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Perception Change of Soundscape as Wind Turbine Alters Community Sound Profile

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Summary

A number of studies show the perception of citizens impacted by wind turbines in their environment varies widely. Some are said to describe the cyclical amplitude modulation of the sound "swoosh" as "pennies dropping in a piggy bank," while others say they "cannot get used to the sound," and find growing sensitivity to an abrasive annoyance and repeated sleep disruption adversely impacts their health. The difference in response between individuals depends on complex factors. This is like the fact that some people have sensitivities or allergies while some do not. This study investigated changes in the soundscape by analyzing digital recordings made in a controlled manner and correlating the results to expressed opinions. Recordings were made before, and after the start up of a single 48 metre rotor diameter wind turbine located from 200m to homes or higher to identify differences between pre-existing sounds such as bird songs, lake waves, and wind in the trees, compared to the sound received in the same environment after the wind turbine altered the community sound profile. The findings show that even though the change in A-weighted sound levels may be minimal or notable, there are marked differences in the characteristics that impact perception.

1. Introduction

Over about 40 years, the concept of a "soundscape" has evolved from early work of projects such as the "World Soundscape Project" established at Simon Fraser

University in British Columbia, Canada. See http://www.sfu.ca/~truax/wsp.html

A description of Soundscape was given by Professor Brigitte Schulte-Fortkamp of the Institute of Fluid Mechanics and Engineering Acoustics of the Technical University of Berlin, Germany as, *"Soundscapes are considered as environments of certain sound sources and the way people feel about those sounds, contributing to the identity of the respective ambiences."* Professor Schulte-Fortkamp's paper *"Sound, Sound Quality, and Soundscape"* (Reference 1) was presented in 2009 at the Sound Quality Workshop sponsored by SAE International, organized by Wade Bray of HEAD acoustics, Inc of USA. The workshop notes can be seen at: http://www.sae.org/events/nvc/workshops/2009/ Much of that sound quality workshop is relevant to the study of the sound from wind turbines, as the workshop considered the interaction between the physics of sound, the psychoacoustics effect on the ear, and the internalized psychology aspects of perceived sound.

Very relevant background information that relates to the work in this paper was presented by Wade Bray and Richard James at NOISE-CON 2011, in Portland Oregon, "*Dynamic measurements of wind turbine acoustic signals, employing sound quality engineering methods considering the time and frequency sensitivities of human perception."* (Reference 2)

The one key driver behind this paper was a communication from Dr. Jo Solet, a Sleep Researcher at Harvard Medical School, who described to me an example of sound quality, attributed to Professor Brigitte Schulte Fortkamp, to the effect that, *"Assessing sound by volume alone is like assessing soup by temperature alone. Two soups may have the identical temperature, yet one tastes pleasing, while the other you want to spit out."* Unfortunately though, we assess the acceptability of wind turbines based on an A-Weighted sound level and largely ignore the aspect of sound quality. This work set out to assess the changes in soundscape in as controlled an example as possible, studying the impact of an array and a single wind turbine installed in a community.

2. Parallels Between Senses Suggest a Soundscape Hypothesis

Even without experience in the field of psychoacoustics, or acoustics, we have many relevant examples to choose from that relate to the soundscape changes posed by wind turbines. Our senses of vision, hearing, smell, and touch are related in ways that are commonly understood. For example, early in the development of the technology of motion picture projection, it was learned that if the transition from one still image to the next was too slow, our eyes (and brain) perceived the moving picture as "jerky", and projectionists corrected for this by installing shutters in motion picture projectors to cause each of the images seen to be projected twice, doubling the overall frame projection rate. Even though there was no increase in the information projected caused by using a shutter, the

eye now found the picture to be fluid instead of jerky. Comparably for our hearing, our ears perceive the sound from a single cylinder gas mower as an identifiable “putt, putt, putt” while when listening to the sound of a two cylinder engine, we perceive the sound as a much smoother “purr.” Similarly, through our related senses of smell and taste, we commonly describe a delectable food or beverage as smooth and pleasant, while we remark on the sharp bitterness of an unripe fruit. Finally, while stroking the family cat is said to be soothing and indeed to lower hypertension, the sharpness of an electric shock or a pinprick is anything but pleasant. It should be no surprise that when conducting soundwalks to record perceptions of a soundscape, the participants will find soothing the sound of waves on a shoreline, and yet find disturbing the strident wail of a police siren, even though the volume may be similar.

These parallel examples from our related senses, lead easily to a hypothesis that the cyclical “swoosh” from wind turbines, with each pulse individually discernable, sharp, yet of a constantly repetitive pattern; will be less pleasant than either a sound where the individual pulses are fast enough that we do not easily discern each individual pulse, as for a refrigerator fan; or for a stochastic (more random) pattern, like lake waves or bird songs. The objective of this paper is to show a repeatable technique to identify differences that lead wind turbines to be described as annoying, and how they influence our perception.

3.0 Data Acquisition

3.1 Components for Data Acquisition

The primary data acquisition was done using the following components;

- Microphone – Earthworks M30 BX - Battery operated 30kHz omnidirectional free-field measurement microphone with built-in preamp, flat +/- 1 dB frequency response from 9 Hz to 30 kHz, -3dB points at 5 Hz and 40 kHz
- Microphone windscreen
    - primary 90 mm foam
    - secondary 450 mm covered with 25 mm layer of open cell foam
- Calibration of the recording system before and after each reading set using Lutron SC-941 1kHz / 94dB Sound Level Calibrator
- Signal digitized using M-Audio Fast Track USB recording interface
- Signal storage and processing using Macintosh iBook G4 computer running Audacity Digital Audio Editor, v1.3.12, available from http://audacity.sourceforge.net/ generally using sampling rates of 11,025 Hz, 22,500 Hz and 44,100 Hz to yield FFT results as follows:
    - 11,025 Hz – FFT results 0.67 Hz to 5511 Hz in 0.672 Hz steps
    - 22,050 Hz – FFT results 1.34 Hz to 11023.6 Hz in 1.345 Hz steps
    - 44,100 Hz – FFT results 2.69 Hz to 22047.3 Hz in 2.692 Hz steps
- A secondary confirmation of sound level was made using a CEM DT-8852 Data Logging Class 2 Sound Level Meter, calibrated before and after use

- Wind speed at microphone monitored with Lutron LM-81AM Anemometer with range from 0.4 to 30 metres per second, a resolution of 0.1 m/s, and an accuracy of +/- 3% of full scale

Figure 1 : Typical Monitoring Setup

3.2 Data Processing

After the digital sound samples, typically of 2 to 4 minutes in duration, were recorded and stored as .wav files using the Audacity Digital Audio Editor, the "analyze" feature of the program was used to carry out frequency analysis of the digital record to create a graph of frequency versus amplitude using a Hanning Window display output from a Fast Fourier Transform (FFT) algorithm. The program permits analyzing nearly 4 minutes of data at a time although the record was listened to in selection of the analysis window to ensure that extraneous signals such as aircraft overhead, or cars passing were not included in the analysis windows. The information on the graph of frequency versus amplitude was output into a table for use in Excel processing, as described later.

