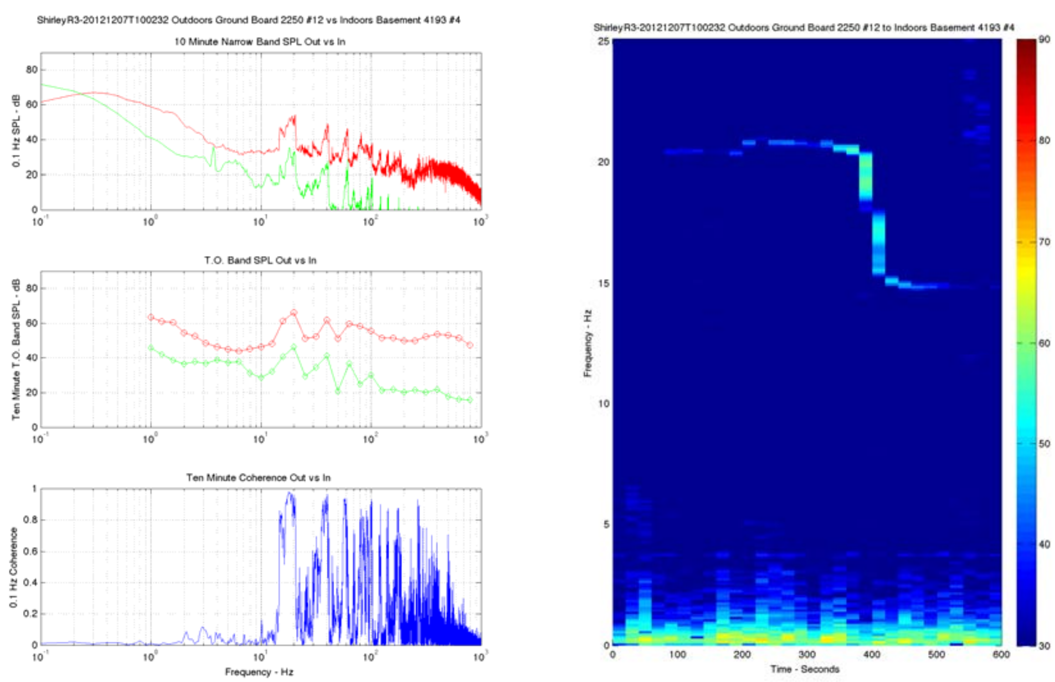

Figure 6. Low Frequency Spectra and Outdoor-Indoor Cross Spectrograph in Basement of R3 with Helicopter flyover. Note Doppler shift of rotor tone from 20.5 Hz on approach to 15 Hz receding. Also note high coherence of the helicopter rotor blade harmonics. Note very low coherence of turbine blade frequencies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

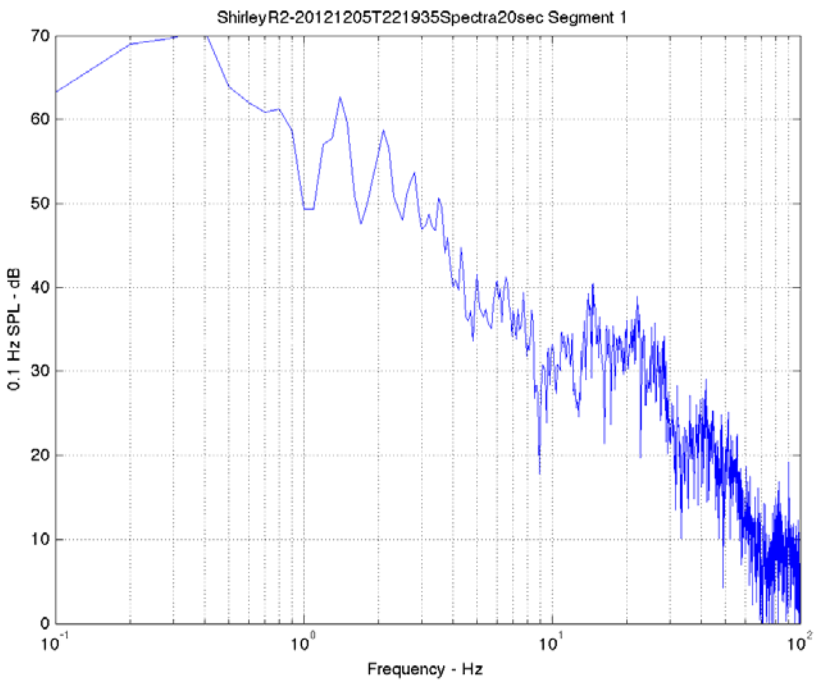

Figure 7. Short (20 sec) duration spectrum with best defined turbine blade harmonics, multiples of 0.7 Hz. Overall SPL of the Blade Pass Signal is 70 dB.

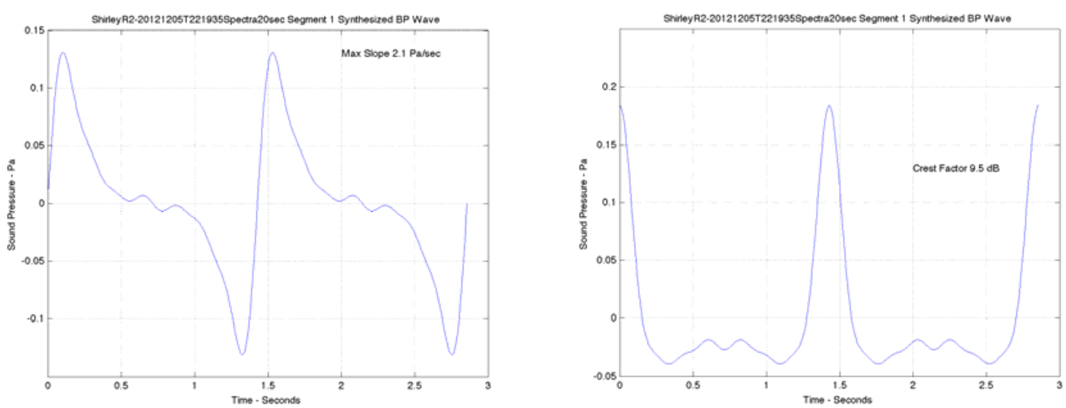

Figure 8. Turbine blade-pass waveforms synthesized from the harmonic series shown in Figure 7. Peak-to-peak SPL of the left-hand, more probable signal is about 82 dB.

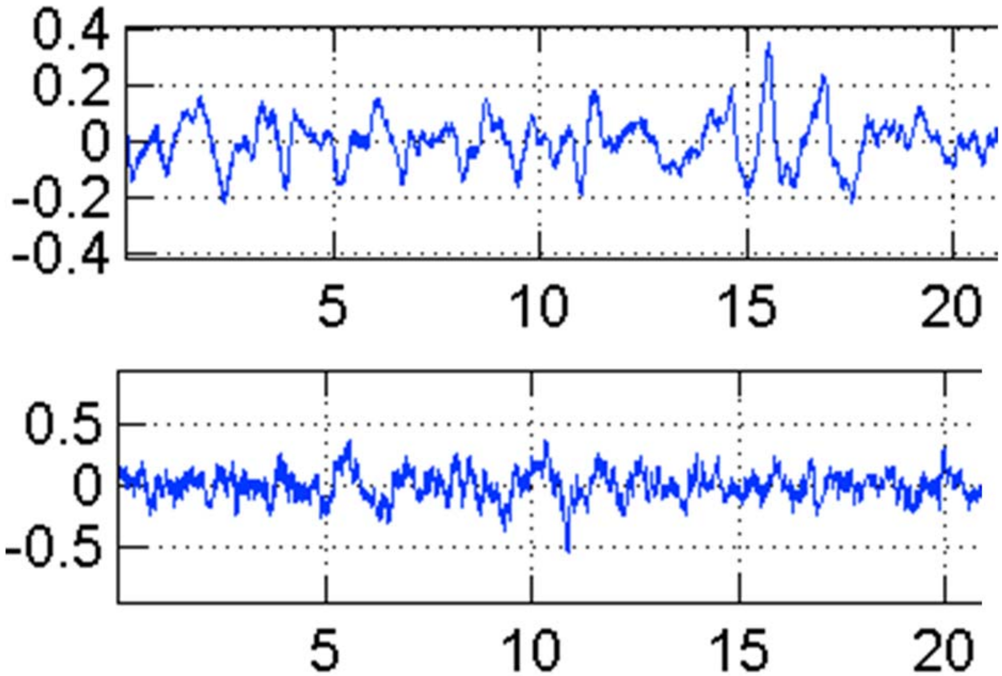

Figure 9. 0.5 Hz Phaseless High-Pass Filtered Waves Indoors (upper) and Outdoors at R2, Corresponding to Spectrum of Figure 7. Note repetitive waves indoors, similar to left-hand synthesized example. Note transient event indoors at 15.5 seconds unrelated to outside noise.

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

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

Shirley	Weight	LA						LC						LZ						LG						L_0.5-100					
ChIA	Channel	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
R1	L1	36.9	32.3	42.4	54.0	43.6		52.5	49.2	53.0	72.0	62.5		93.7	93.5	93.8	111.9	93.4		67.5	67.1	68.3	87.5	72.4		80.7	79.8	80.1	94.9	90.2	
12/4/12	L10	33.7	30.5	34.6	37.7	42.4		50.7	42.9	46.2	60.0	56.2		89.5	89.1	89.4	94.4	86.1		63.9	63.0	64.1	73.0	66.5		74.7	73.7	73.8	82.4	82.1	
20:43:32	L50	33.2	30.1	30.3	32.3	41.5		48.9	39.8	42.7	48.5	53.9		80.6	80.0	80.5	84.7	75.7		58.6	55.7	58.3	62.0	61.6		66.1	65.2	65.2	71.0	70.9	
20:53:32	L90	32.6	29.8	29.6	31.0	41.0		47.2	37.5	40.0	45.5	52.1		67.7	67.0	67.2	71.3	64.5		53.9	49.7	53.2	55.3	57.3		58.5	56.3	56.5	59.7	62.0	
2.2 mps	Leq	33.9	30.2	32.9	76.2	41.7		49.2	41.2	44.4	94.9	55.1		85.0	84.6	85.0	102.6	82.8		60.4	58.9	60.6	89.4	64.2		70.8	69.8	69.9	98.0	79.2	
R1	L1	36.1	32.6	34.8	66.9	49.6		53.2	51.1	50.8	85.3	68.4		104.1	104.0	104.3	112.9	102.6		77.3	77.2	77.5	92.7	79.2		90.7	89.7	90.0	104.1	97.4	
12/4/12	L10	34.0	31.2	30.7	54.8	45.3		51.2	47.2	47.1	76.3	59.8		98.6	98.5	98.8	107.3	94.0		71.9	71.7	72.1	85.7	71.6		84.1	83.3	83.6	96.7	89.6	
21:15:33	L50	33.5	30.3	29.8	44.7	42.2		49.5	42.7	43.5	64.1	55.8		89.8	89.7	90.0	99.0	84.0		64.1	63.3	64.0	77.6	64.7		75.0	74.3	74.4	87.3	78.7	
21:25:33	L90	33.2	29.9	29.4	41.8	41.4		47.9	39.5	40.6	57.6	53.5		76.4	76.2	76.6	86.2	71.5		57.3	54.1	56.2	69.7	59.6		64.8	63.8	63.9	76.7	67.6	
3.2 mps	Leq	35.9	33.7	34.1	54.0	43.5		50.7	46.4	47.0	73.1	58.6		94.6	94.4	94.7	103.2	90.8		68.2	67.9	68.4	82.3	69.2		80.2	79.4	79.6	93.1	86.0	
R1	L1	34.9	32.4	34.4	64.2	51.9		50.4	48.0	48.2	83.5	66.2		100.6	100.4	100.7	111.5	98.4		73.7	73.6	74.0	91.1	75.6		86.4	85.4	85.7	102.0	94.1	
12/4/12	L10	32.5	30.6	30.4	52.6	43.8		48.7	44.5	44.8	75.1	58.8		95.9	95.7	96.0	106.0	91.3		69.1	69.0	69.3	84.4	68.6		80.7	80.0	80.1	94.8	86.4	
21:28:08	L50	32.2	30.1	29.7	43.2	41.7		47.4	41.0	41.5	62.4	54.7		87.7	87.6	87.8	96.7	80.9		61.6	61.2	61.9	75.8	63.0		72.1	71.5	71.5	85.0	75.5	
21:38:08	L90	32.0	29.8	29.0	40.8	41.0		46.2	38.2	38.4	56.4	52.6		74.1	74.1	74.2	83.6	68.6		53.8	52.3	54.5	67.8	58.3		61.5	61.1	60.8	73.8	64.5	
2.8 mps	Leq	32.7	30.3	30.0	51.9	43.2		47.6	42.0	42.4	71.6	57.1		91.6	91.4	91.7	101.7	87.6		65.0	64.8	65.3	80.8	66.2		76.7	75.9	76.0	91.1	82.8	
R1	L1	36.5	36.8	47.5	56.9	44.4		56.9	57.5	63.4	72.7	59.9		96.6	96.2	96.4	92.9	87.4		71.3	71.4	76.8	73.9	68.8		83.9	83.0	83.4	76.0	82.5	
12/5/12	L10	31.9	31.2	39.1	38.7	41.0		48.4	45.8	50.2	60.9	57.8		90.5	90.1	90.5	85.0	78.9		65.2	64.8	67.0	70.2	66.2		76.8	76.0	76.3	67.5	71.7	
12:30:22	L50	31.3	30.1	30.8	37.4	40.4		46.0	41.5	44.7	58.6	55.8		79.8	79.3	80.1	75.5	68.2		57.8	56.4	60.2	66.5	62.2		65.5	64.7	64.8	64.1	63.0	
12:40:22	L90	31.0	29.7	29.3	36.7	40.0		44.2	38.9	40.9	56.3	53.7		67.2	65.8	66.2	65.8	60.9		52.8	50.6	55.2	62.3	57.8		55.6	54.8	55.6	61.1	59.0	
1.2 mps	Leq	32.1	31.0	37.0	53.4	40.8		47.6	45.8	51.0	70.0	56.1		86.1	85.8	86.2	81.8	75.9		61.7	61.5	65.8	69.4	63.2		73.2	72.3	72.6	71.5	70.4	
R1	L1	46.2	30.8	35.0	41.3	42.1		56.0	45.3	49.1	63.0	60.2		83.5	82.6	83.6	89.6	89.9		66.6	58.2	63.0	73.1	69.6		72.6	69.2	69.4	72.1	84.4	
12/5/12	L10	37.3	30.2	30.7	39.7	41.0		53.5	43.1	46.6	61.3	58.4		79.4	78.2	78.7	81.9	82.9		60.6	55.5	60.3	70.6	67.0		64.7	63.0	62.8	67.9	76.5	
13:01:21	L50	36.3	29.9	29.6	38.7	40.6		52.3	40.9	43.4	59.1	56.5		71.2	69.8	69.9	73.8	72.4		56.6	51.8	56.3	66.8	63.0		59.2	56.4	56.3	64.9	66.4	
13:11:21	L90	35.9	29.7	29.2	38.0	40.2		51.3	38.7	40.5	56.9	54.4		59.8	57.4	57.9	65.3	62.7		52.1	47.7	51.7	62.5	58.5		55.1	49.9	51.1	62.0	60.7	
1.4 mps	Leq	40.3	30.0	30.4	39.0	40.7		53.4	41.3	44.2	59.5	56.7		75.0	73.9	74.4	78.8	79.1		59.4	52.7	57.3	67.7	64.0		62.8	59.7	59.8	65.9	73.2	
R1	L1	42.0	44.9	55.5	47.3	58.3		59.4	58.9	64.6	63.9	65.6		100.7	99.0	99.2	88.8	88.2		76.2	73.0	76.0	72.7	68.8		89.8	87.0	87.4	74.4	82.0	
12/5/12	L10	39.9	33.0	41.0	41.0	42.5		56.4	49.1	52.0	61.5	59.2		91.2	90.1	91.5	83.7	79.3		65.8	64.7	67.5	70.3	66.6		78.7	77.3	77.3	69.0	72.6	
13:21:10	L50	33.1	30.0	29.6	38.4	40.3		49.5	44.6	45.9	59.1	56.3		80.1	79.8	81.4	75.0	65.7		57.5	56.7	59.7	67.0	62.5		66.6	65.7	65.8	65.2	62.7	
13:31:10	L90	32.0	29.7	29.1	37.4	31.3		46.4	40.1	41.9	56.8	30.5		65.7	65.9	66.7	66.0	52.6		52.0	51.3	54.5	63.1	25.9		56.6	54.9	55.4	62.2	14.9	
1.5 mps	Leq	54.5	34.3	43.4	39.7	67.1		66.7	48.6	53.1	59.6	79.8		89.0	87.0	87.8	79.6	84.3		74.4	62.3	66.5	67.8	86.8		78.9	75.1	75.4	66.7	83.3	
R2	L1	32.3	31.1	28.9	31.0	49.7		52.1	47.0	46.3	45.1	62.1		92.0	91.1	91.2	91.8	91.5		66.8	64.7	64.7	65.0	72.2							
12/5/12	L10	30.1	30.6	28.7	30.4	48.5		49.5	44.6	43.6	42.6	60.3		87.7	87.0	87.1	87.7	83.2		64.1	61.2	61.5	61.3	69.4							
22:46:57	L50	29.7	30.3	28.5	30.1	47.2		45.7	41.9	39.8	39.6	58.4		79.2	78.8	78.8	79.6	74.5		60.0	56.2	56.8	55.0	65.7							
22:56:57	L90	29.5	30.0	28.3	29.8	45.9		41.5	39.4	36.0	37.4	56.6		65.6	64.6	64.9	65.4	66.7		55.2	51.6	51.7	49.0	61.6							
	Leq	34.0	30.3	28.5	30.2	47.3		48.5	42.5	40.8	40.4	58.7		83.2	82.6	82.6	83.3	80.2		61.4	57.9	58.2	57.4	66.6							
R2	L1	45.3	31.7	35.6	38.3	54.9		63.2	53.9	51.5	61.0	64.7		102.2	101.6	101.0	100.7	92.4		77.8	75.3	74.7	77.0	73.9		90.8	91.2	90.2	89.7	86.9	
12/5/12	L10	37.0	30.9	30.3	32.2	50.4		53.1	46.7	46.2	48.5	62.3		91.4	91.0	91.1	92.0	85.2		67.7	64.9	65.2	66.4	71.2		77.1	76.9	77.3	78.0	79.6	
23:24:20	L50	30.3	30.5	28.6	30.4	48.8		48.3	43.7	42.1	42.4	60.2		82.4	82.1	82.4	83.3	76.5		62.6	58.9	59.5	59.1	67.5		68.5	68.0	68.8	69.5	72.8	
23:34:20	L90	29.7	30.1	28.3	30.1	47.5		44.2	41.2	38.0	39.3	58.3		69.0	68.6	68.9	70.2	68.7		57.7	53.8	54.0	52.3	63.4		59.7	58.4	59.6	60.0	66.8	
	Leq	34.9	30.5	29.4	31.6	58.0		54.3	45.3	44.9	51.5	62.5		89.5	89.2	88.8	89.2	81.8		68.0	63.3	63.5	66.0	68.4		78.6	78.7	77.8	77.5	76.7	
R2	L1	38.8	31.3	31.0	36.8	52.1		55.6	49.4	51.8	53.7	63.0		93.0	93.0	93.1	93.9	90.1		69.1	66.7	68.1	68.0	72.7		80.5	80.6	81.1	81.5	85.0	
12/5/12	L10	32.5	30.7	28.9	31.2	49.2		51.1	45.4	44.8	46.0	61.0		89.0	88.9	89.1	89.7	83.7		65.5	62.9	63.5	63.7	69.9		75.7	75.7	76.2	76.5	78.5	
23:36:11	L50	30.0	30.3	28.5	30.2	47.8		47.0	42.6	40.7	41.5	59.0		81.2	80.9	81.3	81.9	74.7		61.3	57.6	58.1	57.5	66.4		67.7	67.7	68.1	68.5	71.6	
23:46:11	L90	29.6	30.0	28.3	29.9	46.6		42.9	40.1	36.8	38.6	57.2		67.7	67.7	68.1	68.4	67.3		56.6	52.8	52.9	51.3	62.1		59.1	58.3	58.7	59.0	65.5	
2.3 mps	Leq	31.4	30.5	28.8	31.1	48.5		48.6	43.5	43.6	44.5	59.4		84.7	84.5	84.7	85.4	80.0		62.7	59.6	60.6	60.2	67.2		71.6	71.6	72.0	72.5	75.1	
R2	L1	37.5	31.2	30.7	35.4	50.6		53.8	48.6	47.7	49.7	63.3		93.1	92.8	93.1	93.9	93.2		67.9	66.4	66.7	67.3	73.4		79.7	79.7	80.1	80.4	87.0	
12/6/12	L10	32.7	30.7	29.0	31.0	49.3		50.9	46.0	45.0	44.9	61.7		88.9	88.7	88.9	89.6	86.2		65.1	62.9	63.1	63.1	70.8		75.3	75.4	75.7	76.0	80.1	
0:19:35	L50	30.1	30.3	28.6	30.0	47.8		47.1	43.2	41.3	41.5	59.8		80.3	80.1	80.2	81.0	76.7		61.3	57.8	58.3	56.9	67.2		67.9	67.9	68.3	68.6	72.7	
0:29:35	L90	29.7	30.0	28.3	29.8	46.5		43.3	40.5	37.4	38.7	57.9		66.6	66.3	66.6	66.9	68.6		56.7	53.1	53.2	51.2	63.2		59.2	58.8	58.9	59.1	66.6	
3.0 mps	Leq	31.6	30.4	29.0	30.8	48.0		48.4	43.8	42.4	43.0	60.0		84.4	84.2	84.4	85.1	82.4		62.3	59.5	59.9	59.5	68.0		71.2	71.3	71.6	71.9	76.8	
R2	L1	31.8	31.7	41.6	37.9	52.1		57.3	49.9	49.7	52.6	64.1		103.8	98.2	98.5	99.2	95.6		77.4	71.6	71.8	72.7	74.2		91.7	86.2	86.0	86.4	90.0	
12/6/12	L10	30.3	31.0	35.7	31.3	50.1		52.9	46.8	46.7	45.5	62.3		98.4	93.7	93.7	94.6	88.7		72.1	67.2	67.2	68.0	71.4		84.0	79.4	79.4	79.9	82.6	
1:17:54	L50	29.9	30.5	28.9	30.3	48.5		49.1	43.9	43.0	41.8	60.1		89.6	84.7	84.6	85.4	79.0		65.4	60.3	60.6	59.7	67.6		75.6	70.6	70.6	71.2	74.3	
1:27:54	L90	29.6	30.1	28.4	30.0	47.1		45.4	41.2	38.8	39.0	58.2		76.6	71.1	71.0	71.1	69.9		58.9	54.7	54.5	52.2	63.4		67.1	60.6	60.6	60.6	67.6	
3.2 mps	Leq	32.7	33.3	34.4	33.4	48.7		50.9	46.4	45.8	45.7	60.5		94.3	89.2	89.2	90.0	84.9		68.6	63.3	63.5	63.7	68.5		80.8	75.8	75.8	76.2	79.2	
R2	L1	39.7	31.4	32.3	40.3	51.8		56.4	49.2	48.8	57.7	64.2		96.1	95.7	96.1	96.6	97.3		70.4	69.1	69.2	71.2	74.7		83.5	83.7	84.1	84.5	91.9	
12/6/12	L10	32.8	31.0	28.9	31.3	50.7		51.7	47.0	45.5	47.2	62.6		91.2	91.2	91.4	92.1	89.6		67.0	65.0	65.1	66.2	71.6		78.6	78.6	79.0	79.5	83.6	
2:14:13	L50	30.1	30.6	28.5	30.1	49.3		47.8	44.3	41.5	42.0	60.7		83.7	83.6	83.8	84.6	79.7		62.6	59.7	59.8	59.7	67.7		70.9	71.1	71.2	71.7	74.9	
2:24:13	L90	29.8	30.2	28.3	29.8	48.0		43.8	41.6	37.6	38.9	59.0		70.5	70.7	70.4	70.8	70.4		57.7	54.7	54.0	52.7	63.6		61.4	61.0	61.2	61.7	68.0	
3.3 mps	Leq	32.0	30.7	28.9	34.8	49.4		49.3	44.9	42.7	46.9	61.0		87.2	87.1	87.2	88.0	86.2		63.9	61.8	61.9	62.8	68.8		74.7	74.9	75.1	75.5	80.6	
R2	L1	54.9	32.0	44.5	45.6	51.0		76.5	58.2	60.4	78.7	63.2		92.6	91.2	92.4	92.3	89.2		87.9	71.4	74.6	90.5	67.8		87.0	84.1	84.6	87.3	85.7	
12/6/12	L10	44.5	30.4	35.8	35.5	45.8		60.7	45.9	50.2	60.3	57.9		86.0	84.4	84.8	85.3	82.3		71.4	61.2	64.1	72.5	64.3		75.4	72.2	72.9	75.0	77.8	
14:06:21	L50	33.9	29.9	28.9	30.3	42.9		47.0	39.6	40.4	43.8	54.6		77.4	74.8	75.5	76.3	72.1		59.6	53.5	55.5	57.3	60.5		65.7	64.0	64.3	65.6	68.2	
14:16:21	L90	29.4	29.7	28.3	29.9	41.3		40.7	36.7	35.2	37.1	52.7		64.6	61.3	62.5	63.9	62.5		53.8	48.1	49.5	49.3	56.4		56.3	54.1	54.9	55.9	60.4	
2.1 mps	Leq	45.0	30.2	35.3	42.2	47.4		63.1	46.4	50.1	64.5	57.0		83.1	81.8	82.2	82.5	78.7		74.7	60.4	63.7	76.7	62.0		76.2	73.0	74.1	75.0	74.7	
R2	L1	43.5	35.0	35.6	42.8	66.1		66.4	51.7	51.3	69.3	72.2		95.8	95.6	95.2	95.8	95.6		78.6	69.0	69.4	81.9	71.4		81.5	81.0	80.5	81.2	91.0	
12/6/12	L10	36.7	30.8	29.9	35.1	49.5		55.2	44.2	44.7	56.2	59.6		90.0	89.7	89.5	90.1	87.5		68.5	63.6	63.9	69.9	66.5		75.2	73.7	73.9	75.3	81.7	
14:25:47	L50	31.8	30.2	28.7	30.4	46.1		47.5	40.7	40.3	46.2	56.7		81.8	81.5	81.3	82.2	76.9		62.1	56.9	57.9	61.4	62.7		67.9	65.6	66.0	68.0	71.0	
14:35:47	L90	30.1	29.9	28.3	29.9	44.2		42.6	38.1	36.9	40.6	54.9		68.7	67.3	67.3	69.1	66.2		56.7	50.8	51.8	54.7	58.5		59.2	56.1	56.7	59.0	62.7	
1.7 mps	Leq	34.8	30.6	29.5	33.4	53.0		55.0	42.6	42.7	56.5	60.4		86.2	85.9	85.7	86.4	84.2		67.4	60.1	60.6	69.5	64.1		71.7	70.3	70.3	71.7	79.0	
R3	L1	46.6	37.9	41.7		51.8		58.1	58.3	59.0		69.7		98.3	94.9	95.6		98.5		72.3	68.3	73.2		72.5		80.2	81.8	80.9		94.5	
12/6/12	L10	37.4	33.9	34.9		48.6		51.4	52.7	50.9		64.4		90.3	89.7	90.5		91.9		65.9	63.6	65.8		68.1		73.8	74.1	74.0		86.9	
15:57:13	L50	31.2	31.9	30.5		43.9		46.0	48.0	45.5		57.3		81.1	80.6	82.1		82.7		59.7	57.6	59.6		63.7		65.7	65.6	65.9		77.4	
16:07:13	L90	30.1	31.0	29.3		40.1		42.3	45.4	42.0		53.9		67.2	66.7	67.9		71.0		53.8	52.4	53.7		59.3		56.6	56.7	56.3		67.2	
2.8 mps	Leq	40.7	32.6	35.6		45.6		49.3	50.0	49.2		60.7		86.8	86.0	86.8		88.1		63.0	60.5	63.3		65.2		73.2	74.2	73.5		83.5	
R3	L1	47.6	37.0	54.3		50.4		60.5	55.6	64.3		69.4		104.4	104.5	104.4		102.6		80.2	78.2	80.9		80.5		93.6	94.0	92.9		98.7	
12/6/12	L10	39.7	33.1	37.5		47.8		51.1	51.3	50.9		62.5		91.3	91.1	91.4		95.1		66.8	64.9	67.3		70.4		73.2	72.7	73.4		90.9	
16:28:57	L50	32.3	31.5	29.7		44.0		44.2	47.0	43.4		56.7		81.8	81.6	81.9		85.1		58.5	57.5	58.4		63.2		64.1	63.9	64.3		80.8	
16:38:57	L90	30.3	30.8	28.8		40.0		40.5	44.3	40.3		53.0		67.8	67.3	68.2		72.8		52.3	51.4	52.3		58.3		54.5	54.6	54.2		69.0	
2.4 mps	Leq	37.0	32.2	42.1		44.9		54.7	49.8	55.6		59.9		92.1	92.1	92.2		91.7		70.1	66.0	70.5		68.8		80.4	81.1	80.3		87.8	
R3	L1	48.8	34.9	44.4		45.0	51.9	62.7	57.6	60.6		68.1	67.6	98.3	95.3	95.3		85.3	69.9	76.0	69.4	73.1		70.1	72.7	86.8	86.4	85.9		81.1	68.3
12/7/12	L10	38.3	31.8	33.6		40.6	36.6	53.5	50.1	49.8		59.8	52.1	91.8	79.6	80.2		79.0	55.0	68.1	58.7	62.4		65.2	57.2	69.1	65.2	67.9		73.9	53.1
11:20:24	L50	30.9	30.2	29.1		38.0	18.8	43.8	44.7	43.9		53.6	37.3	81.9	70.7	71.3		70.3	41.4	60.3	54.1	56.3		60.9	45.1	58.2	56.4	57.6		64.5	40.5
11:30:24	L90	29.7	29.8	28.6		37.2	15.3	39.6	41.9	40.3		51.2	29.8	66.5	58.2	59.6		60.6	34.1	53.1	49.4	51.1		56.2	37.3	50.7	49.8	50.5		58.1	33.4
1.1 mps	Leq	37.6	30.8	33.6		39.0	41.5	51.7	47.4	49.4		57.4	62.0	87.9	82.1	81.9		75.2	63.7	66.1	57.7	62.3		62.5	62.2	75.6	76.3	75.3		70.4	63.1
R3	L1	36.4	33.9			44.9	37.3	53.7	53.8			65.0	50.4	92.3	80.3			84.7	72.7	67.0	59.4			70.2	64.5	65.0	64.8			80.3	64.6
12/7/12	L10	30.8	31.2			40.1	36.2	45.8	46.6			57.2	47.3	85.9	75.8			77.6	67.5	62.3	56.5			65.1	61.0	60.0	59.5			71.9	59.8
11:46:16	L50	30.0	30.1			37.5	36.0	40.9	43.0			52.5	43.9	73.5	67.8			67.9	59.4	54.2	52.3			60.7	56.3	53.3	52.4			62.4	54.0
11:56:16	L90	29.7	29.8			36.9	35.7	37.8	40.4			49.9	40.9	59.9	55.2			59.2	51.8	49.0	47.6			55.9	50.7	47.7	47.5			56.9	49.0
0.9 mps	Leq	31.4	30.5			38.6	36.0	44.0	44.8			55.0	44.8	81.5	71.6			74.0	63.8	58.1	53.4			62.3	57.8	56.3	55.7			69.0	56.4
R3	L1	36.7	46.8		35.7	71.0	44.1	63.8	74.0	38.7	57.7	81.1	72.7	87.5	83.3		83.9	85.8	79.4	76.8	76.1		69.4	90.4	87.6	69.2	75.8		65.7	84.3	79.1
12/7/12	L10	33.0	37.4		30.6	50.8	37.8	55.0	62.1	38.3	45.9	68.8	59.0	81.0	78.7		79.6	80.1	71.6	62.9	67.3		56.8	77.0	69.5	62.6	66.4		60.4	76.1	65.1
12:02:32	L50	30.1	30.5		29.4	38.2	36.1	43.5	48.2	37.9	35.5	55.5	47.4	73.1	70.9		71.6	70.4	61.9	55.5	56.9		48.7	64.6	59.8	54.9	55.9		52.2	66.1	56.3
12:12:32	L90	29.8	29.9		29.1	36.9	35.8	39.1	41.8	37.4	33.1	50.3	42.2	59.5	59.0		57.4	60.7	54.0	50.0	50.5		41.8	58.0	52.9	48.7	49.6		43.9	58.7	50.7
1.1 mps	Leq	31.2	35.3		30.1	56.5	37.2	52.3	60.2	37.9	44.6	67.4	60.0	77.4	74.4		75.2	76.0	68.0	63.5	65.1		56.4	75.9	73.4	59.2	63.2		56.3	72.7	65.8

CONCLUDING REMARKS

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

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

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

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

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

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

APPENDIX B
by
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Appendix B to Report Number 122412-1

1. Introduction

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

2. Calibration

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

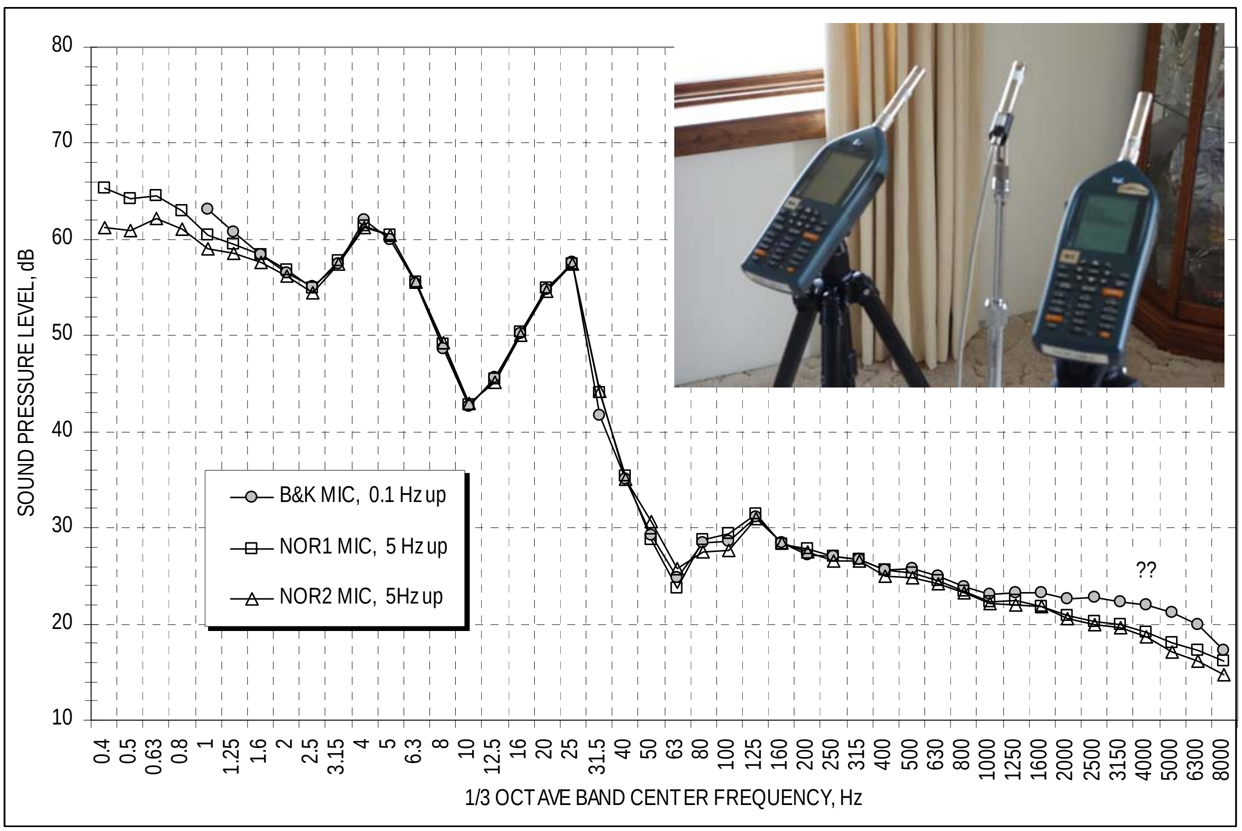

Figure 2.1 *Instrument Calibration Check Relative to High Performance ChIA System*

3. Data Logger

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

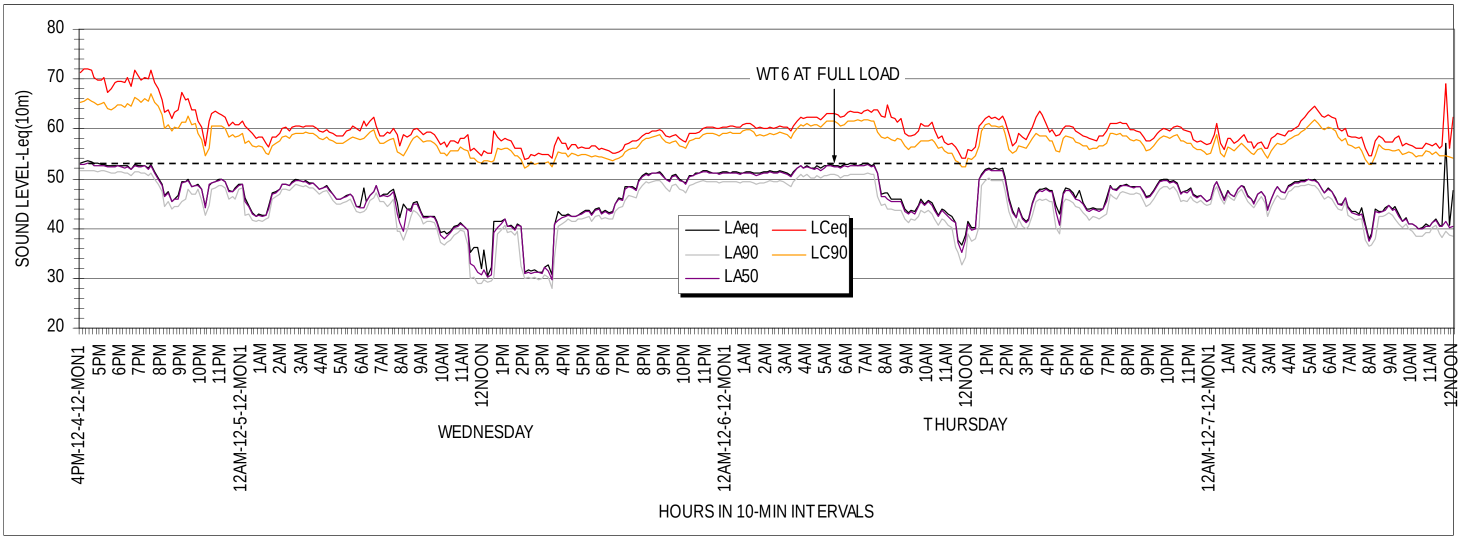

Figure 3.1 *Monitor 1 Results*

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

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

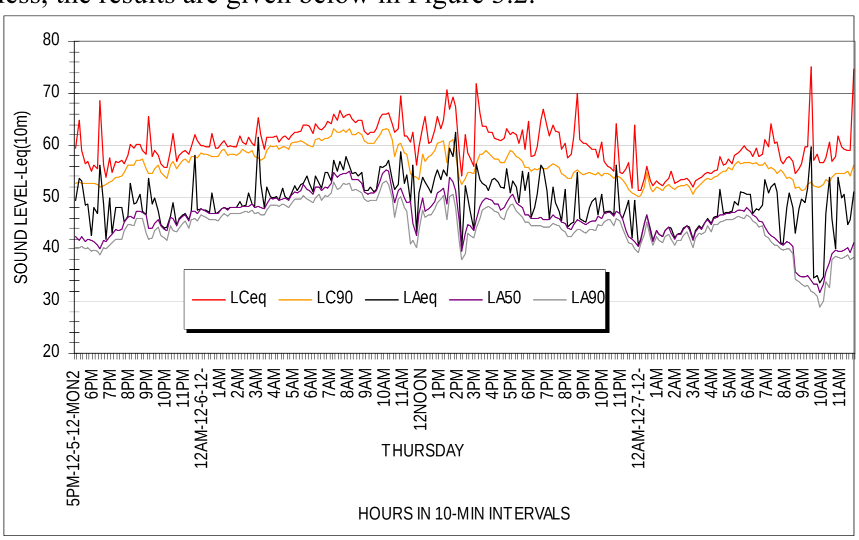

Figure 3.2 *Monitor 2 Results*

4. OUTDOOR/INDOOR Measurements

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

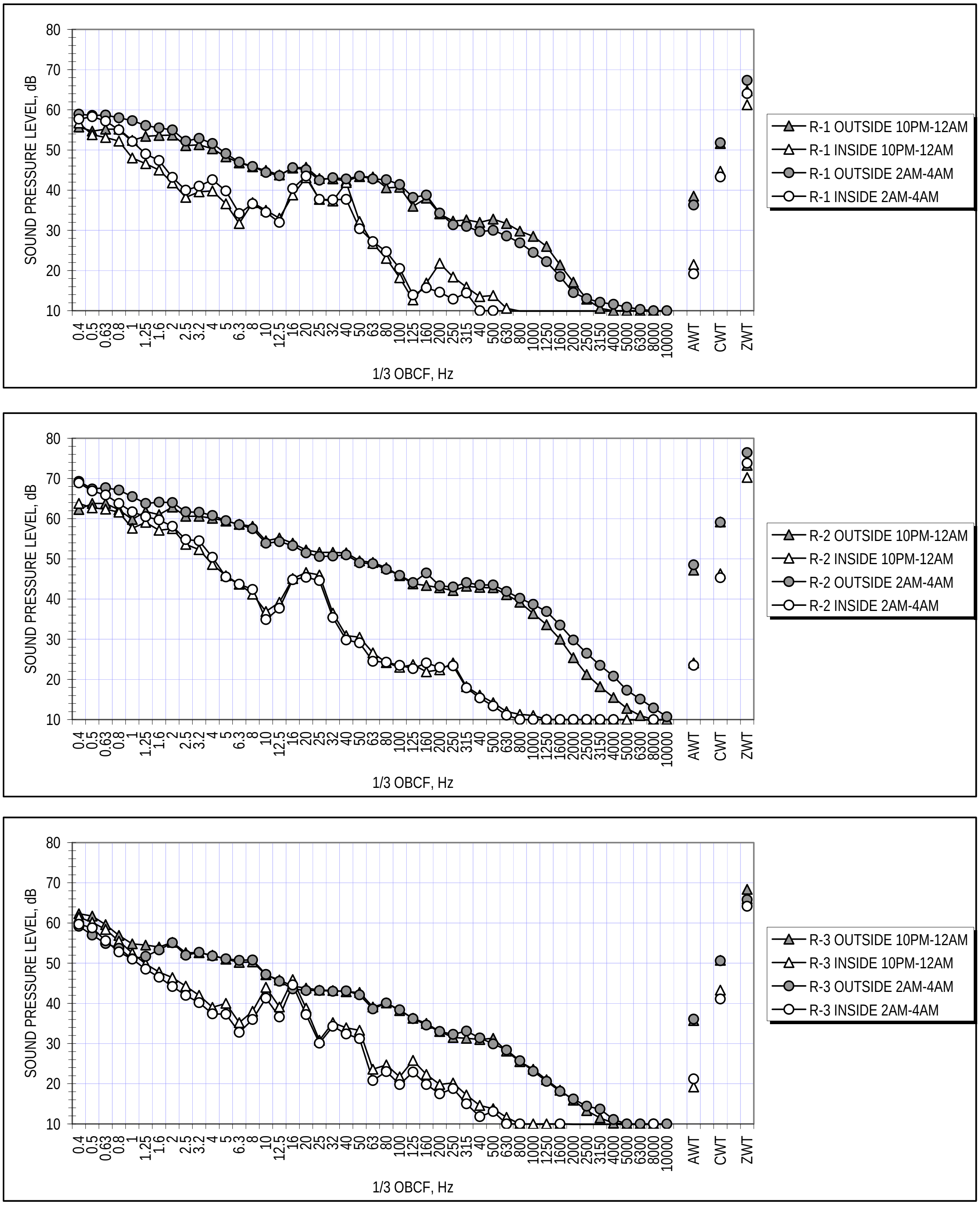

Figure 4.1 *Inside/Outside Sound Levels during Project Operation*

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

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

5. ON/OFF Measurements

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

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

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

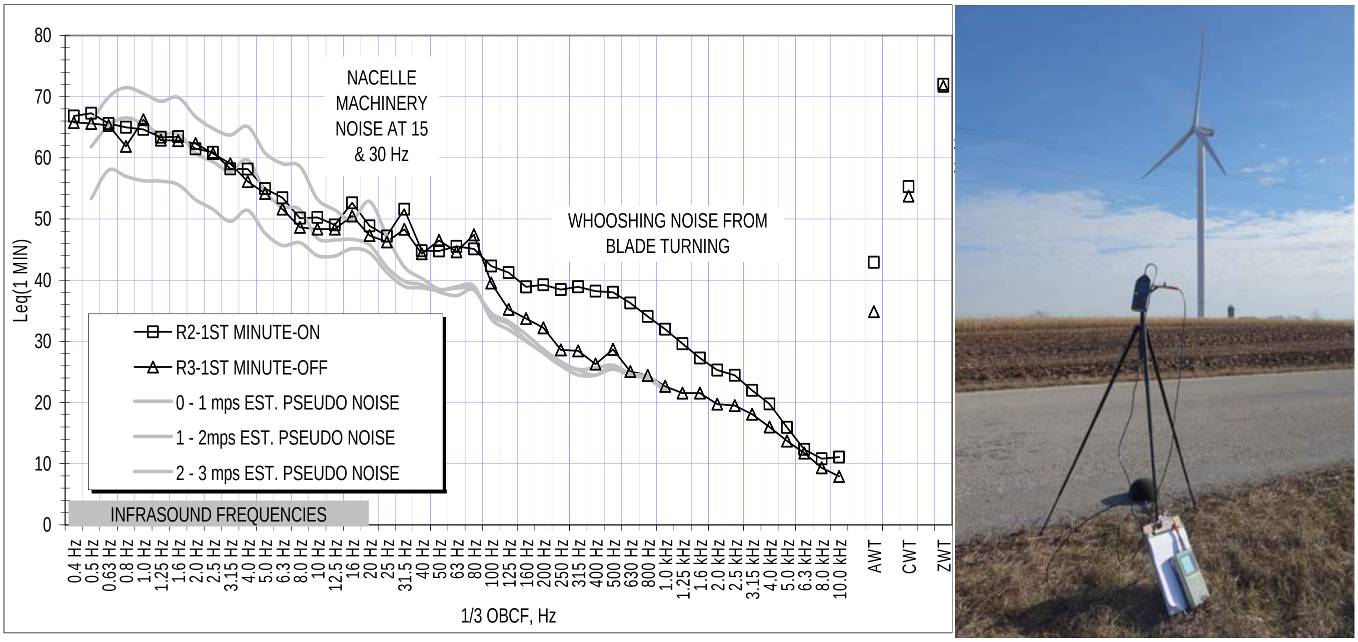

Figure 5.1 *On/Off Sound Levels Outdoors during Project Operation*

6. Proposed Method for Measuring Outdoor LFN in Wind

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

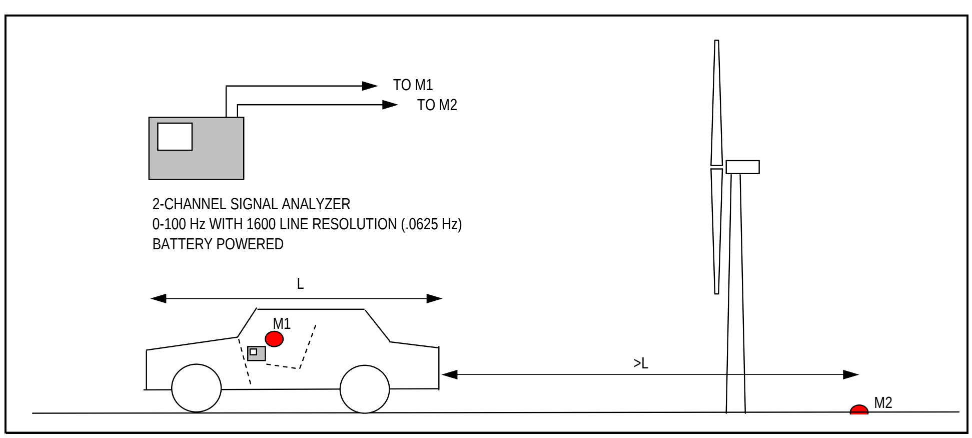

Figure 6.1
Schematic of Alternative, Mobile Measurement Technique for Low Frequency Sound Emissions from Wind Turbines

