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Audible amplitude modulation - results of field measurements and investigations compared to psycho-acoustical assessment and theoretical research

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Summary

In the UK the cause of amplitude modulation (AM) and the ability to predict its occurrence is considered abstruse by many. Few have experienced or measured AM and yet conclusions are frequently made asserting that it is rare and that any action to counter its effects is limited by minimal knowledge surrounding its nature and cause. This paper aims to advance current knowledge and opinion of AM. Methods used to successfully investigate AM are confirmed. AM should be measured during evening (after sunset), night time or early morning periods. Meteorological effects, such as atmospheric stability, which lead to downward refraction resulting from changes in the sound speed gradient alter the character and level of AM measured. AM is generated by all wind turbines including single turbines. Propagation conditions, mostly affected by meteorology, and the occurrence of localised heightened noise zones determine locations that will be affected. Measurements from eleven wind farms have been presented and discussed in relation to current research and theory. Findings confirm that AM occurrence is frequent and can readily be identified in the field by measuring under suitable conditions and using appropriate equipment and settings. Audible features of AM including frequency content and periodicity vary both within and between wind farms. Noise character can differ considerably within a short time period. The constant change in AM character increases attention and cognitive appraisal and reappraisal, inhibiting acclimatisation to the sound. It is advised that those responsible for approving and enforcing wind energy development improve their understanding of the character and impact of AM. This can be achieved by attending a listening room experience which has been trialled and is discussed in this paper.

Introduction

In the UK denial continues that AM is other than rare with reliance placed on a 2007 report prepared for Defra[1] by the University of Salford which found low incidence of

[1] UK Government Department for Environment, Food & Rural Affairs

AM (Moorhouse et al, 2007). Re-analysis of the Salford data confirms many cases were missed (van den Berg, 2009). We and other independent researchers (Hoare, 2009) have also found that the Salford report understated incidence of AM. In the UK we have now identified at least seventy UK wind farms where it is known that AM is the cause of complaints. Many of the wind farms studied in the Salford report were situated in isolated locations with few residential neighbours. Examination of the sites existing in 2007 suggests that many of the wind farms included in the Salford report were unlikely to lead to AM complaints simply due to their isolated locations. As wind farms have spread to more populated parts of the UK, and as turbine hub heights have increased, incidence and complaints of AM have risen.

Few regulators and decision makers visit wind farms under the conditions likely to give rise to enhanced AM, leading to a risk of ill-informed decisions. Other important issues remain in dispute. For example, it has been argued that A weighted variations of less than 3dB are not readily recognised and do not lead to intrusion; something identified as erroneous when observing AM. In an attempt to inform such debates we have trialled a "Listening Room Experience" using data and audio gathered from field measurements[2]. The Listening Room Experience enables lay decision makers to listen to different samples of amplitude modulation varying in character and decibel level. They can then reach independent and informed conclusions regarding audibility and impact of AM. The Listening Room Experience is discussed at the end of this paper.

The following section discusses some of the current research on AM. Section 2 details appropriate procedure to identify and measure AM. Field measurements of AM are presented and discussed in Section 3 with reference to current research. Section 4 explores some psycho-acoustic factors influencing the perception of AM. The Listening Room Experience, a procedure designed to help inform decision makers, is then discussed in Section 5.

Van den Berg's research published in 2005 highlighted the major features and causes of AM. 8 years later, his findings are still either neglected, undervalued or being presented as 'new' information. It appears that the UK is seeking a simple cause and effect relationship between turbine(s) and AM which does not necessarily exist. Indeed the evidence, as discussed below, suggests that all wind development, including single turbines, will generate AM. The exact nature and level of AM that arises, along with the locations where it is prominent, is dependent on a number of contributing site specific meteorological and geographical features.

Van den Berg (2005) recognised the mechanisms generating AM, relating largely to trailing edge noise, and which is generic to all turbines. Van den Berg outlines the following features as generating or contributing to AM: atmospheric stability, near synchronicity, atmospheric absorption increasing prominence of low frequency sound and high turbine noise levels when background noise levels are low. Oerlemans and Schepers (2009) discuss trailing edge noise and swish footprints generated by turbines. They found that under cross wind conditions although the average level is lower, amplitude modulation has a greater peak to trough, up to 5dB, than upwind or downwind directions. Findings were corroborated by measurements at a distance of approximately 240m from a single turbine. Di Napoli (2009) notes the importance of weather conditions for correctly measuring wind turbine noise; measurements were specifically taken during a night time period. Di Napoli measured AM with a peak to

[2] A number of the sound files referred to in this report and used in the Listening Room Experience are presented on our website with interactive graphs.

trough typically of 5dB and up to 12dB. Greatest peak to trough was attributed to decreases in wind speed and occurring towards the end of accelerations in wind speed and blade rotation speed. AM with a double peak was also found (page 6). The importance of measurement in the correct weather conditions and at the correct time of day is again noted in Di Napoli (2011). This study found that smaller, older turbines generated significant AM. Impact from AM was linked to synchronisation of AM pulses and low wind speeds at the immission point. Broadband noise was not found to decrease over distance as expected and in contrast to Oerlemans and Schepers (2009) least AM was measured under cross wind conditions with downwind samples at far field measurement points resulting in highest measured peak to trough level.

Bakker and Rapley (2011) do not directly discuss AM but discuss the occurrence of heightened noise zones which arise around wind farms. They found that noise levels from a single turbine can vary by 2-5dB and multiple turbines can produce noise levels varying by 6-13dB. It was observed that the specific location of equipment was extremely important as noise could vary significantly over very short distances. Cand et al (2012) conclude on review of literature that potential causes of AM relate to non uniform inlet flow likely caused by wind shear or atmospheric turbulence effects. This is further discussed in Smith et al (2012) and includes detached or stalled flow over the turbine blade as a cause of AM. Following a long term study Larsson and Öhlund (2012) describe the impact of meteorology and ground attenuation effects on AM and note its prominence at greater distances from the turbines. Synchronicity / interference between turbines is again noted as a cause of AM at greater distances. Larsson and Öhlund (2012) observed differences in noise level of 6-14dB. They conclude that AM is observed 30% of the time at 400m, 10% of the time at 1km from the nearest turbine and is most common in the evening, night time and morning (p. 5).

The influence of meteorology in causing AM is attributed less weight by Lee and Lee (2013) although the effect on propagation is noted. The discussion by Lee and Lee (2013) provides further evidence that all turbines will cause AM but states that AM is heard at long distances only in certain directions. This changes as the wind direction changes.

Lee and Lee (2013) found that where 'operating and atmospheric conditions are identical, the acoustical characteristics of wind turbine noise can be quite different with respect to the distance and direction from the wind turbine' (p. EL94). They identified mathematically that AM can be caused by all turbines and that variation in spectral content and sound energy changes with distance and angle to the wind direction. Lee and Lee (2013) did not consider atmospheric refraction the effects of which, as suggested by measurements in the above research, complicate predictions of wind turbine noise and AM. These factors may explain the different conclusions reached by Oerlemans and Schepers (2009) and Di Napoli (2011).

Lee and Lee (2013) also found that 'at long distances from the wind turbine, the amplitude modulation is hardly perceived in the upwind, downwind, and crosswind directions…Nevertheless, even at long distances the amplitude modulation is still audible in other directions provided that the background noise is low. In addition, these sounds are no longer similar to the swishing sound. They are low-frequency amplitude-modulated sounds'(p. EL98)[3]. The differences in findings appear in part

[3] In general this agrees with many of our field measurements but is not always the case.

due to atmospheric refraction and ground effects. For example changes in the wind direction can mean the long distance low frequency AM immission level changes from being generated at the top of the blade rotation to the near ground part of the blade rotation. This shifts the source noise from around 120m to around 35m above ground level for a typical turbine. The effect of atmospheric refraction is considerably different at these heights.

Although the paper by Lee and Lee (2013) discusses some important issues in relation to propagation of AM a major limitation is the neglect of refractive effects. Evidence on atmospheric refraction obtained by Wilson (2003) indicates that when atmospheric conditions lead to downward refraction of sound energy, the decibel level at receptors is greater by at least 3-4dB than when conditions lead to upward refraction. Wilson (2003) also shows that the meteorological changes from upward refraction to downward refraction relate directly to the variation in sound speed with height which in turn is influenced by wind speed gradient (wind shear), temperature gradient, temperature fluctuations and to some extent humidity especially over wet surfaces. Small changes in meteorology are predicted to lead to significant change in noise impact near the ground, reflected in the variations identified in the above research.

In summary the following assertions regarding the cause of AM and exacerbating factors can be made:

→ All turbines, including single turbines can cause AM.

→ Trailing edge is the main source of noise on a turbine causing AM.

→ Meteorology affects propagation of AM.

→ Inflow turbulence caused by meteorological / topographical air turbulence causes / exacerbates AM.

→ Synchronicity / heightened noise zones exacerbate AM at distant locations.

→ AM is found in cross wind and down wind conditions but can also occur at lower sound energy levels upwind.

→ Measurements of AM should target evening, night time and early morning periods when there is low cloud cover / high wind shear.

