6th International Conference
on
Wind Turbine Noise
Glasgow 20-23 April 2015

Stationary wind turbine infrasound emissions and propagation loss measurements

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Summary

Microbarometers have been used to quantify the infrasonic emissions (0.05Hz to 20Hz) from five wind farms in Victoria, Australia. The wind farms measured include; Macarthur wind farm (140 turbines type Vestas V112 3MW); Cape Bridgewater (29 turbines type MM82 2MW); Leonards Hill (2 turbines type MM82 2MW); Mount Mercer (64 turbines type MM92 2MW), and; Waubra (128 turbines 3 types of Acciona Windpower 2MW).

Upwind indoor measurements at the Macarthur wind farm during an unplanned shutdown from full power and subsequent startup to 30% load has shown that stationary turbines subject to high winds emit infrasound pressure below 8 Hz at levels similar to the infrasound emissions at blade pass frequencies and harmonics.

The stationary V112 turbine infrasound emissions are caused primarily by blade and tower resonances excited by the wind. It is apparent from the mismatch of resonances and blade pass frequency components that Vestas have carefully designed this unit to minimise fatigue of the wind turbine.

Short range (up to 2km) measurements from the Leonards Hill wind farm have shown the determination of attenuation rate with distance to be problematic due to interference between the two turbines. A model to explain the unexpected attenuation results at Leonards Hill has demonstrated that the commonly observed amplitude modulation of blade pass tones is the result of changing phase between turbine rotor speed and changes in wind speed.

Long range measurements from two different wind farms over a distance of 80km have shown that infrasound below 6Hz has a propagation loss approximating 3dB per doubling of distance.

1 Introduction

Planning development applications prepared by acoustical consultants for wind farms around the world have until recently neglected the potential impacts of infrasound.

A number of recent studies[1,2,3] have described adverse human reactions to infrasound and low frequency sound. Similar adverse reactions have been voiced by residents near other wind farms. The research work described in this paper is based on the measurement of infrasound immissions observed within a number of dwellings near Australian wind farms. Some of the dwellings used to gather infrasound data have been vacated by the owners.

The objective behind this work was to quantify and better understand the propagation and causes of infrasound from modern wind farms having a generating capacity of 2MW and above.

This work was not commissioned by any external organisation and was funded by the author. The author has worked for both the wind farm industry and residents and is not affiliated with any pro or anti-wind organisations.

2 Infrasound Instrumentation

Acoustics professionals are most familiar with the common microphone connected to a sound level meter that has some form of standardisation such as IEC61672. Unfortunately, IEC61672 is designed for the audible frequency range and fails to address infrasound measurements[4].

An alternative to the microphone for infrasound measurement is a MEMS pressure transducer. This type of device can be calibrated at static pressures and is used as a reference to calibrate infrasound equipment that detect nuclear explosions at many listening stations around the world[5]. The nuclear test ban treaty monitoring stations are located outdoors and have wind filters implemented by sampling the air over large areas with the use of tubes connected back to the sensor. This has the potential to influence the frequency response of the system[5] so this approach is not used in these studies.

The equipment (LHA-IR1) used for the monitoring results reported in this paper was developed in-house in accordance with AS/NZS 3817 using a MEMS pressure sensor. Four units were used in this study. The system response is 0.05Hz to 30Hz (-3dB) with phase variation limited to +/- 10˚in the frequency range 0.3Hz to 4Hz. An accurate phase response is required to faithfully represent the infrasonic pressure waveforms from wind turbines that predominantly fall within this frequency range. Calibration was with reference to a Class 1 sound level meter having known characteristics at 20Hz and 10Hz. The MEMS sensor is a static pressure measurement device with known sensitivity. The LHA-IR1 is configured to sample every 3ms and store the time history data in 20-minute blocks. This data is then converted into WAV file format for subsequent post processing. The storage capacity is limited only by the size of the microSDCARD in each unit and allows typically, for a 16GB card, over 100 days of data to be collected without replacement. With a 64GB card it can run unattended for over a year.

The two LHA-IR1 units used in the Leonards Hill wind farm propagation measurements were calibration matched by recording data from both units inside a car near to the wind farm. This measurement setup was recognised as a useful technique to minimise wind noise in the Shirley wind farm study[2].

3 Infrasound Measurements

Infrasound measurements are reported for three wind farms. The Macarthur wind farm has 140 Vestas V112 3MW wind turbines located over flat terrain. Seven measurement locations are reported around this wind farm.

The Cape Bridgewater wind farm has 29 MM82 wind turbines located on the coast in Victoria. Eighteen of the turbines are grouped together in a relatively flat terrain 1000m from a dwelling in which a start-up was observed.

The Leonards Hill wind farm has two MM82 wind turbines located on top of a small hill and measurements are reported from within dwellings located 650m and 2000m away.

At the time of taking measurements at the Leonards Hill wind farm it was thought a good idea to monitor at a remote location indoors 34km to the East in Woodend as a reference ‘zero’. Contrary to obtaining a reference zero it was found that a number of wind farms could be identified from this location. Measurements at this location have proved useful in assessing infrasound propagation from another two wind farms in the area: Waubra and Mount Mercer.

4 Macarthur Results

Figure 1 shows the location of each Vestas V112 3MW wind turbine in relation to seven dwellings around the wind farm (R1 to R7). All measurement results were obtained indoors. Figure 1 shows a 10-minute average power snapshot in a Northerly wind of 8m/s (10m AGL). Each turbine power output is colour coded. Unfortunately, we were not able to obtain such detailed operational data during the infrasound surveys. However, Figure 1 clearly shows how power generation varies across the Macarthur wind farm with the turbines facing the wind generating more power than those downwind that are shielded by the upwind turbines.

Some of the turbines are shown to be inoperative (dark blue) in Figure 1. A power output variation of 2MW across the wind farm is not uncommon.

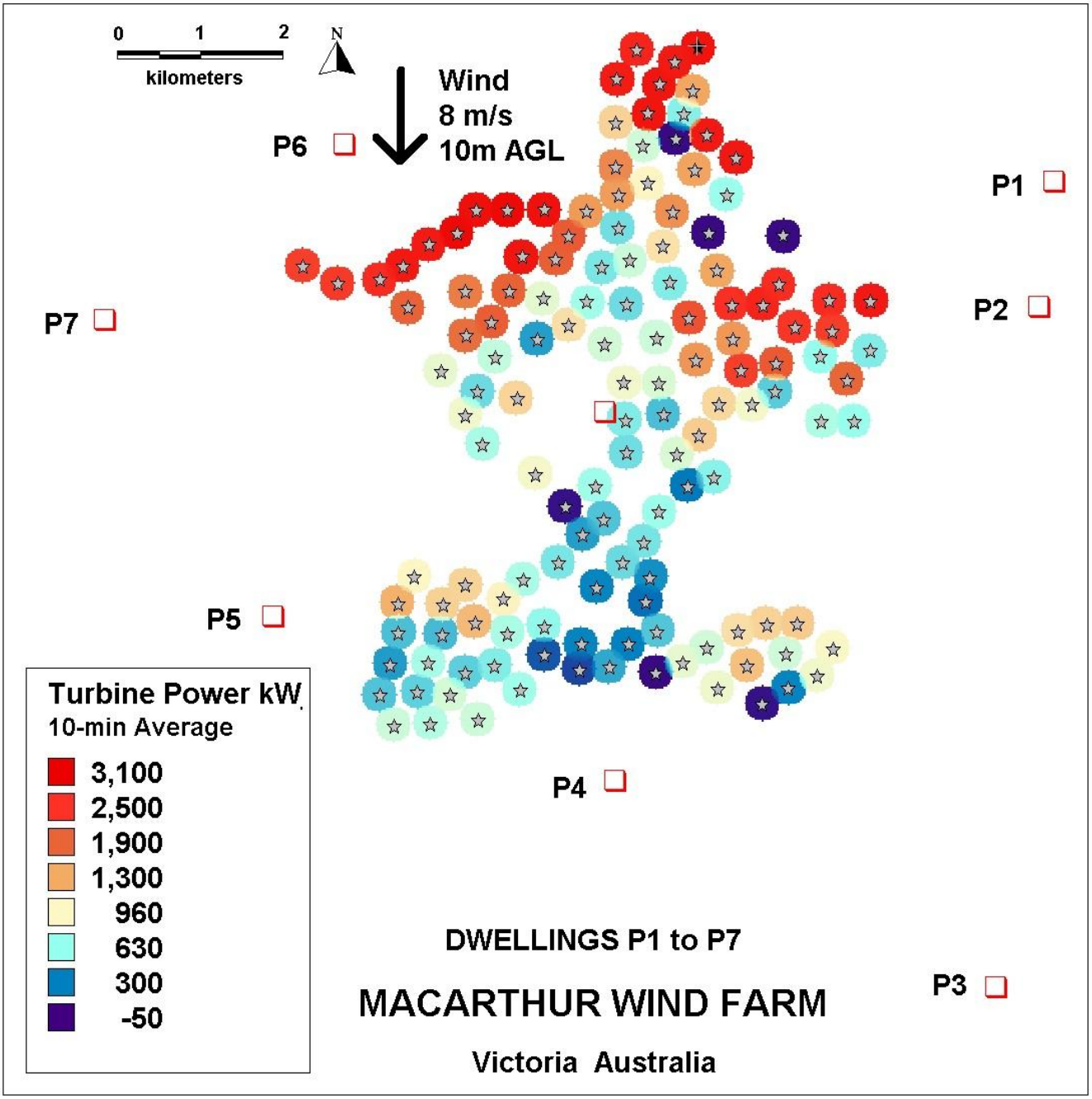


FIGURE 1

Two sets of simultaneous measurements were taken. The first was a measurement pair at P1 and P6. The second set was completed at residence locations P2, P4, P6 and P7.