The number of frequency divisions in the graph can be varied. Selecting a larger number of frequency divisions permits a wider bandwidth of the frequency to be charted, but required a longer sample to be analyzed. A table of approximate limits of the FFT analysis is shown on the next page.

Sampling Rate (Hz)	Sample Size	Approximate Frequency Bandwidth (Hz)	Approximate Minimum Analysis Time (sec)
11,025	16,384	0.7 – 5000	1.5
	8,192	2 – 5000	0.8
	4,096	3 – 5000	0.4
22,050	16,384	2 – 11,000	0.8
	8,192	3 – 11,000	0.4
	4,096	6 – 11,000	0.2
44,100	16,384	3 – 22,000	0.4
	8,192	6 – 22,000	0.2
	4,096	11 – 22,000	0.1

Table 1: Typical Limits of Spectrum Analysis by Audacity Digital Audio Editor

The Audacity analyze function also permits plotting of Autocorrelation using a Standard Autocorrelation routine, a Cuberoot Autocorrelation, and an Enhanced Autocorrelation, all described in the Audio Editor documentation. Again, the resolution of the output charts depends on the initial sampling rate, and on the number of samples the data is broken into. A table of typical limits used in the analysis presented in this paper is shown below. Since the use of Autocorrelation to identify wind turbine low frequency pulses had been identified by Richarz and Richarz (Reference 3) this feature was also examined.

Sampling Rate (Hz)	Sample Size	Approximate Time Span of Output (sec)
11,025	16,384	0 – 0.7
	8,192	0 – 0.3
	4,096	0 – 0.18
22,050	16,384	0 – 0.35
	8,192	0 – 0.18
	4,096	0 – 0.09
44,100	16,384	0 – 0.18
	8,192	0 – 0.09
	4,096	0 – 0.045

Table 2: Typical Impact of Sampling Rates and Size on Output Time Span

4.0 Example Cases Studied

4.1 Port Bruce Turbine Shutdown Case

On Jan. 10, 2013, on a sunny unwinterlike day, with a temperature of about +4°C, the Vestas V82 turbines of the Enbridge Underwood Wind Power

Development were just at the point of starting and stopping. In the hours ending at 3 PM and 4 PM, the Ontario Independent Electrical System Operator reported the 110 turbine array, rated at 181.5 MW output produced just 1 MWh of energy per hour. While testing out a new microphone and wind screen, the opportunity presented itself with the measurement system located as shown in Figure 1 at a site close to 4 wind turbines, and while there, initially the 4 turbines were synchronized to the system, then one at a time the turbines broke synchronism. This can be discerned, as it is possible to hear the contactor opening with a "clunk". Initially the turbine continues at about the same rotational speed, but as soon as the synchronism is broken, the turbine becomes silent instead of producing the characteristic "whoosh." The monitoring site is shown diagrammatically in Figure 2. The closest monitored turbines were effectively downwind of the monitoring site at the time. The upwind turbines southwesterly of the monitoring site are Vestas V80 turbines, which have a higher "cut-in" wind speed than the V82 turbines, and would have been already shut down on low wind conditions. All other V82 turbines in the Enbridge Underwood are at least 2 to 4 times further than the closest four so the predominant effect would have been from the 4 close by turbines, even if some of the more distant turbines were also going in and out of synchronism. All V80 and V82 turbines within 3km of the monitoring site are shown in the Figure.

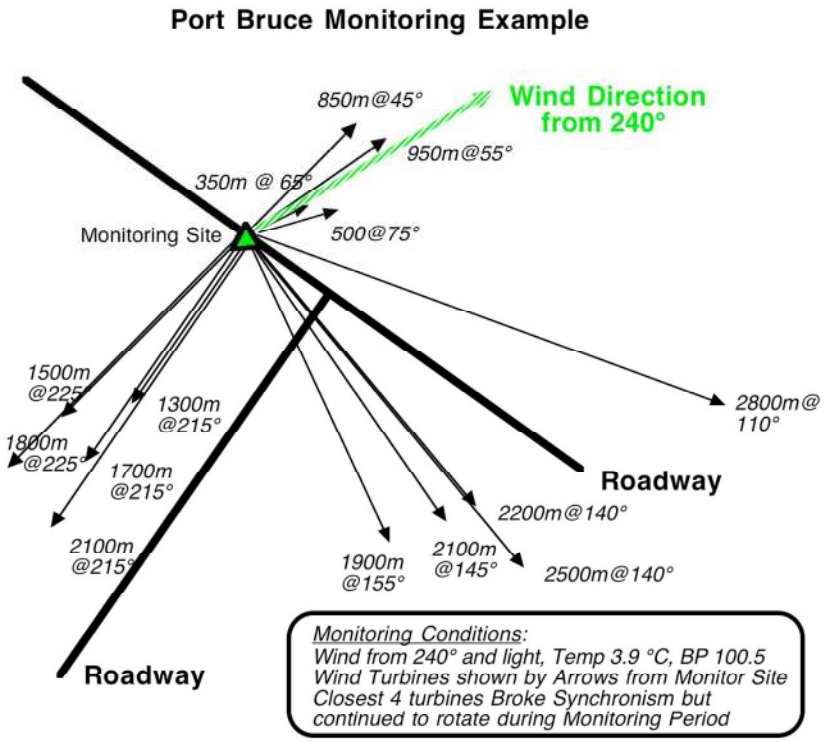

Figure 2: Port Bruce Monitoring Example Showing Monitoring Site and Turbines

The data recorded was processed as described above, and on the following page, the changes in the sound power level, the roughness in the sound signal,

and changes in the autocorrelation are shown, identifying the change in cyclical pattern of the sound.

