5th International Meeting
on
Wind Turbine Noise
Denver 28 – 30 August 2013

Measuring and Analyzing Wind Turbine Infrasound and Audible Immissions at a Site Experiencing Adverse Community Response

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Summary

Measuring the correct value for infrasound and low frequency noise (ILFN) immissions in the field with wind is shown to be quite problematical, but extremely easy to measure incorrectly. Guidance is discussed from work-in-progress on ANSI S12.9 (the U.S. standard for environmental noise) Part 7: *Measurement of Low Frequency Noise and Infra-Sound Outdoors In the Presence of Wind and Indoors in Occupied Spaces*. A simple two microphone test set-up is recommended for quickly acquiring data with off-the-shelf instrumentation so that numerous locations can be measured to access impact or certify immissions from wind turbines. Field measurements at the Shirley wind farm near Green Bay, WI are discussed. A more comprehensive test set is urgently needed and recommended to dispel some of the issues debated at every wind farm application.

1.0 Introduction

This paper is divided into two parts:

- Guidance from ANSI S12.9 Part 7
- Practical measurements at the Shirley wind farm near Green Bay, WI.

Figure 1 shows the title of Part 7 and draft status.

2.0 Measurement Guidance from ANSI S12.9 – Part 7

2.1 Introduction It is my honour and privilege to chair a working group (WG54) of very talented scientists, engineers and interested parties to draft Part 7 of ANSI S12.9, the American standard for environmental community noise. In that capacity, much has been learned in the past two years about the difficulties and solutions of measuring sound in the presence of wind and indoor spaces. An effort will be made to publish the first fully completed draft by yearend.

2.2 Windscreen Design The first consideration for outdoor measurements in wind is proper wind screen design. To that end, seven windscreen variations were tested as shown in the photo of **Figure 2**. The test site was in the Mojave Desert in California that has little man-made noise but plenty of wind. The seven channels were measured simultaneously over a long period and then sorted into wind speed bins. At first, this was called pseudo-noise (turbulence on the microphone) but this is only one signal source and there are others truly acoustic sources such as grass or tree leaf rustle, building wall vibration and low frequency turbulence noise. All of these are directly caused by wind so a better descriptor will be proposed to the WG as “wind noise”.

The overall measured levels (A, C & Z) for all seven designs are ranked in decreasing order (highest to lowest wind noise) and shown in the column chart on **Figure 2** for a moderate wind speed bin of 3-4 m/s. The net improvements over a standard wind screen are shown as the black columns. As expected the poorest performance is the small standard wind screen that is supplied with the meter and the best is the ground plane arrangement described in IEC 61400 - II. A 16 dBC gain is achieved with the ground plane. The next best is the 12" rhombicuboctahedron shape (rhom for short) with an 11 dBC improvement. A sphere of 12" diameter at 20 pores/inch porosity should be as good or better than the rhom.

The right hand sketch shows our current practice of measuring with both of the best windscreens using off-the-shelf instrumentation. If one has more time and depending on the distance "d" shown, more advanced signal processing in the time domain can be done to evaluate coherence, correlations and time delay functions as described thoroughly in references 1 and 2 The intent of the Part 7 standard is to outline a relatively simple methodology using mostly off-the-shelf instrumentation so that ILFN measurements are made on a uniform and comparable basis.

With this in mind, it was desired to find the best windscreen easily mounted above grade because the ground wave and ground reflection effects are important for determining community noise immissions and this is excluded from a ground plane measurement. Also it is not practical to use the microphone-in-a pit method because of calibration issues, and digging a hole at a complainant's residence is too time-consuming when many locations must be measured often.

It is not a trivial matter converting the measured level on a ground plane to the equivalent desired level above grade. The difference involves the geometry of the approaching waves from both the direct and reflected waves from the ground surface **Figure 3** illustrates a special test set-up to measure the difference for comparison to theoretical wave cancellation and amplification reflection effects off the ground plane. For a hard flat ground plane**,** the theoretical conversion of 3 dB should be subtracted from the ground plane result. This accounts for the 6 dBA for pressure doubling on the plane less 3 dBA for the addition of the ground wave. The theoretical dips of 18 and 10 dB would only occur in a perfectly uniform space and off a flat hard ground surface. .Although neither is true in the field the agreement between theory and measurement is quite good.

The correction table of source heights and distances likely to be encountered in practice show that each measurement set-up requires no correction between methods for infrasound frequency measurements, at least from ground plane reflections. It should be pointed out that the ground plane measurement is still superior because of lower wind speed on the surface compared to at 1.5 meters above grade.

Figure 4 plots the 1/3 OBCF spectra for the seven designs at low, moderate and high wind speeds. Note that even at very low speeds, wind creates significant infrasound levels.

2.3 Ideal test set-up for study of wind turbine emissions (Figures 5 and 6)

There are many basic issues disputed in wind farm applications that could be settled with a comprehensive test program. These include the spreading rate where it is often claimed that wind turbine infrasound and low frequency noise (ILFN) do not obey the inverse square law but spreads at a rate closer to 3 dB per doubling. Also, ground effects, appropriate sleep levels, noise reduction of house structures are continually debated.

Figure 5 shows a suggested ideal set-up to address such disputes with careful measurements. Note five semi-portable standardized room structures are used to preclude adverse wind effects. Even though this set-up seems foolproof, one still has to consider wind effects on building walls. **Figure 6**, compliments from ChIA, show the interior office space during calm and moderate outside wind. Note the action of wind on a structure can create infrasound levels 30 dB above calm conditions!

3.0 Practical Measurements from the Shirley Wind Farm Project

3.1 Introduction **Figure 7** shows an aerial view of the Shirley wind farm showing five of the eight total wind turbines. Data was acquired over a three day period to investigate the source of complaints. The abandoned residences labelled R1, R2 and R3 are shown where indoor/outdoor levels were measured. The yellow oval shows the location where turbine output was monitored and the blue oval where ON/OFF data was acquired by chance. **Figure 8** plots the measured A and C-weighted levels over the three day period. Note there were two 3 hour intervals where the level was quite steady at 53 dBA, the computed pressure from the turbines rated sound power of 107 dBA.

3.2 Sound Power The wind farm operator was uncooperative and would not turn off the turbines upon request so that true wind turbine immissions and impact could be measured, i.e. where wind noise and wind turbine noise could each be quantified. Fortunately, a measurement location remote from the roads and close to WTG 6 was found where the turbine output sound pressure could be continuously monitored. The location was 225m to the hub of the turbine so sound power according to IEC 61400-II could be calculated. The two periods of steady 53 dBA yielded amazingly steady pressures with no sporadic sources as shown on **Figure 9.** Note on the photo that the microphone is not on a ground plane to preclude damage in case of wet weather. Nevertheless, sound power from both sets of data yielded a sound power LwA =107 dB re.1pW as shown on **Figure 10**. But note the large divergent low frequency result on Figure 10. This is undoubtedly due to wind noise caused by using an above grade weather treated windscreen in lieu of a ground plane.

3.3 Calculated sound pressure versus measured The best sound pressure spectra were acquired at the residences during the interval of lower wind and lower power (58% load). Hence the sound power developed above could be used in ISO-9613 Part 2 to compute the pressure spectra and overall levels for comparison to measurements. All eight turbines were assumed to be running at a similar load. **Figure 11** plots these results. It is shown that ISO-9613 yields decent agreement and we conclude from the lower right plot that hemispherical divergence (6 dB/doubling used in ISO-9613) is correct for propagation at all frequency ranges.

3.4 Outdoor minus Indoor Noise Reduction **Figure 12** plots the outdoor and indoor 1/3 octave spectra acquired during two nighttime intervals from the 10pm to midnight and repeated 2am to 4am. Surface wind was minimal and a ground plane microphone was used outdoors. The results track one another both inside and outside. Note the presence of fundamental building wall flexure in the ILFN range of 8 to 50 Hz at all three residences. The lower left curve shows this as well in the noise reduction plot. At higher mass controlled frequencies the heavier older plaster/lath board construction is far superior. We believe this source of infrasound has to be considered when trying to explain potential health effects.

