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Hiding Wind Farm Noise in Ambient Measurements - Noise Floor, Wind Direction and Frequency Limitations

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Summary
Apart from inadequacy of dB(A) measurement to identify the acoustic signature of wind farm noise the provision of averaging techniques by use of regression curves related to hub height wind speeds are of no assistance to the community in determining acoustic compliance. Furthermore the frequency limitation of various sound level meters automatically restricts the provision of appropriate noise data related to turbine operations. A further issue of concern relates to the noise floor of the measurement system that by the (intentional or unintentional) selection of microphones can render the measurements of no assistance. Examination of different analysis parameters, instrumentation frequency response and microphone noise floors is provided to identify the above anomalies

1. Introduction
The selection of acoustic descriptors used for general community noise assessments do not specifically address or cater for unique characteristics that may be exhibited in the acoustic signature that alter the subjective response to the noise. It is in response to unique characteristics to the noise that leads to a more detailed assessment to quantify the subjective impact. To the modern day acoustician, with the advantage of sophisticated instrumentation and advanced measurement techniques, utilisation of the more detailed analysis is readily available yet often times ignored.

The use of limited capabilities of instrumentation (intentional or unintentional) does not assist in providing the technical basis of measuring let alone understanding the acoustic impacts associated with the operation of wind farms.

For acousticians who are also involved in the assessment of machine vibration their thought processes give rise to different forms of analysis that do not necessarily occur on a regular basis in the acoustic domain. The analogy of machine vibration may assist in identifying different analysis processes that occur for persons involved in such investigations that could directly relate to some of the unique acoustic issues associated with wind farm noise.

2. Vibration Analysis

When there is a significant level of velocity or acceleration recorded on a machine then in a simplistic nature the justification of vibration problem can be identified on an audible basis when the machine doesn't sound right.

The use of octave band information for vibration work is generally of no real assistance with a preference (for vibration measurements using sound level meters) to utilise one third octaves so as to identify specific operating components generally related to the main driveshaft speed of the machine under investigation.
However looking to identify problems that may occur in a machine, which do not necessarily show up in an overall vibration level or 1/3 octave band analysis, the general procedure is to consider narrowband analysis to determine individual frequencies associated with various operating parameters/elements of the machine.

The vibration engineer is used to looking at a narrowband analysis (for machines that in general terms can be expressed as operating at low speeds) they also consider the frequency analysis in terms of a linear domain rather than a logarithmic domain normally applied to acoustic assessments.

For more complex vibration problems such as gearboxes and bearings there are more complex analyses that are available which look to time history and modulation of the signal (such as Cepstrum analysis and Kurtosis analysis) to extract detailed information such as gearmesh frequencies and bearing resonance effects.
Similarly in dealing with the wide range of vibration levels that can occur for different types of signals the vibration engineer may utilise extremely small accelerometers that will not affect the operation of unit under test and at the same time are normally associated with high shock values. For general machine vibration measurements the accelerometers are typically increased in size and the output sensitivity is increased, whereas for low level vibration, such as that associated with seismic investigations, the accelerometers themselves are much larger and have a much greater sensitivity so as to produce a useful output.

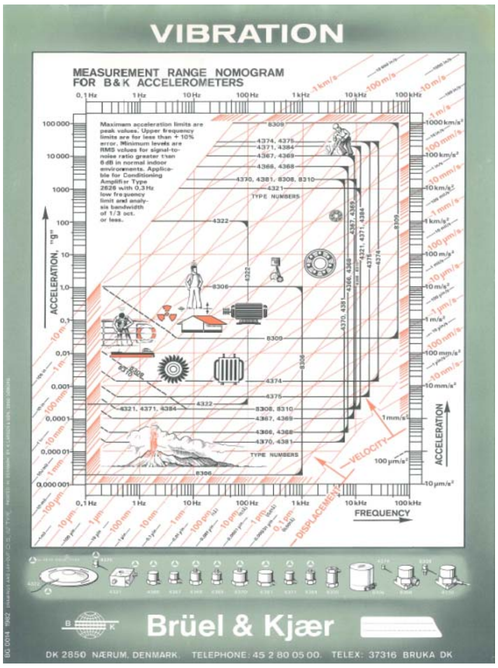

Figure 1 shows a typical accelerometer selection chart from Bruel and Kjaer and indicates that the use of very small accelerometers with low sensitive outputs will be unable to record seismic vibrations, whereas the seismic detector would be overloaded when dealing with high level accelerations such as encountered on the handle of a jackhammer.

In other words in the vibration domain there are different accelerometers for the different types of measurements being undertaken. Furthermore the frequency assessment is predominantly in the linear domain and generally of a lower bandwidth than that encountered in the acoustic domain.

FIGURE 1: Vibration Nomogram

3. dB(A) Levels

The general concept for environmental criteria in relation to the emission of noise from wind farms has been to utilise the A-weighted value when assessed at residential properties.

Whilst dB(A) is appropriate for general environmental noise assessments it is common for the regulatory authorities to include corrections to the measured value to take account of the audible characteristics that may be contained in the subject noise. For example where a noise contains tonal, impulsive or intermittent characteristics various regulations and standards in Australia look to add penalties to the measured level although some penalties do not operate during the night time period.

The presentation of material in simply the dB(A) value has limitations in understanding noise emitted from wind farms in that the A-weighting filter significantly attenuates low frequency noise.
In acoustic matters it is common to provide noise data in terms of octave bands or 1/3 octave bands so as to indicate potential spectral characteristics of the noise.

