Influence of non-standard atmospheric conditions on turbine noise levels near wind farms

Jonathan COOPER[1]; Tom EVANS[1]; Vahid ALAMSHAH[1]

[1] Resonate Acoustics, Australia

ABSTRACT

This paper investigates the accuracy of wind turbine noise predictions under non-standard meteorological conditions. It reviews studies into the influence of meteorological variables on noise emission and propagation. In particular, it presents recent extended wind farm noise measurements undertaken by the authors to investigate the effects of periods of higher wind shear on noise propagation. Wind turbine noise levels were measured at a location 1150 m from a wind farm where wind shear was simultaneously monitored. It is found that wind shear tends to have a negligible influence on noise propagation for the range of operating conditions of the wind farm. The influence of wind direction on noise levels at the monitoring location was found to be much larger than that of wind shear.

Keywords: Wind Farm, Wind direction, Wind shear, Turbulence, Propagation

I-INCE Classification of Subjects Number(s): 14.5.4, 24.6

1. INTRODUCTION

Noise is a common community concern during planning assessments for wind farms, and the accuracy of wind farm noise predictions is sometimes questioned. Factors often raised and said to increase the noise level from the wind farm include meteorological conditions such as higher wind shear, temperature inversions and turbulence.

The authors have previously shown that prediction methods used for wind turbine noise provide suitable accuracy, once topographical effects are accounted for (1). While conditions such as wind shear and temperature inversions are known to increase noise propagation downwind from sources near ground height, this influence of these conditions on wind turbine noise is less clear. There is reason to believe that the propagation of wind turbine noise under varying meteorological conditions may not match that of typical sources, as they are much higher above the ground and also provide turbulent mixing of the atmosphere downwind of the turbines which may disrupt stable conditions conducive to noise propagation.

This paper primarily focuses on the assessment of the influence of wind shear on a data set measured over a period of 8 months near a large grid like array of wind turbines, with conclusions from this analysis compared to previous findings regarding wind shear, turbulence and propagation model accuracy.

1.1 Wind shear

Wind shear refers to the change in wind speed with height. An equation used to approximate wind shear at a site is the empirically developed power law, given by Equation (1).

$$V_1 = V_2 \left(H_1 / H_2 \right)^{\alpha} \tag{1}$$

Where V_1 and V_2 refer to the wind speed at heights H_1 and H_2 respectively, and α is the power law exponent.

Typical average daytime values of the power law exponent range from 0.1 over smooth, hard ground to 0.4 in urban areas with tall buildings (2). Wind shear is highest during stable atmospheric

[1] jon.cooper@resonateacoustics.com

conditions (3).

The propagation of sound downwind from sources such as traffic has been found to increase under periods of higher wind shear, due to the bending of sound waves back towards the ground (4).

Previous studies on the influence of wind shear on the propagation of wind turbine noise have suggested that the influence is not as great for wind turbine sources as it is for sources located near the ground. Søndergaard (5) found that wind shear was "without any real influence" on noise propagation from wind turbines under Danish conditions, while Evans (6) found a small possible increase in low frequency noise generation at the source, but no increase in noise levels in the far field. This paper investigates whether these findings are supported in a new larger data set.

2. MEASUREMENT SITE AND AVAILABLE DATA

The data used for this assessment was gathered continuously over a period of 8 months at a location approximately 1150 metres from the nearest wind turbine. The wind farm is a large flat site with modern turbines rated at approximately 3 MW capacity each. The turbines are located in a grid like pattern, so that the turbines typically operate in the wakes of other turbines. In addition to the nearest turbine at approximately 1150 metres, there are over 25 turbines within 3 kilometres of the monitoring location.

A Type 1 Bruel and Kjaer 2250 sound level meter was used to acquire the noise data, with overall descriptors and third octave band spectrums stored in 10 minute intervals for the full duration of the test. Continuous audio data was also stored for the first 4 months of the measurements, which allowed later review of the noise sources that were controlling the measurements.

The aim of these measurements was specifically to measure the level of wind turbine noise and so it was possible to select an ideal site for this purpose rather than locating the monitoring equipment at a residence where there are more extraneous noise sources. The monitoring station was positioned in the center of a paddock more than 100 m from any significant vegetation, where the noise level was typically controlled by wind turbine noise rather than vegetation noise. There were no major roads or industrial sources anywhere in the vicinity of the monitoring location.

The microphone was protected from wind induced noise using a custom multi-layered 700 mm diameter wind shield. The windshield was originally developed for the purposes of measuring infrasound outdoors, but provides a 7 dB(A) improvement over wind induced noise generated by a standard 90 mm wind shield at any given wind speed, with negligible insertion loss up to a frequency of 12.5 kHz. Measurements of local wind speed adjacent to and at the same height as the wind shield indicated that wind induced noise on the microphone did not influence any of the A-weighted noise measurements.

The hub height 10-minute average wind speed and direction data was supplied by the site operator at all of the wind turbines and met masts located at the site. Also supplied was the wind speed data at approximately half the met mast height to allow the calculation of wind shear during the measurements, rainfall at all of the met masts, and turbine operation data.

Wind shear was determined using wake-free wind speed data obtained from a set of meteorological masts at the site. Wind speeds measured at hub-height and approximately half this height were used to determine the wind shear power exponent for every 10-minute period during the measurements.

3. EXCLUSION OF EXTRANEOUS NOISE

It is known that wind shear is normally greater during the night than daytime, such that any difference in day and night time extraneous noise will adversely affect the analysis of the influence of wind shear on wind turbine noise levels at the monitoring location. For this reason it was important that noise from the extraneous sources was discarded.