Measurement of AM

Determining appropriate measurement locations and observation times

It was evident from an early stage of our research that wind turbine noise levels measured at distances of 500m-1500m from the nearest turbine vary not only with meteorological conditions, such as wind direction, but with relatively small changes in location. Locating sound level meters based on daytime observations led to no more than a chance of reflecting impact after darkness. Descriptions by residents may not always be accurate and so visits at night time when there is high wind shear and / or temperature inversion is recommended to experience enhanced propagation conditions.

It is logical and supported by research (van den Berg, 2005) that atmospheric conditions leading to downward refraction of sound energy will result in higher decibel levels at distant receptors than atmospheric conditions leading to upward refraction. It is also clear from research (Wilson, 2003) that the meteorological changes from upward refraction to downward refraction relate directly to the variation in sound speed with height, which in turn is influenced by temperature and other small changes in meteorology.

In their long term study Larsson and Öhlund (2012) found variations in measured wind turbine noise at 1km of 6-14dB(A). At 400m there was difficulty separating meteorological effects from wind direction. They state that 'meteorological conditions must be taken into consideration starting at distances somewhere between 400 and 1000 m ... the enhanced AM sound is influenced by the propagation path or the interference between several wind turbines rather than changes in the emitted sound' (p.4). Larsson and Öhlund (2012) conclude that 'the occurrence of AM sound increases during evening, night and morning and then decreases during the day. This pattern follows perfectly how the temperature inversion is built up during the evening and nights and breaks up from ground when the rising sun heats the ground' (p.5)[4].

We have found variation of AM at night both temporally and in different locations, sometimes only a few metres apart. This agrees with Bakker and Rapley (2011) who identified heightened noise zones. In some cases the variation between locations is significant and in others impact is more widespread. There is a need to visit affected properties under worst case impact, often between 00:00 and 04:00 hours to identify specific locations to site instruments. Alternatively, where a resident has cogently identified affected rooms in the dwelling or garden area these may be representative; however, care is needed that the conditions monitored reflect those leading to observations by residents. There is no substitute to visiting at the times of impact.

It is important to observe and set up instrumentation when conditions lead to downward refraction of sound energy and when background noise levels are low. These conditions most often occur when there is a stable atmospheric state leading to low wind speeds near the ground. Best results have been obtained with hub height wind speeds at or above those providing maximum noise output. This requires sufficient atmospheric pressure variation (closeness of isobars). As a 'rule of thumb' if it is windy and gusting on a sunny / low cloud level day and this continues at night then significant AM can be expected. Ideally, for measurement of typical worst case noise, more distant receiver locations[5] should fall approximately within a 60 degree arc, assuming clockwise rotation of the turbines, although this will vary depending on the configuration of the turbines, topography and meteorology.

It is important to move to different localities to observe how the impact changes throughout the night, from location to location and with increasing wind shear.

Measurement parameters

Low interference from the sound level meter floor, especially when undertaking internal measurements, is critical to obtaining good data. This is best achieved using a low noise floor microphone, typically below 10dB(A). A type 1 sound level meter measuring LAeq, 1/3rd octave band Leq and measuring at least 125ms intervals,

[4] These findings concur with our own field measurements which we have conducted over the last 7 years.
[5] Those in excess of 500m.

preferably every 100ms[6], is needed. We now measure down to 0.4Hz to enable analysis of infrasound but this is a separate consideration beyond the scope of this paper. Measurements are best synchronised with good quality audio recordings ideally at 24 bit rate and 48kHz sampling rate; however, 16 bit rate may suffice. Some experimentation is often required to avoid "clipping" of the sound recordings and loss of reproducibility.

Where good quality audio recordings are obtained these can be processed using appropriate software[7] to confirm reproduction at the relevant sound levels observed in the field and for representative playback.

In our experience regulators measuring AM noise will place a sound level meter within a dwelling with a hand operated trigger for residents to record AM when it occurs. They rarely use high quality audio and do not normally possess low noise floor microphones. This results in poor quality sound reproduction where the troughs of sound energy are lost and many characteristics of the AM are masked by interference with the noise floor. Regulators often do not record data with a sufficient time interval to see temporal effects. Any spectral information, if recorded, is usually corrupted because of the noise floor of the meter. Remote data analysis undertaken by regulators can fail to identify the psycho-acoustic character of the noise. Through use of inadequate measurement parameters, compliance checks frequently understate the impact of AM and wind farm noise leading to erroneous findings.

Findings in relation to field measurements

The following charts represent a small sample of the data measured from a number of wind energy developments in and around the UK. The findings presented below aim to provoke discussion on the various causes of AM and raise important issues regarding psycho-acoustic aspects of AM perception. Measurements are presented in chronological order. In the UK wind farm noise is generally assessed external to the affected property. The majority of measurements below were recorded externally; where measurements are made within the dwelling an internal noise measurement has been noted.

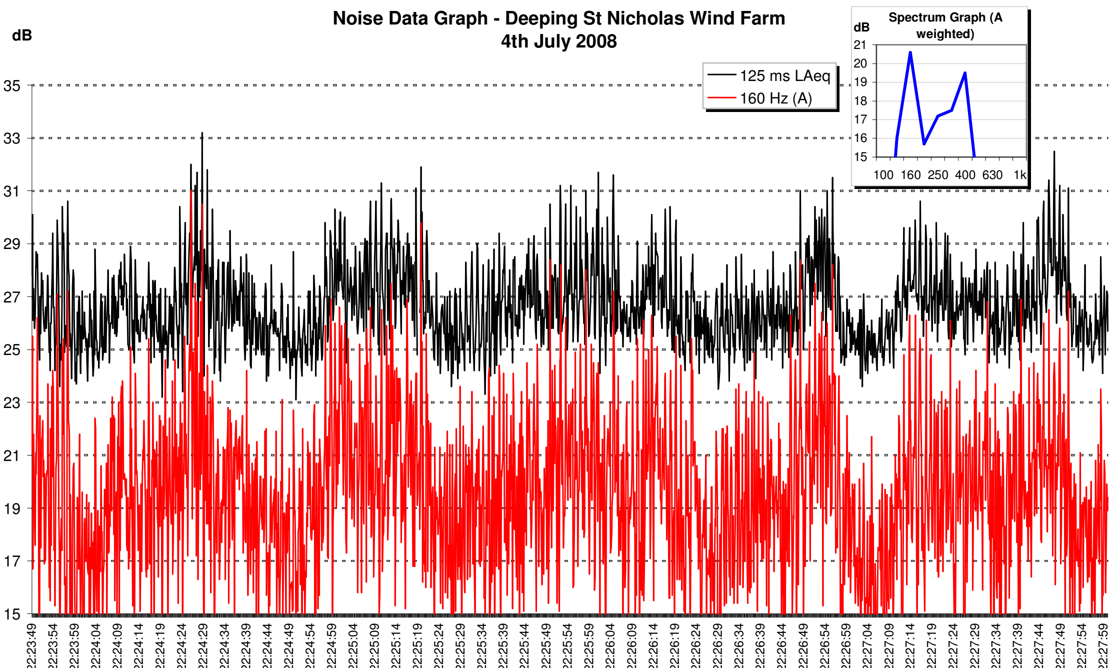
Deeping St Nicholas, Lincolnshire, England

Deeping St. Nicholas Wind Farm is located within the flat fenland area of eastern England. The data shown on the chart below was measured internally, with a window partly open and just over 1000m from the nearest turbine. The wind direction placed the downwind angle for the measurements at just over 30 degrees (clockwise). This concurs with a prediction of low frequency dominance as identified by Lee and Lee (2013).

[6] We have found no benefits using shorter time periods than 100ms and the large data handling requirement becomes an impediment.

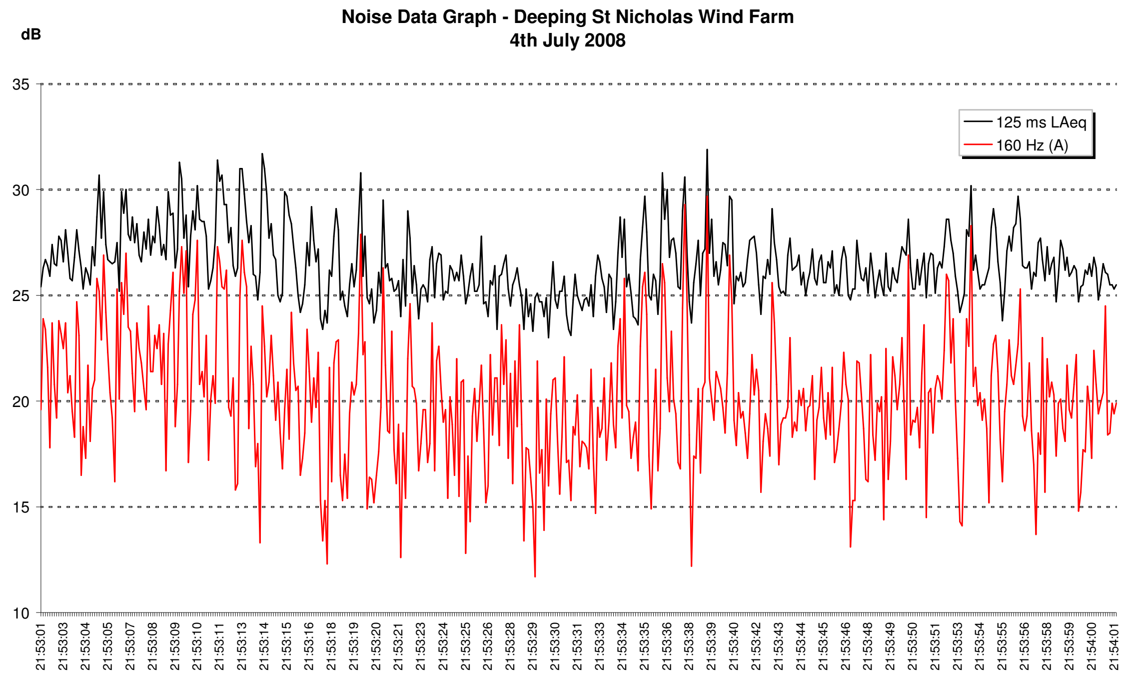
[7] For example, Spectral Plus.