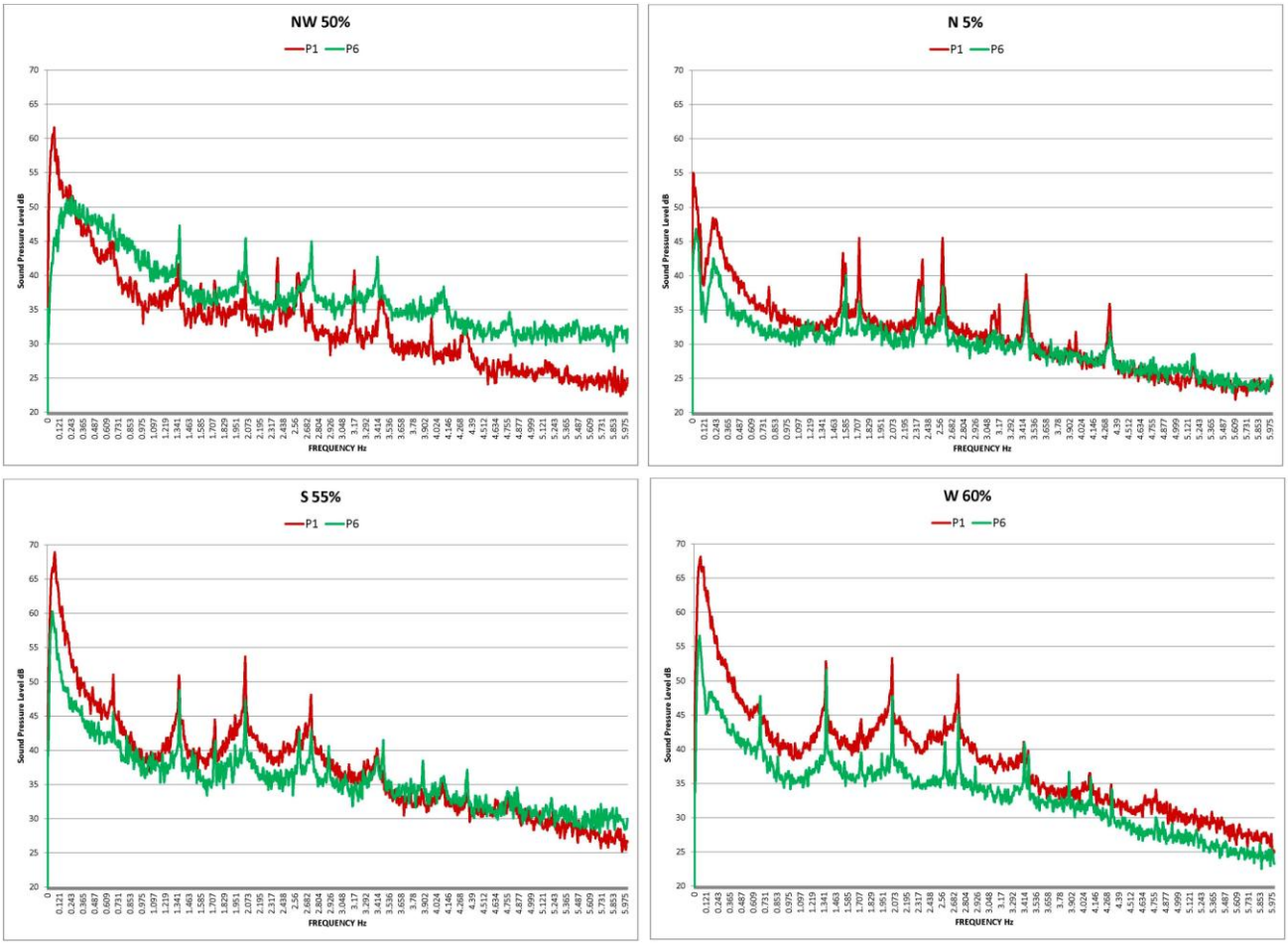


FIGURE 2

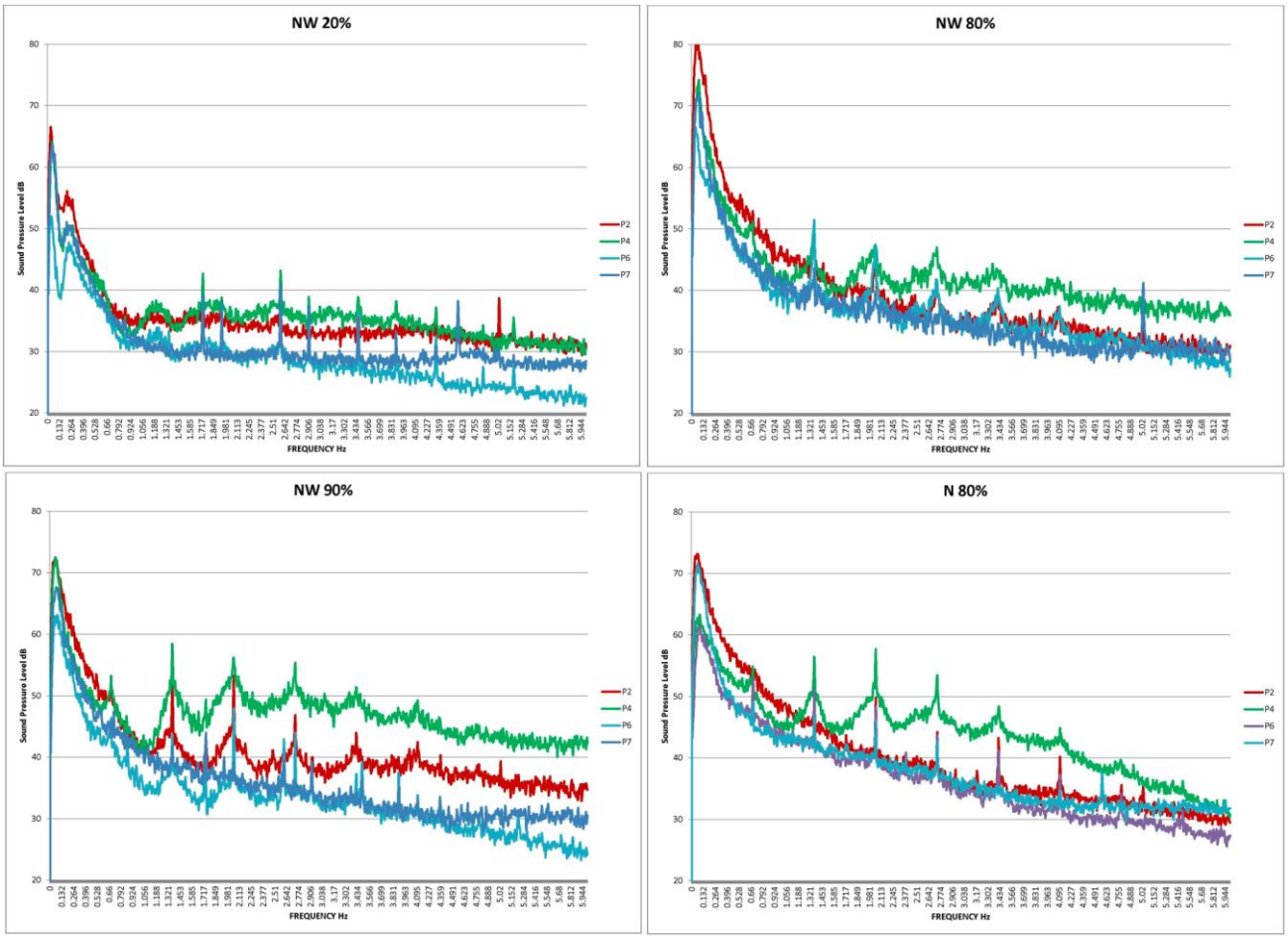


FIGURE 3

P1 is closer to the nearest turbine than P6 and sample results from different wind directions and percentage rated power for the wind farm are shown in Figure 2. Each chart is titled with the wind direction and percentage wind farm rated power at the time. The spectra are averaged over one hour in each case and presented up to 6Hz to improve visualisation of the spectrum peaks.

Figure 2 and 3 show that spectrum peaks are apparent other than the blade pass frequency (0.683Hz) and its harmonics. The figures generally show that broadband infrasound increases with wind speed and also if the monitoring location is downwind rather than upwind.

Analyses of measurements at P3 (5.4km from the nearest turbine) were completed for a range of wind directions and wind farm percentage rated power generation. A selection of spectrum charts grouped into different wind direction is shown in Figure 4.