Figure 3 shows the change in calibrated sound level as a function of frequency for the 44100 sampling rate and for the 11025 sampling rate using a 30 second window in each case, as a 4 turbines are first synchronized (All On) and after the turbines break synchronization. The 44100 sampling rate (which covers frequency from 2.69 Hz to 22,047 Hz) shows only the *"All On"* and *"All Off"* state, while the 11025 sampling rate (with a frequency bandwidth from 0.67 Hz to 5511 Hz) shows the results for *"All On",* the *"2 Closest Turbines Off"* and then *"All Off."* For both cases, it is relevant to note the microphone frequency 3 dB roll off occurs at about 5 Hz, and it then falls sharply lower in output, so the response below 5 Hz although displayed, is not accurate.

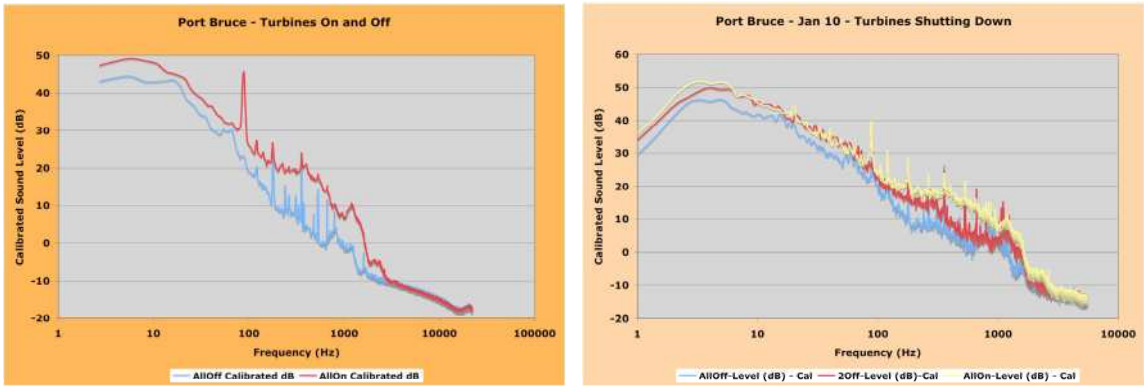

Figure 3: Change in Calibrated Sound Levels As Wind Turbines Break Sync

The charts show that above about 2000 Hz, the differences are small, due to the attenuation with distance. Between about 2000 Hz and about 500 Hz, the 2 turbine case is noted to be below the 4 turbine case, as the 2 closest turbines are at about 350 to 500 metres, while the next turbines are at about 850 to 950 metres. Below about 200 Hz, there is little difference between the 2 turbine case and the 4 turbine case, due to the little attenuation of the lower frequencies in air at these distances. It is remarkable that the 4 turbine case is some 10 to 15 dB higher than the no turbine case for frequencies from about 100 Hz to 2000 Hz. Recall that this is for the case of wind turbines at a very low output, and that the sound levels increase as power output increases as demonstrated previously.

Figure 4, on the next page demonstrate the characteristic of the sound received on the monitoring microphone for the 2 cases of *All On*, *2 Closest Off*, and *All Off*. Each of the waveforms have been amplified by the same gain (25 dB). A representative sample of 1 second has been shown for each case. Note:

- the difference in total amplitude from the 4 to 2 to 0 turbine cases
- the gradual softening (or rounding) of the transitions as the number of turbines decreases

- the roughness (akin to a sawtooth) of the 4 turbine case is reduced as the number of turbines decreases, and as the separation distance increases, removing the higher frequency components.