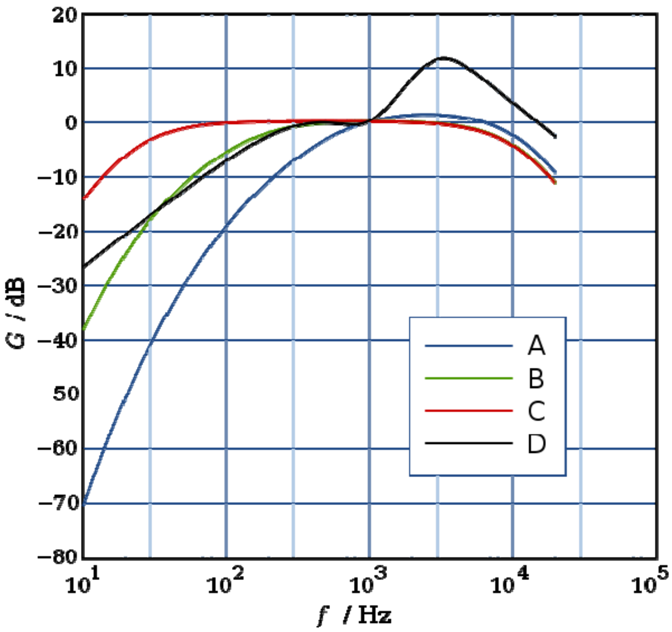

Figure 2 – Common Frequency Weightings

Older acousticians will be used to dealing with octave band information in a linear format whereas there is a general trend in today's digital era to utilise A-weighted spectral information. If one considers low frequency noise to occupy the bandwidth of 20Hz to 200Hz and the infrasound region to be below 20Hz then the significant degree of attenuation provided by the A-weighted curve provides incorrect information as to infrasound energy generated by wind farms (see Figure 2).

Figure 3 provides noise levels measured at distances in excess of 500m from turbines where a sound power level on the basis of hemispherical radiation has been derived for a number of wind farms.

The graph in Figure 3 presents the data in relation to power levels attributed to the turbines in both a linear format and an A-weighted format, where the difference in the spectral shape for the time different frequency weighting is obvious [2].

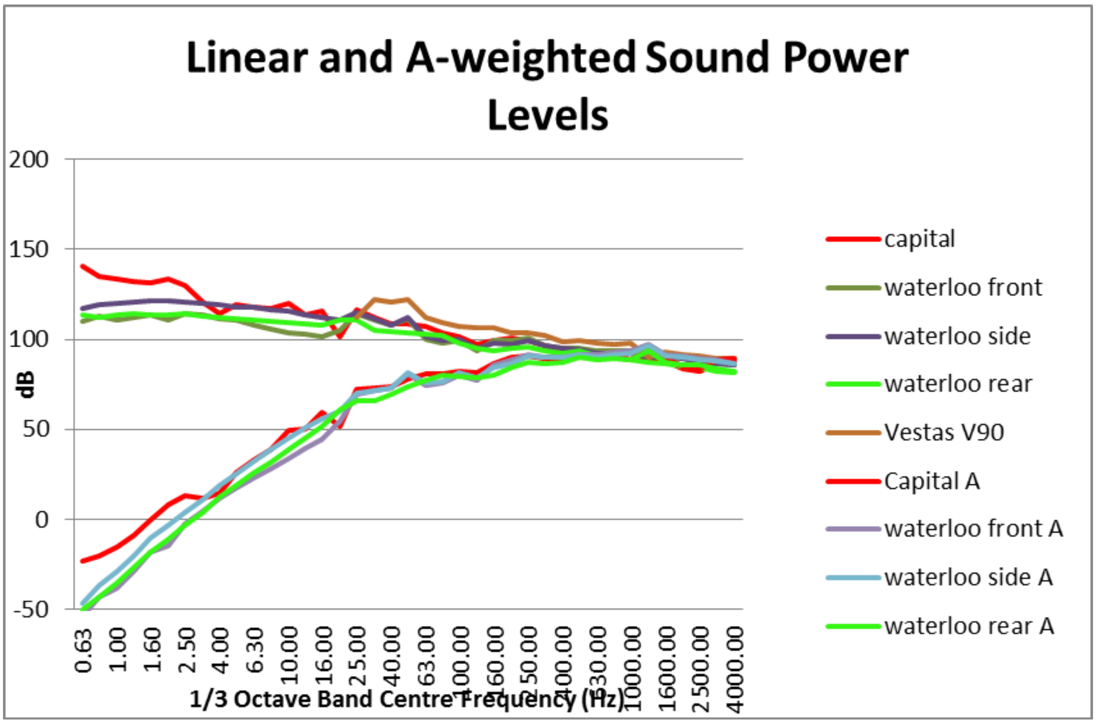

FIGURE 3 Turbine Sound Power Levels (Linear versus A-weighted)

3.1 Audible Characteristics If one is reporting dB(A) Leq levels, adjustments need to be made to account for the subjective nature of the noise. Generally there is a claim there are no subjective characteristics to the noise. If one only utilises Leq and L90 dB(A) levels from noise loggers then there is no attempt to ascertain other characteristics.

Amplitude modulation is one characteristic that can be detected but will not show up in a Leq or a L90 measurement result. The variation in the A-weighted level emitted from a turbine in some cases is identified as a modulation that occurs at the blade pass frequency rate as shown by the time signal in the A-weighted value apparent at a residential locations removed from the turbines – dependent upon the wind direction.

Figure 4 identifies spectral characteristics attributed to operational turbines for a measurement conducted approximately 150m from the base of the turbine with the analysis conducted using a 10 minute time sample to accord with the standards utilised in Australia. The results whilst normally being presented as an L_{eq} level have in the example shown in Figure 5 show there are statistical variations in the noise over the 10 minute sample for all of the 1/3 octave bands.