The analysis was conservative in the exclusion of possible extraneous noise, erring on the side of deleting too many data points, than potentially leaving some that may be extraneous. In the case of excluding rainfall, the measurement point was deleted if rain was recorded at any of the sites met masts during that 10 minute period, or at any of the masts in the ten minute period before or afterwards.

It was impractical to exclude all periods where one or more turbine on the site was not in operation, as on a large site it is rare for every single turbine to be running. Exclusions based on just the number of operating turbines are also not ideal, as 5 inoperable turbines on the far side of the site will have no impact on noise levels, while the shutdown of the 2 nearest turbines will noticeably reduce noise levels at the monitoring location.

The exclusion of periods due to non-operation of turbines was therefore based on both the operational data provided for each of the turbines and a noise model. The model of the site was created in SoundPlan 7.3 with predictions undertaken using the ISO 9613-2 method assuming 50% absorptive ground (G=0.5), and the noise level predicted at the monitoring location from each individual wind turbine. The operational data was used to determine which of the turbines were running during a given 10 minute period, with total noise level from the wind turbines running during that 10 minute period calculated. If the noise level during that 10 minute period was predicted to be more than 0.5 dB below the level with all turbines running, then that 10 minute period was discarded.

While the monitoring location was away from all road, industrial and vegetation noise sources, the analysis of the data indicated significant periods where both frog and cricket noise was dominant, rather than wind turbine noise. This was confirmed by listening to the audio stored by the meter.

Several methods for excluding the extraneous frog and cricket noise were trialed, with the most effective found to be a comparison of energy in the mid frequency third octave bands to the higher frequencies where the frog and cricked noise were dominant (1.6 kHz to 5 kHz). If the energy in the higher frequency third octave bands were not at least 5 dB below the energy in the mid frequency bands that measurement was judged affected by the frog / cricket noise and so discarded. The accuracy of this exclusion method was tested through comparison against exclusion based on the subjective review of the audio in 1,500 of the 10 minute measurements and the results found to be excellent.

Figure 1 shows the total data set gathered during the 8 months of measurements, the data remaining following exclusion of rain and the non-operation of turbines, and the final data set which based on the third octave spectrum is turbine noise controlled. This turbine noise controlled data set was then used for the analysis of the influence of wind shear on the wind farm noise level at the monitoring location. Note that the wind speed used in this figure and the other figures in this paper is the average wind speed taken from the nacelle of the nearest five turbines to the monitoring location. As would be expected, the wind speed from the nearest turbines provides a better correlation to the wind turbine noise levels than a met mast located some distance away.

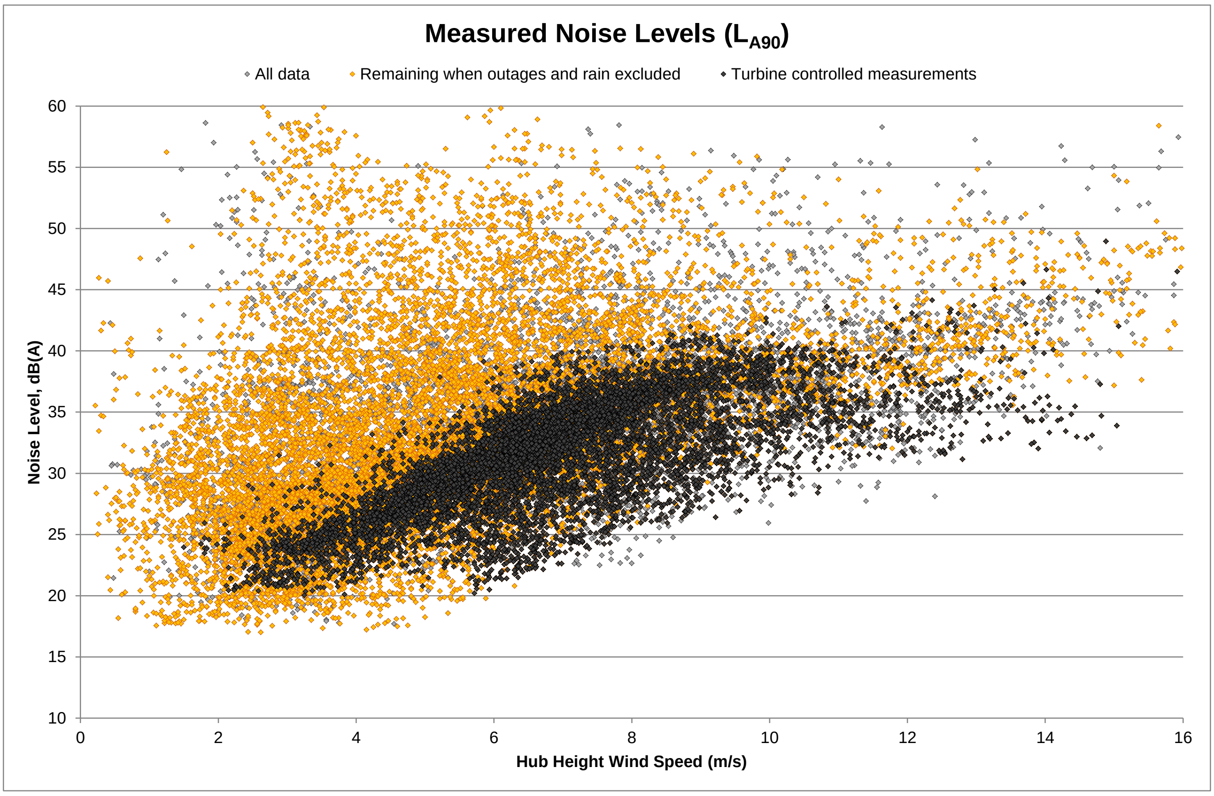

Figure 1 – Total data set, data set following exclusion of rain/non-operation of turbines, and final data set.

