Proceedings of Meetings on Acoustics

Volume 12, 2011 http://acousticalsociety.org/

161st Meeting
Acoustical Society of America
Seattle, Washington
23 - 27 May 2011
Session 3aNSa: Noise

3aNSa2. Collecting data on wind turbine sound to identify causes of identified concerns

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Regulations for wind turbines are generally based on A-weighted sound levels, and typical sound spectrums in the community from a localized source. Regulatory limits are based on levels believed to cause little annoyance. Large industrial wind turbines are a sound emitter that present a spatially distributed source principally arising close to the blade tips, rotating 50 to 150 metres overhead so that sound arises from a wide area. They pose a relatively new source of sound to communities, particularly the quiet rural communities where they are mostly located. Community experience shows that the same A-weighted sound limits that are acceptable for typical sound spectrums and localized sources give rise to a considerable level of annoyance from wind turbines. This paper sets out to identify the differences in the sound found at locations considered acceptable by regulators 500-600 m from wind turbines (about one-third of a mile), in spectrum, intensity, duration, and special characteristics, such as tonality or amplitude modulation compared to the sound levels at control sites distant by at least 5000 m (about 3 miles) from wind turbines. An explanation of the data collection method is given, as well as an analysis of extensive sound samples gathered.

Published by the Acoustical Society of America through the American Institute of Physics

 [DOI: 10.1121/1.3624576]
Received 23 May 2011; published 22 Jul 2011

Introduction – Defining the Problem:

Vivid memory of the look in their eyes haunts me. Over the last 5 years, many people have talked with me, face-to-face, and although using their own words, said the same thing. “I just cannot stand it anymore, since the wind turbines started operating near my home. Can’t you do something, please?” Their eyes told the same story, of hurting, that was not being addressed. These people do not know the specific cause of their hurting, but they know the way they feel changed after the wind turbines near them started to operate. There seemed to be little that I could directly do to alleviate the situation. I do not hold a position of any influence over decision makers responsible for those wind turbines. Perhaps, though, I might help those who could take corrective action to understand what might be causing the hurting. I believe that decision makers do not want to hurt another human, but it might happen if they do not know the cause. Experience with root cause analysis shows when a previously undetected problem occurs; a good place to look for clues to the cause is by examining changes. Rarely is it just “bad luck” that makes adverse impacts happen, usually something changed. An examination of the evidence of the changes in the sound environment caused by wind turbines became the problem to be addressed to bring light on the truth.

This paper documents the collection of sound data at 6 sites associated with a wind power development of 110-Vestas V82 wind turbines in Bruce County, Ontario, Canada. The monitoring sites have a similar environment of open, relatively flat terrain, and are subject to similar environmental wind conditions. By collecting data at more than one location in each measurement set at different distances from wind turbines, for both different conditions of turbine output and different conditions of ground level wind speed, it was possible to determine the impact of the turbines independent of conditions such as the prevailing wind, which was similar at all the monitoring sites.

Initial Data Collection Provided Clues:

Initial steps to try to determine the root cause started out by taking sound level readings using a calibrated IEC 651 Type 2 sound level meter, a CEM-DT-805, with a frequency range of 31.5 to 8 kHz, a measuring level of 30 to 130 dB, frequency weighting of A or C, time weighting of 125 ms (Fast) or 1 sec (Slow) and a rated accuracy of +/- 1.5 dB using a 5 cm wind screen. Several months later in the project, that meter was supplemented by an IEC 61672-1 Type 2 data logging sound level meter, a CEM-DT-8852, with the same frequency range, and measuring levels.

Data were collected at “approved locations” (accepted by regulators as meeting Ontario standards) and at a “control location”, located over 5000 metres from the nearest wind turbine yet, in a similar environment as the “approved locations” near the turbines. The results of the initial survey are shown in Table 1 below. What the table shows is that at the homes near the turbines, not only is the A weighted sound level considerably higher than at the control home, but more significantly, the difference between the A and C weighted sound levels at the homes near the wind turbines is 5 to 15 dB more than at the control home, with an observed range from 17.5 to 33.5 dB.

	dBA	dBC	Δ dBA to dBC	Comment
Control Home	28	42 to 44	14 to 16	5000 m to turbine@24%
Home 1 Mar 8	39.5	60 to 65	20.5 to 25	620 m to turbine@32%
Home 2 Mar 12	40.5 to 42.5	58 to 70	17.5 to 27.5	560 m to turbine@72%
Home 1 Mar 12	40.5 to 41.5	60 to 75	19.5 to 33.5	620 m to turbine@72%
Home 3 Mar 14	41.5	60 to 72	18.5 to 30.5	450 m to turbine@50%
Home 4 Mar 14	41.5 to 42.5	60 to 72	18.5 to 29.5	450 m to turbine@50%
Home 5 Mar 14	40 to 41	60 to 68	20 to 27	650 m to turbine@35%

Table 1: Initial Sound Level Meter Readings at Different Locations and Turbine Powers

The initial data collection could only be considered as presenting an indication of the situation, as it was limited in scope, subject to influence due to the nature of using a hand held meter with a small wind screen, and with only a hand record of the sort of span of the measurement over short sampling periods. It was informative though in showing that while A weighted sound was fairly stable, there was considerably more span in the C weighted readings.

At the 2011 Wind Turbine Noise Conference, George Hessler, of the United States, in his overview of health effects from low frequency noise spoke from his experience with combustion turbines (which present a more steady sound than wind turbines) noting that "if dBC is 60 dBC or less, no one will complain." His comment rang in my mind as I read again over my notes, which showed considerably higher dBC measured values even in the small sample series conducted. Interesting!

A literature review paper published by the Canadian province of Alberta's Energy Resources Conservation Board in 2008, *Incorporating Low Frequency Noise Legislation for the Energy Industry in Alberta Canada,* points out that a 15 to 20 dB difference between dBA and dBC sound level readings can indicate the need for a detailed investigation into the low frequency noise component.

A considerable variety of reports, such as the review of literature published in 2004 for the Canadian Defence Research and Development titled, *"The Effect of Vibration on Human Performance and Health"* notes that "Human response to vibration is strongly frequency-dependent." Consistent with ISO 2631-1, it identifies that frequencies in the range from 1 to 80 Hz are generally of interest, and the concern depends on the intensity of the vibration, the duration of exposure, and the orientation of the affected human.

These sources are not referenced with a goal of trying to identify specific limits being exceeded, but only to suggest that there is a basis for carrying out an investigation to determine if wind turbines do result in a significant change in the low frequency exposure to people living near the installations, as others have alleged. The data collection would need to be much more rigorous, and reproducible though.

Rigorous Data Collection Method:

Again, at the 2011 Wind Turbine Noise Conference, Gunnar Lundmark made a comment from Sweden in presenting his paper, *Measurement of Swish Noise, A New Method* describing his work as being the product of a "garage company." I felt a kindred spirit, as while the data collection method I was employing was intended to be rigorous and reproducible, neither was it being performed in a laboratory, or with the intent of producing precision values. The intent was to show light on the truth, to help further understand reasons for the impact being felt by people.

To collect data on the change in sounds at homes near wind turbines compared to a site distant from wind turbines, in a reproducible manner, the method described in the following text, and shown in Figure 1 was used.

A. The sound was captured using a 0.5-inch Knowles BL-21994 condenser microphone, mounted on a tripod 1.5 metres above ground protected by 2-inch (5-cm) primary and 7-inch (18-cm) secondary windscreens. The specification sheet for the Knowles BL-21994 microphone shows the response is effectively flat from about 20 Hz to 8 kHz. (See Figure 2.) A lithium cell provided voltage supply to the condenser microphone as per the Knowles microphone specifications.
B. The microphone output was input to a M-Audio Fast Track USB Audio interface. The input microphone level was sealed to prevent changes.
C. The M-Audio USB output was recorded on a Macintosh iBook G4 portable computer.
D. The recording program used was either the Audacity Digital Audio Editor recording program version 1.3.12 (the preferred method) or initially using a Record Pad digital audio sound recording program version 2_10 (which was seemed prone to overloading on the Macintosh computer generating a "popping" spurious signal that occurred at a variable time after starting the recording.) Version 4_10 of the Record Pad software was also purchased and tried. All three recording systems produced very similar results when the Record Pad was not impacted by spurious signals, but in general the Audacity Digital Audio Editor seemed to be the most robust.
E. Calibration of the recording system was done before and after readings using a Lutron SC-941 1kHz / 94dB Sound Level Calibrator.
F. Additional tracking was made using a CEM DT-8852 Data Logging Class 2 Sound Level Meter, calibrated before and after use.