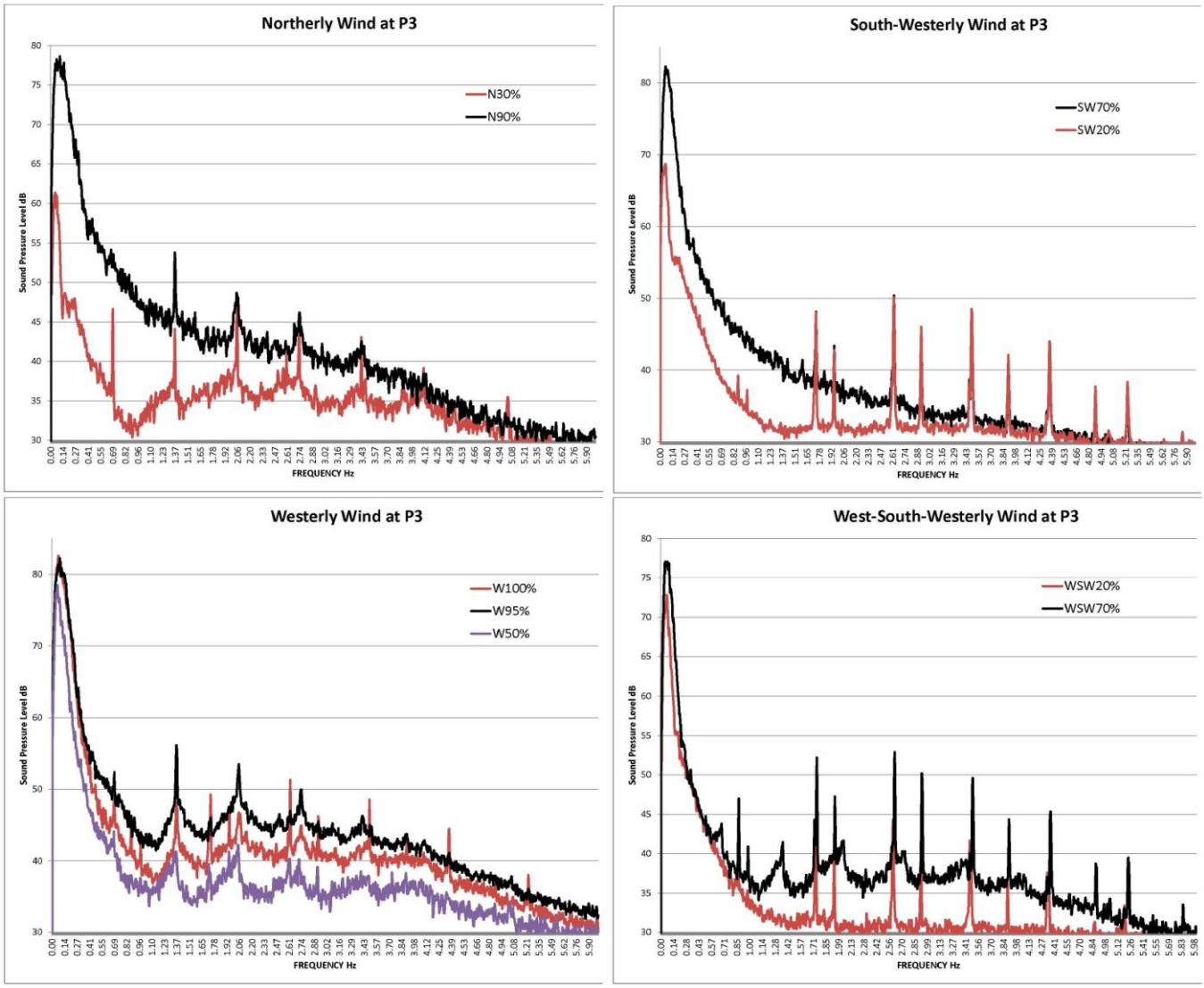


FIGURE 4

The lower left chart in Figure 4 shows three different percentage rated power outputs with non-blade-pass related frequency tones becoming more apparent at 100% rather than 95%. It is expected that many more of the turbines would be pitch adjusted at 100% wind farm rated power compared to the 95% case. This is likely to cause greater turbulence on the blades of the pitch adjusted wind turbines.

4.1 Macarthur Shutdown and Startup Results

A full power shutdown and later startup occurred whilst monitoring at P5. Unfortunately, this was the only location being measured at the time. The Macarthur wind farm stopped to standstill from a wind farm power generating capacity of approximately 95%. After approximately 7 hours the wind farm was restarted.

Figure 5 shows a spectrogram either side of the shutdown and Figure 6 shows a similar spectrogram before and after startup. The wind was from P5 to the Macarthur wind farm (Westerly).

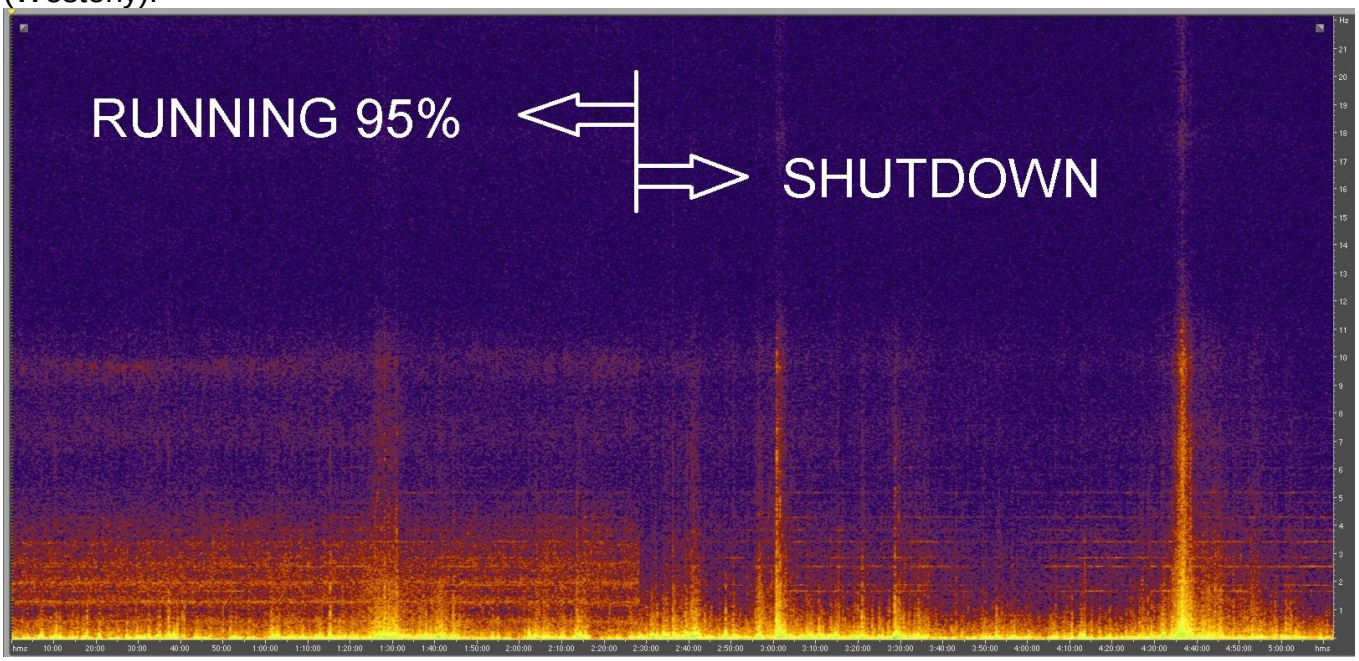


FIGURE 5 5-hour spectrogram during shutdown

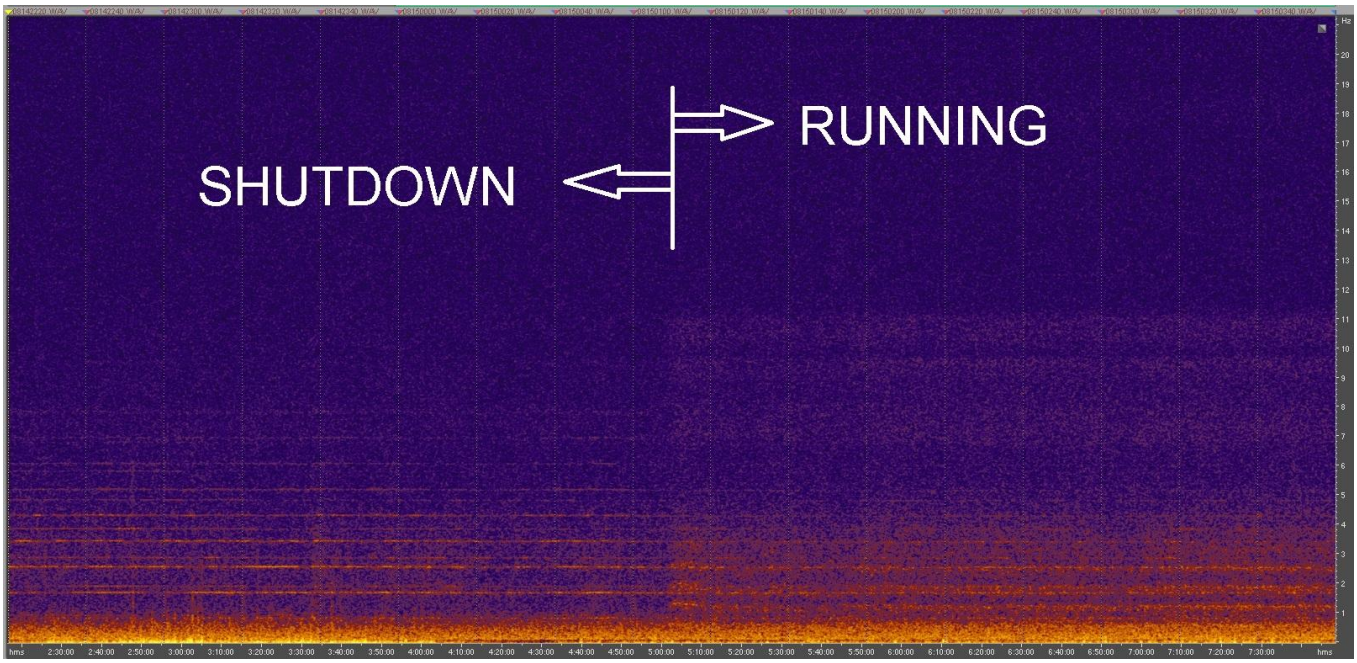


FIGURE 6 5-hour spectrogram during startup

Figure 5 and 6 clearly show that infrasound tones continue to be observed at P5 when all 140 turbines were at standstill. These tones do not align with the blade pass and blade pass harmonic frequencies. It is also interesting to note that the dB(G) filter, that is centred on 10Hz, would show very little differences in level from a shutdown and startup. A dB(G) filter has been used in a number of reports[6,7,8] to assess wind turbine infrasound impacts. Furthermore, the

use of 1/3 octave band analysis would hide the detail available to narrowband spectrum analysis used by the author in presenting data in this paper.