Almost 10,000 data points which were believed to be controlled by wind turbine noise remained at the end of the data exclusion process. The large number of data points that are excluded at this site due to the influence of extraneous noise, despite this site being specifically selected for its distance from extraneous sources, is revealing particularly given that the measurements presented are L_{90} levels and should therefore be less susceptible to extraneous sources. The placement of a noise logger at a site that appears to be wind turbine noise controlled does not guarantee that wind turbine noise will be the dominant noise source in all or even the majority of the measurements. When assessing wind farm noise it is easy to make the mistake to assume that the wind farm is controlling the results. At this site for wind speeds above 6 m/s the measurements controlled by wind turbine noise are the lowest of the measured levels rather than the loudest, a result that the authors regularly encounter during compliance measurements.

Note that the analysis presented in this paper presents the L_{A90} at the measurement location, rather than the L_{Aeq}. Monitoring of wind turbine noise undertaken in Australia uses the L_{A90} metric due to it being less susceptible to short term extraneous noise sources than the L_{Aeq} metric. Previous analysis by the authors at sites which were turbine noise controlled shows that the wind turbine L_{Aeq} is typically 1.5 dB higher than the L_{A90} (7).

4. INFLUENCE OF WIND DIRECTION

Previous assessments of the influence of wind direction on the propagation of wind turbine noise indicate that the wind direction is a significant variable. Evans (8) found that the difference in propagation between upwind and downwind conditions was 6 – 7 dB(A) over a distance of 1000m.

It was therefore necessary to remove the possible influence of wind direction from this assessment of the influence of wind shear. This was achieved by first sorting the data into the upwind, crosswind and downwind data sets, such that the influence of wind shear could be investigated within each data set. This sorting of the data into different wind direction bins also allows an analysis of the influence of wind direction on noise propagation at this site.

Figure 2 presents the wind turbine noise controlled data set sorted into downwind, upwind, and two crosswind sets. Crosswind (S) is the crosswind with wind from the south and crosswind (N) is the crosswind for wind from the north. Downwind refers to the time when the measurement location is downwind of the wind turbine.

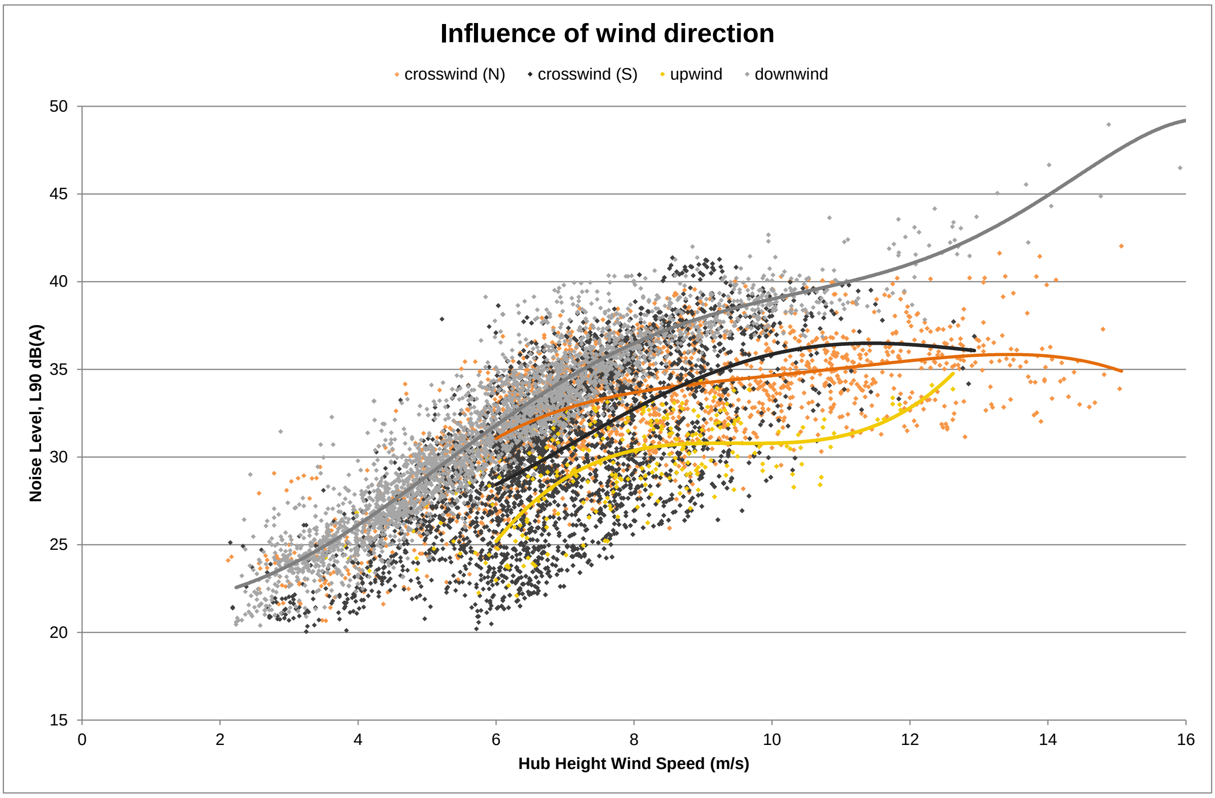

Figure 2 – Turbine controlled measurements split into the four wind directions.