7. Conclusions

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

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

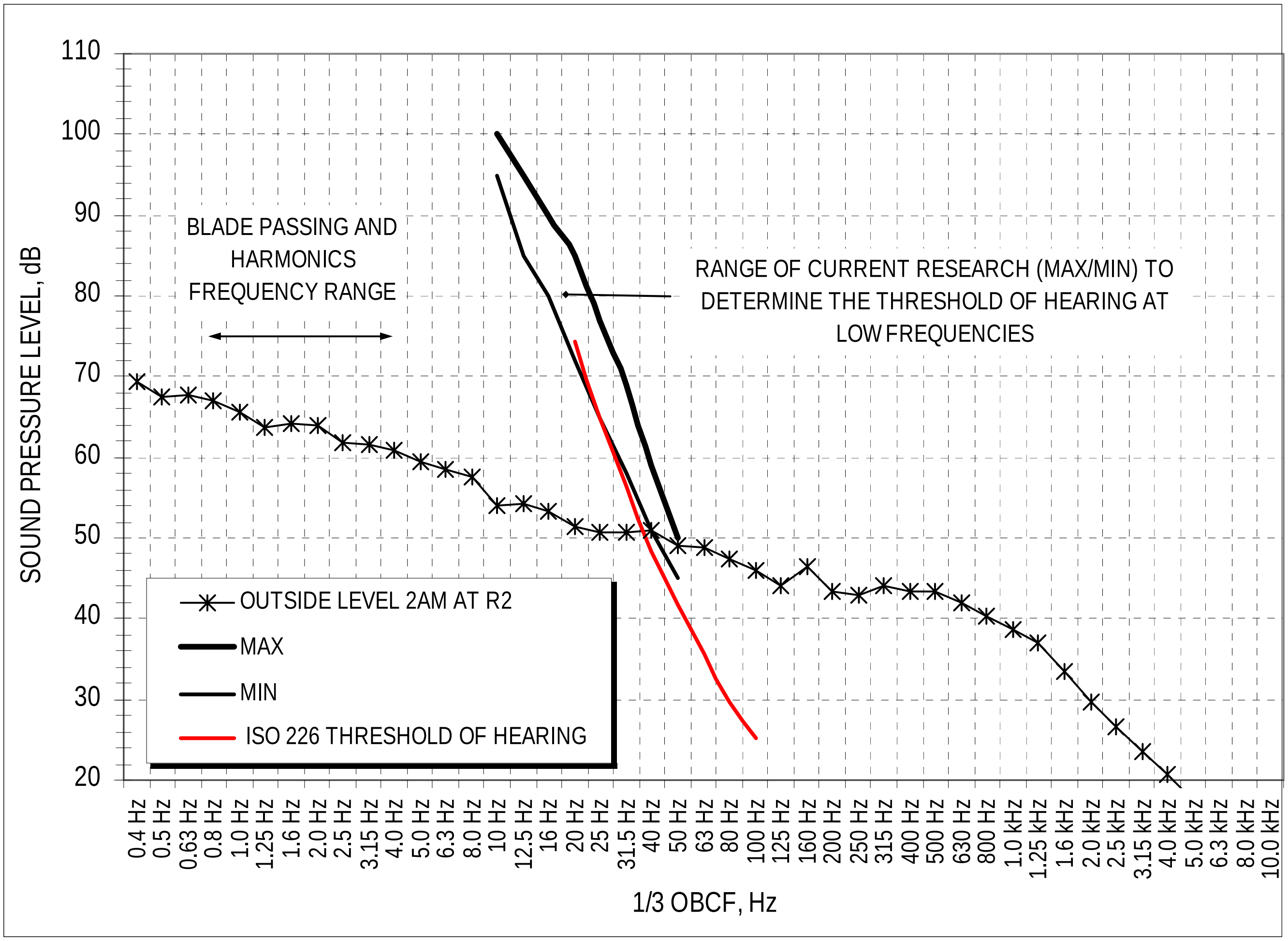

Figure 7.1 *Measured Project Sound Level Compared to Threshold of Hearing*

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

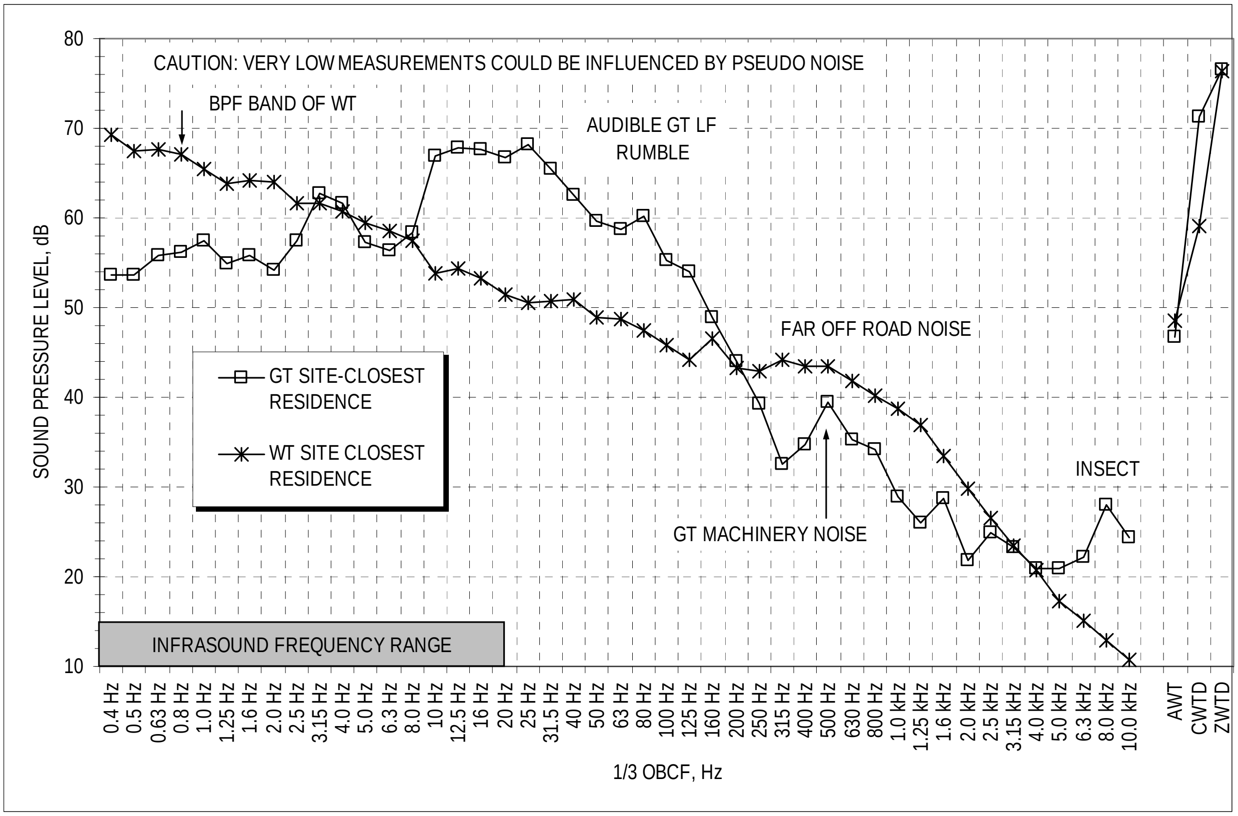

Figure 7.2 *As-Measured Wind Turbine Spectrum Compared to Gas Turbine Sound Level*

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

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

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

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

End of Text

APPENDIX C
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December 21, 2012

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

1.0 Introduction

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

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

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

2.0 Methodology

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

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

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

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

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

2.1 Equipment

Equipment used by Mr. Rand included:

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

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

2.2 Protocol

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

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

3.0 Data collected

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

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

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

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

4.0 Analysis

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

5.0 Results

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

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

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

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

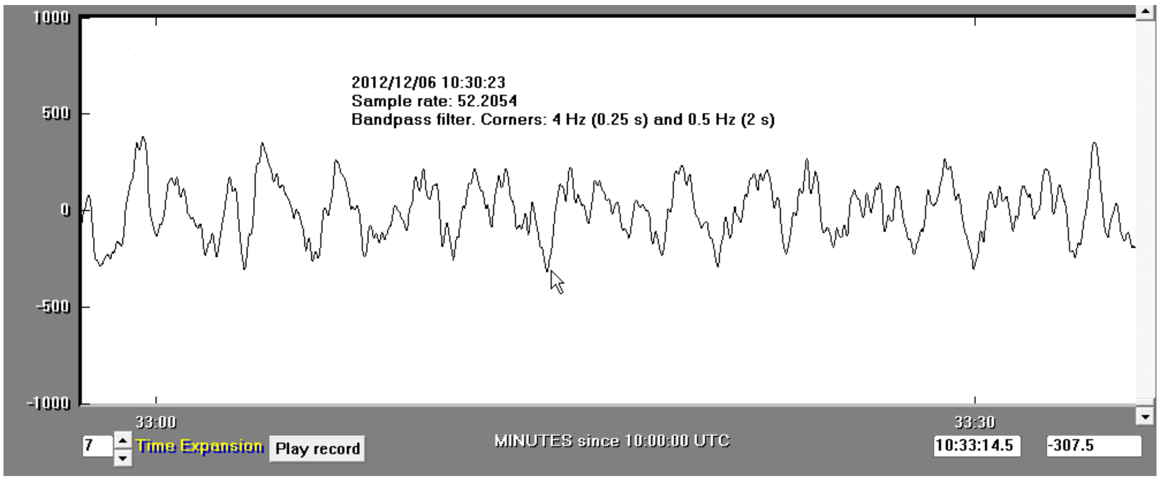
5.3 ***Neighbors retreated to the basement and gained partial relief from symptoms. Tested sound levels are the same everywhere in the home except less in the basement.*** Lower sound levels in the basement matches the neighbor reports to Mr. Rand to the effect that, when the turbines are operating,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

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

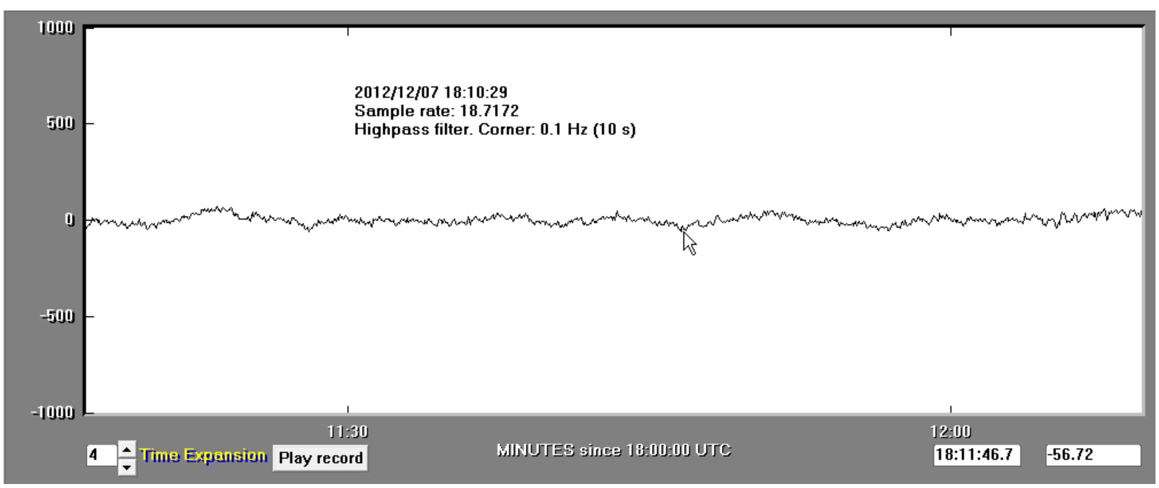
5.6 ***Neighbors reported being highly annoyed by the interior sound. Elevated acoustic energy was observed inside all three homes in the range of 10 to 40 Hz.*** Room, house, wall and floor acoustic modes (resonant frequencies) are found in the 10 to 40 Hz range. The Nordex N100 has in-flow turbulence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

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

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



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



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

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

- **Nausea**
- Headache
- Dizziness

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

Implications

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

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

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4 Nausea/dizziness/headache (very unusual) experienced at three other wind turbine sites including Falmouth, MA, April 2011 (Vestas V82); Hardscrabble, NY, August, 2012 (Gamesa G90-2MW); Vader Piet, Aruba, October, 2012 (Vestas V90-3MW).
5 Samson C. Stevens and Michael G. Parsons, Effects of Motion at Sea on Crew Performance: A Survey. Marine Technology, Vol. 39, No. 1, January 2002, pp. 29–47.
6 Golding JF, Mueller AG, Gresty MA., A motion sickness maximum around the 0.2 Hz frequency range of horizontal translational oscillation. Aviat Space Environ Med. 2001 Mar;72(3):188-92.

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

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

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

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

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

Conclusions

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

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

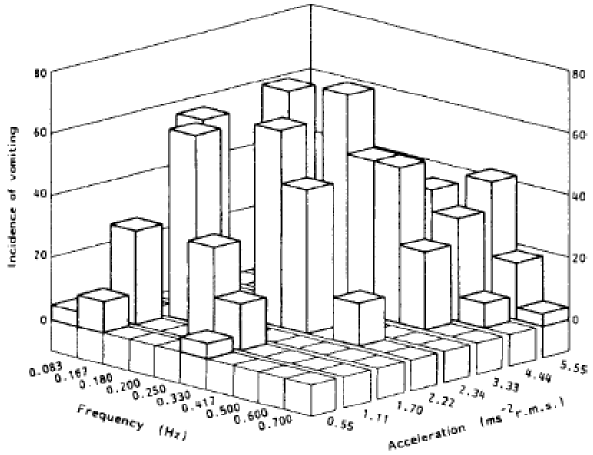

Fig. 5 Incidence of vomiting associated with exposure to various magnitudes and frequencies of vertical oscillation according to McCauley et al (1976)

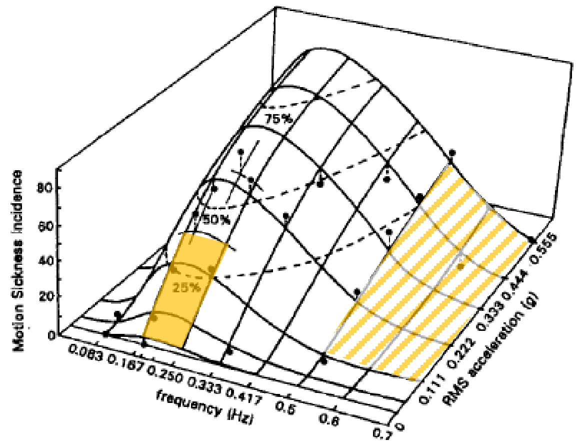

Fig. 6 The model of McCauley et al (1976), describing incidence of motion sickness with subjects inside a ship motion simulator moving sinusoidally in the vertical direction. Incidence of motion sickness was measured in terms of the percentage of subjects vomiting within 2 hours of exposure (Wertheim 1996a, Bos & Bles 2000)

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

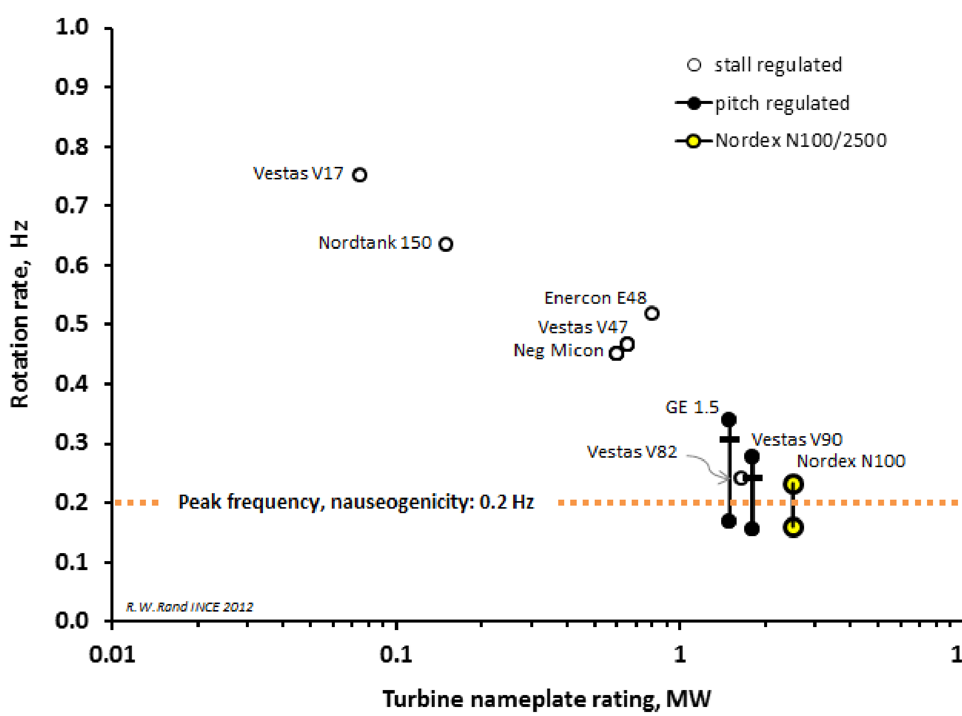

Figure 2. Chart of wind turbine rotation rates (Hz) for various wind turbine models including the Nordex N100. Note nauseogenicity range is 0.1 to 1 Hz with peak potential noted at 0.2 Hz. Note bars on GE 1.5 and Vestas V90 models indicate nominal rotation rate.

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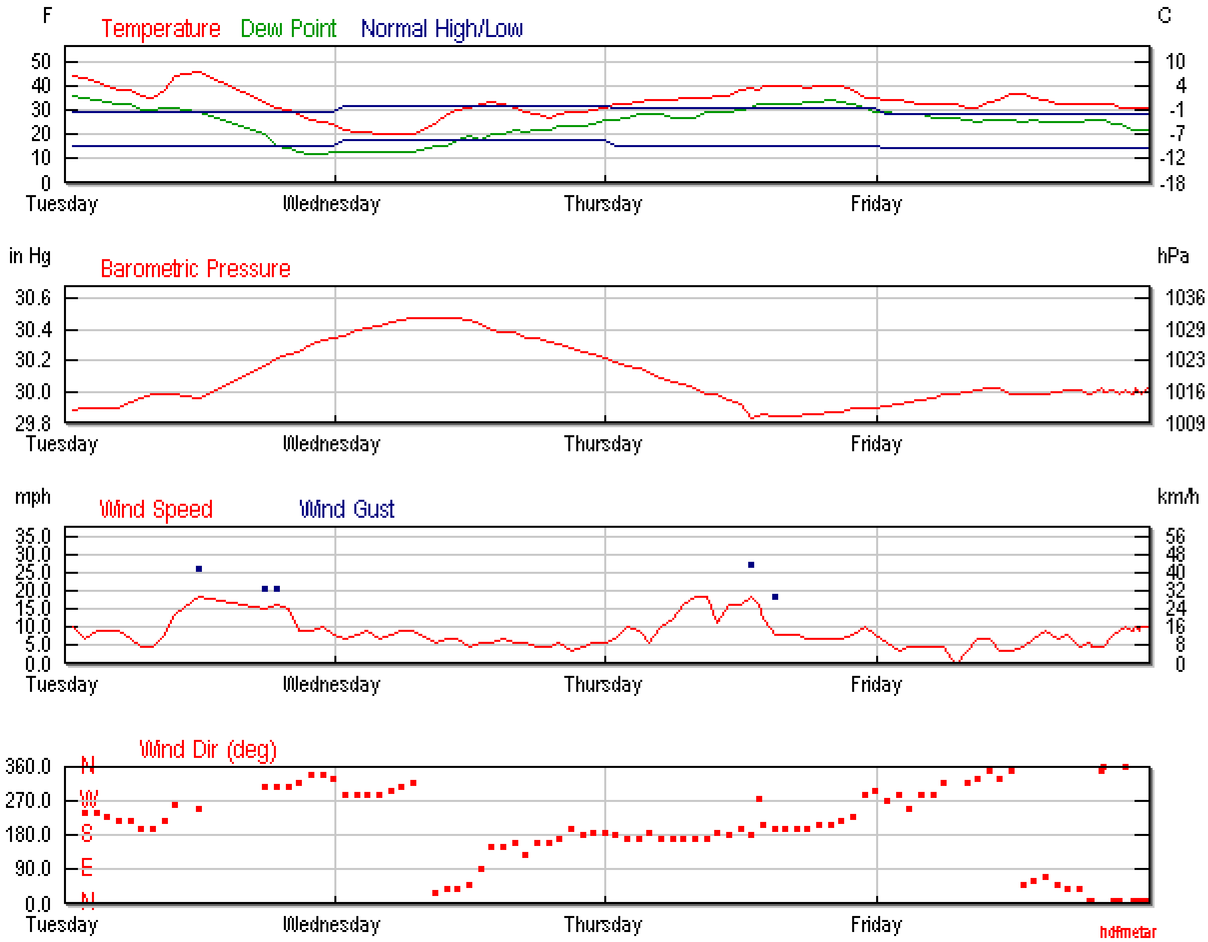
Figure 3. Weather conditions during investigations, December 4-7, 2012.



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

Table 1. Symptom reports logged during investigations.

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

Table 2. Neighbor field notes.

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

Table 2 (continued). Neighbor field notes.

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

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

APPENDIX D
by
SCHOMER AND ASSOCIATES, INC.

SCHOMER AND ASSOCIATES, INC.

Consultants in Acoustics and Noise Control

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December 21, 2012

I) Observations from discussions with residents:

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

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

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

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

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

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

I) Implications of these observations:

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

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

II) Observations from results of measurements:

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

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

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

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

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

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

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

II) Implications of the measurements:

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

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

<u>III) Observations from related literature:</u>

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

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

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

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

<u>III) Implications from the Navy's Nauseogenic Criteria:</u>

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

<u>IV) Descriptors for Wind Turbine Emissions</u>

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

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

V) The Tests We Should Perform

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

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

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

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

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

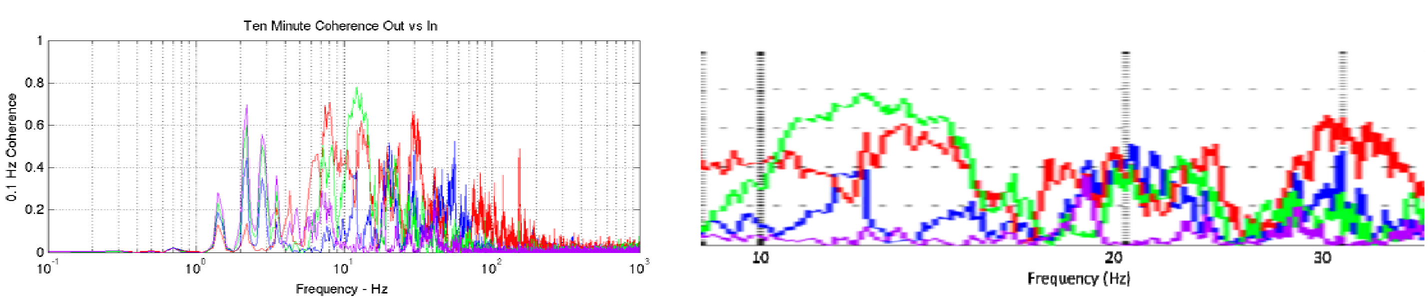


Figure 1a, b: R2-5T212420--coherence with outdoor-ground plane microphone; Living Room-Blue, Master Bed Room- Red, Behind Kitchen- Green, Basement-Purple, b is an expanded view from 9` Hz to 35 Hz

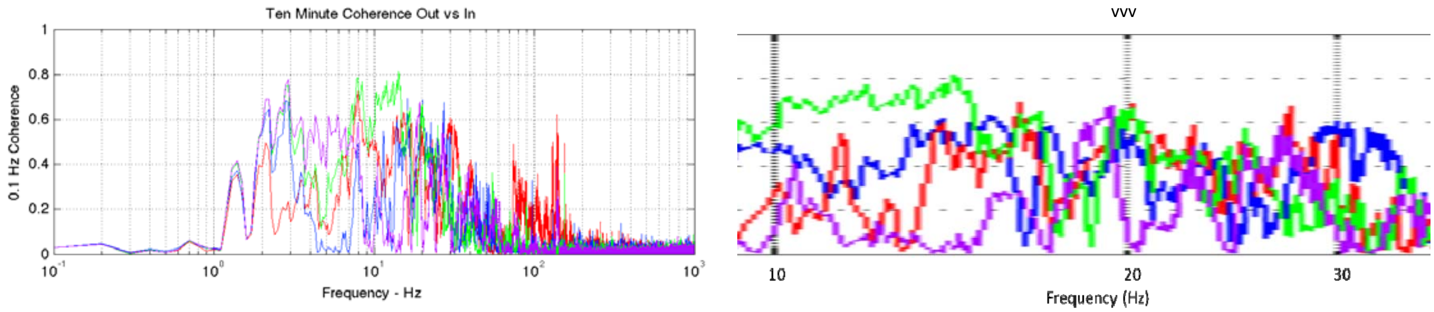


Figure 2a, b: R2-5T204657--coherence with outdoor, ground-plane microphone; Living Room-Blue, Master Bed Room-Red, Behind Kitchen- Green, Basement-Purple, b is an expanded view from 9 Hz to 35 Hz

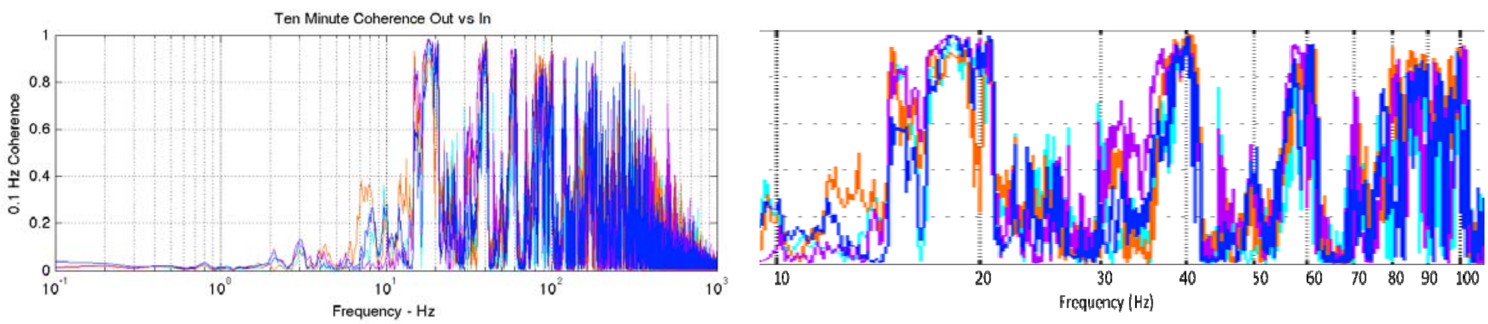
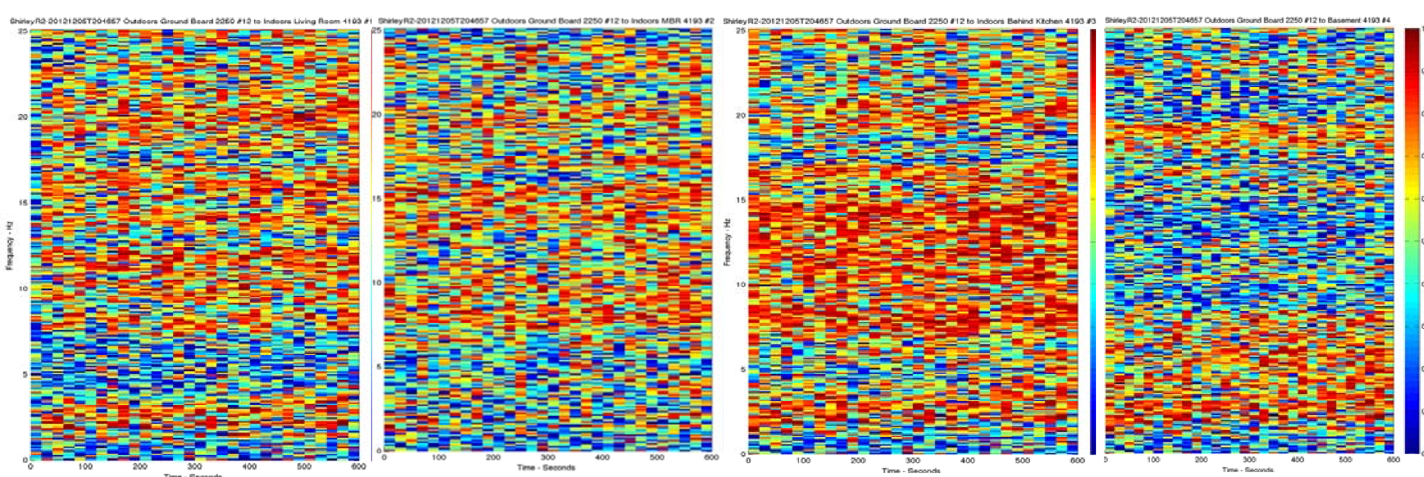


Figure 3a, b: R2-5T204657; Living Room-Blue, Upstairs Bed Room- Orange, Family Room- Turquoise, Basement-Purple, b is an expanded view from 10 Hz to 100 Hz. Note the strong coherence from 20 through at least 80 Hz that resulted from a nearby Helicopter.



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

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

5

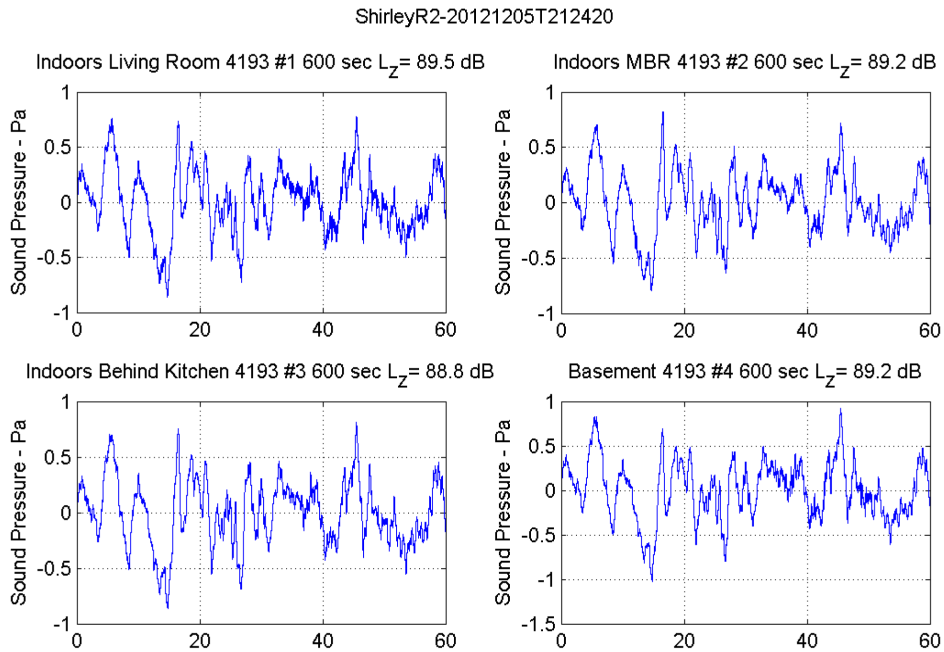


Figure 5- First of the ten minute period of 5T212420. Note that the SPL is very similar for all indoor locations.

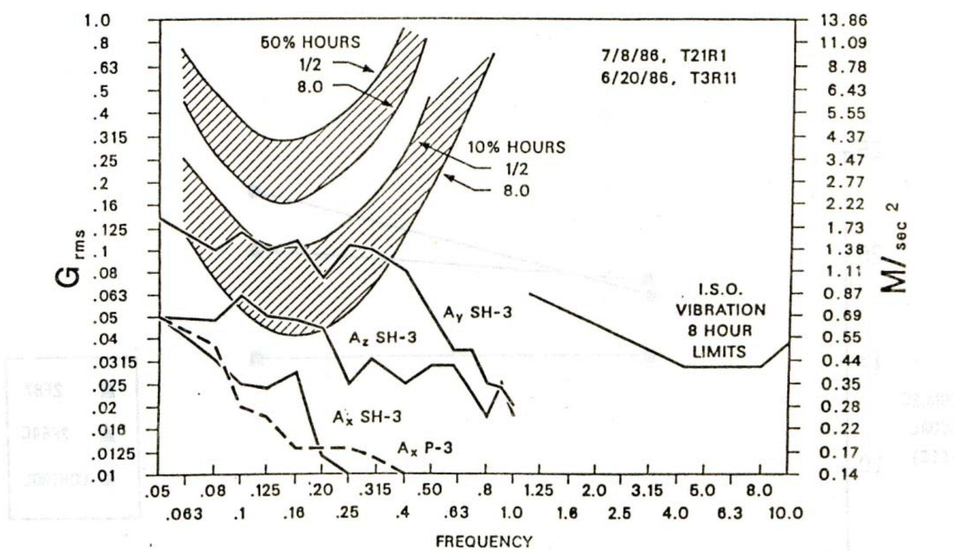


Figure 6. SH3 Sea King Nominal Run vs P-S Orion Nominal A_x

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

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

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Assessing Sound Emissions from Proposed Wind Farms & Measuring the Performance of Completed Projects

NARUC

NARUC Grants & Research

October 2011

The National Association of Regulatory Utility Commissioners

A report for the Minnesota PUC
Funded by the U.S. Department of Energy

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BEST PRACTICES GUIDELINES FOR

ASSESSING SOUND EMISSIONS FROM PROPOSED WIND FARMS
and
MEASURING THE PERFORMANCE OF COMPLETED PROJECTS

October 13, 2011

Prepared for:

The Minnesota Public Utilities Commission

Under the auspices of the National Association of Regulatory Utility Commissioners (NARUC), Washington, DC.

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1.0 Introduction

The noise produced by wind turbines differs fundamentally from the noise emitted by other power generation facilities in terms of how it is created, how it propagates, how it is perceived by neighbors and how it needs to be measured. Essentially everything about it is unique and specialized techniques need to be employed in order to rationally assess potential impacts from proposed projects and to accurately measure the sound emissions from newly operational projects.

Existing ISO[1,2], and ANSI[3,4] standards that are perfectly appropriate for evaluating and measuring noise from conventional power generation and industrial facilities were not written with wind turbines in mind and contain certain provisions that make them unsuitable for application to wind turbines. For example, most test standards, quite sensibly, allow valid measurements only under low wind or calm conditions in order to preclude, or at least minimize, wind-induced directional effects, among other things. At a conventional power plant, which may operate around the clock, this requirement simply implies a wait for appropriate weather conditions. At a wind turbine project, however, there is nothing to measure during calm wind conditions, since the project is normally idle. Significant noise generation largely occurs during wind conditions that are generally above the permissible limit. At the present time, a lone standard, IEC 61400-11[5] exists for evaluating wind turbine sound levels, but only for the specific purpose of measuring the sound power level of a single unit. Sound power level is an arcane, intangible, derived quantity that is used as an input to analytical noise models and has little relevance to the sound level a wind farm is producing at someone's home. Consequently, this highly specialized test cannot be used or even adapted to serve as a way of determining whether a new multi-unit project is in compliance with a noise ordinance, for instance.

What all this suggests is that the standards and methodologies that exist for assessing and measuring noise from conventional industrial noise sources cannot be applied wholesale to wind turbine noise and completely different assessment and field measurement methodologies are required that are tailored to, and take into account, the unique circumstances and technical challenges surrounding their noise emissions. These guidelines seek to address this situation by describing suggested assessment and measurement techniques that have been developed over the past decade through field experience on roughly 70 wind projects, primarily in the Midwest and Eastern United States, nearly all of which were located in rural, yet moderately populated areas. Without question many mistakes were made in the early going into this uncharted field of study and many naïve assumptions about wind turbine noise were found to be incorrect. It is hoped that what was learned from this experience and what is summarized in these guidelines can help others circumvent this learning curve.

After a brief discussion on the nature of wind turbine noise, the following principal topics are discussed:

- Suggested design goals for new projects
- Evaluating potential noise impacts from proposed projects through noise modeling and field surveys of existing conditions
- Measuring the noise emissions from operational projects to determine compliance with design goals or regulatory limits

1.1 Executive Summary

Wind turbine noise differs fundamentally from the noise produced by other power generation and industrial sources in how it is produced, how it propagates and how it is perceived by neighbors. Because existing sound measurement standards were never written with wind turbines in mind they are largely unsuitable for use in wind turbine analyses, if only because measurements both prior to and after construction essentially must be performed in the windy conditions necessary for the project to operate – conditions that are prohibited by virtually all current test standards. Consequently, new and unique evaluation and measurement techniques must be used that are adapted to the special circumstances germane to wind turbines. These guidelines are intended to help remedy this situation by suggesting design goals for proposed project, outlining a methodology for evaluating potential impacts from new projects and describing how to accurately measure the noise emissions from operating projects.

Studies and field surveys of the reaction to operating wind projects both in Europe and the United States generally suggest that the threshold between what it is normally regarded as acceptable noise from a project and what is unacceptable to some is a project sound level that falls in a gray area ranging from about 35 to 45 dBA. Below that range the project is so quiet in absolute terms that almost no adverse reaction is usually observed and when the mean project sound level exceeds 45 dBA a certain number of complaints are almost inevitable. In view of this, it would be easy to avoid any negative impact by simply limiting the sound level from a proposed wind project to 35 dBA at all residences, but the reality is that such a stringent noise limit cannot normally be met even in sparsely populated areas and it would have the effect of preventing noise impacts by making it virtually impossible to permit and build most projects. In fairness then, any noise limit on a new project must try to strike a balance that reasonably protects the public from exposure to a legitimate noise nuisance while not completely standing in the way of economic development and project viability. It is important to realize that regulatory limits for other power generation and industrial facilities never seek or demand inaudibility but rather they endeavor to limit noise from the source to a reasonably acceptable level in terms of either an absolute limit or an allowable increase relative to the background level.

Based on the observed reaction to typical projects in United States, it would be advisable for any new project to attempt to maintain a mean sound level of 40 dBA or less outside all residences as an ideal design goal. Where this is not possible, and even that level is frequently difficult to achieve even in sparsely populated areas, a mean sound level of up to 45 dBA might be considered acceptable as long as the number of homes within the 40 to 45 dBA range is relatively small. Under no circumstances, however, should turbines be located in places where mean levels higher than 45 dBA are predicted by pre-construction modeling at residences. It is important to note that a project sound level of 40 dBA does not mean that the project would be inaudible or completely insignificant, only that its noise would generally be low enough that it would probably not be considered objectionable by the vast majority of neighbors.

Noise impact assessments for proposed projects can be absolute or relative in nature. In an absolute analysis the sound level contours from the project are plotted over a map of the turbine layout and the surrounding potentially sensitive receptors, normally permanent residences, and the sound levels are evaluated relative to the 40 and 45 dBA criteria discussed above. A relative assessment involves, as a first step, a field survey of the existing soundscape at the site followed by a noise modeling analysis. The potential impact of the project is evaluated in terms of the differential between the existing background sound level and the calculated project-only sound level, importantly, under identical wind conditions. As a general rule of thumb, an increase of up to 5 dBA above the pre-existing L_{A90} sound level is usually found to be acceptable whereas greater increases should be avoided. This design approach only holds for background levels of about 35 dBA or above. When lower background sound levels are found a design goal of 40 dBA or less at all residences should be sought.

Commercially available software packages based on ISO 9613-2 are suggested for noise modeling analyses. Recommended modeling procedures would consist of the following steps.

- Begin with a base map showing the turbine locations and all potentially sensitive receptors in and around the project area (residences, schools, churches, etc.)
- Build up the topography of the site in the noise model if the terrain features consist of hills and valleys with a total elevation difference of more than about 100 ft. – otherwise flat terrain can be assumed
- Locate point sources at the hub height of each turbine (typically 80 m)
- Use the maximum octave band sound power level spectrum, measured per IEC 61400-11, for the planned turbine model or the loudest model of those being considered
- Assume a ground absorption coefficient (A_g from ISO 9613-2) appropriate to the site area (a moderate value of 0.5 generally works well as an annual average for rural farmland)
- Assume ISO “standard day” temperature and relative humidity values of 10 deg. C/70% RH unless the prevailing conditions at the site are substantially and consistently different than that
- Plot the sound contours from the project assuming an omni-directional wind out to a level of 35 dBA
- Evaluate the potential impact of the project at residences relative to the suggested 40 and 45 dBA thresholds

A relative impact analysis is recommended whenever unusually high or low background levels are suspected at a site, the project is large or controversial, or when there is simply a desire to carry out a thorough analysis. The baseline field survey of existing environmental sound levels should:

- Use 6 to 14 measurement positions depending on the complexity of the site
- Select positions at residences (to the extent possible) that are representative of all the distinct settings that may be present within the site area, such as sheltered valleys, exposed hilltops, wooded areas, near major roadways, remote and secluded, etc.
- Monitor in continuous 10 minute intervals for a period of at least 14 days to capture a wide variety of wind and weather conditions
- Record a number of statistical parameters, giving precedence to the relatively conservative L_{A90} measure
- Use Type 1 or 2 integrating sound level meters fitted with oversize (7" diameter, or greater) windscreens
- Mount the microphones approximately 1 m above ground level, where feasible, to minimize self-induced wind noise
- Use one or more temporary weather stations at the most open and exposed measurement positions to record wind speed at microphone height and other parameters, such as rainfall.
- Apply a correction, if necessary, to the A-weighted sound levels for wind-induced, self-noise based on the microphone height anemometer readings
- Evaluate the L_{A90} results for consistency over the various measurement positions, segregating the results for different settings if there are clear and consistent differences
- Normalize the wind speed measured by the highest anemometers on all on-site met towers to a standard height of 10 m per Eqn. (7) of IEC 61400-11
- Correlate the design site-wide or individual setting background levels to the normalized wind speed to determine the mean value as a function of wind velocity
- Use the 6 m/s result as the critical design wind speed or determine the site-specific critical wind speed from a comparison between the turbine sound power and background levels
- Use the mean L_{A90} background level at the critical wind speed as a baseline for evaluating the modeled sound emissions of the project under those same conditions

The accurate measurement of noise from an operational project requires a determination of the concurrent background sound level present at the time each sample of operational noise is measured so that the wind and atmospheric conditions are consistent. Background levels measured at a different time and under inevitably different conditions are not suitable for use in correcting operational sound measurements.

The objective of an operational survey is to quantify the project-only sound level exclusive of background noise, which can easily be comparable to the project level at typical set back distances. Ignoring this background component will normally result in an overestimate of the project's actual sound levels.

A methodology is outlined in these guidelines for estimating the simultaneous background sound level by monitoring at a number of positions outside of the site area in locations and settings that are similar in nature to the on-site positions but remote from all turbine noise. In general, an operational survey to determine the sound emissions exclusively due to the project should:

- Use 6 to 10 on-site measurement positions depending on the complexity of the site and focused on the residences with maximum exposure to turbine noise (irrespective of their participation in the project)
- Set up 3 to 4 off-site background measurement positions at positions at least 1.5 miles from the project perimeter in diametrically opposed directions. These positions should be similar in setting and character to the on-site positions but removed from any exposure to project noise
- Monitor in continuous 10 minute intervals for a period of at least 14 days to capture a wide variety of wind and weather conditions
- Record a number of statistical parameters, giving precedence to the L_{A90} measure
- Use Type 1 or 2 integrating sound level meters fitted with oversize (7" diameter, or greater) windscreens
- Mount the microphones approximately 1 m above ground level, where feasible, to minimize self-induced wind noise
- Use one or more temporary weather stations at the most open and exposed measurement positions to record wind speed at microphone height and other parameters, such as rainfall.
- Apply a correction, if necessary, to the A-weighted sound levels for wind-induced, self-noise based on the microphone height anemometer readings
- Evaluate the off-site L_{A90} results for consistency over the various measurement positions, segregating the results for different settings if there are clear and consistent differences. Develop one or more design background levels to be used to correct the on-site levels.
- Subtract the appropriate design background level from the total measured level at each on-site receptor to derive the project-only sound level at each receptor position
- Normalize the wind speed measured by the highest anemometers on all on-site met towers to a standard height of 10 m per Eqn. (7) of IEC 61400-11
- Plot the derived project-only sound levels as a function of time or wind speed.
- Exclude all data points measured during calm conditions when the project was not operating
- Exclude all data points that appear to be associated with local contaminating noises; i.e. noise spikes, usually occurring at only one position, that are not accompanied by a simultaneous spike in wind speed
- Evaluate the final results with respect to the applicable design goal or ordinance limit. If the measured levels are lower than the design target at least 95% of the time the project can be considered in compliance.

2.0 Characteristics of Wind Turbine Noise

The magnitude and nature of wind turbine noise is entirely dependent on time-varying wind and atmospheric conditions, whereas a conventional fossil-fueled power station operates, often continuously and steadily, in a manner that is completely independent of the local environment. Consequently, a combustion turbine plant, for example, is most apt to be perceptible and a potential noise problem during calm and still weather conditions while a wind turbine project would, under most normal circumstances, not make any noise at all under those same conditions. During moderately windy conditions increased background noise would tend to diminish the perceptibility of the fossil fueled plant while the wind project would generally be at its loudest relative to the background level. At very high wind speeds background noise often becomes dominant to the extent it can obscure both sources.

In addition to simply being dependent on prevailing wind and atmospheric conditions, wind turbine noise usually has a distinctive, identifiable character to it that makes it more readily perceptible than other industrial sources of comparable magnitude[6,7,8]. The fundamental noise generation mechanism, the turbulent interaction of airflow over the moving blades, is dependent on the characteristics of the air mass flowing into the rotor plane. For example, when the airflow is fairly constant and steady in velocity over the swept area noise is generally at a minimum. While such ideal, laminar flow conditions may exist much of the time, particularly during the day, they do not occur all of the time, and the reality is that the wind often blows in the form of intermittent gusts separated by short periods of relative calm rather than as a smooth continuous stream of constant velocity. In addition, the flow may contain turbulent eddies, may be unstable in direction and the mean velocity may vary considerably over the vertical diameter of the rotor, which is typically in the 77 to 112 m (250 to 370 ft.) range on the utility scale turbines now in common use. These uneven and unstable airflow conditions generally cause more noise to be generated - and it is generated sporadically as each gust sweeps past and as the wind varies amorphously in speed or direction over the rotor plane. Such unstable conditions can lead to sound levels that change very noticeably in the short-term not only in general volume but also in character.

Qualitatively, under average circumstances rotor noise, as perceived at a common set back distance of around 400 m (1200 ft.), might be described as a churning, mildly periodic sound due to blade swish, particularly when there are several units at comparable distances from the point of observation. The normally non-synchronized and incoherent sounds from multiple units tend to blur the sound and minimize the perception of swish, although it is most commonly weak during "normal" circumstances even if only one unit is present. Another common description is that the noise is reminiscent of a plane flying over at fairly high altitude. This apt comparison is probably partly due to the basic similarity in frequency content of the two sounds but also to the phenomenon where the sound can fade in and out randomly. In the case of an actual plane it is the intervening non-homogeneous atmosphere that alternately enhances or hinders sound propagation from the distant source producing this effect while, in the case of the wind turbine, it is more likely to be short-term variations in noise generation at the source itself, or a combination of both source and path effects.

A pure path effect that occasionally occurs is the enhanced propagation of turbine noise due to thermal layering, known as a stable atmosphere, where the air is warmer above the surface than at the surface causing sound rays to diffract downward and making a distant sound louder than it would otherwise be. At night, this phenomenon, most likely in combination with the wind speed gradient, is most likely to lead to an increase in periodic noise (generally referred to as amplitude modulation, or AM)[9,10]. The exact mechanism behind this noise, particularly when it becomes unusually pronounced, is not entirely understood, but, in simple terms, it is thought to be caused when the wind speed at the top of the rotor is significantly higher than the wind speed at the bottom; i.e. when the vertical wind speed gradient is more slanted and less vertical, as is usually the case at night. Having said that, however, this phenomenon is not always present or particularly pronounced at all sites, but *when of sufficient magnitude*, the fairly pronounced swishing or thumping sound that can result on certain evenings can and does give rise to quite legitimate complaints. In fact, this is probably the primary cause of serious complaints about wind project noise. In general, the occurrence of this phenomenon in its pronounced or enhanced form is rather rare making detailed measurements difficult[11] but a major effort[(ibid)] is currently underway in the United Kingdom seeking to quantify and further understand this noise.

2.1 Low Frequency Noise and C-weighted Sound Levels

When the swishing, thumping or beating noise alluded to above does occurs it is usually at a rate of about once per second, or 1 Hz, which is the blade passing frequency of a typical three-bladed rotor turning at 20 rpm. Although the "frequency" of its occurrence at 1 Hz obviously falls at the very low end of the frequency spectrum, this noise is not "low frequency" or infrasonic noise, per se. It is simply a periodic noise where the actual frequency spectrum may contain some slightly elevated levels in the lower frequencies but where the most prominent noise is roughly centered around 500 Hz near the middle of the audible frequency spectrum. In general, the widespread belief that wind turbines produce elevated or even harmful levels of low frequency and infrasonic sound is utterly untrue as proven repeatedly and independently by numerous investigators[12,13,14,15,16] and probably arose from a confusion between this periodic amplitude modulation noise and actual low frequency noise. Problematic levels of low frequency noise (i.e. those resulting in perceptible vibrations and complaints) are most commonly associated with simple cycle gas turbines, which produce tremendous energy in the 20 to 50 Hz region of the spectrum – vastly more than could ever be produced by a wind turbine.

The mistaken belief that wind turbines produce high levels of low frequency noise can also be attributed, perhaps even more definitively, to wind-induced microphone error where wind blowing through virtually any windscreen will cause the low end, and only the low end, of the frequency spectrum to substantially increase due to self-generated distortion. The magnitude and frequency response of this error has been theoretically/mathematically quantified by van den Berg[10] and empirically by Hessler[17] by subjecting a variety of commonly used windscreens to known air speeds in a massively silenced wind tunnel – thereby directly measuring the frequency response to air flow alone (the specific results of this study and its applications are discussed further in Section 5.1). The results of this wind tunnel experiment were used to evaluate measurements of actual wind turbine noise at a site in Southern Minnesota by Hessler in 2008[18]. Figure 2.1.1 below shows, as an example, the frequency spectra measured under fairly windy conditions in a rural soybean field 1000 ft. from an isolated unit and, at the same time, in an identical soybean field 3 miles away from any turbines.