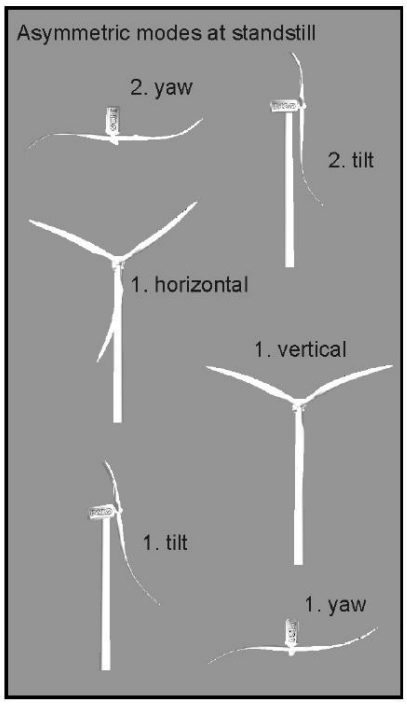
Styles[9] measured the lower frequency torsion and bending modes of a Nordex N80 tower to be 3Hz, 0.45Hz, 4.1Hz and 4.6Hz respectively. These modal frequencies would be different for a V112 wind turbine but the order of magnitude would be similar.

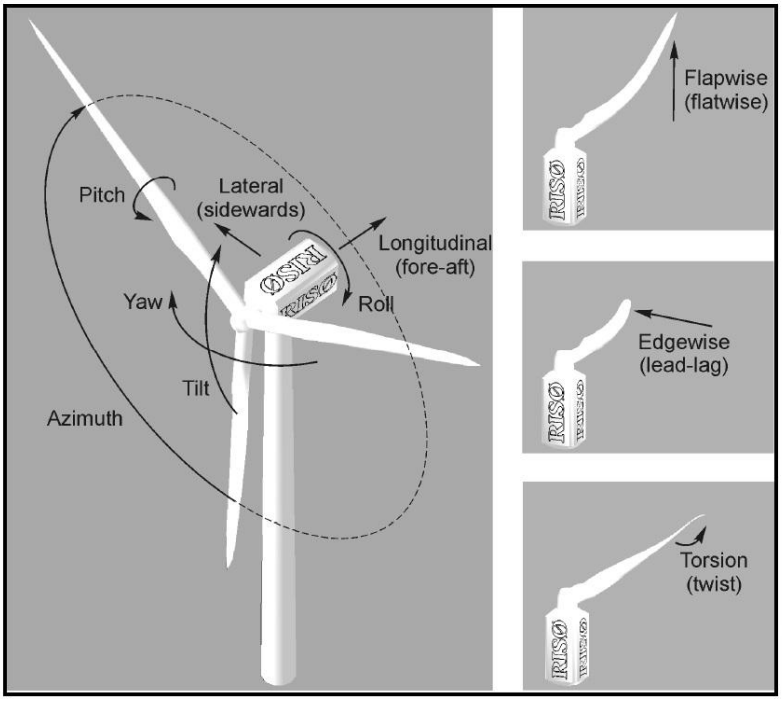
Otero et al.[10] presents blade vibration modes from their example analysis as follows:

Mode	Frequency Hz	Mode	Frequency Hz
1	0.707	6	6.47
2	1.02	7	6.69
3	1.82	8	8.01
4	3.34	9	8.24
5	3.95	10	9.78

Again, V112 blades would have different frequencies for each mode but the results indicate ten blade modes below 10Hz and five tower modes below about 5Hz.

The following extract (Figure 1 of their text) from Chauhan et al.[11] show the modes of a standstill wind turbine.





The spectrum charts shown in Figure 2, 3 and 4 show tones that are caused by resonant modes of the V112 wind turbines. It is apparent from the mismatch of resonances and blade pass frequency components that Vestas have carefully designed this unit to minimise fatigue of the wind turbine.

One-hour averaged sound pressure level changes before shutdown, after shutdown, before startup and after startup have been calculated.
The average overall sound pressure level change in the frequency range 0.5Hz to 8Hz from running at 95% rated wind farm capacity to 0% is -3.6dB.
The average overall sound pressure level change in the frequency range 0.5Hz to 8Hz from stopped at 0% to 30% rated wind farm capacity is 1.5dB.

Acciona issued a Note[12] summarising a meeting on 17 June 2010 between Acciona staff and a number of complainants. Comments made by a complainant, who lived near the Waubra wind

farm but who has since vacated his home, reported that 'Before turbines commissioned they were causing vibrations (like a big tuning fork) and affected Noel and Janine during strong winds from the South East, (this is before the turbines were energised).' The Acciona Note explains that the notes are not a transcript but reflect the nature of the comments made.

It would appear that there are individuals who can hear/sense infrasound/vibration from stationary turbine modes in strong winds. The data presented above show that stationary wind turbine infrasound at similar levels to operating turbines exist. This statement is made because a 3dB increase in sound level occurs when two similar sound levels are added together, or conversely a 3dB reduction is seen when one sound source is removed. Since the shutdown showed a 3.6dB reduction in sound level it would suggest that the resonant modes create infrasound levels similar to the contribution of the blade pass frequency and harmonics tones. At startup there was only a 1.5dB increase suggesting that the infrasound tones from resonant modes were dominant at 30% rated wind farm capacity.

Further detailed analysis of the data recorded at Macarthur is planned.

5 Cape Bridgewater Results

Analysis of infrasound measurements at Cape Bridgewater is in progress. However, the measurement of a startup is presented.

Figure 7 shows the spectra taken inside a dwelling 1km to the east of a group of 18 MM82 2MW wind turbines. The inset shows the turbine locations and measurement location CBR1. Again, wind direction and percentage generating capacity of the wind farm is shown for each trace. Unfortunately, detailed operating conditions for each turbine during the survey were unavailable to the author.

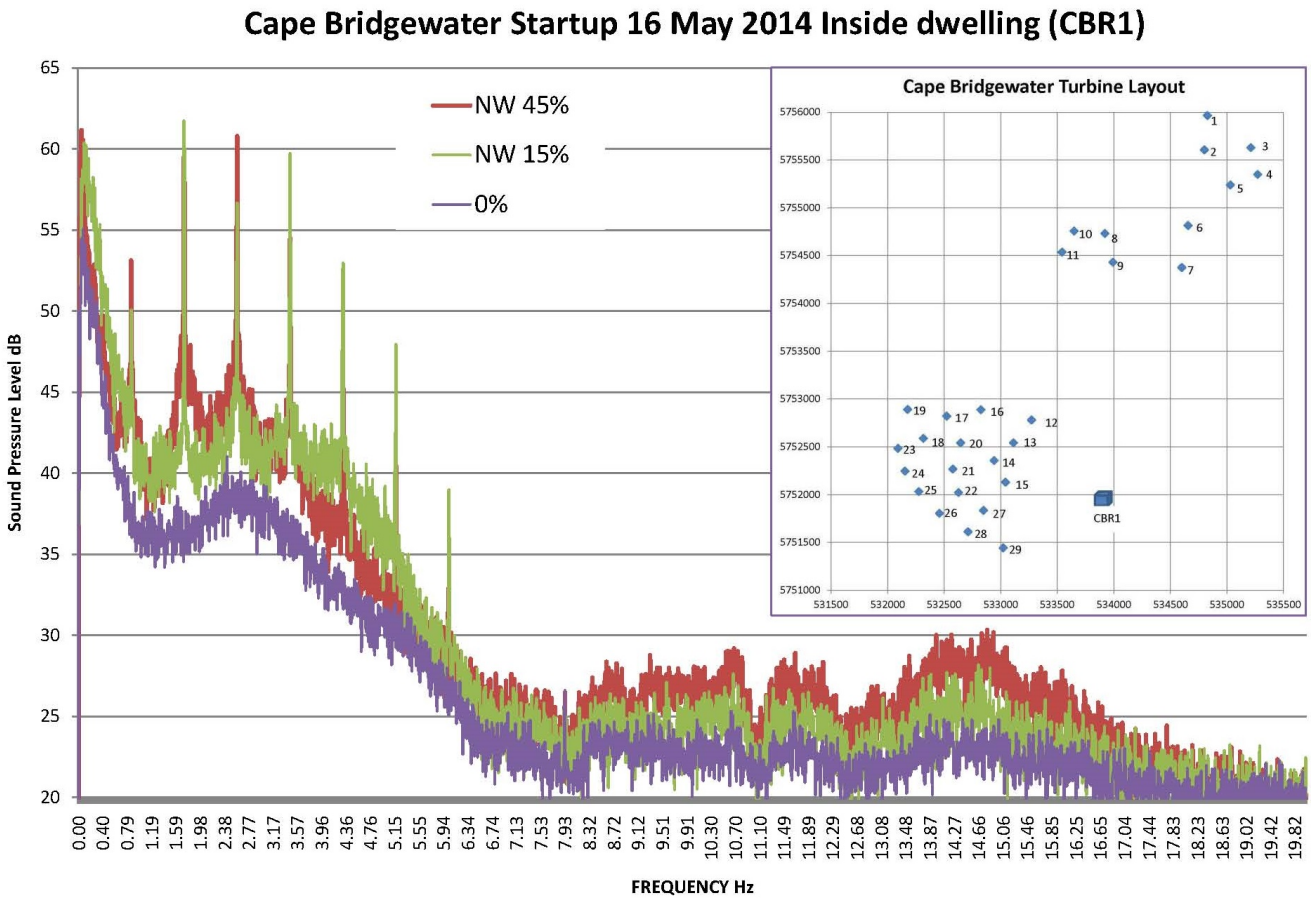


FIGURE 7

Again, as for the Macarthur shutdown and startup, a dB(G) filter would not reflect the part of the acoustic spectrum below 6Hz where the majority of infrasound energy is found to change after startup.

The startup recorded infrasound increasing by over 20dB in the frequency range from 0.5Hz to 6Hz with slightly greater levels shown at 15% wind farm capacity compared to 45%. Stationary infrasound tones from wind turbine resonances are not as clearly observable as those from the Vestas V112 3MW wind turbines.