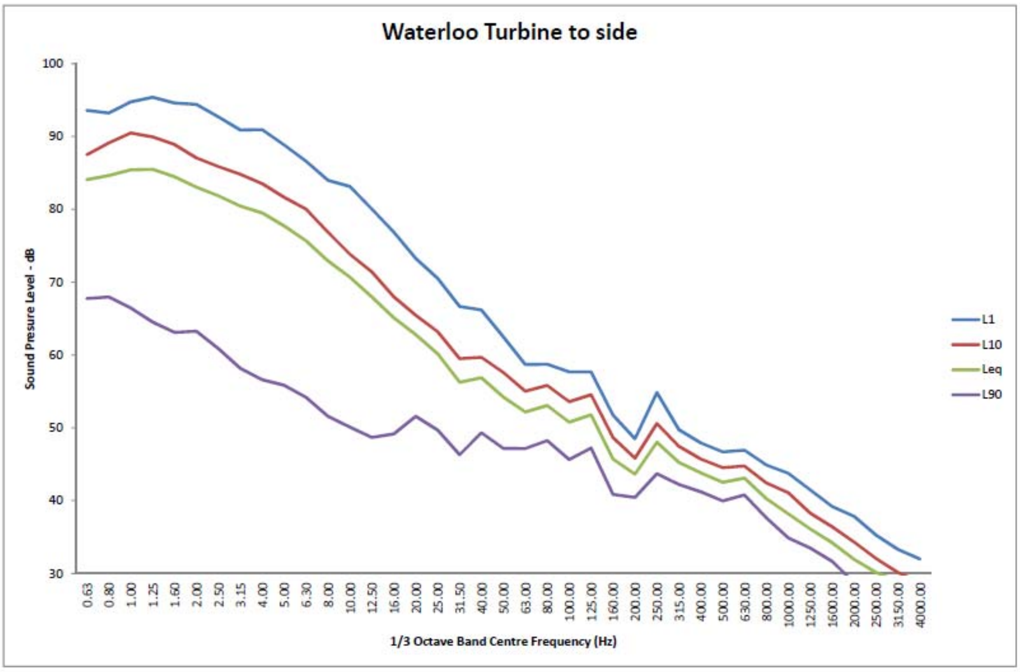

FIGURE 4: 1/3 Octaves at 150 metres from turbine

When the spectrum at residential receivers contains tones that are clearly audible at the location the use of the typical adjustments with a 1/3 octave band levels, either as a 1 sided or 2 sided assessment procedure, tend to identify that the sound is non-tonal despite narrowband analysis showing tones to be present.

As in the vibration analogy discussed earlier, when one looks to specific components associated with wind farm noise emission there are a series of different narrowband components associated with the emission that do not necessarily show up in 1/3 octave band analysis yet such narrow bands may be present.

If one considers the low-frequency region, and in particular the infrasound region, examination of the 1/3 octave bands may not reveal the presence of any discrete components due to a merging of the harmonic pattern associated with the blade pass frequency and its harmonics and other tones that becomes clearly evident if one uses narrowband analysis over the infrasound region as shown in Figure 5.

3.2 Infrasound The use of narrowband analysis permits one to identify the peak frequency components in the wind turbine signature that occur in the infrasound region that by definition will not be contained in the A-weighted level.

For the purpose of considering wind turbine noise in Australia we have utilised the descriptor of *Wind Turbine Signature* where the pattern associated with the blade pass frequency and the first 5 harmonics can be detected both near the turbines and at residential dwellings on a regular basis. None of these low-frequency patterns can be detected by use of the A-weighted parameter and therefore are hidden in the assessment.

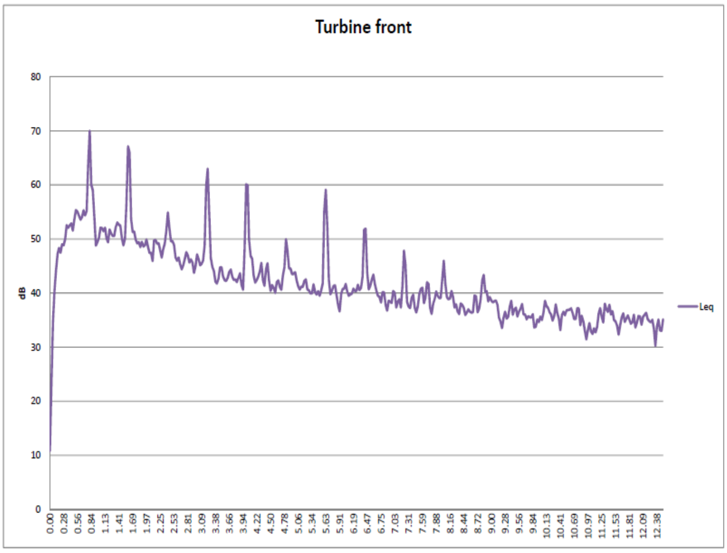

FIGURE 5: At 150 metres from turbine

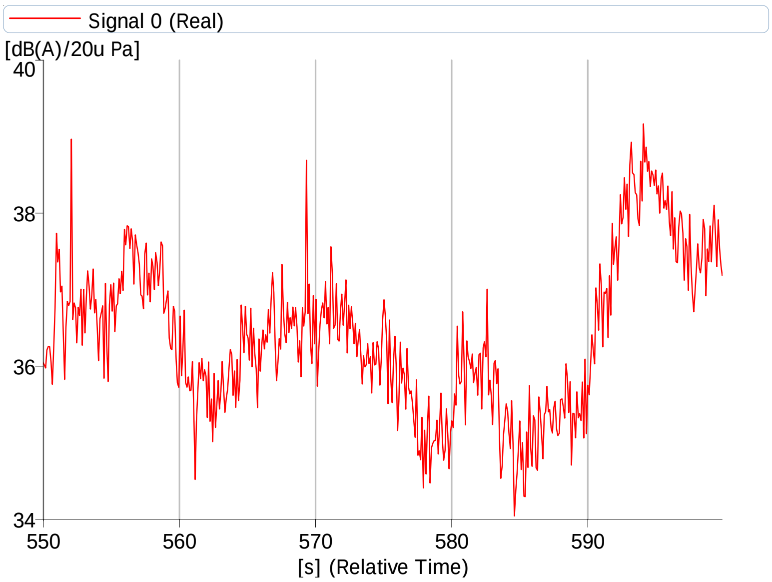

FIGURE 6: dB(A) over time

3.3 Amplitude Modulation

One proposed criterion to address amplitude modulation [3] is if there is a variation of greater than 4 dB(A) at the blade passing frequency then modulation will be considered as an excessive level requiring a 5dB(A) penalty to the predicted or measured level from the wind farm. The modulation characteristic penalty applies only if the modulated noise from the wind turbine is audible at the relevant receiver.