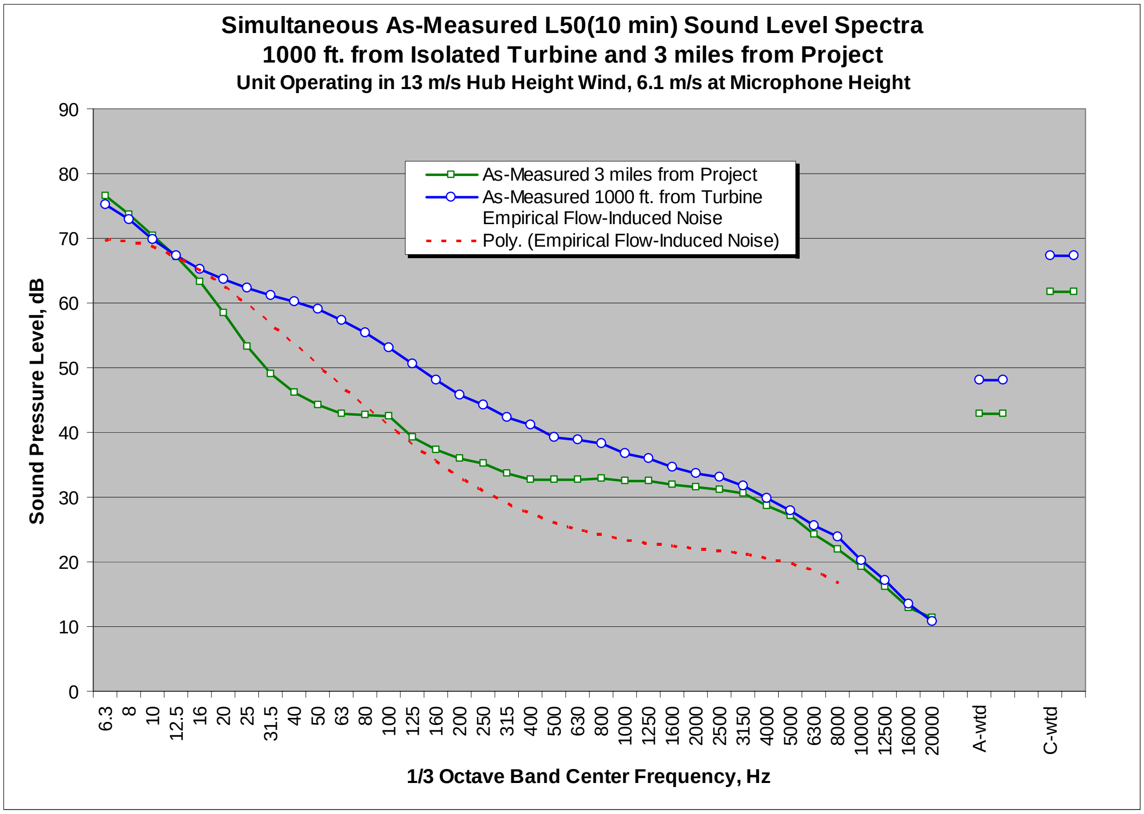

Figure 2.1.1

The two measurements show the same values in the lowest frequency bands. Since there is clearly no source of low frequency noise present in the background measurement, the low frequency levels - in both measurements – simply represent self-generated distortion and are not the actual sound emissions of anything. This can be confirmed from the wind tunnel study where the measured frequency spectrum for this particular windscreen (7” diameter) subjected to a 6.1 m/s wind is also plotted in Figure 2.1.1[a].

What all this shows is that virtually any measurement taken under moderately windy conditions will be severely affected by false-signal noise in the lower frequencies, even

[a] It should be noted that the wind tunnel results quantify the minimum amount of false-signal noise measured under more or less laminar flow conditions in the absence of possible further distortion from turbulence and atmospheric conditions.

when a large windscreen is used as in the example above. The measurement will appear to show high levels of low frequency noise - whether a wind turbine is present or not.

Figure 2.1.1 also illustrates another important point concerning C-weighted sound levels; namely, that the C-weighted levels at 1000 ft. and 3 miles are somewhat similar at 67 and 62 dBC, respectively. The significance of this is that C-weighted sound levels, as opposed to the much more common A-weighted metric, are normally used for the specific purpose of quantifying, investigating or placing a limit on noise sources that are rich in low frequency noise. The reason for this is that C-weighting does not mathematically suppress the low frequencies the way A-weighting does making it highly sensitive to and usually dominated by the low frequency content of a sound. Figure 2.1.2 shows this graphically for the example measurement at 1000 ft. from a wind turbine.

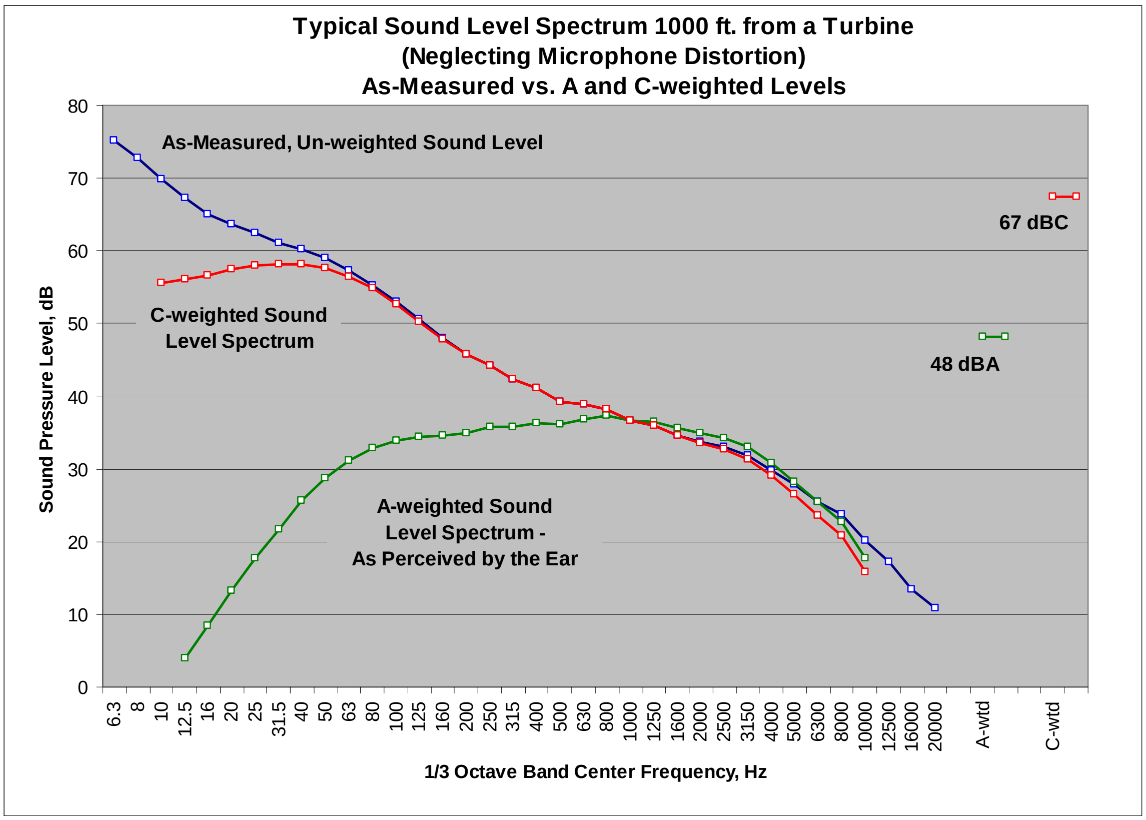

Figure 2.1.2

The as-measured sound level, warts and all, without any weighting applied is the blue trace. C-weighting reduces the low end of the frequency spectrum by a moderate amount whereas A-weighting reduces it substantially. There is no tangible or physiological rationale behind C-weighting but A-weighting serves the very useful purpose of adjusting the frequency spectrum of the sound so that it matches the way it is subjectively perceived by the human ear, which is relatively insensitive to low frequency sounds. Figure 2.1.2 shows that what is actually heard at 1000 ft. from this turbine is mid-frequency sound from roughly 100 to 2500 Hz – and even if the artificially elevated low frequency levels were actually attributable to the turbine nothing would still be audible in the low frequencies (recall that this measurement is unadjusted for low frequency false-signal noise).

The ultimate point of this discussion is that C-weighted sound levels cannot be measured in any kind of meaningful way in the windy conditions associated with turbine operation, since they essentially quantify the level of low frequency microphone distortion rather than any actual noise.

As another example, the plot below shows the C-weighted sound levels measured over a two week period at a residence surrounded by several wind turbines and simultaneously by a monitor located miles away from the project area in a similar setting (rural Midwestern farm country).

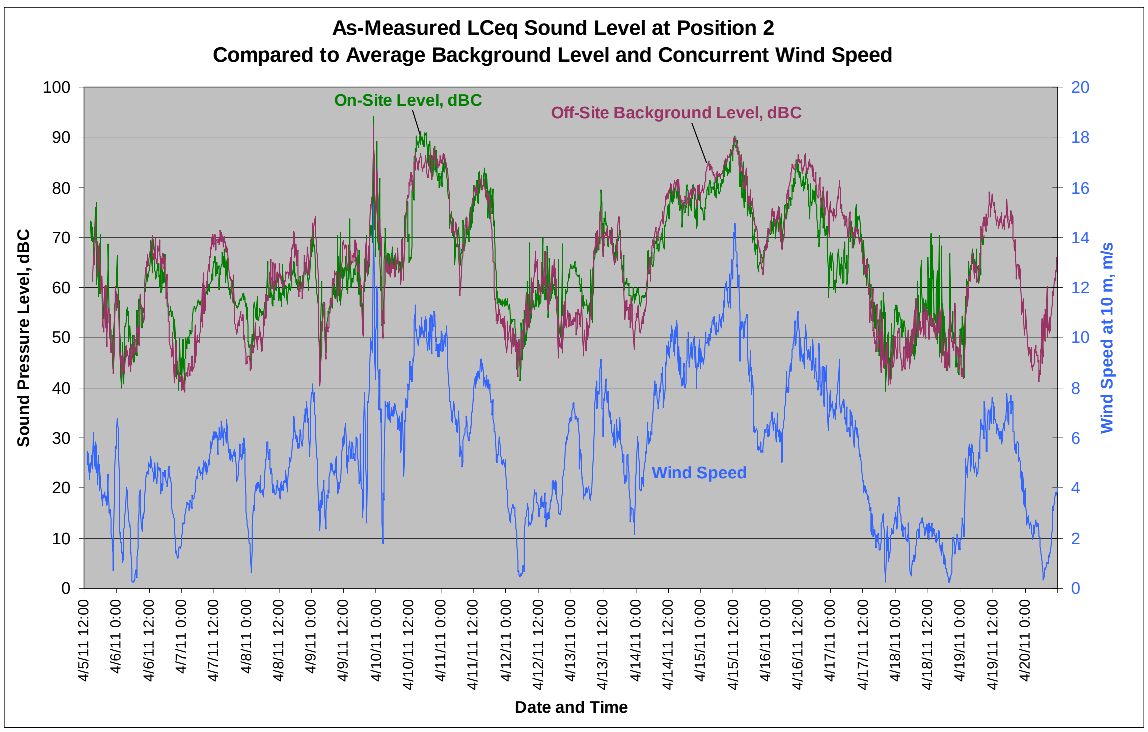

Figure 2.1.3

In essence, the levels are largely the same at both places and are more a measurement of the prevailing wind speed and its effect on the microphone rather than any real source of low frequency noise.

Consequently, despite their occasional appearance in local ordinances as an intended way of limiting the low frequency noise emissions from wind projects, by either an absolute limit or a dBA-dBC differential, C-weighted sound levels have no practical place in the measurement of wind turbine sound.

3.0 Recommended Design Goals

It would be a trivial solution to set an extremely low sound level of, say, 30 dBA as a permissible sound level for a new wind project at potentially sensitive receptors or to impose massive set back distances to any residences. While such restrictions would probably ensure that there was no adverse impact whatsoever from the project, the effective inaudibility of project noise would be due more to the fact it was never built than to its low sound emissions. Realizing virtual inaudibility or maintaining set backs of several thousand feet from all residences is generally an impracticality at all but the most remote sites. In fairness then, any noise limit on a new project must try to strike a balance that reasonably protects the public from exposure to a legitimate noise nuisance while not completely standing in the way of economic development and project viability. It is important to realize that regulatory limits for other power generation and industrial facilities never seek or demand inaudibility but rather they endeavor to limit noise from the source to a reasonably acceptable level either in terms of an absolute limit (commonly 45 dBA at night) or a relative increase over the pre-existing environmental sound level (typically 5 dBA[19]).

Research, principally by Pedersen[20,21] and Persson-Waye[22], on what the reaction is to wind turbine sound levels and what levels might be considered acceptable has been on-going for some time now in Europe. These studies analyze the responses to blind questionnaires distributed to residents living near wind farms in Sweden and The Netherlands in an effort to correlate the level of annoyance with noise and other factors with the calculated project sound level at each residence. In general, the results suggest among many other important findings that a project sound level in the 40 to 45 dBA range can lead to relatively high annoyance rates of around 20 to 25%[(ibid)]; however, it important to understand that these numbers refer to the percentage of those with exposure to such sound levels and not the entire population in the vicinity of the projects. Viewed within the context of the total survey population the rate of adverse reaction comes down to a handful of individuals or very roughly about 4 to 6% when residences are exposed to project sound levels in the 40 to 45 dBA range.

A somewhat similar rate of complaints/annoyance expressed as a percentage of the total population living within 2000 ft. of a turbine was found by Hessler[23] during compliance sound testing at a number of typical, newly operational wind projects in the United States. In each survey the total number of residents where complaints or even mild concerns about noise had been called in was obtained from project operations and the actual sound levels at all of these locations were measured over 2 to 3 week periods. The fundamental results are summarized in the following table.

Table 3.0.1 *Number of Observed Complaints Relative to the Total Number of Households in Close Proximity to Turbines [Hessler, 23]*

Project	Total Households in the Site Area (Approx.)	Number of Complaints as a Function of Project Sound Level (dBA) (a)			Total Number of Complaints	Percentage Relative to Total Households
		< 40	40 - 44	45 or Higher		
Site A	107	0	2	1	3	3%
Site B	147	0	3	3	6	4%
Site C	151	0	3	0	3	2%
Site D	268	0	2	4	6	2%
Site E	91	1	1	4	6	7%
					Overall Average:	4%
(a) Sound levels expressed as long-term, mean values						

Although the purpose of these surveys was to confirm compliance with regulatory noise and not specifically to evaluate community reaction, the findings, taken together with the European research mentioned above, suggest that the vast majority of residents living within or close to a wind farm have no substantial objections to project noise, particularly if the mean sound level is below 40 dBA. It is important to add that all of the sites investigated in these studies were just as prone as any other site to all the adverse character issues mentioned above, such as amplitude modulation, stable atmospheric conditions, highly variable sound levels and higher nighttime noise levels. While the possibility of annoyance, if not serious disturbance, can almost never be completely ruled out, it appears that the total number of complaints would be fairly small as long as the mean project level does not exceed 40 dBA. Above that point, specifically in the 40 to 45 dBA range, complaints can be expected with some certainty but, as indicated in Table 3.0.1, still at a fairly low rate of about 2% relative to the total population in close proximity to the project.

Consequently, it would be advisable for any new project to attempt to maintain a mean sound level of 40 dBA or less outside all residences as an ideal design goal. Where this is not possible, and it frequently is difficult to achieve even in sparsely populated areas, sound levels of up to 45 dBA might be considered acceptable as long as the number of homes within the 40 to 45 dBA range is relatively small. Under no circumstances, however, should turbines be located in places where mean levels higher than 45 dBA are predicted by pre-construction modeling at residences. A project sound level of 40 dBA does not mean that the project would be inaudible or completely insignificant, only that its noise would generally be low enough that it would probably not be considered objectionable by the vast majority of neighbors based on the actual reaction to other projects.

It is important to note that the sound levels in Table 3.0.1 and the suggested sound level targets discussed above are mean, long-term values and not instantaneous maxima. Wind turbine sound levels naturally vary above and below their mean or average value due to wind and atmospheric conditions and can significantly exceed the mean value at times. Extensive field experience measuring operational projects indicates that sound levels commonly fluctuate by roughly +/- 5 dBA about the mean trend line and that short-lived (10 to 20 minute) spikes on the order of 15 to 20 dBA above the mean are occasionally observed when atmospheric conditions strongly favor the generation and propagation of noise. Because no project can be designed so that all such spikes would remain below the 40 or 45 dBA targets at all times, these values are expressed as long-term mean levels, or the central trend through data collected over a period of several weeks.

4.0 Noise Impact Assessments

4.1 Noise Modeling

The principal mechanism for evaluating the potential impact of a proposed wind project is to analytically model its noise emissions. A sound level contour map showing the expected sound emissions from the project relative to all the residences in the area is essentially a graphic illustration of the potential impact. It follows from the preceding discussion of ideal design goals that predicted levels below 40 dBA at residences can be associated with a relatively low adverse impact, while higher levels, particularly those higher then 45 dBA, suggest a relatively high probability of serious complaints.

Because there are few options to reduce noise from a project once it becomes operational, any necessary noise abatement must essentially be designed into the project while it is still in the planning stage. Computer modeling allows the potential noise impact to be visualized but, importantly, also allows mitigation options to be explored, since the effects of relocating or removing individual turbines or using alternate turbine models can be easily evaluated. Such optimization studies are best performed early in the development process while there is still some flexibility to move things around. This process can be repeated iteratively as the design develops and lease and easement agreements evolve to help keep community noise levels as low as possible within the context, of course, of many other constraints.

4.1.1 *Acceptable Sound Propagation Standards*

Wind turbine noise is actually rather simple to model because the project consists of more or less ideal point sources located high in the air. Consequently, the dominant sound propagation factor is simply spherical wave spreading with distance, which is an axiomatic law of physics that is built into every modeling software package. All other effects, such as ground or air absorption, are minor subtleties by comparison so great sophistication in modeling software is not required. In fact, all that is really necessary is to calculate sound propagation from the project using ISO 9613-2 *Acoustics – Attenuation of sound during propagation outdoors. Part 2: General method of calculation* (1996)[24], which is, by far, the prevailing and most widely accepted worldwide standard for such calculations and the basis for essentially every commercial noise modeling program.

Like the other test standards alluded to in the introduction, ISO 9613-2 was not written with wind turbines in mind and its applicability to elevated sources (usually 80 m) and long propagation distances is occasionally questioned. Table 5 in the standard gives the estimated accuracy of the method for noise sources up to 30 m high and for propagation distances up to 1000 m. This 30 m height figure is sometimes interpreted to mean that the standard cannot be used for 80 m high sources, but it is just that no specific accuracy estimate is given for such cases, not that the standard is inappropriate. As mentioned earlier, the principal sound propagation loss in wind turbine modeling is simple geometric spreading of the sound wave, which is a phenomenon that has no dependence on the specific point of origin or its height above ground level.

Source height is a factor, however, in the relatively minor ground absorption loss (i.e. the tendency of the ground surface to variously absorb or reflect sound waves) but measurements of actual wind turbine sound levels vs. predictions show reasonably good agreement indicating that the calculation of the ground absorption loss and, indeed, the entire methodology, is perfectly valid for wind turbines.

Having said that, it should be noted that ISO 9613-2 does not consider atmospheric conditions, such as the wind and temperature gradients, stability, turbulence, etc., and was always intended to portray very long-term or average propagation conditions under slightly conservative downwind conditions. Consequently, the model results using this standard need to be interpreted as the expected sound level under "average" conditions, meaning that the actual sound level will be close to the prediction much of the time but higher *and* lower levels will occur with about equal regularity due to fluctuating atmospheric conditions, which affect both the generation and propagation of wind turbine noise. The plot below shows a typical comparison between the measured project-only sound levels over a two week period compared to predictions at various wind speeds. The model predictions tend to agree with the central trend line. The scatter evident in this chart is normal and inevitable and reflects the natural variability of wind turbine sound levels as observed at a distant point.

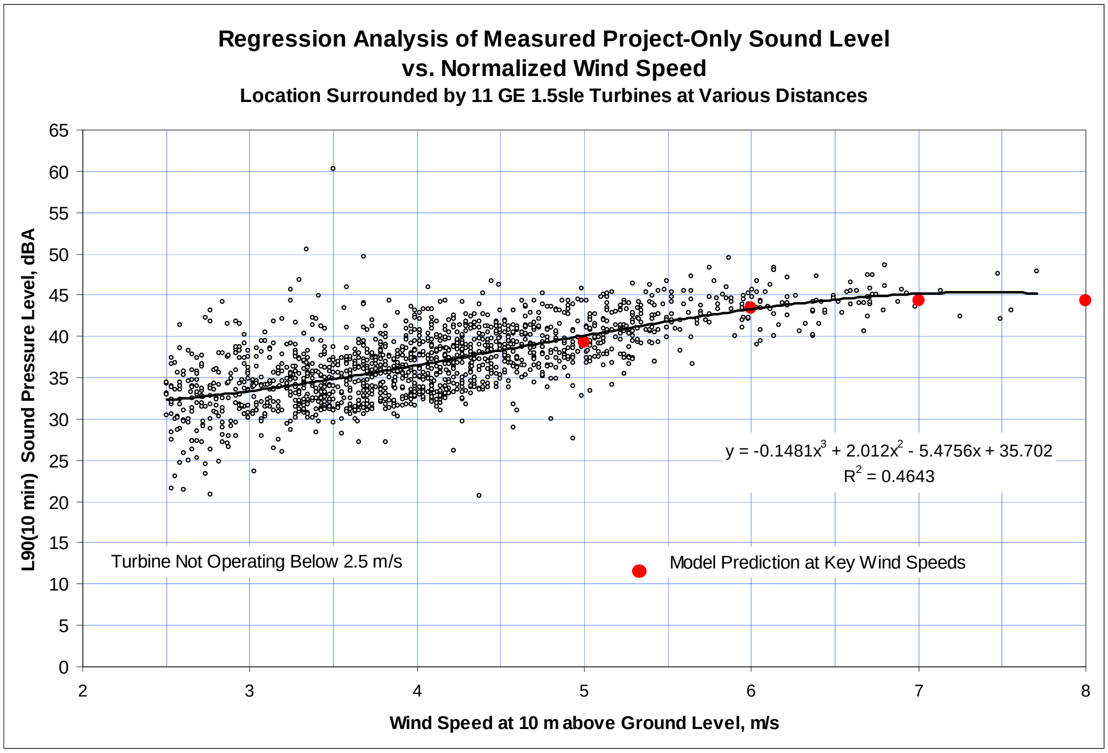

Figure 4.0.1

It should be pointed out that there is an alternative prediction methodology to ISO 9613-2 that takes atmospheric conditions into account: NORD2000[25], which is a proprietary software package that has been in development in Denmark for quite some time. However, it is rather complicated and is not in wide use partially because it has not been integrated or fully integrated into the most commonly used modeling programs. This sound emissions model is based on the fundamental mathematics of wave propagation rather than the empirical studies that form the basis for most of the propagation losses in ISO 9613-2, but despite its sophistication it does not seem to yield substantially better results than ISO 9613-2[26]. As exemplified by Figure 4.0.1, there is no reason why the more common and simpler ISO 9613-2 methodology should not be used.

4.1.2 *Modeling Software*

In theory, then, any program based on ISO 9613-2 can ostensibly be used to model wind turbines but there is more to it than the calculation of sound propagation losses. What emerges as the key differentiation between programs is basically how well and easily the site plan can be imported into the program and the quality and nature of the program's output.

Typical wind projects consist of dozens of units either spread out over many square miles in flat or rolling country or strung out along ridgelines. At the first type of site the turbines are frequently mixed in with potentially sensitive receptors (typically permanent residences) that can easily number into the hundreds. With ridgeline projects the nearest receptors are usually all around the base of the mountain or promontory on which the turbines are proposed and the effective project area (i.e. the region where residences exist within possible earshot of the project) can be vast. Consequently, it is best, if not essential, to use a modeling program that allows for the reasonably easy importation and scaling of a site map that shows not only the turbine locations but also all of the surrounding potentially sensitive receptors. Such a map is normally in shapefile (.shp) format with a layer for the turbines, a layer for structures (unfortunately not often differentiated into houses, barns, garages, commercial buildings, etc.) and layers for other features such as roads or topography. While nominally possible, it is not normally desirable to use only numerical tables of turbine coordinates to create the model for the principal reasons that a separate base map needs to be found and imported and different coordinate systems can become confused. In addition, publically available maps (used as a base map for the model) almost never show, or at least accurately show, all the residences in the vicinity of the project.

In addition to the turbines and houses the topography of the site often needs to be considered in the model – not only because of the line sight between the turbines and houses may be partially blocked or obstructed, but more generally because the source-receptor distance at sites with fairly dramatic terrain is affected and usually lengthened when modeled in three-dimensions. Consequently, a program that has the ability to import terrain contours and then mathematically consider their effect on sound propagation is essential for any project in a hilly or mountainous setting. This factor can only be safely ignored for sites with fairly flat or gently rolling topography.

In terms of output the most important element is the ability of the program to map sound contours in high resolution over the input base map. The potential impact from any wind project is normally graphically evaluated from contour plots. It is the number of houses within a certain threshold or sound level that usually determines whether the project is likely to result in complaints or not or whether it will comply with regulatory noise limits.

In terms of specific programs, Cadna/A® developed by Datakustik GmbH (Munich, Germany), appears to be used most often by engineers and consultants and is fully capable of importing shapefiles, modeling complex terrain and producing detailed contour maps.

The second most common noise prediction program is the sound emissions component of the WindPRO® software package (EMD International A/S, Denmark), which is a generalized siting tool for wind farms. The noise prediction module is only one aspect of the much larger program.

SoundPLAN® (Braustein & Berndt GmbH, Backnang, Germany), is evidently similar in capability to Cadna/A® but, for reasons that are unclear, is not often used for wind turbine analyses despite its apparent capability to integrate the NORD2000 algorithm as an optional calculation methodology.

One other program, WindFarm® (ReSoft Ltd, U.K.), is another general project design package of which the noise component is only a small part.

Any one of these programs would be generally acceptable for modeling the noise from a new project.

4.1.3 *Model Inputs*

In contrast to models of acoustically complex fossil fueled power plants that consist of dozens of major sources, the sound levels of which often need to be estimated, the input to a wind turbine project model is a single sound power level spectrum that is known with considerable accuracy. Turbine sound power levels are tested in accordance with IEC 61400-11[5], in which highly specialized and meticulous techniques are used to derive the sound power level of a wind turbine over a range of wind speeds from 6 to 10 m/s (as measured at 10 m above ground)[b]. The best input to use for any model is the maximum octave band sound power level frequency spectrum taken directly from a field test report.

Although such reports are sometimes made available by manufacturers, it is more common for the acoustical performance to be reported second-hand (based on either an IEC 61400-11 test or analytical calculations) in a technical specification document published by the manufacturer. The reported sound levels may or may not contain an explicit design margin and/or may be stated as warranted sound levels. While input sound levels that have been artificially inflated would tend to needlessly overstate the potential impact of a project, there often isn't any alternative to using whatever performance the manufacturer decides to publish. Whatever the source of the data is, it should be clearly stated in the impact assessment report.

4.1.4 *Modeling Methodology*

Recommended procedures for modeling wind turbine project noise are as follows:

- Begin with a base map showing the turbine locations and all potentially sensitive receptors in and around the project area (residences, schools, churches, etc.)
- Build up the topography of the site in the noise model if the terrain features consist of hills and valleys with a total elevation difference of more than about 100 ft. – otherwise flat terrain can be assumed
- Locate point sources at the hub height of each turbine (typically 80 m)
- Use the maximum octave band sound power level spectrum for the planned turbine model or the loudest model of those being considered
- Assume a ground absorption coefficient (A_g from ISO 9613-2) appropriate to the site area (a moderate value of 0.5 generally works well as an annual average for rural farmland, although higher values specifically for farm fields during summer conditions may be appropriate. A value of 0 (100% reflective ground) is likely to produce highly conservative results)

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[b] In its current edition (2.1). A revision to this standard has been in development for some time that would expand this wind speed range and add a number of other refinements (and complexities) to the test procedure. It is unclear whether this new edition will ever actually be adopted.

- Assume ISO "standard day" temperature and relative humidity values of 10 deg. C/70% RH unless the prevailing conditions at the site are substantially and consistently different than that
- Plot the sound contours from the project assuming an omni-directional wind out to a level of 35 dBA (shading the area between each 5 dBA gradation with a different color often greatly improves legibility)

The assumption of an omni-directional wind means that the sound power level of the turbine, which is measured in the IEC 61400-11 procedure downwind of the unit, is modeled as radiating with equal strength in all directions; i.e. the sound level in every direction is the downwind sound level. Although this may seem be depict an unrealistic situation and over-predict upwind sound levels, the fact of the matter is that this approach generally results in predictions that are consistent with measurements irrespective of the where the receptor point is located. Although somewhat counterintuitive, the reason for this is that wind turbine noise under most normal circumstances is not particularly directional and generally radiates uniformly in all directions. As an example, the plot below shows the sound levels measured in three directions 1000 ft. from a typical unit in a rural project in Southern Minnesota. Although there are periods when the levels differ, implying some directionality, the majority of the time all three sound levels are generally about same irrespective of the wind direction. Moreover, the sound level at the downwind position is almost never elevated relative to other directions as one might expect.

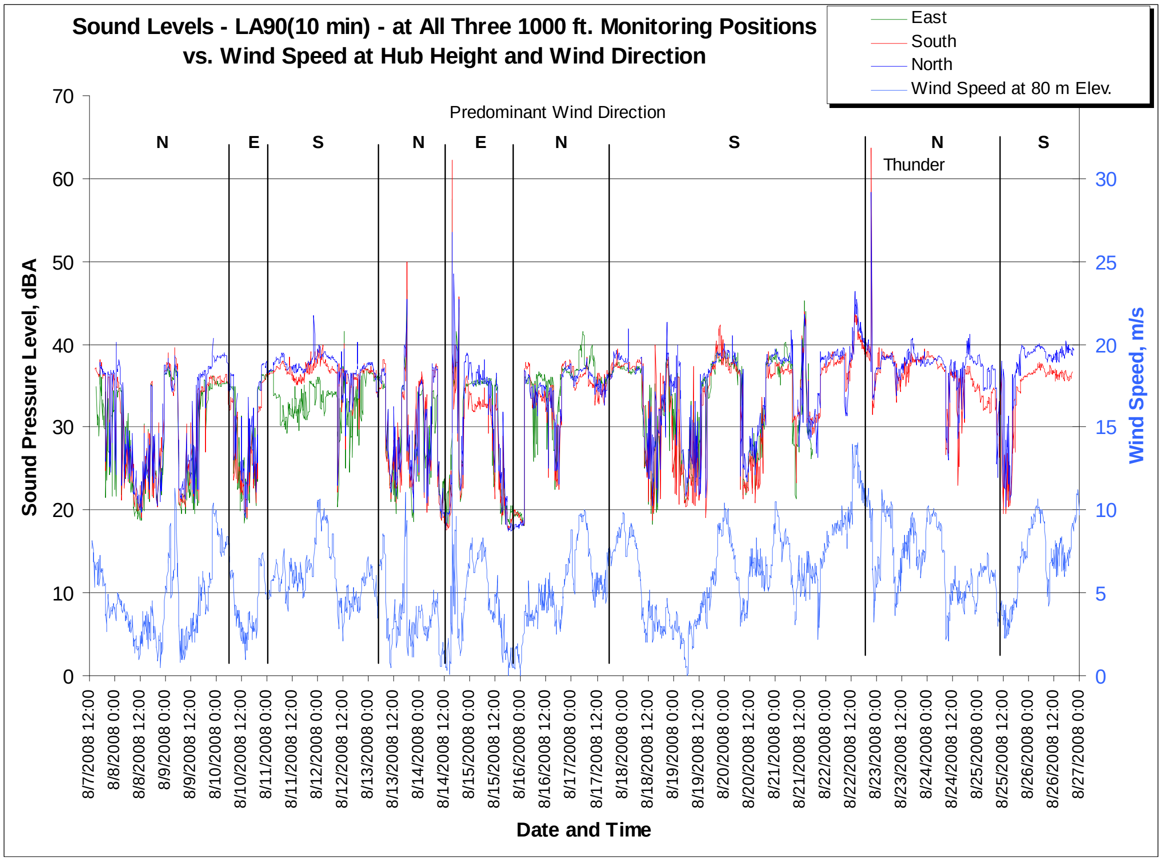

Figure 4.1.4.1 *Sound levels at 1000 ft. from a Typical Unit in Three Directions*

4.1.5 *Interpretation of Model Results*

An example plot for a hypothetical project, prepared using Cadna/A® and the procedures outlined in Section 4.1.4, is shown in Figure 4.1.5.1. In this instance, the units are located on a fairly prominent ridgeline and the topography has been recreated in the model.

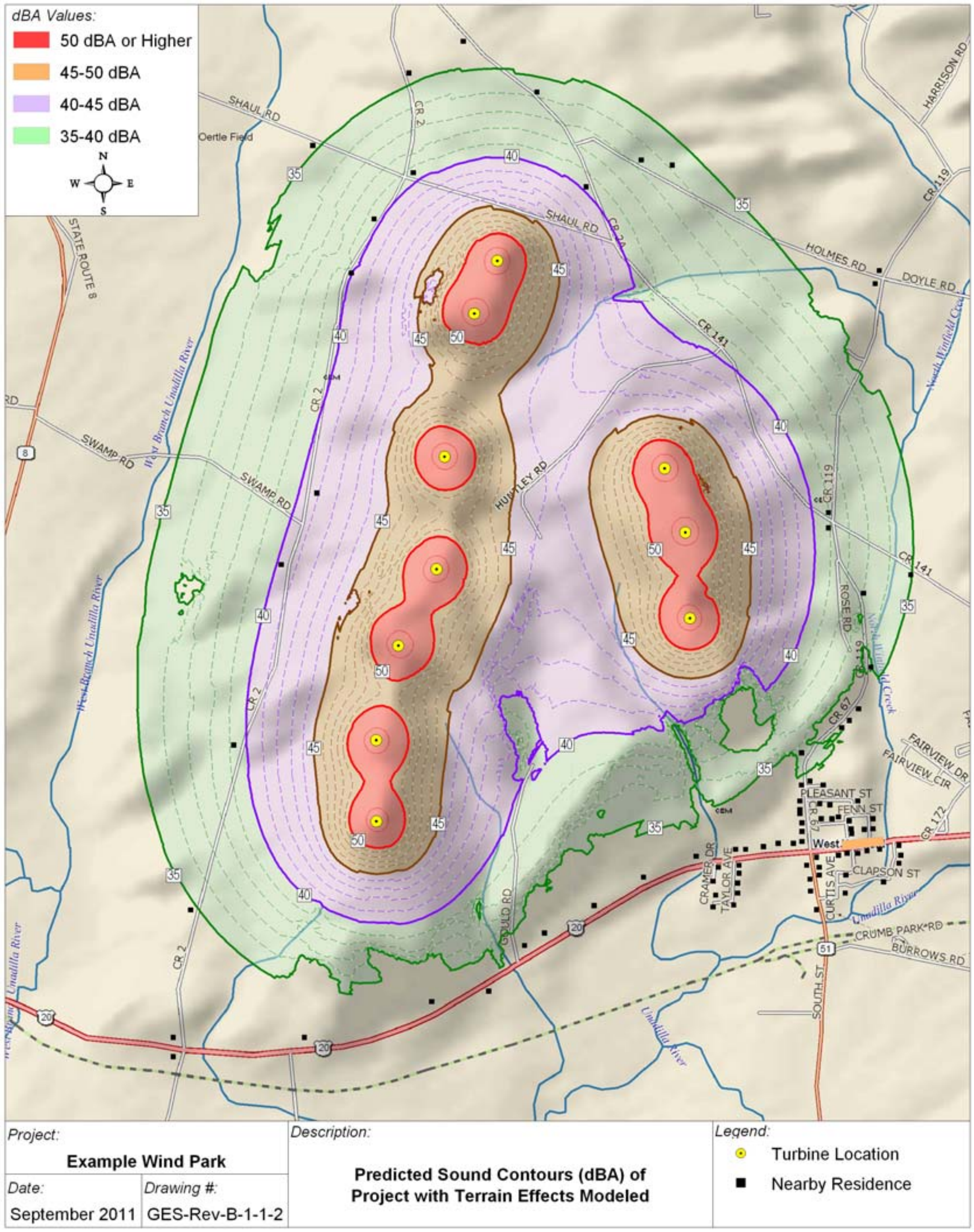

Figure 4.1.5.1 *Noise Model Plot – Example A*

Based on the plot, the potential noise impact from this project can be characterized as being fairly mild in the sense that nearly all of the residences in the vicinity of the project are expected to see a mean sound level of 40 dBA or, in most cases, less. The few houses that are nominally above 40 dBA are only marginally above that threshold and none are close to the 45 dBA absolute upper limit. The green region between 40 and 35 dBA generally represents the area where in all likelihood project noise would still be readily audible some of the time, if not much of the time, but at a fairly low magnitude. The audibility of and reaction to sound levels in this range would be somewhat dependent on the level of natural background sound in the area, since environmental sound levels in rural areas are commonly in the mid to high 30's dBA during the moderate wind conditions necessary for the project to operate – or, in other words, the background sound level could be roughly equivalent to the project sound level limiting its perceptibility. Below 35 dBA project noise generally becomes so low that it is only rarely considered objectionable even in extremely low noise environments. Complete inaudibility does not occur for quite some distance from most projects in quiet areas because of the distinctive, periodic nature of wind turbine noise. The actual distance to the point of inaudibility varies amorphously with atmospheric conditions and is generally much further at night than during the day. Consequently, the exact reaction to any project can never be predicted with certainty because project noise is often audible to some extent, at least intermittently, far from the project. However, the studies of response to wind turbine noise discussed in Section 3.0 suggest that the threshold between a mild or acceptable impact and a fairly significant adverse reaction is a gray area centered at 40 dBA.

An additional sound contour plot is shown in Figure 4.1.5.2 representing another hypothetical but typical project, this time in essentially flat Midwestern farm country.

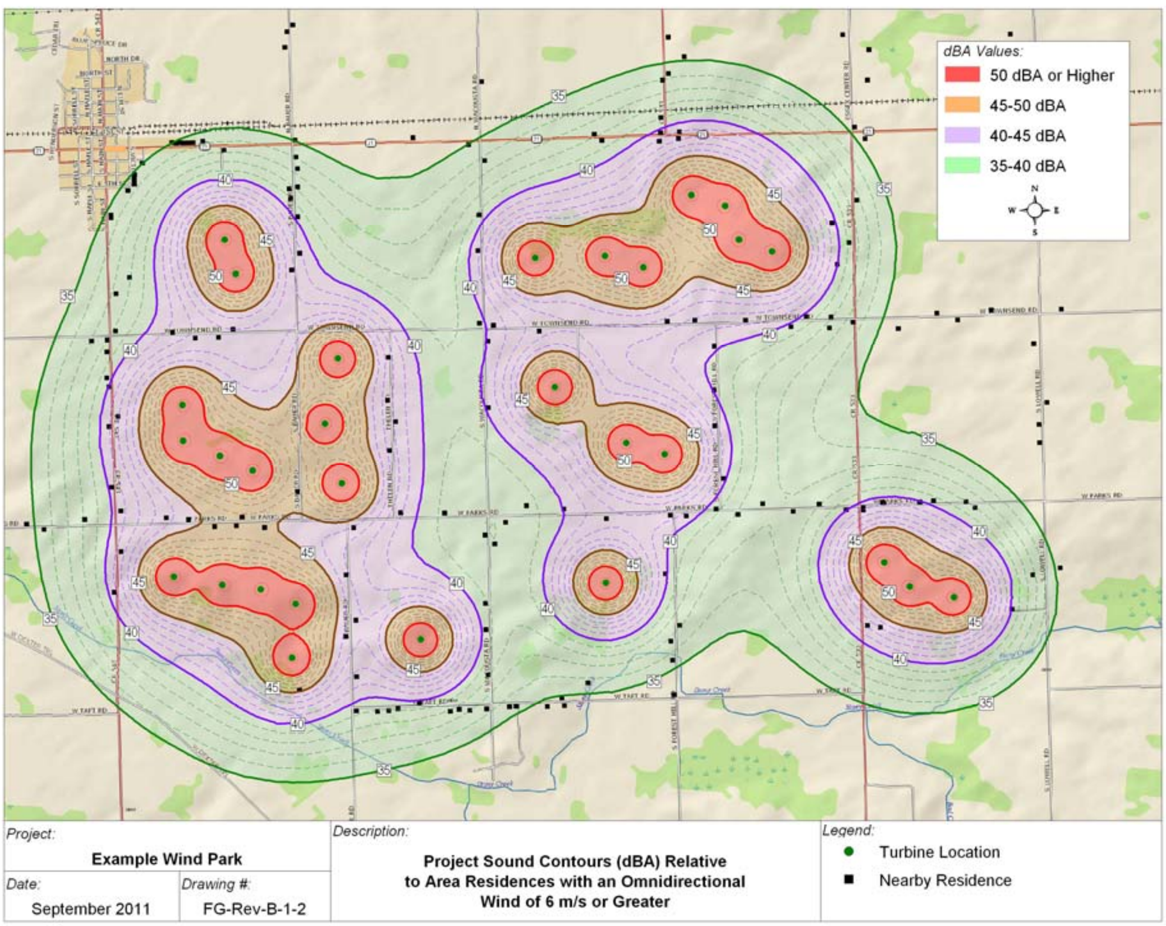

Figure 4.1.5.2 *Noise Model Plot – Example B*

In contrast to Example A, there are many homes inside of the 40 dBA sound contour in this scenario and even a few above 45 dBA, which is a common occurrence. One would have to conclude that at least a few complaints about noise would arise from this project if it were to proceed to completion in this configuration. The population density is such at this site that an optimization study should be undertaken to evaluate the feasibility of removing and relocating turbines outside of the present site area so that sound levels are substantially reduced at the homes with predicted levels of above 45 dBA and so that the number of residences above 40 dBA is dramatically diminished.

4.2 Pre-Construction Background Sound Surveys

Noise impacts can be evaluated in both absolute and relative terms. In the discussion immediately above the reaction to the example projects was estimated directly from the predicted project sound levels, neglecting background noise or essentially assuming a rural setting with generally quiet background sound levels. However, not all sites are the same and it is often prudent to perform a survey of existing conditions to establish just what the baseline sound levels are at residences in the proposed project area. In general, the audibility of, and potential impact from, any project is a function of how much, if at all, its noise exceeds the prevailing background level. A comparison between the predicted/modeled sound level from a proposed project and the actual background sound level measured in the project area under comparable wind and weather conditions gives a site-specific indication of the potential relative impact from the project.

Such a survey is not essential in all cases but is recommended when:

- Unusually high background levels are suspected (e.g. due to the proximity of a major highway, urban areas or existing industrial facilities)
- Unusually low background levels are suspected
- The project is unusually large or controversial
- There is simply a desire to carry out a complete and thorough assessment

4.3 Recommended Field Survey Methodology

The objective of a pre-construction survey is to establish what levels of environmental sound are currently being experienced at typical residences within the general project area in order to form a baseline against which the predicted sound emissions from the project can be compared. There is no need, nor would it be practical, to measure at every house. The idea is to get a set of samples that can be considered representative of the overall site area. In rural areas away from significant sources of man-made noise, it is common to find that the sound levels at all positions are generally similar indicating that background sound levels are for all intents and purposes uniform throughout the site area.

Contrary to popular belief, such a survey is *not* useful for the purpose of establishing the pre-existing environmental sound level as a baseline against which to compare the measured sound emissions from the completed project. The background sound level varies dramatically with time, typically over a dynamic range of 30 dBA or more, depending not only on the wind speed but many other factors, such as the prevailing atmospheric conditions, the time of day, season of the year, etc., so the level measured one or two years earlier cannot be taken to accurately represent the background level present during an operational compliance test. In fact, the only valid background level is the background level occurring, literally, at the same time that the operational sound level is measured. A methodology for overcoming this seeming impossibility is discussed later in Section 5.1.

4.3.1 *Measurement Positions*

Specific monitoring positions should ideally be located at or near typical residences in the site area. It is the sound level where people actually are most of the time and especially at night that is of primary importance (rather than at property lines, for instance). Permission to set up equipment on private property is usually freely granted upon request.

If a site is largely flat and homogenous in nature (e.g. rural farmland away from any major highways, urban areas or industry) monitor positions should be selected at points that are more or less evenly distributed over the project area. In such simple cases, 6 to 8 monitoring positions are usually more than sufficient even if the project area is fairly large.

For more complex sites, where the topography is significant or where man-made noise sources already exist, more monitoring positions will generally be required with the objective of capturing sound levels at residences in each kind of setting. A “setting” is defined as an area where the prevailing environmental sound level is suspected of differing significantly from other parts of the project area. For example, houses in the bottom of ravines or valleys may experience different ambient sound levels than nearby houses on exposed hilltops. Monitors should be located at positions representative of both of these settings. Another type of unique setting might be at homes that are located directly on a major road or highway or in an urban area versus others in the project area that are in remote areas. In some cases, a wind farm already exists adjacent to the area where a new project is proposed. Measurements should be made at homes that have maximum exposure to the sound emissions from the operating turbines for comparison to measurements at residences that are remote from the existing project. The total number of monitoring positions is generally limited by equipment availability and logistical concerns but no more than about 12 to 14 positions are normally required, even for the most complex sites.

4.3.2 *Survey Duration and Scheduling*

Short duration spot samples are insufficient to capture environmental sound levels over the variety of wind and atmospheric conditions that are relevant to project operation. For example, a brief sample on a calm, quiet night is meaningless in the sense that it does not represent the background sound level that will exist on a continuous basis or during the moderately windy conditions necessary for the project to generate noise. In fact, background sound levels in the rural areas where wind projects are most commonly sited are remarkable for their variability and substantial dependency on wind speed. It is the background sound level that occurs when it is moderately windy that is actually of interest for comparison to project sound emissions. In the very typical example below, the background sound level measured at four positions widely distributed over a proposed wind project site in the Midwest can be seen to parallel the concurrent wind speed and, moreover, to vary dramatically from 17 dBA during calm conditions to 54 dBA during windy conditions.

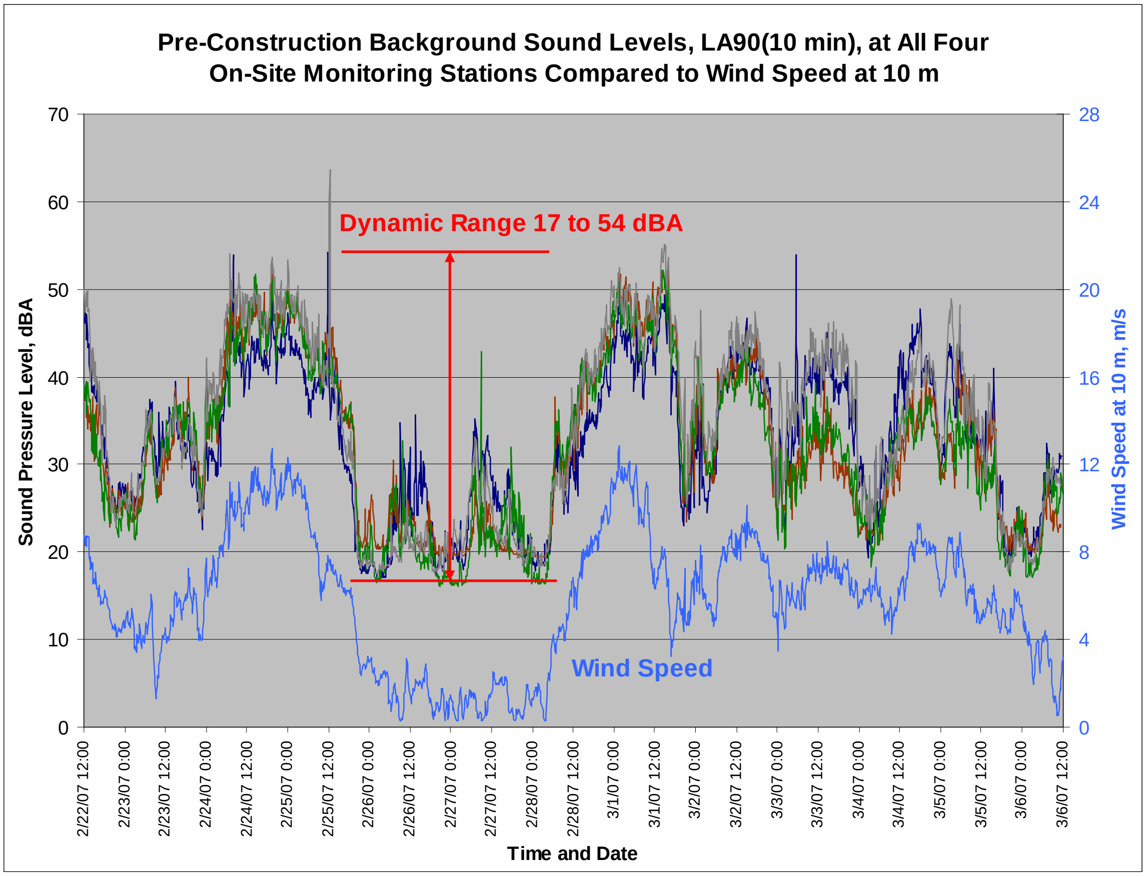

Figure 4.3.2.1

Consequently, a long-term, continuous monitoring approach is needed in which multiple instruments are set up at key locations and programmed to run day and night for a period of about two weeks or more. In essence, it is necessary to cast a wide net in order to capture sound levels during a variety of wind and atmospheric conditions and provide sufficient data so that the relationship between background noise and wind speed can be quantitatively evaluated.

Field experience suggests that an adequate range of wind speeds, from 0 to 10 m/s at 10 m above ground level, will usually be observed over any given 14 day period at most wind energy project sites, except perhaps during the low wind season at sites that might have very pronounced seasonal wind characteristics. Probably the principal reason for this observation is that this length of time is large relative to the time normally taken for weather patterns, wind directions and general atmospheric conditions to change, which essentially ensures that the data are statistically independent, as discussed in great detail in ANSI S12.9-1992/Part 2[27]. Data independence implies that the test results can be taken to represent the longer-term acoustic situation for that area, at least for the general time of year of the test. However, if a review of the weather conditions that occurred during the survey period shows that the winds were unusually calm or if an insufficient number of data points were collected at the higher wind speeds, the survey may need to be extended for another two weeks. Low wind conditions are most commonly captured and the vast majority of the measurements will be for conditions below or just above the cut-in wind speed. High winds normally occur intermittently over a few hours or a few days separated by sometimes lengthy periods of relatively calm conditions. It may sound counterintuitive, but it is not critical to capture extremely high wind conditions, say higher than about 12 m/s at 10 m, since most complaints and issues with wind turbine noise occur during moderate or even light wind conditions, while background noise tends to predominate under very windy conditions.

As a practical matter, the instruments for such a survey are set up, started and left to run unattended for the nominal two-week test period following which they can be retrieved and downloaded. Of course, one could stay on site through the test making additional intermittent manned measurements and observations but the very high cost of such an effort would be difficult to justify, particularly since it would not necessarily guarantee a better or more definitive result than could be derived from the monitor data alone.