3.5 ON/OFF Measurements While testing for another purpose near WTG 8 close to R2, power company operators showed up and shut down the turbine. The resulting ON/OFF measurements are shown on Figure 13. The only audible change that occurred was the vanishing "whoosh" from the blades. There is no apparent infrasound from this turbine, i.e. it is buried or below the ambient "wind noise".

4.0 Conclusions

It is shown that measuring infrasound immissions at potentially sensitive receptors at the large distances typical between turbines and residences is a real challenge. The task involves separating ambient "wind noise" from wind turbine noise by using effective wind screen designs and advanced signal processing. The author knows of no test to date where this has been done successfully over an area sufficiently large to draw definitive conclusions about infrasound sound propagation principles of wind turbine noise. An idealized test set-up is suggested.

References

[1] B. Walker, *"Coherence Issues in Wind Turbine Noise Assessment"*, Proceedings from the Fourth International Meeting on Wind Turbine Noise, Rome, Italy, 12-14 April 2011

[2] B. Walker, *"Time domain analysis of low frequency wind turbine noise",* Proceeding from the 15th International Meeting on Low Frequency Noise and Vibration and its Control, Strtford upon Avon, UK, 22-24 May 2012

FIGURE 1

Title page for S12.9 Part 7 Standard

BSR/ASA S12.9, Part 7
DRAFT 3, 10/3/12

DRAFT AMERICAN NATIONAL STANDARD

ANSI S12.9 - Part 7: Measurement of Low Frequency Noise and Infra-Sound Outdoors In the Presence of Wind and Indoors in Occupied Spaces

Secretariat:

Acoustical Society of America

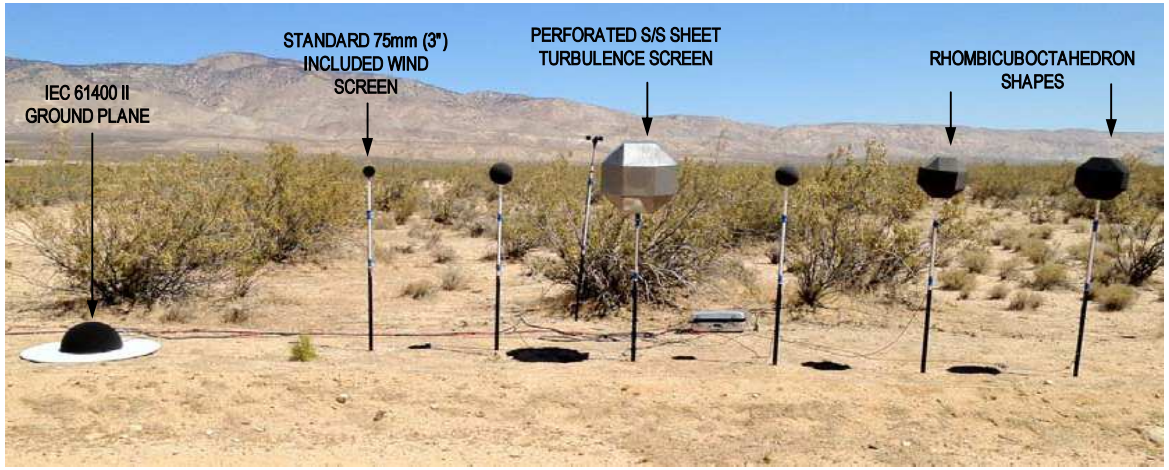
Draft - Not approved by:

American National Standards Institute, Inc.

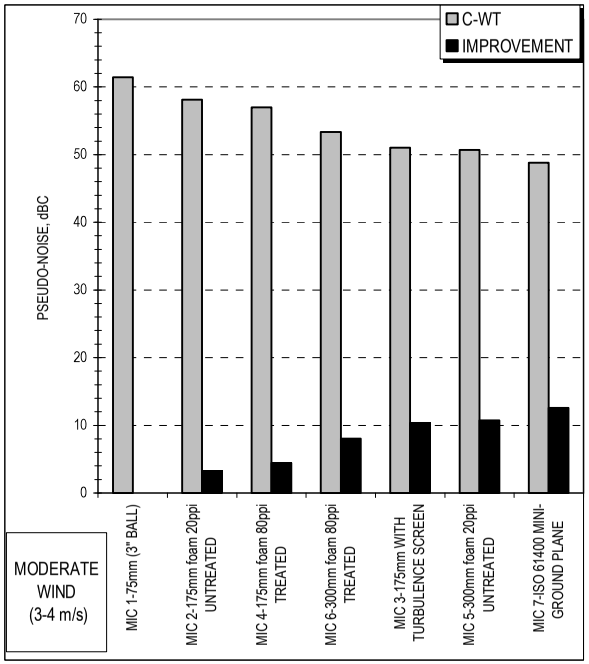
Abstract

Part 7 describes cautions and unique techniques for measuring low frequency noise (LFN) outdoors in the presence of wind. It is necessary to measure in wind for wind turbine projects and for countless other industrial power and facilities where environmental wind speed cannot be controlled or levels are specified under downwind conditions. The standard also describes a uniform and repeatable methodology for documenting LFN levels and spectra indoors in occupied spaces where modal considerations are important. The principle concern outdoors is pseudo noise created by wind and turbulence on the microphone that depends on the effectiveness of the windscreen in use. The best estimates of pseudo noise versus wind speed are presented based on past survey data at quiet sites and special testing conducted by the working group for this standard. The effectiveness of standard size foam windscreens (as furnished by the instrument

FIGURE 2 Set-up to measure "wind-noise" in Mojave Desert



RANKING (FOR 3-4m/s WIND SPEED AT MICROPHONE) NOTE FROM PRELIMINARY ANALYSIS		IMPROVEMENT OVER STD WS
	A-WT	
MIC 1-75mm (3" BALL)	29.5	--
MIC 2-175mm 20ppi FOAM 20ppi UNTREATED	27.5	2.0
MIC 6-300mm 80ppi FOAM TREATED	27.0	2.5
MIC 4-175mm 80ppi FOAM TREATED	26.2	3.3
MIC 3-175mm WITH TURBULENCE SCREEN	26.1	3.3
MIC 5-300mm 20ppi FOAM UNTREATED	26.0	3.5
MIC 7-ISO 61400 MINI-GROUND PLANE	27.4	2.1
	C-WT	
MIC 1-75mm (3" BALL)	61.4	--
MIC 2-175mm 20ppi FOAM 20ppi UNTREATED	58.1	3.3
MIC 4-175mm 80ppi FOAM TREATED	57.0	4.5
MIC 6-300mm 80ppi FOAM TREATED	53.4	8.0
MIC 3-175mm WITH TURBULENCE SCREEN	51.1	10.4
MIC 5-300mm 20ppi FOAM UNTREATED	50.7	10.7
MIC 7-ISO 61400 MINI-GROUND PLANE	48.8	12.6
	Z-WT	
MIC 1-75mm (3" BALL)	85.8	--
MIC 2-175mm foam 20ppi UNTREATED	84.0	1.8
MIC 4-175mm foam 80ppi TREATED	82.8	3.0
MIC 6-300mm foam 80ppi TREATED	79.8	6.0
MIC 3-175mm WITH TURBULENCE SCREEN	79.3	6.5
MIC 5-300mm 20ppi FOAM UNTREATED	78.2	7.7
MIC 7-ISO 61400 MINI-GROUND PLANE	74.2	11.6