As can be seen from the spectrum graph in the top right hand corner, sound energy is focused between the 125Hz and 400Hz third octave bands. The 160Hz third octave band is dominant. The A weighted AM peak to trough was typically 6dB, although modulation in the 160Hz third octave band is considerably greater. Background noise levels measured in the bedroom were below the noise floor of the meter (18dB(A)). From experience background noise levels are likely to be in the region of 12-15dB(A). All data is A weighted to allow direct comparison.



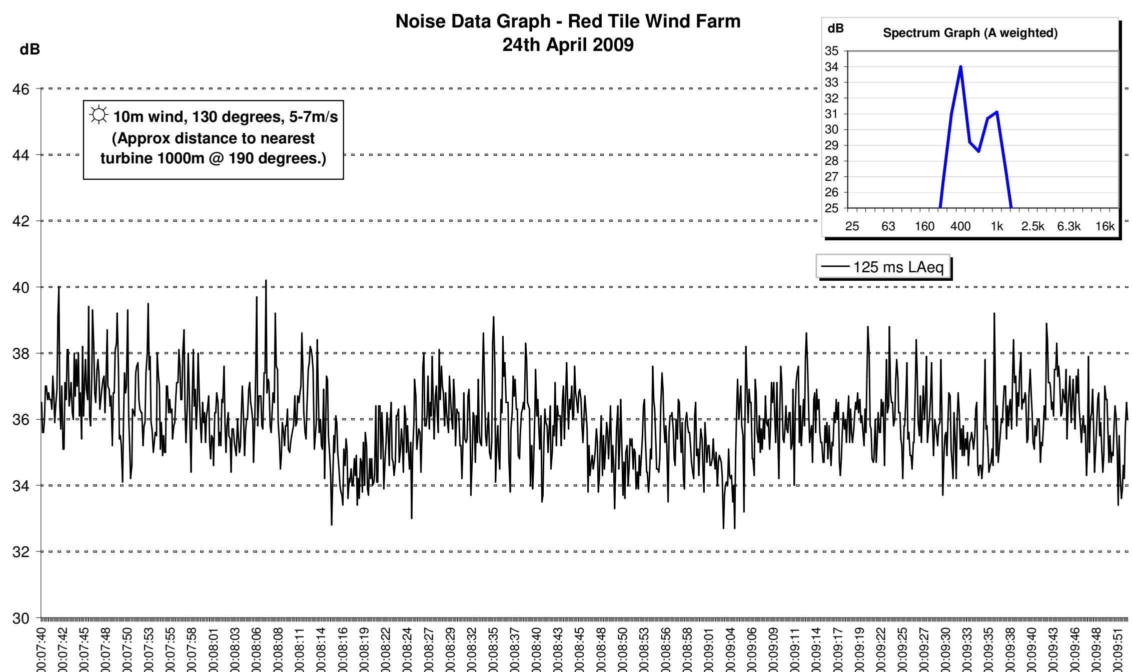
Analysis of the data from this site, as with other sites, reveals a time shift in the spectrum data. Sound energy within different third octave bands arrives at the microphone successively a fraction of a second apart. As a consequence the overall A weighted level does not fluctuate peak to trough to the same extent as the individual third octave bands fluctuate. This masks the true effects of varying sound energy in different frequency bands and supports the approach in the New Zealand Wind Farm Noise Standard (2010) and the DTI report on the measurement of low frequency noise at three UK wind farms (Hayes McKenzie Partnership Ltd, 2006) both of which look separately at observing the varying third octave band levels as well as the fluctuation in the A weighted AM. The above data also agrees with predictions by Larsson and Öhlund (2012) and Lee and Lee (2013) of greater low frequency dominance in the immission levels at increasing distance from the wind farm.

The chart below was obtained earlier the same evening and shows the extent of the third octave band fluctuations in the 160Hz third octave band. Peak to trough variations are in the region of 9-17dB. Some of the A weighted Leq peaks can be seen to be dominated by this low frequency fluctuation.



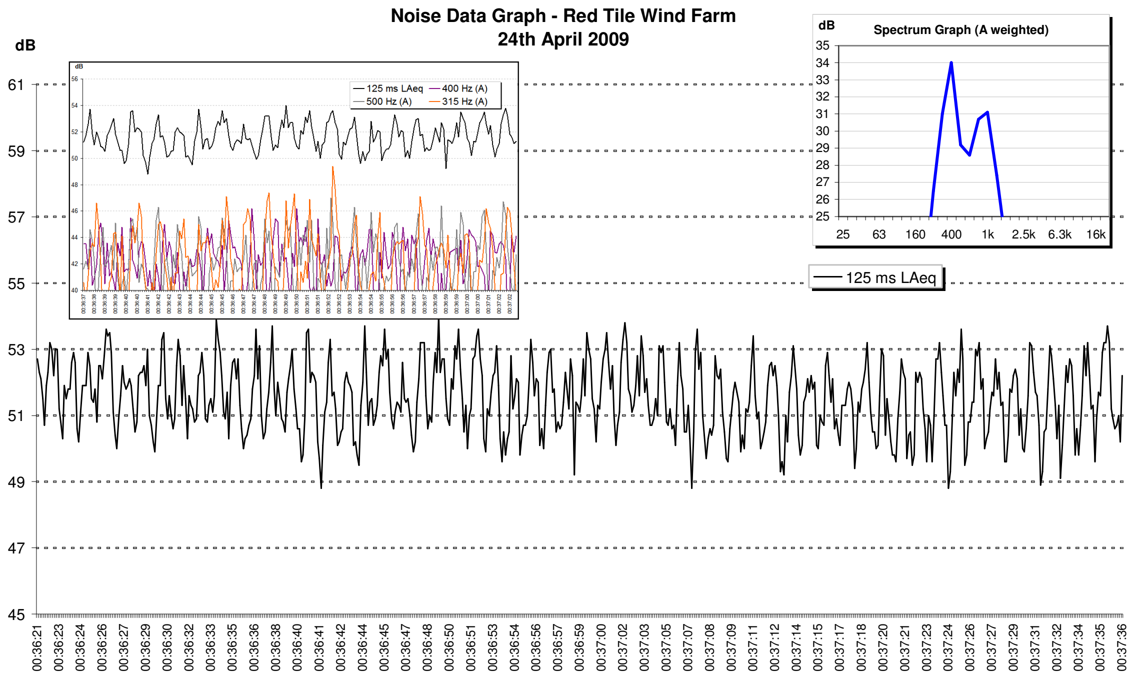
Red Tile Wind Farm, Cambridgeshire, England

Red Tile Wind Farm is located on a flat site in eastern England. Measurements were made approximately 1000m from the wind farm.



The example AM trace shown here is erratic both in peak level and shape. AM peak to trough is typically 4-5dB. Sound energy is focused in the 400Hz third octave band with some contribution from the 1kHz third octave band. This frequency content is of slightly higher frequency content than has been observed in AM measured at other wind energy developments. Although measurements were taken at a similar distance to those shown for Deeping St Nicholas Wind Farm, slightly higher frequency content is expected due to cross wind measurement conditions.

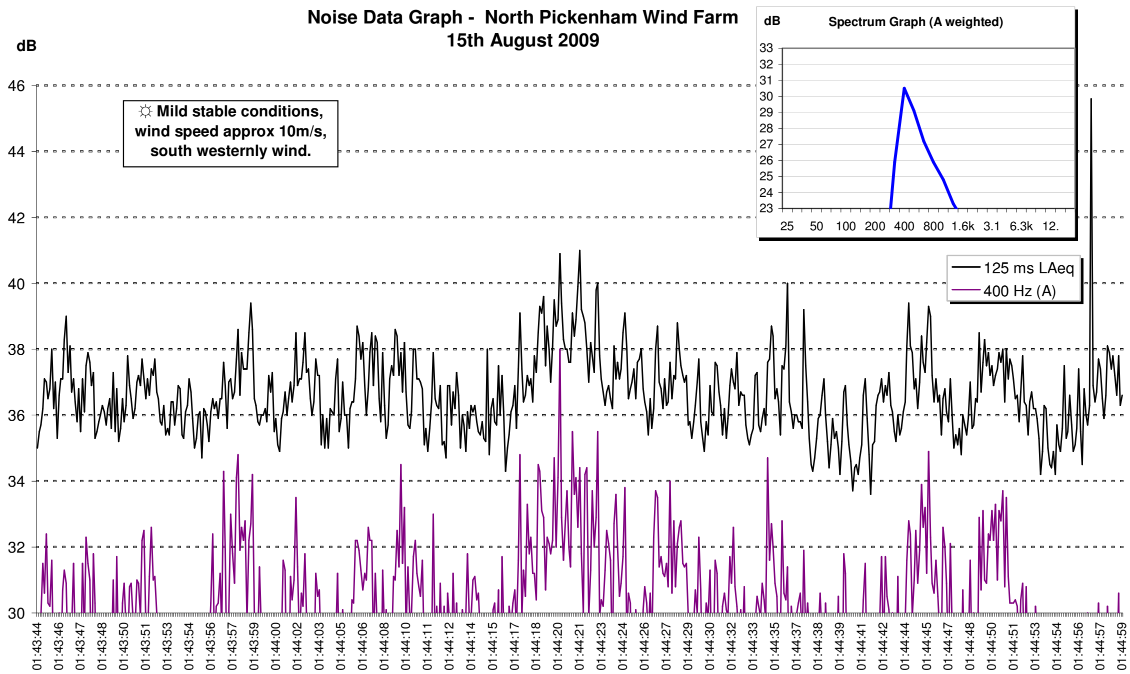
The AM in the chart below was measured slightly later in the night than the chart above and closer to the turbines. The AM is now less erratic in peak range and level.