In terms of scheduling, it is highly preferable to conduct this type of survey during cool season, or wintertime, conditions to eliminate or at least minimize possible contaminating noise from summertime insects, frogs and birds. In addition, it is best for deciduous trees to be leafless at sites where they are present in quantity to avoid elevated sound levels that might not be representative of the minimum annual level. Human activity, such as from farm machinery or lawn care, is also normally lower during the winter. While summertime surveys can be successful they should, as a general rule, be avoided wherever possible because nocturnal insect noise, for instance, can easily contaminate the data and make it impossible to quantify the relationship between sound levels and wind speed.

In addition to seasonal concerns, it is desirable, when practical, to attempt to schedule the survey set up to just precede a predicted period of moderate or high winds. This not only ensures that the survey period will capture these winds but also creates an opportunity for manned observations and measurements to be made for a day or two to augment to the longer term monitoring survey.

4.3.3 *Instrumentation and Test Set-up*

As with any field sound survey, what equipment is used and how it is deployed must adhere to certain minimum technical standards. These requirements are generally described in numerous standards, such as ANSI S12.9-1992/Part 2[27]; however, the focus of this section is not to repeat and belabor those details but rather to point up what adaptations need to be made for the specific application of performing general site-wide surveys for wind turbine projects. As mentioned earlier, no standard exists that can be directly used for this purpose, if only because they limit data collection to low wind conditions.

In terms of instrumentation, most environmental sound measurement standards recommend the use of Type 1 precision equipment per IEC 61672-1[28] or ANSI S1.43-1997[29] while also allowing for the use of Type 2 equipment. There is certainly no reason on technical grounds to oppose this recommendation but, from a practical perspective, it is often necessary to use Type 2 equipment for surveys of this type because of the large number of instruments needed. The normally negligible difference in technical performance between these two instrument classes is totally inconsequential within the inherently and unavoidably imprecise nature of this type of survey. It is much more important that the equipment is durable, reliable and specifically designed for extended use in the outdoors. Delicate and expensive Type 1 precision grade equipment can be unreliable in such applications or even unable to be programmed as a data logger.

Although high cost and extreme precision are not essential, the functional capabilities to statistically integrate sound levels over a user defined time period and automatically store the results are necessary. Because the on-site wind and weather monitoring towers, or met towers, normally integrate and store measurements in 10 minute increments it is convenient, if not necessary, to measure and store sound data in synchronization with the wind data collected by these towers for later correlation. It is evidently universal practice for met towers to store data 6 times an hour in 10 minute intervals that begin at the top of the hour; as in 9:00, 9:10, 9:20, etc. Consequently, sound data logging should be started using a trigger function to begin at the top of an hour and not randomly by the manual push of the start button. The timers on all instruments should be exactly synchronized to local time. Of course, all of the instruments must be field calibrated at the beginning of the survey and checked again for drift at the end of the survey.

Because this long-term survey approach involves unattended monitoring, the instrument and the microphone must be capable of withstanding damage, interference or outright destruction from rain and snow, which, among other things, means that the ground plate technique specified in IEC 61400-11 – where the microphone is laid flat in the center of a board on the ground and covered with one or more hemispherical windscreens – is not a viable option, despite its otherwise highly desirable advantage of minimizing wind-induced pseudo noise. Consequently, the microphone must be mounted above ground level and protected from wind-induced distortion by a spherical weather-treated windscreen, which normally entails a higher density foam that is hydrophobically treated to shed water (windscreens and wind-induced noise are discussed in detail later). As a general rule, a slightly lower than normal microphone height of about 1 m above ground level is preferred for this application on the premise that wind speed diminishes exponentially with decreasing elevation theoretically going to zero at the surface, or boundary layer. To illustrate this, the nominal wind speed profile, or shear gradient, per Eqn. (7) in IEC 61400-11 is illustrated below in Figure 4.3.3.1 for a common turbine operating condition where the wind speed is 6 m/s at the standard elevation of 10 m above ground level.

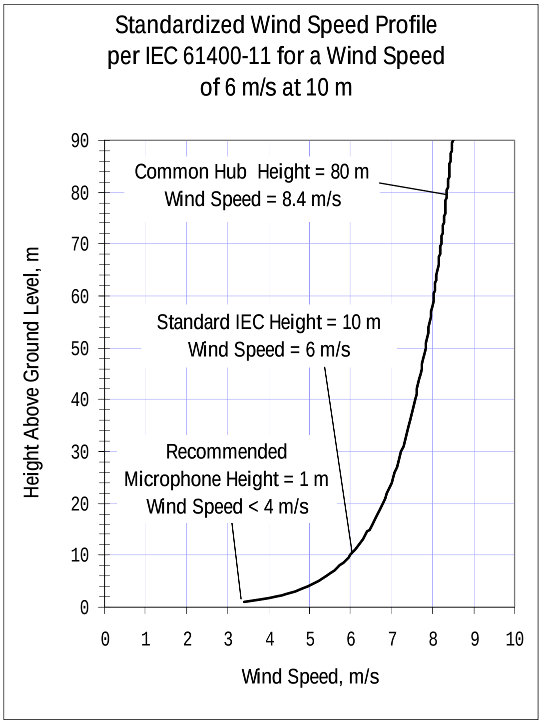

Figure 4.3.3.1

For these moderate wind conditions, the wind speed at a 1 m microphone height would be less than about 3 or 4 m/s, which as shall be seen later, means that distortion from wind blowing through the windscreen is of little or no consequence with respect to the A-weighted sound level so long as an extra large windscreen is used (typically 7” in diameter, as a minimum).

In addition to arranging for the microphone to be about 1 m off the ground so that it is not adversely affected by precipitation, it is also necessary to keep the instrument itself dry and secure in a waterproof case, which is best mounted above the ground on a fencepost, utility pole or other support.

While the microphone can be remotely connected to the instrument with a cable and independently supported, another option is to use a self-contained system where the microphone is attached to the instrument case with a rigid boom to hold the microphone away from the box and the entire assembly is mounted 1 m above ground level with a strap as shown, for example, in Figure 4.3.3.2. While there is nothing wrong with supporting the microphone separately on a tripod there is a tendency, unique to wind turbine survey work, for tripods to blow over, even after being weighted down and/or firmly staked to the ground. The use of temporary metal fence posts to support either the microphone alone or the entire system is a more reliable option and is sometimes the only option in places where there are no existing supports, such as in open fields.

Figure 4.3.3.2 *Typical Integrating Sound Monitor with 7" Weather-treated Windscreen*

In addition to sound level meters it is also advisable to set up at least one temporary weather station at the most exposed measurement position in order to measure the wind speed at microphone height and other parameters such wind direction and rainfall. All weather data should also be logged in 10 minute increments for later correlation to the sound data.

4.3.4 *Measurement Quantities*

For a background survey of this type the principal quantity of interest is the L_{A90} statistical measure, which is the A-weighted sound level exceeded 90% of the measurement interval (10 minutes in this case). What this means is that the sound level is higher than the L_{A90} value most of the time and, conversely, that the L_{A90} level represents the near-minimum sound level for each interval. It essentially captures the momentary, quiet lulls between sporadic noise events, like cars passing by, and, as such, is a conservative measure of the environmental sound level.

The average A-weighted sound level, or L_{Aeq}, which is the fundamental metric for highway noise surveys and the calculation of the Day-Night Average Level, L_{dn}, is unsuitable for wind turbine background surveys in rural areas because this level is extremely sensitive to contaminating noise events, such as from occasional traffic, planes flying over or dogs barking – things that cannot be relied on to be consistently present and available to potentially mask project noise on a permanent basis. The L_{A90} measure, on the other hand, automatically excludes these events for the most part and essentially defines the true "background" noise floor.

4.4 Analysis and Interpretation of Results

4.4.1 *Data Analysis and Wind Speed Correlation*

At the completion of the survey the L_{A90} sound levels measured at all positions should be plotted together to evaluate their consistency and to determine if the levels in different settings should be segregated. For example, if the sound levels at sheltered valley locations are consistently lower than measurements on higher ground then the data should be analyzed separately to develop typical background levels for each setting. Somewhat surprisingly, the need for this kind of separate treatment is rare and the much more common result is for the sound levels at all of the positions to be generally similar in magnitude at any given time with each generally following the same temporal trends and intertwining with each other. As a typical example, the as-measured L_{A90} levels at 7 positions spread over a fairly large site in Southern Minnesota are shown below.

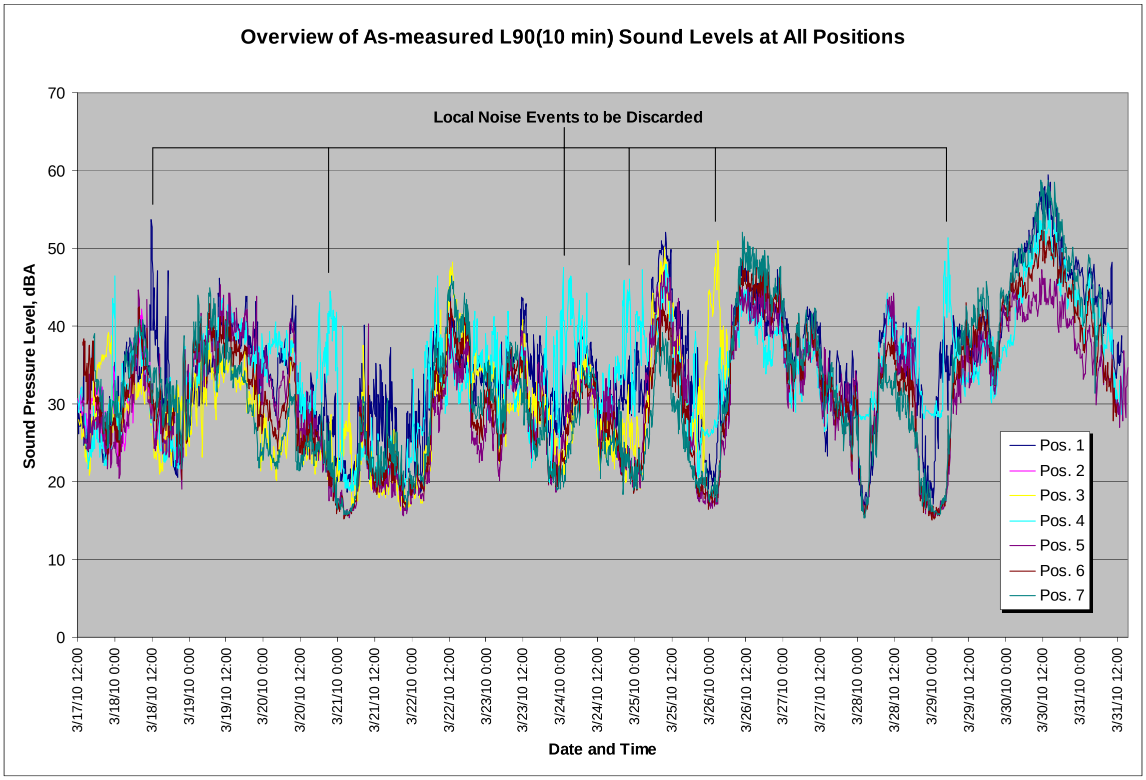

Figure 4.4.1.1

All positions follow each other and there is no one position that is consistently higher or lower than the others. Since these positions are miles apart from each other one would not expect exact agreement yet the levels are remarkably similar indicating that the environmental sound level over the entire site are is more or less uniform (sometimes termed a “macro-ambient”). If obvious contaminating events - those occurring at only one position - are discarded (as noted in the figure) the arithmetic average of the remaining data points can reasonably be considered the typical sound level over the site area. However, the question becomes: what is the sound level? The level varies substantially with time from almost complete silence (17 dBA) to nearly 60 dBA. The background level is obviously not a single number. The reason for this variation becomes clear if the average site-wide sound level is compared to the concurrent wind speed (Figure 4.4.1.2).

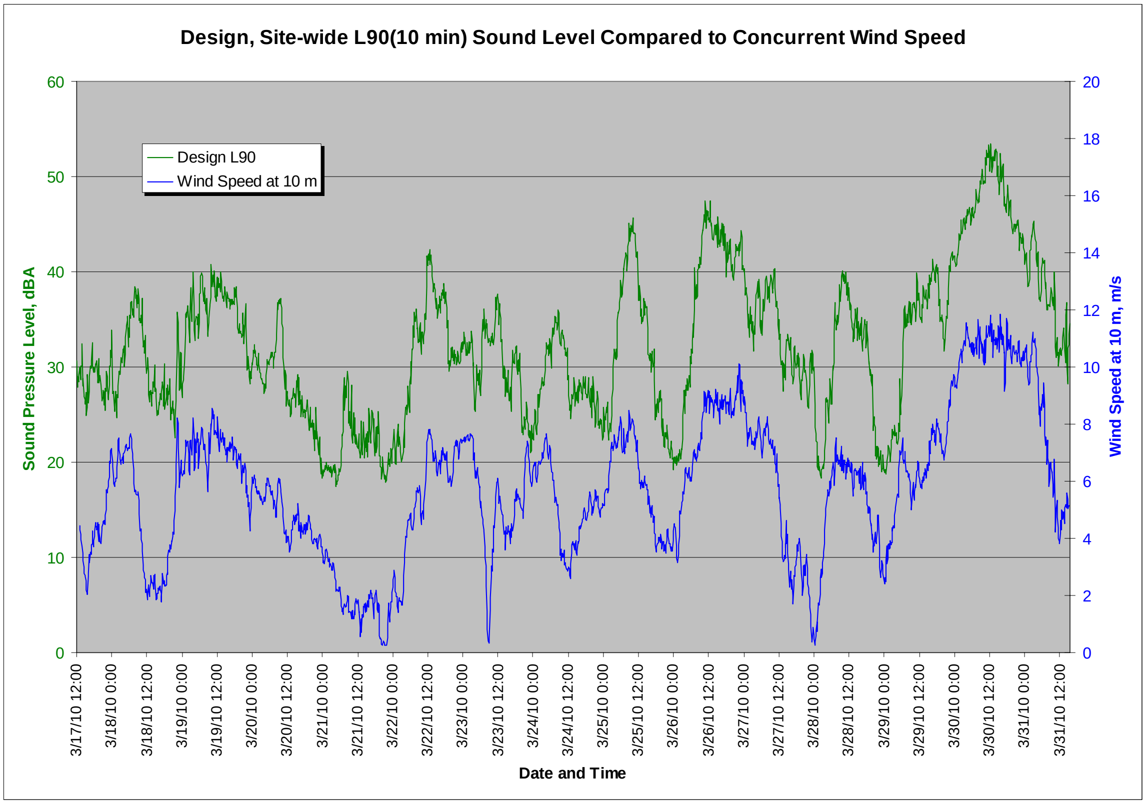

Figure 4.4.1.2

Clearly, the sound level in this area is driven by wind-induced sounds; in this case, mostly grass or crops rustling. Consequently, the sound level is almost entirely a function of the wind speed occurring at any given moment. This relationship can be quantified by re-plotting the sound levels in Figure 4.4.1.2 as a function of wind speed (normalized to a standard height of 10 m per Eqn (7) in IEC 61400-11).

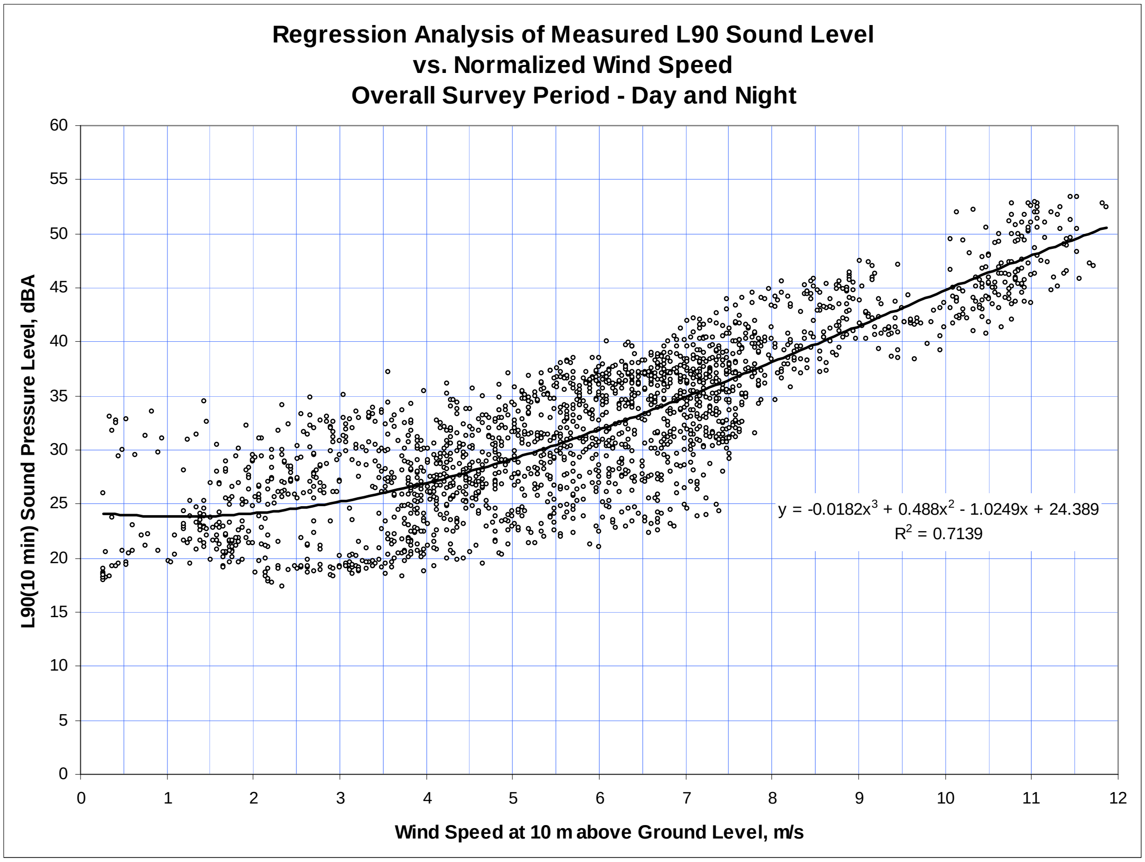

Figure 4.4.1.3

The central trendline through the data gives the mean L_{A90} sound level for any particular wind speed – at least in terms of the overall survey period.

It is important to point out in this context that, although the wind speed correlated to the sound data is the normalized value at the IEC standard elevation of 10 m, the measurement is actually taken at the top of the met tower, usually 60 m (197 ft) above ground level. Thus, the wind speed associated with turbine operation (not far below hub height) is directly correlated to the sound level measured near ground level; where the wind speed may well have been negligible. In other words, Figure 4.4.1.3 is *not* showing the relationship between the sound level and wind speed at the measurement position, as is quite often supposed.

4.4.2 *Daytime vs. Nighttime Levels*

Since nighttime conditions are of the most relevance with respect to potential disturbance from project noise, the data should be broken down into daytime (7 a.m. to 10 p.m.) and nighttime (10 p.m. to 7 a.m.) levels to see if it is significantly quieter at night - something that is not always particularly apparent in the level vs. time data (Figure 4.4.1.1). In this instance, the nighttime levels (Figure 4.4.1.4) are substantially quieter than during the day (Figure 4.4.1.5), particularly, in the vicinity of 6 m/s, which is usually the point where wind turbines first start to generate significant noise but the background level is typically still rather low thereby maximizing the potential audibility of project noise. In these examples, the mean background level for 6 m/s wind conditions during the day is 34 dBA while the nighttime level is about 28 dBA. Both of these levels are extremely quiet, but 28 dBA is so low that any potential masking from background noise can essentially be neglected as insignificant.

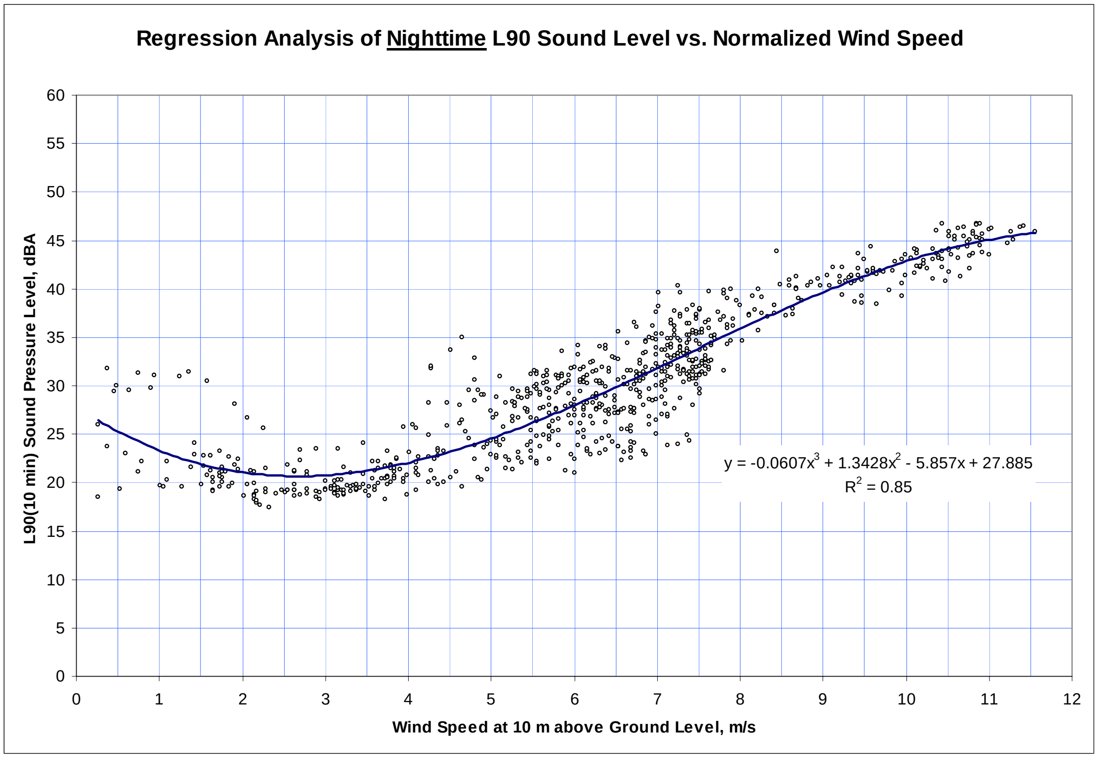

Figure 4.4.1.4

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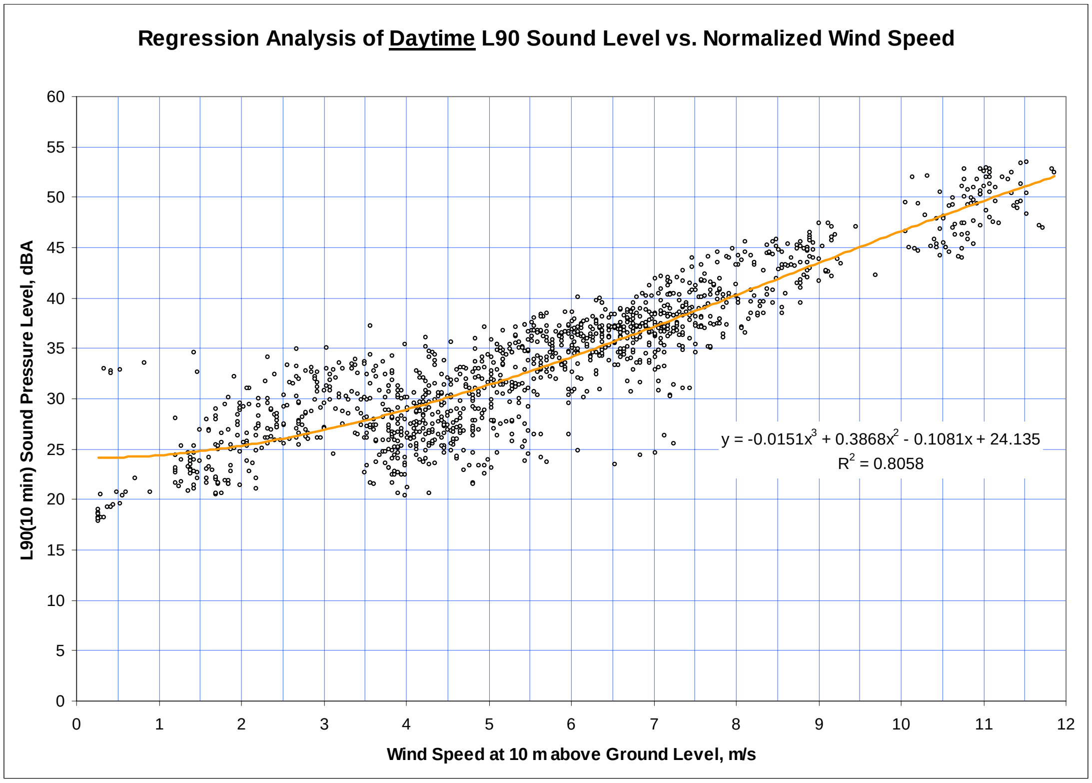

Figure 4.4.1.5

4.4.3 *Assessing the Potential Impact*

The sound levels measured in this survey, especially at night, indicate this site is an extremely quiet rural environment where any masking from wind-induced background noise can effectively be disregarded during moderate wind conditions (4 to 7 m/s). Under high wind conditions, say around 10 m/s, background noise is in the mid-40's dBA irrespective of time of day and therefore will act to partially obscure project noise, but during low wind conditions when the project is operating at low load an adverse impact can be expected unless the mean project sound level is kept to a relatively low level at residences. In this instance, it would be advisable to strictly design the project so that all residences are predicted to have average sound levels no higher than 40 dBA.

In general, background survey results may be used to establish a very rough impact threshold of 5 dBA over the ambient when the nighttime L_{A90} is about 35 dBA or more under what is usually the critical wind speed of 6 m/s. For example, if the measured level is 40 dBA then little adverse reaction might be expected from project levels up to 45 dBA (predicted with the project operating during comparable 6 m/s wind conditions). This 5 dBA increase metric does not hold for very low background levels (<35 dBA) because the background sound level and the project level both become so low as to be insignificant in absolute terms. If the background were 10 dBA, for instance, there would be no need to design a project to not exceed 15 dBA – both levels represent almost complete silence and are inconsequential. For low background situations like the example discussed above the outcome of the survey would be to set a firm upper limit of 40 dBA at residences. In terms of a potential noise impact, a low background level combined with predicted project levels of more than 40 dBA at numerous residences would be an undesirable situation likely to lead to complaints.

Although 6 m/s may be assumed in most cases to be the critical wind speed - i.e. the point where turbine noise is likely to be loudest relative to the amount of background noise available to potentially obscure it – the site-specific critical wind speed may also be calculated by comparing the sound power levels of the particular turbine model planned for the project with the L_{A90} background levels actually measured at the site. The critical condition corresponds to the point where the simple differential between these two values is maximum, as illustrated in the following example.

Table 4.4.3.1 *Comparison of Turbine Sound Power Levels to Measured Background Levels to Determine Critical Wind Speed*

Wind Speed at 10 m, m/s	Measured Overall L_{90}, dBA	Turbine Sound Power Level, dBA re 1 pW[c]	Differential
4	27	95	68
5	29	99	69
6	**32**	**102**	**70**
7	35	104	69
8	38	104	66
9	41	104	63
10	45	104	59
11	48	104	56

In this case (based arbitrarily on the data in Figure 4.4.1.3) the maximum differential of 70 occurs at 6 m/s – meaning that the sound emissions from the turbine are the highest at this particular point relative to the background level indicating that project noise would theoretically be most audible under these conditions. Ironically, the maximum audibility point does not usually correspond to the wind speed when the turbine first reaches its maximum noise emission point (in this example 7 m/s and a sound power level of 104 dBA re 1 pW).

As a side note, this analysis illustrates one of the reasons why it is beneficial to normalize the met tower wind speed data to 10 m; namely, because wind turbine sound power levels are expressed as a function of wind speed at 10 m above grade (and not at hub height). Consequently, the background sound levels and the turbine sound levels are all compared on an equal footing.

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[c] The fundamental unit of sound power is Watts and sound power levels are expressed with reference to 1 picoWatt, or 10^{-12} W. By convention this reference is explicitly stated to help distinguish power levels from pressure levels, which are measured in terms of Pascals.

5.0 Measuring Wind Turbine Sound Emissions

5.1 Project-wide Compliance Testing

5.1.1 *Historical Approaches*

In general, it has been difficult, historically, to devise or settle on a completely satisfactory methodology for testing newly completed wind projects for the purpose of determining whether or not they are in compliance with permit or regulatory conditions. One of the principal stumbling blocks has generally been accounting in some meaningful way for background noise, since the total measured sound level at the typically substantial distances to residences and, therefore, the point of measurement, commonly contains a very prominent background component that cannot be disregarded without causing the result to be erroneously high. It is, of course, the project-only sound level and not the total sound level that is limited by regulations. Consequently, it is the project-only sound level that is sought in such surveys.

Existing guidelines and standards that mention the topic of compliance testing at all do not lay out or detail test procedures that are entirely satisfactory in this and other respects. For example, the often beleaguered[30] ETSU-R-97 report *The Assessment and Rating of Noise from Wind Farms*[31] published by the Department of Trade and Industry in the U.K. addresses the issue of background noise in one sentence, quoted below, by suggesting simply that one might want to measure operational turbine noise at night.

> To minimize the effects of extraneous noise sources it may be necessary to perform these measurements during night-time periods when other human and animal activity noise sources are likely to be at a minimum.

This approach, which involves measuring only for a relatively short period of time (20 to 30 $L_{A90,\ 10\ min}$ samples), is connected with the idea of taking measurements only at, or close to, a specific critical wind speed identified from "monitoring", carried out in an unspecified manner, and correlated to logged observations by complainants as to when the "noise is most intrusive" (ibid). In short, the idea is for the test engineer to be physically at the location and ready to take measurements when the wind conditions that result in maximum noise are occurring - so long as those conditions are happening at night on a night when the background sound level is negligible (i.e. roughly 10 dBA or more lower in magnitude than the turbine sound level). As might be imagined, the unfortunate reality is that the probability of all these things coming together at the same time is miniscule. In particular, it is typically difficult, for a number of reasons, for a test engineer to schedule a site visit to coincide with a particular wind speed or direction.

In general, the notion of being on hand to observe and measure wind turbine noise when it is at its loudest may sound reasonable on paper but it is seldom practical to actually do it.

Another approach to the issue of background noise that has been used, for example in the New Zealand Standard NZS 6808:1998 *Acoustics – The assessment and measurement of* *sound from wind turbine generators*[32], is to measure the background level at one time, say, prior to construction or start-up, and the operational noise from the project at another time - and then subtract the two to derive the project-only sound level. While this is often thought of or suggested as a reasonable approach, the problem is that both the background and wind turbine sound levels are extremely dependent on circumstances that vary significantly with time in both the short and long-term. The two sounds are highly specific not only to the prevailing wind speed at a particular time but also to factors such as the stability of the wind (whether it's gusty or constant in nature, for instance), wind direction, shear gradient, thermal gradient, time of day and time of year. Moreover, the background level is also exclusively influenced by foliage (bare trees vs. leafed out trees, for example), insects, frogs, distant or nearby traffic, farm equipment and a myriad of other human activities that occur sporadically and unpredictably. Consequently, a background sound level measured days, months or years before can't be used with a tremendous amount of confidence to correct a later measurement of operational noise, even if both have been normalized to similar wind speed conditions, because so many other unquantifiable factors may have had a hand in shaping the final results. What is needed, of course, is the background sound level that would have existed at that particular time and at that place if the project had not been operating.

This latter objective can sometimes be essentially realized by using the technique of temporarily shutting down, or parking, the nearest turbines to a measurement position, if not the entire project. While this technique has its applications, which will be discussed later, it is not usually a practical method that can be used for a general site-wide compliance test. Widespread or complete shutdowns would be required repeatedly over a variety of wind speed conditions and times of day to get even a minimally complete set of usable background levels.

Thus, there are certain impracticalities associated with the few existing guidelines, standards or common practices that deal with the testing of operational noise from wind turbine projects.

5.1.2 *Test Methodology*

The suggested methodology outlined below, which has been developed over time through field experience on a variety of wind projects, does not purport to completely solve the problems of background noise and capturing the periods of maximum noise, among other things, but it has been found to work very well in numerous field applications.

5.1.3 *Survey Duration and Scheduling*

In order to overcome the problem of being on hand to take short-duration measurements when conditions might favor noise generation at the source and/or sound propagation from the turbines to typical receptor points, a long-term, continuous monitoring approach is needed in which multiple instruments are set up at key locations and programmed to run day and night for a period of about two weeks or more. In essence, it is necessary to capture sound levels during a variety of wind and atmospheric conditions; something that is extremely difficult to achieve by taking intermittent manned samples, which amount to static snapshots of a dynamic situation.

Field experience suggests that an adequate range of wind speeds, from 0 to 10 m/s at 10 m above ground level, will usually be observed over any given 14 day period at most wind energy project sites, except perhaps during the low wind season at sites that might have very pronounced seasonal wind characteristics.

As a practical matter, the instruments for such a survey are set up, started and left to run unattended for the nominal two-week test period following which they can be retrieved and downloaded.

In terms of scheduling, it is highly preferable to conduct this type of survey during cool season, or wintertime, conditions to eliminate or at least minimize possible contaminating noise from summertime insects, frogs and birds. In addition, it is best for deciduous trees to be leafless at sites where they are present in quantity to decrease this source of wind-driven background noise and maximize the signal to noise ratio. Human activity, such as from farm machinery or lawn care, is also normally lower during the winter. While summertime surveys have been successful they should, as a general rule, be avoided wherever possible because nocturnal insect noise, for instance, can easily render the project sound level indeterminate at some or all of the measurement positions. If measurements are required during the summer, and they often are for reasons of project scheduling, high frequency contamination can be analytically factored out by taking the measurements in octave or 1/3 octave bands and correcting the spectra, as will be discussed later in greater detail.

In addition to seasonal concerns, it is desirable; when practical, to attempt to schedule the survey set up to just precede a predicted period of moderate or high winds. This not only ensures that the survey period will capture these winds but also creates an opportunity for manned observations and measurements to be made for a day or two to augment to the longer term monitoring survey. There is generally nothing to observe or measure at a wind turbine site when the winds are calm, so if one can be on site with the proper equipment just before a windy period useful short-term measurements can probably be made that can later be viewed within the context of the long-term monitor results for that time period.

As an alternative or supplemental approach, another opportunity for these supplemental manned observations can sometimes be arranged by coordinating the instrument retrieval visit with a predicted windy period. The specific end date for the survey is usually flexible, although instrument battery life is normally the limiting factor. The principal danger in carrying out manned measurements just before the end of a survey, however, is that all of the long-term monitors may not still be recording due to power supply issues or any number of other lamentable and sometimes comical things, such as tampering, weather damage or the removal of the windscreen by livestock.

5.1.4 *Test Positions*

The test positions should be selected to capture data at a number of potentially sensitive receptors (usually non-participating and participating residences within or near the site area) or other relevant points of interest, where maximum project sound levels might be expected either from modeling or a simple inspection of the site plan. In just about every case, it is not practical or even possible to establish a monitoring station at every house in the vicinity of a project so it is necessary to carefully select a limited but adequate number of sites that are representative of the worst-case exposures at potentially sensitive receptors in all relevant settings. Examples of specific settings would be: homes in sheltered valleys below ridge top turbines; homes on high, open ground with exposure to the wind and nearby project turbines; homes in generally flat open country with turbines in multiple directions; homes in wooded area; homes on the outer edge of a project area, etc. Because every site is unique the number of monitoring stations required to adequately evaluate project noise will vary but the general concepts are to reasonably account for different settings, to cover a number of points were maximum project sound levels are likely to occur at residences and to cover the entire project area with a generally even but somewhat random distribution. Adding one or two deliberately random positions can help increase the statistical independence of the data and avoid inadvertent bias. For sparsely populated sites in open and uniform farm country only about 4 or 5 on-site monitors might be needed while at more densely populated sites with more complex topography the number of monitoring stations would only be limited by the quantity of equipment reasonably available to the test engineer either from in-house stock or outside rental. Realistically, it is seldom possible to gather enough equipment for more than about 10 to 14 on-site monitoring points, but that is normally enough. A typical survey at a fairly large project site with numerous residences intermixed with the turbines might call for about 10 positions at receptors within the project area.

As mentioned above, the general objective is to capture sound levels throughout the site area at key receptors in all distinct settings within the project area. In addition, it is commonly necessary and desirable to establish a measurement position at all homes where complaints or concerns about noise have been expressed to the operations staff. In these instances, it is sometimes possible to enlist the help of residents by having them try to keep a date and time log of when the noise becomes particularly noticeable or unusually loud or when other non-project sounds are present; for example, from lawn moving, farm activity, etc. When this is actually done the comments can provide some valuable insights that help explain and identify peaks in the recorded sound levels.

It is often assumed that project noise is of no concern to project participants who were, and presumably still are, favorably disposed to the project and are receiving lease royalties for units on their land; however, experience at a number of sites suggests that this is not always the case largely due to the confluence of two factors: (1) these residences are typically the closest ones to turbines (sometimes only a few hundred feet away) and (2) the actual sound levels from these nearby units can turn out to be substantially louder than they expected them to be or they were led to believe. Consequently, monitoring at the homes of project participants in response to complaints is fairly common – even though participants are often, but not always, technically exempt from ordinance or permit noise limits.

It is usually best to start the site selection process a week or two in advance of the actual survey by circling proposed measurement areas on a site map or sound contour plot and submitting this to operations personnel at the site for their input on who, within or near each designated area, might be willing to host a sound monitor at their house and where else, outside of these proposed areas, it might be also be desirable to measure (at complaint locations, for instance). The objective of this preparatory review is to obtain approval and permission from homeowners to set up equipment on their property prior to arrival. Although it is desirable to inspect the proposed locations and make a judgment as to their suitability in person, attempts to arrange for permission on the day of the survey are often unsuccessful due to the simple fact that people are not at home and cannot be reached. Calling ahead usually settles the issue before the equipment is shipped to the site. Setting up the equipment in the rear yard of a house where permission has been obtained generally ensures that the equipment will still be there upon returning at the end of the survey, that the equipment won't be interfered with and that it can be minimally attended to, if necessary (replacing the windscreen after the family dog has run off with it, for example). Positions that are not at anyone's house, such as on utility poles along the public right-of-way, are sometimes necessary to collect data at strategic locations without a suitable host, but they do not have any of these advantages and, in fact, the risk of theft or tampering is uncomfortably high.

In terms of the specific placement of the monitor at each position, it should be located in an area representative of but away from the house, or any other building with large reflective surfaces, and that is not prone to frequent activity or contaminating local noises, such as from air conditioning units, milking machines at dairy farms or flowing streams or rivers.

As a final note on placement, it is best to avoid using fences or posts to mount the monitor or microphone in areas where livestock or other domestic animals may be able to get at the equipment during the survey. Microphone windscreens are evidently of keen interest to cows, horses and dogs, among others.

5.1.5 *Background Noise*

On the important issue of background noise, an approach that has worked well in a number of field applications is to set up a number of monitoring stations outside of the project area in settings similar to those at the on-site monitor positions. Of course, considerable judgment is involved in selecting these positions but in an ideal situation of, say, an isolated project in open farm country that is largely uniform in character both within and beyond the project area one would want monitors at least 1.5 to 2 miles from the perimeter of the project (nearest turbines) in the four cardinal directions. The locations should be far enough away that project noise is negligible and yet close enough that they are reasonably representative of the site area. At the end of the survey the off-site positions can then be evaluated for consistency. If the levels are generally similar, and, somewhat surprisingly, this is usually the result, the average can be taken as a time history record of the background sound level that probably would have existed within the site area and then used to correct the on-site measurements taken, importantly, at the same time under identical environmental conditions.

Figure 5.1.5.1 below is an example from a site in the Eastern United States where the landscape is rural and generally homogenous in nature within the project area and for some distance beyond it in terms of topography (rolling hills), vegetation (a mix of farm fields and wooded areas) and population density (farms and residences scattered more or less uniformly over the site area). The 80 or so 1.5 MW turbines are spread throughout a roughly 20 sq. mi. project area on numerous parcels of private land and thoroughly intermixed with the residences in the area. Proxy background measurement positions were set up about 1.5 miles beyond the perimeter of the turbine array to the northwest, east and south of the project (a neighboring wind project to the west prevented measurements in that direction) at locations that were similar in character to the various settings near on-site residences: one was on an open and exposed hilltop, another was at the edge of a field with nearby trees and a third was essentially in a forested area. The expectation was that there might be a consistent difference between these different positions – with the sheltered forest location being quieter than the windy hilltop, for instance – in which case background corrections for a particular setting would be applied to on-site measurements at positions with comparable settings. However, as can be seen from the figure, the levels at all three locations, each many miles from the others, were largely the same at any given time and, perhaps more significantly, no one position is consistently higher or lower than the others. Consequently, the arithmetic average of all three, with the site area physically lying between them, can be taken as a reasonably reliable estimate of the on-site background level at any particular time that accounts for the specific wind speed, direction, time of day and atmospheric conditions prevailing during that 10 minute period.

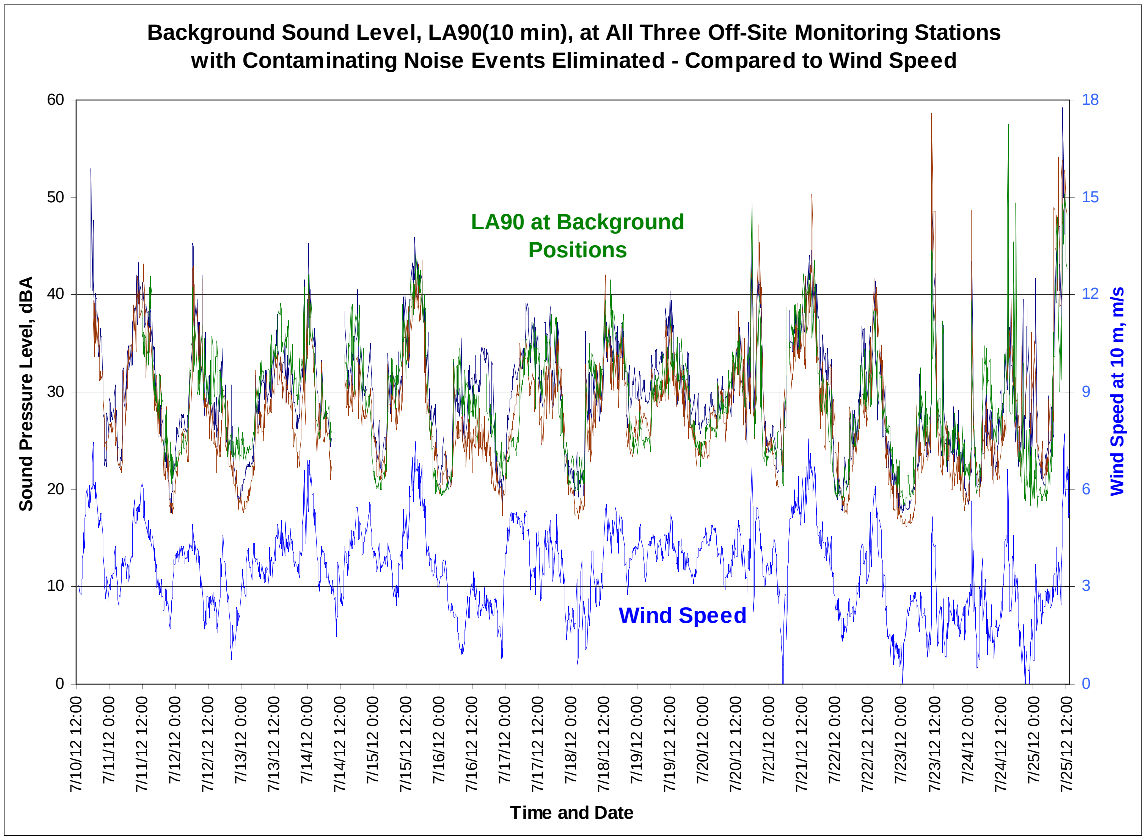

Figure 5.1.5.1 *Measured Background Sound Levels at Three Off-Site Proxy Positions*

The data in Figure 5.1.5.1 have been edited to remove noise spikes that were observed only at one position and not at any others, indicating a contaminating local noise event that is not representative of the area as a whole. Spikes were also deleted (from both the on-site and background data) if there were no concurrent spike in wind speed, even if they may have occurred at multiple locations, on the premise that the noise was not associated with the turbines and may have been due to thunder, rain, a helicopter flyover or some other area-wide noise event.

The results shown in the example above are not unique to that site and a similar consistency between the off-site proxy location sound levels has been observed at a number of other projects in rural areas even though the background monitors are deliberately set up in diverse settings. Fortunately, for the purpose of estimating simultaneous background sound levels, most wind projects are located in rural areas but, of course, not all of them are and other situations exist. In urban settings or near major highways the background sound is no less important, in fact more so, but its dependence on wind and atmospheric conditions is greatly diminished, if not relegated into complete insignificance. In such cases, the proxy background technique is still theoretically viable although the selection of background positions that are representative of receptors potentially affected by project noise becomes highly specific to the circumstances at each receptor. In the case of a highway, for instance, one might try to find a background position that is the same distance from the roadway as the actual point of interest and similar in all other ways but far enough from any turbines that they are undetectable. In this kind of a complicated situation where the background level is more dependent on man made noise than natural, wind-induced sounds it may be necessary to perform a pre-construction survey at the key receptors near turbines and at a number of candidate background positions to evaluate the validity of the proxy locations before the project turbines become operational.

5.1.6 *Sound Test Equipment and Set up*

As with any field sound survey, what equipment is used and how it is deployed must adhere to certain minimum technical standards. Most environmental sound measurement standards recommend the use of Type 1 precision equipment per IEC 61672-1[28] or ANSI S1.43-1997[29] while also allowing for the use of Type 2 equipment. There is certainly no reason on technical grounds to oppose this recommendation but, from a practical perspective, it is often necessary to use Type 2 equipment for surveys of this type because of the large number of instruments needed. The utterly intangible difference in technical performance between these two instrument classes is totally inconsequential within the inherently and unavoidably imprecise nature of this type of survey. It is much more important that the equipment is durable, reliable and specifically designed for extended use in the outdoors.

Although high cost and extreme precision are not essential, the functional capabilities to statistically integrate sound levels over a user defined time period and automatically store the results are necessary. Because the on-site wind and weather monitoring towers, or met towers, normally integrate and store measurements in 10 minute increments it is convenient, if not necessary, to measure and store sound data in synchronization with the wind data collected by these towers for later correlation. It is evidently universal practice for met towers to store data 6 times an hour in 10 minute intervals that begin at the top of the hour; as in 9:00, 9:10, 9:20, etc. Consequently, sound data logging should be started using a trigger function to begin at the top of an hour and not randomly by the manual push of the start button. The timers on all instruments should be exactly synchronized to local time or to the project's SCADA control system clock, if it is different from the actual time, which it often is.

Of course, all of the instruments must be field calibrated at the beginning of the survey and checked again for drift at the end of the survey.

Because this long-term survey approach involves unattended monitoring, the instrument and the microphone must be capable of withstanding damage, interference or outright destruction from rain and snow, which, among other things, means that the ground plate technique specified in IEC 61400-11 – where the microphone is laid flat in the center of a board on the ground and covered with one or more hemispherical windscreens – is not a viable option despite its otherwise highly desirable advantage of minimizing wind-induced pseudo noise. Consequently, the microphone must be mounted above ground level and protected from wind-induced distortion by a spherical weather-treated windscreen, which normally entails a higher density foam that is hydrophobically treated to shed water (windscreens and wind-induced noise are discussed in detail later). As a general rule, a slightly lower than normal microphone height of about 1 m above ground level is preferred for this application on the premise that wind speed diminishes exponentially with decreasing elevation theoretically going to zero at the surface, or boundary layer.

For these moderate wind conditions, which are often when turbine noise tends to be most prominent relative to the background level, the wind speed at a 1 m microphone height would be less than about 3 or 4 m/s, which as shall be seen later, means that distortion from wind blowing through the windscreen is of little or no consequence with respect to the A-weighted sound level.

In addition to arranging for the microphone to be about 1 m off the ground so that it is not adversely affected by precipitation, it is also necessary to keep the instrument itself dry and secure in a waterproof case, which is best mounted above the ground on a fencepost, utility pole or other support.

While the microphone can be remotely connected to the instrument with a cable and independently supported, another practical option is to use a self-contained system where the microphone is attached to the instrument case with a rigid boom to hold the microphone away from the box and the entire assembly is mounted 1 m above ground level with a strap. While there is nothing wrong with supporting the microphone separately on a tripod there is a tendency, unique to wind turbine survey work, for tripods to blow over, even after being weighted down and/or firmly staked to the ground. The use of temporary metal fence posts to support either the microphone alone or the entire system is a more reliable option and is sometimes the only option in places where there are no existing supports, such as in open fields.

5.1.7 *Weather Stations and Wind Speed Monitoring*

In addition to the sound monitors it is also advisable to establish at least one temporary weather station at the sound monitoring position with the most exposure to wind. The primary reason for this station is to measure the maximum wind speed at microphone height (about 1 m) for use in correcting the measured sound data for wind-induced distortion as described in a later section. Wind speed at 1 m, direction and rainfall are the primary parameters to be recorded by this station, or others set up in other settings as appropriate, such as at a sound monitoring position sheltered from the wind by the local terrain (to demonstrate, for instance, that wind-induced distortion is negligible at such locations). This data should be integrated and stored in 10 minute blocks in synchronization with the sound monitors.

This temporary anemometer at 1 m above ground is solely there to evaluate microphone wind exposure and it is the on-site met tower anemometers, usually at 50 to 80 m above ground level, that should be used to correlate the measured sound levels at ground level to the wind speed essentially experienced by the turbine rotors. Turbine nacelle anemometers scattered throughout the site may also be used to determine wind speed, but this is somewhat less desirable because a free field correction usually needs to be applied to this data to account for the energy extracted from the wind by the rotor just upstream of the wind speed sensor.

It is customary to normalize mast top or nacelle wind speeds to a standard elevation of 10 m above grade per IEC 61400-11. It is this result that is compared to the measured sound levels.