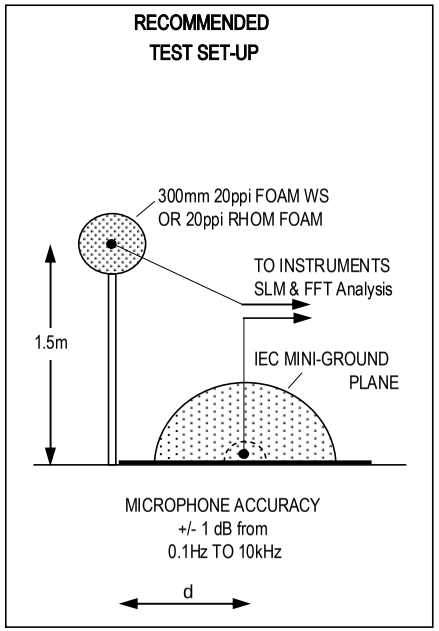


FIGURE 3 Conversion from ground-plane to above-grade measurement set-up

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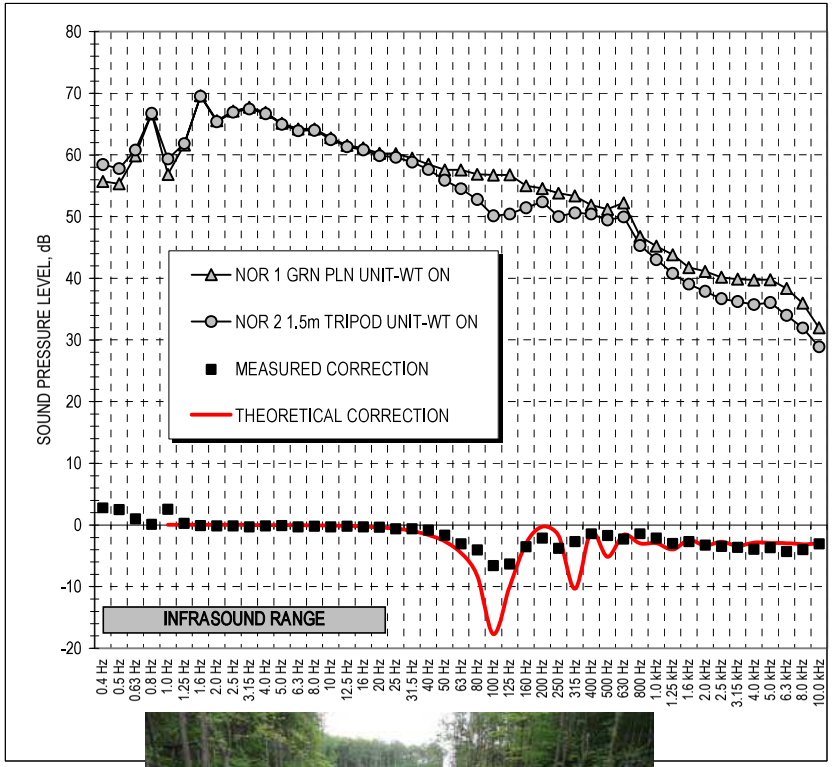
$L_{1.5m} = L_{gp} + Kr + Kw$
where:
Kr = addition of ground reflection wave to ground pane measureemnt without it.
Kw = adjustment for wind-noise difference at ground and 1.5m height



METERS			O.B. CENTER FREQUENCY, Hz													
Hs	Hr	D	1	2	4	8	16	32	63	125	250	500	1K	2K	4K	8K
5	1.5	100	0	0	0	0	0	0	0	0	-1	-2	-10	-2	-3	-4
10	1.5	100	0	0	0	0	0	0	0	-1	-2	-10	-2	-3	-4	-3
20	1.5	100	0	0	0	0	0	0	-1	-2	-10	-2	-3	-4	-3	-3
40	1.5	100	0	0	0	0	0	0	-2	-9	-2	-3	-3	-3	-3	-3
80	1.5	100	0	0	0	0	0	-1	-6	-4	-3	-3	-3	-3	-3	-3
160	1.5	100	0	0	0	0	-1	-3	-10	-2	-4	-3	-3	-3	-3	-3
5	1.5	200	0	0	0	0	0	0	0	0	0	-1	-2	-10	-2	-3
10	1.5	200	0	0	0	0	0	0	0	0	-1	-2	-10	-2	-3	-4
20	1.5	200	0	0	0	0	0	0	0	-1	-2	-10	-2	-3	-4	-3
40	1.5	200	0	0	0	0	0	0	-1	-2	-10	-2	-3	-4	-3	-3
80	1.5	200	0	0	0	0	0	0	-2	-9	-2	-3	-3	-3	-3	-3
160	1.5	200	0	0	0	0	0	-1	-6	-4	-3	-3	-3	-3	-3	-3
5	1.5	400	0	0	0	0	0	0	0	0	0	0	-1	-2	-10	-2
10	1.5	400	0	0	0	0	0	0	0	0	0	-1	-2	-10	-2	-3
20	1.5	400	0	0	0	0	0	0	0	0	-1	-2	-10	-2	-3	-4
40	1.5	400	0	0	0	0	0	0	0	-1	-2	-10	-2	-3	-4	-3
80	1.5	400	0	0	0	0	0	0	-1	-2	-10	-2	-3	-4	-3	-3
160	1.5	400	0	0	0	0	0	0	-2	-9	-2	-3	-3	-3	-3	-3
5	1.5	800	0	0	0	0	0	0	0	0	0	0	0	-1	-2	-10
10	1.5	800	0	0	0	0	0	0	0	0	0	0	-1	-2	-10	-2
20	1.5	800	0	0	0	0	0	0	0	0	0	-1	-2	-10	-2	-3
40	1.5	800	0	0	0	0	0	0	0	0	-1	-2	-10	-2	-3	-4
80	1.5	800	0	0	0	0	0	0	0	-1	-2	-10	-2	-3	-4	-3
160	1.5	800	0	0	0	0	0	0	-1	-2	-10	-2	-3	-4	-3	-3
5	1.5	1600	0	0	0	0	0	0	0	0	0	0	0	0	-1	-2
10	1.5	1600	0	0	0	0	0	0	0	0	0	0	0	-1	-2	-10
20	1.5	1600	0	0	0	0	0	0	0	0	0	0	-1	-2	-10	-2
40	1.5	1600	0	0	0	0	0	0	0	0	0	-1	-2	-10	-2	-3
80	1.5	1600	0	0	0	0	0	0	0	0	-1	-2	-10	-2	-3	-4
160	1.5	1600	0	0	0	0	0	0	0	-1	-2	-10	-2	-3	-4	-3

NOTE 1: RECOMMENDED A MAXIMUM OF -3 dB IN ANY ONE BAND BE USED.
NOTE 2: METHODS EQUAL FOR INFRASOUND WAVE REFLECTIONS BUT GP METHOD HAS LESS WIND-NOISE.

	O.B. CENTER FREQUENCY, Hz													
Frequency band	1	2	4	8	16	32	63	125	250	500	1K	2K	4K	8K
Kr	**0**	**0**	**0**	**0**	**0**	**-1.5**	**-3**	**-3**	**-3**	**-3**	**-3**	**-3**	**-3**	**-3**
Band identified by formula →														

FIGURE 4

Measured 1/3 OB spectra for "wind noise" of seven wind screen designs at three levels of wind speed.