Trend lines are fitted to the datasets to show the average noise level with each wind direction at each speed. The trend lines of the crosswind and upwind data sets have not been extended below 6 m/s as all the low sound level measurements below this speed are lost to the extraneous noise from ambient background noise or the sound level meter noise floor. This leaves only the loudest wind turbine noise controlled measurements at these speeds, artificially dragging those trend lines at low speeds higher than they should have been.

Comparison of the downwind, upwind and crosswind measurements over wind speeds where sufficient data is available (6 – 10 m/s) indicates the downwind noise level is 6 – 8 dB above the upwind wind turbine noise level. The average of the crosswind results sits between the downwind and upwind noise levels, at about 3 – 4 dB quieter than the downwind noise level. These results match well to our previous results at a more topographically complex site over a distance of 1000m (8).

5. WIND SHEAR ANALYSIS

The four sets of data for each of the wind directions where each analysed to determine the influence of wind shear for the wind direction. Figure 2 shows the downwind data with shear during each of the measurements identified.

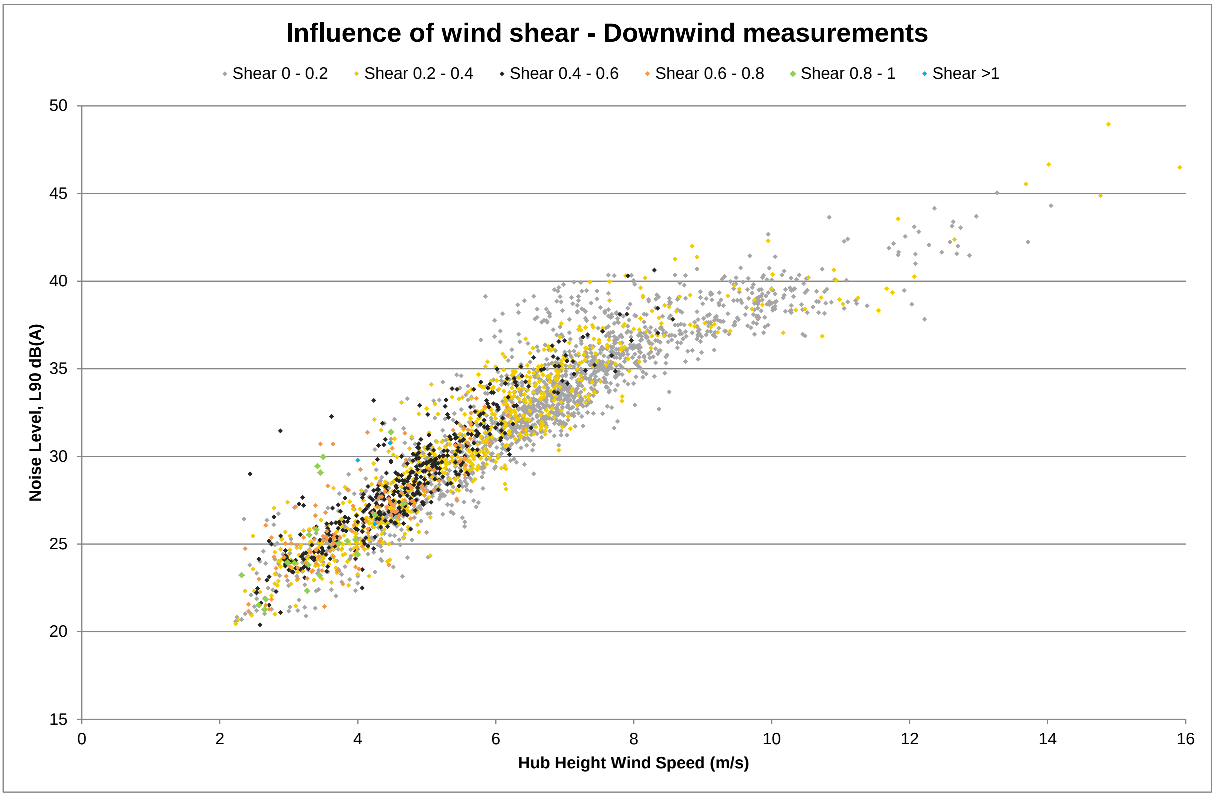

Figure 3 – Wind shear during each of the downwind noise measurements.

The influence of wind shear on the measured noise level shown in Figure 3 is unclear due to the relatively large scatter of the data. To allow an easier examination of the influence of wind shear on the noise level at the receiver location, a trend line was fitted to each of the four direction datasets. The deviation of each data point from the trend line is calculated and plotted against the wind shear during that measurement. If wind shear is influencing the wind turbine noise level at the measurement location 1150 m from the nearest wind turbine it would be expected that deviation from the trend line would increase (either positively or negatively) with wind shear exponent. Figures 4 to 7 present the results of this analysis for the downwind, upwind and two crosswind directions respectively.