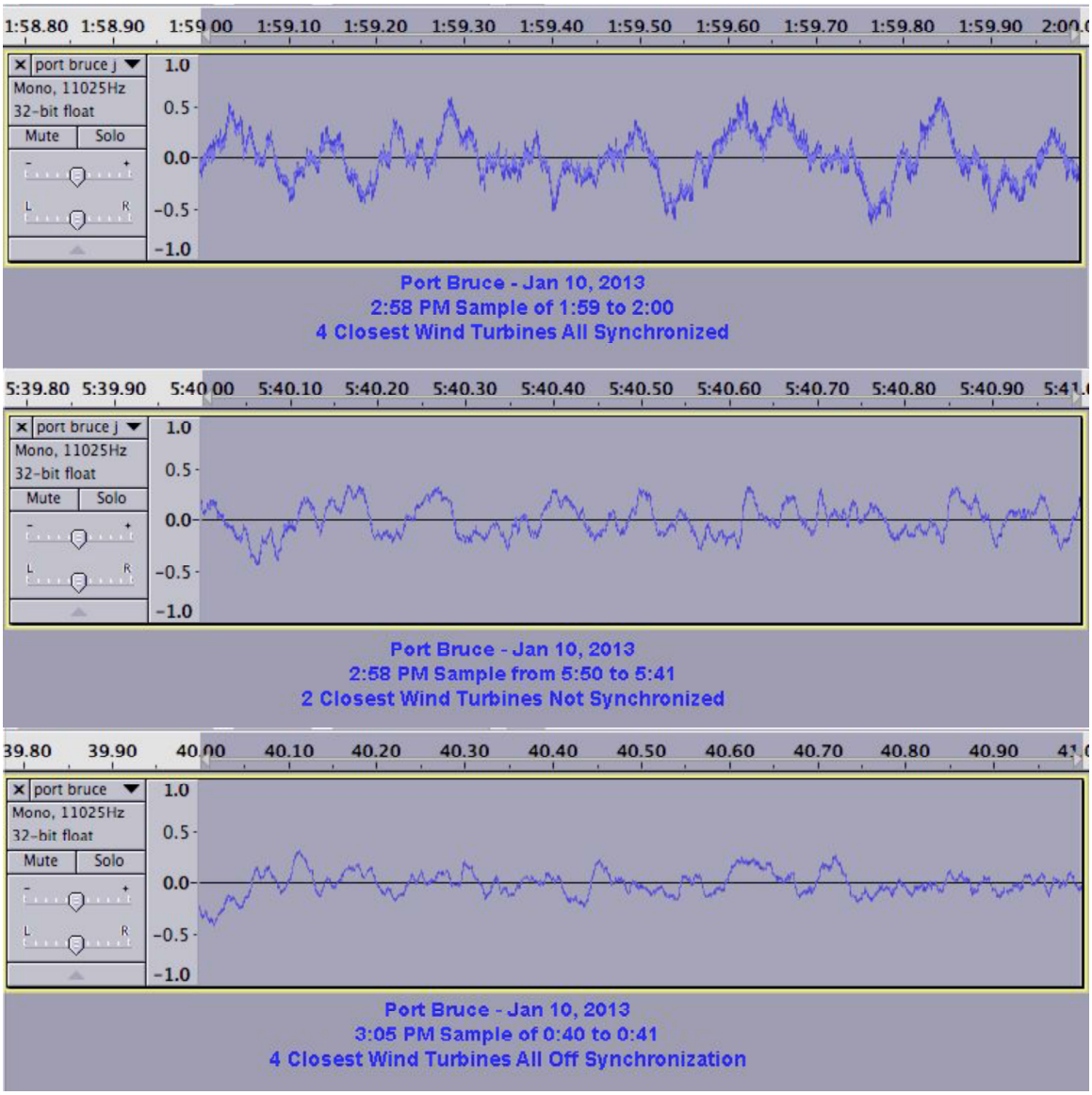

Figure 4: Change in Sound as Number of Wind Turbines Synchronized Falls

Figure 5 to 7 on the next page shows the changes in Autocorrelation of the wind turbine sound as the number of wind turbines synchronized to the electrical grid falls at the same site within minutes. The charts on the left (with turbines) show cyclical peaks, while the charts on the right (with no turbines) show much smaller peaks, even with the scale magnified. The output of the Autocorrelation routine of the Audacity Digital Audio Editor automatically creates a chart to fill the same vertical span, so what is happening is that for the “All Off” case, the scale for the

Standard Autocorrelation is roughly doubled, while for the Enhanced Autocorrelation case, the scale is magnified by a factor of 3 to nearly 10.

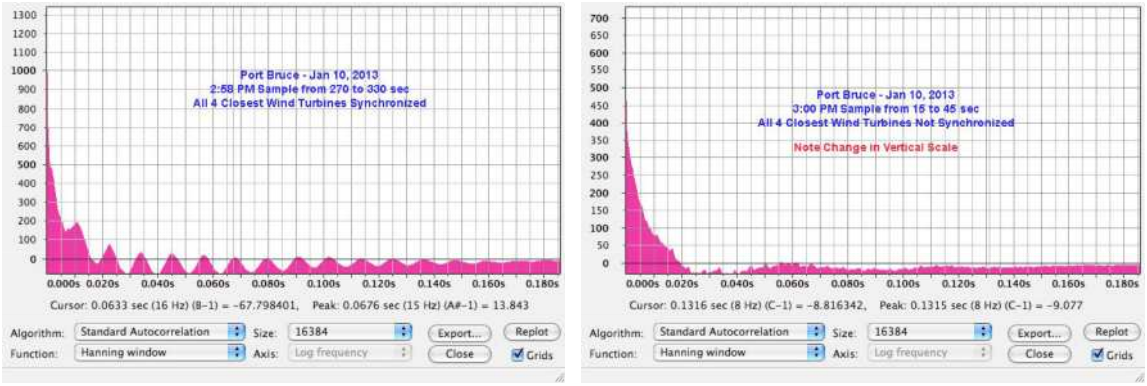

Figure 5: Standard Autocorrelation – All On / All Off – 0 to 0.180 seconds

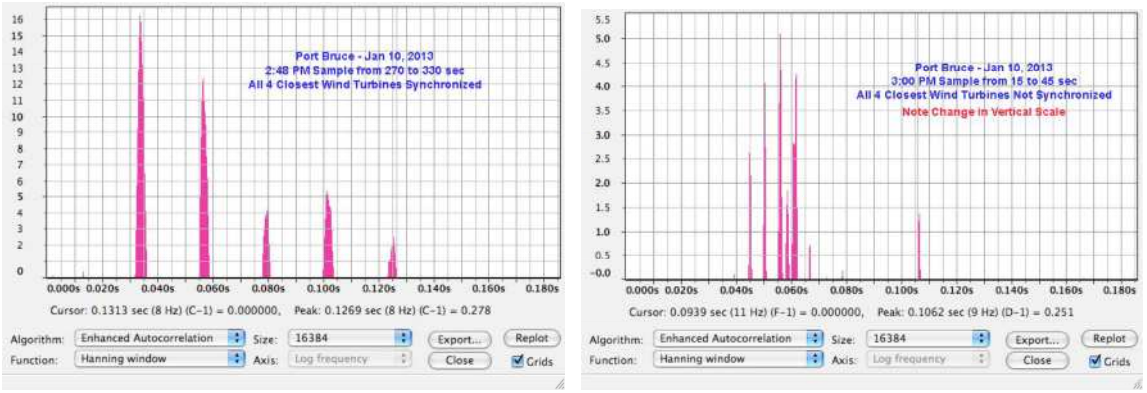

Figure 6: Enhanced Autocorrelation – All On / All Off – 0 to 0.180 seconds

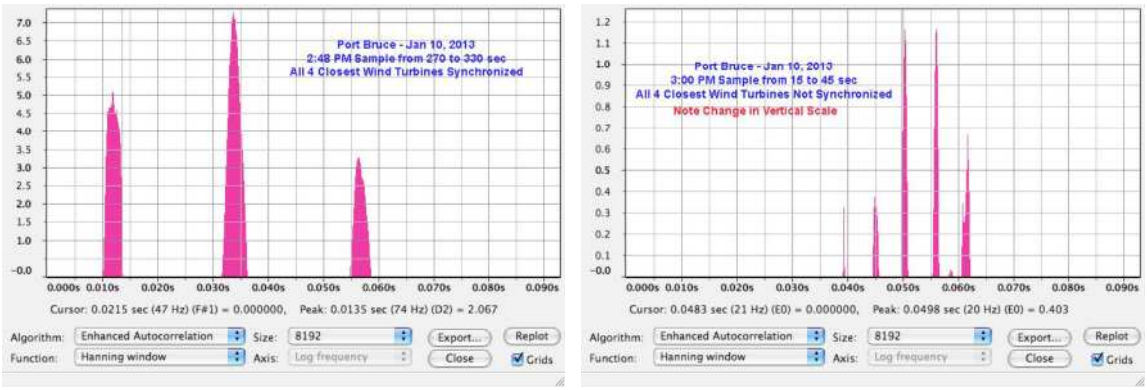

Figure 7: Enhanced Autocorrelation – All On – All Off – 0 to 0.090 seconds

4.2 Saugeen Shore CAW Single Wind Turbine Case

In January of 2012, a single Enercon E-48 wind turbine, with a 48 metre rotor, on a 76 metre tower was erected at the Canadian Auto Workers (CAW) Family Education Centre in Saugeen Shores. The Town of Saugeen Shores council had refused to approve the turbine at this site in the town, but that ruling was

overturned by an Ontario Municipal Board Hearing after objections by the CAW and the Province of Ontario. Although this wind turbine, 100 metres tall, has a nominal nameplate rating of 800 kW, by committing to restrict the output to 500 kW, which lowered the rated sound power level of the turbine to 101.5 dBA, it fell below the 102 dBA criterion applied by the Ontario Ministry of the Environment that requires a 550 metre setback to homes. Further, the acoustical consultant for the project described the setting the turbine would be installed in (a cottage and resort area) as a Class 2 Urban Setting where “urban hum” dominates the daytime, which permitted the maximum limitation on the turbine to be to meet a 45 dBA sound level at a receptor instead of a 40 dBA limit. The turbine setting amidst some of the monitored homes around the turbine is shown in Figure 8. About 117 homes are located within 550 metres of the turbine. Some of the closest homes are 210 to 220 metres from the turbine, one separated across a paved parking lot as shown in the picture (analyzed in the acoustical noise prediction as having Ground Attenuation factor of 0.7, that of soft tilled earth.)