Compared to infrasound levels recorded from the two MM82 wind turbines at Leonards Hill there is certainly a cumulative effect of having an additional 16 wind turbines, despite the CBR1 dwelling being 1km from the nearest turbines compared to 650m for the R1 dwelling at Leonards Hill.

6 Leonards Hill Results

Figure 7 show the measurement locations R1 and R2 in relation to the two MM82 wind turbines T1 and T1. R1 is situated equidistant from T1 and T1. A westerly wind was prevalent throughout the survey period.

Figure 8 is a 24-hour spectrogram at R1 showing a change from low power generation before 6am to stable operation (constant rotor speed) after 6am. The spectrogram observed at R2 on the same day is shown in Figure 9. A group of tones are shown in both figures between 13Hz and 17Hz that are clearly associated with the wind turbines after attaining stable operation.

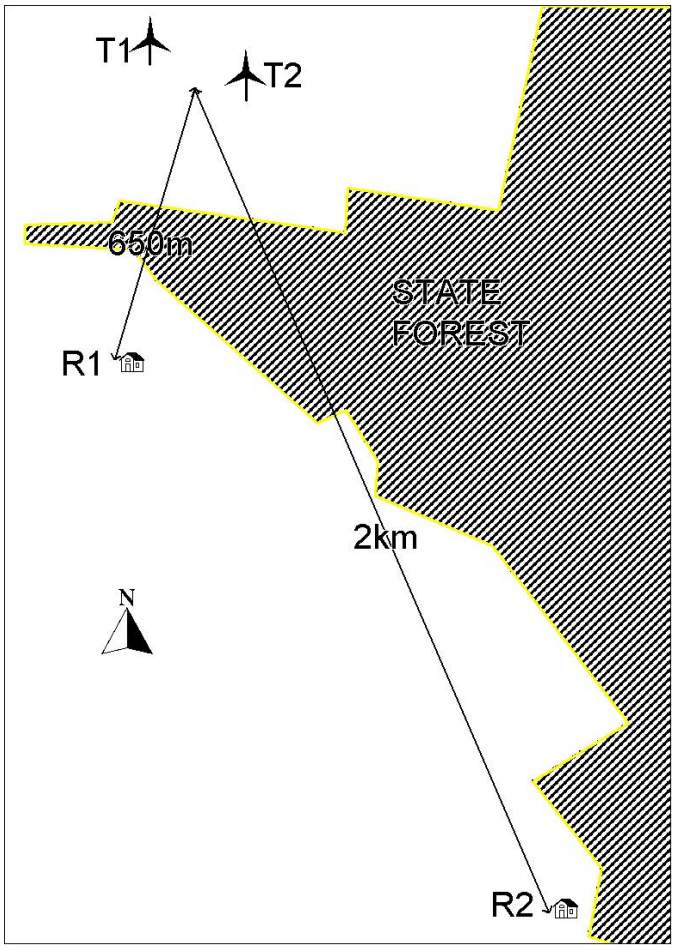


FIGURE 7

The attenuation in dB for each of the tones shown in the spectrograms has been calculated from 65536 point FFT spectra averaged over the same 1-hour period after 6am between R1 and R2. The attenuation obtained for each tone is shown in Figure 10 and is found to change with frequency.

The attenuation expected over a distance 650m and 2000m from a sound source is shown marked on the chart assuming 3dB per doubling of distance and 6dB per doubling of distance.

Measurements at R1 were inside a 3m by 3m bedroom but measurements at R2 were in a large open plan kitchen/living area having a room dimension of approximately 12m by 10m. The tones generated by the wind turbines in the frequency range 14Hz to 17Hz show a gain in sound pressure level, not the expected attenuation.

Standard calculations show that the room modes at R2 are causing an amplification of these turbine tones.

The R2 dwelling has been vacated by the owners who cite unacceptable health effects that correspond with turbine operation

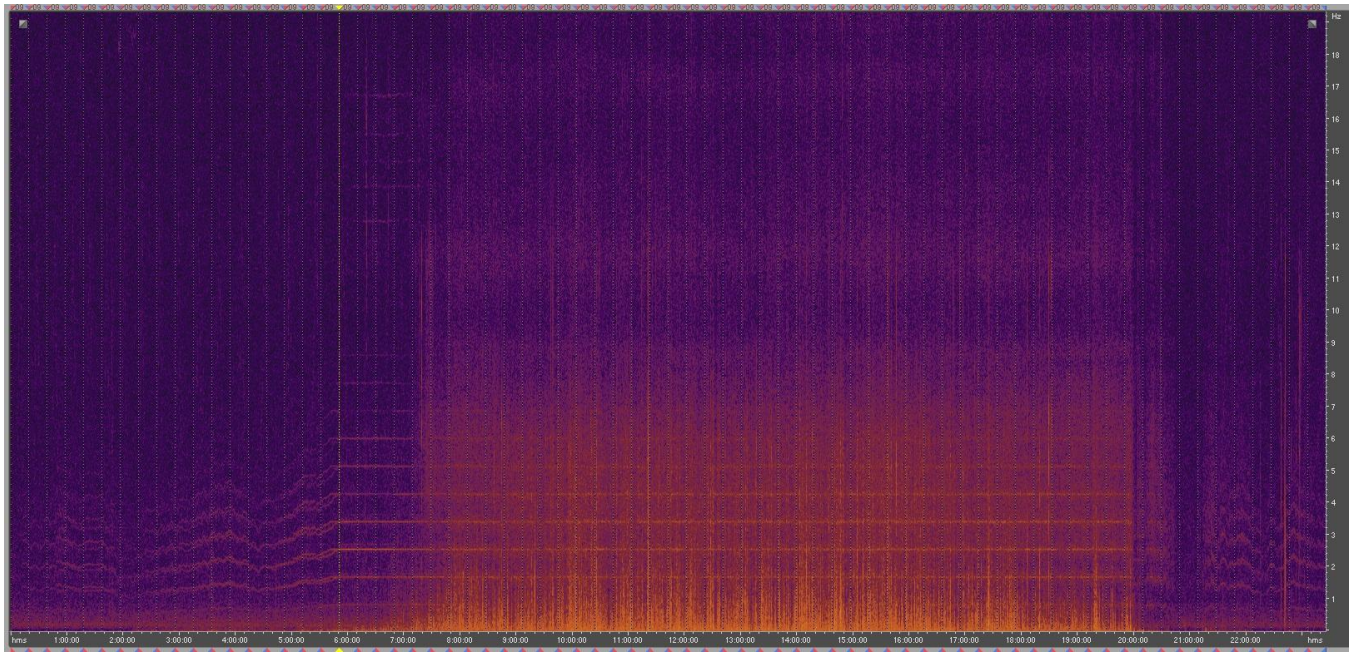


FIGURE 8 24 hour spectrogram at R1

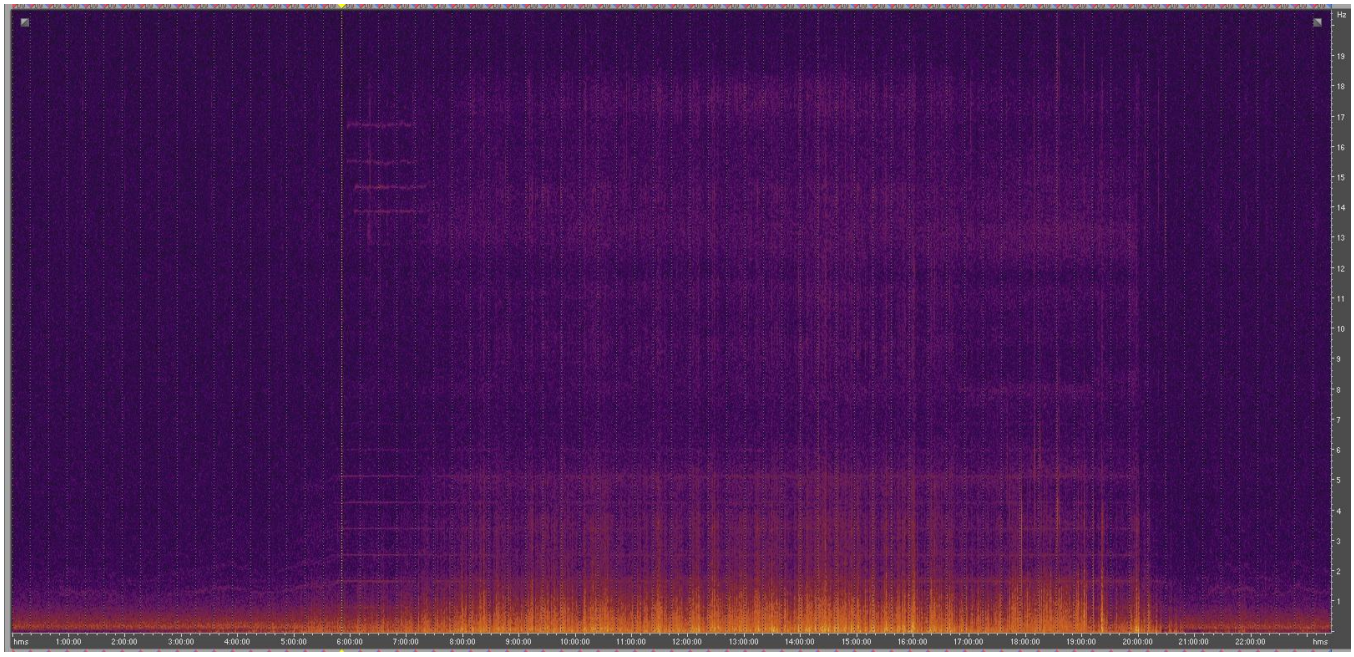


FIGURE 9 24 hour spectrogram at R2

Figure 11 shows another sample period measured up to 9Hz. The attenuation pattern changes from day to day. The measured attenuation results between 650m and 2000m from the Leonards Hill wind turbines show attenuation rates that vary between 5 LOG(Distance) and 32 LOG(Distance) for particular wind turbine tones.