Figure 1: The Typical Recording Equipment Arrangement

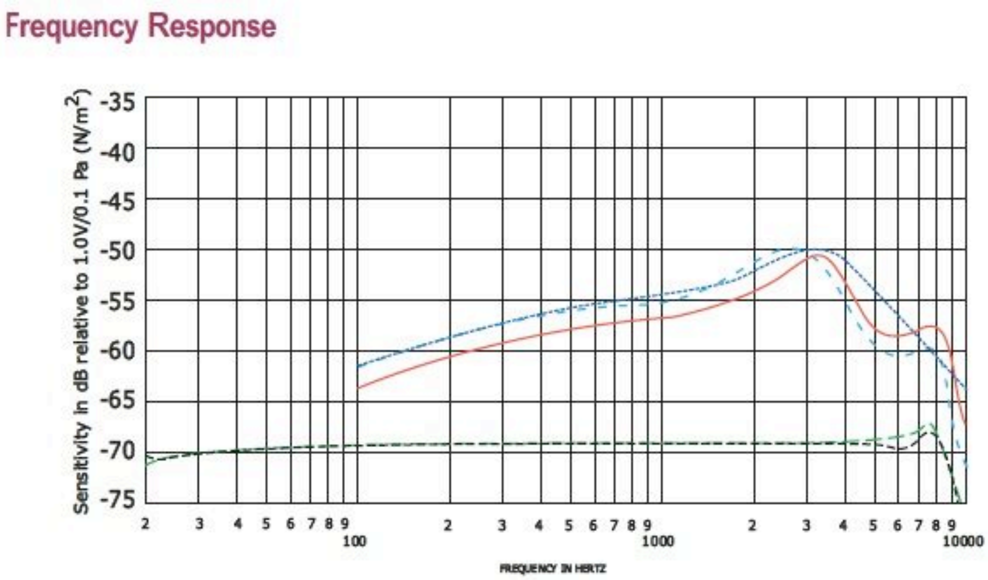

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Figure 2: The Knowles BL-21994 Microphone (from Knowles Website) – The frequency response for the model used is the dashed black line on the chart.

Data Processing:

After collecting the data in the manner described above, it was necessary to listen to the digital recording to ensure it was not exhibiting transient extraneous sounds such as road traffic, aircraft, birds, or wind noise. The Audacity Digital Audio Editor Program was used for this listening test. An example of the trace derived for a sample recording is shown in Figure 3. The program gives the ability of examining the data in a number of ways, and selecting specific windows to listen to, or to perform a “loop play” operation to listen to the same data segment over and over.

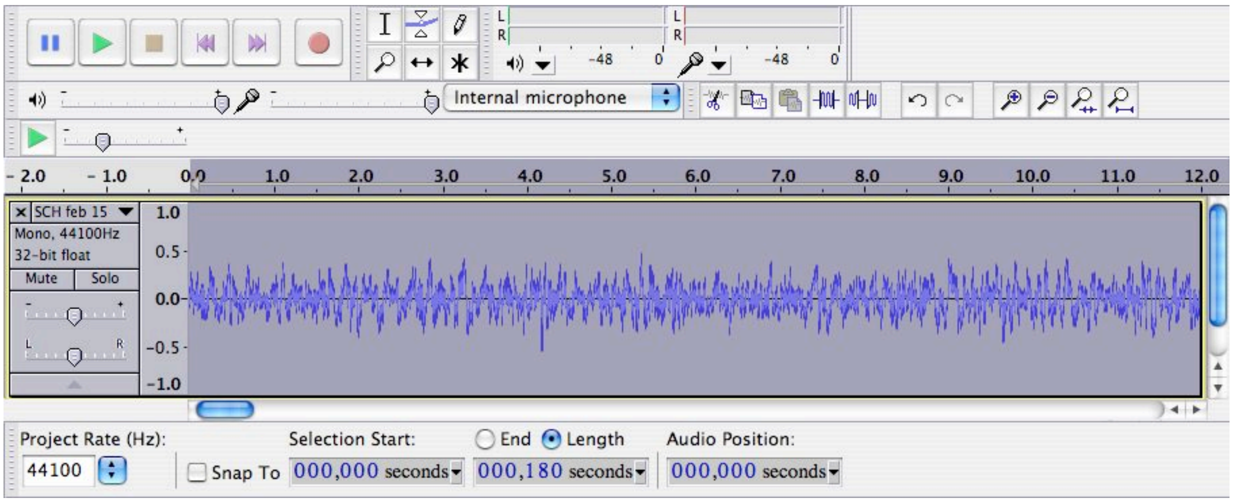


Figure 3: A Typical Sound Sample Displayed by Audacity

Each sound sample was processed, generally after selecting a 30 second window, using the Audacity “analyze” tab, to plot the fast fourier transformation spectrum, using the “Hanning Window” and a 16,384 sample size. A typical output of the frequency analysis is shown in Figure 4.

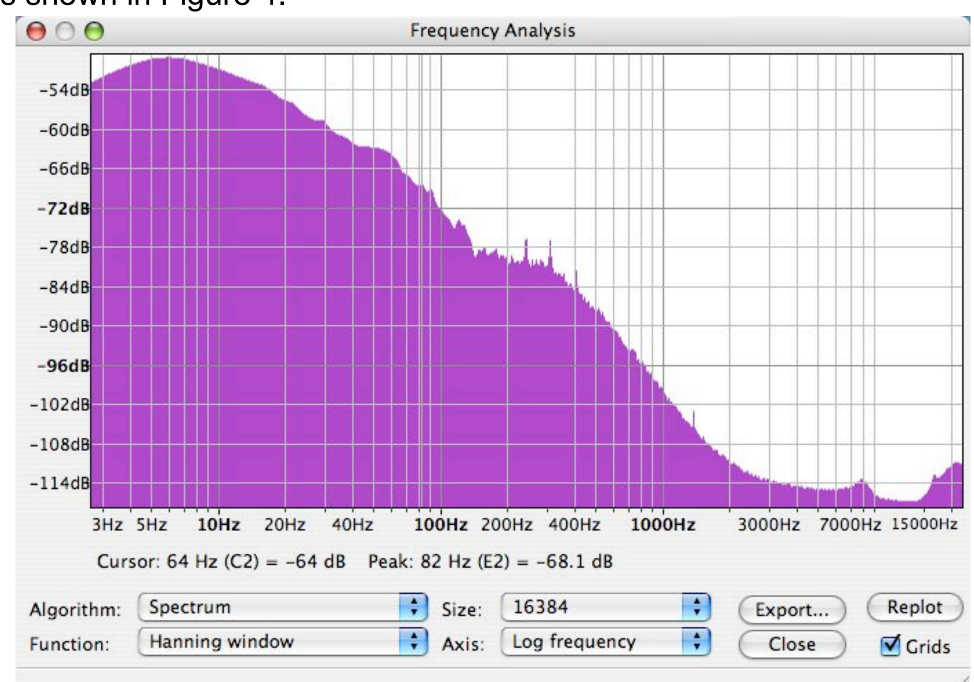


Figure 4: Typical Audacity Frequency Analysis Display

From the Frequency Analysis window, the "export" button was used to create a text file of the frequency spectrum analysis in a tabular format of 8191 values of the output every 2.69 Hz from 2.69 Hz to 22,047 Hz. The frequency spectrum file was copied into a spreadsheet in which the A weighted and C Weighted values were calculated for each discrete frequency based on the formulas given below, as shown in Wikipedia, and other sources.

$$R_A(f) = \frac{12200^2 \cdot f^4}{(f^2 + 20.6^2) \quad \sqrt{(f^2 + 107.7^2)\,(f^2 + 737.9^2)} \quad (f^2 + 12200^2)} \ ,$$

$$A(f) = 2.0 + 20\log_{10}\left(R_A(f)\right)$$

and

$$R_C(f) = \frac{12200^2 \cdot f^2}{(f^2 + 20.6^2) \quad (f^2 + 12200^2)} \ ,$$

$$C(f) = 0.06 + 20\log_{10}\left(R_C(f)\right)$$

The offset of 2.0 added to the A weighting, or 0.06 added the C Weighting are to ensure normalization at 1000 Hz.

These terms are expressed in the spreadsheet by dividing the calculated A value by 0.79435, which normalizes the 1000 Hz value, and so that taking 1/20 LOG (0.79345) adds the 2.0 offset, and by dividing the calculated C value by 0.99290, so that taking 1/20 LOG (0.99290) adds the 0.06 offset. The A-weighted and C-weighted values are calculated for each frequency after adding the calibration factor. For example if the 94 dB calibrator produces a -11.2 dB reading in the Audacity spectral analysis, a calibration factor of 94 + 11.2 is added (logarithmically) to each raw value.