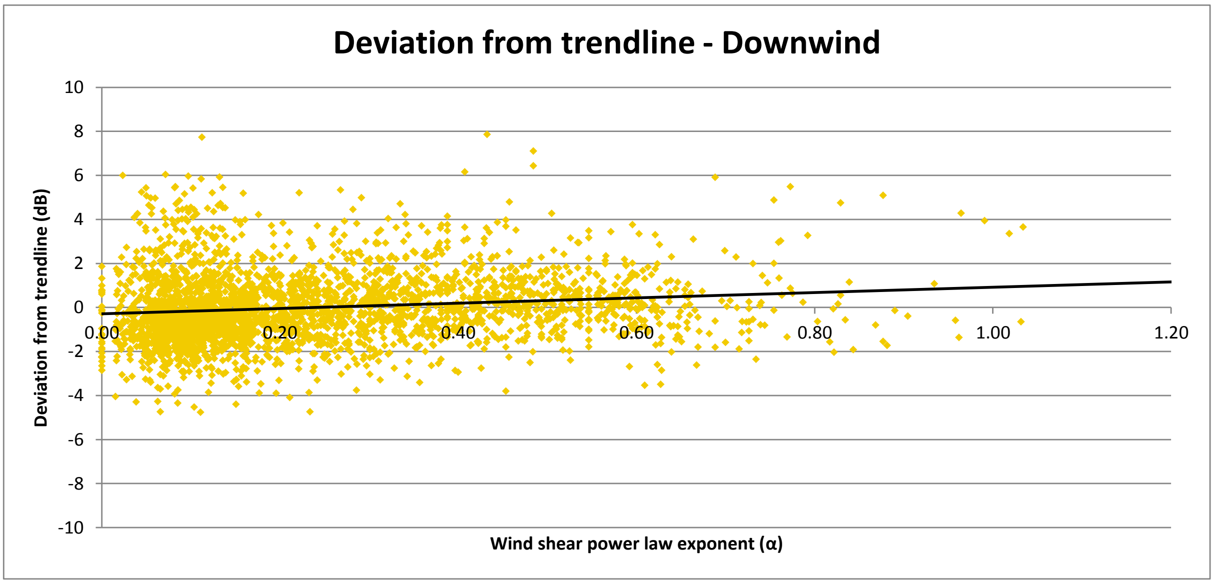

Figure 4 – Deviation from trend line during downwind noise measurements.

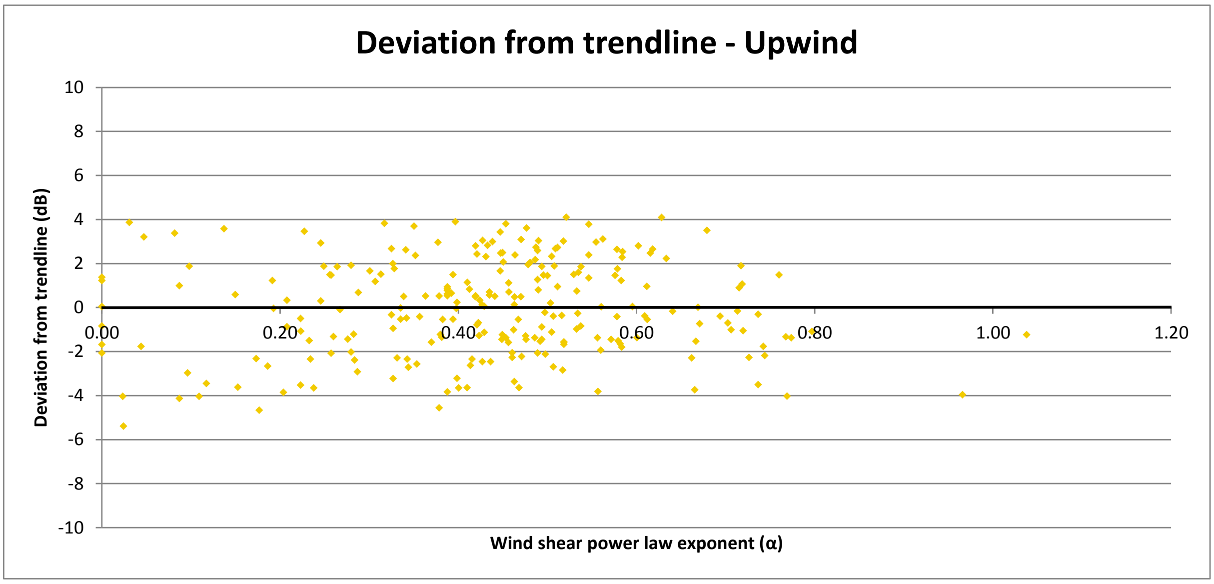

Figure 5 – Deviation from trend line during upwind noise measurements.

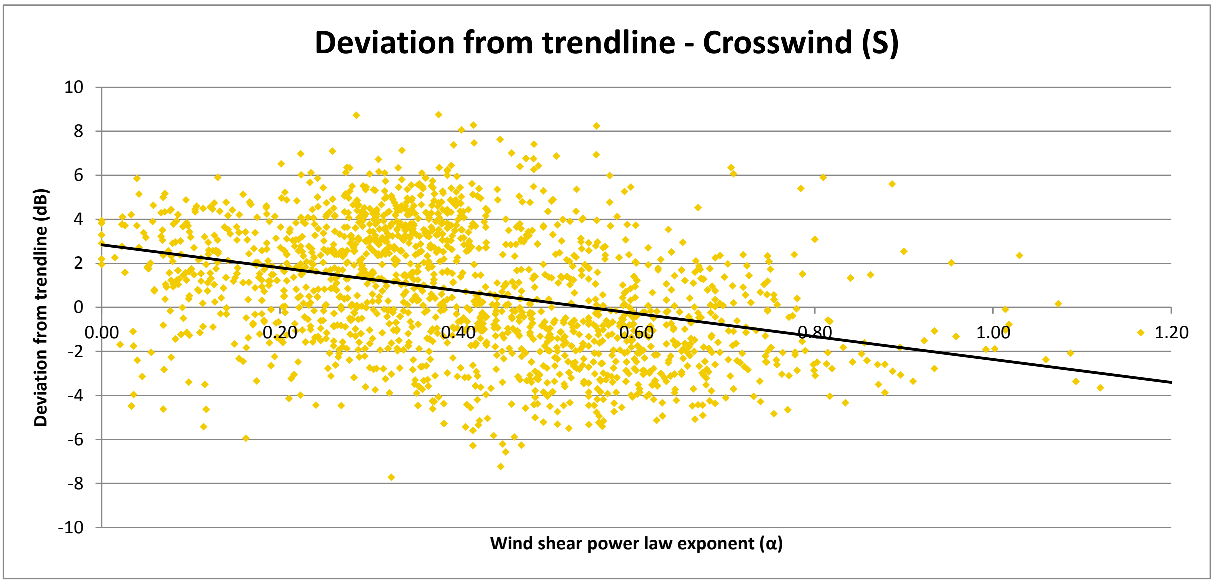

Figure 6 – Deviation from trend line during Crosswind (Southerly) noise measurements.