A power fault at Leonards Hill caused a shutdown of the turbines that was observed at R1 and R2. It was apparent that three tones and their harmonics remained after shutdown, Figure 12. Two of the tones at 1.676Hz and 1.829Hz are identified to be from the Waubra wind farm located 46km from Leonards Hill. It is not yet known if the remaining tones are caused by stationary turbine modes.

An overall attenuation factor has been calculated from the Waubra tones observed at R2 and those same tones observed in Woodend at the same time over an averaging period of 1.5 hours. The average rate of attenuation downwind was found to be 12 LOG (Distance in m).

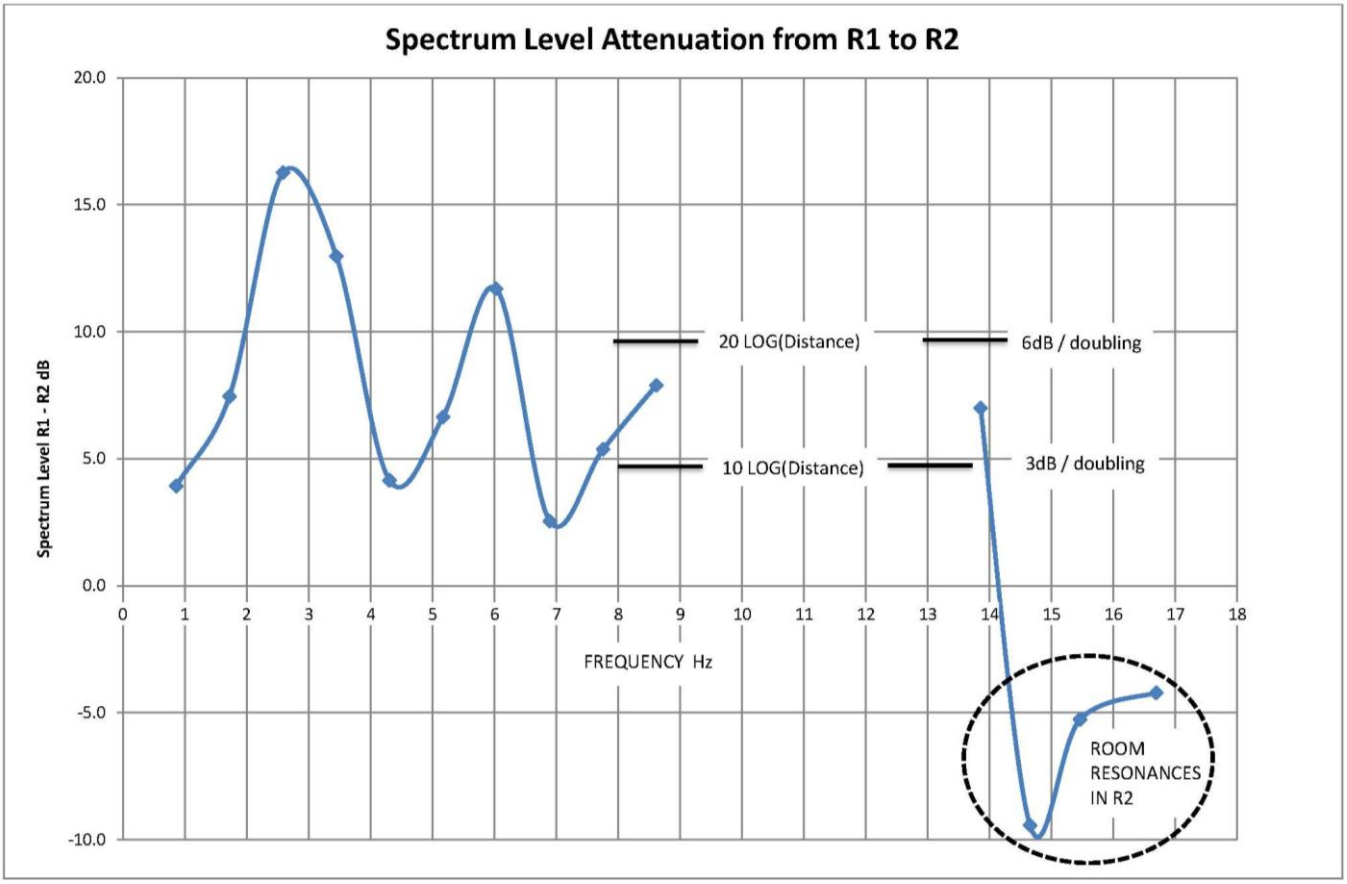


FIGURE 10

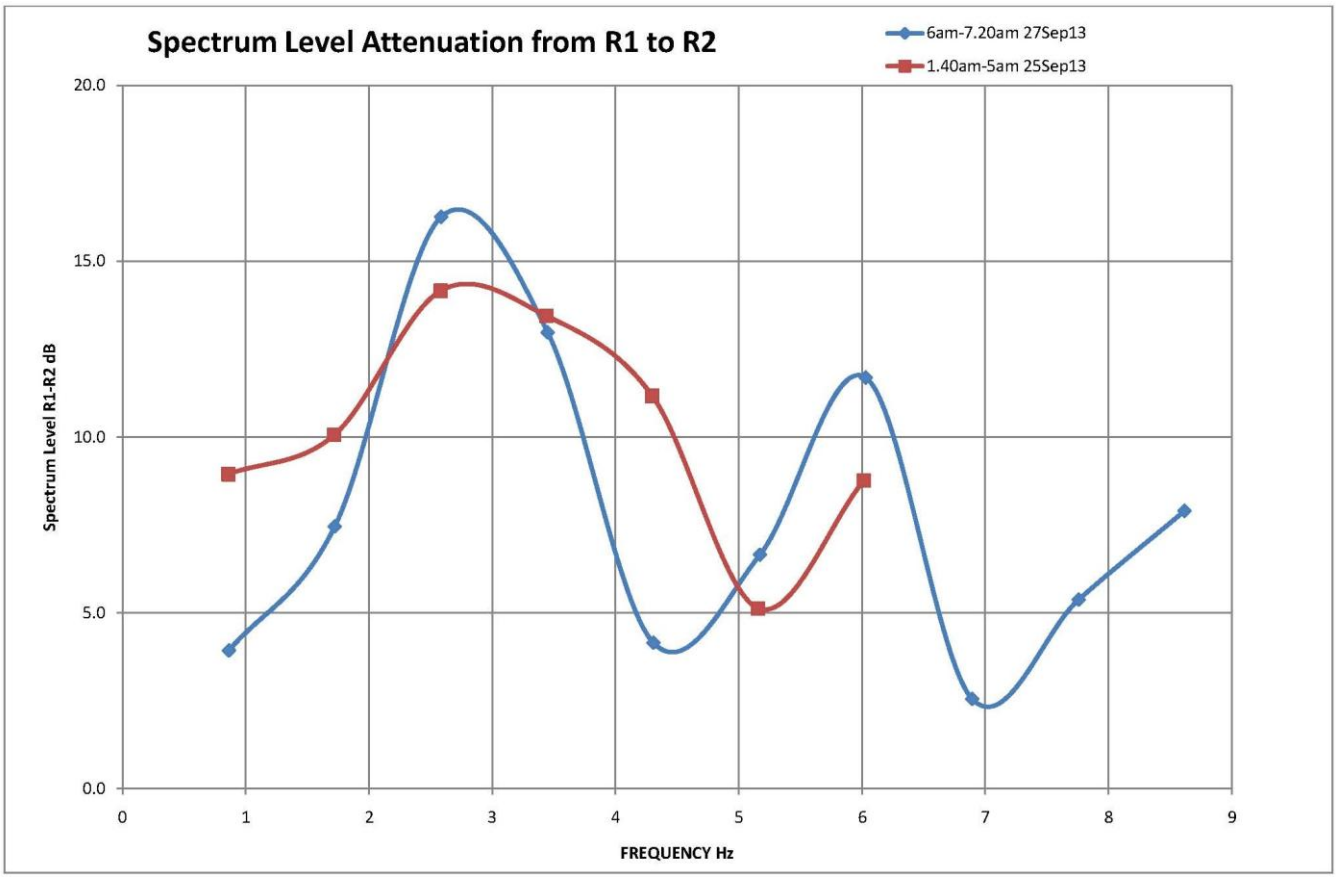


FIGURE 11

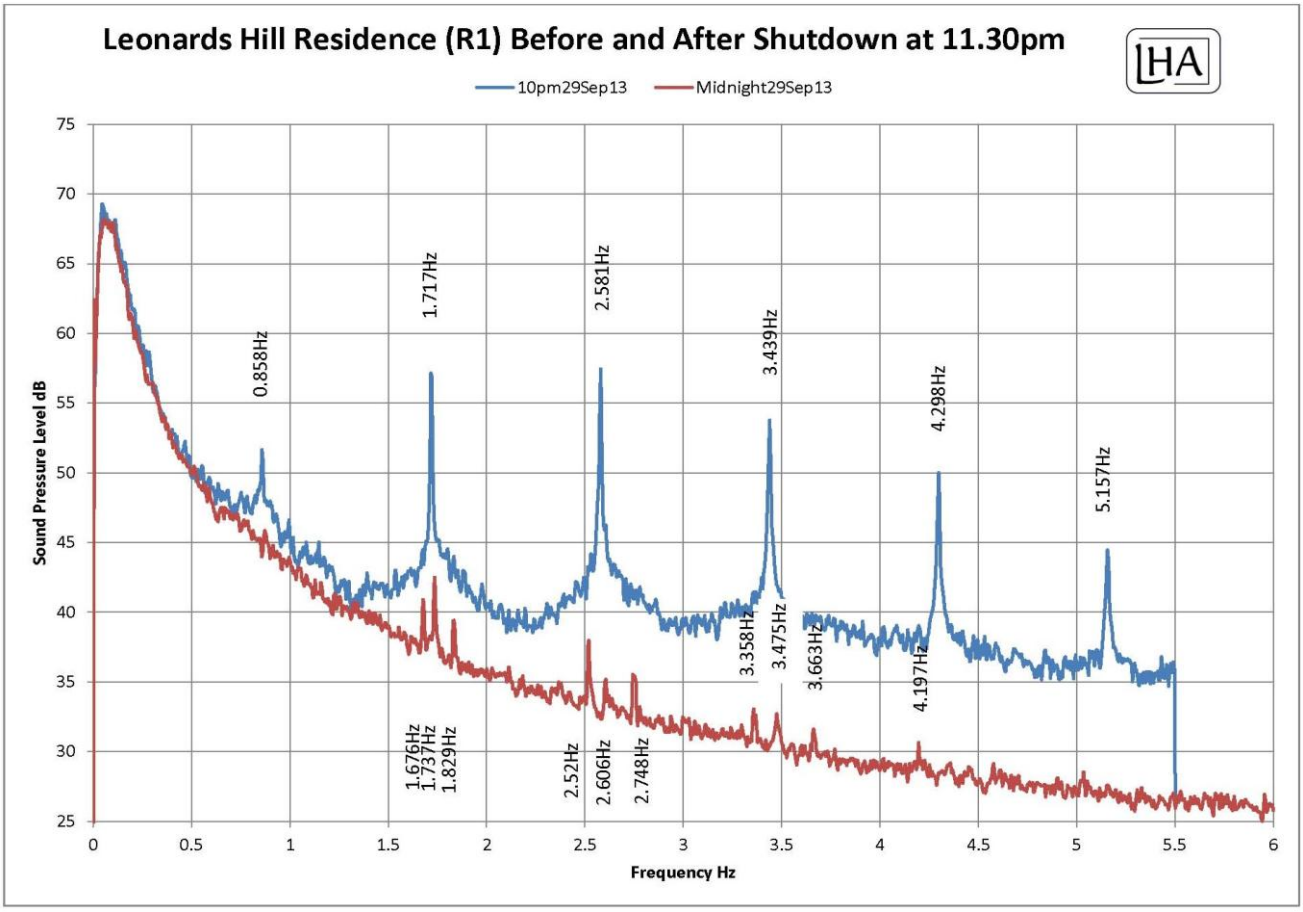


FIGURE 12

6.1 Attenuation modelling

A model has been prepared to explain the attenuation differences below 9Hz shown in Figure 11. The model uses the geometry of the turbine location and two receiver points 650m and 2000m away. Assuming that the two turbines can together produce a unity output in each frequency sample, spaced 0.1Hz apart from 0.5Hz to 9 Hz, it can simply be shown that the attenuation between two points located 650m and 2000m away from the sound source follows a varying, yet predictable pattern. The attenuation variations observed are caused by the interference pattern generated by phase differences between the rotors of the two wind turbines. The model includes variables for sound velocity and phase between the two turbine rotors with fixed parameters for turbine distances to R1 and R2.

An example of the predicted attenuation between R1 and R2 is shown in Figure 13 for two sound velocities and no phase difference between turbine rotor speeds. Although the measured data points shown in Figures 10 and 11 have been connected by fitted curves, the reality is that these sample frequency points lie on a more complicated attenuation curve similar to that shown in the top two charts from the model results in Figure 13. The apparent attenuation 'curve' using only the turbine tone frequencies is shown in Figure 13 below the corresponding finer resolution chart. Results in predicted attenuation between R1 and R2 with a 2m/s sound velocity change are shown side by side in Figure 13.