The spreadsheet also calculates the unweighted one-third octave and full octave values. From these, the A weighted and C weighted values are calculated and given as results.

As a result of the Data Processing, the calibrated values of the sound level across the frequency spectrum are available, as well as the one-third and full octave band unweighted, A-weighted, and C-weighted values of the sound.

<u>The Monitoring Sites</u>:

In order to investigate if wind turbines produce any effect on the environment, a set of readings were taken at a series of locations in the similar environment, of terrain, proximity to roads and forests, so that all readings in each set were taken within a 2 hour time window. In that manner, the same instrumentation was used, the weather conditions were relatively unchanged, and the turbine output was nearly constant. All reading sites were bounded by about a 7.5 km (<5 mile) radius from a central point. The difference was the proximity of turbines to the measurement locations. All sites were approved for predicted sound levels of < or = 40 dBA. A map showing the monitoring sites as related to the turbine locations superimposed onto the topographic map of the Natural Resources Canada website “The Atlas of Canada” as shown in Figure 5.

Site Descriptor	Nearest Turbine (metres - mi)	Number of Turbines within 1 km	Number of Turbines Within 2 km	Number of Turbines Within 3 km
TLE	5500 m – 3.44 mi	0	0	0
HEM	1013 m – 0.63 mi	0	5	7
SMI	617 m – 0.39 mi	1	8	21
SR10	450 m – 0.28 mi	4	5	9
CSK	450 m – 0.28 mi	6	11	13
SCH	453 m – 0.28 mi	6	14	26

Table 2: The Monitoring Sites and their Proximity of Wind Turbines

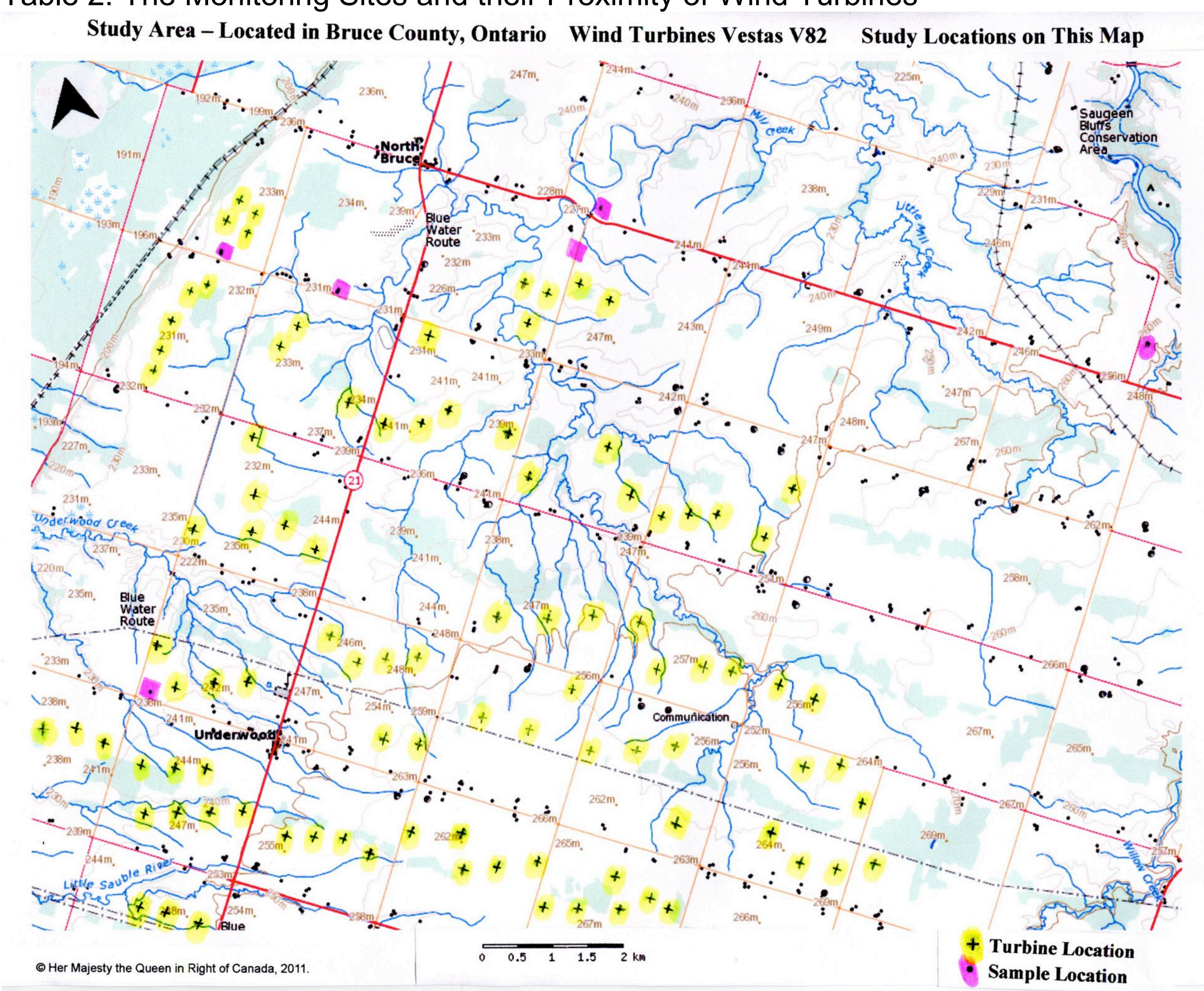
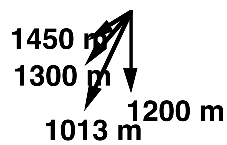


Figure 5: Study Area on Topographic Sheet Showing Turbines and Monitoring Points

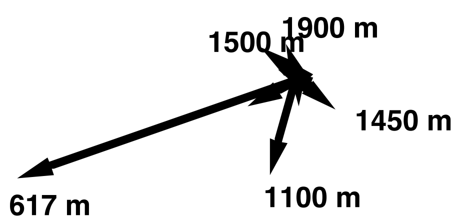
In attempt to portray the impact of turbines, sketches of the measurement sites are shown below to represent of the compass bearing of the nearest turbines, and a vector proportional to the reciprocal of the square of the distance from the turbine to the measurement site. Thus, nearest turbines show as larger vectors.

HEM Monitoring Site



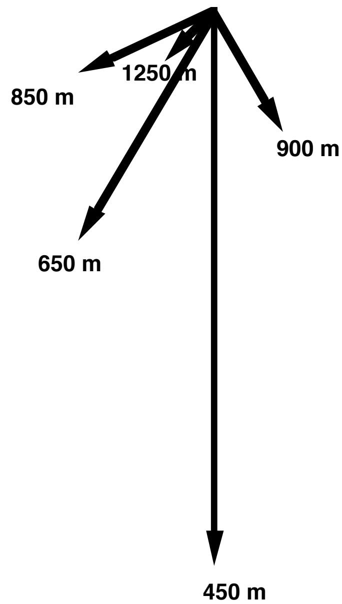
Wind from 90 degrees (E) to 135 degrees (SE) places site crosswind to turbine (blade downcoming side)

SMI Monitoring Site



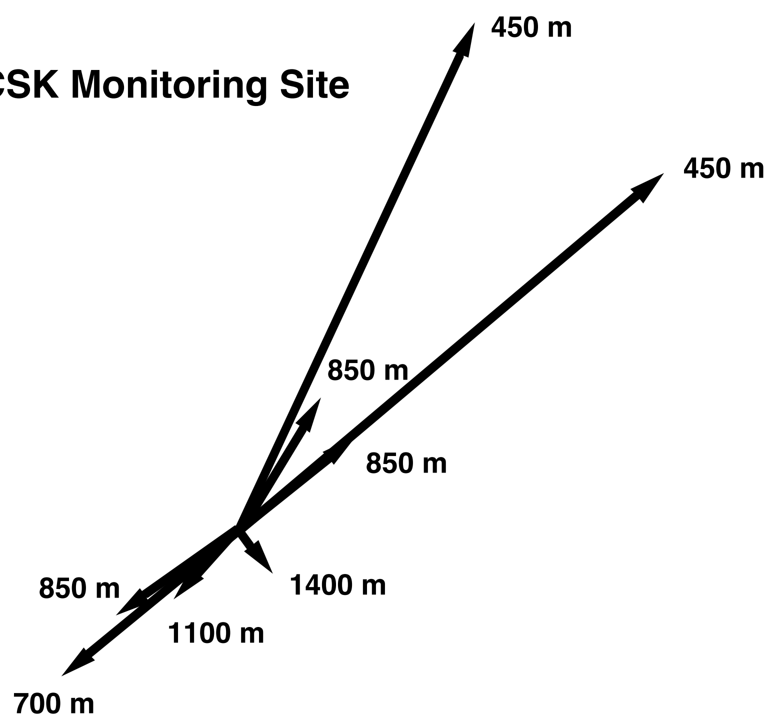
Wind from 150 degrees (ESE) places site crosswind to turbine (blade downcoming side)