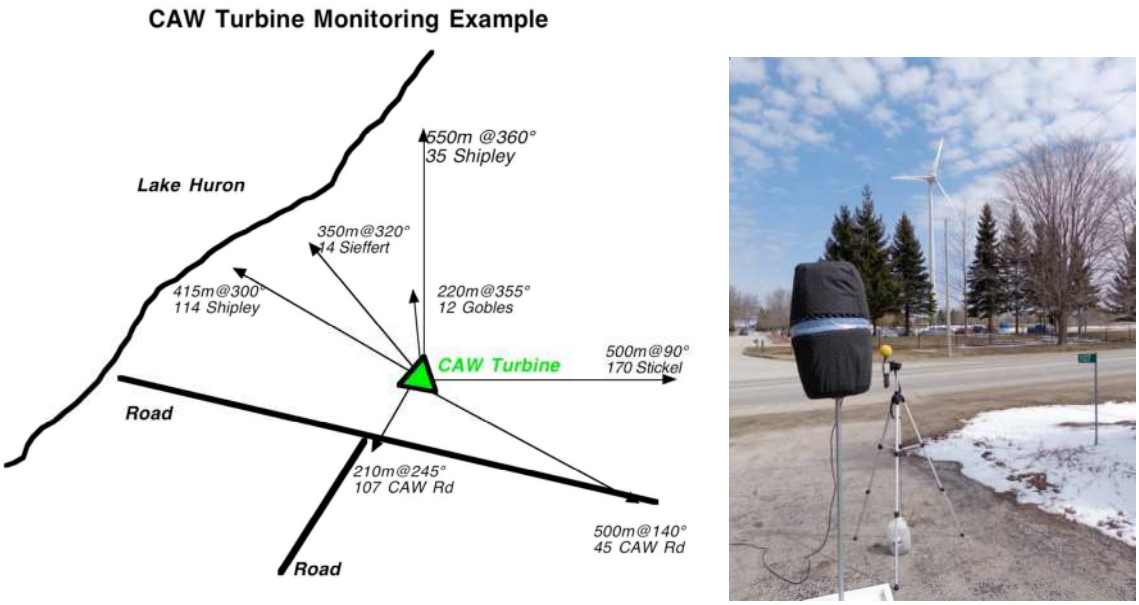

Figure 8: CAW Wind Turbine Monitoring Example

It is remarkable that the MOE accepted that the soundscape of the cottage resort area surrounding the CAW wind turbine is dominated by urban hum, representative of a major city during the daytime, as sound samples (before the turbine was installed) shows that the dominant sounds are birds, waves on the beach, and perhaps a neighbourhood BBQ gathering. The nearest multi lane roadway that permits speeds of 80 km/hour is over 50 kilometres away, and the closest comparison to a major airport of a city is the grass strip of the Port Elgin Airport, that has about 1000 mostly single engine aircraft “movements” (takeoffs or landings) in a year. Urban hum is an unusual perception of the soundscape that predominates the cottage resort area surrounding the CAW wind turbine.

An opportunity was presented on April 4th of 2013 during testing of the wind turbine to record the soundscape at a number of surrounding sites with the turbine off, then on, then off again over about a 4 hour duration. Ambient conditions at the time were a temperature from 5 to 7°C, with wind speeds recorded at the nearest Environment Canada weather station from 24 to 37 km/hr (6.7 to 10.3 m/s at 10 metres) from 230 degrees, with a barometric pressure of about 99.1 kPA and clear conditions. What is notable about this location is that a number of the monitoring sites, such as the site at 12 Goble Pl. are roughly 15 metres below the elevation of the CAW turbine, which was on an ancient lake shoreline, while where 12 Goble Place is located would have been in the lake. As a result, the "below the hill" sites were protected from the surface winds this day, and while wind in the tree tops could be heard, there was very low wind speed of 0.5 to 1.5 m/s impingent on the actual microphone windscreen. Meantime, the turbine with it's blade tips 115 metres above the monitoring location was freely exposed to a similar wind velocity as was producing about 66% full power at the Enbridge wind turbines some 8 km to the south.

The difference in sound level with the turbine shutdown, then operating, and then shutdown again are shown in Figure 9. The figure shows a difference in sound levels of about 5 dB between the turbine *"Off"* and turbine *"On"* states for frequencies below about 1000 Hz. However, the frequency plot also shows quite distinct frequency spikes in both operating recordings at about 58 and 116 Hz.