The implication of this result is that minor sound velocity changes can cause large variations in propagation attenuation between two points at distances out to 2km. The same result would be obtained if the sound velocity remained constant but the wind speed changed by 2m/s. Similarly, different predicted attenuations arise if the phase between the turbine rotors is changed.

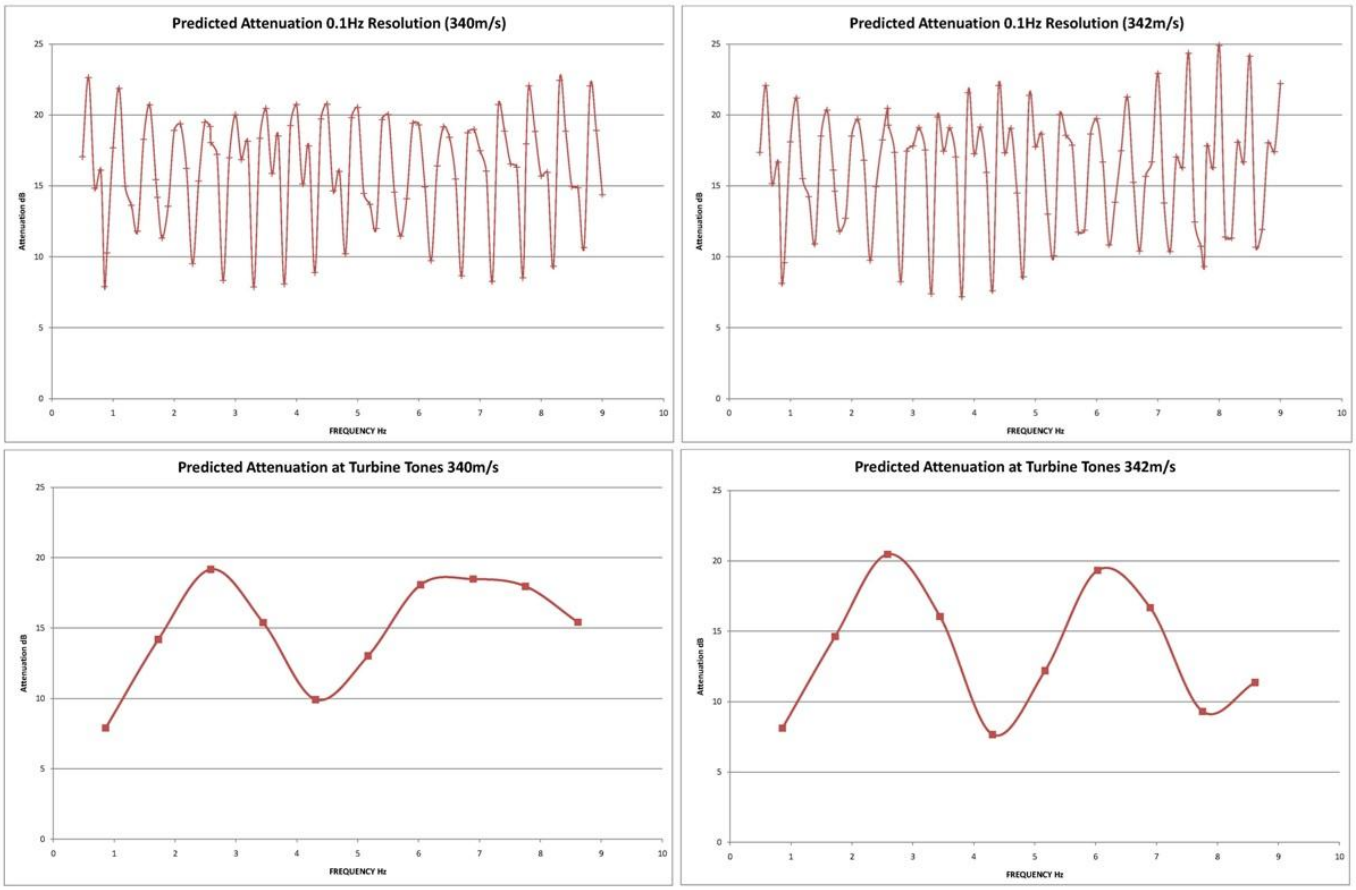


FIGURE 13

Closer examination of infrasound measurements in the time domain show that individual tones vary in amplitude and with no apparent relation to each other. All blade pass generated tones do not rise and fall together over time. For example, a 3-minute averaged spectrum sample can show a high second harmonic of blade pass frequency for a turbine and a low third harmonic. In the next 3-minute sample the relative amplitudes can reverse. This amplitude modulation of the blade pass tones has a relationship with both the rate of change in wind speed and the rate of phase change between the turbines. The same also applies to infrasonic emissions from static turbines observed at the Macarthur wind farm.

7 Woodend Measurement Results

Recent measurements taken in a Woodend dwelling have shown that it is possible to clearly identify the infrasound spectrum contribution from the three nearest operating wind farms. Figure 14 shows the geographic locations of Woodend and the three nearest wind farms.

The Waubra, Mount Mercer and Leonards Hill wind farms were all operating at 80% of rated capacity at the time of measurement for the spectra shown in Figure 15. Mount Mercer was built and became operational after the measurements were taken at Leonards Hill in September 2013 (Figure 12).

Unusually, the Windtest report SE09001B4 for the MM92 wind turbines used at Mount Mercer has sound power measurements in one third octave bands from 1Hz to 20Hz. If we assume a simple cumulative total sound power level from 65 MM92 turbines to be +10LOG(65) we can calculate the attenuation rate overall to Woodend 80km away.

From the measured sound pressure levels in downwind conditions to Woodend in the 1.6Hz, 2.5Hz and 8Hz one third octave bands the average attenuation rate is:
12.5 LOG(Distance from source in m).