SR10 Monitoring Site



**Wind from 240 degrees (WSW) to 335 degrees (NW)
places site crosswind to turbine
(blade downcoming side)**

CSK Monitoring Site



**Wind from 295 degrees (WNW) to 320 degrees (NW)
places monitoring site crosswind to turbine
(on blade downcoming side)**

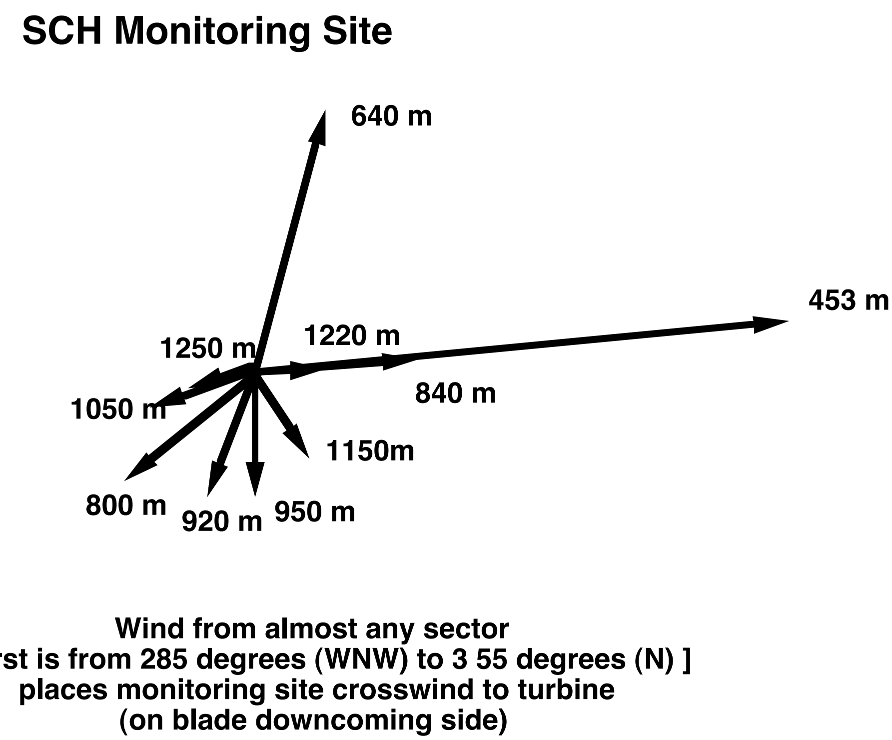


Figure 6: Representation of Impact of Turbines (5 sites near turbines displayed)

Observation derived from the data collected:
Conditions under the following sets of conditions are presented:

A. No turbines operating – Figures 7 & 8
B. Turbines operating, but at very low power (~ 0% output) – Figures 9 & 10
C. Turbines operating at 25% output – Figures 11 & 12
D. Turbines operating at high power level (~88% output) – Figures 13 & 14

For each case, the unweighted sound levels were plotted as a function of the logarithmic display of the frequency. The sound levels were also plotted as a function of the full octave analysis of the frequency spectrum, and the A-weighted and C-weighted total.

Review of the case with no turbines operating, shows that all 5 cases are similar in the sound displayed except for obvious differences observed by listening to the individual digital recordings.

- At the TLE site, the presence of flies arising out of the grass is heard on the recording as a “hum.” This is visible on the plot of the unweighted sound levels as several peaks in the range between 2000 and 4000 Hz. These are also evident on the octave analysis.
- At the SCH site, the presence of “sea gulls” overhead is heard on the recording as intermittent “screeches.” These can be observed on the unweighted sound levels and the octave band analysis as peaks in the 2000 and 4000 Hz centre octaves.

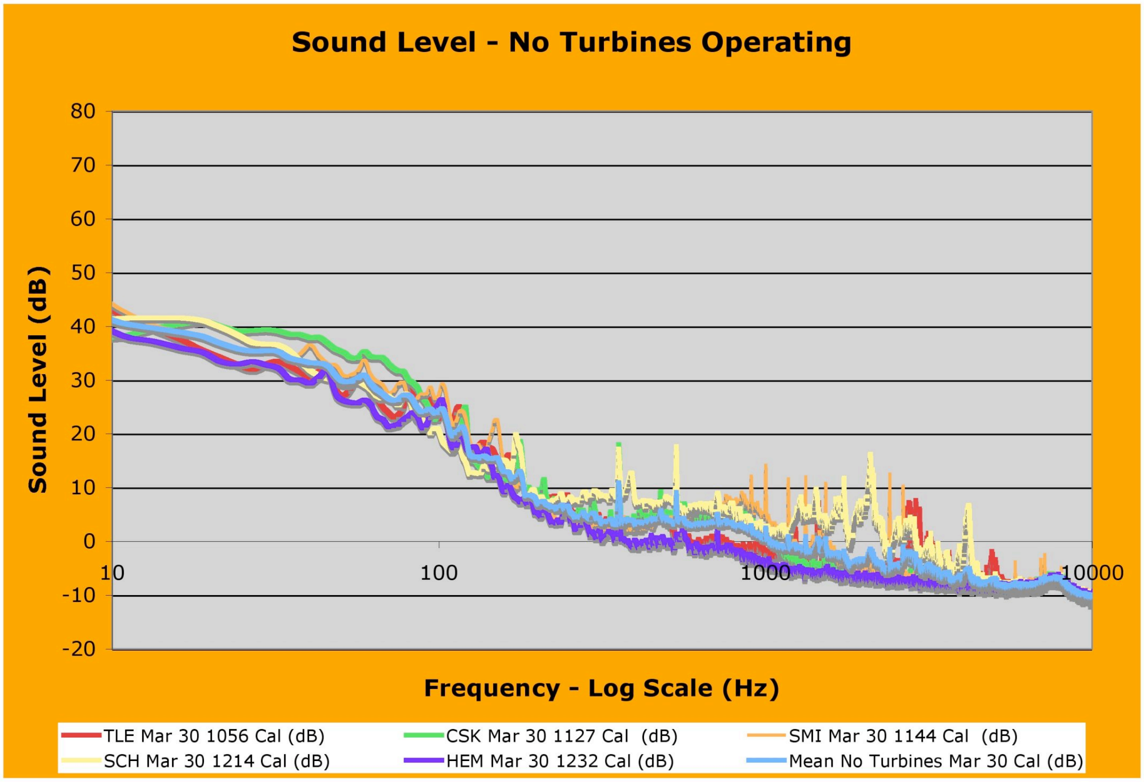


Figure 7: No Turbines Operating – Unweighted Sound Level Plotted against Log of Frequency