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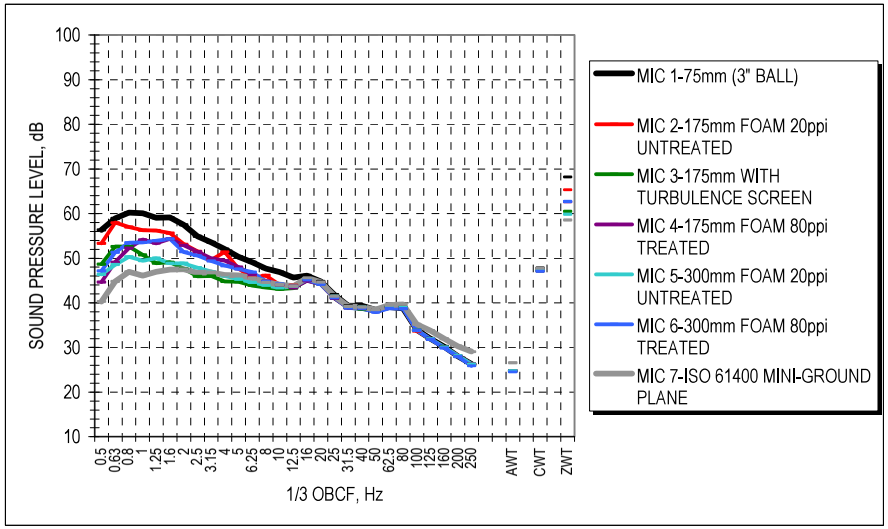
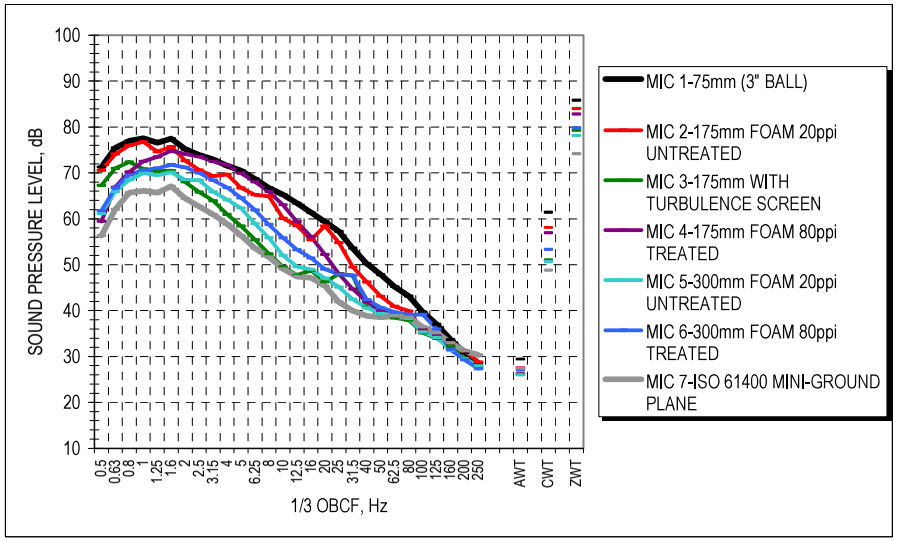
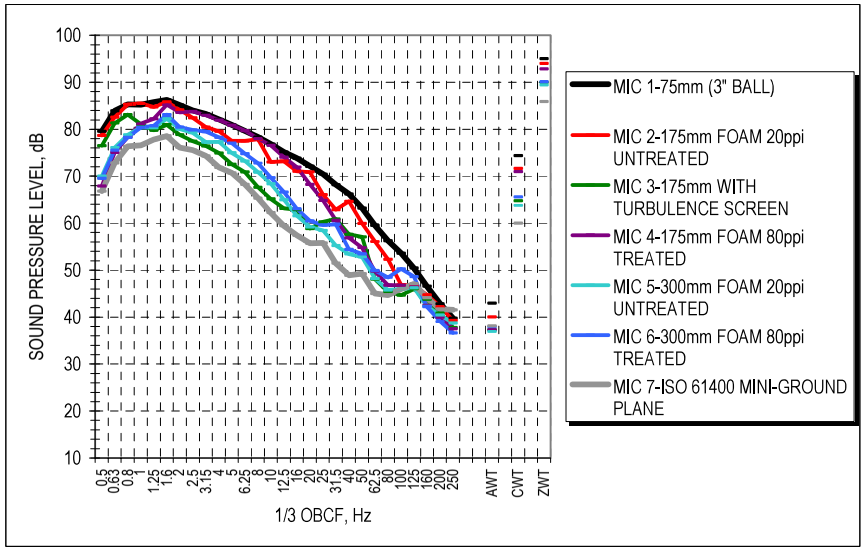


LOW WIND SPEED (0-1 m/s BIN)



MODERATE WIND SPEED (3-4m/s BIN)



HIGH WIND SPEED (6-7 m/s BIN)

FIGURE 5 Ideal test set-up to study sound propagation basics of wind turbine noise including ILFN freqencies

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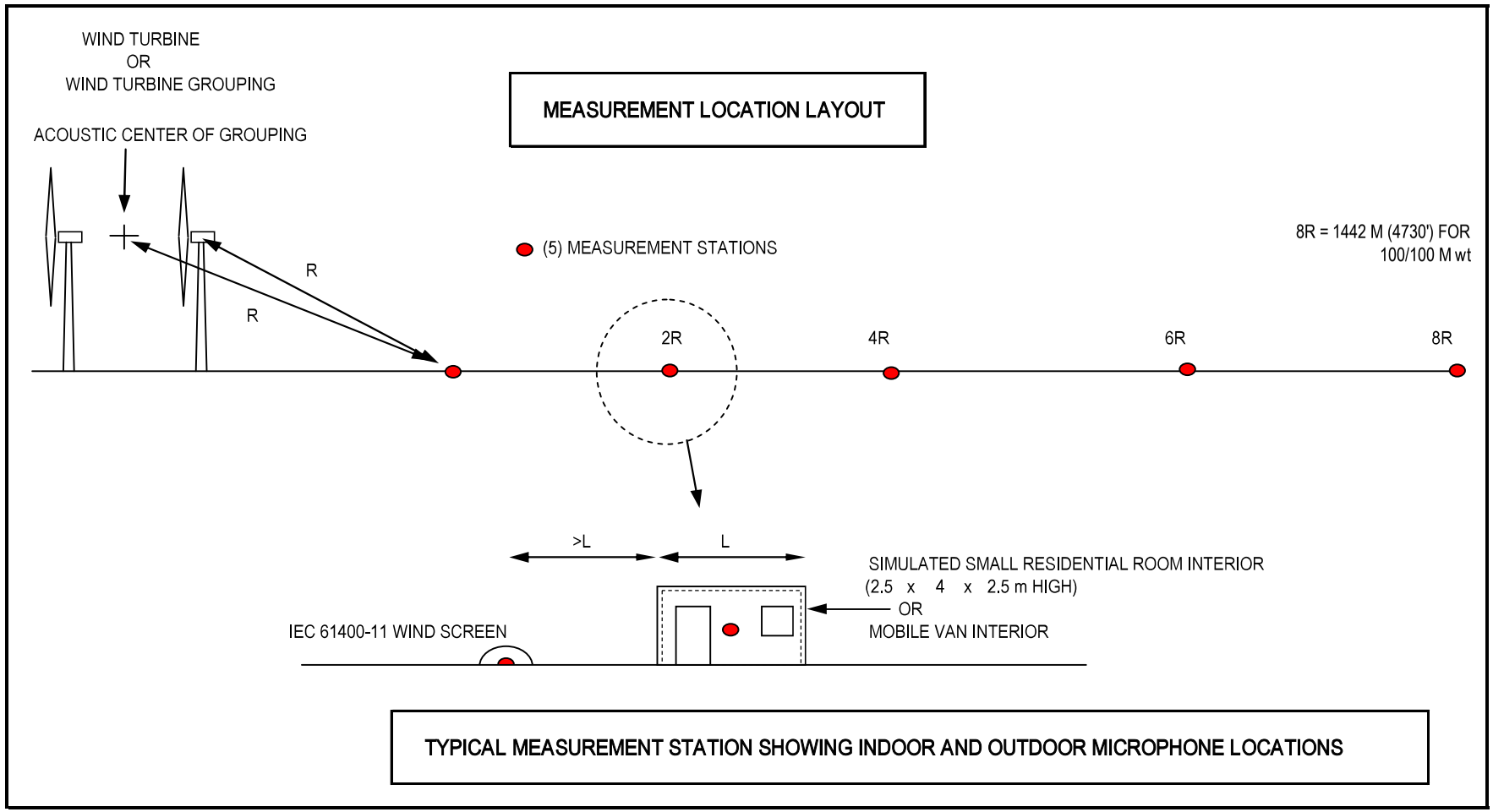

1. SIMULTANEOUS MEASUREMENTS AT R THRU R8
2. 1/3 OBCF AND NARROW BAND FFT TO 0.05 Hz RESOLUTION
3. OUTSIDE & INSIDE OF SIMULATED ROOM W/ AND W/O WINDOW CLOSED
4. MEASURE HEMISPHERICAL SPREADING RATE
5. MEASURE GROUND ABSORPTION RATE
6. EVALUATE QUALITY OF ILFN IEC 61400 Lp TO Lw MEASUREMENTS
7. EVALUATE QUALITY OF ISO 9613 MODELING

FIGURE 6

Measured background level in ChIA Office during a calm day and windy day showing apparent infrasound attributable to wind alone. Compliments of ChIA.