5.1.8 *Measurement Quantities and Parameters*

The objective of a compliance survey is to extract the project-only sound level from the total soundscape and compare that result to the permissible limit. As such, the principal challenge is identifying and eliminating contaminating noises that are unrelated to the project over many days and thousands of measurements. If it were practical to take a manned sample for 20 minutes, removing spurious noises by pausing the instrument or discarding contaminated subsamples, and declare the result as the performance of the project it would be a trivial matter; however, over a relatively long time period of unattended monitoring it is necessary to use the L_{A90} statistical measure to generally perform this function in an automated manner, since it captures the consistently present sound level during relatively quiet periods between common interfering and identifiable noise events like cars passing by or planes flying over. A 10 minute sampling duration has been found to work very well since it allows direct correlation with met mast wind speed data and is generally short enough that fairly rapid changes in project noise are captured.

The use of the average, or $L_{Aeq,\ 10\ min}$, sound level or a finer time resolution of, say, 1 minute come to mind as alternatives to the L_{A90}, but these approaches have their own serious drawbacks. If the L_{Aeq} is used to measure at on-site positions with the idea of better quantifying turbine sound levels, then the L_{Aeq} measured at the proxy background positions must also be used as an apples-to-apples correction factor. But the L_{Aeq} is often completely unusable for this application. As an example, multiple statistical measures were recorded at the off-site background measurement positions previously mentioned in connection with Figure 5.1.5.1, including the L_{Aeq}. Figure 5.1.8.1 below shows the average L_{A90} and L_{Aeq} levels measured at all three locations compared to wind speed.

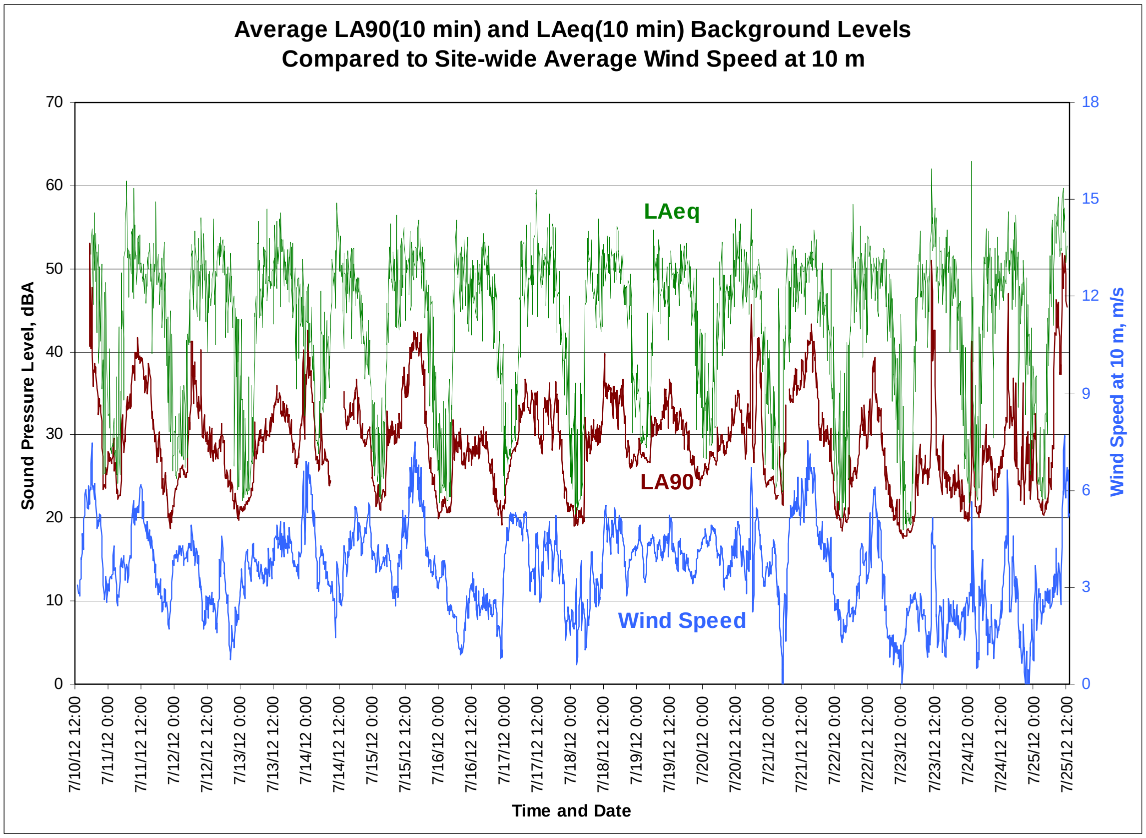

Figure 5.1.8.1

What is immediately obvious from this plot is that the $L_{Aeq,\ 10\ min}$ level is clearly driven by daily human activity; primarily intermittent vehicular noise on nearby sparsely traveled roads (noise that is filtered out by the L_{A90}). The L_{Aeq} levels rise to about 53 dBA every morning, stay there all day irrespective of the wind conditions and then gradually fall off in the evening hours bottoming out briefly somewhere around 23 dBA every night. The L_{A90} level, on the other hand, is clearly more attuned to the natural environmental sound level, which in rural areas like this one is normally a function of wind speed. The unsuitability of the $L_{Aeq,\ 10\ min}$ as a measure that might quantify project noise can be seen in Figure 5.1.8.2 where the average background L_{Aeq} level from Figure 5.1.8.1 is compared to the L_{Aeq} level measured at a typical, randomly selected on-site receptor.

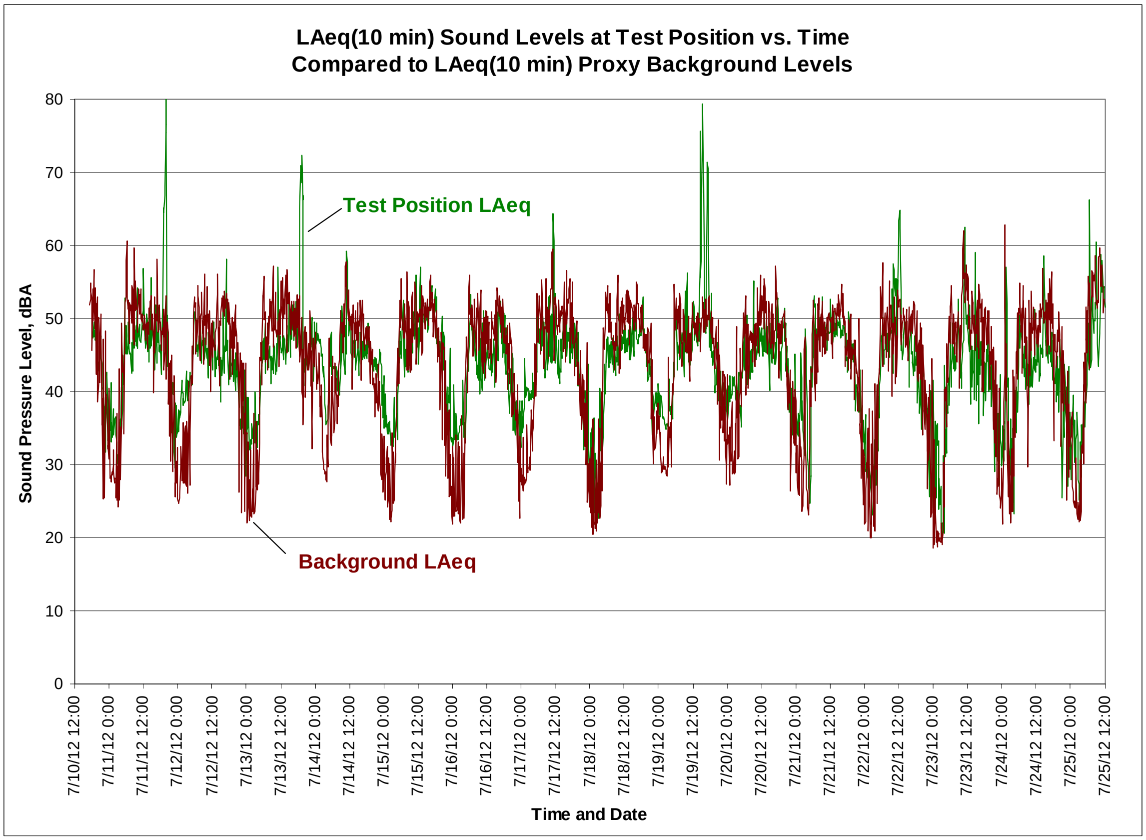

Figure 5.1.8.2

The $L_{Aeq,\ 10\ min}$ sound levels at both positions are virtually indistinguishable meaning that the project-only sound level simply cannot be deduced. Furthermore, it could even be reasoned that project noise is utterly inconsequential at this location because the on-site level is about the same or even lower than the off-site level, which is entirely free of any turbine noise, but, as we shall see later, that is not at all the case at this particular test position.

Finally, it is desirable to use instruments capable of measuring the frequency spectrum in 1/3 octave bands at one or two key locations with, usually Type 2, monitors measuring overall A-weighted levels at the majority of positions. The use of one or more frequency analyzers at key positions allows for some frequency analysis, although great caution must be exercised with the lower frequency bands, as discussed later, since wind-induced false signal noise is largely inevitable and the low frequency results cannot be taken at face value. Fortunately, this phenomenon does not significantly affect the measurement of A-weighted sound levels, however.

The use of 1/3 octave band analyzers is largely essential for surveys that, for one reason or another, must be conducted during summertime conditions when insect, frog or cicada noise is present. Measurements taken under these unfavorable conditions can be "corrected" to a certain extent by smoothing the high end of the frequency spectrum, where this kind of noise is usually obvious, and then recalculating the overall A-weighted sound level as shown in the (generic) example below.

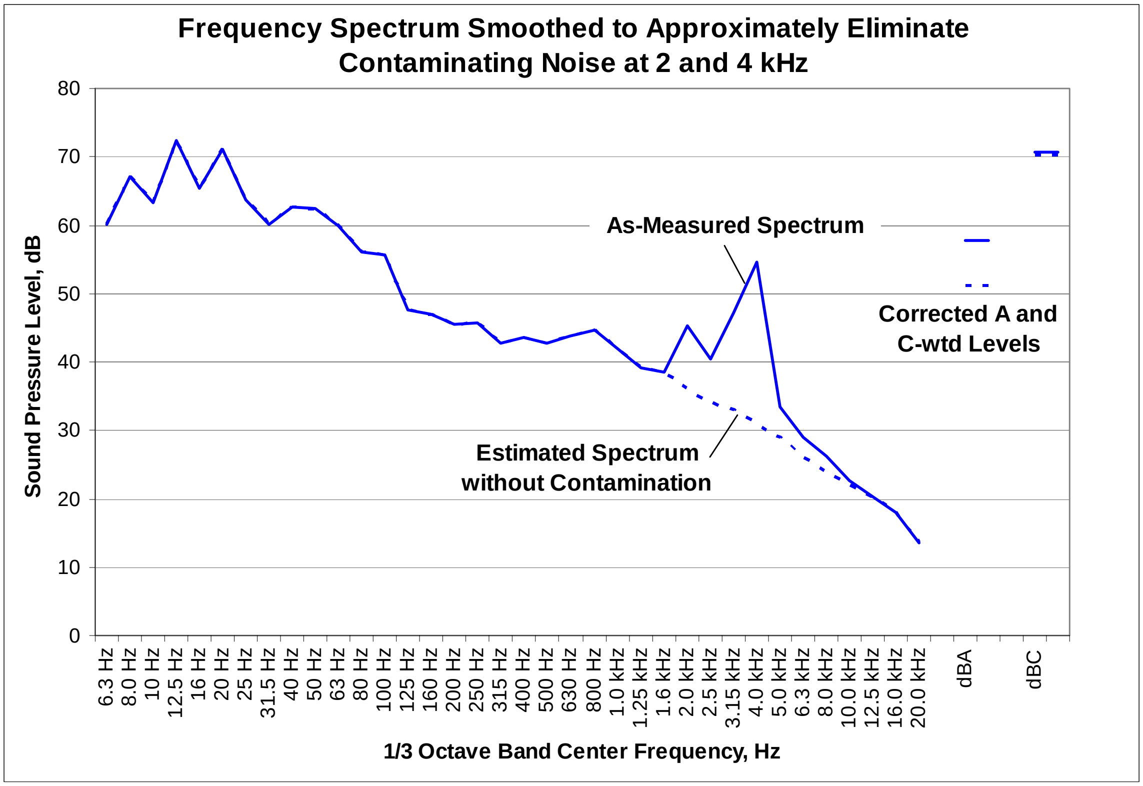

Figure 5.1.8.2

Of course, this correction would be laborious to perform for thousands or even just dozens of measurements so it is usually necessary to determine a typical correction, such as the -7 dBA adjustment that resulted in the example above, and apply that to all periods when this noise was apparently present. This is, of course, an imperfect remedy and the best policy is to avoid, if possible, measuring under these circumstances in the first place.

A solution to this common problem is currently being proposed by Hessler[33] and Schomer[34] in the form of a modified A-weighted network, termed "Ai-weighting", where all of the measured sound above 1000 Hz, or the 1250 Hz 1/3 octave band, is disregarded in situations where insect noise is present and an adjusted A-weighted sound level is calculated from the truncated spectrum.

5.1.9 *Wind-induced Microphone Distortion*

One of the principal errors in measuring wind turbine noise is false signal noise from wind blowing through the windscreen and over the microphone tip, which is manifested in the form of artificially elevated sound levels in the lower frequency bands. Taken at face value any measurement made in moderately windy conditions will ostensibly indicate relatively high levels of low frequency noise, irrespective of whether a wind turbine is present or not. This measurement error is probably one of the principal reasons wind turbines are mistakenly believed to produce high, if not harmful, levels of low frequency and infrasonic noise.

Some degree of distortion is essentially inevitable in any measurement taken above ground level when the wind is blowing, even when using an extra-large windscreen. It is in an effort to minimize this error that the IEC 61400-11 test procedure prescribes measuring on a reflective plate at ground level, where the wind speed is theoretically, although often not actually, zero. As previously mentioned, this ground plate technique is fine for short-term, attended measurements but is impractical for long-term surveys due to the potential for rain or melted snow to damage the microphone. Consequently, for lengthy compliance and evaluation surveys it is necessary to measure above ground level using a large, weather-treated windscreen - perhaps augmented with a very large secondary windscreen, although the practicality of such devices is questionable in harsh winter conditions.

Because environmental sound measurements of most other sources apart from wind turbines are not generally conducted in windy conditions as mandated by applicable standards, the significance and even existence of this measurement error has long gone unnoticed. Although this phenomenon and its physical basis were theorized decades ago by Strasberg[35,36] it is only fairly recently that its relevance to wind turbine sound measurements has been examined in detail and quantified. In particular, the subject of wind generated self-noise was thoroughly reviewed in 2006 by van den Berg[37] where he showed that the magnitude of the distortion depends not only on the mean incident wind speed but also on the amount of atmospheric turbulence present at the microphone position (largely a function of the local surface roughness) and on atmospheric stability. Measurements taken at 1 or 2 m above a smooth surface during stable, nighttime atmospheric conditions, when the surface winds are usually light, generally contain the least amount of self-generated noise ultimately replicating the case where the principal noise generation mechanism is wake turbulence trailing off the windscreen. In other less ideal circumstances self-noise levels can be developed by estimating the local surface roughness and atmospheric turbulence factor, Ψ, from wind speed measurements at two heights and/or from observations of cloud cover, time of day, general wind conditions, or meteorological data, if available.

The minimum level of false-signal noise due to wind, excluding the effect of atmospheric turbulence, can be estimated based on an empirical wind tunnel study carried out by Hessler and Brandstätt in 2008[38] in which conventional ½" microphones fitted with an array of common windscreens and were subjected to known wind velocities in a massively silenced wind tunnel. The measured sound levels during each test were essentially a direct measure of the false-signal noise – although for more or less laminar flow conditions corresponding to an outdoor setting with a very low surface roughness in neutral atmospheric conditions. Nevertheless, for the specific windscreens examined it is possible to generally estimate both the overall A-weighted or un-weighted (dBZ) sound level of the distortion from the microphone height wind speed and then subtract it from the total measured level to *largely* reverse the error.

An example is shown in Figure 5.1.9.1 where the overall A-weighted level of self-noise is calculated as a function of wind speed and subtracted from the as-measured sound level. The plot is a three day detail of a wind turbine survey where oversized 175 mm (7”) diameter treated windscreens (ACO Model WS7-80T) were used. This particular windscreen was found to be the best performer, in terms of minimizing wind-induced self-noise, in the wind tunnel study.

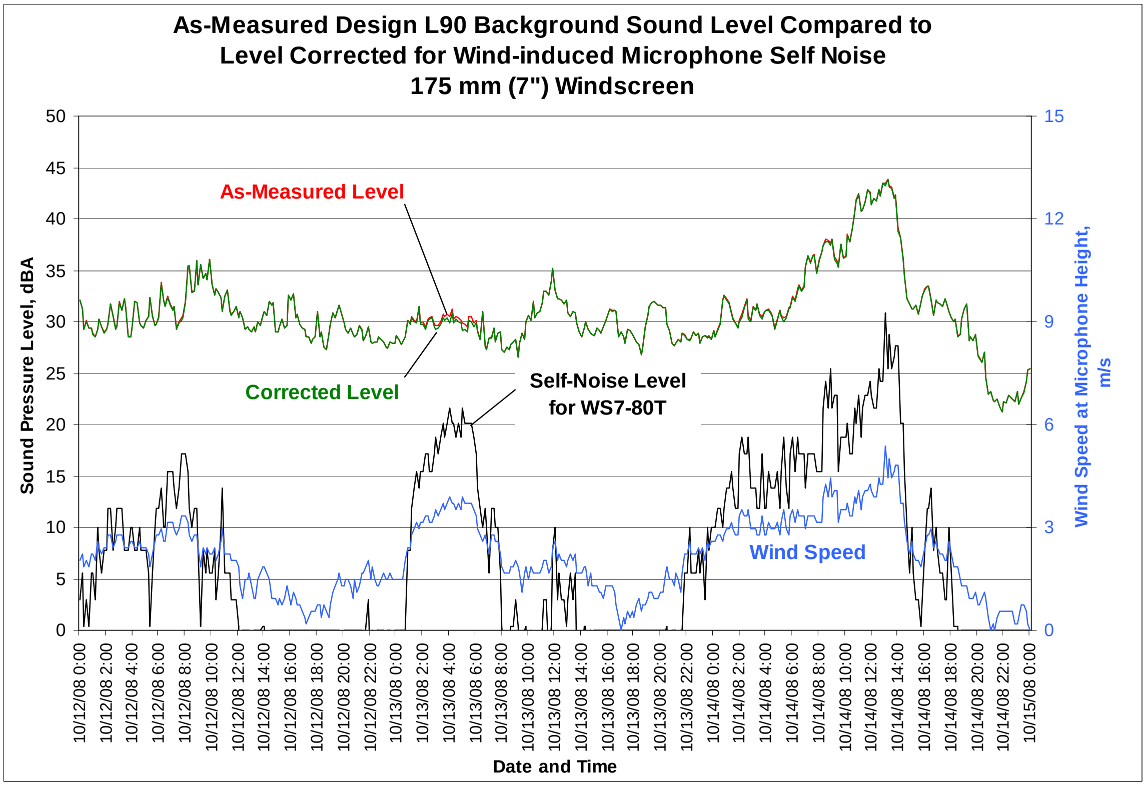

Figure 5.1.9.1

This figure shows the very typical result, at least where extra-large windscreens are used, that the correction is insignificant and can be essentially neglected when it comes to A-weighted sound levels. This is because with a large windscreen the distortion is confined to the very lowest frequencies where it has almost no impact on the A-weighted sound level. With a conventional 75 mm (3”) windscreen, on the other hand, wind-induced noise begins to become significant in the mid-frequency region, between about 63 and 400 Hz, where it has much more influence on the A-weighted sound level. Consequently, standard windscreens are not recommended for this type of survey and windscreens with a minimum diameter of 7” are recommended for wind turbine field work.

The empirical wind tunnel study results for 175 and 75 mm treated windscreens are shown below.

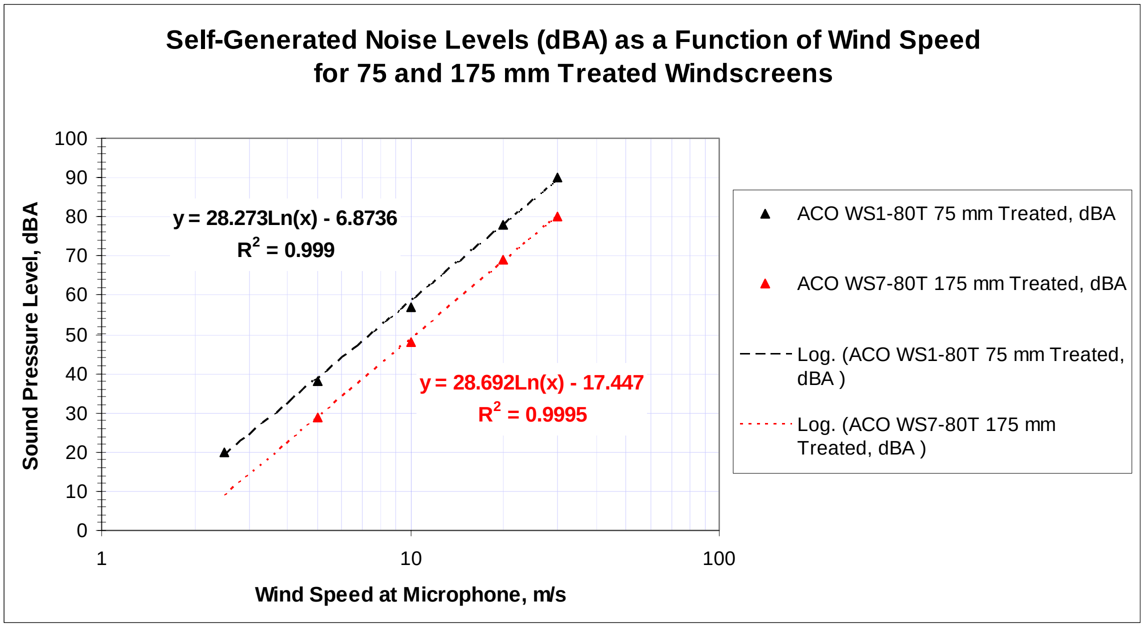

Figure 5.1.9.2

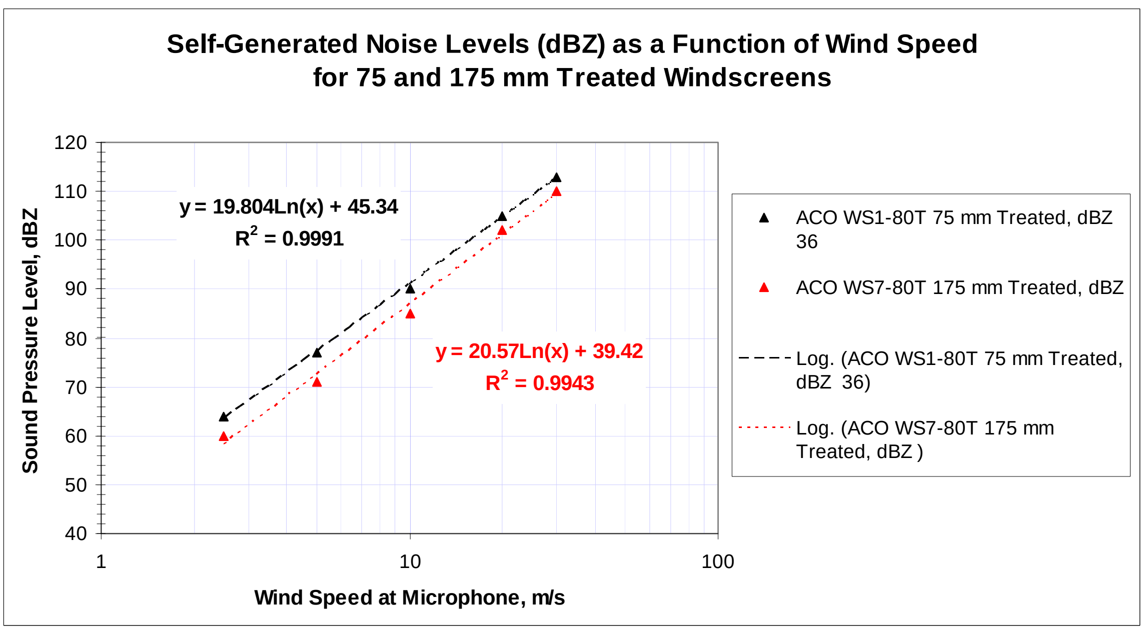

Figure 5.1.9.3

The overall level of self-generated noise for these windscreens may be estimated from the general expression below with the understanding that local atmospheric turbulence is not accounted for and a neutral atmosphere is assumed.

$$L_{p,self} = A \ln(v) + C, \text{ dB} \quad \text{for } v>1.5 \text{ m/s} \quad (1)$$

Where A and C are constants given in the table below and v is the normally incident wind speed at the microphone in m/s.

Table 1 *Constants for A and Z-wtd Self-Noise Calculation Algorithm (Neglecting Atmospheric Turbulence)*

Windscreen Type	A-weighted Sound Level, dBA		Un-weighted Sound Level, dBZ	
	A	C	A	C
75 mm (3") Treated	28.273	-6.8736	19.804	45.34
175 mm (7") Treated	28.692	-17.447	20.57	39.42

In a real atmosphere the sound level may be higher or lower than given in Table 1, depending on the turbulent energy present, which again depends on the stability of the atmosphere. In a neutral atmosphere, which occurs at higher wind speeds (> 6 m/s at 10 m height) or in very clouded conditions, the wind-induced level might be anywhere from 5 to 9 dB higher than the levels shown above. After sunset, when the atmosphere is more prone to be stable, the wind-induced noise levels will be more similar to the values given above.

5.1.10 *Correction for Background Noise*

Once a design L_{A90} background sound level has been developed from averaging the data collected at the off-site proxy positions it can then be subtracted in the usual logarithmic manner[d] from the levels measured at each of the on-site positions to deduce the project-only sound level. However, this correction process is only relevant to samples recorded while the turbines were actually in operation and not necessarily to all samples; consequently, the data must be sifted to ignore all periods of calm winds. This can be accomplished by dealing only with data sets collected above the effective cut-in wind speed for the turbine model in question (bearing in mind whether that wind speed is measured at 10 m or hub height) or, more preferably, by comparing the measured data to a time history of project electrical output obtained from the SCADA, or project control system. For this latter option it is best to compare the operational output of the 2 or 3 units closest to each on-site measurement position rather than the total project output because this not only accurately defines the on and off times at each monitoring station but also may reveal, the fairly common occurrence, that certain units were temporarily down for maintenance or due to some unexpected malfunction. The relevance of this, of course, is that the measurements of project noise during this period would not have captured the maximum possible sound level.

Because the proxy background level is, for practical reasons, an inexact estimation of the site-wide background level, there will usually be instances when the background level exceeds the total measured level at certain on-site positions. Under this circumstance, and when the background level is below but within 3 dB of the total level, the project-only sound level would normally be considered indeterminate. While the calculation of

[d] $Lp_{Project} = 10 \log [10\text{^}(Lp_{Total}/10) – 10\text{^}(Lp_{Background}/10)]$, dBA

the project-only sound level is mathematically possible when the background level is below but within 3 dB of the total level, doing so tends to create spurious mathematical artifacts where the project level can be estimated at unrealistically low and obviously incorrect sound levels. Since most standards, such as ISO 3746[39], essentially disallow this calculation it is best to follow that policy here as well.

5.1.11 *Typical Test Results and Comparison to Model Predictions*

Representative examples from typical test positions within two different wind projects using two different turbine models and located in two different states are discussed below as a way of illustrating the outcome of the test methodology outlined above.

Example 1

The first example is from a test position at a residence within a project in a rural area in the Eastern United States where the turbines and homes are thoroughly mixed together – a common situation in this region and the Midwest. This location is surrounded in nearly all directions by a number of turbines at various distances, the closest being about 490 m (1600 ft.) away from the home with another 10 lying within a 1500 m (4900 ft.) radius. The terrain is gently rolling hills with a mixture of open fields and wooded areas. Mild complaints about noise had been received by the project from the residents of this home, which is the primary reason it was selected as a monitoring position.

The overall test results from a two week measurement survey in terms of the total measured level at the test point, the design background level derived from proxy positions and the normalized 10 m wind speed, are shown in Figure 5.1.11.1. This is same test position that was previously discussed in conjunction with Figure 5.1.8.2 and L_{Aeq} sound levels.

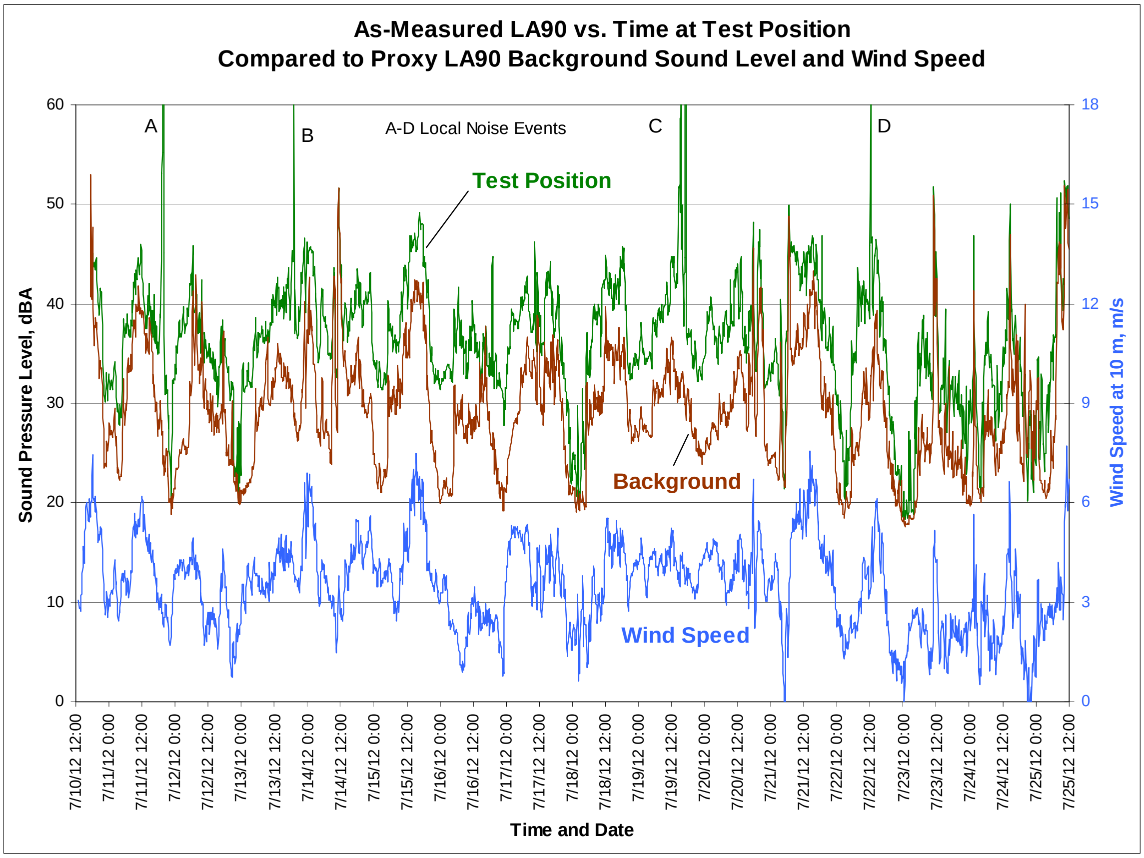

Figure 5.1.11.1

Although the raw results may appear unintelligible at first glance, a closer look reveals that the design background level (developed from an average of three off-site measurement positions) and the sound level at the test position both generally parallel the wind speed indicating that the measured levels are due to wind-induced sounds associated with the natural environment in the first case and to both natural and wind turbine sound in the second. As expected, the on-site level at the position surrounded by almost a dozen turbines is usually substantially higher than the background whenever a moderate wind is blowing and, also as expected, the on-site level is similar to the background during calm conditions when the project is not operating. It is the difference between these two levels during windy conditions that essentially constitutes and quantifies the noise impact of the project. As is evident from the plot, it is an ever-changing dynamic situation where the project sound level variously exceeds the background by anywhere from 0 to 10 dBA. This figure graphically points up the inadequacy of attempting to determine the project's noise emissions from a few short-term manned samples. The greatest differentials between the on- and off-site level tend to occur at night but it is important to note that while the project level may be quite a bit higher than the background, the sound level at the receptor point often remains very low in absolute terms with unadjusted raw levels commonly in low to mid 30's dBA.

Taking these test results through the next steps of correcting the on-site level for background noise and parsing out the low wind periods when the project was idle produces the following plot where the nominal project-only sound level is shown as a function of time over the survey period.

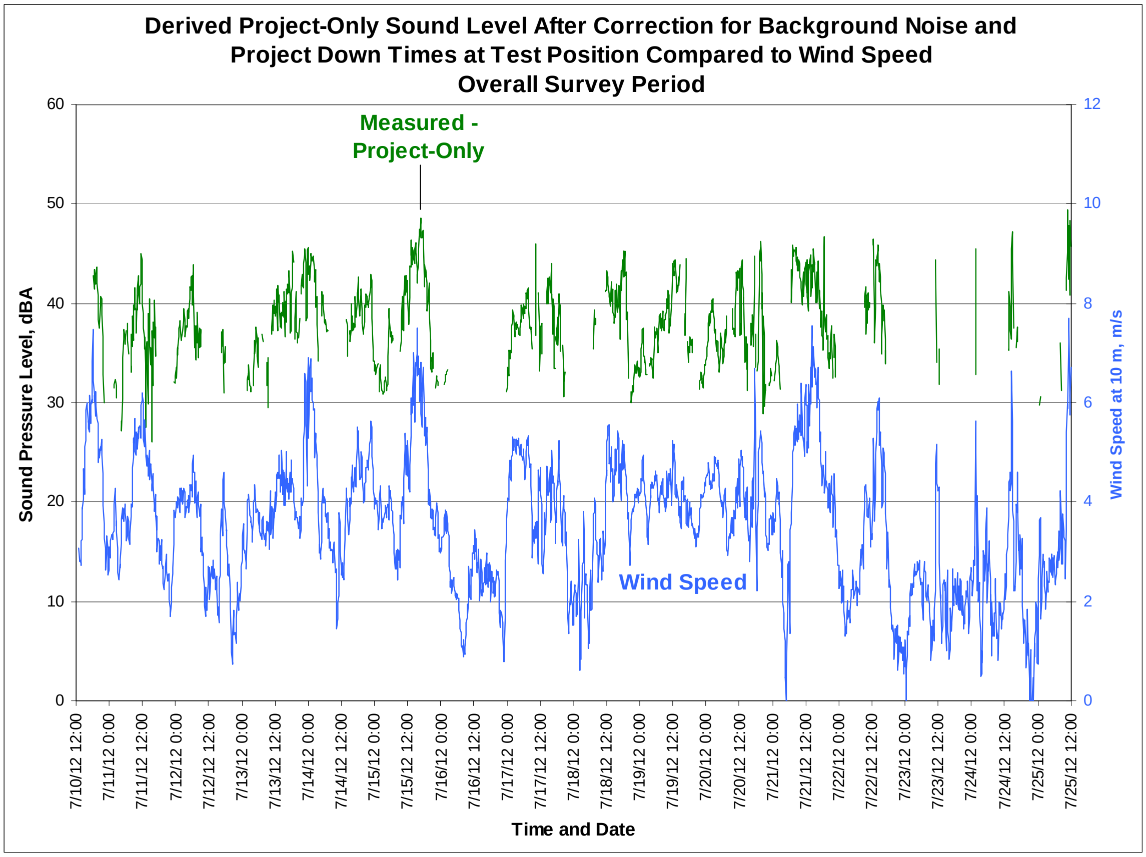

Figure 5.1.11.2

In terms of magnitude the project apparently generates sound levels ranging from 30 to 49 dBA at this location, depending largely but not only on wind speed. The fact that the project sound level does not exactly parallel the wind speed (which was derived from high elevation, rotor height anemometers) indicates that other atmospheric factors play a significant role in determining exactly how loud the project is at this location at any given moment.

What Figure 5.1.11.2 is technically showing is the baseline - L_{A90} - project sound level that is consistently present during each 10 minute measurement period. This means that somewhat higher sound level excursions lasting a few seconds to a few minutes are possible, if not probable, but it is not practical to capture the moment to moment variation over the lengthy survey period needed to adequate evaluate long-term project sound levels. However, comparing these results to model predictions based on the turbine sound power level indicates that the L_{A90} approach does not inadvertently underestimate project levels, as might be suspected. Figure 5.1.11.3 plots the modeled project sound level at this test position (using the procedures outlined in Section 4.1) against the measured project-only sound level. For clarity a detail of a representative three day period from the third to the sixth day of the survey is shown.

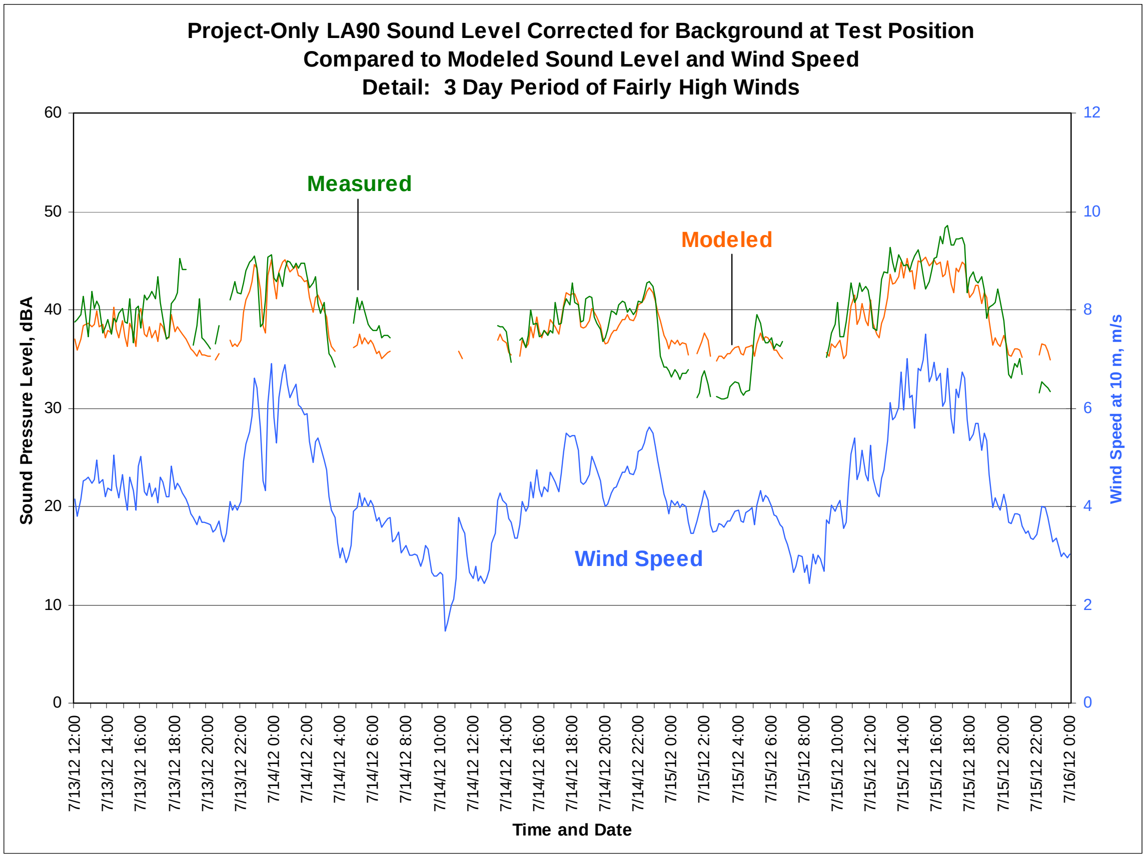

Figure 5.1.11.3

The modeled level is derived using a curve-fit polynomial function based on the predicted project sound level at integer wind speeds, which in turn is based on the turbine sound power level at those wind speeds taken directly from an IEC 61400-11 field test report. In general, the plot shows that the model prediction, based solely on the turbine's sound power level at specific wind speeds, provides a reasonably good approximation of the actual observed sound level.

Example 2

The second example is from a site in the Midwestern United States where the turbines are again intermixed with scattered homes and farms in a rural setting. This particular test location was adopted in response to, what turned out to be understandable, complaints about noise from a participant's "own" turbine that had been sited at the unfortunate distance of only 180 m (600 ft.) from the house. The raw test results are summarized in Figure 5.1.11.4.

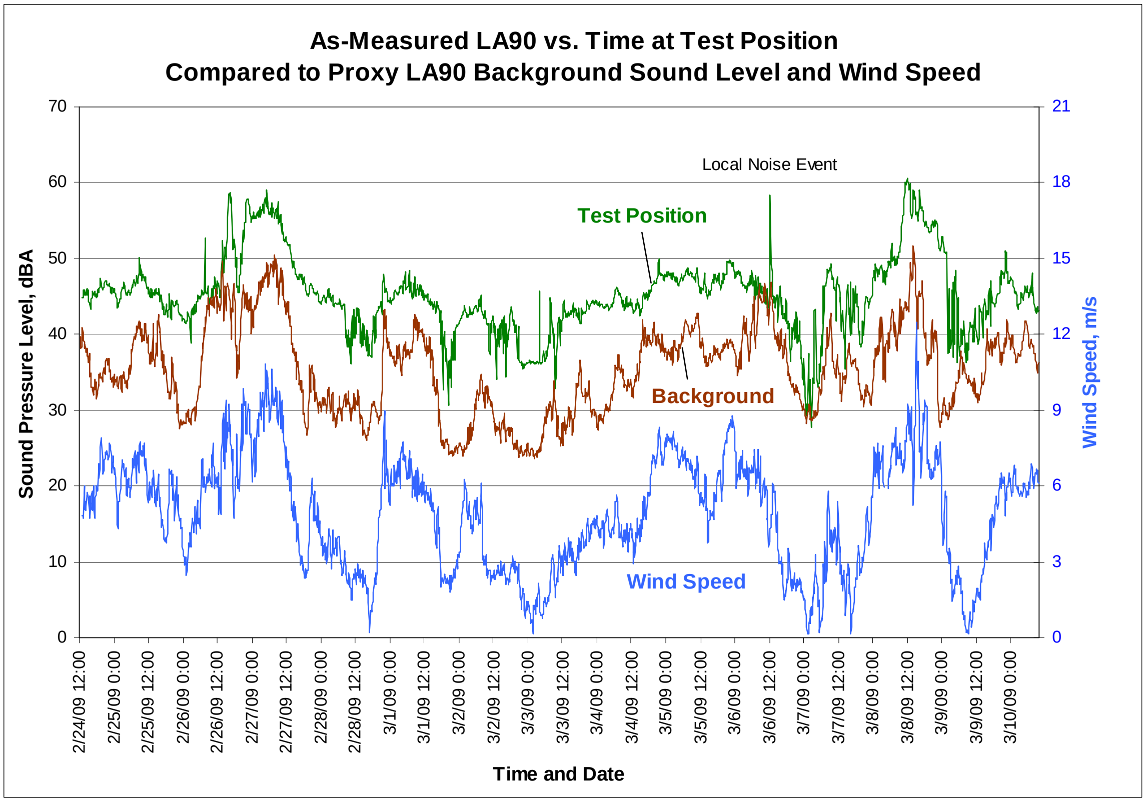

Figure 5.1.11.4

In this instance, the total sound level at the house is consistently and not surprisingly well above the background level developed from four off-site monitoring stations, meaning that much of the time background noise was largely insignificant, if not inaudible. The corrected project-only sound level for a three day windy period near the beginning of the survey is shown below compared to model predictions.

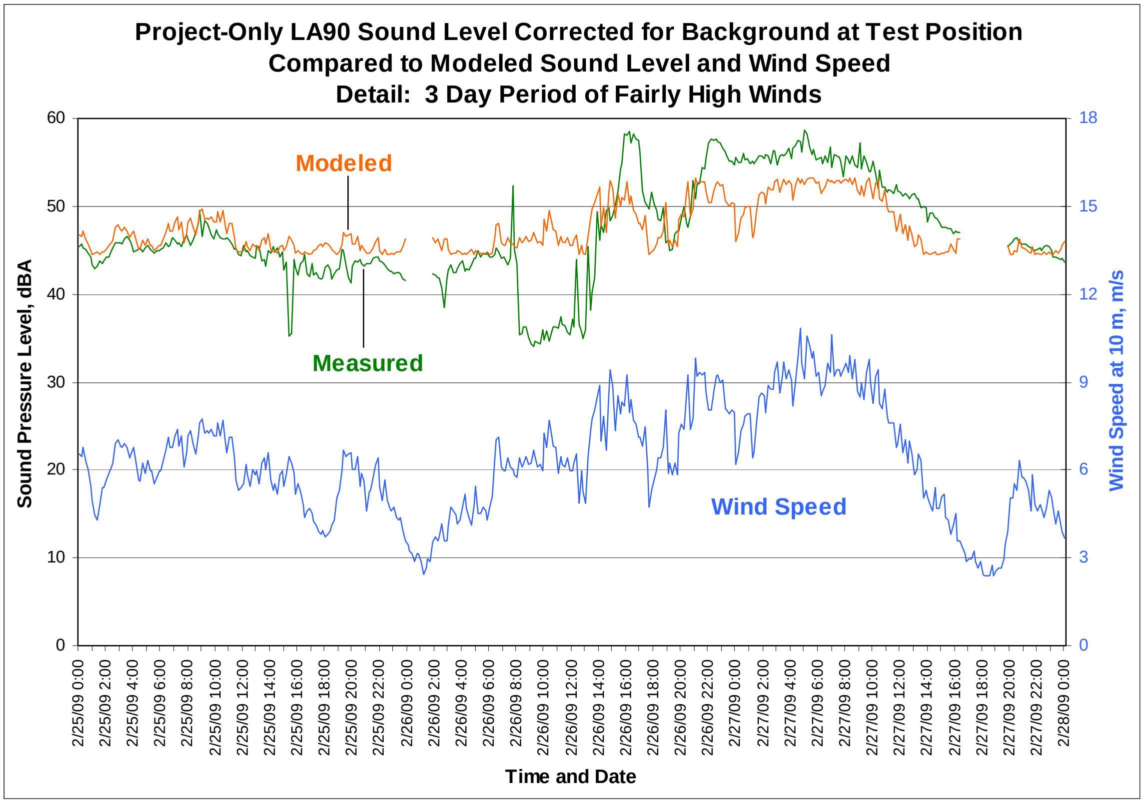

Figure 5.1.11.5

In this instance, as with Example 1, the predicted level intertwines with the measured level, sometimes over-estimating, sometimes underestimating but generally capturing the mean project sound level. The variation above and below the predicted level is largely a measurement of how all other factors beyond the simple wind speed are affecting the total sound level perceived at this location. One of these factors may be unique to the turbine model used at this site, which, based on other surveys and observations, appears to have a tendency to produce sound levels in excess of the manufacturer's stated performance in high wind conditions, which may be part of the reason the actual level significantly exceeds the expected levels in the second half of this sample period. This same departure between the predicted and measured levels also appears in the regression analysis below for the entire survey period where the project-only sound levels are plotted as a function of wind speed.

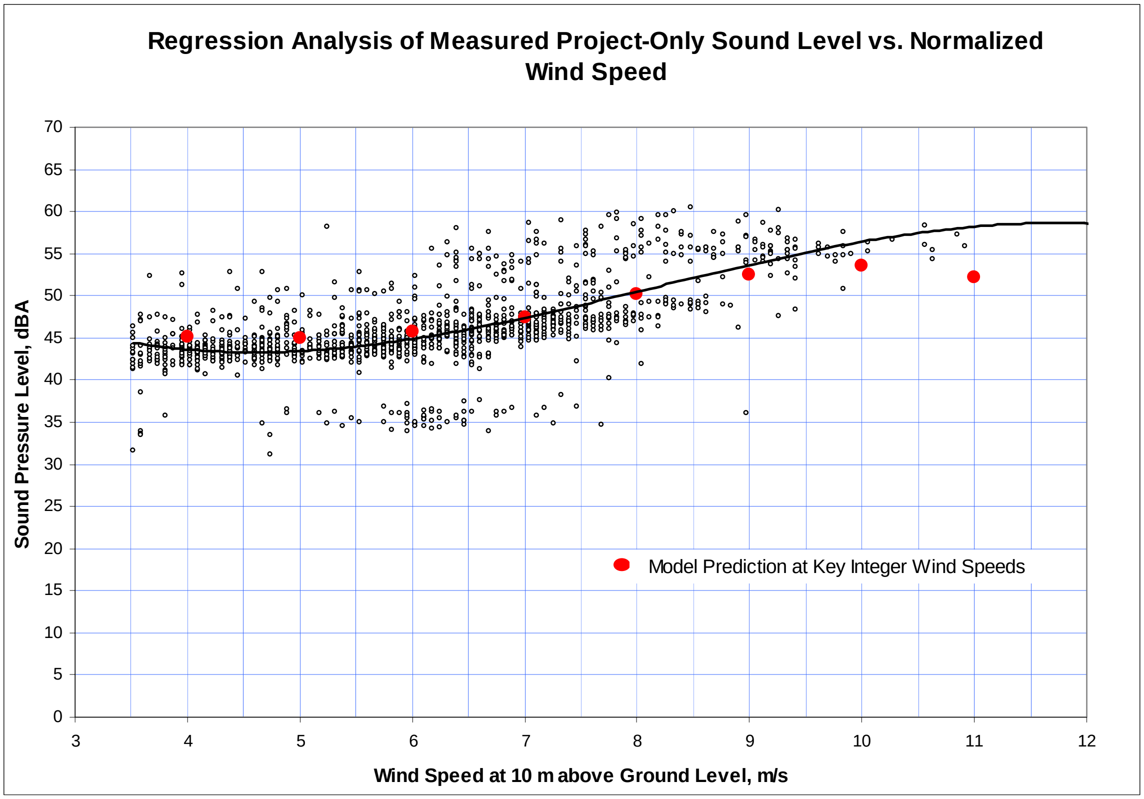

Figure 5.1.11.6

Good agreement with the mean trend is evident up to about 9 m/s but not beyond it.