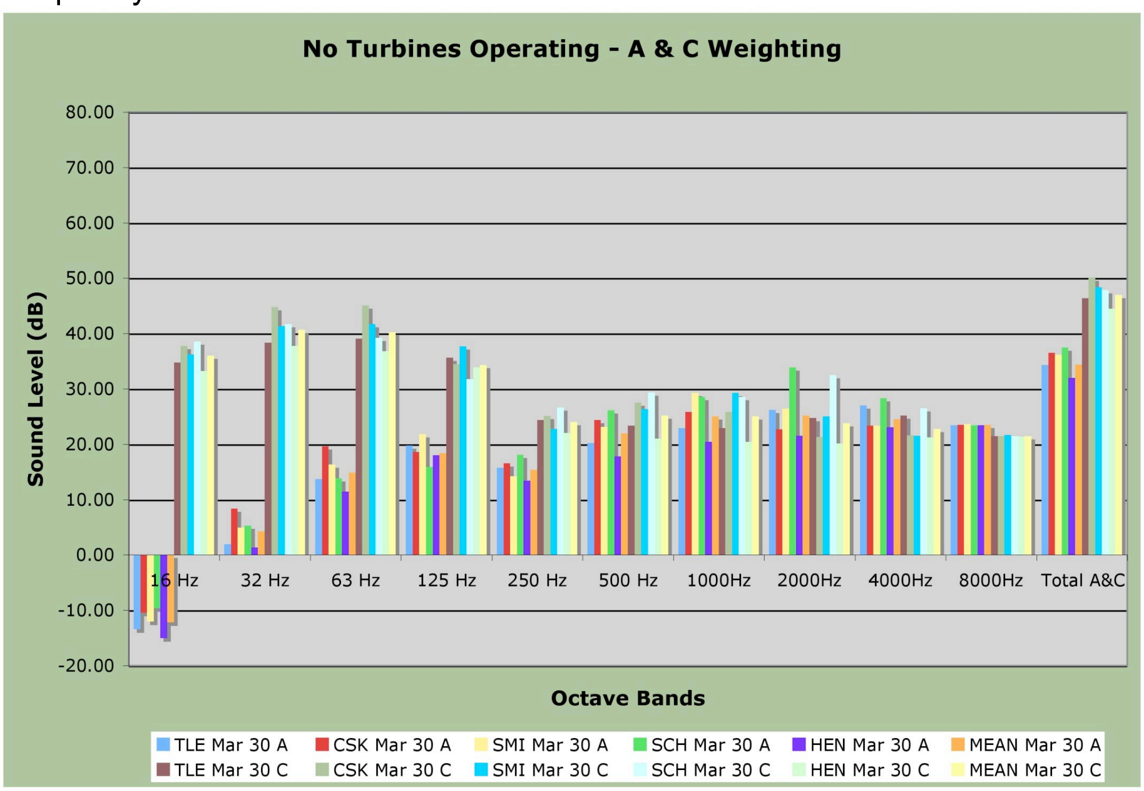


Figure 8: No Turbines Operating – Sound Level by Octave Bands and Total Weighted by A & C Filters

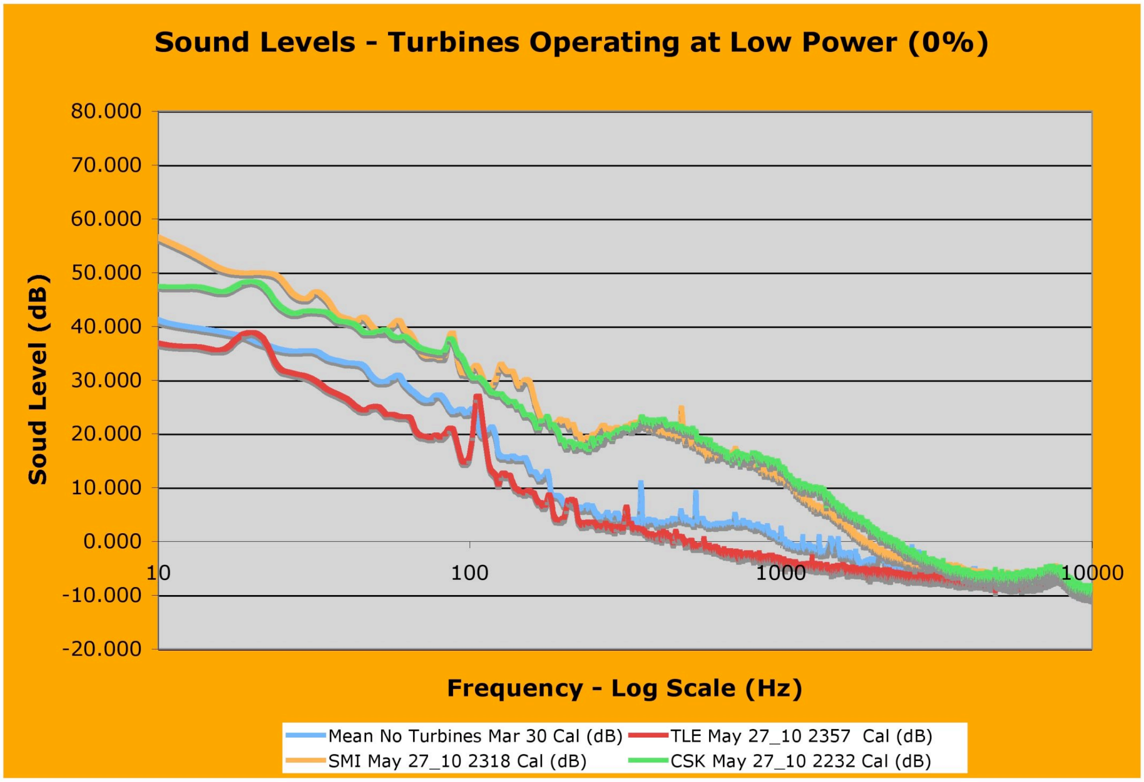


Figure 9: Turbines Operating at Very Low Power (0% output) – Unweighted Sound Level Plotted against Log of Frequency

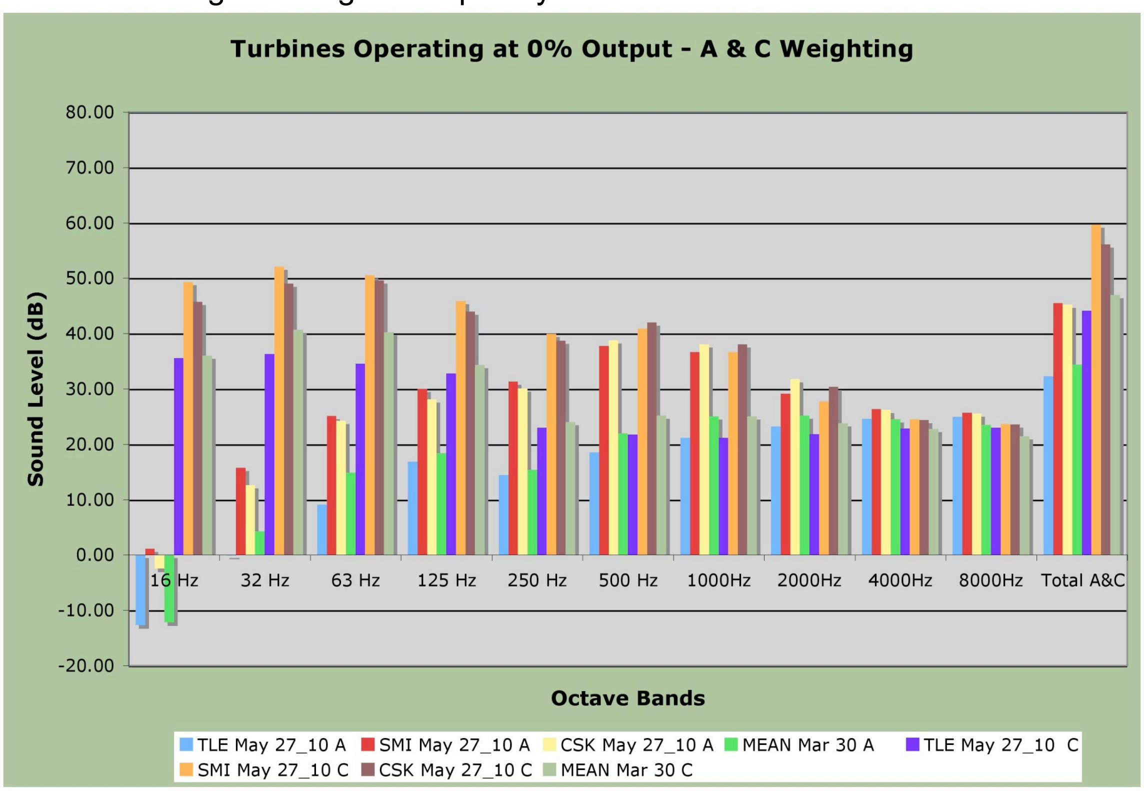


Figure 10: Turbines Operating at Very Low Power (0% Output) – Sound Level by Octave Bands and Total Weighted by A & C Filters