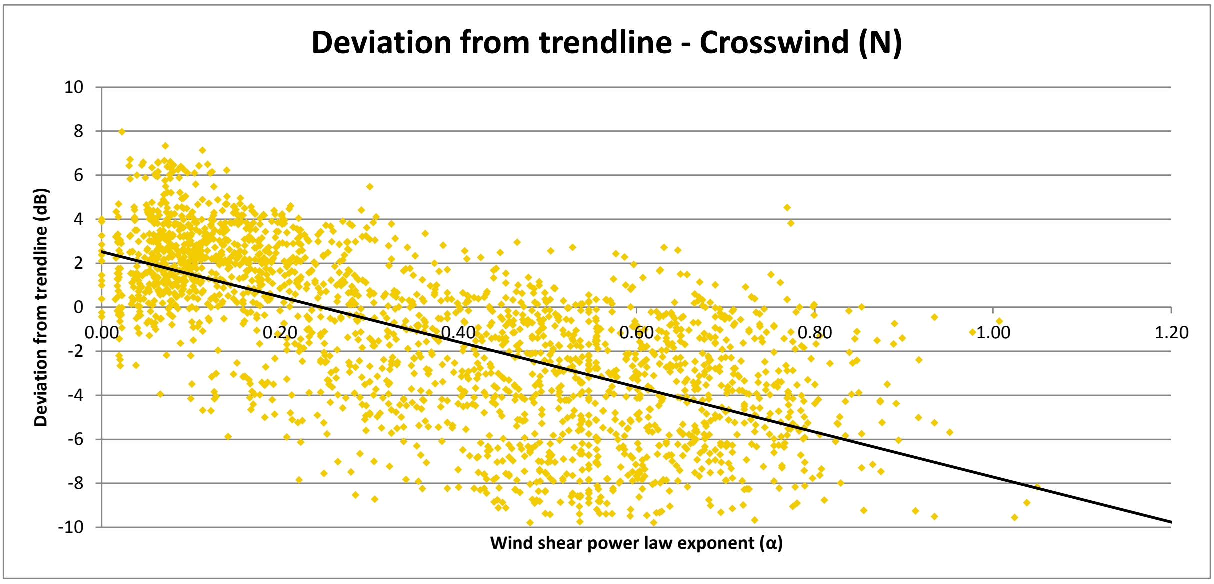

Figure 7 – Deviation from trend line during Crosswind (Northerly) noise measurements.

The downwind results shown in Figure 4 indicate that wind shear had little or no influence on the wind turbine noise level at the measurement location. If increased wind shear had noticeably increased noise levels at the receiver location this would have been indicated by all of the high shear measurements being above the trend line (positive deviation from trend line)—this was not the case. While there may have been a minor upwards trend, it required the rare event of a wind shear exponent of over 1 before the measured noise level would have even increased by 1 dB. While the size of the upwind measurement dataset shown in Figure 5 is relatively small, no trend in propagation is shown for upwind conditions.

The deviation from the trend line for the two crosswind directions are shown in Figure 6 and Figure 7. Both of these Figures show comparatively strong relationships between wind shear and the measured noise level, with the highest noise levels measured under periods of low wind shear. Periods of low wind shear occur at times when the atmosphere is unstable, so are more common during the daytime and at times of higher wind speeds. The result that low wind shear increases noise levels at the receiver is contrary to the widely accepted theory that noise levels are higher at receivers during times of greatest atmospheric stability. One possible explanation for this unusual result may have been that lower wind shear is associated with greater relative ground level wind speeds, and this ground level wind is increasing wind induced noise on grass near the microphone, which is then detected as wind turbine rather than extraneous noise. However, that explanation would not provide a reason for the lack of a similar result in both the downwind and upwind data sets.

Further analysis of the crosswind data sets was undertaken to find the reason for this unlikely result. The cause of the apparent relationship to wind shear under only cross wind conditions was found to be the result of three factors, as listed in Sections 5.1 to 5.3.

5.1 Strong Influence of Wind Direction on Propagation

As identified in Section 4, wind direction does significantly alter noise levels at the monitoring location. While the average crosswind noise level was found to be about 3 – 4 dB lower than the down wind conditions, there is a very large range of noise levels measured under crosswind conditions at any given speed, when compared to the downwind and upwind datasets. The large range of measured levels under crosswind conditions is as a result of some of the data points being at the boundary of downwind conditions (resulting in high noise levels), while other points are at the boundary of upwind conditions (resulting in low noise levels). There is not a step change in noise levels with wind direction—noise levels at the monitoring location gradually decreased as the wind moved from a downwind to upwind direction.

While this relationship between wind direction and noise propagation provides no explanation alone for the crosswind shear relationship, when combined with the following two factors it explains the cause of the cross wind shear result.

5.2 Non-Uniform Wind Shear at Wind Farm Site

An analysis of the wake free wind shear measured at the wind farm site indicated that the average wind shear exponent during the 8 month monitoring period was 40% greater for upwind directions than the wind shear exponent when the measurement location was downwind of the turbines. Like the propagation of noise, there was no step change in shear with wind direction—there was instead a gradual increase in average wind shear as the wind direction moved from downwind to upwind.