Although the AM peak often consists of two or multiple peaks, it is constant in this character and peak to trough difference is consistently in the region of 3-4dB. Average sound energy spectral content is shown, in the top right hand graph, to be dominated by 400Hz third octave band energy; however, the top left hand graph, showing the third octave band 125ms time trace, reveals that most peaks are dominated by energy in the 315Hz or 500Hz third octave band. There is rarely any synchronisation in third octave bands and the phasing is consistently different, reflected in the multiple peak character of the AM. The AM has a sweeping tonal characteristic, which is most likely generated by the non simultaneous contribution of different third octave band sound energy to the AM peaks over time.

North Pickenham Wind Farm, Norfolk, England

AM measured from this site, approximately 1000m from the nearest turbines, is fairly erratic. The chart below shows approximately 1 minute of AM with peak to trough values typically of 4dB. The spectral content of the period is dominated by 400Hz third octave band noise. Closer inspection of the 125ms 400Hz third octave band time trace, plotted on the chart, suggests that this band does not dictate the AM peaks to the same extent as has been found at other sites. Although much of the measured noise is more broadband in nature and could be interpreted as more typical of general wind farm noise there are still lower frequency thump elements that can be heard within the data but not easily attributed to specific frequency content.

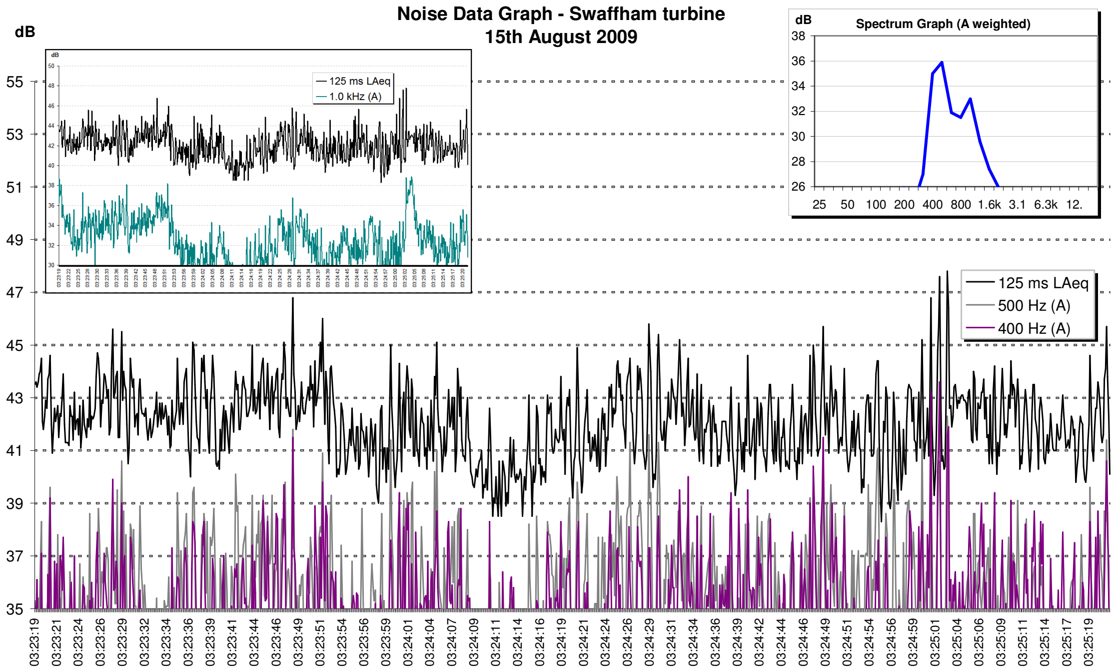


The measurement location was at varying angles to the turbines due to their geographical spread. This may be the cause of the less distinct peak to trough variations in both the A weighted 125ms trace and the individual third octave band levels. However, peak to trough variations in the 125Hz third octave band were in the region of 8-10dB. This could explain the perceived intrusion from low frequency content although it is not indicated by an A weighted analysis as dominant.

Swaffham Wind Turbine, Norfolk, England

Measurements from this single turbine were taken at a distance of approximately 320m, closer than the majority of measurements presented. The measurements were taken on the same night as those at North Pickenham Wind Farm.

AM peaks are much clearer from this single turbine compared to the multiple peak trace measured at Red Tile Wind Farm and North Pickenham Wind Farm. Dominant frequencies within the 400Hz and 500Hz third octave bands can be seen to clearly dictate specific AM peaks. AM peak to trough values were typically 4dB although differences of up to 6dB were measured.

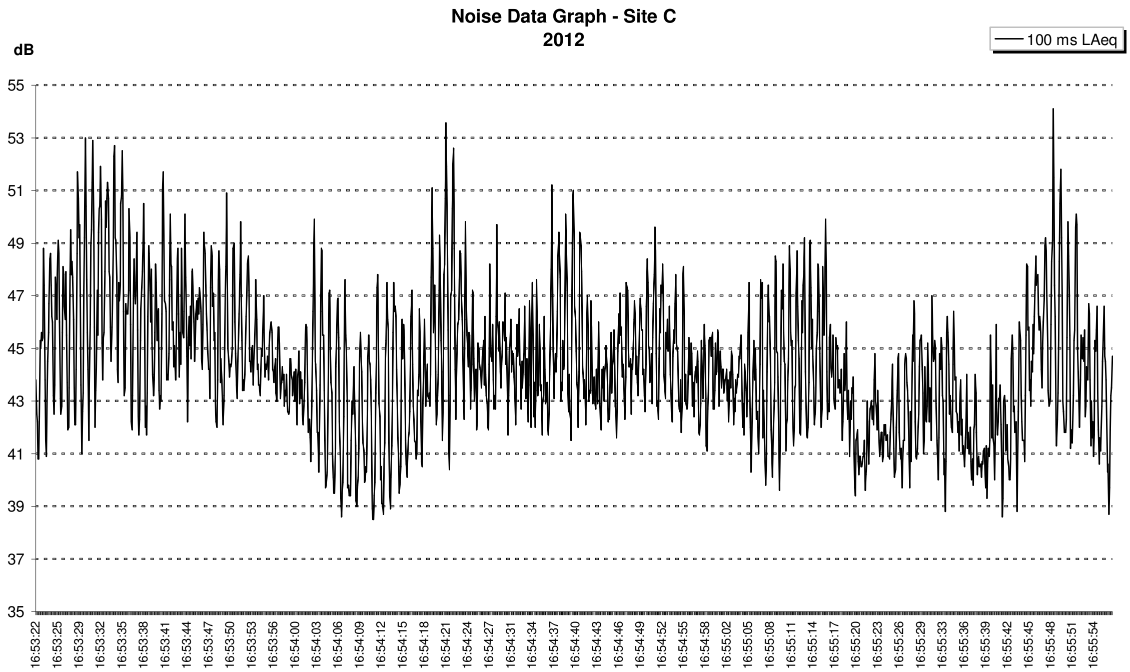


Although a peak in the spectrum graph for the period is observed in the 1kHz third octave band, see top right hand side of the above chart, it is not a major contributor to the AM. The main chart shows energy in the 400Hz and 500Hz third octave bands mapping well with the 125ms LAeq peaks. The graph on the top left hand side of the above chart shows the same period with the 1kHz 125ms third octave band time trace added. The 1kHz third octave band energy follows the main shape of the 125ms LAeq trace but does not modulate to the same extent as the 400Hz and 500Hz energy, shown in the main graph, and does not contribute significantly to AM peaks.