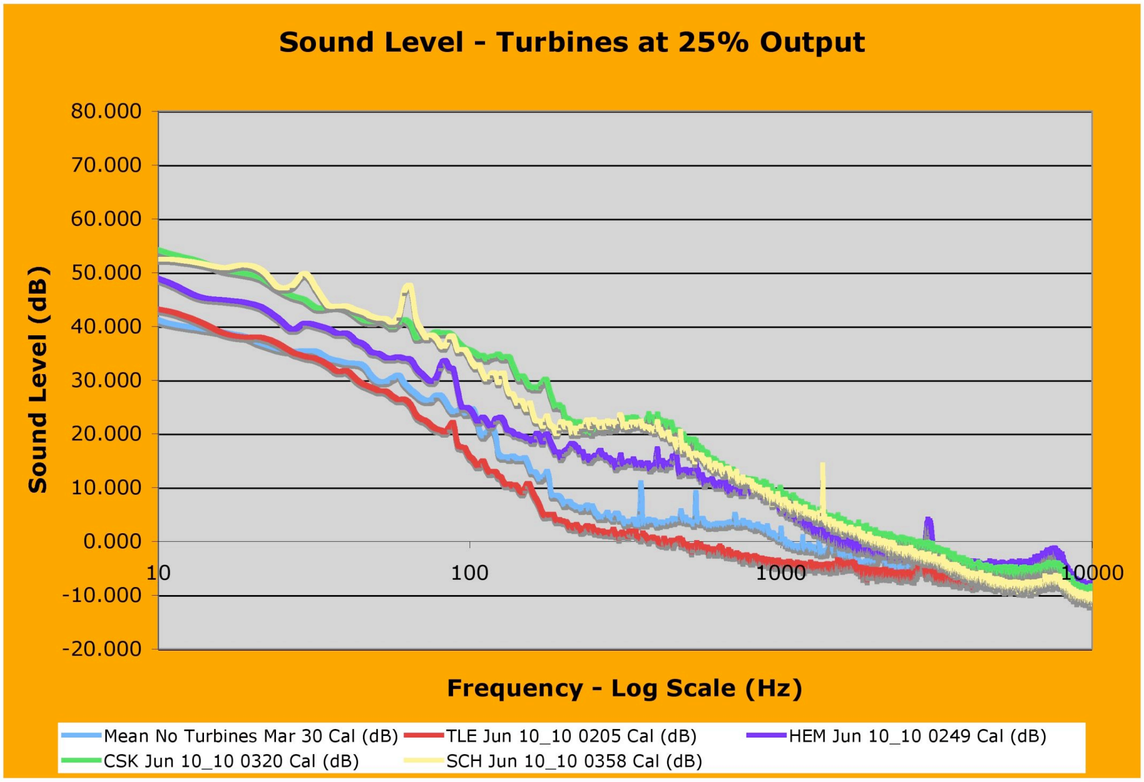


Figure 11: Turbines Operating at 25% Output – Unweighted Sound Level Plotted against Log of Frequency

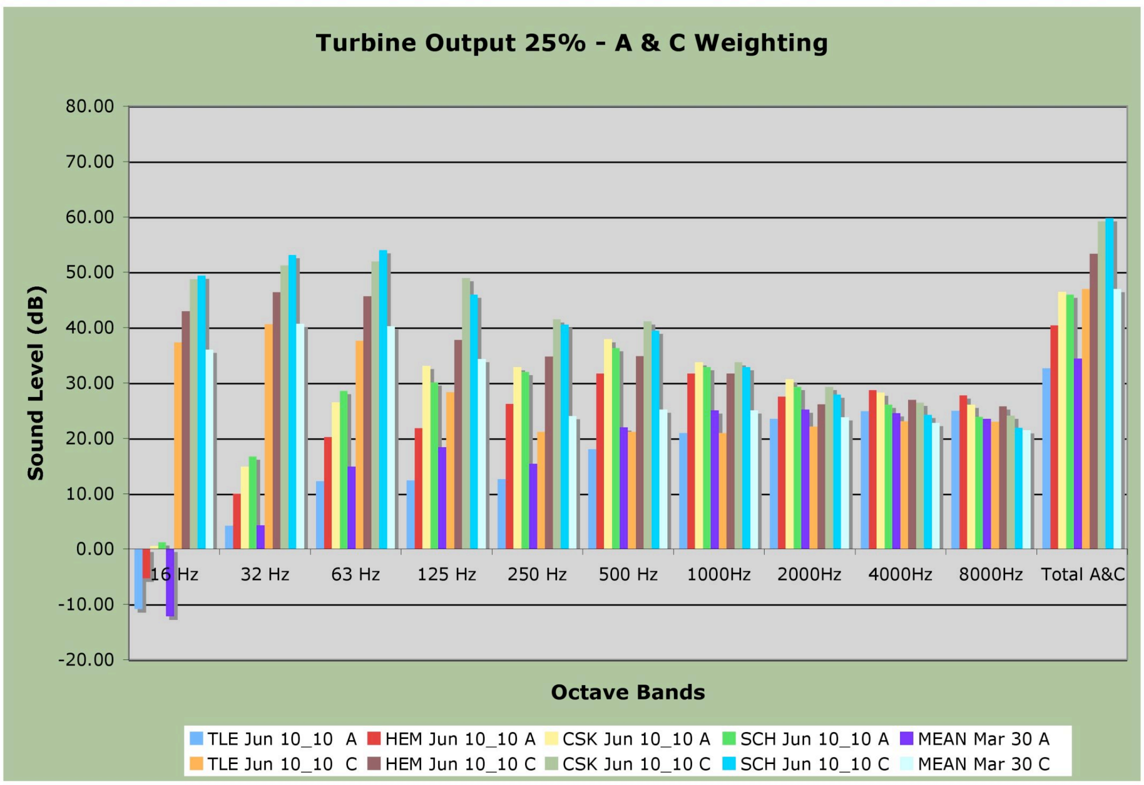


Figure 12: Turbines Operating at 25% Output – Sound Level by Octave Bands and Total Weighted by A & C Filters

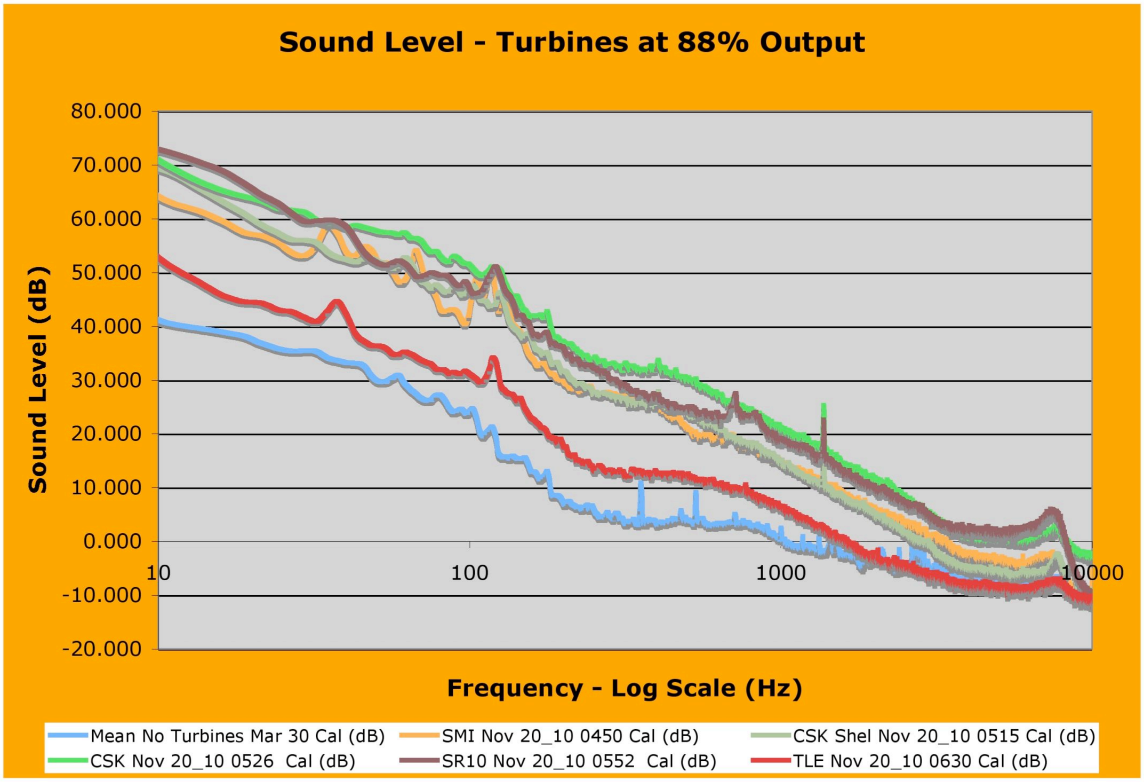


Figure 13: Turbines Operating at 88% Output – Unweighted Sound Level Plotted against Log of Frequency