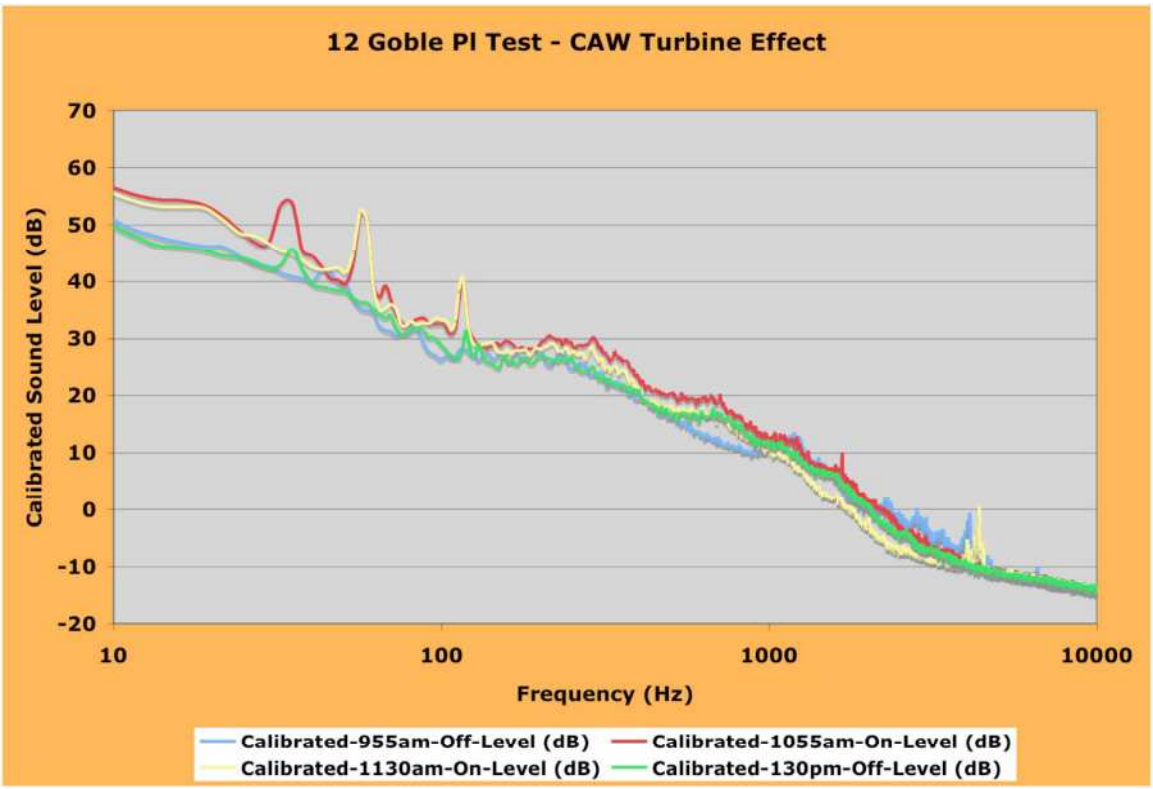

Figure 9: Sound Levels Recorded at 12 Goble Pl with turbine Off/On/On/Off

The figures below show the results of Autocorrelation for 4 cases at 12 Goble Pl

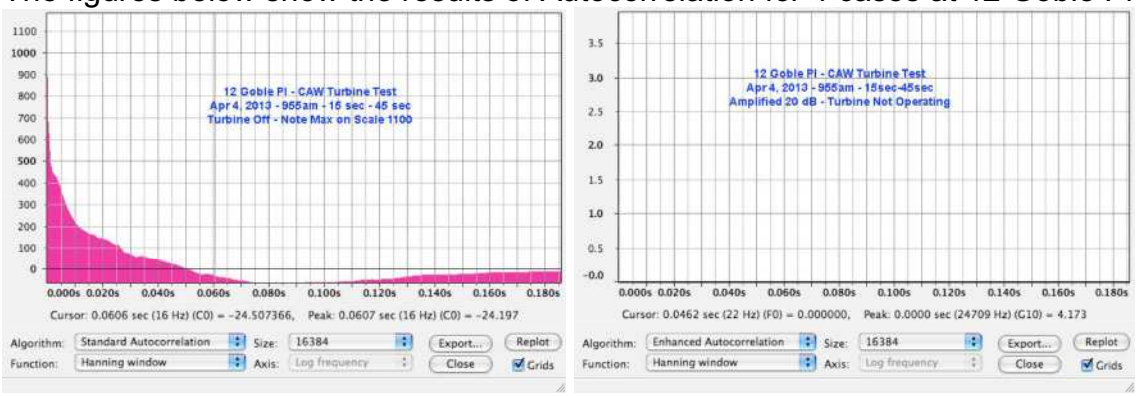

Figure 10 (above): Standard and Enhanced Autocorrelation 955am – Turbine Off

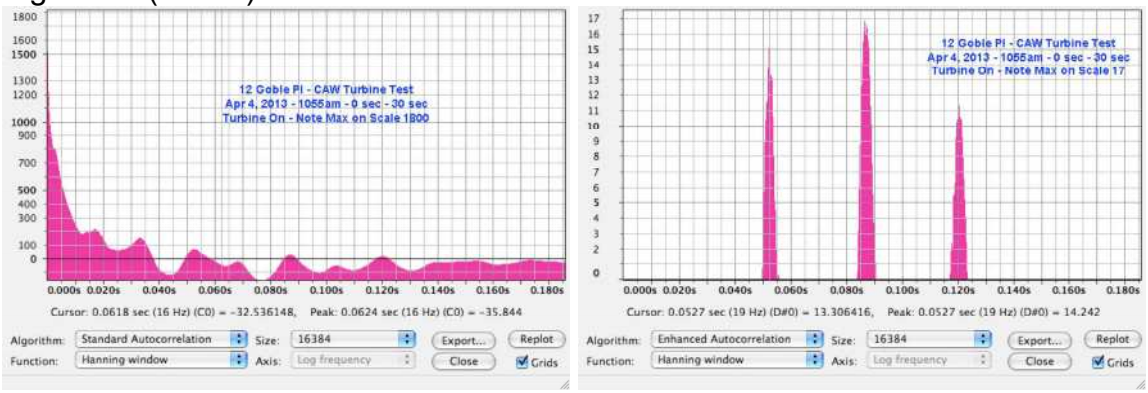

Figure 11 (above): Standard and Enhanced Autocorrelation1055am – Turbine On

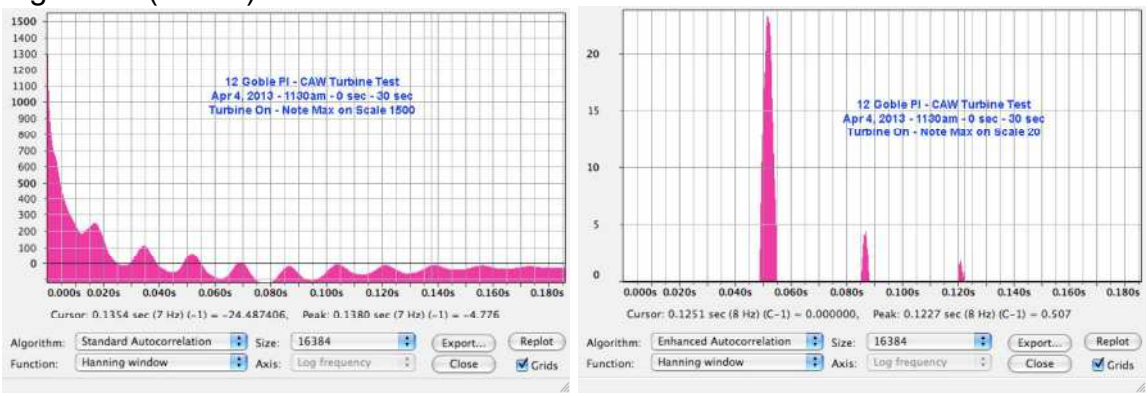

Figure 12 (above): Standard and Enhanced Autocorrelation1130am – Turbine On

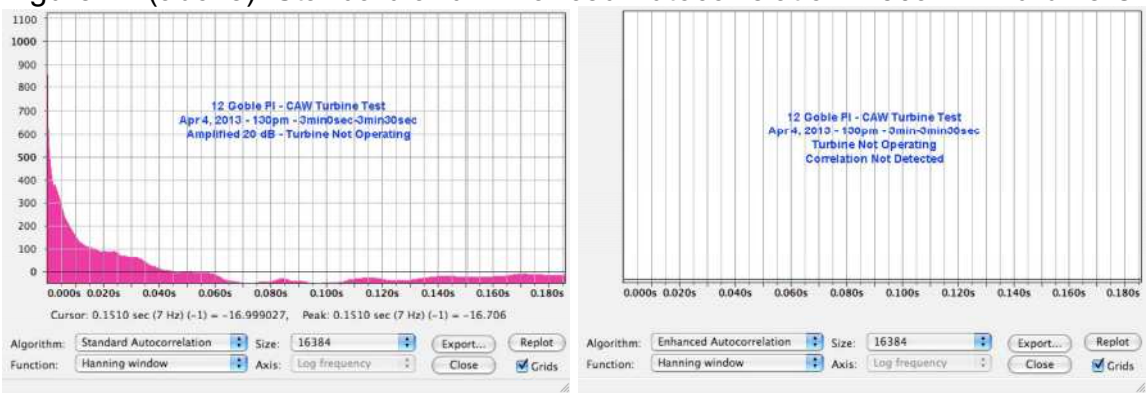

Figure 13 (above): Standard and Enhanced Autocorrelation 130pm – Turbine Off

Figures 10 through 13 on the previous page show a significant amount of correlation for the two operating conditions of the turbine, visible both on the Standard Autocorrelation display as a “ripple” and particularly on the Enhanced Autocorrelation case where the time signatures are repeatable. Again, note that the turbine *“Off”* states are displayed on charts with an expanded scale, display no ripple on the standard Autocorrelation charts and do not distinguish any Autocorrelation spikes at all on the Enhanced Autocorrelation curves, compared to the distinct spikes seen on the operating or Turbine *“On”* cases.

Figure 14 on the next page shows a typical one second trace from the digital recordings for each of the four cases, each amplified by a 20 dB gain factor to make the traces visible on an equal basis. As before, the amplitude is greater with the turbines *“On”* than *“Off”* but of more significance to the soundscape, note the distinct change in the rate of rise of the sound over the different states, the differences in the sharpness of the transitions, and the difference in the overall roughness between the curves.

Since this paper exceeds target length, it will not be possible to give detailed examples of many of the other cases that have been analyzed both before the CAW turbine came into operation, and after, but they are available upon request. Table 3 summarizes some of the highlights of some of the other cases.

Date	Time	Turbine Status	Environmental Conditions	Notable Points
May 3 2013	430 am – 530 am	Rotating at 5 RPM	Wind Dir 100° Wind Spd ~ 2m/s	Turbine not generating. No Correlation in Std or Enhanced
Apr 22-23, 2013	2317pm-0023am	Very slow rotation	Wind Dir 130° Wind Spd ~5m/s	Turbine not generating. No correlation in Std or Enhanced.
Apr 20, 2013	645pm-820pm	Rotating at 28rpm	Wind Dir 290° Wind Spd ~5m/s	Lots of wind noise. Strong correlated signal related to turbine
Apr 18, 2013	643-654pm	Rotating at 28rpm	Wind Dir 230° Wind Spd~5m/s Rain	Correlated signal related to turbine, especially at lower sampling rates
Apr 2, 2013	157pm-358pm	Rotating at 28rpm	Wind Dir 270° Wind Spd ~7-9m/s	Some correlated signal available, even though high wind noise
Mar 28, 2013	1057am-150pm	Rotating ~ 28RPM	Wind Dir 360° Wind Spd~2m/s	Strong indications of correlated noise signals.
Mar 18, 2013	327pm-448pm	Not yet operating	Wind Dir 90° WindSpd~8m/s	Windy, little or no correlated noise.