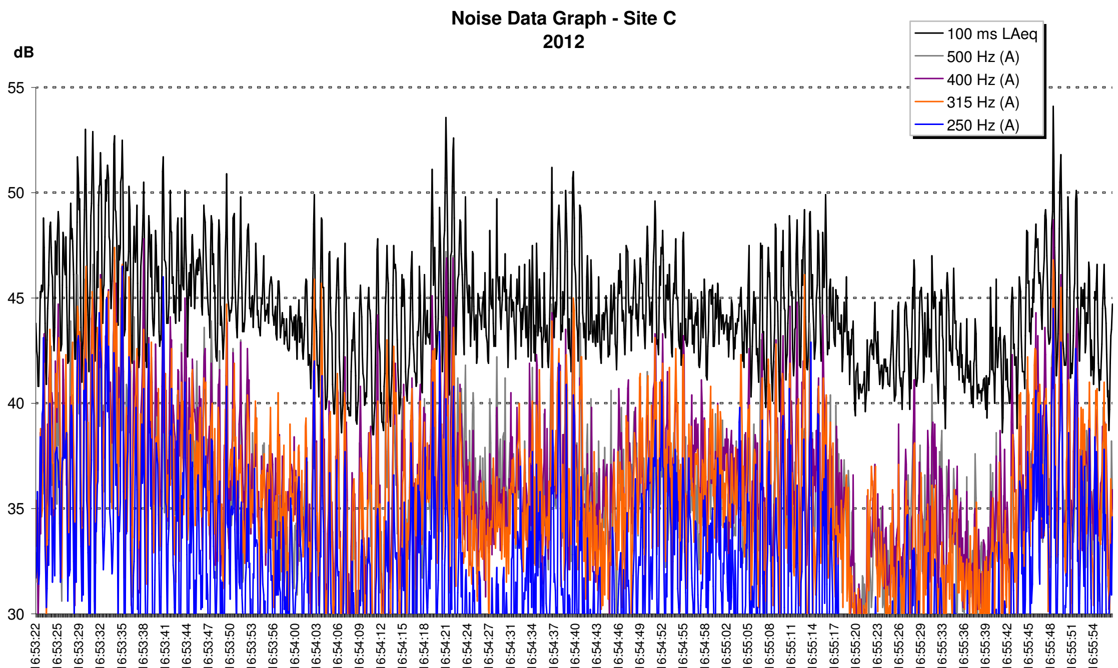
Site C, D & E

These locations remain anonymous at this stage at the request of the affected parties. The measurements were made in three different external amenity areas located in a remote rural area. AM occurs frequently at the sites. The three extracts below were measured on three separate occasions in 2012.

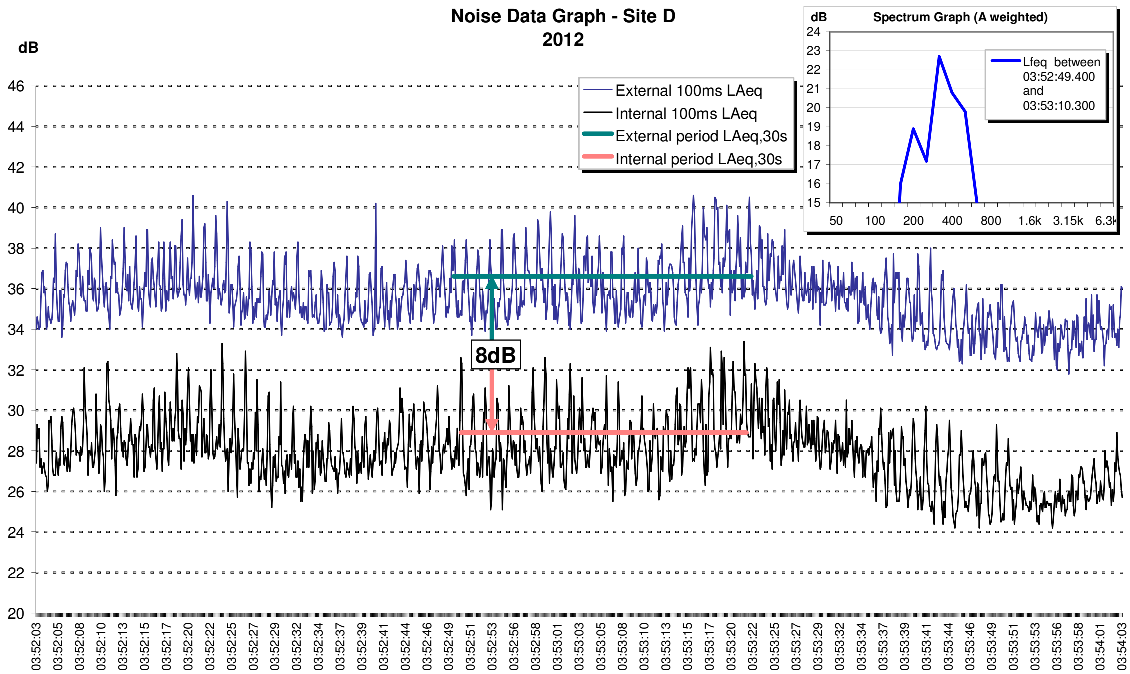
Site C is 450m from 3 turbines with AM measured in a cross wind situation. The wind turbine noise is dominating and at least 10dB above the background noise level. In contrast to other cases, significant AM was measured from this wind farm during daytime hours. AM peak to trough is regularly 8-10dB.



Peaks are determined by different frequency bands; generally noise in the 315Hz third octave band is dominant with contribution also from energy in the 500Hz, 400Hz and 250Hz third octave bands. These variations were judged to arise due to the variation in contribution from different turbines and varying degrees of synchronicity.



At site D internal (with the window partly open) and external measurements, in the garden area, were obtained and are compared in the chart below. Site D is approximately 1000m from nine turbines with several turbines almost equidistant from the residence. The wind direction during measurements resulted in the property being between a cross wind and downwind direction from the turbines.

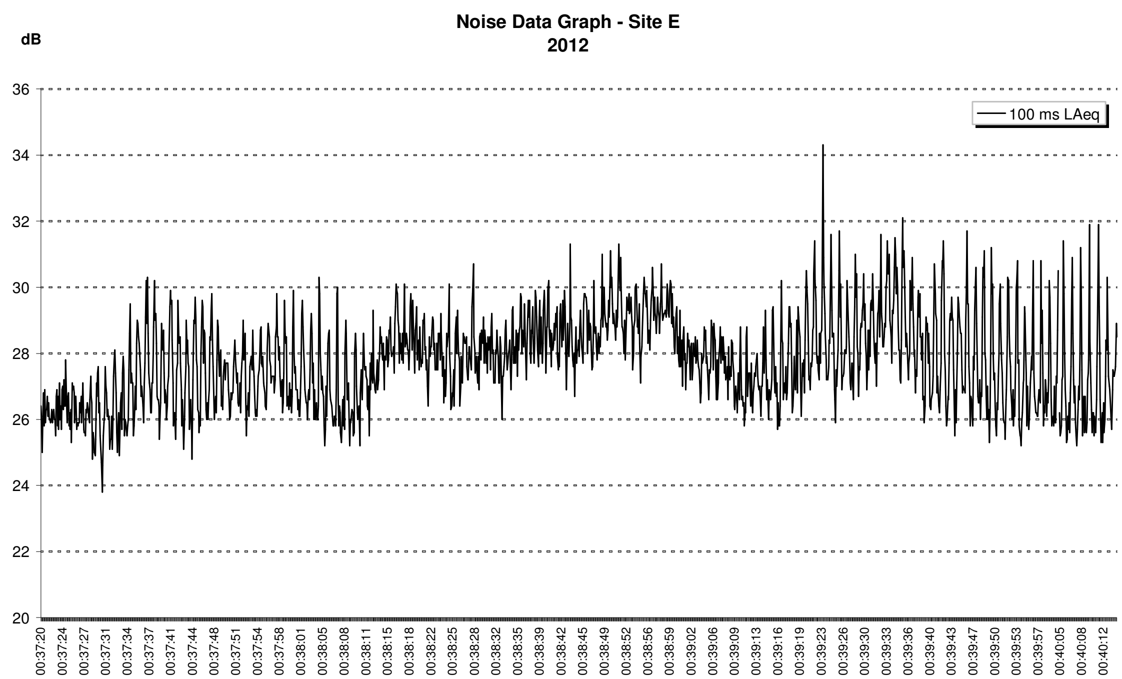


With the window partially open, reduction in noise level was approximately 8dB. Peak to trough levels externally were generally 4-6dB. Internally the peak to trough difference was approximately 1dB greater. The internal spectrum graph is shown in the top right hand corner of the chart above[8]. The 315Hz third octave band energy is dominant with significant contribution from 400Hz and 200Hz third octave band noise. Whilst the sound energy levels and peak to trough range varied slightly, prolonged periods of impact arose with little variation in the peak to trough range. The data indicated a high level of synchronicity.