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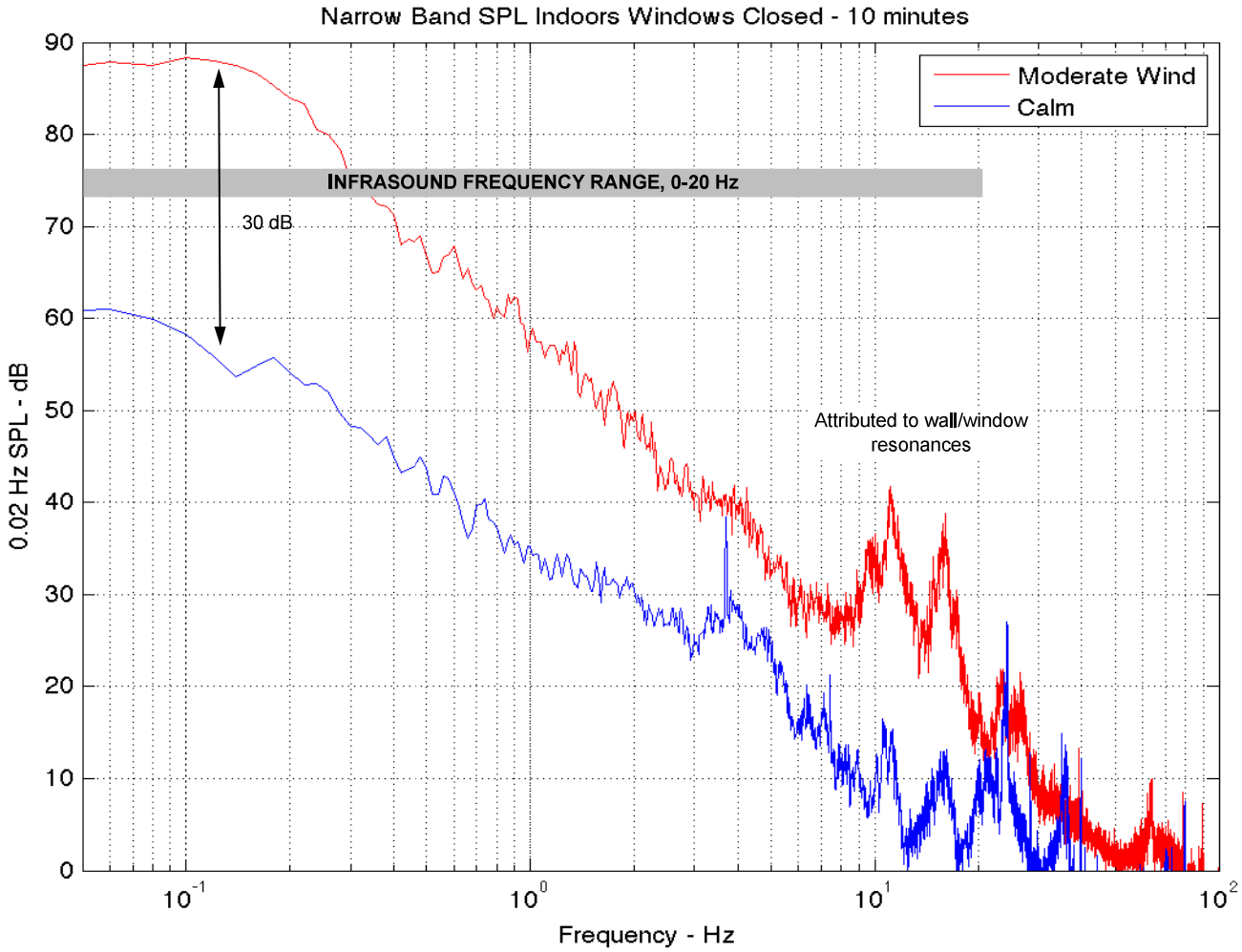

FIGURE 7 Aerial view of Shirley wind farm

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1--SOUND POWER MEASUREMENT, 2--CALCULATE ISO9613 SPECTRA TO COMPARE WITH MEASURED
3--CALCULATE OUTDOOR - INDOOR SPECTRA, 4--MEASURE ON/OFF IF POSSIBLE

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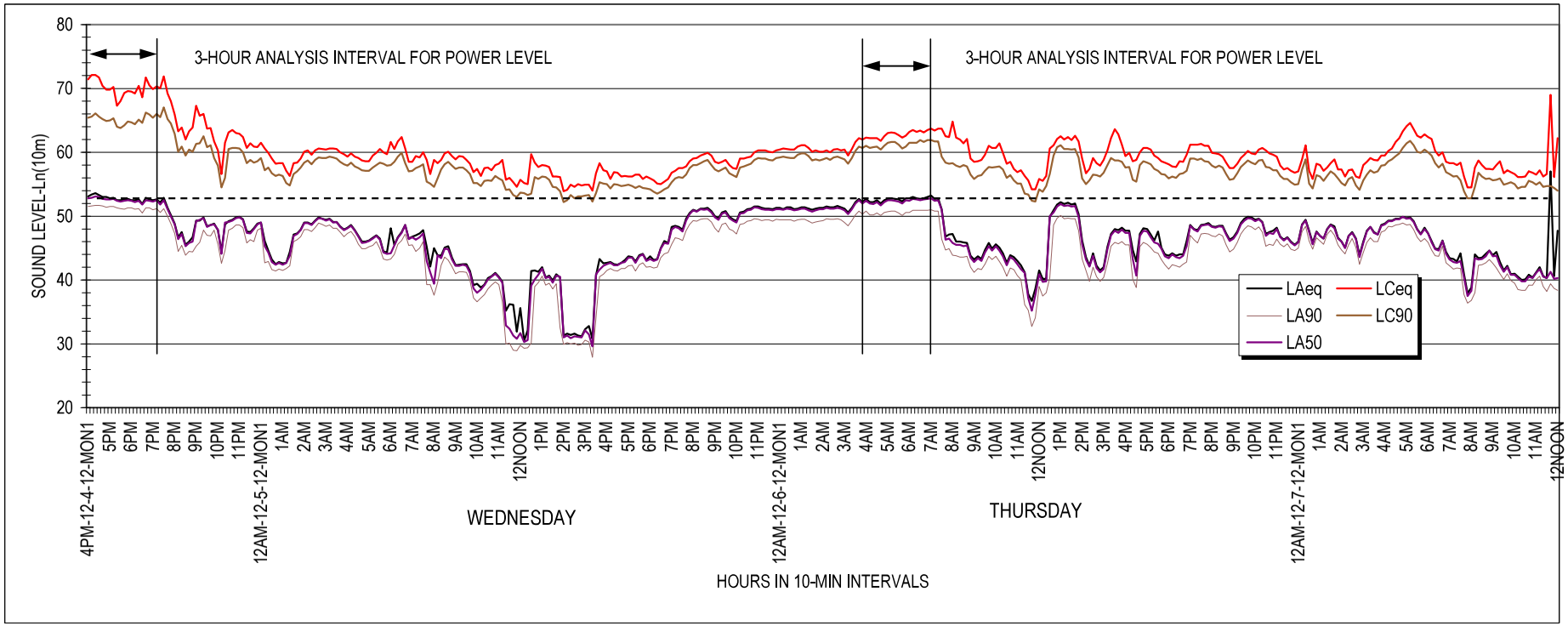
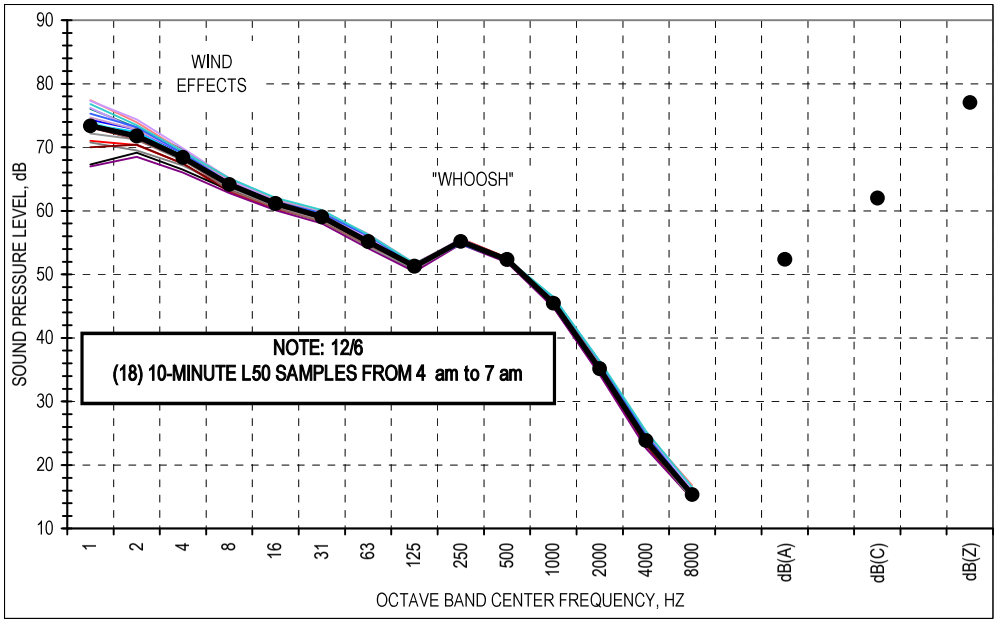
FIGURE 8