What does that definition of excessive modulation mean? Is it peak to peak of individual waves? Is it the peak to peak of the modulation or the extremities of the overall level?

Figure 6 provides an expanded view of a 10 minute sample of the wind farm noise at a residential property 2.6 km from an operational wind farm. The noise from the wind farm was audible as was a modulation.

Figure 7 is the narrow band analysis of the 10 minute sample (from which Figure 4 was extracted) and identifies a number of distinct peaks in the low frequency region. Whilst Figure 8 covers the infrasound region with the main peak being the second harmonic of the blade pass frequency.

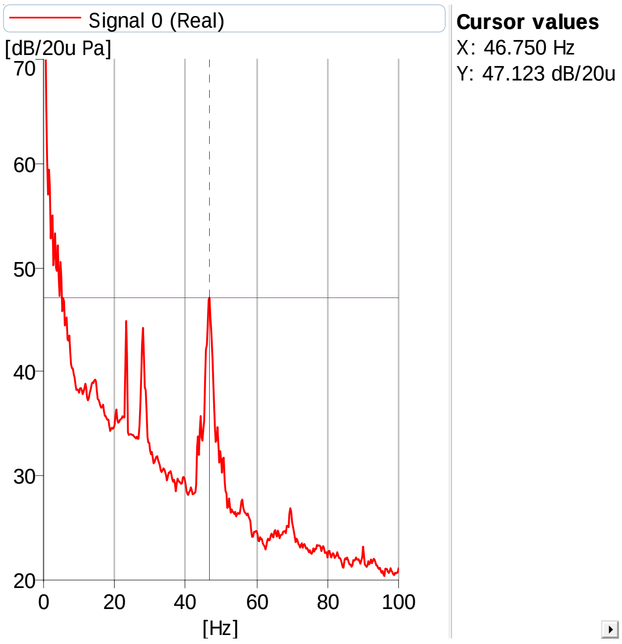

FIGURE 7: FFT 0-100Hz

The modulation is not apparent for noise logger measurements shown in Figures 10 and 12, unless one undertakes wave file recordings then amplitude modulation is not detected. Note the Wind Turbine Signature evident in Figure 5.

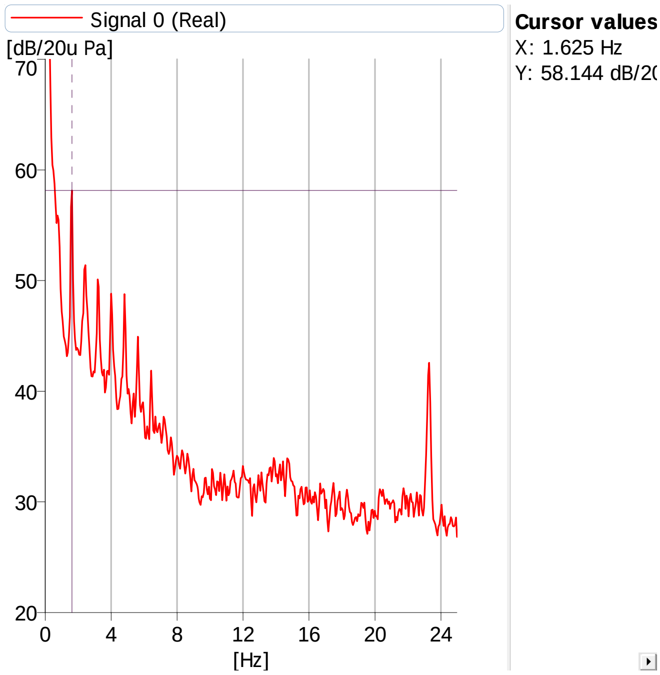

FIGURE 8: FFT 0 -25Hz

3.4 Hearing the infrasound modulation Acousticians may remember that in early days of vibration analysis instrumentation did not go low enough to measure the signature of operating machinery and by use of variable speed instrumentation recorders one could measure the signal at one speed and play back at a higher speed (typically 10 times speed) to conduct the analysis. A similar procedure has been used in relation to acoustic scale modelling of concert halls.

One can take wave files and modify the parameters so as to increase the speed 100 fold so as to then be able to audibly hear the blade pass frequency and the harmonic relationships from the infra sound region.

Similarly by the use of wave file measurements recorded on site one can, without increasing the speed of the signal listen to the audio as a post processing method where additional gain can be supplied and identify acoustic signals in the receiving location even though at the time the persons in attendance may not necessarily be able to detect the noise.

Another issue that has come to light in relation to hiding wind farm noise in ambient measurements has been the selection of averaging times used in the analysis, particularly when looking at modulation and narrowband components. When dealing with constant percentage bandwidth filters the analysis time required to have a valid signal must agree with BT=1. If one looks to frequencies below the audible band then the time period for analysis automatically increases.

For an assessment in Australia was suggested that the averaging time of the analysis be increased to 10 seconds to cater for low-frequency infra sound components in assessing the G-weighted level or the linear levels from which the time signal of the event bears no relationship to what actually occurs.

Similarly for narrowband analysis one can select the number of averages that under linear averaging can lead to different results.

4. Hub Height Wind Speed versus Background Level and Regression Analysis

The procedure used in Australia for determining the criteria to apply at residential receivers uses ambient background level measurements at residential locations referenced back to the wind speed recorded at the wind farm site for either a position 10m above ground level or (now) more commonly at the hub height. The regression analysis does not identify wind direction or wind speed at the residential receiver. The regression analysis reveals a spread of results with derived line representing an average background level rather than the repeated minimum background level used for industrial noise assessments in Australia.