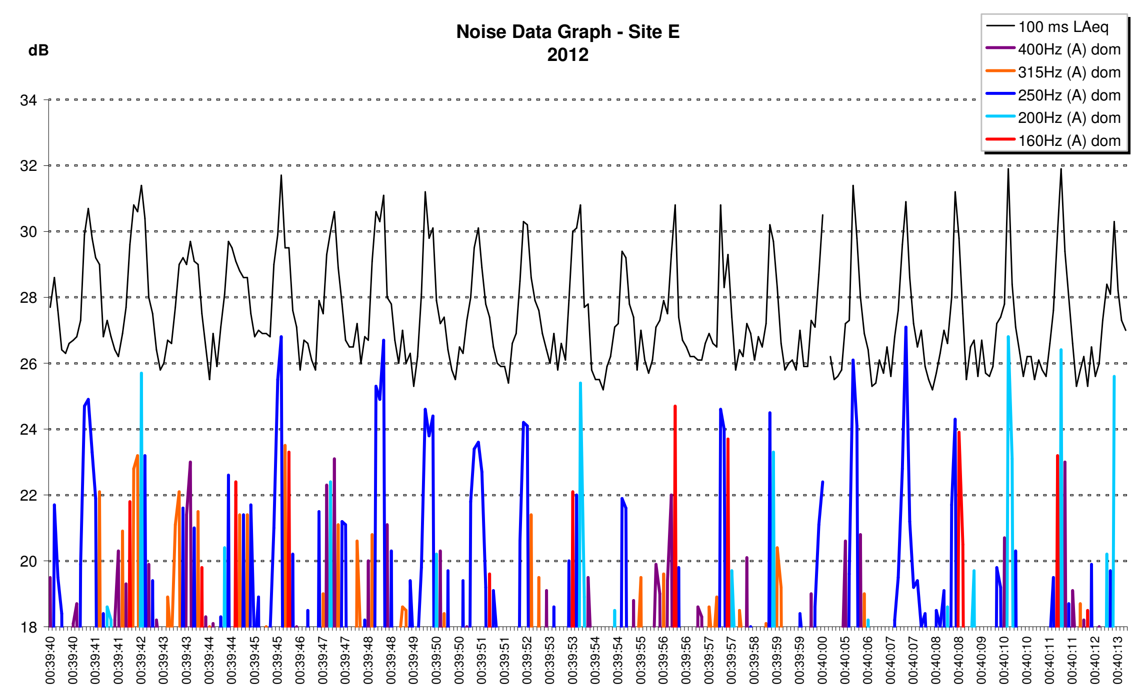
Site E is approximately 1000m from the wind farm. Measurements were made downwind of the turbines. On this occasion dominant lower frequency noise was measured internally.

[8] External spectral data was not recorded.

The chart below shows the noise trace, indicating a peak to trough range of 4-6dB. The chart shows intermittency with periods of greater peak to trough variation lasting for a few seconds and periods of diminished AM. This was found to be a common pattern observed in the measurements at this location.



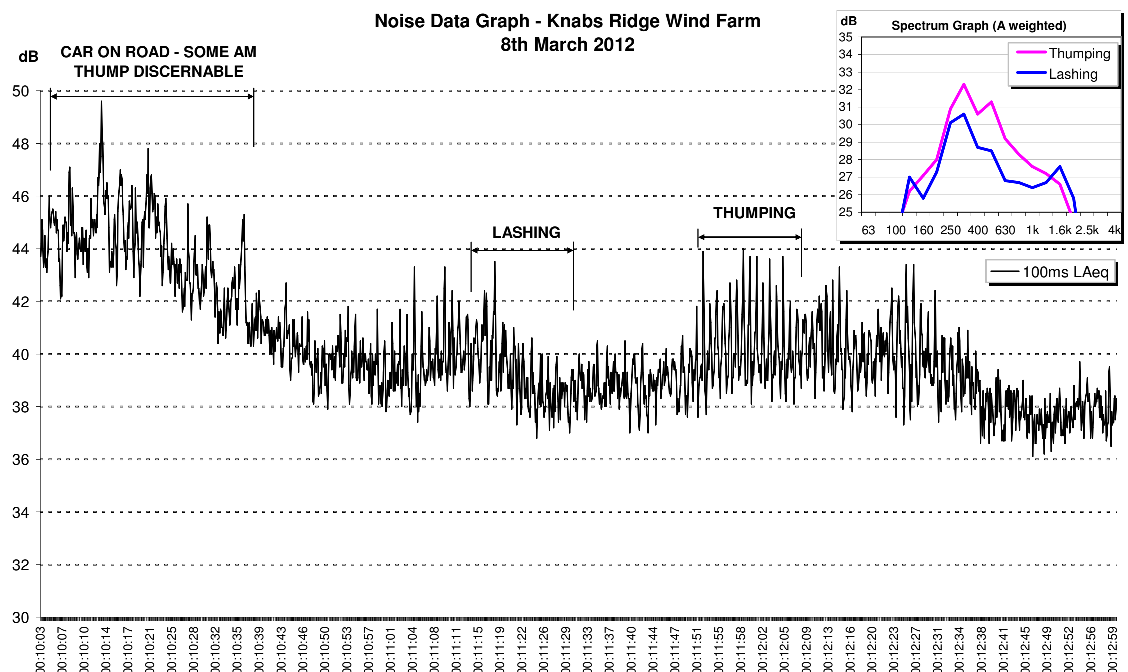
Analysis of the last 30s of the above period, shown on the chart below, demonstrates the changing dominance of low frequency noise.



The 100ms LAeq trace is shown with corresponding spectral analysis. Most AM energy was found between the 160Hz and 400Hz third octave bands. To assess the dominance of each third octave band in each AM peak, for each 100ms sample only the third octave band with the highest decibel contribution is plotted. Thus, the chart shows the most dominant third octave band at a given point in time. The last three peaks of the extract can be seen to be dominated by 200Hz third octave band noise, the fourth peak from the end is equally dominated by 250Hz and 160Hz third octave band noise and the fifth and sixth peaks from the end of the period are dominated by 250Hz third octave band noise. Not only does the variation in the peak to trough difference change but there is also a noticeable change in the character of the sound energy of the peaks; this was considered to exacerbate the effect on listeners.

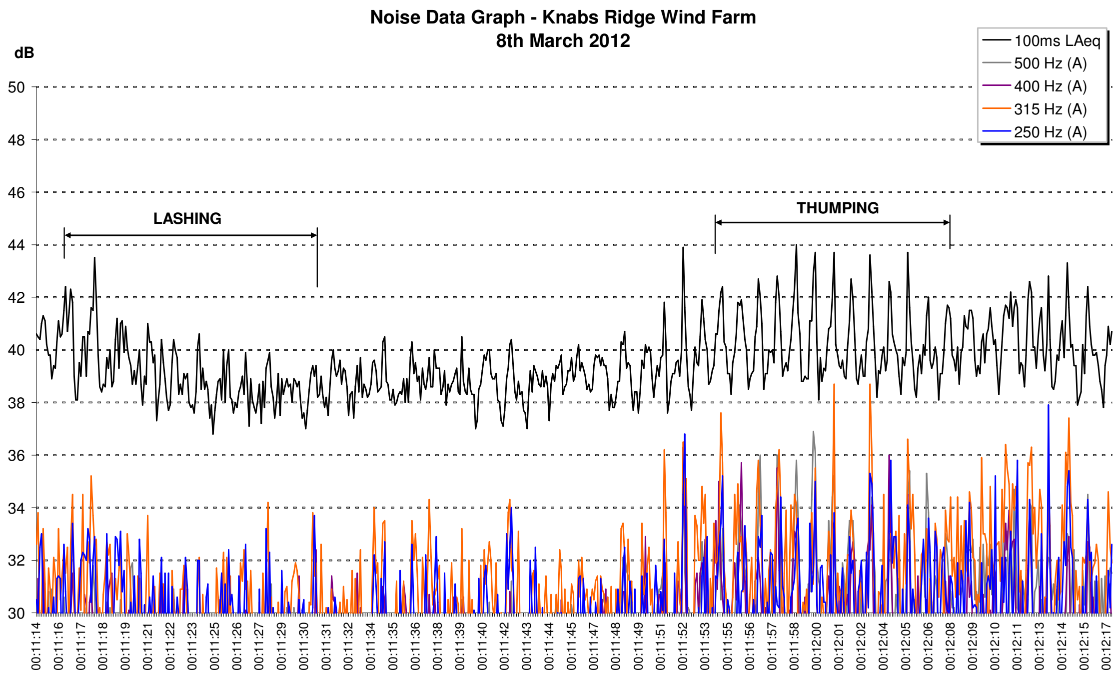
Knabs Ridge Wind Farm, North Yorkshire, England

AM from Knabs Ridge wind farm was measured on a nearby caravan site approximately 550m from the nearest turbine. At the beginning of the chart below a car passes on a nearby road. Noise from the car pass-by does not audibly mask the AM noise although it interferes with the noise trace. Two distinct types of AM can be heard and seen in this period, described as 'lashing' and 'thumping'.



The thumping AM has a clear single peak with energy focused in the 315Hz third octave band. Whereas the lashing AM sounds more high frequency dominated, there is a 125Hz third octave band component to the noise along with the main 315Hz third octave band energy and some higher frequency energy around the 1.6kHz third octave band. See the top right hand graph in the chart above.

The chart below shows that the lashing AM consists of poorly aligned peaks from several third octave bands. The thumping AM is dominated by 315Hz and 250Hz third octave band energy that is often synchronised. These characteristics are lost when examining the average spectrum graph for the period and demonstrates the need to look at the spectrum during each peak.