Level-time trace for three day sampling at approximately 200m from turbine WTG6





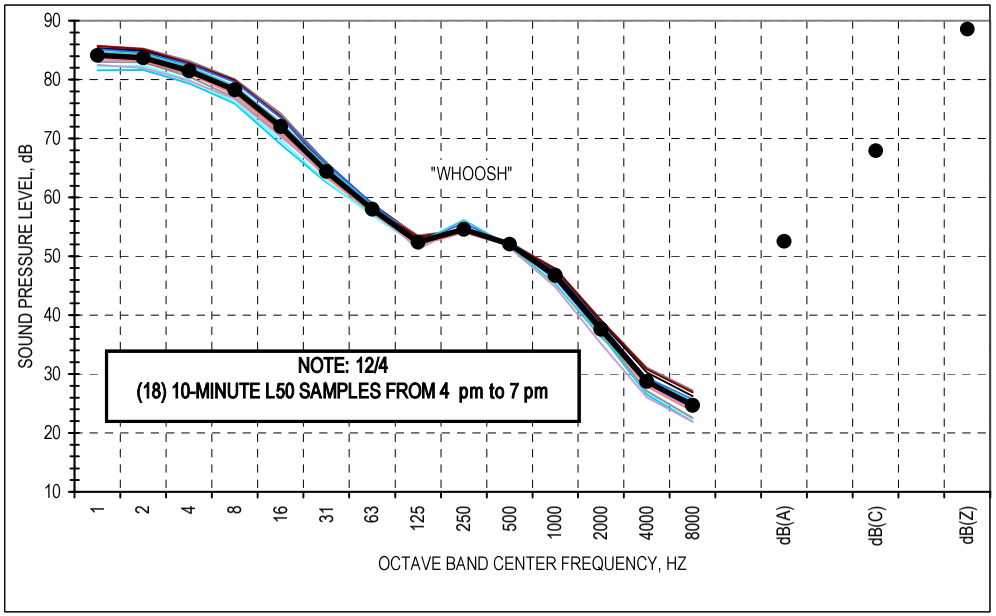


FIGURE 9

Data quality for (two) a.m. and p.m. 3 hour periods

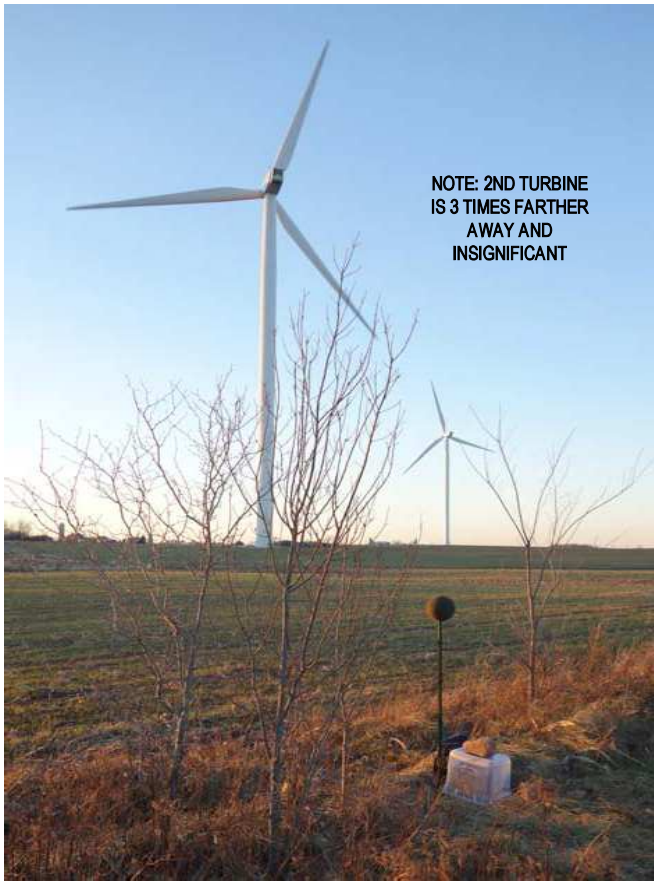


FIGURE 10 Calculated sound power for (two) 3-hour periods

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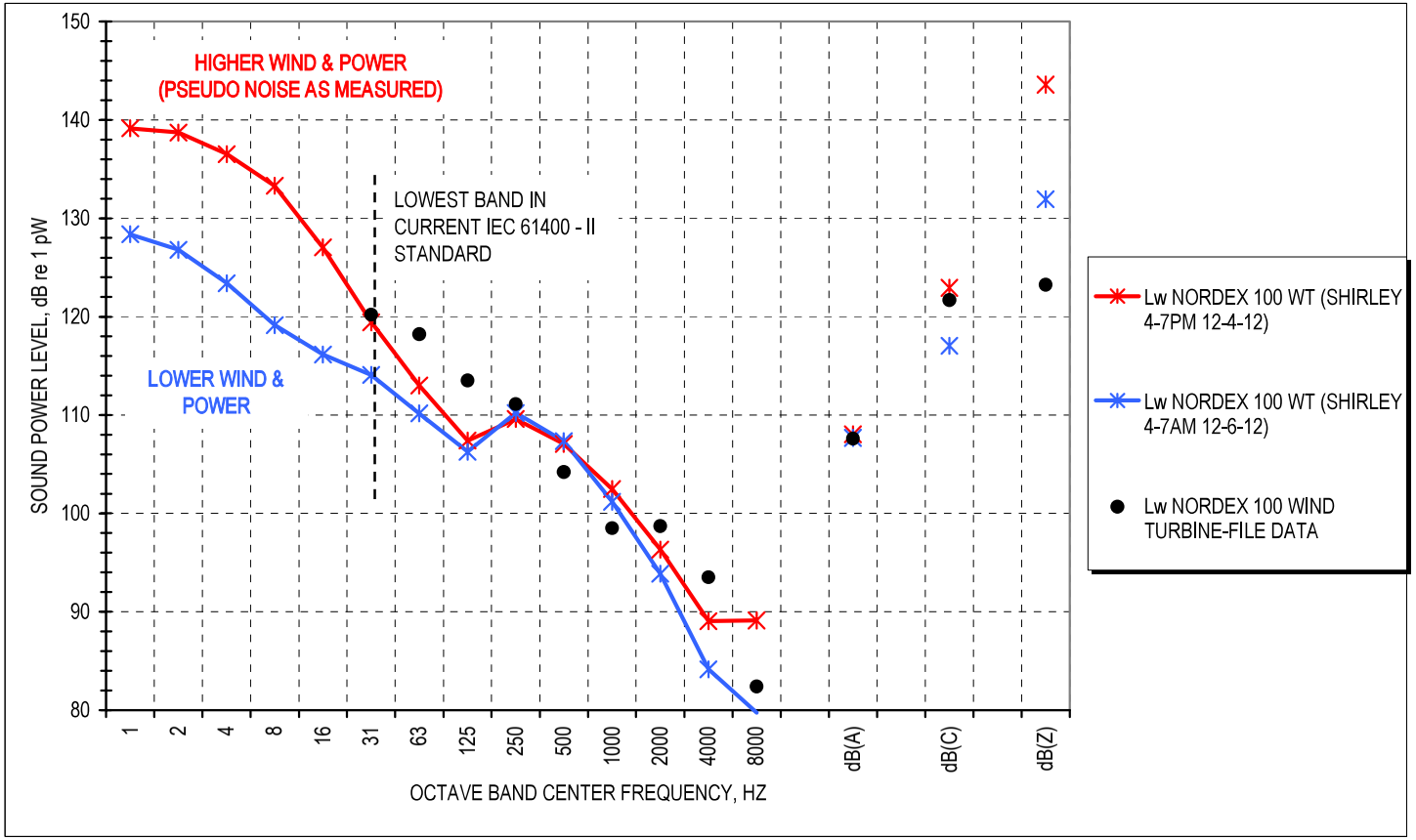