What does the difference between the wind speed and direction at the receiver location versus the hub height?

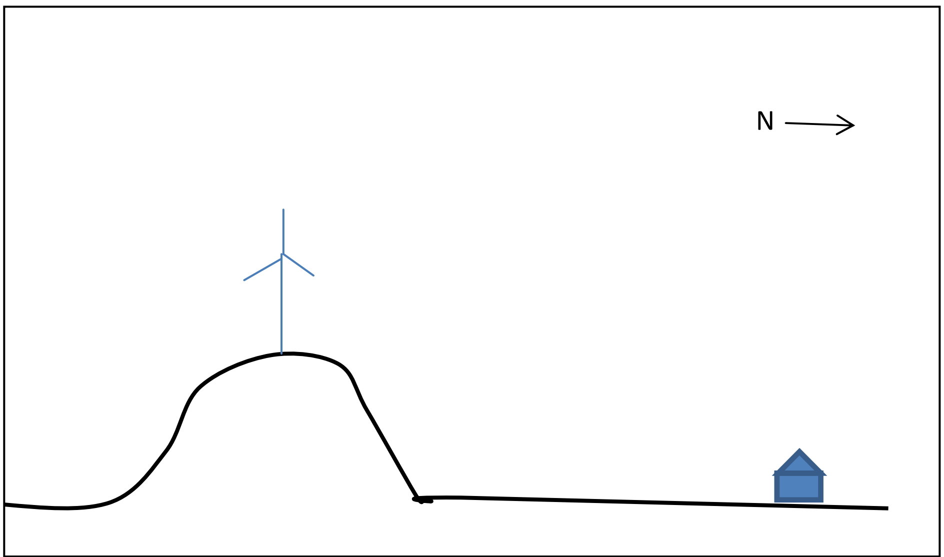

FIGURE 9: Wind Direction Example

Consider the situation in Figure 9 of a residential location located on the northern side of a hill upon which is located a turbine. If one assumes at the present point in time that the wind has a constant speed for different heights then for a wind direction blowing from the south to the north the turbines will be subject to wind but the residence being in the lee of the hill may not receive any wind. In this situation the residential premises would be downwind of the turbine and therefore could be expected to have a higher noise level than if one considered a stationary noise source under still wind conditions.

For the reverse situation of a wind blowing from the north to the south the residents could experience, depending upon the wind strength, an increase in the background level but would also be expected to have a reduction in the turbine noise level emitted under neutral conditions by reason of the residence now being upwind of the noise source.

Therefore for the same hub height wind speed the background level at the residential dwelling can be different for the 2 different wind directions depending upon the strength of the wind, as can the noise emission from the turbine under the different wind directions and wind speeds.

If one was to undertake wind speed and direction measurements at residential locations when the ambient noise level was being recorded, and that material was presented then there could be a correlation between the ambient background level at the residence unclear different prevailing weather conditions with that at the hub height.

Figure 10 provides a graph of noise level over time at a residence depicted in the concept in Figure 9 where the author was in attendance at the time. If one looks to the time around 5pm the ambient background level outside the residence was 30dB(A) and there was no wind at the residential property, nor was there any apparent wind at the turbines in that the turbines were not operating [4].

The noise graph shows an increase in the ambient background level when expressed as an L_{90} level utilising 10 minutes samples and correlates with the nominal power output of the wind farm that is provided from an engineer who collates wind farm power output data and publishes the material in the public domain, i.e. the wind industry does not provide any readily readable material in a graphical format for the output of wind farms, nor do they provide the hub height wind speed.

At 9pm the ambient background level is found to be 43dB(A) for which there was no wind that could be detected at the residential property. On a subjective basis the ambient background level was as a result of the operating turbines.

The application of that wind farm nominated for maximum power output of the turbines the noise level generated by the wind farm would not exceed 34dB(A) at the residential location (shown on a contour map), or 32 dB(A) specified in a Table (in the Environmental Assessment).