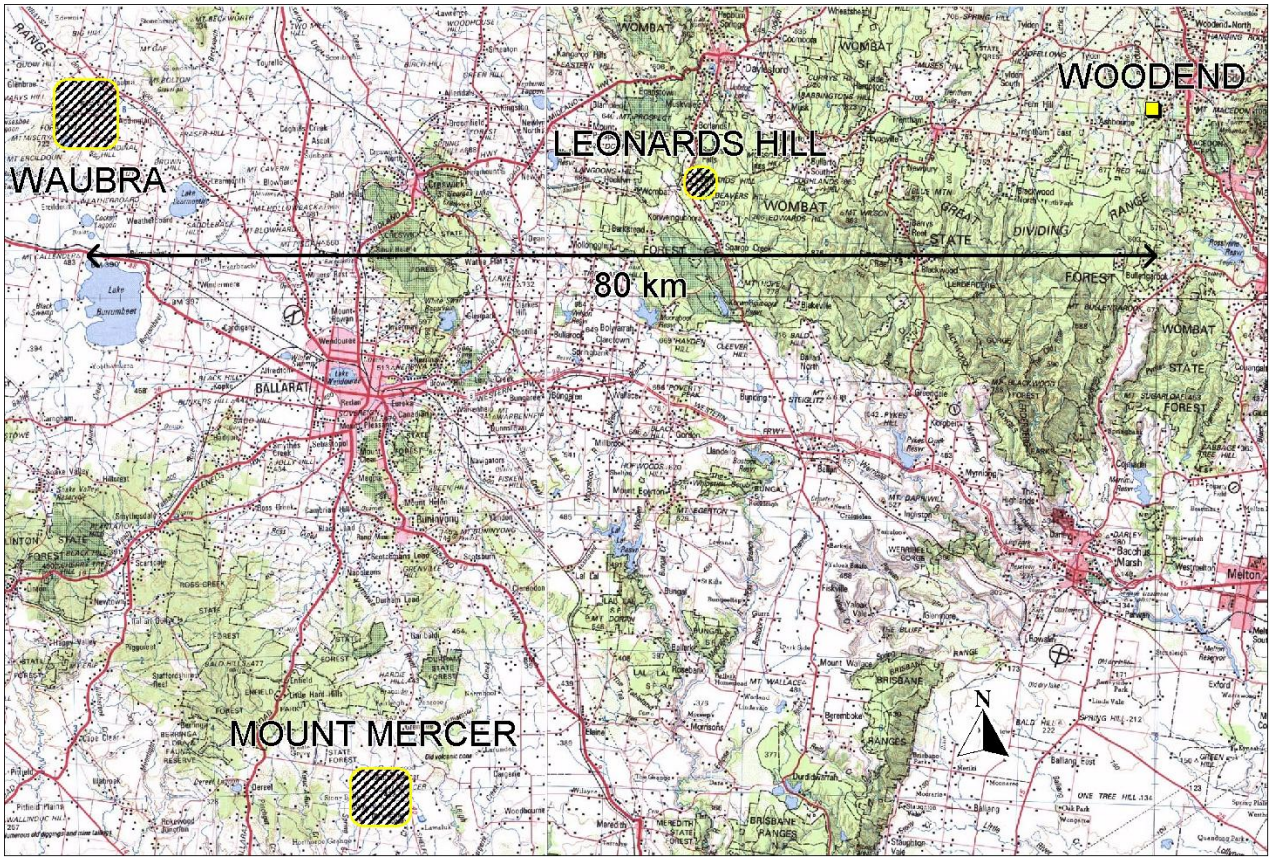


FIGURE 14

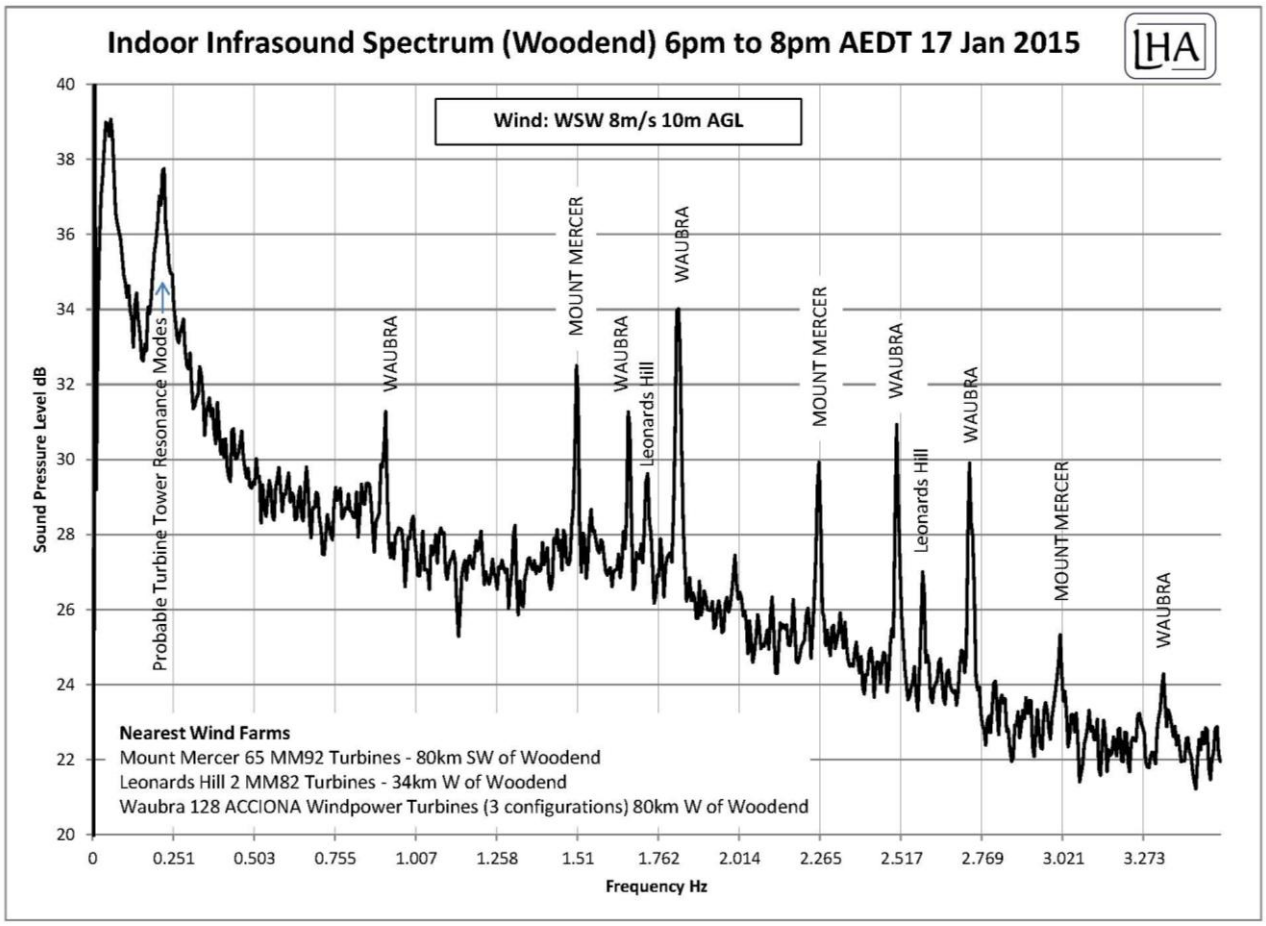


FIGURE 15

8 Conclusions

Infrasound spectrum results have been presented for a number of wind farms in Victoria, Australia, in conditions of shutdown, startup and normal operation. The narrowband spectra presented are derived from typically 1-hour averaging periods. Shorter 3-minute individual spectra within each 1-hour average show that amplitudes of the dominant tones observed vary (amplitude modulation) and often exceed the 1-hour averaged result by 6dB.

Simultaneous measurements surrounding the Macarthur wind farm in different wind directions show that downwind broadband infrasound levels increase compared to upwind locations.

It has been shown that there are infrasound emissions from stationary V112 3MW wind turbines at the Macarthur wind farm. Infrasound emissions from stationary and operating wind turbines in winds capable of producing maximum generating capacity are similar. The measurements show that for winds capable of generating 30% rated capacity the resonant (stationary condition) modes emit higher infrasound than those caused by blade pass effects.

For the Macarthur V112 wind turbines the average overall sound pressure level change in the frequency range 0.5Hz to 8Hz from running at 95% rated wind farm capacity to 0% was -3.6dB. The average overall sound pressure level change in the frequency range 0.5Hz to 8Hz from stopped at 0% to 30% rated wind farm capacity was 1.5dB.

Wind turbine resonant modes are more prominent on the 3 MW V112 turbines than the MM82 2MW turbines. This may be due to the different blade and tower properties.

The use of 1/3 octave band analysis would hide the detail available to narrowband spectrum analysis used by the author in presenting data in this paper. The results also show that the dB(G) filter, when used as a measure for wind farm infrasound emissions, effectively hides the frequencies below 6Hz where most infrasound energy is found.

The measured attenuation results between 650m and 2000m from the Leonards Hill wind turbines show attenuation rates that vary between 5 LOG(Distance) and 32 LOG(Distance) for particular wind turbine tones. A model was prepared to explain the seemingly odd results.

From measurements and the subsequent modelling of the two-turbine Leonards Hill wind farm it has been demonstrated that the variation in calculated attenuation rates observed at two fixed locations is dependent upon the apparent sound speed (speed of sound +/-wind speed) and the phase between the rotation of each turbine. Changes in amplitude of the dominant wind turbine tones below about 10Hz are related to wind speed and the phase relationship between turbine rotors. The rate of change of amplitude at a fixed location (amplitude modulation) is related to the rate of change in wind speed and the rate of change in phase between turbine rotors. This effect can become extremely complex, yet predictable, with numerous wind turbines.

Long-range propagation loss measurements (46km and 80km) downwind show a propagation loss of around 12 LOG(Distance).

Long-range propagation loss calculations from the measured sound pressure levels in downwind conditions at Woodend, over 80km from the Mount Mercer wind farm, and published sound power test results for the MM92 wind turbine in the 1.6Hz, 2.5Hz and 8Hz one third octave bands provides an average attenuation rate of 12.5 LOG(Distance).

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