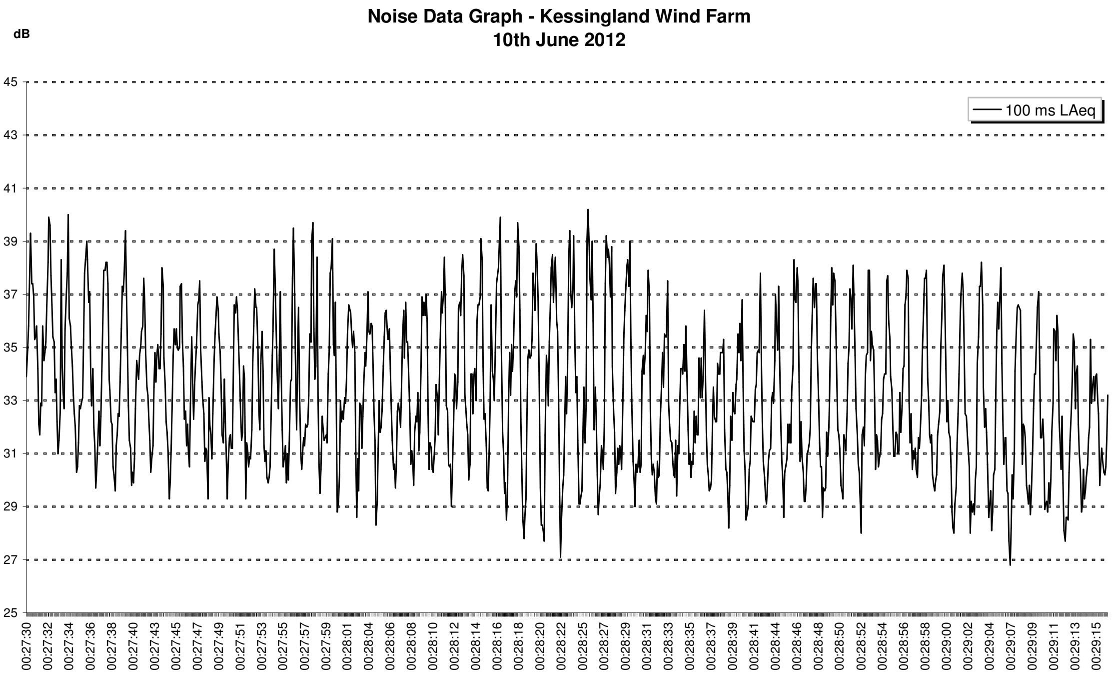


During much of the period shown on the chart above the peak to trough level is around 3dB or less, but is audibly judged as similarly intrusive to AM with higher peak to trough due to its spectral content and the manner in which it changes. In the 2006 DTI report peak to trough ranges of 2-6dB were identified as unacceptable and considered by the author as warranting a penalty[9].

Kessingland Wind Farm, Suffolk, England

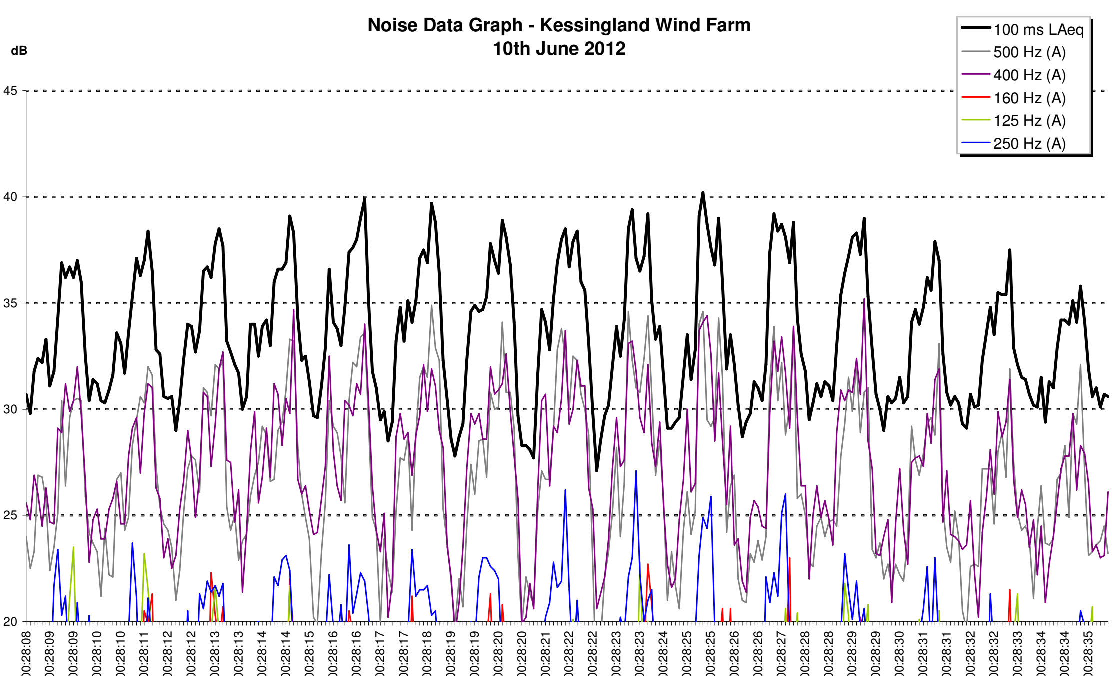
Located close to the eastern coast of the UK, AM from the two turbines at Kessingland is frequent in occurrence. The majority of the local community have been complaining and campaigning for the turbines to be turned off. Despite noise monitoring exercises being undertaken the noise issues have not yet been resolved. We have measured AM from the two Kessingland turbines on three different occasions. Whilst AM is fairly consistently present when the turbines are operating at night time, there are different features to the noise at different times. The chart below shows a period of approximately 2 minutes measured on 10th June 2012 at a distance of 550m from the nearest turbine. The typical peak to trough range is 8-10dB.

[9] The DTI report and Freedom of Information releases on the report confirm this.

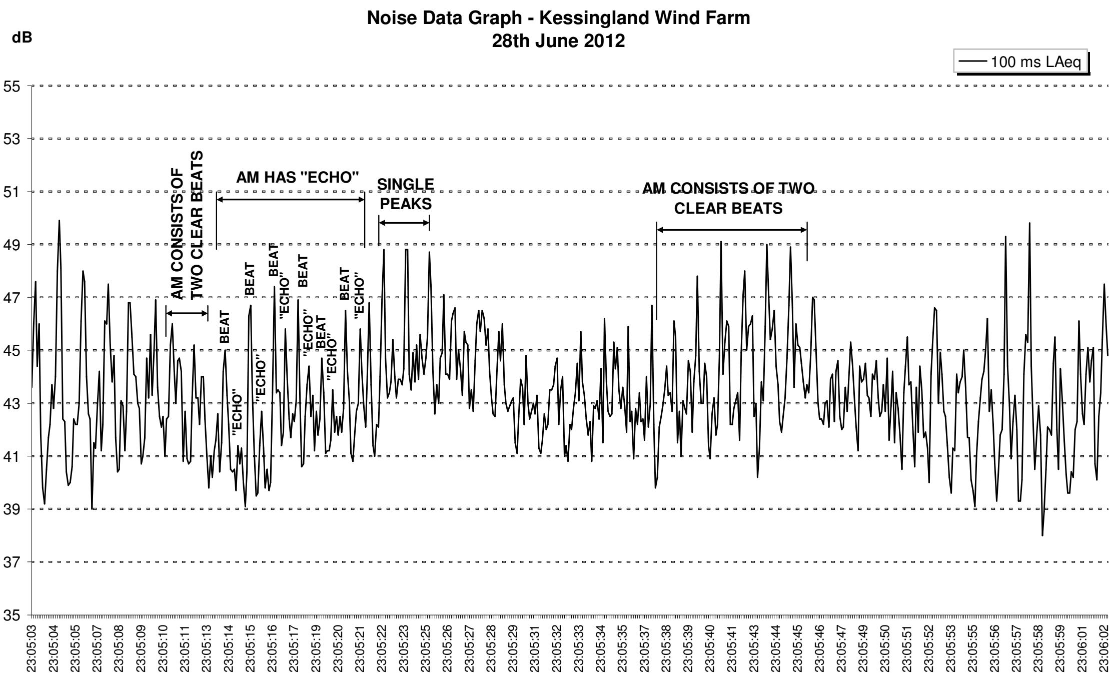


The chart above appears to show mainly one recurrent peak of noise and although audibly it is initially heard as one sound, two characteristics, a pulse and a 'swish', within the peak can be heard.

The chart below shows a sample from the middle of the above period. The expanded 100ms LAeq now demonstrates that the AM peak is in fact a double peak. The main component frequencies are within the 400Hz and 500Hz third octave bands. Lower frequency contribution is also present occasionally within the 250Hz third octave band and minimally in the 125Hz and 160Hz third octave bands. Energy within the 250Hz octave bands can be seen to contribute more within the middle of the period.