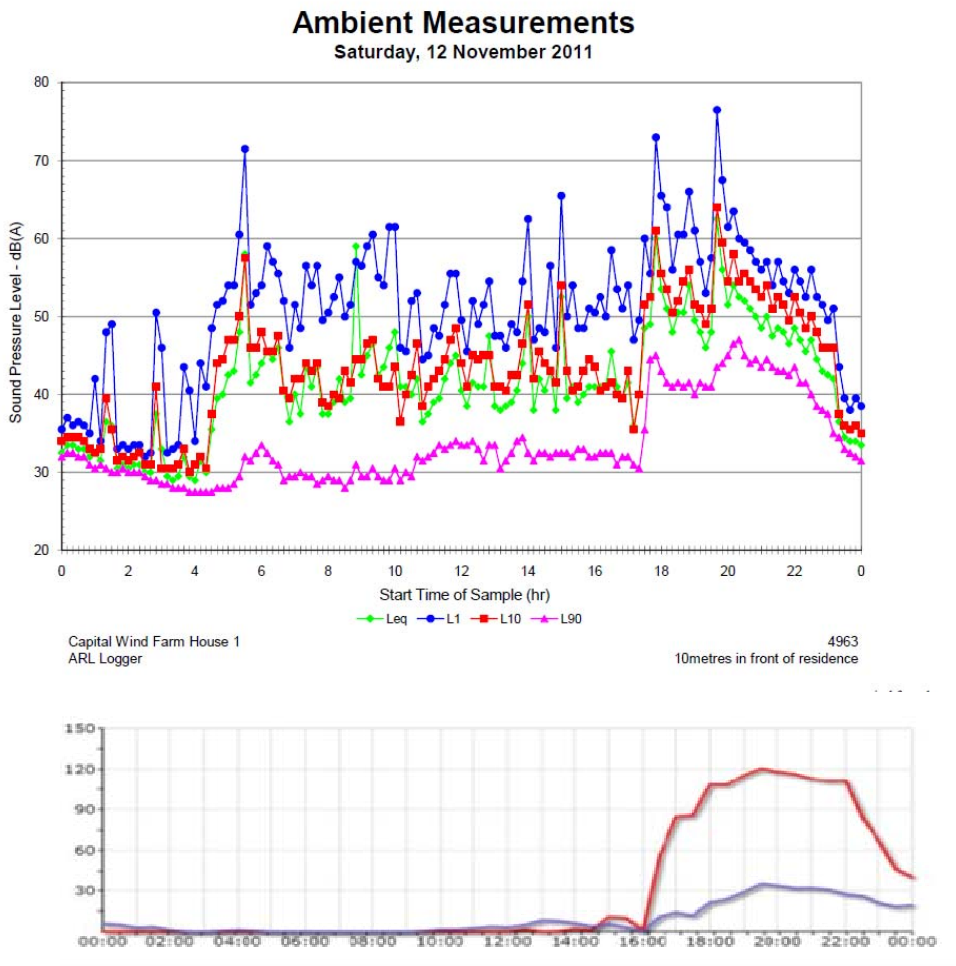

FIGURE 10: Residence in Figure 9 – downwind situation

It would therefore follow that the noise detected at the residential location exceeded that predicted by the applicant and a breach of the conditions of consent – that were based on a regression line analysis.

However the wind farm operator disputed there was a matter of non-compliance, by reason of the noise level measured at the residential receiver not being correlated with the hub height wind speed [5]. The simple explanation as to why one cannot correlate the hub height wind speed data with the measurements is that the wind farm operator does not provide in the public domain any hub height wind speed data. Therefore it would appear impossible for any independent monitoring to ascertain compliance with the conditions of consent because one of the key components for determining compliance is not available.

Arising from the claim of not being able to establish compliance we conducted continuous monitoring over some 4 months at another residence near the residence shown in Figure 9 where wind speed measurements were conducted at the microphone throughout that period, and for a portion of the time also at 10m above the microphone location. The results when correlated with the power output of the wind farm again indicated noise levels significantly greater that nominated in the environmental assessment.

If the true assessment criterion is reacted to the noise emission contribution from a wind farm versus the ambient background level at a receiver location then it must be acknowledged that wind at any assessment location will affect the background level.

But how much will the background level be affected?

To this end utilising the subject monitoring system that is being used at a number of wind farms the system was located on the side of an exposed hill being a residence in proximity to a proposed wind farm. There were no trees within 500m of the monitoring location and as the hillside was fully exposed we were able to determine the regression line applicable to the monitoring system for wind speed at the microphone versus the background level (see Figure 9). This permits us on utilising the same system for monitoring purposes and recording the wind speed at the microphone height to then take any of the measurement results that have been obtained in the presence of wind farm noise and logarithmically subtract the background level attributed to the wind at the time, to then end up with the noise contribution from the wind farm.

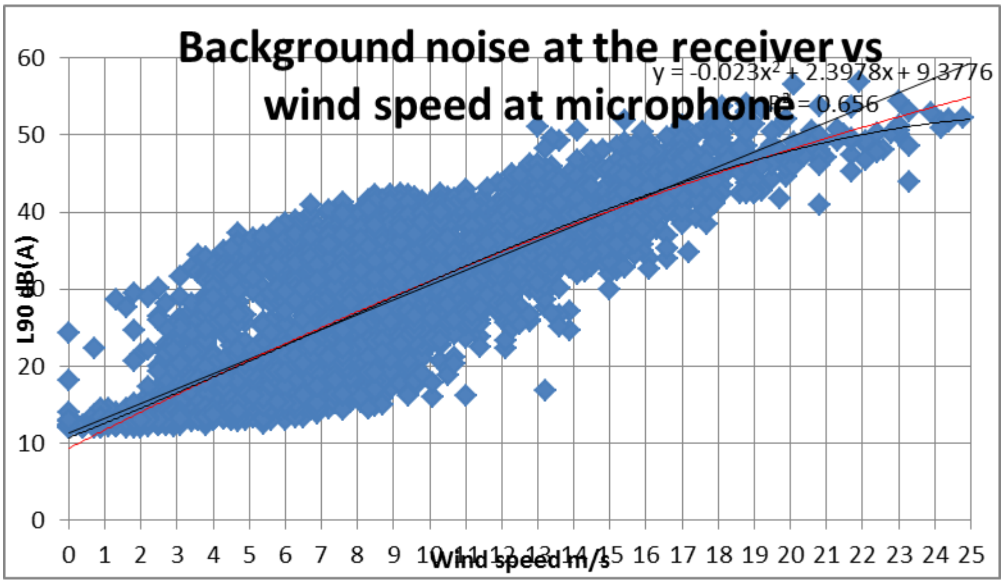

FIGURE 11: Exposed Hillside (furrowed ground) – No Turbines, No Trees within 500 metres

Therefore if we have been able to determine a regression line at the residential location showing the background versus the wind at that residential location one has a base level for assessing (when the wind farm is operational) the actual impact of the wind farm and the matter of compliance with a criterion of a base level or background +5dB being the true background recorded at residential dwellings. Therefore for a number of proposed wind farms we have measurement data that identifies the regression curve for the ambient background versus the wind at the residential location. This curve is completely independent of the hub height wind speed. With such information to hand it then becomes a relatively easy process to identify the noise impact of the wind farm in the environment in which it occurs without the obstacle of (deliberately not) having access to hub height wind speed.

In considering the above information it is apparent that for different wind directions there will be different levels of noise obtained at residential locations both in terms of the A-weighted value and the spectral components

Figure 12 provides a series of graphs recorded at a residential location 2.6km from an operating wind farm showing the noise levels over a 24-hour period. Superimposed on the A-weighted noise levels (that are the statistical 10 minute parameters) is the wind speed at the microphone position, with the graph below that showing the direction of the wind speed and the bottom figure being the power output of the wind farm available for that day.