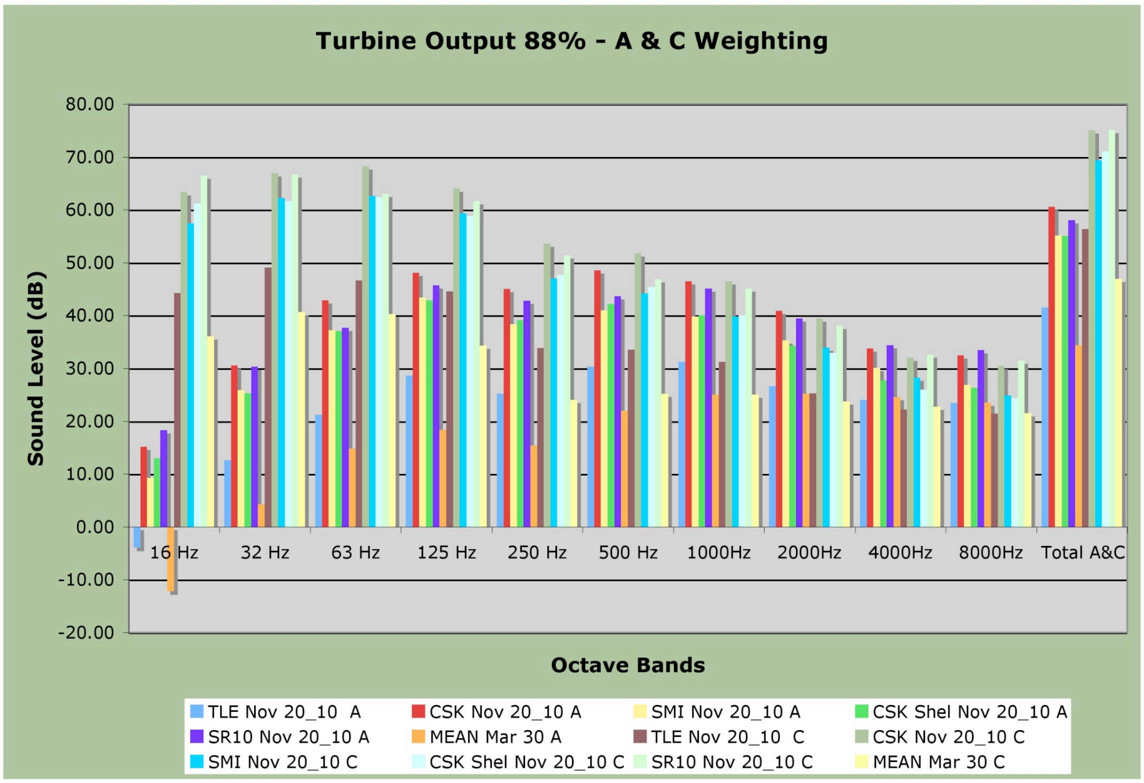


Figure 14: Turbines Operating at 88% Output – Sound Level by Octave Bands and Total Weighted by A & C Filters

At the 2011 Wind Turbine Noise Conference, David Hessler, of the United States in presenting his paper, “Accounting for Background Noise When Measuring Operational Sound Levels From Wind Turbine Projects” suggested the use of “proxy” monitoring stations to create a history of on-site background sound levels. He noted that for many wind arrays, the background sound level is very similar at monitoring sites within up to 22 km from the proposed turbine site. He noted the need to monitor background at the same time as wind turbine sound conditions are recorded to be able to properly account for the background at the wind farm site. He noted that in some cases, the project itself was “very obtrusive” compared to the background measured at the same time.

In the observations presented here, when no turbines were operating, the background sound levels were very close to each other, other than for the differences that were noted. Thus, it was reasonable to calculate a “Mean” no turbine case by calculating the mean sound level at each frequency for the 5 cases. This “Mean” value was also plotted on all the plots for comparison purposes. Additionally, It gave confidence that the TLE site, which is within 10 km of the centre of the centre of the turbine monitoring sites, could be used as representative of the non-turbine background condition for each of the monitoring sites, since without turbines, it was subject to very similar conditions of wind speed, terrain, vegetation, and proximity to roads.

When looking at the case with the turbines operating but at very low (~0%) power output, the charts show that the TLE site stayed very close to the Mean of the 5 sites for the no turbine state, but the two sites with turbines within 1000 metres (SMI and CSK) increased in noise level to be about 20 dB above the TLE site for all frequencies below 1000 Hz, and only stayed within 3 dB of the TLE site (the level that can be readily discerned by most people) for the 4000 and 8000 Hz octave bands.

Perhaps remarkably, at 25% output, there was only a slight increase in the sound level at the sites near the turbines from the zero power case. What this says is that at any times the turbines are operating people living near them are facing some 20 dB higher at all frequencies up to 1000 Hz than they would have faced before the turbines. Since most people can generally discern a 3 dB change in sound levels, the difference is clearly significant.

During the measurement set made when the turbines were at 88% power output level, the wind speed measured about 7 to 10 metres above the ground was about 8 metres per second (28 km per hour, or 18 miles per hour). At this wind speed, generally known as Force 5 on the Beaufort scale, or a fresh breeze, small trees are swaying noticeably. Under these conditions, the sound level at the TLE site distant from the turbines, had increased by some 10 dB above the Mean sound level at all the sites under very low ground level wind conditions. However, at the same time, the sound levels at the sites near the wind turbines had increased to be some 30 dB above the Mean conditions at low ground level wind conditions, to remain some 20 dB above the conditions at the TLE site.

Observation of the test results show that it is clear that ground level winds are not "masking" the additional noise generated by the wind turbines under any conditions, either at low or high power. Sound levels at "approved sites" near the wind turbines are about 20 dB above levels at a "control site" distant from the wind turbines during all conditions that the turbines are operating.

Shifting Frequency – Increased Audibility:

At the 2011 Wind Turbine Noise Conference, at least three speakers (Carlo di Napoli, Sidney Xue, and Nick McCabe) referred to information that showed that as the angle of attack of the wind impinging on wind turbine blades change, wind turbines exhibit a change in modulation. The dominant frequency can shift lower or higher.

It was noted that the change in angle of attack might result from either microclimate wind direction changes during turbulence, or from wind speed changes across the rotor arising from wind shear noted by David McLaughlin at 2011 Wind Turbine Noise. A wind shear of 0.43, typical across a large wind turbine rotor means a 1.6 factor of increase in the velocity of the wind impinging on the blades from the bottom of the rotor circle to the top of the rotor circle.

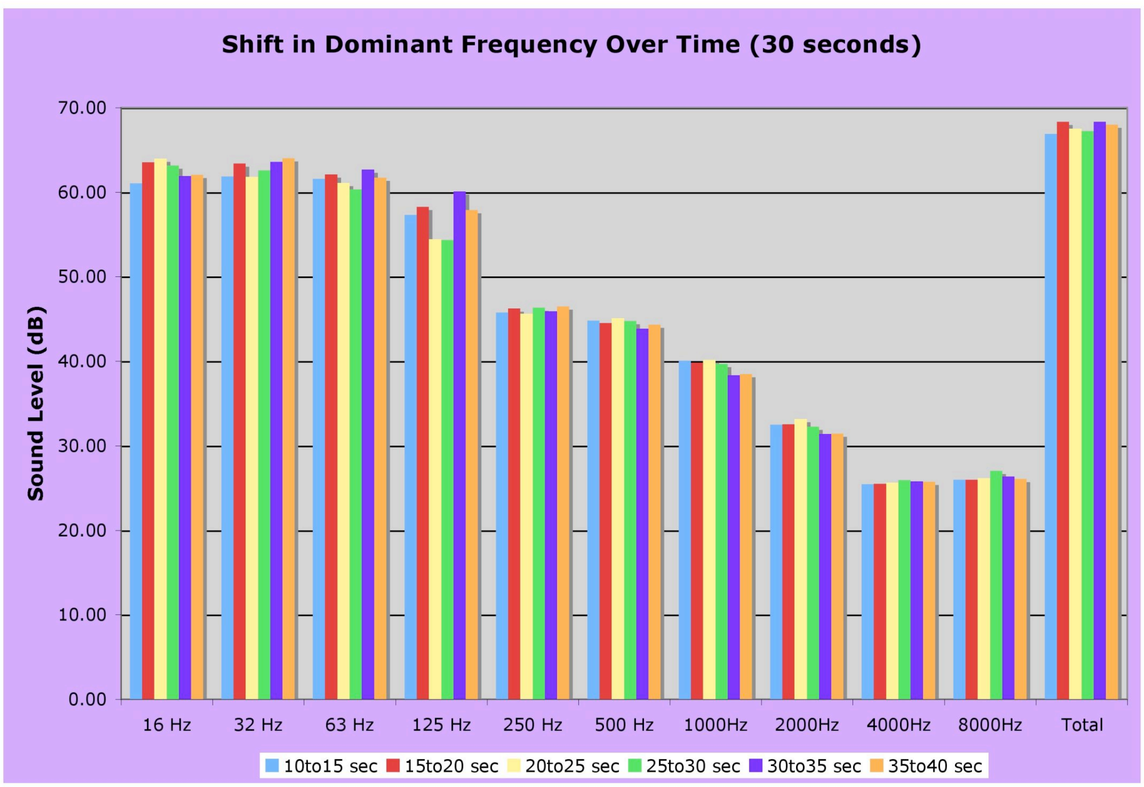


Figure 15: Change in Dominant Frequency over Time

The stored data records were examined to see if evidence of this frequency shift might be revealed. One example, occurring in the nighttime period is shown in Figure 15. Examination of this plot, made by taking 6 sequential 5 second time samples over a 30 second period shows that over the 30-second period studied, there is a shift in dominant frequency up and down. What comes to mind is the “bee” – “boo” or “wee” – “woo” oscillation of frequency used in sirens of emergency vehicles to make them more noticeable.