Table 3: Sample of Some Other CAW Wind Turbine Monitoring Findings

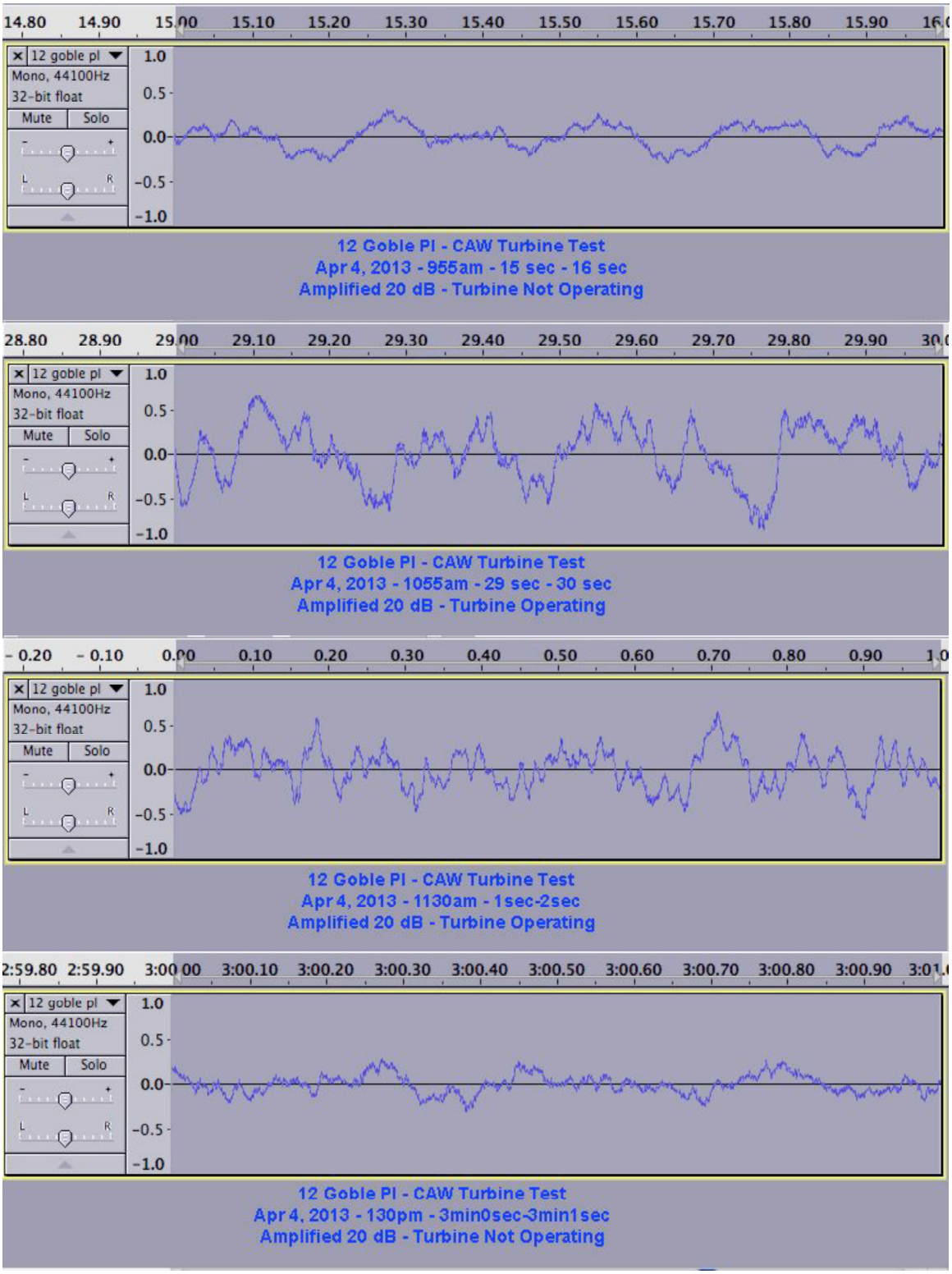

Figure 14: Change in Sound as Turbine “Off” / “On” / “On” / “Off” over 4 hours

5. Conclusions

This paper set out to examine if there is truth to the hypothesis that the cyclical "swoosh" from wind turbines, with each pulse individually discernable, sharp, yet of a constantly repetitive pattern; will be less pleasant than either a sound where the individual pulses are fast enough that we do not easily discern each individual pulse, as for a refrigerator fan; or for a stochastic (more random) pattern, like lake waves or bird songs. This required proving if this was the characteristic of the soundscape received near wind turbines, and to be able to show if the condition was repetitive.

Soundscape data was recorded in situations when the wind turbine condition was changing over a fairly short monitoring period, so that other conditions would remain relatively unchanged, as a means of controlling other variables. This was important to ensure that changes of wind direction, wind speed, temperature, barometric pressure, and extraneous sounds such as vehicles and birds, do not impact the observations.

Examination of the data consisted of comparing the spectrum – amplitude versus frequency, processing the data using autocorrelation techniques, and examining a visual record of the sound recording to examine for rate of rise of sound levels, the sharpness of the transitions, and the general "roughness" of the trace.

For both the case of a multi-turbine array where the turbines nearest the monitoring point were shutting down, and for a single turbine case where the turbine was *"Off"* / *"On"* / *"On"* / *"Off"* over a short time period the examined data made it clear that operation of wind turbines does create an easily identifiable, and repeatable change in soundscape. Even though there might be background noise from the wind, the differences were easily observed for the turbine *"On"* state:

- Higher amplitude of sound levels was observed ranging from 5 to 15 dB for frequencies below about 2000 Hz
- A more rapid rise and fall in sound levels over time was observed
- Sharper transitions from rise to fall in sound level was observed resulting in a pattern more like a sawtooth, than a smooth wave
- Autocorrelation of the sound samples showed that distinct low frequency pulses were created when turbines were *"On"* but no such pulses were seen when turbines were *"Off"* even when wind in the trees was readily apparent, or the sound of lake waves was obvious. These sounds might make it harder to hear the wind turbines, but they continued to be bothersome, and the autocorrelation showed that the low frequency pulses were not masked by either the wind or the waves.

In the course of collecting data, residents living near wind turbines identified without being prompted, observations that supported the hypothesis that something was different in the sound from wind turbines. As an example,

observers independently noted that they “loved” to listen to the lake waves, but they could not get used to the sound from the wind turbines, even though it might not be as loud as the lake. They still noticed and were bothered by the wind turbines even though the lake might be rough and noisy.

Examples have been given in relation to other human senses of vision, touch, taste and smell, to give a strong corollary that a sound which is jerky, or sharp (having a rapid change of state) as opposed to fluid, and having a slower rate of change will be less pleasant. The existence of an unpleasant state for an ongoing period is easily perceived to be annoying, much like continually being pricked by a needle is annoying. Like the “Mosquito” audio emitter from “Moving Sound technologies” which emits an annoying sound so that youth want to leave an area (see http://movingsoundtech.com/news-and-press/popular-content/teenagers-flee-annoying-noise) many people want to flee from the annoying sound from wind turbines. When fleeing is not readily possible, because the environment happens to be in their home, which it is not easy to walk away from, then it is not hard to progress from an annoyance to a stressor, and thus to a health hazard. Examples of this were presented in a paper at the 21st International Congress on Acoustics – 2013 in Montreal. (Reference 4) A summary of evidence was also presented at the Canadian Acoustical Conference – 2011 in Quebec City. (Reference 5)

The World Health Organization (Europe) report, *“Burden of Disease from Occupational Noise (Quantification of healthy life years lost in Europe)”* (Reference 6) issued in 2011 begins, *“This publication summarizes the evidence on the relationship between environmental noise and health effects, including cardiovascular disease, cognitive impairment, sleep disturbance, tinnitus, and annoyance.”* That report concludes, *“There is sufficient evidence from large-scale epidemiological studies linking the population exposure to environmental noise with adverse health effects. Therefore, environmental noise should be considered not only as a cause of nuisance but also as concern for public health and environmental health.”*

This paper has made it clear that a cause of the annoyance from wind turbines is discernable, as it is possible to analyze the sound output from the turbines to determine if there are low frequency pulses, using autocorrelation techniques. It is also true that regulatory limits typically based on A-weighted sound levels will neither detect the cause of the annoyance, nor will propagation models used to predict the sound levels at receptors be effective to protect the public from the annoyance that affects a human senses as outlined in this paper. The words of Jeremiah 5:21 come to mind.

We are told, indeed commanded, to love our neighbours, and to come to the aid of those who are suffering. (Reference 7) Addressing known irritants proven to be present where people are suffering is a good place to start.

6. References

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