The results indicate an ambient background level in the early hours of the morning with relatively little wind and little power output to be in the order of 12dB(A) for the monitoring system used with a noticeable increase in the background noise level following the increase in the wind and the increase in the power output.

The grouping of the various plots in Figure 12 shows for the majority of the day a relatively steady power output from the wind farm. However one can see the changes in the background level as there is a difference in the wind direction, yet the wind speed is relatively steady at the microphone until around 8pm when the microphone wind speed drops.

Use of a calibrated monitoring system versus the wind speed at the microphone permits one to determine the noise emission from the wind farm without the need for the hub height wind speed. The graphs show the concept that different wind direction for the same wind speed will give rise to different noise levels at residential properties and therefore different impacts. Following the completion of these measurements a certification letter as to acoustic compliance of the wind farm appeared that apparently is a result of 'extensive testing' (no test results provided) but a simple curve in terms of power output of the wind farm nominated noise levels at the subject residents. The noise level is versus the hub height wind speed and without the hub height wind speed one is unable to challenge that material.

However the results in Figure 12 indicate noise levels greater than that predicted for even the maximum output of the turbines. Figure 12 highlights the differences in terms of the noise emission on just using a dB(A) basis and how one can undertake averaging to determine (or downgrade) the actual noise impact.

But the L_{eq} level of the wind farm will be higher than the background level and may also require adjustments for modulation and tonality.

Wave file analysis of the same time period reveals an audible modulation of the wind farm noise was apparent which is not been included in the raw measurement data.
At the time of the paper being written the hub height wind speed information is not available but is expected to be available for the presentation to then place this material in its correct context.

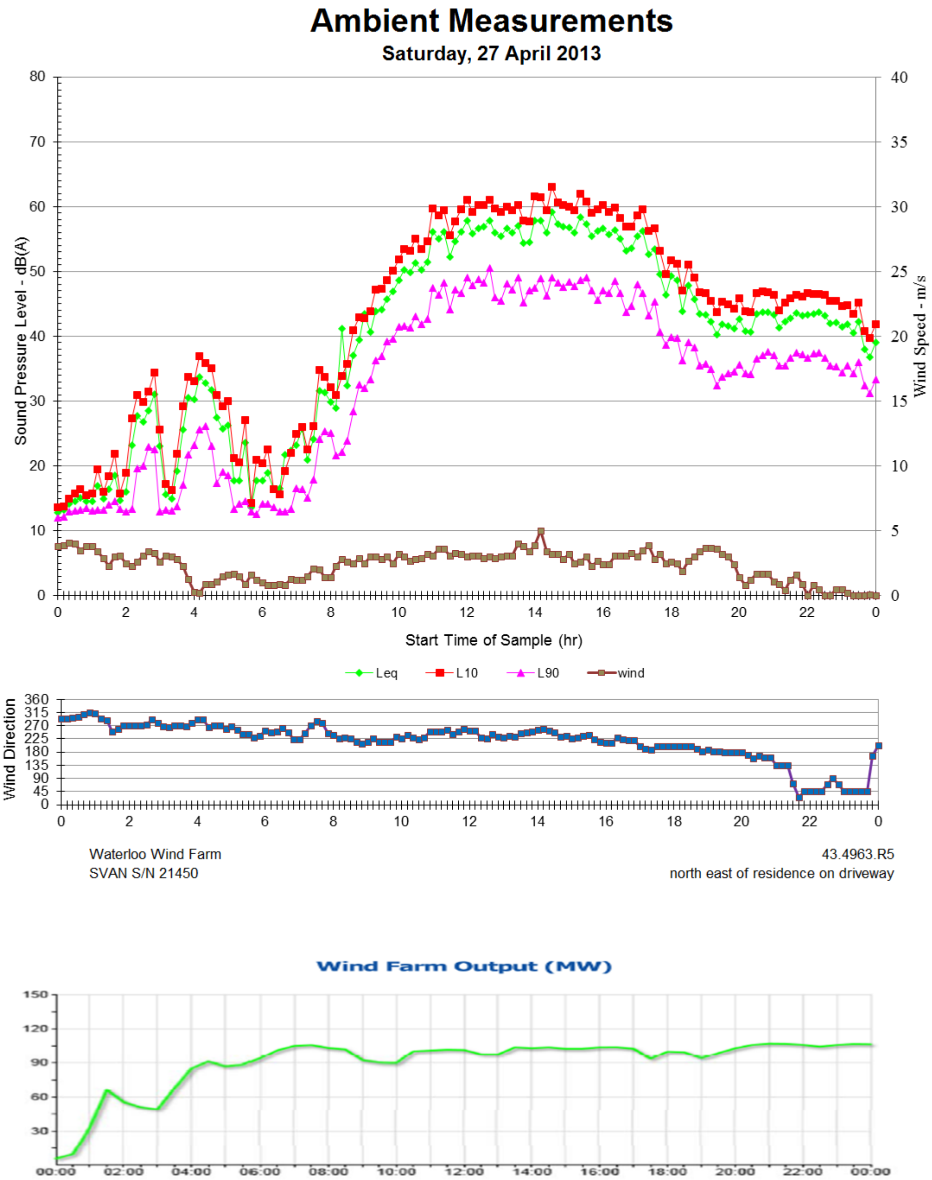

FIGURE 12 Waterloo Wind Farm Monitoring

5. Microphone Selection

Utilising the above vibration analogy one can establish there are different microphones that in themselves will have different frequency responses and different dynamic ranges that in turn require careful consideration in the selection of such equipment.

As experienced acousticians in terms of typical environmental measurements will be aware that there is an upper limit to the dynamic characteristics of a microphone such that in the general course of assessments one reduces the size of the microphone so as to permit the measurement of higher levels. For example one may consider a typical 1 inch microphone to have an upper dynamic limit in the order of say 145 dB with an open circuit sensitivity typically expressed as 50mV/Pa, whereas a quarter inch microphone is capable of measuring levels in the order of 160 - 185 dB and has an open circuit sensitivity at or below 4mV/Pa.