The increased wind shear when the measurement site is close to upwind of the turbines corresponds to the times when close to upwind propagation results in lower measured noise levels. It is by chance that the periods of high wind shear are more common when the upwind propagation is providing the lowest wind turbine noise level. This gives the impression of a link between lower noise levels and higher wind shear, when in fact the change in both noise and shear are the result of the wind direction.

While it might be suggested that the wind shear is the reason for the difference in noise level between the downwind and upwind situations (rather than the wind direction itself altering noise propagation), the results of Figures 4 and 5 clearly show that wind shear had negligible influence on the up and downwind propagation.

5.3 Exclusion of Extraneous Noise

The naturally greater wind shear at this site for upwind directions was exacerbated by the exclusion of extraneous noise. While before exclusion of extraneous noise the average upwind shear was 40% greater than downwind directions, after the exclusion of extraneous noise the average upwind shear exponent was 80% greater than downwind. As can be seen from Figure 5, under upwind directions very few low wind shear periods were wind turbine noise controlled. This is in strong contrast to the downwind measurements, where there was no change in average shear between the pre and post extraneous noise exclusion data sets.

There are two possible explanations for the majority of the low wind shear measurement from the upwind data set being excluded due to the influence of extraneous noise. Either; there was an increase in background noise during low wind shear measurements, or, there was a reduction in wind turbine noise during periods of low wind shear. The measurements results in Figure 5 indicate no relationship between wind shear and wind turbine noise under upwind conditions, such that the only remaining explanation is that there is an increase in extraneous noise during low wind shear periods. This is a likely cause, given the greater ground level wind speeds at low wind shear, and the possibility of more extraneous noise during the day time period when low wind shear typically occurs. The downwind measurements were not similarly affected, as being 6 – 8 dB louder, they would be less influenced by an identical level of extraneous noise.

5.4 Summary of Crosswind Shear Result

While Figures 6 and 7 suggested a trend of reduced noise propagation with increased wind shear for cross wind conditions, the further analysis of the data indicates that this is not the case. Rather, this apparent trend was the result of the strong relationships between wind direction and propagation, and wind direction and wind shear, and the exclusion of low wind shear measurements under upwind conditions. There is no reason to believe that the crosswind propagation of wind turbine noise is any different to both the up and down wind propagation, where negligible relationship between wind shear and wind turbine noise propagation was found.

6. INFLUENCE OF TURBULENCE ON PREDICTION ACCURACY

While no new data has been presented in this paper on the influence of turbulence on measured noise levels, it is still possible to investigate the likely importance of turbulence on A-weighted noise levels at receiver locations based on a comparison of the measured and predicted noise levels.

As a wind farm with a large number of turbines in a grid like arrangement, it is relatively common for the turbines nearest the monitoring location to be operating in the wake of other close by turbines. In fact, when the monitoring location is downwind of the nearest turbines those turbines are all in the wakes of other turbines—for some downwind directions there are as many as 30 upwind turbines. A comparison of the predicted wind turbine noise level against the measured wind turbine noise level would indicate if the noise model under predicts noise levels at times when the turbines are operating in the wakes of many other wind turbines.

In 2012 (1) we identified that, for flat sites, the ISO 9613-2 noise model provided accurate downwind predictions of wind turbine noise when a ground hardness of G=0.5, humidity of 80% and temperature of 10°C were used as model inputs.

Note for clarity that the Australian custom is for L_{eq} sound power levels to be used to predict noise levels at a height of 1.5 m above ground, with the result at the receiver being assessed using a measured L_{A90}. This differs from the UK approach of adjusting the L_{eq} sound power level to an L_{90} for the noise modeling, and predicting noise levels at 4 m above ground. The results of both modeling approaches are broadly equivalent; with the correction from L_{eq} to L_{90} sound power level approximately equivalent to the increase in noise level due to predicting at a height of 4 m above ground.

The predicted wind turbine noise level based on the ISO 9613-2 model and sound power levels measured for the turbine model installed at the site are overlaid on measured wind turbine noise levels in Figure 8. Note that the grey trend line included on this figure is the trend line fitted to the downwind noise measurements over speeds for which measured sound power levels were available for this turbine. Excellent agreement between the predicted and measured noise levels is achieved, with by far the largest difference being a 1.5 dB over prediction of the noise level at 4 m/s.

The excellent agreement between the predicted and measured A-weighted downwind noise levels on this site where the turbines are operating in the wakes of many upwind turbines suggests the model suitably accounts for turbulence. The excellent agreement between modeled noise levels at this site (with significant turbulence) and other sites where there was minimal turbulence suggests that the influence of turbulence on A-weighted noise levels at receivers is negligible.