FIGURE 11 ISO 9613 Calculation of WTG level compared to measured levels at R1, R2 and R3

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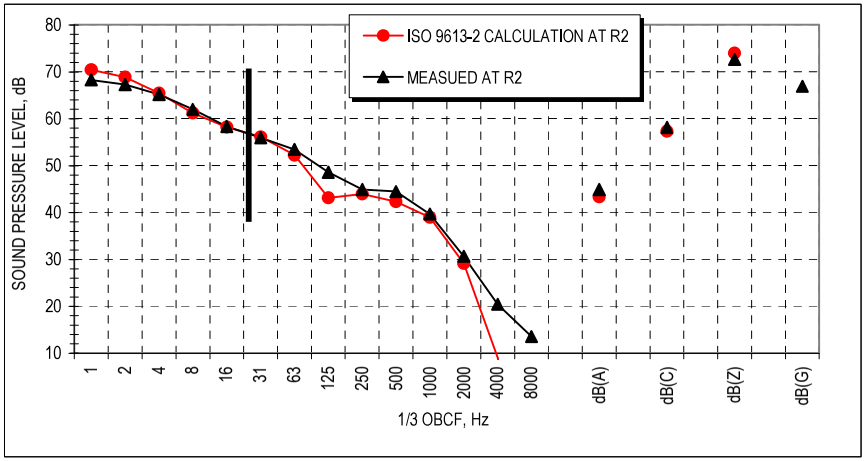
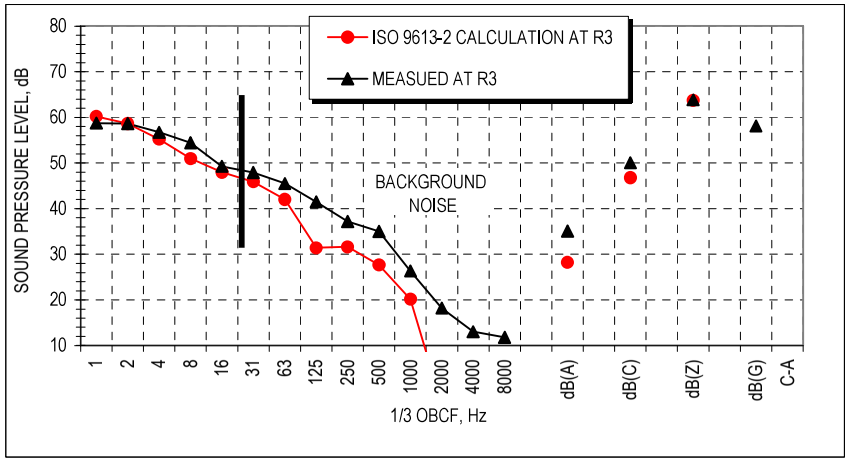
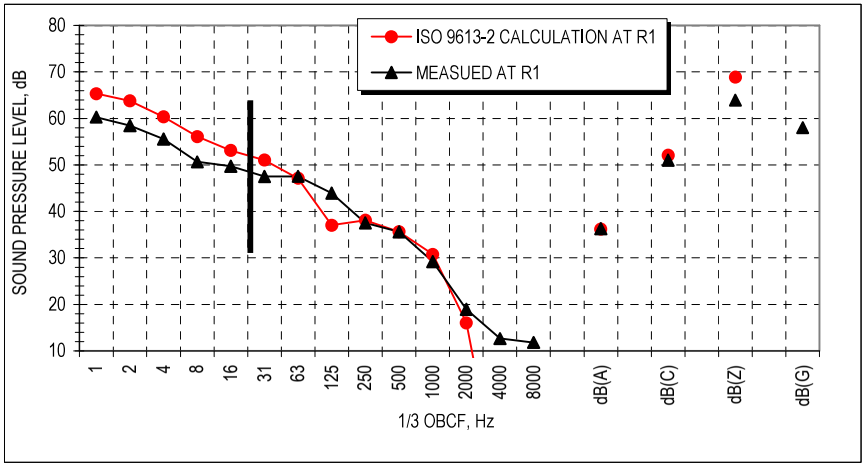