The plot also shows that in the 125 Hz octave, for example, there is an amplitude variation of greater than 5 dB as the frequency shifts to the lower frequency dominance, and then back to the higher frequency dominance. Research has established that such a frequency shift and amplitude variation makes the warning of an emergency vehicle siren, or crosswalk audible aids for visually impaired pedestrians more noticeable than a single frequency, single amplitude tone. The evidence suggests a reason for the routinely observed statement that the sound from wind turbines is more noticeable and annoying than other typical sounds.

<u>Observation from Proponent Monitoring</u>:

The final observation is made from examining data collected on behalf of a wind turbine development proponent in response to a noise complaint from a citizen. The citizen had complained that after the wind turbines near their home commenced operation, sleeping at night had been disrupted, and other adverse effects were being noted. The proponent contracted for an unattended sound sampling regime, by an independent acoustical consultant, which collected data for about 150 days. Recordings were made each hour of the A-weighted Leq, the A-weighted L90, and the wind speed 10 metres above the ground. High sound conditions triggered a recording for later review.

In a report submitted to the citizen, the acoustical consultant noted that review of a number of the highest sound samples had revealed:

- Road noise
- Birds
- Wind noise
- And even a lawnmower

The consultant noted that wind turbines were not detected in the highest sound samples.

This put one to thinking. The complaint had been based on not being able to sleep due to excessive noise. It is extremely unlikely that the complainant would have been mowing his lawn in the overnight period, and it is known that bird noise and road traffic is greatly diminished at night. This suggested that the listening test triggered by the highest noise conditions was probably not based on the nighttime conditions that were causing the concern.

The data collected by the proponent were examined and the conditions at midnight on all sample days were noted. The data were then sorted by Leq, and all cases where Leq exceeded L90 by more than 6 dB were set aside. A difference over 6 dB suggests intermittent conditions such as a car pass on the road might have occurred in the recording hour. The number of events when Leq was greater than L90 by more than 6 dB amounted to a small fraction of the data, leaving 113 nights when the difference between Leq – L90 was less than 6 dB.

The information was plotted, as shown in Figure 16, after adding in the turbine output values at midnight, available from the Independent Electrical System Operator.

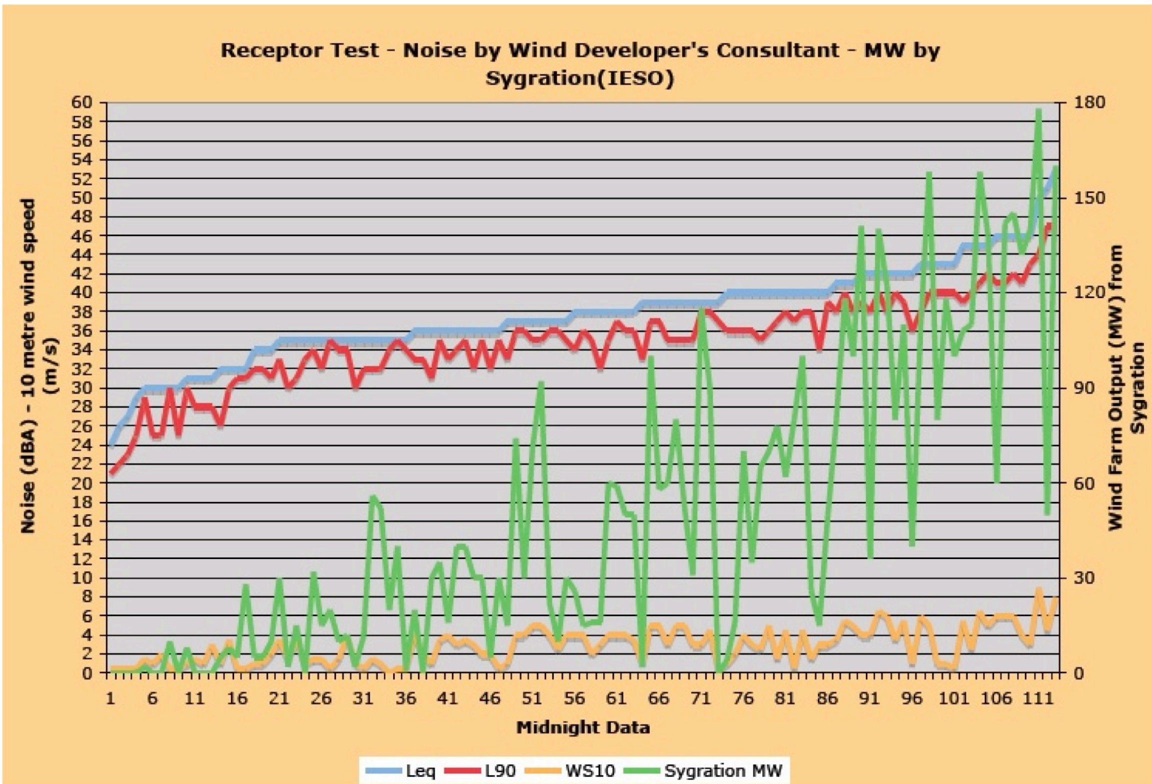


Figure 16: Proponent Monitoring

The conditions under which the certificate of approval had been issued for this wind power development showed that the residence in question would have a maximum sound power of 36.6 dBA when wind speeds at 10 metres were 6 metres per second or less. Yet, review of the chart shows that on fully half of he nights the sound level exceeded 37 dBA even while the wind speed at 10 metres was less than 6 metres per second. On at least one-quarter of the nights, the sound level was 3 dB or more above the maximum predicted value. Considering that a number of other homes in the same development were predicted to have sound at 40 dBA, it suggests that the test values showing sound levels greater than 40 dBA are indeed valid.

Summary:

- A rigorous method of monitoring the sound levels from wind turbines has been demonstrated.
- Monitoring reveals that operating wind turbines, at all power levels, from zero power to high power raises the sound level at "approved locations" 20 dB above the sound level at "control locations" more than 5000 metres from wind turbines but otherwise in the same environment at all octaves from 1000 Hz and lower. This significant change in low frequency amplitude is not well detected by an A-weighted licensing criterion, but is evident by a rise in C-Weighted sound.
- Evidence of frequency and amplitude variation is shown arising from the operation of wind turbines that makes the sound pattern even more noticeable than a single frequency, single amplitude pattern.
- Evidence from monitoring performed on behalf of a wind power development identifies that the actual A-weighted sound level exceeded the predicted sound level on over half of the nights, and was 3 dB or more (the sound level readily determined by most people) above the predicted sound level on 25% of the nights.
- It is clear that monitoring based on predictions from an A-weighted criteria alone are not adequate to protect citizens when the sound level is changing significantly in the lower frequency octaves, exhibits shifts in frequency and amplitude, and is above the predicted value at least half of the time. The current conditions are permitting C-Weighted sound to rise above 75 dBC, and to be over 20 dB higher at homes near wind turbines than at sites distant from turbines. They also permit a frequency and amplitude variation of 5 dB to occur that increases the disruption caused by the wind turbines.

Acknowledgements:

This paper has benefited from the contributions of many in its attempt to bring light on the truth. These specific contributions are acknowledged. Thank-you!

- John Coulter for loan of Knowles microphone and M-Audio Fast Track USB interface
- Werner Richarz for providing the spreadsheet template octave band calculator
- Carlo di Napoli and Sidney Xue for raising frequency shift as an issue at the 2011 Wind Turbine Noise Conference
- George Kamperman, Rick James, and Harvey Wrightman for review and comments on draft
- The people suffering effects of wind turbines who permitted recordings taken at their homes (CS, VS, NS, JH, HF, JT, GB, SJ, KA, TW, HS and others)
- The encouragement of countless friends and those suffering from the effects of wind turbines

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