These two examples are presented to illustrate the outcome of the test methodology and are generally representative of the typical results obtained at a number of test positions over a number of such surveys. That is not to say, however, that the method is infallible and that mismatches between measured and predicted levels will never be found. Testing wind turbine noise is challenging and inherently imprecise because the sound sources themselves and the propagation of sound from them to a given point of interest is dependent on the environment in general and amorphous wind and atmospheric conditions in particular.

5.1.12 *Interpretation of Test Results Relative to Permit Limits*

The regression plot above (Figure 5.1.11.6) exhibits the typical behavior where there is a scatter to the test results and the project sound level is not a perfectly fixed quantity at a given wind speed. This is an unavoidable consequence of the nebulous atmospheric conditions mentioned above. The question that this raises, however, is how to interpret the results of the survey relative to the absolute, or in some cases relative, noise limits contained in planning consent or permit conditions. Excursions, sometimes very substantial excursions, above the mean project sound level are inevitable and under all normal circumstances it would be a complete impossibility to design and lay out a project so that the sound level never exceeded a specific value at a particular point or, more realistically, at a large number of residences within the vicinity of the project. Only projects in obviously remote locations could ever be comfortably designed to such a limit. Consequently, the possibility, even likelihood, that project noise will occasionally spike for short periods should be factored in to regulatory limits. That this issue is not addressed in current laws or limits pertaining to wind turbines is simply a result of the understandable fact that few are aware that it is even an issue.

As a suggestion, it seems reasonable to conclude that a project is in compliance with an absolute regulatory limit if the measurements indicate that the project-only sound level is lower than the stated limit at least 95% of the time, taking that number from the commonly used statistical confidence interval.

5.2 Single Site Investigations

In addition to evaluating operational sound levels on a project-wide basis with regard to regulatory compliance, it is sometimes necessary to carry out dedicated field surveys, usually in response to complaints, that are focused only on a specific point. Although each of these situations is certainly unique, the general test approach outlined above can generally be applied with the exception that more resources can be brought to bear on understanding the project sound level at that particular location.

5.2.1 *General Test Design*

The general test set up for a diagnostic or investigative sound survey at a single point would follow the procedures described for a site-wide test in terms of survey length, equipment and measurement technique with the following enhancements.

The primary measurement position will be outside the residence or point of interest where it is usually prudent to use multiple instruments for redundancy and/or increased functional capability. For example, it is highly desirable to measure the overall A-weighted sound level, the frequency content in 1/3 octave bands and to store audio recordings whenever an appropriate trigger level is reached. While all three of these things can be achieved by some instruments, it would be safer to use the 1/3 octave band analyzer to store numerical data and use a second instrument to store both back-up A-weighted data and the audio files. In any case, having multiple instruments can also allow for additional time resolutions (beside the standard 10 minute periods) to be recorded at the same time; 1 minute or 1 hour data, for instance. In addition to the sound recording equipment a weather station recording wind speed at microphone height, wind direction and rainfall, among other common parameters, should be set up nearby.

The specific measurement position should be at a location with exposure to all of the nearest turbines or at a place that replicates the exposure of the residence to the project but is removed from any sources of local contaminating noise (HVAC equipment, farm machinery, human activities, etc.).

As with a more general survey, the background level is still of just as much concern so 2 to 3 proxy background measurement positions should be found in opposite directions that are remote from any turbines and, in this particular case, replicate as closely as possible the setting of the principal test location in terms of terrain, exposure to wind and exposure to other noise, such as from a road.

The principal and proxy background positions above will theoretically determine what the project sound level is at the residence but may not indicate why it is. To this end several additional monitoring stations close to the 3 or 4 nearest turbines are recommended that are ideally located in line with the principal position at the standard IEC 61400-11 test distance of the hub height plus half the rotor diameter (typically around 125 m, or 400 ft.). A hypothetical test set up involving four nearby turbines is shown in Figure 5.2.1.1.

Figure 5.2.1.1

Note that several of the intermediate positions are slightly off the direct sight line to keep them in open and reasonably accessible areas. Although this hypothetical example was conveniently conducive to this test set up, additional complications are likely to arise; in particular access to private property, which may call for some creativity in designing the test layout. Nevertheless, the idea is to gauge the individual contribution from all of the nearest units over a variety of wind directions and weather conditions to determine if the problematic noise levels are principally associated with perhaps one unit or a particular set of wind conditions. Moreover, the principal purpose for measuring the noise emissions of all the nearest units is to be able to estimate the actual sound power level of each unit and analytically calculate, by means of a simple spreadsheet model, or modeling software, the total sound level at the house for comparison to the measured level there. This approach allows the individual contribution from each unit to be quantified for different conditions and also helps confirm, in a manner independent from the proxy monitoring approach, how much of the received signal at the principal measurement location is due to the project and how much is background noise. In addition, the sound power level of each unit can be informally checked against the manufacturer's warranty value.

While the ground board technique specified in IEC 61400-11 is not practical for long-term, unattended measurements - mainly because of concern about rain - a comparable, if somewhat less rigorous, result can be obtained from measuring at 1 m above grade by placing the microphone or monitor on a tripod or temporary post at the appropriate distance. In Figure 5.2.1.2, for example, measurements were made simultaneously at 1 second resolution with a microphone on a ground plate and with two additional microphones at 1 and 2 m above it. The average and consistent differential between both above ground positions and the microphone on the reflective plate was 2.7 dB, which is close to the ideal 3 dB differential that one would expect.

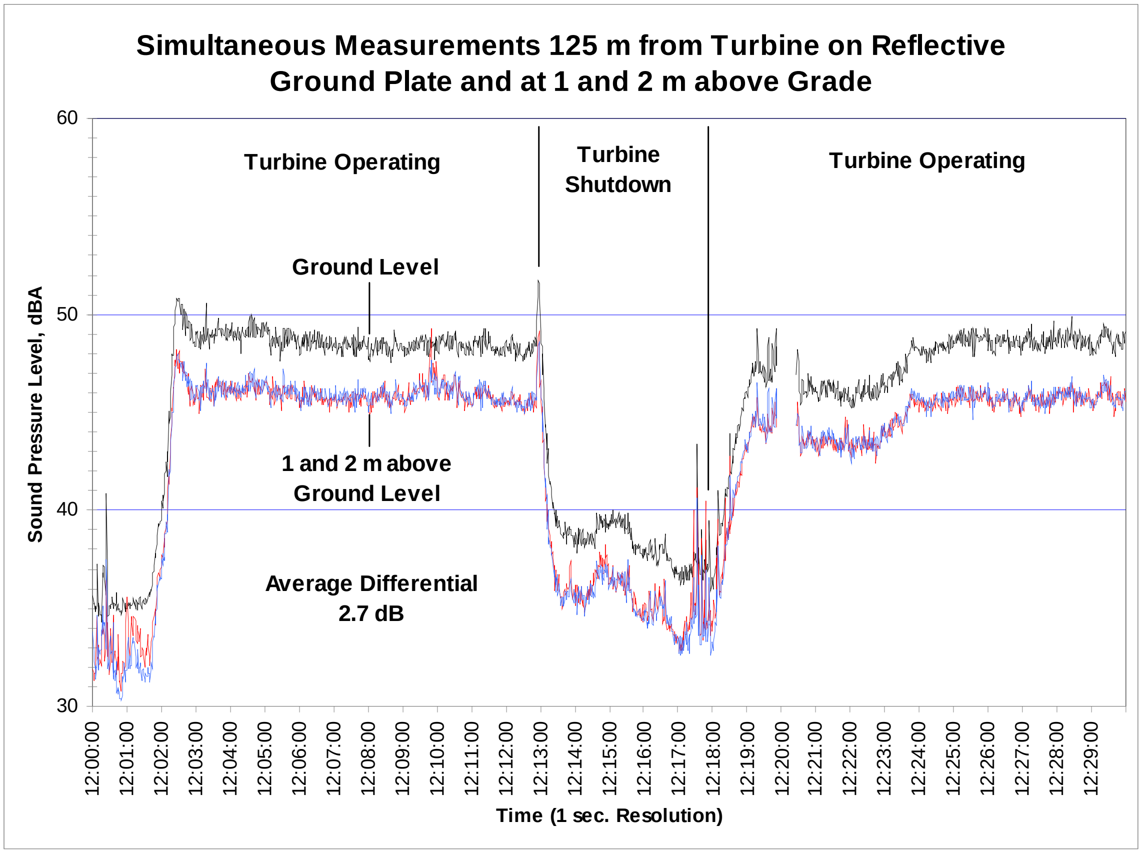

Figure 5.2.1.2

This example illustrates that it is possible under certain circumstances to reasonably measure the apparent A-weighted turbine sound power level above ground level without serious degradation due to wind distortion. Of course, this may not be true when it is particularly windy at 1 m above ground level. Another potential complication arises when multiple turbines are in unusually close proximity to each other, as they are in Figure 5.2.1.1, and background noise or cross-contamination from one unit to another must be taken into account in such cases. In general, however, the only substantive modification to the IEC 61400-11 process for calculating sound power level would be to change the constant "6" to "3" in Eqn. (9) of the standard since above ground measurements are being used.

As suggested by Figure 5.2.1.2, an additional tool that is normally useful and practical for single site investigations is to temporarily shutdown, for 10 to 20 minutes, the nearest turbines to the point of interest, if not all those that could conceivably be affecting the sound level there, in order to obtain direct measurements of the background level so the project-only level can be derived with some confidence from the operational sound levels occurring just before or after the shutdown. A short-duration shutdown helps ensure that the wind and weather conditions are essentially identical for both the on and off measurements. This technique also offers a way of verifying the validity of the levels measured at the off-site background positions. It is usually during the times of peak noise that it is most desirable to have an exact measurement of project's sound level, since these are the noise levels that most likely engendered the complaint in the first place. Consequently, it becomes a matter of either being there when these conditions occur, which is frequently at night, to organize the shutdown - or putting control over the shutdown in the hands of the resident who can call in by pre-arrangement to the control room if and when the noise becomes objectionable in terms of its overall magnitude and/or begins to exhibit some adverse character, such as from amplitude modulation. Although this latter approach of allowing the resident identify the time of maximum noise has been used successfully to quantify the overall magnitude of project noise and its frequency content in 1/3 octave bands, one must really be on hand to manually measure amplitude modulation, since it calls for the use of an extremely fine time resolution, on the order of milliseconds, to capture the sound oscillations that normally have a period of roughly 1 second. Such manual measurements can be taken indoors, where this kind of noise is most often observed to be objectionable, as well as outdoors.

Only with attended measurements it is possible, and then only occasionally, to measure indoor sound levels in any kind of meaningful way because contaminating noises can be observed and, hopefully, factored out. Long-term monitoring is effectively limited to the outdoors for the fundamental reason that there is no way to ascertain the background sound level inside of a dwelling at a particular time with the project operating. This is because the background sound level indoors is driven by a unique set of seemingly minor but significant sound sources that cannot be replicated by a proxy measurement position. Indoor background sound levels are partially a function of the outdoor conditions, particularly when it is windy or raining, but are also driven by such things as air flow from the heating and air conditioning system, appliances, computers and, of course, human activity even when it is in a distant part of the house. These usually very minor sounds are significant because the intruding noise level from the project is often very low or extremely low in terms of the A-weighted sound level. For example, it would not be unusual for a project sound level to be in the vicinity of 30 dBA inside of the house (perhaps being in the 40 to 45 dBA range outdoors). The successful measurement of the project-only sound level would then require the indoor background level to be 20 dBA or less, which is usually not the case. Sound levels in a bedroom at night are commonly at least 30 dBA even when no wind project is present.

In any event, it is sound level outside of dwellings that is normally (but not always) restricted by regulations or permit conditions and this level can typically be measured with the long-term monitoring methodology described above.

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A possible criterion for wind farms

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A possible criterion for wind farms

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Opposition to wind farm noise is not abating and shows no sign of doing so in the future. In a January 2017 paper in Sound and Vibration, Hessler, Leventhal, Walker and Schomer come together to report that independently they have come to about the same conclusion for a proper threshold of wind turbine noise. The same A-Weighted criterion has shown to come up in a variety of independent ways. This paper is not for pie in the sky desires for no sound. Rather, it attempts to recommend a criterion to use for determining the limits of wind turbine noise. This criterion is based off of the data of four independent sources: (1) CTL, (2) ANSI S12.9 Part 4, (3) Michaud et al. (2016), and (4) a State of Minnesota Department of Commerce survey of criteria set in various foreign countries and provinces. This paper recommends the use of A-weighting and a 24-hour Leq as the metric. 36-38 dB is recommended for the criterion.

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1. INTRODUCTION

A. BACKGROUND

Like most other industries or sources of transportation, noise and noise criteria are a matter of consternation to all sides involved in the siting and development of wind farms. Industry wants the permitted acoustical levels as high as possible, the community wants them as low as possible, and the municipality or county wants to maximize the dollars in their budget. For the past 10 or 15 years there has been an evolution towards developing a metric and criterion for wind turbine noise. Many turbines were built with what turns out to be rather high levels. They were designed with the community level being set at 50 or even 55 dB (A). Gradually, these levels have decreased, but friction between the community groups, the developers of the wind farms, and local government continues to this day.

B. PURPOSE

The purpose of this paper is to explain and evaluate the metric by which the community response to wind turbine noise is gauged and the limits appropriate to that response function. Chapter II deals with selection of the metric, and Chapter III presents the data and methods used to establish criteria and a criterion, based on the metric selected.

C. APPROACH

The approach to the selection of a metric is pragmatic. When looking at the present situation, A-weighting is the only appropriate metric for most noise sources. Based on all that we know, it could well be that C-weighting is preferred, or even Z-weighting or lower would be an improvement. But pragmatically, what is in use today and has corresponding response functions is A-weighting. These issues are dealt with in Chapter II.

In the second and more major part of the paper, various *independent* references and their procedures are used to find data on which to base the selection of a recommended criterion. These data come from four very independent sources. The use of four totally independent sources of data, independent from each other and independent from the issues at hand cannot be stressed enough. For example, the community tolerance level (CTL) was developed based on road traffic and airport noise, totally independent of wind turbine noise (WTN), totally independent of American National Standards Institute (ANSI) S12.9 Part 4, totally independent of the Health Canada study, and totally independent of the Minnesota Department of Commerce study. Similar statements can be made of each of the four sources, and these four sources are equally independent from the parties concerned (industry, community, and local government). They are totally independent of the results from the ANSI S12.9 Part 4 calculation, because these results were developed without having wind turbines mentioned or included in any way, as this was just a general procedure for environmental noise. Any assessment here is certainly independent from the Minnesota Department of Commerce existing criteria levels. The average and extremes of those data are what they are; nothing we do here can influence that. CTL is derived for other sources and other places, and not constructed for WTN, so its application is totally independent from wind turbine noise sources. The Health Canada data are not totally independent of the issues at hand, but the authors argue that the Health Canada data are equally independent for all three parties. In the same test with the same subjects, the Health Canada study finds that there are no health effects that can be found at the resolution that one gets with about 1200 subjects, but that there are substantial annoyance effects with these same subjects in the same study. One finding for industry, one finding for the community. That is, with the same sampling, the same noise measurements, the same noise predictions, the same surveyors, the same survey instrument, the same subjects, one gets half of the results that in some sense support industry, and half of the results that in some sense support the community. At least to this authors' mind, Health

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Canada represents an independent government entity not aligned with any of the three parties. The four sources are as follows:

1.data inherent to community tolerance level (CTL);

2.ANSI S12.9 Part 4

3.data from Health Canada, used to establish the equivalency between wind turbine noise and other noise;

4.the Minnesota Department of Commerce

Note: None of the data was developed by these authors and each of the sources is independent from any of the three primary groups involved: community, developer/operator, and local government. Thus, our approach is to present and explain these sets of data or procedures, and to show how they relate to the general method and the criterion that is ultimately selected.

1. CTL provides a one-number assessment of a set of cluster data from an attitudinal survey. Depending on what is held constant, almost any situation can be compared in decibel units of day-night level (DNL). Keeping with current practice, road traffic noise is used as the baseline. The difference in CTL between a data set under study and road traffic noise is the decibel difference between the two CTL values, respectively.
2. ANSI S12.9 Part 4 is directly used to form a small range of levels for potential development of a criterion.
3. Direct use of the Michaud *et al.* data and other similar international data to set a criterion.
4. Data from a State of Minnesota Department of Commerce survey of criteria set in various foreign countries and provinces.

2. SELECTION OF A METRIC

A. DISCUSSION OF WEIGHTING

As is well known, most sources are assessed using A-weighting with perhaps an adjustment for sound character (e.g. tonal or impulsive). A basic version of this assessment metric has been used since at least 1971 when the first version of ISO 1996 (International Organization for Standardization) was approved. The only source for which A-weighting is not used is high-energy impulsive noise, e.g. sound from demolition, open pit mining and quarrying, sonic booms, and noise from military training. For these sources, C-weighted data are collected, and these data are transformed to equivalent A-weighted levels in terms of equal annoyance (ANSI S12-9, ISO 1996-1).

There is no function that relates C-weighted wind turbine noise to an equivalent A-weighted level, nor is there a function that relates Z-weighting to an equivalent A-weighted level. The C-weighting procedure for high-energy impulsive noise took about 25 years to validate and get into use. Correlation between A-weighting and C-weighting in response to turbine noise has been shown, but this does not show that either of the weightings is correct. There is no conversion tool upon which to develop equivalent A-weighted levels. A response function is required. But it can be observed that a high degree of correlation between A- and C-weighting exists; so high that there is virtually no difference between using C-weighting or A-weighting. When one has a class of sources that all have the same spectrum, then the difference between different linear filters that all measure at least some part of the sound will all be highly correlated with one another. The difference between A-weighting and other weightings is that response functions have been created and scrutinized for A-weighting.

A constant, 24-hour A-weighted equivalent level (Leq) computed over the day and night periods, is the recommended metric, and in nearly all cases, the metric of interest is the nighttime Leq resulting from wind farm operations. So, as with aircraft and other noise categories that are dominated by one kind of source, comparisons can be made from one situation to another because the spectral content has not changed from one situation to another. For example, if one is measuring traffic noise, then the Leq for the hour beginning at 1500 measured on Tuesday should be similar to the hour measured at 1500 on Wednesday.

If the appropriate computational procedures are chosen, then one can install a barrier, have a reasonable chance at predicting a reduction, and subsequently produce a meaningful reduction for the community. That is not the situation with wind farm noise. It has been shown that the correlation from one type of wind turbine to another, and from one size to another, results in a set of numbers that properly order different situations because there is no change to the spectrum from one wind turbine to another. But this is not the case if one performs mitigation and predicts the benefit based on A-weighting. A barrier can be built alongside a highway and the reduction can be predicted. The corresponding decrease in community annoyance can also be predicted, at least to a reasonable degree. We cannot make the same statement about wind farm noise.

The reader should be cautioned not to believe that A-weighting is the correct weighting function for wind farm noise assessment. This simply has not been shown. Currently, however, the A-weighted levels assigned to different community responses seem to fit current wind farms in terms of response and level, at least in terms of annoyance based on attitudinal survey data. A-weighting is not chosen because it has been shown scientifically to be better than other metrics. Rather, it is chosen because at the current state of development, to date, no one has shown any metric to be superior. Even if it were available today, it would still take quite a while to gain acceptance for such a metric.

B. METRIC

The choice of a metric is limited. In principle, all of the readily available noise metrics are those built into sound level meters and other similar devices. The non-time integrating metrics are very limited in the data provided. Lmax and Lmin are two non-integrated choices, but it is clear that Lmax may be something that occurs for a short time every once in a while (e.g., once an hour or once a day). In the class of time-integrated metrics, there are three prominent choices: Leq, Ldn, and Lden. These three are not significantly independent; rather, there are very clear and consistent differences among them. Leq 24-hour is predicated on the assumption that wind farm noise emissions from a given turbine throughout the 24-hour day are more or less constant (read ±1 dB). The question is: how far above Leq must the DNL be such that the calculation of Leq during daytime added to (Leq+10) dB at night equals to DNL? The difference between the numerical value for Leq and DNL when the Leq is held constant is about 6-7 dB. A similar number exists for DENL. DNL or DENL provide no additional information as compared to the simpler, constant 24-hour Leq. Were Leq not a constant, and Ld and Ln are not constant, then a more complicated difference between DNL and 24-hour Leq would be required.

3. METHODS AND PROCEDURES BY WHICH A CRITERION FOR WIND TURBINE NOISE CAN BE SELECTED

A. DIFFERENCES IN COMMUNITY TOLERANCE LEVEL (CTL) BETWEEN ROAD TRAFFIC AND WIND TURBINE NOISE

At this point, it is proposed that a relationship between percent highly annoyed and various nighttime Leq levels be established. However, the recent papers by Fidell et al. and Schomer et al. relate percent highly annoyed to DNL. These two papers also introduce the concept of community tolerance level (CTL). This paper will establish the relationship between nighttime Leq, CTL, and DNL for wind turbine noise. Once that is done, we will compare various DNL and CTL levels with wind farm levels. As a part of this comparison, we will include the transformation of CTL or DNL data to nighttime Leq in order to have valid comparisons. First, DNL will be discussed, followed by CTL.

Up until the introduction of CTL, all community attitudinal survey data were analyzed by using linear regression analysis. There was no underlying functional relation. With CTL, it is hypothesized that the community response to environmental noise is similar to the basic human loudness function where loudness is proportional to the independent variable raised to the 0.3 power. Secondly, it is hypothesized that the functional form of a relationship is a transition function, and for the sake of simplicity, the simplest form of a transition function is used: e^{-v}. It becomes:

$$\%HA = 100 * e^{-1/(10^{(\frac{Ldn-Lct+5.306}{10})^{0.3}})} \quad (1)$$

where 5.306 is an arbitrary constant K. The property of K is such that when Ldn=Lct, then Lct corresponds to the 50th percentile for %HA. That is, for purposes of convenience, the value of CTL for a given community is standardized at the midpoint of the exponential function. A CTL value thus corresponds to the DNL value at which half of the people in a community describe themselves as highly annoyed by transportation noise exposure. As Fidell *et al*. (2011) show, the constant 5.306 follows from the definition of CTL as the midpoint of the exponential function. That is, when DNL = CTL, the %HA = 50%. (Definition of CTL at a point other than 50% on the exponential function would merely result in a change to the constant 5.306, with no loss of generality.)

Fidell *et al.* (2011) gives the percent highly annoyed as a function of DNL for all noise caused by airport operations. Schomer *et al.* (2012) does the same for highway and railroad noise. The convention is that all noises are compared to road traffic noise. The difference in the value of K between any source and road traffic yields the numerical difference in dB between the two situations. For example, the CTL for all road traffic is 78 dB and the CTL for all aircraft is 73 dB. So, aircraft is 5 dB less tolerable than road traffic noise. CTL can quantify the difference between any two situations one wants to consider. For example, one could look at the difference between nighttime and daytime, the difference between hilly country and flat country, the difference between urban, suburban, and rural, or the difference between communities on the ocean and those landlocked.

Michaud *et al.* (2016) calculates the CTL for wind turbine noise to be 62 DNL. That is, 16 dB must be added to the DNL of road traffic noise to make it equivalent to that of wind turbine noise. Michaud et al. also calculate the CTL for each of his two study areas, Prince Edward Island and Ontario, independently. In addition, they calculate the CTL for other surveys that provide the necessary data to calculate the CTL (Pedersen et al. 2004, 2007, 2009; Yano et al. 2013). Michaud shows that the CTL for Ontario is very similar to the CTL for Pederson et al., 2004 and Yano et al. 2013. The CTL for PEI is shown to be very similar to the CTL for Pederson et al 2007 and 2009. The CTL for Ontario is about 7.5 dB lower than the CTL for PEI. They also compute the average CTL for windfarms and that is what is used herein.

B.USE THE DIRECT HEALTH CANADA AND THER COMPARABLE INTERNATIONAL SURVEY DATA OF %HA AT VARIOUS TURBINE NOISE LEVELS

This method is the simplest, it says that the %HA at a certain dB(A) is exactly what is measured. There are three data points provided by the Health Canada analysis: the ranges are from [30-35) dB, [35-40) dB, and [40-46) dB. The corresponding %HA are 1%, 10%, and 14%.

In this paper, several primary sources of data are used to develop the functional relationship and select the criteria. Once a DNL is chosen as the metric, the second step is to establish percent highly-annoyed as a function of DNL. This %HA can then be compared to the results from Michaud *et al*. to form a criterion.

C. USE THE S12.9 TO DIRECTLY DEVELOP A CRITERION

ANSI S12.9 Part 4 uses DNL as its primary metric. ANSI S12.9 Part 6 establishes 55 DNL as the criterion for start of impact from noise. Part 4 also establishes the adjustment of 10 dB for quiet rural areas, i.e. the criterion drops to 45 DNL. In terms of a 24-hour A-Leq, this criterion drops to 39 dB. So, we find 39 dB to be a criterion, independent of the noise source. This derivation never mentions wind turbine noise.

D. USE THE MINNESOTA DEPARTMENT OF COMMERCE FINDINGS

Minnesota, like 29 other states (reference 2 from Haugen 2011), has a state renewable energy objective that calls for “25% of the state’s electrical energy to come from renewable sources including wind energy by 2025 (reference 3 from Haugen 2011).” “While many people support wind energy, some have become concerned about possible impacts to their quality of life due to wind turbines, including noise, shadow flicker, and visual impacts…” Because of these concerns surrounding wind power, the state set out to survey a variety of players in the wind energy industry, from many foreign regions and countries. “For this report, a variety of professionals working on renewable energy issues within national and regional governments, wind energy associations, wind energy development companies, and other areas were contacted by email.”

The Minnesota findings are shown in Figure 1. This figure shows national and regional wind farm limits in two different kinds of areas: (1) residential and other noise sensitive areas, and (2) all other areas. These are represented in the figure as a solid blue bar for the sensitive areas, and a solid green bar going above the blue for the other areas. Only 3 of the 19 jurisdictions are above 40 dB: Spain, Portugal, and the Netherlands, and the average is 36 dB.

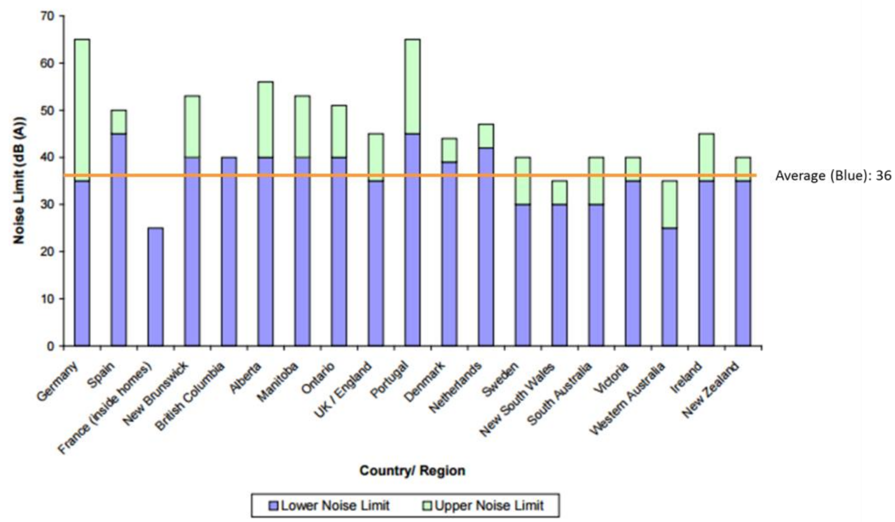

Figure 3: Country Wind Turbine Noise Limits at Residences

Figure 1: International wind turbine noise limits obtained by the Minnesota Department of Commerce

4. EVALUATION OF CURVES EQUATING DNL TO %HA

In this report, data from six different sources are examined in an attempt to develop a %HA criterion for wind turbine noise (and most other noises): Schultz, the Committee on Hearing, Bioacoustics, and Biomechanics (CHABA), the Federal Interagency Committee on Noise (FICON), CTL (Fidell *et. al.*, Schomer *et. al.*), Miedema and Oudshoorn (2003), and Miedema and Vos (1997). Schultz, CHABA, and FICON are all based on the Schultz's 1978 synthesis of social surveys on noise annoyance, with the CHABA curve being virtually identical, and FICON being mysteriously low in the relevant DNL interval (60-75 DNL). Miedema and Oudshoorn is an improved version of Miedema and Vos, and along with CTL is used in the current version of ISO 1996-1. Schultz, CHABA, and FICON use data from a combination of aircraft and road traffic noise sources to arrive at their %HA values, whereas CTL, Miedema and Vos, and Miedema and Oudshoorn all make a distinction between aircraft and road traffic. The curve given by Miedema and Vos is shown in the figure for reference as a dashed blue line, but is not included in the analysis that follows because they are two variant data fits to the same data base by the same organization, and using both of them could bias the calculations that follow.

These five sources and their %HA from 50 to 70 DNL in 5 dB increments are shown in Table 1. In this table, Miedema and Oudshoorn and CTL both have separate equations for road traffic and air traffic. CHABA and FICON each use their own single equation for all modes of transportation; planes, trains, and automobiles. Research has conclusively shown that aircraft sound is more annoying than other sound for the same numerical value, which implies that the DNL values Schultz, CHABA, and FICON attribute to a corresponding percentage of high annoyance must be biased high for use with road traffic. And conversely, the %HA for aircraft noise must be biased low. Part A of Figure 2 shows the five functions described for road traffic noise, and Part B shows the five functions described for aircraft noise. From the figures, it would seem that the biased low is a much stronger factor than the biased high. In fact, from the data, one would be tempted to say there is no bias high, but from the logic, this seems to be impossible. As shown in Figure 2A, the Schultz, CHABA, and FICON curves fit somewhat closely to the road traffic curves, but understates the %HA value. For aircraft noise (Figure 2B), %HA values are understated by a very large amount, nominally 15%.

ROAD:					
Group	**M&O**	**CTL**	**CHABA**	**FICON**	**SCHULTZ**
50	3.8	0.7	2.3	1.7	1.3
55	6.6	3.1	4.6	3.3	3.9
60	10.6	8.6	8.7	6.5	8.5
65	16.5	17.6	15.2	12.3	15.2
70	25.1	29.2	24.5	22.1	24.6
AIR:					
Group	**M&O**	**CTL**	**CHABA**	**FICON**	**SCHULTZ**
50	5.3	3.1	2.3	1.7	1.3
55	11	8.6	4.6	3.3	3.9
60	18.6	17.6	8.7	6.5	8.5
65	27.8	29.2	15.2	12.3	15.2
70	38.5	41.9	24.5	22.1	24.6

Table 1: %HA values at different DNL levels for 5 sources

There is no doubt that both Schultz and CHABA represent excellent researchers and excellent organizations. Their results differ from more recent results by Miedema and Oudshoorn, Fidell, and

Schomer. The only conclusion one could come to is that the two databases being analyzed are not the same, and that is known to be the case. The database used by Schultz contained 11 clustering surveys, of which six were aircraft, four were road traffic, and one was railroad. In contrast, the three more recent curves are based on a much larger database. Fidell used 43 aircraft surveys for his work, and Schomer used 39 road traffic surveys and 11 railroad surveys, totaling 93 surveys used to create the CTL method. Miedema and Oudshoorn is based upon a similar quantity of data. A large quantity of the data is used both for CTL and Miedema and Oudshoorn. For a variety of reasons, the authors of this paper will use the methods based on the larger database, Miedema and Oudshoorn, CTL, and CHABA.

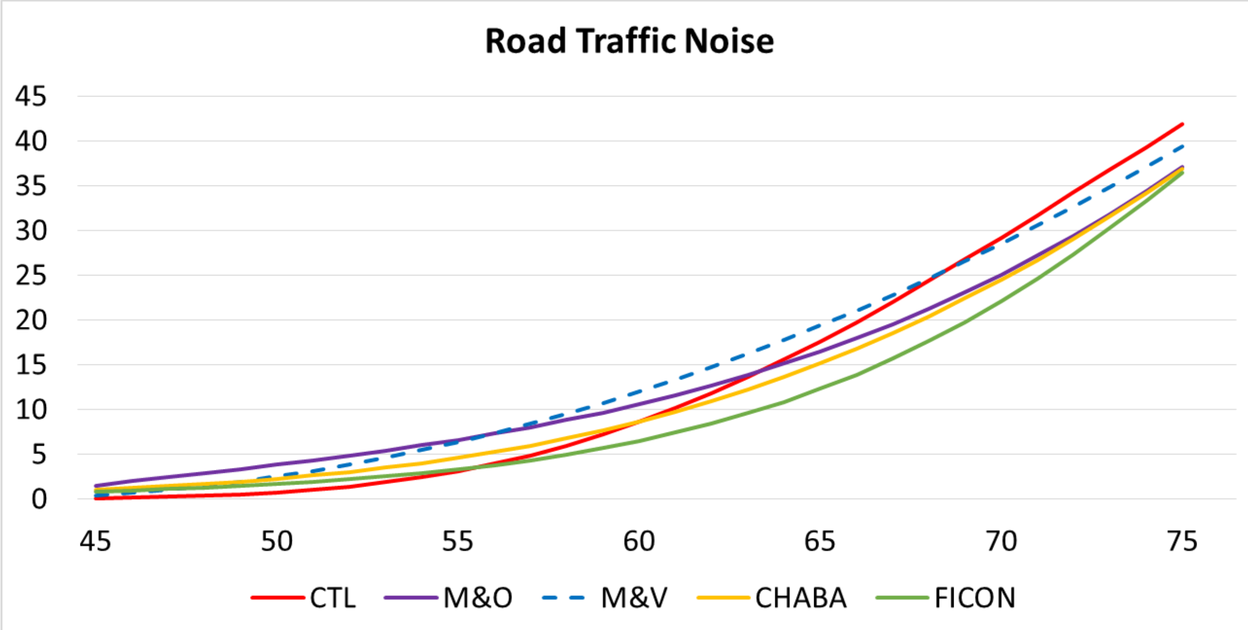

Figure 2A: 5 curves for determining %HA for road traffic noise

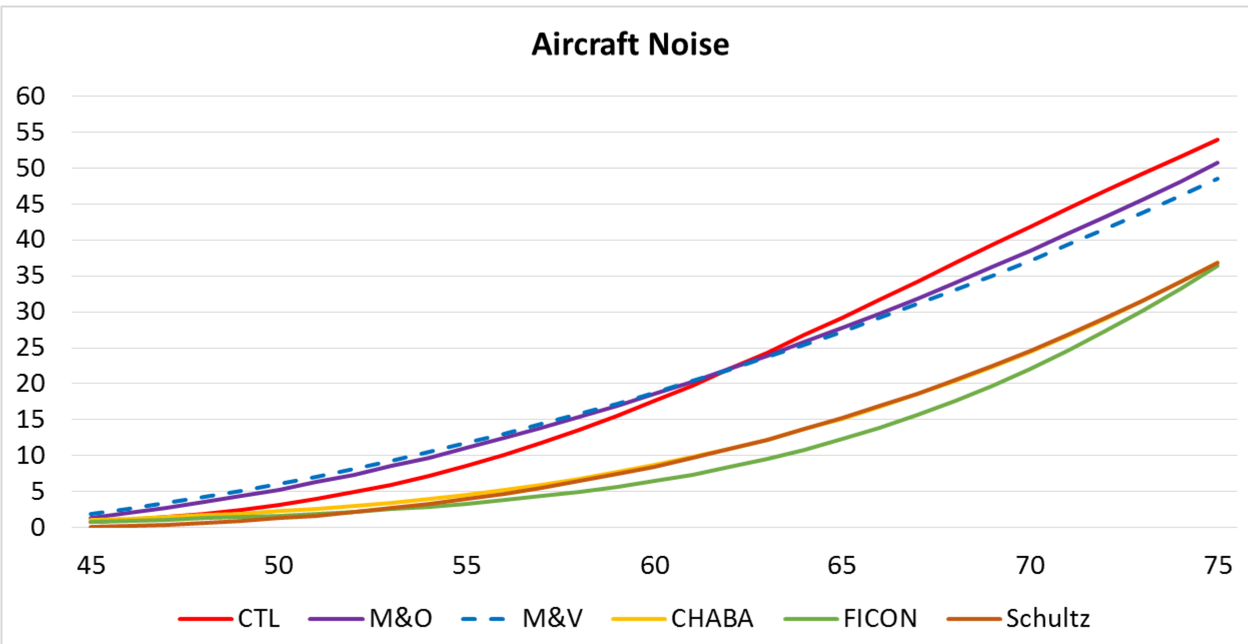

Figure 2B: 6 curves for determining %HA for aircraft noise

5.WHAT IS THE ACCEPTABLE LIMIT FOR PERCENT HIGHLY ANNOYED (%HA)?

A. ESTABLISHING A FUNCTION FOR %HA vs DNL

Since the purpose of this report is to establish data and relations for the selection of a wind turbine noise criterion. In this section, four independent methods are given with which to establish a relation by which to judge wind turbine noise annoyance. During at least the last several years, it has been common to use road traffic noise as the "yardstick" by which other noises are measured. Miedema and Vos (1997), Miedema and Oudshoorn (2003), Fidell *et al.* and Schomer *et al.,* as well as ISO 1996-1 all use road traffic noise for this purpose.

In 2005, Schomer examined the metrics and criterions used by nearly every federal agency and board, by recommendations in national standards, and by international recommendations such as those made by the World Health Organization. These, and multiple other sources agree to 55 DNL as an acceptable criterion for road traffic noise. Therefore, we will use 55 DNL as our intermediate criterion. The term "intermediate" is used because the real issue is annoyance and not decibels. It is very common to relate %HA to decibels, but it is almost always decibels that are measured and not annoyance. For a DNL of 55 dB, 4 different estimates of %HA were found in the literature. CTL equates 55 DNL with about 3% HA, Miedema and Oudshoorn equates 55 DNL with about 7% HA, for road traffic and aircraft noise separately, and CHABA predicts about 5% for a DNL of 55, for both air and road traffic combined. Herein, we will be using the average of these four estimates, which is 5%.

B. CHOOSING A CRITERIA

1. The first method, the method that is dependent on %HA, relates the data from Health Canada to the 5% value established above. Michaud *et al.* (2013) writes that "Consistent with Pedersen et al. (2009), the increase in wind turbine annoyance was clearly evident when moving from [30–35) dB to [35–40) dB, where the prevalence of wind turbine annoyance increased from 1% to 10%. This continued to increase to 13.7% for areas where WTN levels were [40–46] dB." Michaud relates 3 different values for %HA values with 3 corresponding decibel levels: 1%HA is related to 32.5 dB(A), and 10%HA is related to 37.5 dB(A). Therefore, 5%HA would be related to a value between 32.5 and 37.5 dB(A), most likely around 35 dB(A). With this method, a 5%HA criterion is related to 35 dB(A). A more conservative criterion is given by the doubling of the %HA from 5 to 10%. For this second %HA limit, the corresponding dB(A) level is 37.5 dB(A).

2. The second method compares CTL for road traffic noise to CTL for wind turbine noise. The average CTL for road traffic noise (Schomer *et al.* 2012) is 78.3 dB. In comparison, the average CTL for wind turbine noise is 62 dB. So, a 16 dB difference is found between wind turbine noise and the traffic noise "yardstick." To complete this comparison, one must have a value for an acceptable DNL for road traffic noise. Here, a range of DNL is considered: 55-60 dB. Subtracting 16 yields a range of 39-44 dB for wind turbine noise. As per section II-B above, 6-7 dB is subtracted from DNL in order to calculate Leq. This subtraction yields a range of 32-38 dB as a limit for wind turbine noise.

3. A third method to develop a criterion is to directly apply ANSI S12.9 Parts 4 and 5. Part 5 recommends a DNL of 55 dB for residential areas as a limit based on the start of impact. Part 4 recommends a 10 dB

penalty on the limits for quiet rural areas. Most wind farms are built in quiet rural areas, so this penalty is applicable in this case. In a quiet rural area, the DNL limit becomes 45 dB. But this is DNL, to get to Leq we must subtract 6-7 dB, so that the recommendation becomes an Leq of 38-39 dB.

4. Data published by the Minnesota Department of Commerce, shown in Figure 1, give noise limits for sensitive rural areas and non-sensitive areas. As an example of land use designations, wind turbine noise limits in South Australia are based on the highest level applicable between: rural areas at 35 dB(A), non-rural areas at 40 dB(A), or 5 dB(A) above background measured as L90. The average value of the noise limits for sensitive areas given by the Minnesota report is about 36 dB(A).

6. ANALYSIS AND CONCLUSIONS

Four independent data sources are used to create four estimates of an acceptable 24-hour A-weighted Leq criterion for wind turbine noise. Two methods use 5% highly annoyed as the estimated start of impact for a receiving person. The remaining methods examine both adjustments to a recommended DNL indicating start of impact, and an analysis of existing wind turbine noise limits. The four estimates of a criterion are listed below:

1. 5% HA is shown to be a very approximate average to a criterion for %HA. In order to be conservative, the range from 5 to 10% is considered herein. Applying a 5% HA value to the Health Canada data gives a limit between 32.5 dB and 37.5 dB, or about 35 dB(A). Applying a 10% HA value to the Health Canada data gives a limit of 37.5 dB(A) (Michaud *et al.* 2016b).

2. A 16 dB difference is found between the CTL for road traffic noise and WTN, and if the metric is Leq, then the difference between WTN and Leq is another 6-7 dB, for a total of 22-23 dB difference. Comparing the CTL for wind turbine noise to the CTL for road traffic at the lower limit of 55 DNL for road traffic suggests a limit of 32-33 dB(A). Comparing the CTL for wind turbine noise to the CTL for road traffic at the upper limit of 60 DNL for road traffic suggests a limit of 37-38 dB(A).

3. Applying ANSI S12.9 Parts 4 and 6 to determine the level at which impact will start in a quiet, rural area gives a limit of 38-39 dB(A).

4. The average of existing worldwide limits found in the Minnesota Department of Commerce report for sensitive areas is about 36 dB.

As applicable, Table 2 lists the minimum, average, and maximum Leq criteria for wind turbine noise for each of the four methods above:

	Minimum (dB)	Average (dB)	Maximum (dB)
1-%HA		35	37.5
2-CTL	32		38
3-ANSI		38	39
4-MN DoC		36	
AVERAGE	**32**	**36.3**	**38.2**

Table 2: Minimum, average, and maximum Leq criteria

The average of the top-end values is about 38 dB(A) and the average of the middle values is about 36 dB(A). The minimum level, 32 dB, is not emphasized. These four sets of independent data result in criteria recommendations that are remarkably close to one another, lending support to a 24-hour A-weighted Leq wind turbine noise criterion in or around the range of 36-38 dB(A).

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Health effects from wind turbine low frequency noise & infrasound: Do wind turbines make people sick? That is the issue

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Health Effects from Wind Turbine Low Frequency Noise & Infrasound

Do Wind Turbines Make People Sick? That is the Issue.

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Do wind turbines make people sick? That is a contentious issue in licensing wind farms. In particular, low frequency sound emissions (infrasound and "pulsed" and steady low frequency sound) from wind turbines are blamed by opponents but vigorously denied by project proponents. This leads to an impasse of testifying "experts," and regulators must decide on the basis of witness credibility for each project, leading to inconsistent findings. This article presents the opinions of four very experienced independent investigators with wind turbine acoustics over the past four decades. The latest Threshold-of-Hearing research down to 2 Hz is compared to today's modern wind turbine emissions. It is jointly concluded that infrasound (0-20 Hz) can almost be ruled out, subject to completion of recommended practical research, and that no new low frequency limit is required, provided adequate "A"- weighted levels are mandated.

Claims of adverse health effects are made by individuals and organized community groups at some operating wind turbine sites located around the world. Adverse publicity is intense at about a dozen operating sites in the United States, the United Kingdom, Canada, Scandinavia and Australia. Health effects attributed to wind turbines include symptoms similar to those of motion sickness, such as, dizziness, nausea, vomiting and a general feeling of discomfort or not feeling well. Sea sickness (a form of motion sickness) is well understood as a disturbance of the inner ear, and the cause is both obvious and indisputable. Motion sickness is more subtle and is caused by the brain receiving conflicting messages about what is seen by the eye as opposed to what is felt or sensed.[1] For example, air sickness can result from plane motion caused by invisible turbulence in the air. To date, no such similar connection has been found at wind turbine sites, although some residents claim they can sense when wind turbines become operational without benefit of sight or hearing.

It has now been demonstrated by multiple independent researchers that wind turbines, like any other rotating fan, emit measurable tones at the blade-passing frequency (BPF) and up to about the fifth harmonic plus broadband noise. For a typical large three-bladed wind turbine rotating at 16 RPM, the BPF and harmonic tones are at frequencies of 0.8, 1.6, 2.4, 3.2, 4 and 4.8 Hz. These very-low-frequency tones are commonly called infrasound, defined as low-frequency noise in the 0-20 Hz frequency range. A better definition used by one of the authors is "pulsed LFN," since the tones result from analysis of pulses produced by tower blade interaction. The 0-20 Hz measurements are all well below the threshold of hearing, as established by the latest research at frequencies down to about 2 Hz. But it might at least be asked: Are the pulses the invisible source of conflicting messages to the brain? Reference 1 states that messages "are delivered from your inner ear, your eyes (what you see), your skin receptors (what you feel) and muscle and joint receptors," but there is the open question of whether the low levels of pulsed LFN or infrasound from wind turbines excite any of these receptors.

Permitting authorities for new projects must evaluate adverse health effect claims presented as proven factual data by opposition forces, countered by project advocates that state no physical link to health effects has ever been demonstrated at wind turbine sites. This debate has now raged for at least a decade and is now at an impasse.

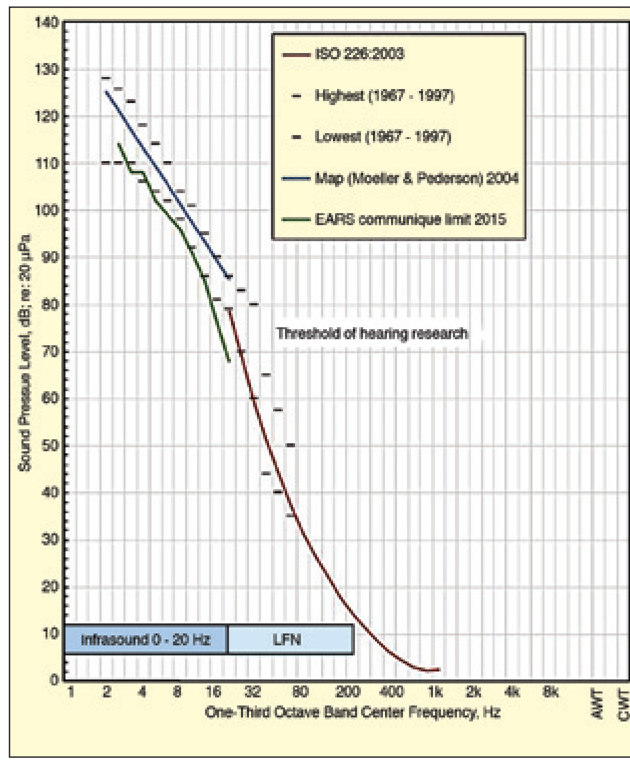

Figure 1. Research summary for determining threshold of hearing at low frequencies.

It has been the first author's privilege and pleasure to associate and collaborate with three prominent co-author scientists in the wind turbine acoustical field. All four authors do not doubt for a moment the sincerity and suffering of some residents close to wind farms and other low-frequency sources, and this is the reason all four would like to conduct, contribute or participate in some studies that would shed some light on this issue. It must also be said that it is human nature to exaggerate grievances and that some qualitative measure must be made available to compensate affected residences.

The first author has asked each co-author to independently summarize their opinions and recommendations on how the current impasse can be broken.

Current Research on the Threshold of Hearing

Research to measure the threshold of hearing at low frequencies can be summarized in one graphic (see Figure 1). The highest and lowest gray bars encompass the results of 10 studies over the listed 30-year period that is nicely shown in the Noise & Health Journal.[2] These are the min. and max. at each 1/3-octave-band frequency for any of the 10 studies. The graphic also plots ISO 226:2003(E) that covers the entire audible range from 20 Hz to 12,500 Hz (plotted to 1000 Hz). The green line comes from Project EARS funded by the

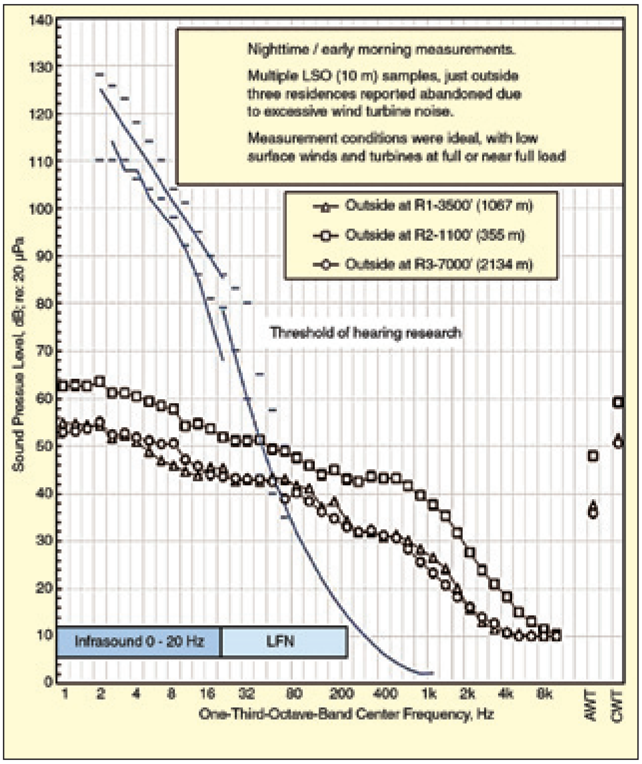

Figure 2. Typical wind turbine spectra and levels compared to threshold of hearing at low frequencies.

European Union[3] and represents "acceptance levels" based on the 10% percentile hearing threshold values determined in the EARS Project and is the latest research on the subject.