R2 CLOSEST TO TURBINES



R3 FARTHEST FROM TURBINES



R1 BETWEEN R2 ABD R3

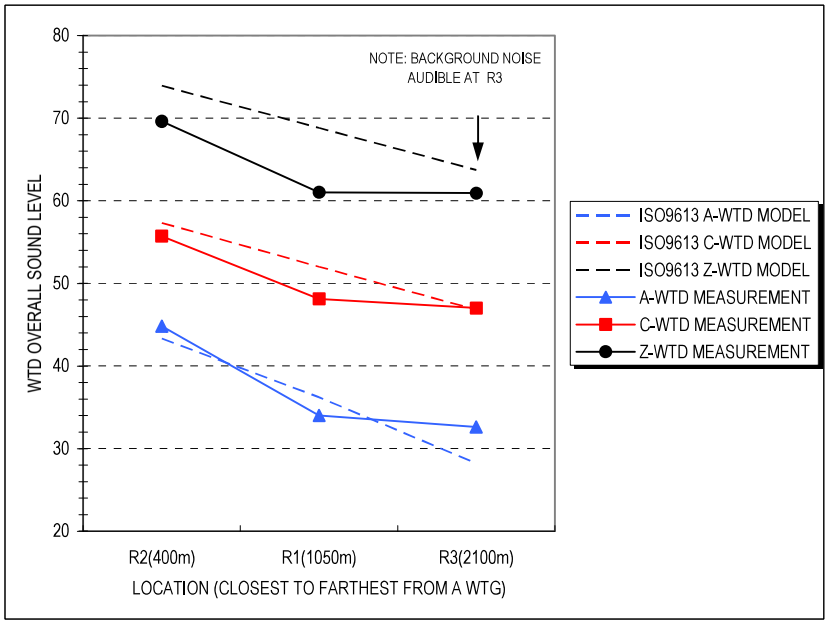


FIGURE 12

Outdoor/Indoor spectra at Shirley R1, R2 & R3

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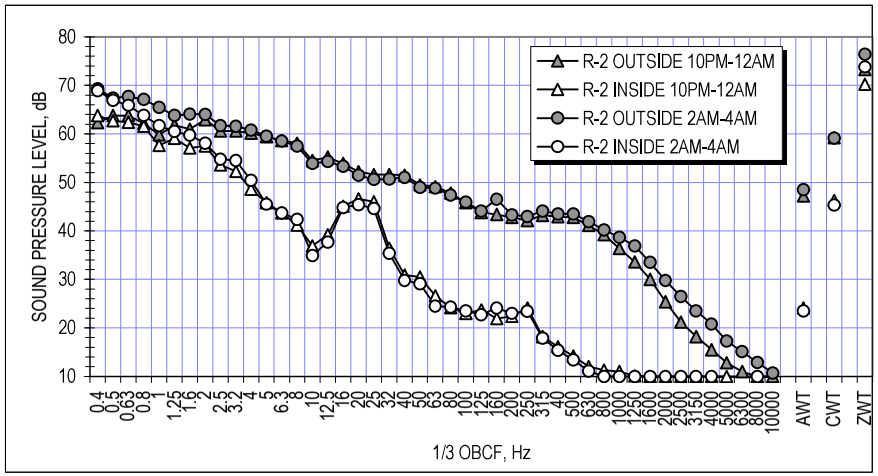
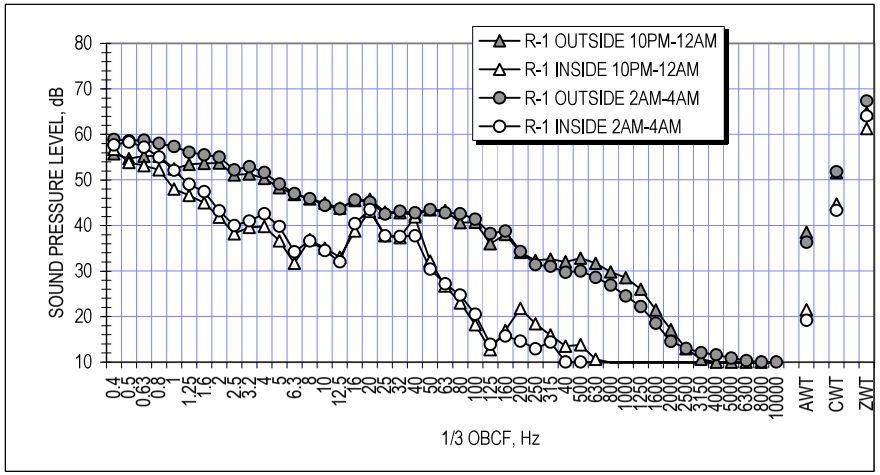
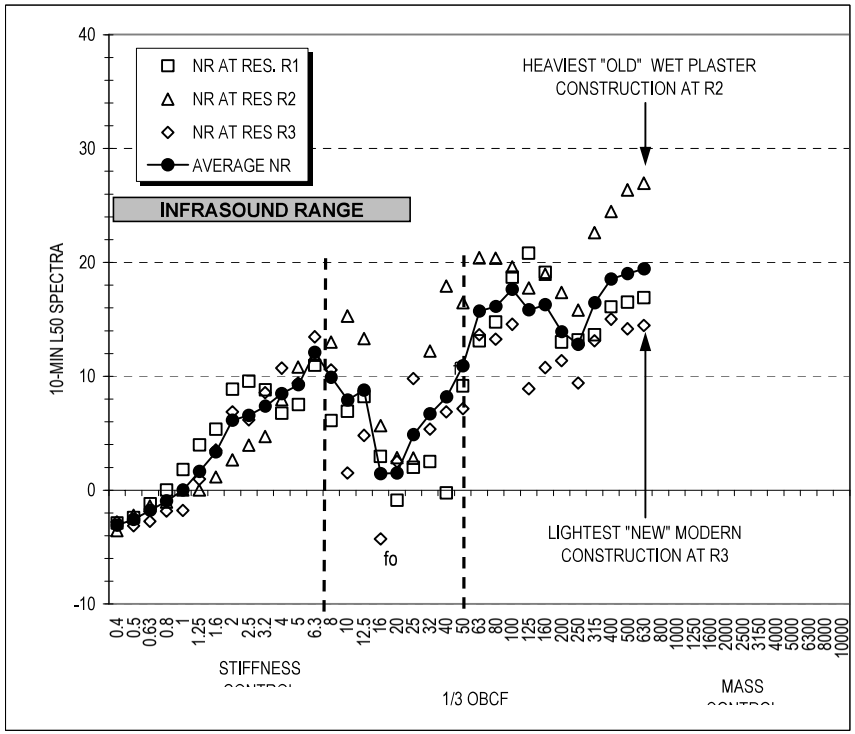
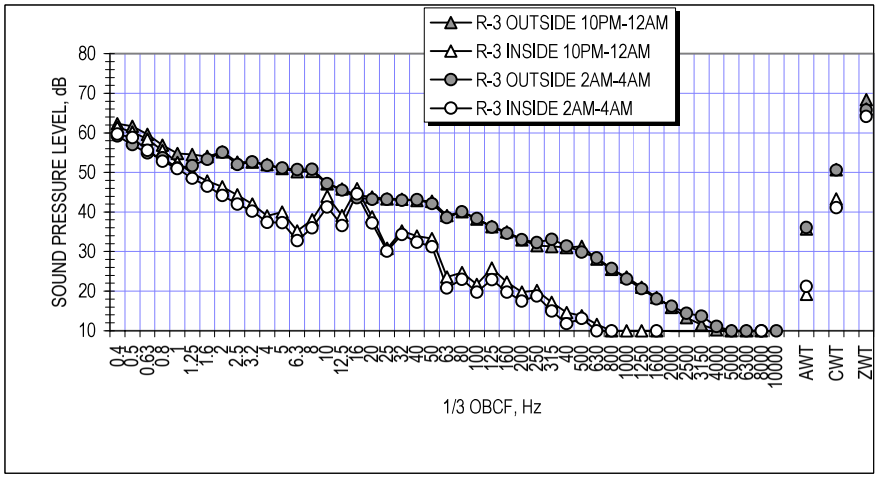


R2 CLOSEST



R1 INTERMEDIATE DISTANCE





R3 MOST DISTANT FROM TURBINES

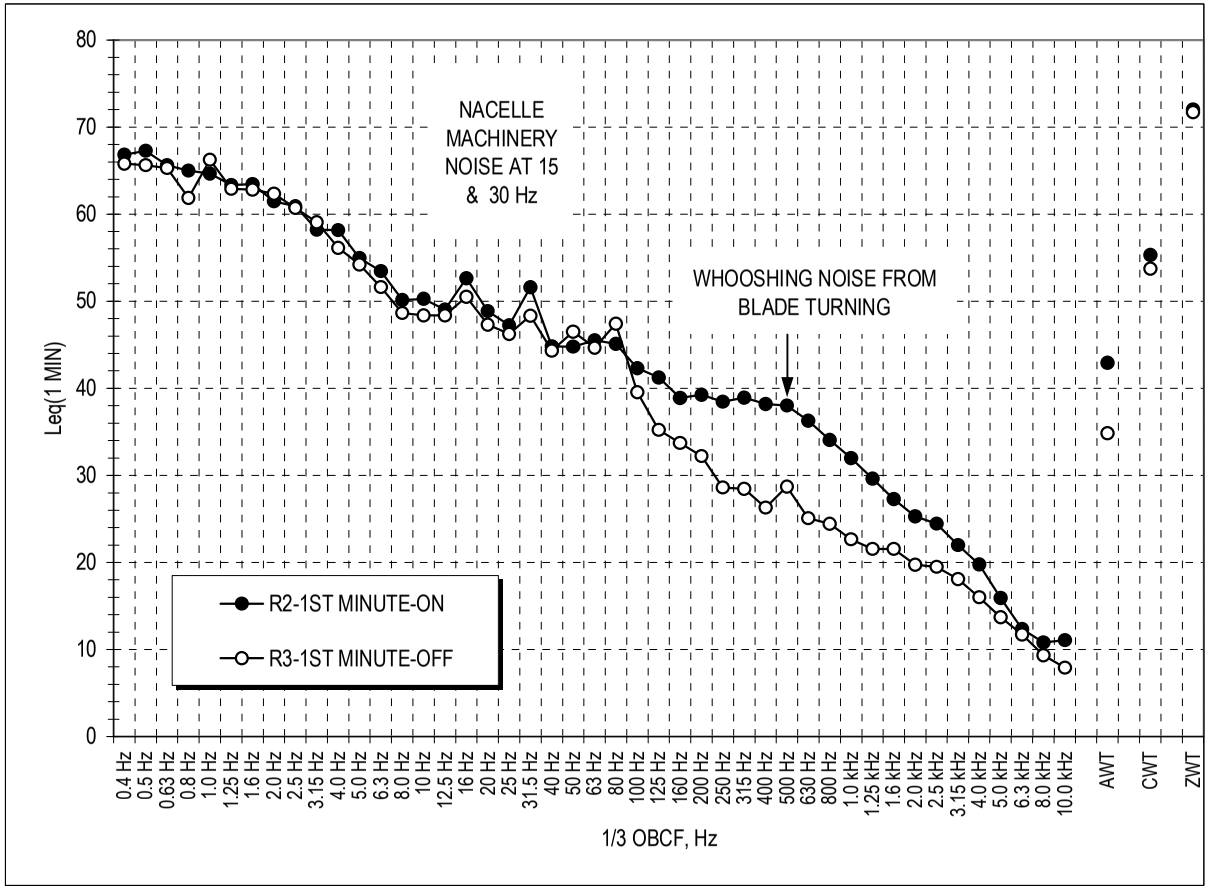



FIGURE 13 Limited low power ON/OFF test at Shirley