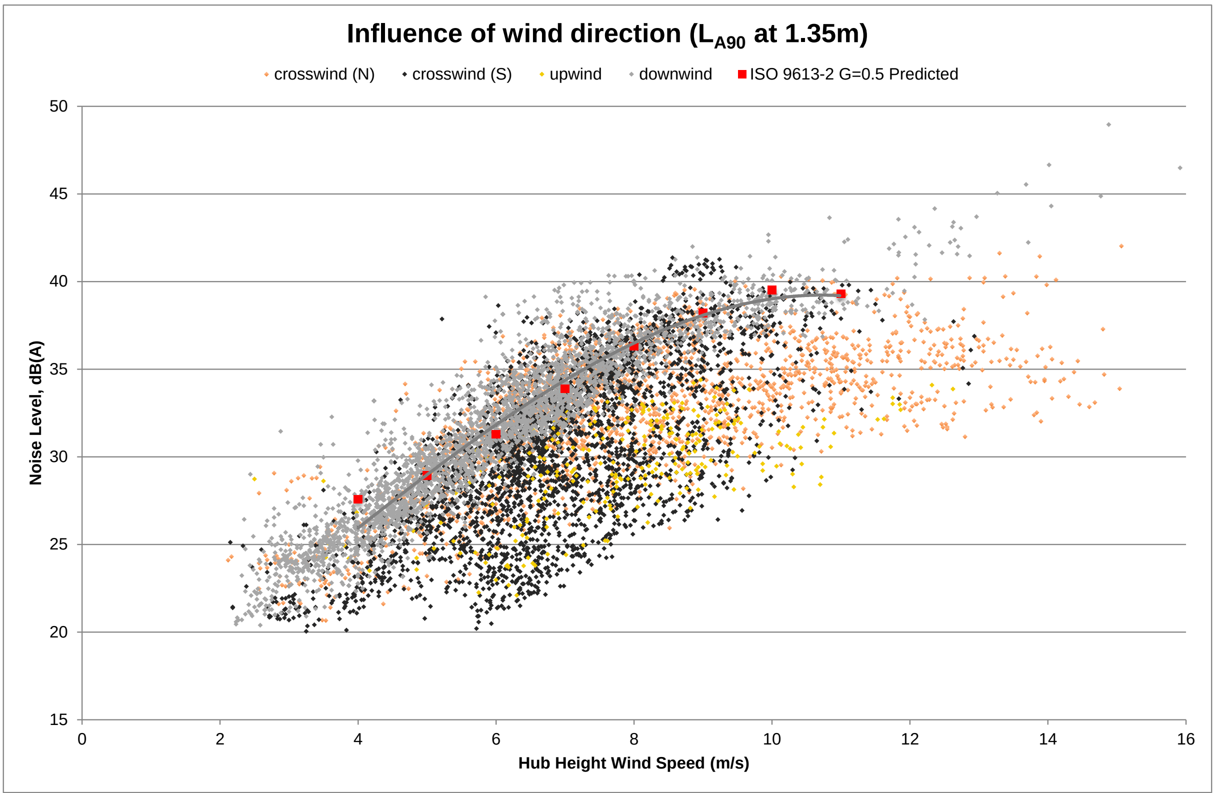

Figure 8 – Comparison of predicted and measured noise levels.

This outcome was to be expected based on previous assessments of the influence of turbulence on the level of noise emission from the source (6,9). Those measurements included measurements when the wind turbine operated in the wake of nearby adjacent turbines and while a small increase in low frequency noise was measured at low wind speeds there was negligible increase in the A-weighted level of the source.

7. CONCLUSION

This paper has presented the results of an analysis of wind shear on wind turbine noise levels measured a location 1150 m from a large array of modern wind turbines. The turbines are arranged in a grid like manner over a flat site.

The analysis of the influence of wind shear also provided datasets for the analysis of the influence of wind direction on the propagation of wind turbine noise. It was found that as expected, wind turbine noise levels are highest when the wind blows from source to receiver. The increase in level under downwind conditions compared to upwind conditions was 6 – 8 dB, with crosswind conditions resulting in levels on average 3 - 4 dB quieter than the downwind levels.

The noise level measured at the monitoring location showed very little dependence on wind shear for both the upwind and downwind situations. While the initial assessment of results suggested a strong relationship between shear and measured noise levels in both cross wind datasets, this is believed to be the result of the strong relationships between wind direction and propagation, and wind direction and wind shear, and the exclusion of low wind shear measurements under upwind conditions. It therefore appears that wind shear has negligible influence on wind turbine noise propagation for all wind directions.

While this paper provides no analysis of turbulence data, this wind farm site provides a worst case situation where the turbines nearest the monitoring location are downwind of many nearby wind turbines when the monitoring location is downwind from the site. The excellent agreement between predicted and measured noise levels at this site despite the significant wake induced turbulence suggests that turbulence is of negligible importance to A-weighted noise levels at receivers.

REFERENCES

1. Evans, T & Cooper, J, 2012, ‘Comparison of predicted and measured wind farm noise levels and implications for assessments of new wind farms’, Acoustics Australia, vol. 40, no. 1, pp. 28-36.
2. Ray, ML, Rogers, AL & McGowan, JG, 2006, ‘Analysis of Wind Shear Models and Trends in Different Terrain’, Conference Proceedings: American Wind Energy Association Windpower, Anaheim, 22-25 May 2006.
3. Sathe, A & Bierbooms, W, 2007, ‘Influence of different wind profiles due to varying atmospheric stability on the fa-tigue life of wind turbines’, Journal of Physics: Conference Series, vol. 75, 012056.
4. Foss, RN, 1978, Ground Plane Wind Shear Interaction on Acoustic Transmission, Research Project Y-1739, Washington State Department of Transportation, Olympia.
5. Søndergaard, LS, 2012, ‘Noise from wind turbines under non-standard conditions’, Proceedings of Internoise 2012, New York, 19-22 August 2012.
6. Evans, T, and Cooper, J, 2013, ‘Effects of different meteorological conditions on wind turbine noise’, Proceedings of Acoustics 2013, Victor Harbor, 17-20 November 2013.
7. Cooper, J, Evans, T and Najera, L (2012) Comparison of compliance results obtained from various wind farm standards used in Australia, Acoustics Australia, 40(1), 37-44.
8. Evans, T and Cooper, J (2012b) Influence of wind direction on noise emission and propagation from wind turbines, Proceedings of Acoustics 2012, Fremantle.
9. Cooper, J & Evans, T, 2012, ‘Influence of upwind turbines on wind turbine sound power output’, Proceedings of Acoustics 2012, Fremantle, 21-23 November 2012.