Defining the Problem

How does ILFN from a modern wind farm compare to the above summary? Figure 2 replots the contents of Figure 1, all in blue, and adds the measured spectra and overall levels at three locations from a study[4] funded by Clean Wisconsin (an environmental organization) and the state of Wisconsin. This study was carried out at a wind farm located among residences in a quiet environment of residences and farmland, typical of wind farm sites in the American midwest and northeast. Response at this site has been adverse, to say the very least. The three plots are near residences reported to be abandoned due to adverse health effects. Several things may be deduced form this plot.

First, the wind farm was designed to a standard of 50 dBA at nonparticipating residences, and that level is not endorsed by any of these four authors. All of us have been at or near 40 dBA for many years. Had 40 dBA been used, there would not be a wind turbine as close as 1100 feet at R2, where a level of 48 dBA was measured. Wind turbine sound was readily detectable by the test engineers at R2, but not at R1 and R3 where levels are less than 40 dBA.

Second, the levels at all the residences in the infrasound range (0-20 Hz) are far below perceptible levels in this range. This strongly suggests the source of any message to the brain is not from wind turbine infrasound directly but may occur as audible LFN or pulsing LFN at the blade-passing frequency well inside the infrasound range.

Third, a wind turbine is not a classic LFN noise source – a source heavily weighted with LFN. Such sources typically have C-weighted levels 15 or 20 dB above A-weighted levels. Observe from the plot that C-weighted levels are both relatively low (<60 dBC) based on typical C-weighted guidelines, and the C-A differential is less than 15 dB.

To understand just how difficult this issue is, consider that the residents (husband, wife and young baby) at R2 experienced their child awakening at night screaming, but not on nights away from home. The wife was highly annoyed, and the husband had "no problem at all" with wind turbine sound. Add to this that there is a home across the street, the same distance and direction from

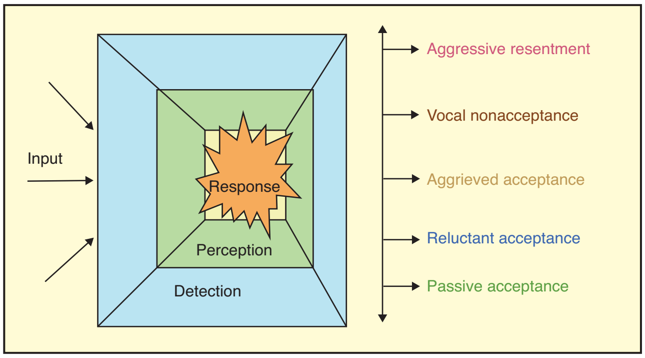

Figure 3. Response process (left) and range of responses (right).

the turbine, but the owners accept "good neighbor" payments. Could any payment be enough if suffering serious health effects?

And last, there are thousands of landowners that lease their land for wind turbines and live very close to turbines. It is hard to abandon the notion that higher levels closer to the source should produce higher levels of affected residents, but a recent large-scale, long-term measurement survey in Australia showed no correlation between complaint locations and measured levels.

It would seem one promising direction of a study could be extensive interviews of such folks exposed to high levels of wind turbine noise that could reveal common symptoms and/or the number of folks seriously affected.

Opinions and Recommendations of Geoff Leventhall

Wind Turbine Noise and Health. Wind turbine noise spans a range from below 1 Hz up to 10 kHz or more. A one-third-octave spectrum typically drops off at between 4 dB/octave and 6 dB/octave. Blade-passing tones are added into the falling spectrum in the range from about 1 Hz to 7 or 8 Hz and have normally disappeared from the spectrum by 10 Hz, although they may reappear at a low level at higher frequencies. (Zajamšek, Hansen *et al.* 2016). The high correlation between wind turbine dBA and dBC, (Keith, Feder *et al.*, 2016) is explained by this generalized falling spectrum from infrasound to high frequencies, also described by Tachibana *et al.*, who found 4 dB per octave fall-off (Tachibana, Yanob *et al.*, 2014).

Sound level at nearest residential distances of, say 500 m, may be around 60 dB at 10 Hz, while the hearing threshold is close to 100 dB at this frequency. A falling spectrum of 6 dB/octave (20 dB/decade) gives 80 dB at 1 Hz for a level of 60 dB at 10 Hz. The hearing threshold is not well known at 1 Hz but is likely to be about 130 dB, since measurements have shown a threshold of 120 dB at 2.5 Hz (Kuehler, Fedtke *et al.*, 2015)

Levels of wind turbine infrasonic blade tones are well below our normal hearing threshold, while at higher frequencies, say 30-50 Hz, the blade harmonics, if present, may approach median threshold. (Zajamšek, Hansen *et al.*, 2016).

Wind turbine sound fluctuates due to short-term variations in propagation, with typical maximum fluctuations of about 15 dB (Bray and James 2011). Wind turbine low-frequency noise normally becomes just audible to the average listener at frequencies above 40-50 Hz. Higher audible frequencies, 250-1000 Hz from aerodynamic noise may vary in level at the blade-passing frequency, giving amplitude modulation (swish) of about once per second. Frequencies in the higher kilohertz range are heavily attenuated by air absorption and are not normally a factor in wind turbine noise at residences.

Does wind turbine noise, as experienced at typical residential distances, affect health through either direct or indirect mechanisms? There is wide variation in human response to audible noise, especially to low levels of noise like that produced by wind turbines, but these low levels are not known to have direct and adverse physiological effects on the body. The term "physiological effects" must be used carefully, since any response to a stimulus is a physiological effect. The great majority of these responses are harmless, beneficial or essential to our proper functioning.

Figure 3 shows a simplified diagram of the hearing process, leading to perception and response to a noise (Leventhall 1998). Input noise is detected, stimulating perception via the auditory cortex. Response, the reaction to perception, is very variable, as in Figure 1, depending on many personal and situational factors and conditioned by both previous experiences and current expectations. Response to the same noise from within a large group might range from passive acceptance (I can hear it, but it does not bother me) to aggressive resentment (I can't stand this noise – it's ruining my life).

Daytime disturbance by noise leads to irritation and aversion, while sleep disturbance may be an additional night effect, although investigations have shown similar numbers of poor sleepers and good sleepers both close to and remote from wind turbines (Nissenbaum, Aramini *et al*. 2012) (Jalali, Nezhad-Ahmadi *et al*. 2016) (Michaud, Feder *et al*., 2016). Cognitive behavioral therapy reduces disturbance from noise through a process of desensitization and can improve sleep and quality of life (Leventhall, Robertson *et al*., 2012).

The main effect of low levels of unwanted audible sound is creation of hostile reactions and negative thoughts, leading to stress and to the adverse health effects that might follow. Stress has different intensities, ranging from cataclysmic events (war and earthquakes), to acute personal stress (bereavement), and to chronic low level stress (long-term illness or persistent personal problems) (Benton and Leventhall, 1994). Stress from wind turbines, if it arises, is normally low level but, in a very small number of people, it may become intense and overpowering so that opposition to wind turbines is the dominating emotion in their lives. Unfortunately, concentrating attention on an unwanted noise aggravates any problems. Anticipatory stress also occurs following approval of a wind farm, although it has not yet been built, and a few anxious residents may experience similar symptoms to those that they believe to be associated with an active wind farm (Mroczek, Banas *et al*., 2015).

Reaction to noise, especially low-level noise, is largely conditioned by attitudes to the noise and its source. Noise level contributes only about 20-30% of the total annoyance from noise (Job, 1988), while feelings, fear and opinions shape many of our responses, influencing tolerance levels. Negative emotions give an additional impact to an unwanted stimulus. The attitudes of nearby residents toward wind turbines is a major factor in the effects that turbines may have on their health (Rubin, Burns *et al*., 2014). It has been shown that sham exposures to infrasound, (Crichton, Dodd *et al*., 2014) or to sham electric fields (Witthoft and Rubin, 2013) produce symptoms in those who have been primed to expect an effect from exposure. The human being is clearly very complex in its reactions to physical and psychological stimuli.

Infrasound has a special place in discussions of the health effects of wind turbines, with many claims centered on direct pathological interactions, initially fostered by media scare stories originating in the 1960s and still continuing (Leventhall, 2013a).

In his 1974 popular science book *Supernature*, Lyall Watson described infrasound as causing deaths ("fell down dead on the spot"), while focused infrasound "can knock a building down as effectively as a major earthquake." This is unfounded, but an aura of mystery and danger persists around infrasound deep in the minds of many people, where it waits for a trigger to bring it to the surface. A recent trigger, heavily manipulated by objectors and media, has been wind turbines (Deignan, Harvey *et al*., 2013).

A concept from psychology is the "truth effect," which explains how we can develop belief in false statements through their repetition by others (Henkel and Mattson, 2011).

- We believe statements that are repeated, especially by different sources.
- The path to our belief is made easier by each previous repetition.

Advertising and political propaganda are clear examples of the operation of the truth effect, which is also known as "illusory truth."

We all also have our preferred beliefs. When there is a choice, we tend to believe what we wish to believe. We feel comfortable when our existing beliefs are confirmed, and if we have become antagonistic to wind turbines we readily absorb negative statements about them.

Some objectors to wind turbines further their cause by generating anxiety on effects on health, particularly from infrasound and low-frequency noise, in populations close to proposed wind farms. Persistent repetition that infrasound from wind turbines will cause illness develops stressful concerns in residents, but repetition is neither evidence nor proof. However, a nocebo effect may occur, by which expectation of an outcome may lead to realization of that outcome (Chapman, Joshi *et al*., 2014).

There are a large number of coordinated objector groups working internationally. A web page (https://quixoteslaststand.com/) gives links to more than 2000 groups that share information on wind turbines, while some make unsubstantiated, anecdotal claims about their effects. However, there is no doubt that when stress is persistent it may result in somatic effects in a small number of people who have a low-coping capacity, although the ability to cope can be enhanced (Leventhall , Robertson *et al*., 2012).

In considering infrasound and other sound from wind turbines, it is necessary to take a very analytical, critical, unemotional view of the topic and to remain free of the influence of incorrect, but frequently repeated, statements.

There is no evidence that inaudible infrasound from wind turbines affects health, but there are indications from exposure tests that it does not (Tonin, Brett *et al*., 2016). Inaudible infrasound has not been shown to affect those exposed, but just audible infrasound has a sleep-inducing effect (Landström, Lundström *et al*., 1983).

Comparisons have been made of levels of infrasound from wind turbines at dwellings with the levels of infrasound that occur from man-made sources in urban and industrial areas and also levels that occur naturally in coastal and other regions. The infrasound exposure levels are similar (Turnbull, Turner *et al*., 2012).

There is a persistent microbarom frequency of about 0.2 Hz caused by interacting sea waves, which goes to high levels during storms, propagating long distances over land. Microbarom six-hour averages have been measured in the region of 60-70 dB, while power spectral densities as high as 120 dB at 0.2 Hz have been observed (Shams, Zuckerwar *et al*., 2013). We are not affected by this infrasound, which is at higher sound pressure levels than wind turbine infrasound at 0.2 Hz.

Investigations to find a link between infrasound from wind turbines and adverse physiological effects include work by Salt, who used high-level 5-Hz infrasound to bias the hearing of guinea pigs and noted that the outer hair cells (OHC) responded to this stimulus. The response threshold was lower than the hearing threshold, which is determined by the inner hair cells. Salt used the single measurement as a point on an OHC threshold curve and deduced an OHC threshold for humans by considering the low-frequency mechanics of the ear and comparison of human sensitivity with guinea pig hearing sensitivity. The human OHC threshold was determined as 100 dB at 1.0 Hz, falling by 40 dB/decade, so that it meets the inner-hair-cell threshold at about 100 Hz (Salt and Hullar, 2010). They conclude: "The fact that some inner ear components (such as the OHC) may respond to infrasound at the frequencies and levels generated by wind turbines does not necessarily mean that they will be perceived or disturb function in any way. On the contrary though, if infrasound is affecting cells and structures at levels that cannot be heard, this leads to the possibility that wind turbine noise could be influencing function or causing unfamiliar sensations."

Wind turbine emissions are generally below the OHC threshold so that, under these circumstances, the threshold is not relevant to wind turbine infrasound. The effects of stimulation of the OHCs remain unknown. The OHCs are the main component of the cochlear amplifier and are continuously active, being the source of otoacoustic emissions (Ashmore, Avon *et al*., 2010). But wind farms at which nausea and similar effects are reported, may have a spectrum that is entirely below the Salt OHC threshold, so that it is not exceedance of this threshold that is the cause of distress.

Salt's further publications, seeking to support the adverse effects of infrasound, use examples in which the frequencies and levels are higher than those from wind turbines (Salt and Lichtenhan, 2014). As pointed out by Dobie, Salt and Lichtenhan, quote effects resulting from 30 Hz at 100 dB and 120 dB and from 50 Hz

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at 85-95 dB (Dobie, 2014). These low-frequency pure tones are not directly relevant to wind turbine noise, which does not contain such high-level tones. Salt's connection of his work to wind turbine infrasound is not yet convincing.

Over the past 45 years, popular culture has attributed a number of unpleasant, even fatal, effects to infrasound, but none has been sustained by evidence. Concerns on inaudible infrasound from current designs of wind turbines commenced 10-15 years ago, linked to objections to the growth of wind farms, and have accelerated over the past 5-10 years. It is inevitable that, in the absence of good supporting evidence, these speculative claims will become discredited over the next 5-10 years.

At the present time, conclusions are:

- Audible wind turbine noise acts through annoyance and stress, which may lead to poor sleep quality, especially in hostile people. Hostility is heightened by the actions of objector groups. There is no known direct effect on health from the low levels of audible wind turbine noise. However, stress may develop from an individual's reaction to the turbines.
- There is no established evidence that the inaudible infrasound from wind turbines affects health, but there are indications that it does not.

Opinions and Recommendations of Paul Schomer

Currently, I think this group of four find ourselves in the following situation: We all agree that sound flowing through the cochlea is not the source of problems below the threshold of hearing. That statement leaves two of what I will call technical possibilities. One possibility is that there are pathways other than through the cochlea for the infrasound to get to the brain. A second possibility is that to date we have missed something in the audible sound range that is the source of problems or that both of these situations exist.

Are There Noncochlear Paths for Infrasound to Reach the Brain? The following is a relatively simple study that could test whether individuals who claim they can detect the turning on and off of turbines can actually do this without visual or audible clues. There are at least a few small groups in the United States, Australia, and Canada that claim to have this ability. The results could be that none of these people could detect the turning on and off, or it could be the reverse and everyone would be able to detect the turning on or turning off. It is likely that the result will be somewhere in between.

In Shirley, Wisconsin, there are residents who say they have this ability. This study could be readily performed in Shirley; however, it requires the cooperation of the energy company.

Suggested Test 1

Consider the two houses in Shirley where there is no audible sound; the R-1 house and the R-3 house. The residents of the houses, and others, who would be subjects, would arrive at the house with the wind turbines off. The test itself would likely take 0.5 to 2.5 hours to perform.

Sometime during the first 2 hours, the wind turbines(s) that had been designated by the residents as the turbines they could detect, might or might not be turned on. It would be the residents' task to sense this "turn on" within some reasonable time designated by the residents – say 10 or 30 minutes. Correct responses, "hits," would be correctly sensing the turbines being turned on, or sensing no change if they were not turned on. Incorrect responses, "misses," would be failure to sense a turn on when the turbines were turned on, or "false alarms" would be sensing a turn on when the turbines were not turned on. Similar tests could not necessarily be done starting with the turbines initially on because the subjects, when sensitized, find it more difficult to sense a turn off. More information about this test can be found in Schomer *et al.*, 2015.

Possible Overlooked Audible Path. This pathway is predicated on several key facts described below. The main hypothesis is that the electric power being generated changes the acoustic signal without changing the A-weighted level. If the electric power correlates better than A-weighted level to subject response, then this would indicate that the electric power being generated controls some aspect of the sound that the subjects are sensing. This is important for two reasons:

- The subjects are incapable of having detailed knowledge of the electric power.
- If this is all true, it is something that is potentially correctable.

Facts:

- *Discussion with Geoff Leventhall*. At one point when I suggested to Leventhall that 30 and 40 years ago, the reported effects were very similar to today's reported effects and that we had much the same problem, he remarked that the sound at that time period was low-frequency audible sound at around 40-50 Hz. The problems with infrasound and low-frequency noise that occurred 30 and 40 years ago is that they produce the same symptoms as today, but were for frequencies in the 40-50 Hz range – not infrasound.
- *Steven Cooper*. Cooper finds and reports in his Cape Bridge Water Study that the subject's response correlated better to the electric power being generated, to turbine operations hovering around cut in speed, and to large changes in the electric power being generated rather than to the acoustic signal.
- *Bruce Walker*. "I did a lot of work with Hansen's cleanest data set. When the extremely narrow band spectrum was plotted on a linear frequency scale, it conformed pretty well to sin(x)/x envelope with lobes at ZF, 30 and 45 Hz (more or less) and lines every blade-passing frequency. The lines in the 45 Hz lobe would combine into a wave packet that exceeded the audible threshold briefly once every blade pass. Walker added, "One thing I've observed with modern 100-meter rotors is that when producing power, the blades deflect axially to pass pretty close to the tower near the tip, into a region where the upstream flow deficit could be significant, though not separated as in downwind designs. Overly aggressive pitch programming could cause periodic brief stalls that might produce the requisite steep edge on the pulses."
- *Discussions at the ASA meeting in Salt Lake City*. Discussions at the meeting made it clear that the frequency may not be limited to 45 Hz but may be based on the manufacturer and the specifics of the blades. It was also suggested that these frequencies might interact with chest cavity resonances. Rainford and Gradwell (2012) find, using their procedure outlined in Rainford (2006) that the typical chest cavity has a resonance at about 50 Hz. This does not seem to be a factor, since Leventhall reports that below 80 dBA, at 50 Hz there is no chest cavity response.
- *George Hessler*. The measurements at Shirely show a relatively constant noise being generated during the day and time of the R2 measurements. However, the measured acoustic level was 1.5 dB below the expected level for full power with a Nordex N-100/2500 wind turbine, the turbine used at Shirley. Nordex literature reports that the acoustic output of the N-100/2500 is a constant for wind speeds measured at a height of 10 meters. At a wind speed of 4 m/s, the Nordex sound level is down about 1.0 dB from the maximum. Wind turbine noise vs. wind speed plots are unusual. As the wind speed increases from 0, it reaches a speed where the rotors of the turbine can start to turn. From this point, the noise from the turbine begins and goes up rather rapidly with increasing wind speed until it reaches a transition plateau where the sound level no longer increases with wind speed. However, the power generated by a wind turbine goes up much more gradually in power as a function of wind speed and only reaches its maximum several meters per second above the acoustic limit. The result is that for a very small change in sound level generated by the wind turbine, there can be a very large change in the electric power generated. This is true for the Nordex N-100/2500. Table 1 is compiled from Nordex literature and gives the relationship shown between acoustic power emitted and electrical power generated as a function of wind speed.
- *Geoff Leventhall*. Leventhall reports that the highest reaction to low-frequency sound occurs in the 40 to 50 Hz range. However, his data (Figure 4) show almost equal responses in the 30 to 40 Hz range and the 70-80 and 80-90 Hz ranges.
- *Shirley Report*. The Shirley report shows levels of 25-30 dB in the 40-50 Hz range, and it shows room resonances and possibly some wall resonances. Room resonances are in the 35-100 Hz

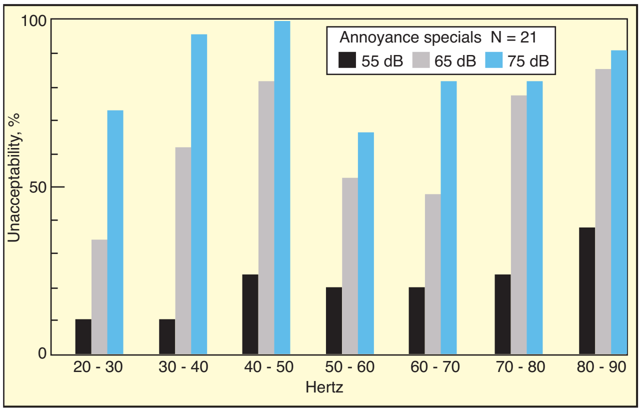

Figure 4. Unacceptability ratings for group of "specials" to noise stimuli.

range. Wall resonances are typically in the 10-30 Hz range.

- *Threshold of Hearing*. The pulses, roughly one per second, that result from the blades passing the support tower, appear to have about a 10% duty cycle and would drop the threshold of audibility by about 8 to 10 dB. Figure 1 shows threshold of audibility based on several sources along with the lowest and highest levels of audibility at a given frequency. These levels are for continuous sinusoidal signals. With a 10% duty cycle, the thresholds go down by about 9 dB. For the most sensitive subjects, this indicates a threshold of hearing of about 31 dB at 50 Hz to 35 dB at 40 Hz.
- *Bruce Walker*. Bruce Walker's findings that the tone at 45 Hz was above the threshold of hearing stands in support of the theory that low-frequency audible sound exists in the vicinity of wind turbines and could be the source of problems. There is a possibility that these offensive signals can only be found using narrow-band analysis as Walker used. Constant bandwidth filters may be too broad.
- *Steven Cooper*. It is somewhat amazing that Cooper's findings fit this situation so well. He found that the peoples' responses correlated to large changes in electric power, turbine operations hovering around a cut in speed, and the absolute level of the electric power being generated better than to the acoustic level. Table 1 supports Cooper's findings. The electric power changes gradually until full power is reached; the acoustic signature rises quickly and then becomes a constant. Please note that the subjects could know when the turbine was on or off, but the data in Table 1 clearly shows that there is no way to know what percent of the maximum electric power is being generated from any data available to the subjects. So the fact that the subjects' responses correlated with the electric power, which is something the subjects could have no way of knowing, lends strong support to Cooper's findings. The acoustic data during "large" transitions in percent of full electric power should be analyzed, since it could be a potential source of problems.
- *The Energy Company*. Clearly, it would be nice to have trustworthy confirmation of this analysis. To date, the power company at Shirley has not given any clear data on the actual power generated (or any other physical parameters, such as blade rpm, wind speed, or direction) for any time during our measurements. So we are limited to the indirect analysis of estimating a large change on the basis of a 1 dB acoustic change.

Table 1. Electric power (kW) and acoustic A-weighted power level (dB) both as functions of WS (m/s).

Wind Speed, 10 m m/s	Electricity Generated, kW	Percent of Full Power	Acoustical Power Level, A-weighted dB
3*	34	1	95.5
4	88	4	100.5
5	237	9	103.0
6	448	18	106.5
7	738	30	107.5
8	1123	45	107.5
9	1604	64	107.5
10	2043	82	107.5
11	2321	93	107.5
12	2467	99	107.5
13	2500	100	107.5
14	2500	100	107.5

*3.5 m/s for electric power; 3.0 m/s for acoustic power.

This all suggests that the Shirley signals would be slightly too low to trigger this chain of reactions. There are at least two possibilities. One possibility is that there are other undiscovered mechanisms and pathways. Another possibility is that the acoustic level is higher than we measured, because we measured on a quieter day. We do not know, because we do not have the physical parameters. Bruce Walker suggests that sufficiently high levels exist at some wind farms. Hessler's relatively constant measured data suggests we are not at a low power. So it seems this is another conundrum, but again this is a needless problem that the power company could sort out.

Analysis and Hypothesis Development

Point 1: Suggests looking for something in the 40-50 Hz range as our possible "culprit."

Point 2: Suggests that the electric power being generated is a very important parameter to a person's response. As Table 1 shows, the acoustic output is more or less constant over a wide range of wind speeds, but the electrical power being generated is changing with wind speed. It is true that the subjects in Cooper's study could have known when the sound, hence the wind farms, were turning on and off, but they would have no way of knowing the electric power from the acoustical signal. This lends strong support to Cooper's results.

Point 3: Suggests that there is a source of low-frequency audible sound that is produced each time a blade passes the support tower (or the low point of each blade during each revolution). The wind turbine blades flex so that the blade tips come closer to the support tower (the flex increases) as the electric power being generated increases. The reverse occurs as the power being generated decreases; the flex decreases and the minimum distance between the support pole and the blade tip increases. So, this particular sound increases and decreases in step with changes in the electric power being generated.

The physical mechanism that is at work here is the same as a stick or pole placed in a river. The pole represents an object that can disrupt the regular flow. There is a big wake downstream as everybody knows, but if one examines the situation a little more closely, you realize that there has to be pressure reflected upstream off this pole in the river, and that causes some disturbance upstream. The closer one is to the pole, the stronger the upstream reflection effect is. Much the same is happening with the wind turbine. As the blade gets closer to the support tower, it gets into more of this upstream disturbance.

In summary, there is a sound source that produces low-frequency pulses at the blade passage frequency, and the sound level of the source goes up and down in accordance with the amount of electric power being generated. The facts in this analysis indicate that this should be studied further, since this may be an important factor in the community response – both annoyance and other physiological effects. Moreover, the fact that this sound source can be controlled by the operator, to some degree, gives some promise to our ability to mitigate or eliminate this problem.

The hypothesis is that there is a frequency that will be characteristic of a specific blade and manufacturer that based on the discussion at ASA appears to be in the 25-60 Hz range. This tone modulated at 1 Hz causes a reaction in at least some people. This potential phenomenon should be able to be tested in a variety of ways, most of them quickly and inexpensively.

Suggested Test 1

Diary Test. Using a diary study, one could ask respondents to keep the following information:

- When they are at home and awake.
- The times when they feel a sensation caused by the wind turbines.

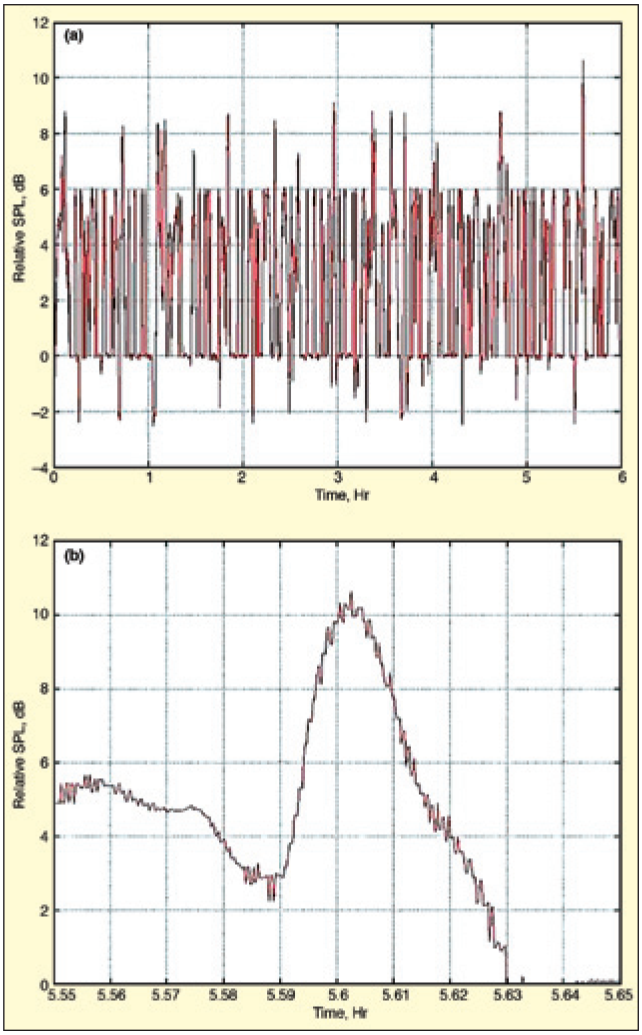

Figure 5. (a) Computed variations in SPL from a five-turbine array with unequal rotation rates relative to incoherent result; (b) expansion of largest peak.

- If so, how strong is the sensation?

This information could be related with electric power generated and other physical parameters.

Suggested Test 2

Response Comparison. There are certainly some data that can be examined that were gathered in conjunction with peoples' responses. Hopefully, the Cooper data will show if specific tones in this region are present, how strong they are, and how they compare with the peoples' responses.

General Tests

The two following tests are more general and would aid in understanding the phenomenon we are dealing with.

- *Direct Human Testing*. Direct human testing could be done in laboratory and field settings but, as has been testified to, there may be a period of time for the symptoms to incubate. A good start on this is underway at the University of Minnesota.
- *Direct Animal Testing*. A cat or guinea pig's ear could be used to test for reaction to wind turbine noise. Monitoring could be done on the nerve that emanates from the otolith and from the nerves emanating from the cochlea as a function of wind turbine sound amplitude both above and below the threshold of hearing.

Opinions and Recommendations of Bruce Walker

Modern large wind turbines produce pressure fluctuations as the result of a variety of mechanisms. The time scales of these fluctuations range from minutes to milliseconds (conversely the frequency scales range from millihertz to kilohertz). Two aspects of wind turbine noise that have received significant attention over the past decade are amplitude-modulated broadband noise and quasi-periodic "thumps" generated by interaction between rotor blades and support towers. The focus of this review is the latter, which is most commonly identified as wind turbine infrasound (WTIS). In modern turbines, the time scale of this disturbance is on the order 1 second. However, the details of the individual disturbance events appear to hold the key to whether or not WTIS results in human response.

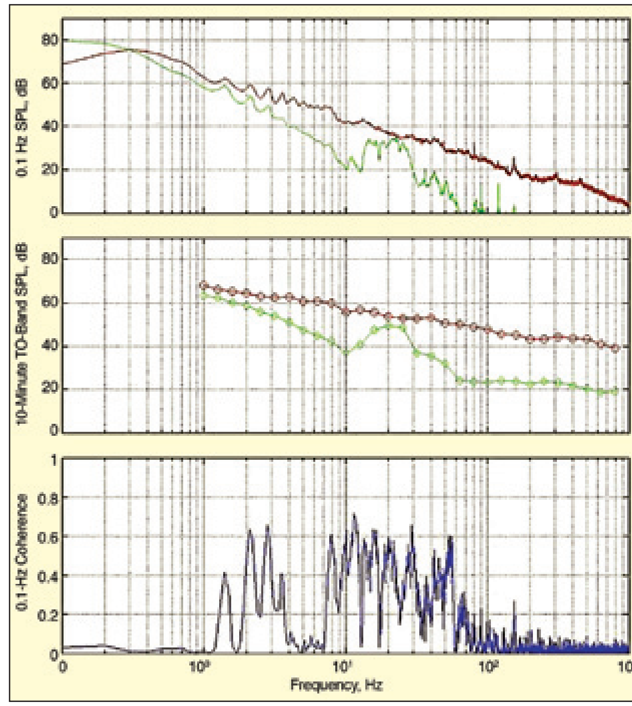

Figure 6. Example of field measurement data.

Modeling

There has been a temptation to model WTIS using the same techniques as for modeling audible sound: summation of spectral sound pressure squared from multiple point sources. At Wind Turbine Noise 2011,[5] the modeling issue was addressed by observation that the waveforms of WTIS were likely to be deterministic and therefore add coherently, so that the more correct modeling would be summation of time-domain sound pressures and subsequent computation of peak and average sound pressure levels.

For multiple turbine installations, this would produce a wide range of potential outcomes, depending on the relative synchronization of the turbines. Figure 5 shows a hypothetical result for five turbines turning at random speeds over a narrow range. For a few minutes over a six-hour simulation period, peak levels over 10 dB above the SPL predicted from pressure-squared summing were encountered. Receptors exposed to this momentary period of enhanced pulsation levels could be highly annoyed or awakened by it, while enforcement personnel might measure for hours and never witness it.

Measurement

There has been a temptation to measure WTIS using the same techniques as for measuring audible sound: time-averaged weighted levels and power spectra. Typical field measurement results are similar to those shown in Figure 6 acquired a few hundred meters from a 2-3 MW range turbine. Spectral peaks are seen at several multiples of the 0.75-Hz blade-passing frequency. The sound pressure levels at each of these peaks is far below the generally accepted sensation threshold.

However, the putative blade/tower interaction genesis of the WTIS would suggest that the actual acoustic signal would be a sequence of relatively narrow pulses. Further, the unsteadiness of rotation speed would cause higher harmonic content of the signal to migrate among conventional PSD analysis bins and appear as broadband noise.

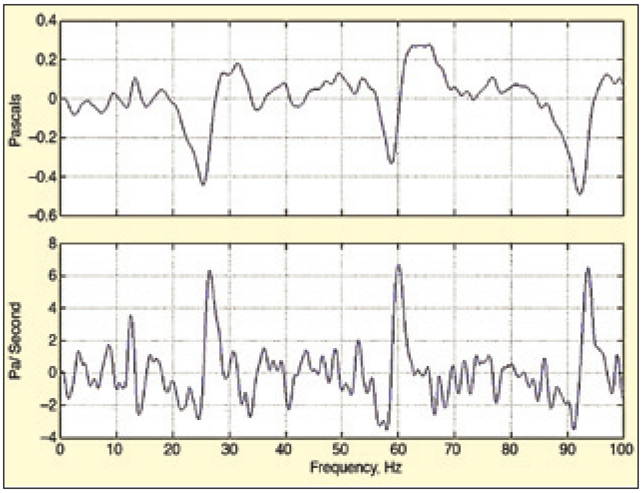

Figure 7. Example ensemble average waveform and time derivative with wind direction 140° re mic orientation.

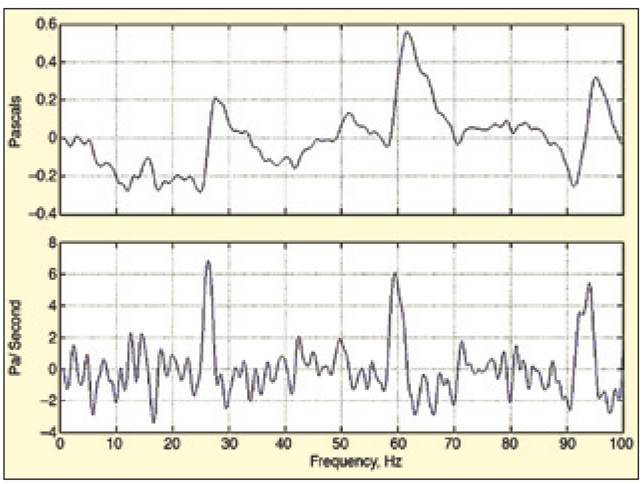

Figure 8. Example ensemble average waveform and time derivative with wind direction 60° re mic orientation.

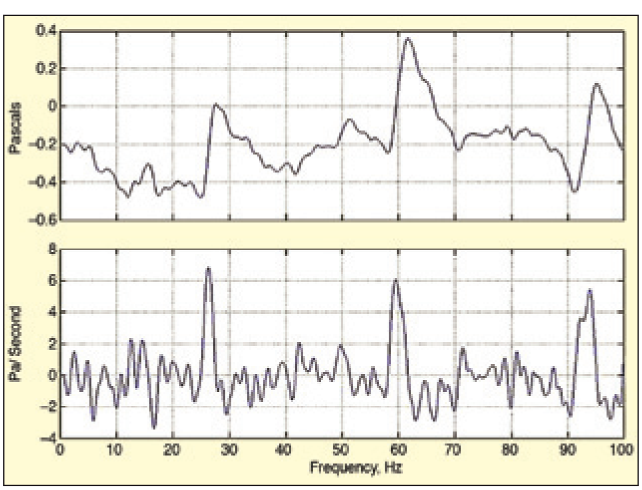

Figure 9. Shaft-order spectrum for wave shown in Figure 8.

At Low Frequency Noise 2012,[6] Wind Turbine Noise 2013[7] and ASA 2014,[8] methods were described for capturing the wave form emitted by large wind turbines by synchronous sampling and ensemble averaging several-minute recorded samples from a three- and four-microphone array. These measurements confirmed that the emitted infrasound was confined to less than 10% of the blade-pass period, as shown in Figure 7. One set of measurements suggested that the phase of the BPF signal component depended on azimuth, as shown in Figure 8. The algorithms used to simulate synchronous sampling left too much residual jitter to retain time resolution better than approximately 50 ms.

Figure 10. Loudspeakers for WTIS synthesis in 43 m^3 test room.

Synthesis

An electro-acoustic system was assembled starting in 2012 to synthesize periodic signals with fundamental frequency 0.8 Hz and up to 65 harmonics in a residential bedroom. A photo of the system is shown in Figure 10, and a schematic of the test facility is shown in Figure 11. Three 18-inch "woofers" are driven by a DC-coupled, 300-watt amplifier, excited by Fourier-synthesized waves from 16-bit, D-to-A converters. A second loudspeaker can provide synchronized amplitude-modulated, Dopplerized, audible sound if desired. An infrasound microphone is suspended above the evaluator's head. The system was described in detail at Wind Turbine Noise, 2015.[9]

Spectra corresponding to variations on that shown in Figure 12 were presented to a variety of volunteers at levels extending to approximately 15 dB above those reported from field measurements. Harmonic phases were adjusted to maximize or minimize signal crest factor and signal peak slope. If the upper limit of spectral content was 20 Hz or below, no evaluator reported any sensation. With the upper limit extended to 32 Hz and the level above 20 Hz spectrally uniform, one evaluator reported significant unease after a few minutes exposure. Subsequently, this evaluator reported unease when exposed only to amplitude-modulated audible sound.

In 2014, Hansen *et al.*,[10] obtained field measurement data that displayed periodic spectral detail that extended to above 50 Hz, as shown in Figure 13. At ASA 2014 and Wind Turbine Noise 2015, Palmer[11] showed correlations of resident response to nearby operations of turbines that depended on resident positions inside rooms. This suggested the possibility that the residents were affected by sound of frequency high enough to excite room resonances, typically 30-40 Hz and above.

The Hansen data were analyzed extensively and results presented in Wind Turbine Noise 2015.[12] All spectral lines were separated by the turbine BPF, but in some ranges, the actual frequencies were not exact multiples of BPF. The mechanism for generating such a spectrum could be brief bursts of mechanical resonance once per blade pass or the effect of multiple turbines at slightly different speeds. The spectra were forced into a harmonic series and synthesized for evaluation. Because the reported power spectra lacked phase information, all harmonics were assumed to be at zero phase simultaneously.

Response

Threshold, annoyance and sleep interference were informally investigated using the full Hansen spectrum, then with high-pass filtering at 20 and 30 Hz and finally with low-pass filtering at 20 Hz. In summary, high-pass filtering had no effect on any parameter, and low-pass filtering resulted in no response, even with 10 dB exaggerated levels.

The results of these informal tests were presented at Wind Turbine Noise 2015, with admonition that they represent small samples and relatively brief (10 minutes to 2 hours) exposure. It was recommended that more extensive similar investigations be undertaken.

Follow-Up

During Wind Turbine Noise 2015, and discussions with co-authors, it appeared that the Hansen spectrum could be approximated by a uniform BPF harmonic series, weighted by a $\sin(\pi f/18)/(\pi f/18)$ shape function.

The resulting waves and spectra are shown in Figures 14-16. Figure 16 demonstrates that once each blade-pass period, the signal harmonics from the third spectrum lobe may constructively combine, producing a periodic "thud" that at levels just slightly above hearing threshold, produces an illusion of infrasound that is devoid of actual infrasonic energy. Note that near 45 Hz, the

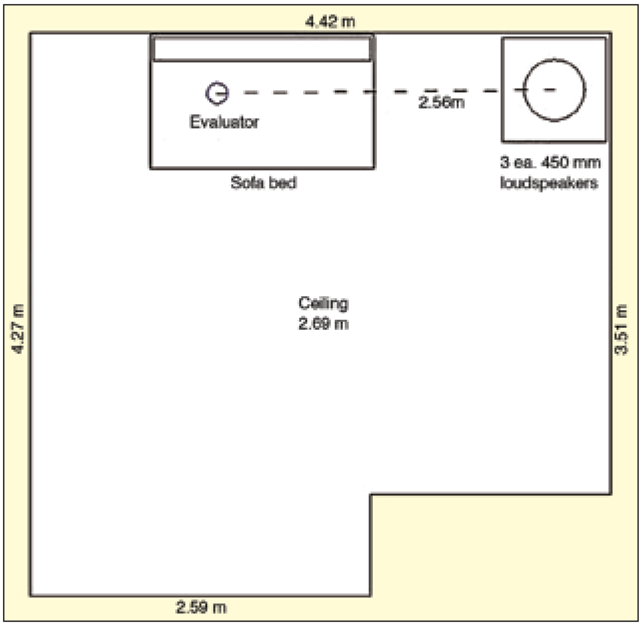

Figure 11. Layout of WTIS evaluation test room.

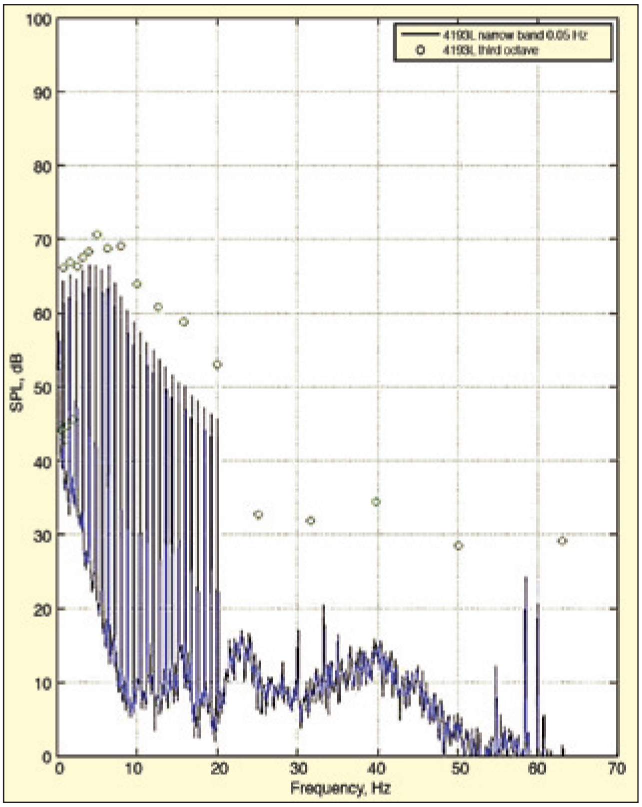

Figure 12. Generic WTIS spectrum used for initial evaluations.

maximum SPL is 13 dB above L_{eq}, so a measured spectral "hump" that appeared to be well below threshold could easily produce audible "thumps" that would be mistaken for infrasound. The time between the negative and positive peaks in the full-spectrum wave is 0.055 seconds, in which time the rotor blade tip would travel 4.6 meters at 84 mps tip speed. This seems reasonable for the approximate width of the support tower or its bow wake, supporting blade/tower interaction as a genesis mechanism.

An observation from the idealized spectrum shown in Figure 14 is that the phases of the components in the second lobe would be reversed relative to the first and third lobes. This detail was not followed in perception testing. In Figure 15, the effect of the phase reversal on the composite waveform is displayed. The crest factor and wave "sharpness" are clearly increased with the second lobe phase properly reversed. When reproduced at 10× frequency

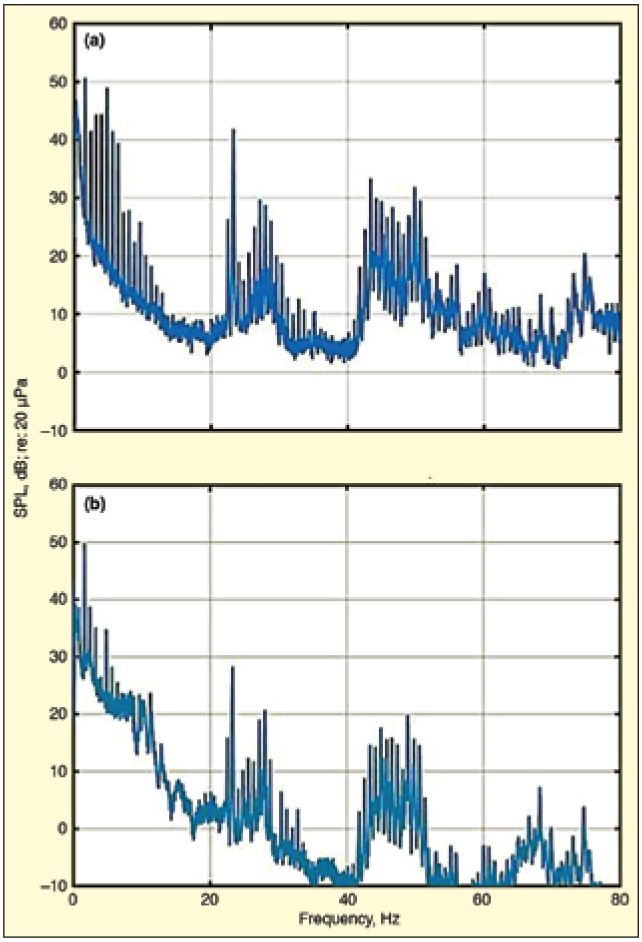

Figure 13. Outdoor (a) and indoor (b) spectra of WTN measured by Hansen.

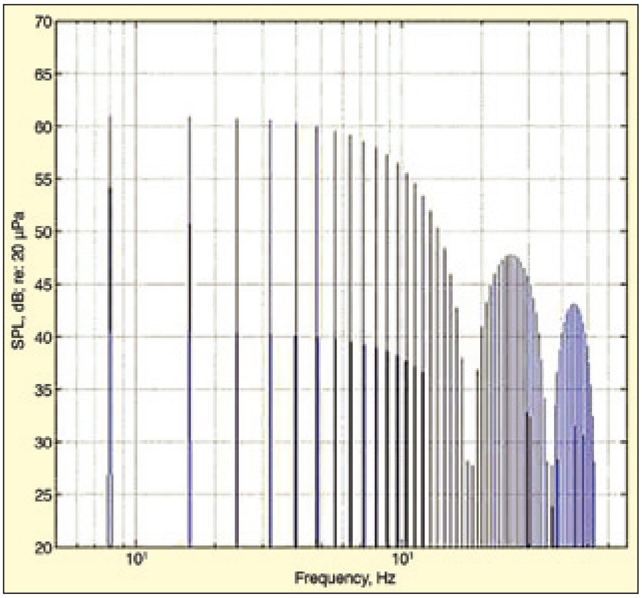

Figure 14. Spectrum of sin(x)/x-weighted BPF harmonics.

on loudspeakers, the properly phase-reversed signal is distinctly more impulsive sounding. The effect on perception at full-scale frequency is currently being explored.

Summary and Collective Recommendations

Disclaimer. The preceding sections are the sole and exclusive work of each author. There has been no attempt at editing or reaching agreement among authors.

Areas Identified for Needed Practical Research

Simulation. Walker has demonstrated that wind turbine infra-

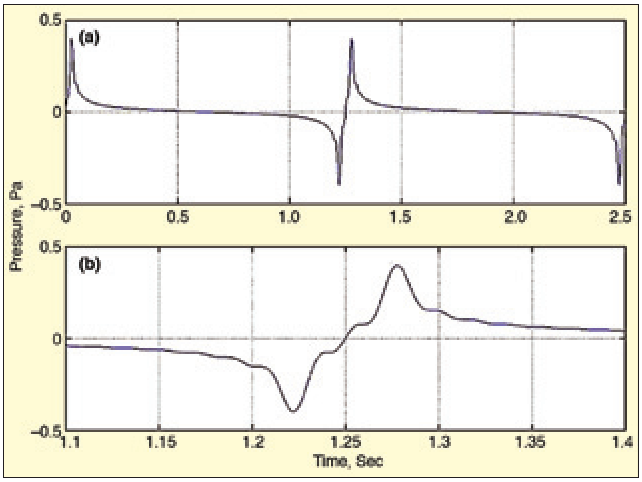

Figure 15. Waveform of spectrum shown in Figure 14.

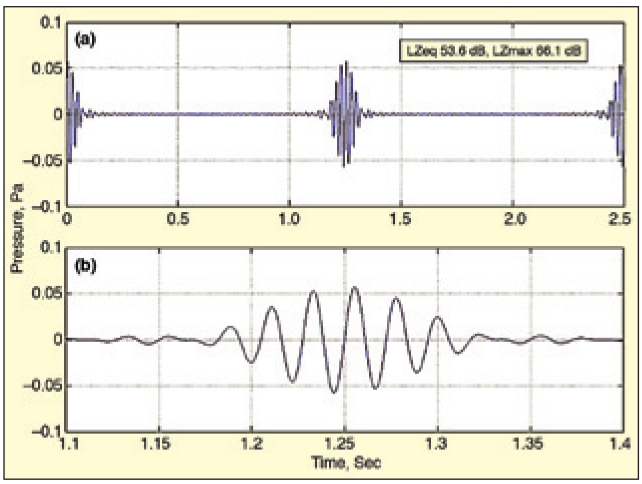

Figure 16. Wave-packet representation of third-spectrum lobe components.

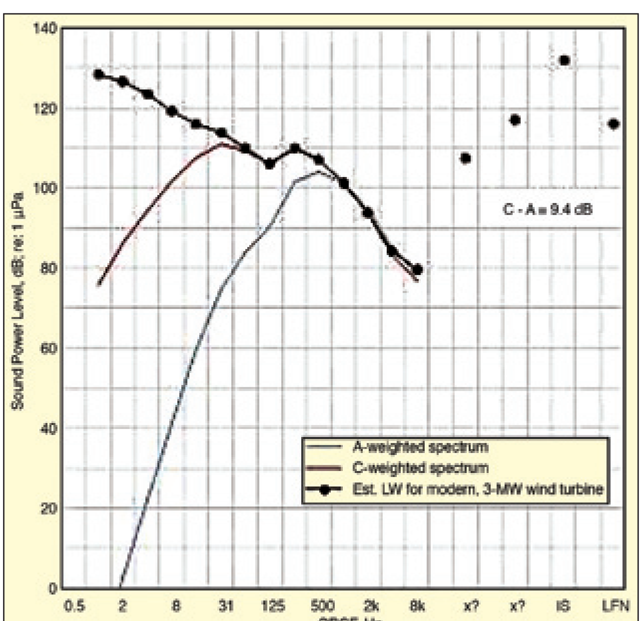

Figure 17. Typical spectrum from a large, modern, , 3-MW wind turbine.

sound and pulsed LFN, which may be upper harmonics of the Infrasound pulsations, can be mathematically defined, duplicated and simulated with loudspeakers for subject evaluator testing. A more formal and expanded set-up, perhaps at a university using student volunteers exposed to both low and high levels could establish the threshold of perception for both steady and pulsed LFN for the particular and unique source of environmental noise from

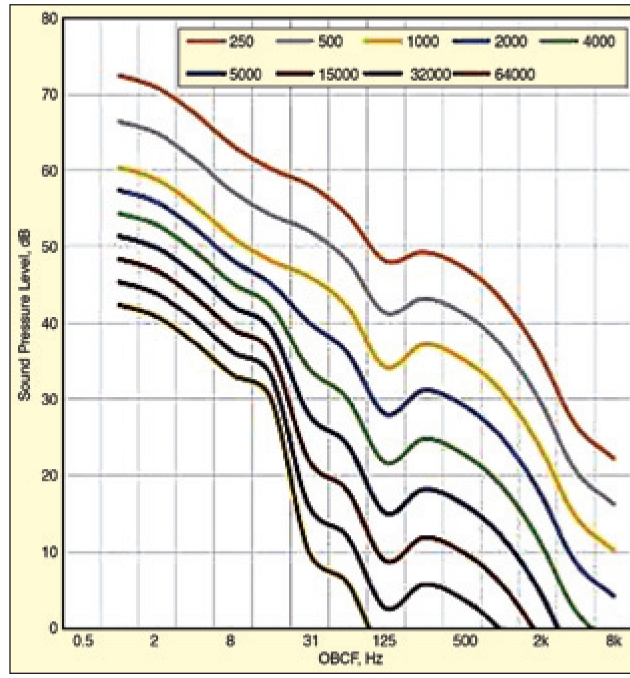

Figure 18. Calculated Lp spectra as function of distance.

wind turbines. Studies in this area are progressing in Australia.