It is also generally acknowledged that typical ½ inch and 1 inch environmental microphones may have an open circuit frequency response varying from a few Hz to 10 kHz or 20 kHz, whilst the ¼ inch and 1/8 inch microphones have a much higher frequency response sometimes extended up to 140 kHz.

Utilising the general concept as expressed in the dynamic range of accelerometers then there must be a limit in terms of the dynamic range of the microphone so as to respond to the measured pressure levels.

Just as one would not use a typical 1 inch microphone in seeking to record a sound pressure level in the order of 170 dB it therefore must follow that a 1/8 inch microphone would be not suitable for recording general community acoustical measurements where background levels are less than 40 dB(A).

Just as in vibration measurements specialised accelerometers are required for the measurement of very low vibration levels, then in dealing with very low sound level measurements such as those encountered in test laboratories there are specialised microphones and preamplifiers to permit low level measurements.

The majority of our equipment is based around Bruel and Kjaer but it is acknowledged that there are other manufacturers who produce both low level sound measurement microphone/preamplifier combinations, and also at the other end of the dynamic spectrum high level sound measurement microphones for blasting.

There is no doubt that the measurement of noise at either the very low level or high sound levels is a lot more expensive than general purpose microphones. To obtain accurate results for even general-purpose sound requires a different classification of a microphone (and expense) to that obtained from a low-cost omnidirectional microphone that may be purchased in a typical electrical outlet store.

Having identified that there are different microphones for different purposes (and those microphones will have different dynamic capabilities) then one needs to expand the consideration of microphones to the fact that they will have different noise floors and also different frequency responses.

Our earlier investigation into wind farm noise utilised our general purpose microphones but with a Bruel and Kjaer Pulse system permitted to undertake both constant percentage bandwidth and narrowband analysis.

Our measurements revealed the presence of narrowband components in the acoustic signature of noise emitted from turbines as external to an inside residential dwellings removed from the wind farm. With any new investigations found a number of limitations in our analysis method it in pulse system by default incorporated a 22.4Hz filter which may be appropriate for general acoustic matters but not specifically for wind farms.

The electrical noise floor of the microphone was an issue that in turn led to extensive testing in our small anechoic room to evaluate the different noise floors of general purpose meters, microphones and our more specialised systems. We are able to determine the threshold of the microphones with respect to the introduction of both white noise and narrowband tones to find that a number of our general purpose meters were unable to measure the full spectrum inside residential dwellings, i.e. their noise floor was not low enough.

To this end we used as a control microphone a Bruel and Kjaer 4179 low noise microphone with a 2660 pre amp with the specification by Bruel and Kjaer indicating a capability to measure down to -2.5dB(A). The microphone has a flat specification to 10Hz and a curve to show the roll off below 10Hz to be 10 dB down at 1Hz.

We have established that the use of 200v polarised Bruel and Kjaer microphones give us a lower noise floor than for non-polarised microphone and with a specialised low-frequency extended range calibrator we can determine the frequency response of our microphones to 1Hz but limited to a measurement at 1 Pascal. What happens at lower SPLs can be tested by the use of signals but at the moment we do not have a low frequency calibrator with adjustable SPLs.

We have seen the trend in some measurements in Australia to nominate use of the Bruel and Kjaer low-frequency microphone type 4193 with the low frequency adapter to extend frequency response down to 0.05Hz. The problem that we have found is that the microphone has a relatively low sensitivity and that with the use of the UC adapter there is a 9 to 13dB increase in the noise floor (i.e. less sensitivity) than without the adapter. In this regard we have found the microphone to be of no assistance in measuring indoors where the ambient background levels are below 20dB(A) – to be expanded upon in the presentation.

On conducting multichannel measurements in the one room on a simultaneous basis we have sought to use our reference 4179 microphone and either 200v polarised microphones that at valid down to 1 or 2Hz.

For the measurement of infrasound we have found it necessary to look carefully into the microphone threshold levels and the selection of microphone used for such measurements, as the issue that has become apparent in Australia is not a matter of audibility of infrasound but the threshold of perception by residents that occurs at levels well below the threshold of hearing.

6.0 Conclusion

The conduct of measurements of wind farm operations, on behalf of communities in Australia, has identified that the dB(A) noise levels specified by Regulatory Authorities do not protect the acoustic amenity of residents and that there are a number of fundamental issues in relation to your the criteria so nominated.

Another paper presented by the author during this conference [6] identifies issues with respect to the dB(G) parameter and the use of Z weighting, suggesting consideration of the use of Linear (un-weighted) levels from 0 – 20 Hz for infrasound measurements.

Whilst the dB(A) provides the basis of assessment for wind farms then the characteristics of the A- weighting curve and the use of Leq or L90 levels does not identify the special characteristics associated with Industrial Wind Turbines.

Regulations in Australia are currently expressed in terms of noise level versus the hub height wind speed. When one evaluates site-specific locations one finds the criteria to be inappropriate.

Furthermore as the community is unable to obtain the hub height wind speed then the matter of acoustic compliance testing on behalf of the community is doomed to failure.

The regression curve used for general assessment purposes of wind farms in Australia does not address the relationship of the acoustic environment at the receiver locations versus the wind at those locations, nor does the relationship of the ambient background levels of residential dwellings take into account the direction of the wind.

Residents report sleep disturbance and other impacts at noise levels less than that nominated by regulatory authorities which has led various acousticians to investigate both low-frequency sound and infrasound as a potential source of the disturbance.

These investigations have revealed difficulties in conducting measurements when incorrect instrumentation is used. If the instrumentation is unable to actually measure the noise that occurs at residential properties, by either limitations in frequency response of the instruments, low sensitivity of instrumentation (dynamic range) and simply relying upon dB(A) measurements, then all the results of such investigations must lead to incorrect conclusions as to noise emission from wind farms.

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