Survey of Wind Turbine Projects Participating Residents. Landowners who lease their land for wind turbine installations may experience sound levels well in excess of proposed limits for normal siting practices and experience higher levels than nonparticipating neighbors. There should be an absolute wealth of information to be learned from these residents collected by a well-designed national survey. Such a survey must have the complete cooperation and possible sponsorship from the industries' national representative, AWEA (American Wind Energy Association) in America and others throughout the world. The authors would like to suggest questions to any study team.

Noise Source Reduction. The designers and suppliers of wind turbines must make a continued and concerted effort to reduce noise emissions from their turbine designs. Reductions can be accomplished by a combination of blade design and operational software. A universal design goal based on measurable established standards (IEC-61400) for sound power level would encourage these efforts.

Perception Testing. Schomer suggests pathways that could support some test findings in America and Australia that suggest from statistical correlation that some residents could perceive wind turbine operation and/or operational changes without benefit of sight or audibility. A detailed discussion is offered on practical perception testing that could discover something unknown to us at this time and is highly recommended for implementation.

Discussion and Collective Conclusion

None of these opinions and recommendations answers the posed question: does ILFN from wind turbines make people sick? It is abundantly obvious that intense adverse response occurs at certain sites. Realistically, it is not even possible to answer the posed question to all parties' satisfaction with practical research. For examples, a direct link to adverse health effects from yesterday's tobacco and today's excess sugar can be denied forever, because any research that could actually prove a link to all parties would take longer than forever and would be totally impractical. The wind farm industry must accept that there are enough worldwide sites that emit excessive wind turbine noise resulting in severe adverse community response to adopt and adhere to a reasonable sound level limit policy. Likewise, wind farm opponents must accept reasonable sound limits or buffer distance to the nearest turbine – not pie-in-the-sky limits to destroy the industry.

The A-weighted sound level is commonly used for assessing noise from wind farms as well as most all other large power genera-

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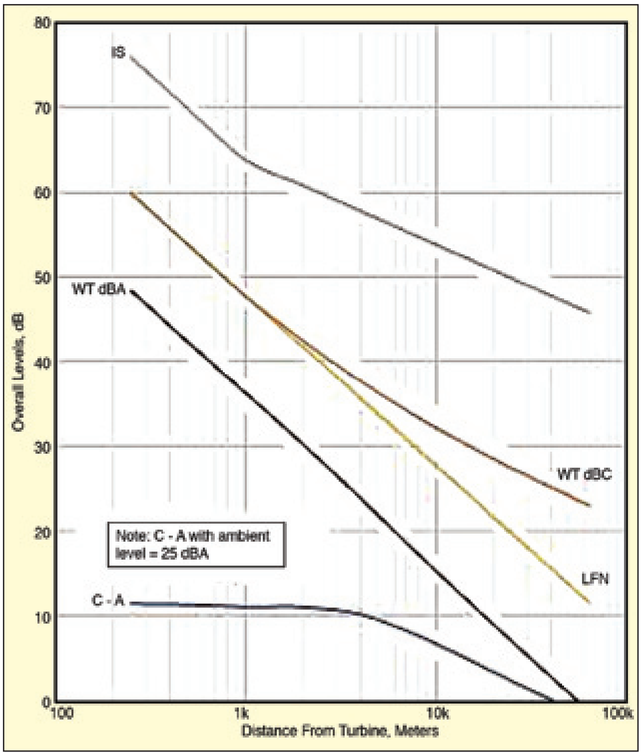

Figure 19. Overall levels as function of distance.

tion facilities. Each author has been recommending the following limits for wind farm noise emissions for years: Hessler[13] – 40 dBA design goal, 45 dBA max limit; Leventhall – 40 dBA; Schomer – 35-39 dBA; and Walker – 45 dBA in high ambient areas but lower in lower area ambient locales. The authors have generally found that wind farms designed to a level of 40 dBA or a bit lower at nonparticipating residential receptors have an acceptable community response. Surveys at wind farm sites for a decade have consistently shown good statistical correlation between wind farm noise level emissions and the percentage of highly annoyed residential receptors (% HA).

The question arises if an A-weighted criterion alone is adequate to protect receptors from infrasound (IS), LFN and pulsed LFN shown to be present in large wind turbines. Figure 17 plots the measured spectrum from a typical, nominal, 3-MW wind turbine plus the most commonly used overall levels. Infrasound (IS), the highest overall level, is calculated by summing the bands 1-16 Hz (0.7-22 Hz) and LFN by summing the bands 31.5-125 Hz for a frequency band of 22-177 Hz. Note that the overall C-weighted level and LFN levels are quite close together. Notice also that C-weighting filters out IS and would not be a good metric for assessing wind turbine IS but would be excellent for assessing LFN from wind turbines.

Hessler[14] and Broner[15] have recommended C-weighting limits for low-frequency industrial sources based principally on extensive experience with open-cycle combustion turbines. Both have concluded independently that a level of 60 dBC is a desirable criterion to minimize adverse response from neighboring communities as shown in Table 2[14] and Table 3.[15] the C-weighted level from wind turbines will always be comfortably below 60 dBC when emitting 40 dBA or less.

Figure 18 illustrates the computed pressure spectra from 250 m (820 feet) to 64,000 m (40 miles). The calculation uses ISO-9613 algorithms for hemispherical divergence, air absorption and ground effects assuming a 100-m hub height. Note that 3 dB/doubling distance in lieu of 6 dB is used for IS beyond 1 km as measured in the recent extensive Health Canada study. The reason for doing this calculation is to determine the overall levels with distance that is shown in Figure 19.

Looking at the octave-band spectra, it is apparent that the indicator of a potential low-frequency noise problem, C-A level, should increase with distance, since the A-weighting level is reduced by excess attenuation while low frequency noise is not. The result is 11 increasing to 24 dB if the ambient is not considered in the calculation. However, when a macro residual ambient of 25 dBA is assumed, the quantity starts at 11 dB and actually decreases to zero, as shown on Figure 19. This classic indicator of a potential low-frequency problem when C-A reaches 15 to 20 dBC will not occur when assessing LFN at wind turbine sites.

Table 2. Maximum allowable C-weighted sound level, LCeq, at residential areas to minimize infrasound noise and vibration problems.

	Normal Suburban/Urban Residential Areas, Daytime Residual Level, L^{90} > 40 dBA	Very Quiet Suburban or Rural Residential Areas, Daytime Residual Level, L^{90} > 40 dBA
Intermittent day-only or seasonal source operation	70	66
Extensive or 24 / 7 source operation	65	60

Table 3. Criteria for assessment of LFN.

Sensitive Receiver / Operation		Range	Critera Leq, dBC
Residential	Nighttime / plant ops. 24 /7	Desirable Maximum	60 65
	Daytime / intermittent 1 - 2 hours	Desirable Maximum	65 70
Commercial / office	Nighttime or plant ops. 24 / 7	Desirable Maximum	70 75
Industrial	Daytime or intermittent 1 - 2 hours	Desirable Maximum	75 80

Collective Conclusions

Our analysis illustrates that a wind turbine is not a classic LFN source; that is, one with excessive low-frequency spectral content. But a wind turbine is a unique power-generating source with spectral content down to the 1-Hz octave band, emitting measurable IS in addition to LFN. Infrasound (IS, 0-20 Hz) from wind turbines can almost be ruled out as a potential mechanism for stimulating motion sickness symptoms. But to be thorough and complete, we recommend that one or two relatively simple and relatively inexpensive studies be conducted to be sure no infrasound pathways to the brain exist other than through the cochlea. Pending the results of these studies, we feel that no other IS or LFN criteria are required beyond an acceptable A-weighted level.

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Recommended noise level design goals and limits at residential receptors for wind turbine developments in the United States

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Potential impacts from operational noise produced by wind turbines is a major issue during the project planning and permitting process, particularly for projects east of the Mississippi River in fairly populous areas. While still an issue farther west, more buffer space and lower population densities sometimes make noise less of a factor. In general, however, noise may be the principal obstacle, from an environmental impact standpoint, to the more rapid growth of this renewable energy source in the United States. Proposed projects are frequently opposed on noise concerns, if not outright fear, usually aroused by the highly biased misinformation found on numerous anti-wind websites. While significant noise problems have certainly been experienced at some newly operational projects, they are usually attributable to poor design (siting units too close to houses without any real awareness of the likely impact) or to unexpected mechanical noises, such as chattering yaw brakes or noisy ventilation fans. A common theme at sites with legitimate complaints is that no one—not the developer, their consultants or the regulatory authority—really understood the import and meaning of the sound levels predicted at adjacent homes in project environmental impact statement (EIS) noise modeling. This paper seeks to address this lack of knowledge with suggested design goals and regulatory limits for new wind projects based on experience with the design of nearly 60 large wind projects and field testing at a number of completed installations where the apparent reaction of the community can be compared to model predictions and measurements at complainant's homes.

Primary subject classification: 69.3; Secondary subject classification: 14.5.4

1 INTRODUCTION

Typical wind turbine generators (WTG) used today are generally in the 1.5 to 3 MW range of electrical generation capacity and all of them produce a moderate amount of generally mid-frequency aerodynamic noise. All are three-bladed with the rotor forward, or upwind, of the supporting tower so that the blades do not pass through the tower wake avoiding the low frequency noise issues observed in the eighties[1] by downwind blades. This experience appears to have initiated the persistent but incorrect idea that wind turbines are substantial sources of low frequency noise, which, extensive field testing clearly shows, is not at all the case with modern units.

Subjectively, fairly close to a typical wind turbine, one can observe a "whoosh" or "swish" sound with periodicity of about 1 second generated by the down-coming blade. While the "frequency" of this sound is low at about 1 Hz this sound is not low frequency or infrasonic noise, but rather a repeating, mid-frequency sound (with its peak generally around 500 Hz).

This periodic sound becomes less distinct with distance and, usually together with neighboring units, blends into a more continuous low magnitude "churning" sound that is often likened to a plane flying over at fairly high altitude; particularly since the sound tends to fluctuate or fade in and out randomly in the same way that aircraft noise is usually perturbed by the intervening atmosphere. Wind turbine sound emissions sometimes contain minor tones associated with mechanical components (usually ventilation fans) but almost never produce prominent "pure tones" per the commonly used EPA definition[2].

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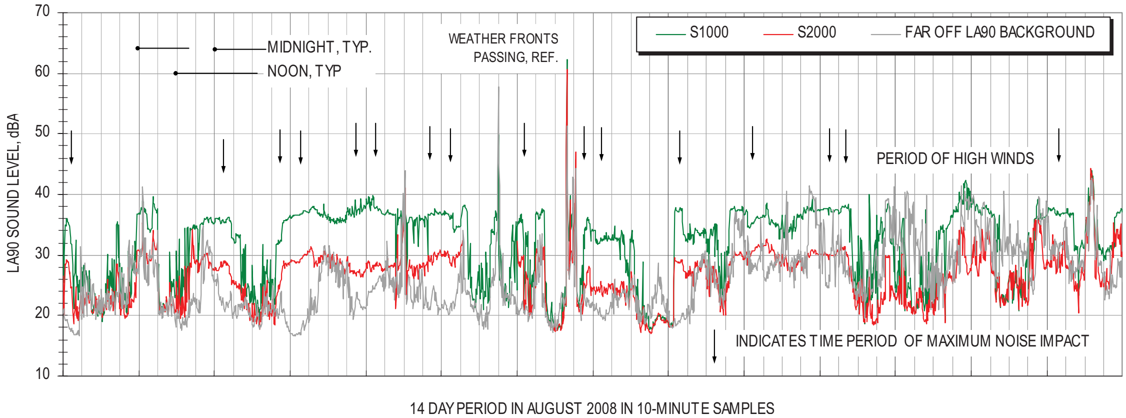

Fig. 1—Operational measurements over a 14-day period at two distances (1000 and 2000 feet south, 300 and 600 meters) from a single wind turbine compared to the prevailing macro area ambient sound level at the same locations for determining noise impact.

2 POTENTIAL FOR ADVERSE NOISE ANNOYANCE

Adverse impact in the form of annoyance and complaints can occur if facility noise emissions significantly exceed the prevailing environmental background sound level, as with any power project. Because wind turbine sites are typically in rural areas the existing background sound level is often very low, even when its dependence on wind speed and wind-induced sounds is taken into consideration.

As an example, Fig. 1 shows over 2000 ten minute residual measurements (LA_{90} Level exceeded 90% of the time) over a 14 day survey at distances of 300 and 600 meters from an operating single wind turbine compared to the average concurrent background level measured at several off-site locations. Hypothetical noise impacts exist wherever the turbine sound level significantly exceeds the background level. In Fig. 1, the maximum differential between the measured sound level and the background level often occurs at night on nights when the winds are fairly light. When it's windy the differential and the perceptibility of the project is usually less irrespective of time of day as wind generated sources of environmental sound become more dominant.

This time-of-day dependency can be explained by examining the typical wind speed gradient with elevation as a function of time of day. Figure 2 shows the shear exponent, a term that corresponds to the curvature of the gradient, measured empirically over a two year period at a planned wind project site in the Midwest. The shear exponent is low during the day time hours due to atmospheric mixing resulting in a more vertical gradient, as shown in Fig. 3, while the exponent is significantly higher at night due to thermal layering; a phenomenon that is more pronounced during lower wind conditions. As described and reported by van den Berg[3], at night the upper elevation wind speed can be high enough to operate the turbine while at ground level it is quite low, which can lead to relatively low sound levels, such as those observed most nights in Fig. 1.

It can be concluded from these data that the potential for annoyance is most likely during the evening and nighttime and less likely during the day implying that any design goal or regulatory limit should focus on the nighttime sound level.

As a final note on background levels, Fig. 4 shows a typical set of natural background sound levels (without any turbine noise) measured in a quiet rural environment plotted as a function of wind speed at a typical hub height elevation of 80 m. Modern wind turbines begin to produce power at a cut-in speed of roughly 3 m/s. The red lines on this graphic show an analytical model by Donovan[4] where the background sound has two components: the residual level (shown here at 38 dBA) and the wind generated level plotted as the 6th power of wind speed, which would be expected from a flow-induced acoustic source. The logarithmic summation

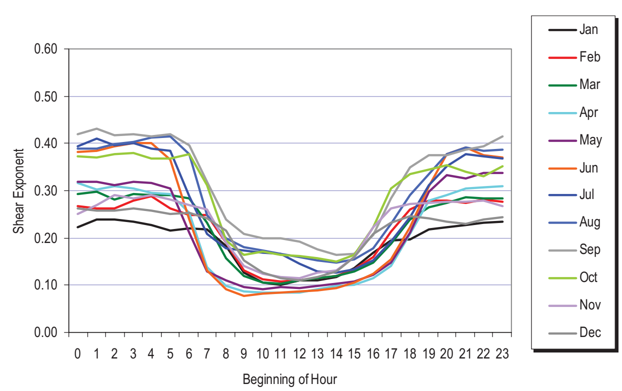

Fig. 2—Wind Shear Exponent, α, as defined by $V1/V2 = (H1/H2)^{\alpha}$ where V and H stand for velocity and height above grade.

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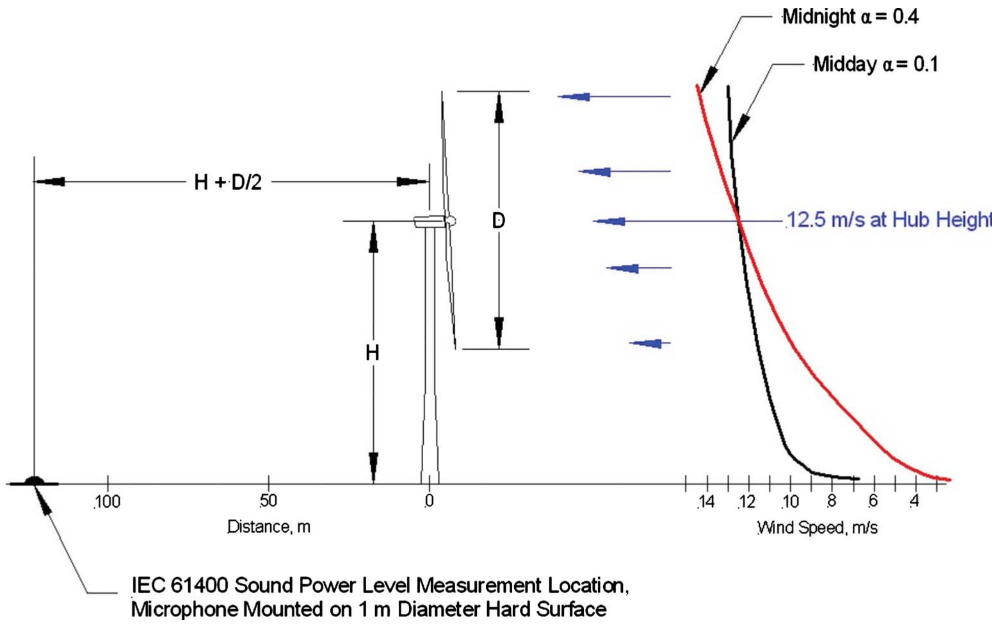

Fig. 3—Typical wind profiles for day and night periods. The figure also shows the measurement location for IEC 61400.

of these two components would closely track the mean linear trend of the measured data (black line).

3 NOISE LIMITS FROM THE LITERATURE

3.1 World Standards and Guidelines

The World Health Organization (WHO) published the following 1999 guidelines[5] for community noise in residential environments:

55 dBA Leq Daytime Levels: "Serious Annoyance, daytime and evening"

50 dBA Leq Daytime Levels: "Moderate Annoyance, daytime and evening"

45 dBA Exterior/30 dBA Interior Leq Nighttime Levels: To avoid sleep disturbance issues.

The nighttime sleep disturbance threshold has recently been reexamined by the WHO (2009)[6] and has been lowered from 45 dBA to 40 dBA outside of residences. No inside value is specified. The level is expressed as a design target to protect the public. Considering this guideline, nighttime sound levels from wind developments outside of residences should be generally targeted at 40 dBA as an ideal design goal to avoid sleep disturbance issues.

3.2 World Wind Turbine Noise Limits

Wind turbine development in European countries and in other parts of the world has been proceeding for

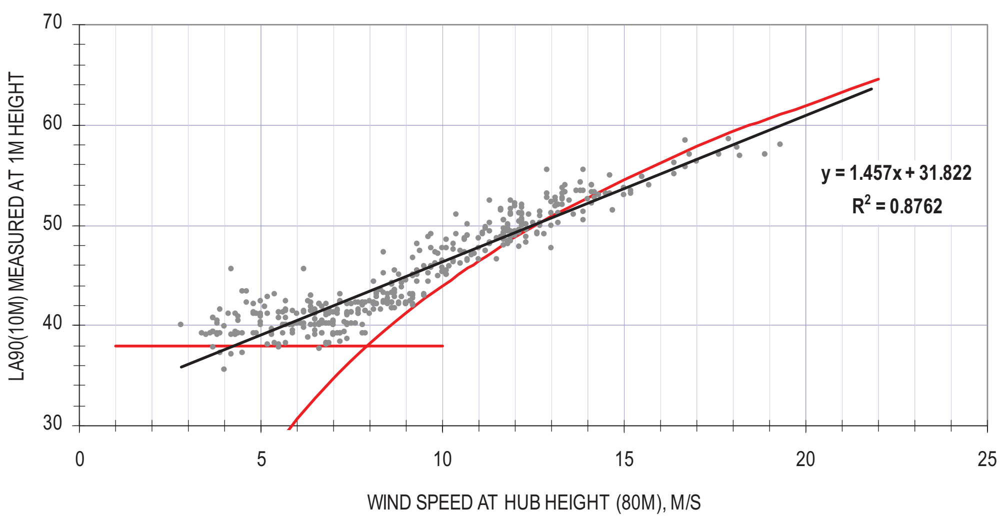

Fig. 4—Typical LA90 measurements as a function of wind speed at hub height.

Table 1—Typical worldwide wind turbine noise limits.

LOCATION	CRITERIA VALUE(S)	METRIC	FEATURES
ALBERTA, CANADA	50D/40N	dBA	
QUEBEC, CANADA	45D/40N	dBA	
ONTARIO, CANADA	45D/40N	dBA	
MANITOBA, CANADA	60D/50N	MAX dBA	MAX ACCEPTABLE
MANITOBA, CANADA	55D/45N	MAX dBA	MAX DESIRABLE
DENMARK	40	L_{eq} dBA	DAY AND NIGHT
GERMANY	60D/45N	dBA	MIXED RESIDENTIAL/COMMERCIAL
	55D/40N	dBA	GENRAL LIVING AREAS
	50D/35N	dBA	PURE LIVING AREAS (1)
NETHERLANDS	40D/30N	L_{eq} dBA	
NEW ZEALAND	40	L90 dBA	PRIMARY, WHICHEVER
NEW ZEALAND	AMBIENT+5	L90 dBA	IS GREATER
UK	43N	dBA	
UK	35–40 (37.5 FOR AVERAGING)	dBA	FOR LOW NOISE ENVIRONMENTS
UK	AMBIENT+5	dBA	DAY AND NIGHT
UK	35	dBA	AVOIDS AMBIENT STUDY
ARITHMETIC AVERAGE	45D/40N		(1)-USE FOR AVERAGING

some time now while widespread development has only really started in the United States within the last 5 years or so. Thus, the question of allowable limits specifically for wind turbines has already been addressed by a number of other countries. Storm[7] presents a summary of world standards in Tables 3 and 4 of his paper, the core of which is reproduced here in Table 1.

3.3 U.S. Federal Standards

The U.S. federal government issues no standards for industrial noise but does promulgate noise regulations for major transportation systems. These regulations by the Federal Aviation Authority (FAA) and the Federal Highway Administration (FHWA) are fundamentally predicated on the idea that some noise annoyance is justified or offset by the public good provided by the systems. Generally, acceptable regulatory levels in the 60 to 65 DNL (day night sound level) range have been shown to "highly annoy" approximately 10 to 20% of affected residential receptors. However, these published standards are not particularly useful for wind turbine noise emissions, since the public good of a new power plant or industrial facility is not obvious to its immediate neighbors, and conscientious owners would ideally want no annoyed neighbors.

The U.S. EPA Office of Noise Abatement was unfunded in the late seventies but did issue a landmark report suggesting guidelines for environmental noise in residential communities from all environmental sources. The report[8] is often referred to as the "*Levels*" document for short and has become a de facto standard for such organizations as the World Bank and others. Unfortunately, this report is often misused and the cited recommended level of DNL=55 dBA for residential land use is commonly interpreted as an acceptable criterion level for new noise sources in any type of residential environment—whereas the intent was to provide a guideline, or national goal for total environmental noise (ambient noise including all industrial and transportation sources). The report acknowledges that no cost-benefit analysis was performed.

In addition, the report clearly indicates that the level of DNL=55 dBA is applicable to an urban residential background and must be normalized to the specific environments under consideration to obtain an acceptable level of correlation between DNL and community response. Without background normalization, correlation is very poor based on the analysis presented in the levels document and elsewhere. This is no surprise since a level of DNL=55 dBA cannot be expected to be satisfactory at the same time in both a very quiet rural and noisy urban residential setting. Schomer[9] suggests that an adjustment of 10 dBA should be subtracted for quiet rural environments and perhaps another 5 dBA if the project is newly introduced into such a long-standing quiet setting.

For a steady source, which a wind turbine could be broadly considered, a level of 39 dBA would be equivalent to DNL=55 dBA if reduced by 10 dBA; or 34 dBA if reduced by 15 dBA to compensate for a very quiet rural setting.

The EPA did conclude in the levels document that an outside sound level of 45 dBA at night (10 p.m. to 7

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Table 2—Tabulation of state nighttime noise regulations and siting standards.

STATE	NOISE LIMIT AT RESIDENTIAL RECEPTORS "A" WTD. EMISSION LEVEL	COMMENTS
MARYLAND	55	EMISSION LIMIT, ANY AMBIENT
DISTRICT OF COLUMBIA	55	EMISSION LIMIT, ANY AMBIENT
DELAWARE	55	EMISSION LIMIT, ANY AMBIENT
ILLINOIS	51	EMISSION LIMIT, ANY AMBIENT-EQUIVALENT A-WTD LEVEL FROM SPECIFIED OCTAVE BANDS
CONNECTICUT	51	EMISSION LIMIT, ANY AMBIENT
MINNESOTA	51	EMISSION LIMIT, ANY AMBIENT
NEW JERSEY	50	EMISSION LIMIT, ANY AMBIENT
OREGON	50	L50 IN ANY ONE HOUR IN "QUIET" ENVIRONMENTS
COLORADO	50	EMISSION LIMIT, ANY AMBIENT
MAINE	45	50 dBA WHEN AMBIENT LEQ > 35 dBA, 45 dBA BELOW (USE L_{eq}=33 dBA)
MASSACHUSETTS	40	MAXIMUM OF 5 TO 10 dBA ABOVE LOWEST L90 AMBIENT (USE MIN L90=33+7 dBA)
WASHINGTON	39	EMISSION LIMIT DEPENDING ON RURAL (39) OR RESIDENTIAL (42) ZONING
CALIFORNIA	38	MAXIMUM OF 5 dBA ABOVE L90 AMBIENT (FOUR QUIETEST CONSECUTIVE HOURS, USE MIN L90=33 dBA)
NEW YORK	38	MAXIMUM OF 5 dBA ABOVE UNDEFINED AMBIENT (USE MIN L90 OR L_{eq}=33 dBA)
MEAN STATE NIGHTTIME LIMIT:	50	
AVERAGE STATE NIGHTTIME LIMIT	47.7	

a.m.) is adequate to preclude sleep-interference issues. This was based on a typical noise reduction of 10 dBA with open windows that would result in an interior bedroom level of 35 dBA. The much later work by the WHO mentioned above now recommends an exterior background level of 40 dBA to avoid sleep issues.

Considering the EPA guidelines as published in the seventies and later analysis, DNL levels from wind developments outside of residences should ideally be targeted at DNL=45 dB, or preferably 5 dBA less. A DNL level of 45 dBA is equivalent to 45 dBA day/35 dBA night or a steady 24 hour level of 39 dBA. A 45 dBA CNEL (Composite Noise Equivalent Level with a 5 dBA evening weighting) would be even more ideal at 45, 40 and 35 dBA for day, evening and nighttime levels, respectively.

3.4 State Standards

Just over a dozen states have codified regulations, zoning guidance or siting standards, presented in Table 2, that fundamentally have the same result as regulations for industrial noise. Most allow a higher limit for daytime hours. The *nighttime* limits for industrial noise sources are tabulated in Table 2 for fourteen states. For the three states using an ambient based limit (CA, MA and NY), we use a representative background level of 33 dBA as an approximate, if somewhat conservative, design datum.

Clearly, there is a large variance, ranging from 38 dBA to 55 dBA, in what is considered "acceptable" for nighttime noise emissions at sensitive receptors. Not all can possibly be appropriate.

It should also be mentioned that the units and time periods of measurements for "emission limits" are not always well defined and one must refer to the actual standard for guidance.

Eight states use absolute 'maximum emission limits' for daytime and nighttime hours that are applicable at residential receptors regardless of the acoustic environment in those areas. While simple to codify and enforce, it is illogical that the same level could be satisfactory for any residential environment ranging from noisy urban to quiet rural residential locations. The state of Maryland[10] acknowledges this and has found

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Table 3—Summary of existing guidelines and standards relevant to typical wind projects.

Source	Effective Limits	Comments
WHO	40 dBA Night	Sleep Disturbance Threshold
Consensus of Int'l Limits Specifically on Wind Turbine Noise	45 dBA Day/40 dBA Night	Arithmetic Average of all Standards
U.S. EPA	45 dBA Day/35 dBA Night	DNL=45 dBA
State Standards	38 to 40 dBA Night	Based on the 3 States using an Ambient-Based Approach

that fully 50% of excessive noise complaints occur in situations where the noise source is in compliance with the State's regulations. Maine and Washington acknowledge differing ambient environments by including a clause that reduces the allowable emission limit for "quiet" areas in Maine and "rural" areas in Washington.

The states of New York, Massachusetts and California use ambient-based emission levels, i.e., the allowable emission level is calculated based on a prescribed increase to the existing ambient, or background sound level. An ambient-based method is based on the *perception* of the new sound in the *specific* residential community. A perception-based method is clearly a better approach than a single absolute limit, and, in fact, many years of experience have shown that this approach is working well in these three states. Based on an assumed generic background level of 33 dBA for rural areas where wind projects are usually sited, the effective design level for a new project would range from 38 to 40 dBA in these three states.

3.5 Local Standards

Finally, it should be mentioned that countless counties and local municipalities have enacted noise laws and ordinances specifically with respect to wind turbine projects—usually in response to a proposed project. Most commonly an absolute limit of 50 dBA is prescribed. Field experience, which is discussed in further detail in Sec. 4, indicates that such a limit is insufficient to avoid annoyance from wind turbine noise if the actual project sound level closely approaches this limit.

3.6 Summary of Existing Guidelines and Standards

Table 3 summarizes the general noise limits and guidelines from all known existing entities domestic and foreign that would be relevant to typical wind turbine projects in rural areas.

4 DIRECT EXPERIENCE AND PREVIOUS ANNOYANCE STUDIES

It is only through field experience testing newly operational wind projects that the actual community reaction can be directly compared to the sound levels produced by a project. Over the last few years we have had the opportunity to conduct sound surveys at 8 new operational wind turbine sites, of which 7 may be considered representative of the typical U.S. domestic project in the sense that a fairly large number of turbines (50 to 100) are sited over a large area within which there is a fairly uniform distribution of farms and homes; i.e., the turbines and residences are thoroughly intermixed. Out of these 7 typical project sites long-term sound monitoring surveys were carried out at 5, usually over a 2 to 3 week period. The principal objective of these surveys was to determine whether the projects were compliant with the applicable regulatory noise limit (usually 50 dBA) but they also afforded important opportunities to quantify the sound levels produced exclusively by the project at a number of the closest homes and to compare these measurements with model predictions. In addition, the community reaction to each project could be generally discerned because monitors were deliberately placed at the homes of all those who were known to have complained or otherwise expressed concern about noise, whether participating in the project or not. Monitoring stations were also set up at other homes where no complaints had been received but where maximum project sound levels were expected based on modeling. Informal discussions about the resident's subjective reaction to project noise occurred at most monitoring positions.

In general, these studies involved continuous monitoring in 10 minute increments over at least a 14 day period at numerous on-site positions supplemented by a number of off-site monitors generally 2 miles beyond the project perimeter recording the likely concurrent background sound level without any project noise. In this way it was possible to reasonably correct the

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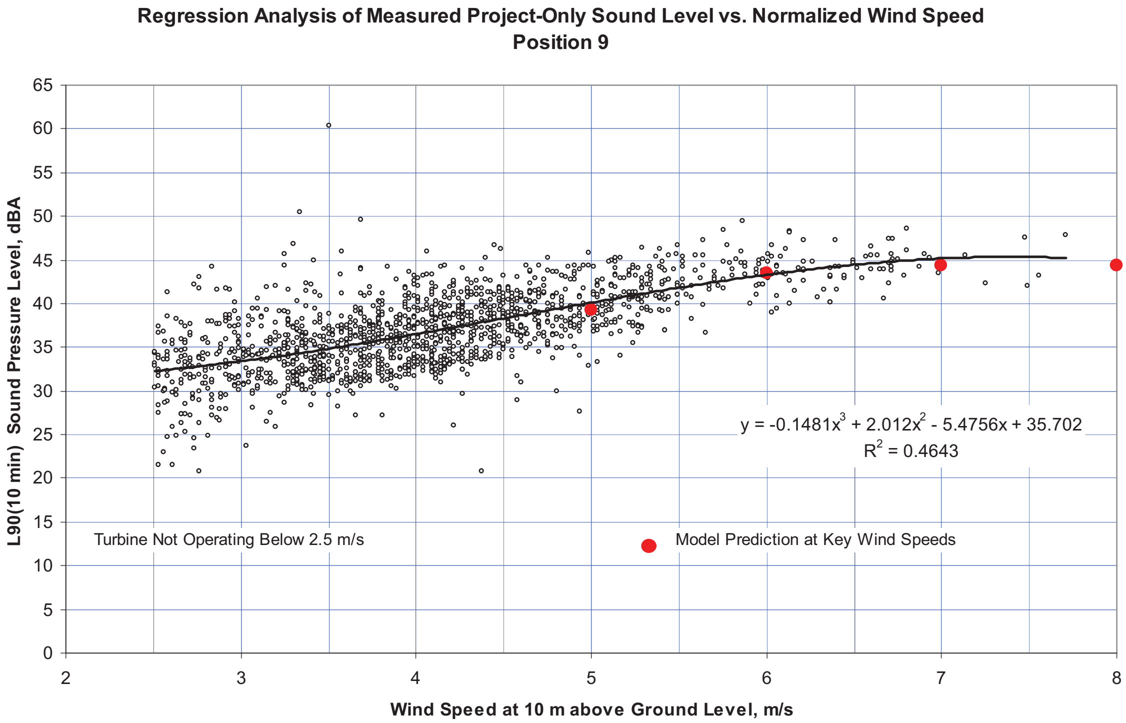

Fig. 5—Measured vs. modeled sound levels at a typical on-site receptor.

on-site sound levels for background noise contamination (which is often very significant during windy conditions) thereby deriving the project-only sound level at each position—the quantity predicted by analytical models. As an example, Fig. 5 is a typical plot that shows the corrected project-only sound level as a function of wind speed rather than time. The scatter in the data, which is typical and expected, is due to fluctuations in the project sound level at the observation point due to variations in atmospheric conditions (path effects) and fluctuations in the aerodynamic noise produced by the rotor due to inevitable inconsistencies in wind speed, gradient or direction (source effects). More importantly, Fig. 5 shows the essentially universal result from all positions in all the surveys that the model predictions at integer wind speeds agree extremely well with the mean trend through the measured performance, thus demonstrating that ISO 9613-2[11] (assuming a moderate 0.5 ground absorption coefficient) is a perfectly valid methodology for predicting wind turbine sound levels, recognizing that path and source effects will lead to levels that vary by about +/−5 dBA about the predicted mean.

In terms of noise impact, the results of these studies indicate that the actual degree of adverse impact, defined as the number of serious complaints relative to the total number of households in the project area (within 2000 ft. of the project perimeter), was fairly small at about 4%. The specific numbers associated with each project are tabulated in Table 4.

Just because the total number of complaints is fairly small in each case one should not be dismissive of these people, because there were usually one or two at each site that were profoundly disturbed by project noise. However, it must also be said that the vast majority of people apparently had no objections to noise, even people who consistently experienced turbine sound levels in the 45 to 50 dBA range. Based on discussions with non-participating and participating residents at more or less randomly selected monitoring positions in close proximity to turbines, the most common reaction was generally that operational noise was certainly audible, particularly during certain wind conditions or times of day, but that it was to be expected and they didn't pay any real attention to it. Of course, this general assessment is not the result of a rigorous scientific study on wind turbine annoyance; that was never the objective of the surveys, but a milder than anticipated reaction was observed at each site.

The low apparent rate of adverse reaction to projects where numerous residences were exposed to relatively high sound levels (up to 55 dBA in some cases) was surprising because it stood in stark contrast to the results of previous annoyance studies; in particular, the extensive work carried out from 2000 to 2007 in Sweden and the Netherlands by Pedersen and Persson Waye[12] and Persson Waye[13]. These studies generally predict an annoyance rate ranging from 10 to 45%, or more, for wind project sound levels in the 40 to 45 dBA range. For example, the earliest study[12], based on questionnaire responses collected in 2000 from residents living in proximity to five small wind projects in Sweden, found the annoyance rate as a function of sound level plotted in Fig. 6.

Table 4—Number of observed complaints relative to the total number of households in close proximity to turbines.

Project	Total Households in the Site Area (Approx.)	Number of Complaints as a Function of Project Sound Level (dBA) (1)			Total Number of Complaints	Percentage Relative to Total Households
		<40	40–44	45 or Higher		
Site A	107	0	2	1	3	3%
Site B	147	0	3	3	6	4%
Site C	151	0	3	0	3	2%
Site D	268	0	2	4	6 (2)	2%
Site E	91	1	1	4	6	7%
					Overall Average:	4%

(1) Sound levels expressed as long-term, mean values

(2) There were only 3 reported complaints at this site but others may have existed that we were not made aware of; hence a total number of 6 were assumed

This steeply rising curve apparently indicates that a sound level of 40 dBA, for instance, leads to a 26% annoyance rate, implying that out of the study population of 513, 133 were highly annoyed. However, this is not at all the case. On further analysis it turns out that the response curve percentage is not related to the overall study population—i.e., the total number of households within the project area with a predicted sound level of 30 dBA or more, whether they responded to the survey or not—but rather to the percentage of people exposed to a particular sound level that reported annoyance due to that sound level (see Table 5 of the paper). Now it must be pointed out that only 351 of the 513 individuals forming the study population returned the questionnaire, so the views of the missing 32% are not known, but in the 37.5 to 40 dBA category, for example, 20% of the 40 respondents exposed to that sound level range reported being highly annoyed—which is just 8 people. Viewed in terms of the overall population of 513 that is equivalent to a highly annoyed response of just over 1% for that particular sound level range (37.5 to 40 dBA). In general, across all sound level ranges the total number of people responding that they were highly annoyed was 31, or 6% of the total number of households. In contrast to the alarmingly steep response rate curve in Fig. 6, this 6% figure agrees much more closely with the 4% complaint rate (based on the total number of households) observed during our own field studies of projects in the United States. A further and much larger questionnaire study modeled on the 2000 study was performed in the Nether-

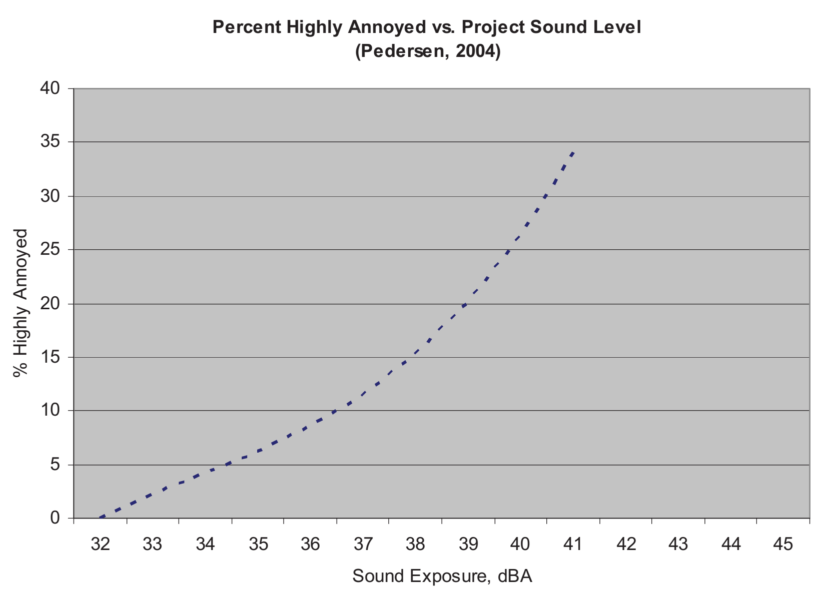

Fig. 6—Response analysis from Pedersen[14].

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lands in 2007 and reported in 2009 (Pedersen et al.[14]). This study is the most representative of current projects with large turbines and essentially flat topography. In this study out of 1948 queries sent out 708 were received. Across all sound level categories a total of 29 respondents (back-calculated from the results expressed as percentages in Table 2) reported being very annoyed. If only the 708 respondents are assumed to make up the pool of potentially affected residences in the project area (rather than 1948), this equates to a 4% rate of high annoyance.

On the other side of the coin, the number of individuals concerned about or annoyed by noise at each of the sites we studied may not have been definitive, since the number represents those who were troubled enough to call in and complain, as reported by project management, and any others we may have learned of indirectly in discussions with neighbors. The possibility that others were annoyed certainly cannot be ruled out and, in fact, seems likely but it appears that the actual rate of serious annoyance to noise from wind projects may not be nearly as high as previously supposed.

5 LOW FREQUENCY NOISE AND ADVERSE HEALTH EFFECTS

Harmful, or at least disturbing levels of low frequency or infrasonic noise and potential adverse health effects are almost always feared, based largely on internet misinformation, and cited as major reasons why proposed projects should not go forward. However, the fact of the matter is that wind turbines do not produce significant or even remotely problematic levels of low frequency noise and that a link between health complaints and turbine noise has only been asserted based on what is essentially anecdotal evidence without any valid epidemiological studies or scientific proof of any kind. The latter assertions are all the more suspect in that they are often predicated on or directly associated with the assumed existence of high levels of low frequency noise.

It is well outside the scope of this paper to go over the basis for these conclusions but readers are referred to a recent review by a panel of independent doctors on wind turbine health effects[15] and some extensive testimony by the leading experts in the field (now public record) regarding potential low frequency noise impacts recently filed in conjunction with a proposed wind project in Wisconsin[16].

Because low frequency noise from wind turbines, essentially irrespective of distance, is well below the point where it might begin to be audible or initiate perceptible vibrations (windows or dishes rattling, for example) there is no actual need for a design goal or regulatory limit. However, if one desires just to be on the safe side, so to speak, a limit of 65 dBC might be used. In over 30 years of investigating countless genuine low frequency noise complaints, usually associated with simple cycle combustion turbines, there was only one outlier below 65 dBC. A maximum regulatory limit of 70 dBC is recommended if one must have a low frequency limit.

Having said that, it must be strongly cautioned that C-weighted sound levels do not mix well with wind turbine applications because it is extremely difficult to accurately measure C-weighted sound levels in the presence of any kind of wind[17]. Self-generated, false signal noise, which occurs in the low frequencies, from wind blowing through even sophisticated windscreens and over the microphone tip will drastically elevate the apparent C-weighted sound level and, by extension, the *apparent* low frequency sound level. Consequently, it would be a significant technical challenge to accurately field verify the C-weighted performance of a wind turbine project. Any casual measurement in a windy field will ostensibly yield a relatively high C-weighted sound level, possibly in excess of the 65 to 70 dBC levels suggested above, whether a wind turbine is present—or not.

Finally, Fig. 3 also shows the measurement location prescribed in IEC 61400-11 for determining the sound power level from wind turbines. Sound pressure is measured on a reflective ground plane with the microphone on the surface where wind speed is theoretically zero, but a $\frac{1}{2}$ sphere wind screen will blow away unless attached securely. Still another common example is dry leaves blowing along the ground in fall. Even with this test set up, measurement of LFN is problematical.

6 RECOMMENDED DESIGN GOALS AND NOISE LIMITS

Based on the existing guidelines and limits outlined in Sec. 3, combined with our direct experience summarized in Sec. 4, the following design goals and regulatory limits given in Table 5 are recommended.

The nighttime level of 40 dBA is suggested as an ideal design goal rather than a firm regulatory limit because a legal limit must reasonably protect the public from legitimate annoyance and, at the same time, not stand completely in the way of economic development, which 40 dBA would tend to do in some instances. Because the actual number of complaints observed at sites where the project sound level exceeded, or even substantially exceeded, 40 dBA is small at 4%, a sound level of 45 dBA at residences, as an ordinance or legal limit, appears to balance the desire on everyone's part to avoid complaints and annoyance on the one hand with practical constructability on the other. Sound levels of less than

Table 5—Recommended regulatory noise limits and design goals for wind turbine projects.

	Sound Level, dBA (1)	Applicable	Time of Day
Regulatory Limit:	45	Outside Residences	Day and Night
Design Goal:	40	Outside Residences	7 p.m. to 7 a.m.

(1) Long-term, mean project sound level (normally measured in terms of the L90(10 min) statistical sound level)

45 dBA would theoretically lead to a very low complaint rate of 2% based on the data in Table 4.

It is important to note that both of the levels above are mean, long-term values and not instantaneous maxima. Wind turbine sound levels naturally vary above and below their mean or average value due to wind and atmospheric conditions and can significantly exceed the mean value for brief periods. As illustrated in Fig. 5, project sound levels commonly fluctuate by roughly +/−5 dBA about the mean trend line but short-lived (10 to 20 minute) spikes on the order of 15 to 20 dBA above the mean are occasionally observed (less than 1% of the time) that are ostensibly attributable to turbine noise—although the possibility exists that some or all are extraneous noise events. Because it would be completely impractical to design any project so that all such spikes would remain below the 40 and 45 dBA, these values are expressed as long-term mean levels, or the central trend line through the data scatter as shown in Fig. 5.

Some degree of dissatisfaction due to audibility is largely inevitable. The very definition of noise is unwanted (audible) sound. For example, in isolated incidences we are familiar with complaints have been engendered by wind project sound levels as low as 23 and 34 dBA. Therefore an objective of completely eliminating the possibility of any negative response is largely impractical and the imposition of extremely low regulatory noise limits or of vast minimum setbacks—as championed by James and Kamperman[18], for instance—would not necessarily eliminate all adverse impact but would, in fact, make most projects impossible to build, even in sparsely populated areas of the country.

During the design phase of a wind project, particularly for projects where the turbines are interspersed amidst a number of homes, there are several options, outlined below, that are available for mitigating potential project noise and bringing the project, hopefully, into conformance with one or both the recommended noise levels.

6.1 Site Layout Optimization

The most useful and effective method by far is the optimization of the site plan through iterative noise modeling. This technique, which has been successfully applied to a number of projects, involves developing a baseline model of the project as initially conceived in terms of a sound contour map and then hypothetically relocating or removing certain units in order to *ideally* place all of the potentially sensitive receptors within the site area outside of the 40 dBA contour line.

The baseline layout is usually driven by where participating land parcels are in general and where the wind resource is best on those parcels in particular, rather than by noise concerns. Consequently, some degree of improvement, i.e., a reduction in the predicted sound levels at residences, can almost always be realized—so long as it is early enough in the design process that significant changes can be made. In fact, the best time to start evaluating potential noise impacts is when a project has just begun to coalesce and is considered generally viable, even if only a hypothetical or estimated turbine layout is all that is available for modeling. All too often noise is only considered at the eleventh hour just prior to submittal of the permit application, or even construction, when the flexibility to move turbines has been utterly lost.

Because of the numerous other constraints that always exist on exactly where turbines can be built, it is often necessary to go through several iterations of noise modeling to find the optimal arrangement that minimizes noise and still satisfies all other concerns.

6.2 Low Noise Operating Modes

If physical changes to the turbine site plan cannot be made or are still insufficient to realize the desired performance, further targeted reductions can sometimes be made by operating specific units in low noise operating mode—something that can also be evaluated prior to construction through iterative modeling. While still not universally available as an option on all turbine makes and models, there now appears to be a trend towards incorporating this capability into most new units or retrofitting it on existing models. Noise reductions of up to 5 dB relative to normal performance (it is claimed by some manufacturers) can nominally be achieved primarily through electronic manipulation of the blade pitch. Although this operating mode could theoreti-

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cally be employed at all times, it adversely affects power production at higher wind speeds so it not desirable, or in some cases even economically unfeasible, to permanently de-rate the turbines; consequently, this option is more appropriate for use as a temporary measure under certain weather conditions or times of day, most likely during the critical nighttime hours when noise is typically more of an issue.

6.3 Operational Curtailment

Curtailment of operation, or temporarily shutting down specific turbines, is obviously onerous to the economics of a project that clearly involves a large capital investment, but it may be less devastating than first thought. The temporary shutdown of just one unit (overnight, for instance) can sometimes make a dramatic difference in the sound level at a particular point of interest. Depending on the geometry of the situation, model simulations taken from actual projects indicate that noise reductions from 2 to 8 dBA can be achieved by shutting down only the *single nearest* turbine to a particular house.

7 CONCLUSIONS

Measurements of operational wind turbine projects indicate that turbine noise is usually most perceptible relative to the background level at night suggesting that design goals and regulatory limits should either be focused on nighttime conditions or have differing goals for night and day

Existing guidelines and regulatory limits, interpreted within the context of the quiet rural environments in which wind projects are normally sited, generally point to a design goal sound level of 40 dBA at night and 45 dBA during the day.

Experience in measuring the sound levels produced by newly operational wind projects and comparing those levels to actual community reaction indicates that the number of complaints relative to the total number of potentially affected households within a given project area is fairly low at roughly 4% in cases where project sound levels exceed or even substantially exceed 40 dBA at residences. This finding was also found to generally agree with previous European research but only when the number of questionnaire responses reporting high annoyance is similarly viewed relative to the overall number of potentially affected households rather than by exposure levels.

Field surveys of operational projects also generally indicate that complaints engendered by wind turbine sound levels below 40 dBA are very rare therefore suggesting that new wind projects should use a nighttime sound level of 40 dBA as an ideal design goal at all residences to minimize the probability of annoyance and complaints with a higher level of 45 dBA applicable during the day. However, the low (2%) rate of complaints observed in the studies when the project sound level was below 45 dBA points to this value (45 dBA) as an appropriate regulatory limit, irrespective of time of day, since it appears to strike a balance between the reasonable prevention of annoyance and what is generally achievable in terms of project sound levels at typical project sites.

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