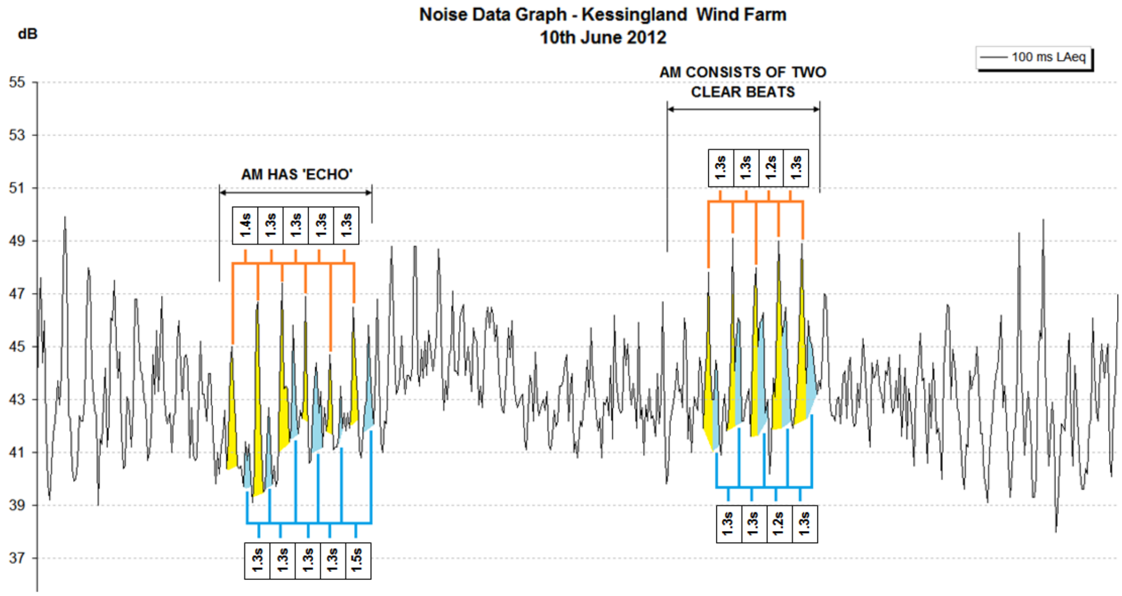
Measurements at Kessingland obtained on the 28th June 2012 were more varying in level and nature than those obtained on 10th June 2012. The chart below shows an AM trace lasting approximately 1 minute. Within this period the AM can be heard as one distinct and strong peak, a peak consisting of two beats and a beat and "echo" effect. The "echo" is not a reflection but an AM peak at a lower level[10].



As with the measurements on 10th June, the main component frequencies are within the 400Hz and 500Hz third octave bands, although some AM peaks have significant, though not dominant, 200Hz and 250Hz third octave band content which phases in and out. Comparison of the AM beat and echo sequence and the AM period consisting of two clear beats strongly indicates that the "echo" and second peak in the double peak AM have a common source. Similarly, the AM beat, from the beat and echo sequence, and first peak in the double peak AM are also likely to have a common source.

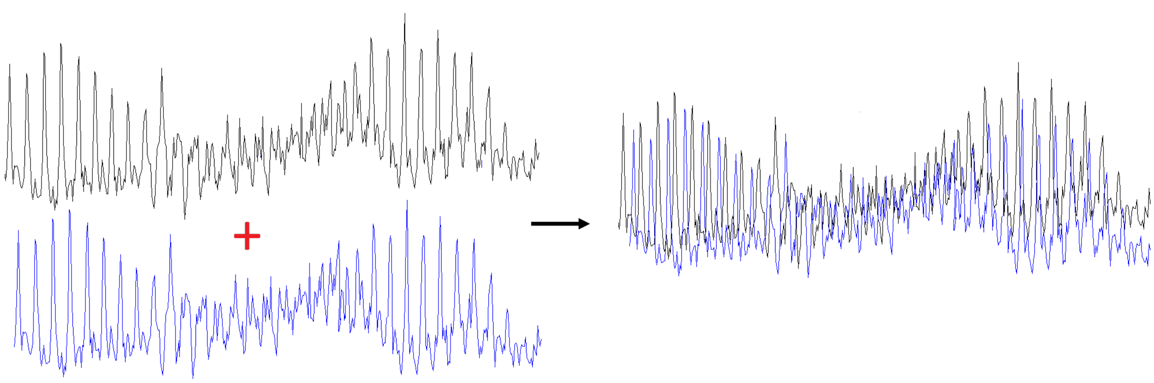
10 The sequence of a strong pulse followed by a pulse lower in level gives the impression of an echo.

The chart below shows the time difference between the 'beats', 'echoes', first peaks of the double peak AM and second peaks of the double peak AM. There is equal periodicity observed.



The above graph suggests that the AM beat and echo and double peak characteristics could be caused by difference in phasing between the two turbines. When the two turbines are out of synchronisation the AM is heard as two separate sound events.

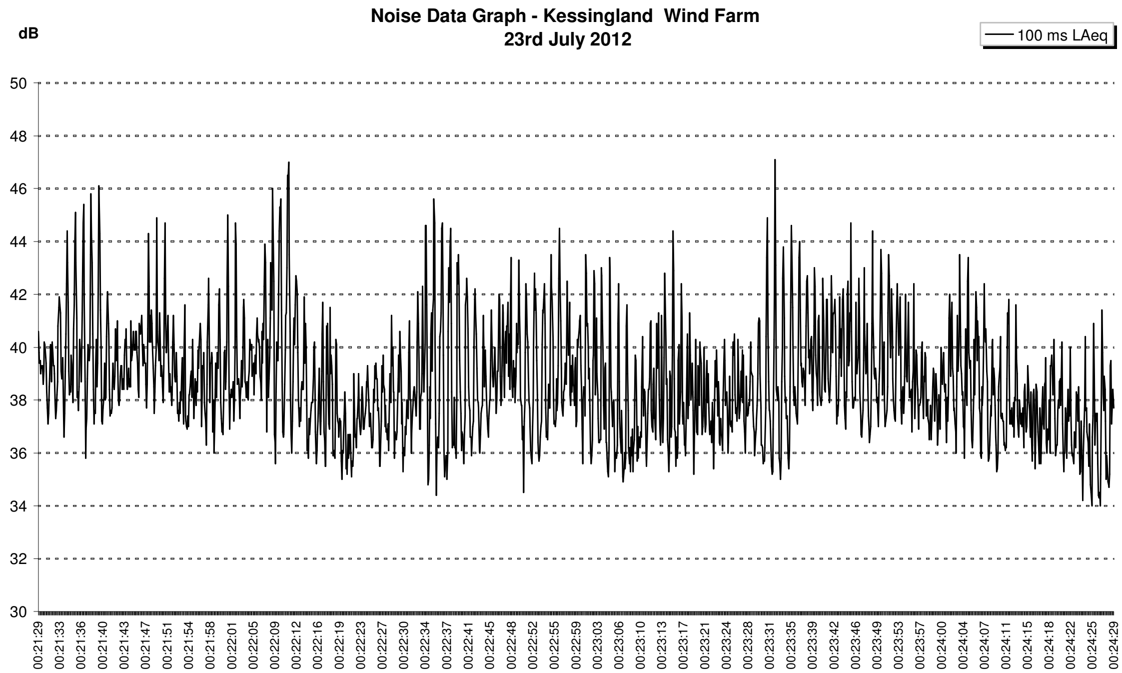
As the peaks from the two turbines move closer together in phase the peaks become merged and heard as one sound event with two pulses. This is demonstrated in the example image below where for illustration purposes it is assumed both turbines have the same sound energy emissions but one is delayed.



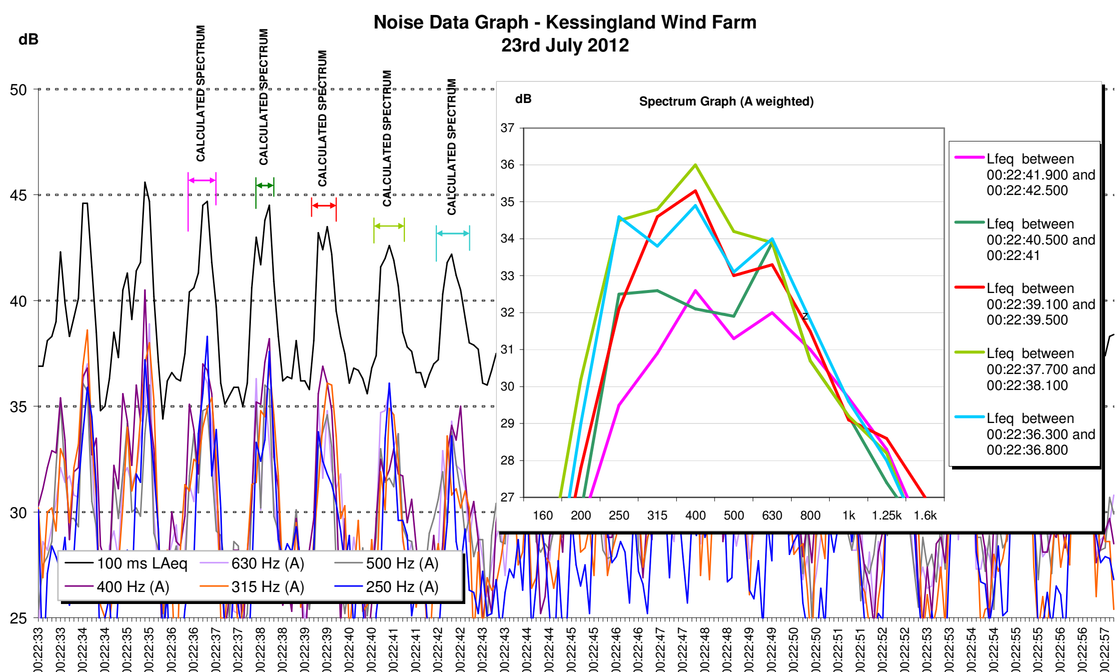
Single uniform AM peaks of greater amplitude may occur when AM from the two turbines is synchronised. These characteristics are considered to exacerbate the impact[11].

[11] This is further discussed in section 4 below on psycho-acoustic perception of AM.

The graph below shows a period of AM measured at Kessingland on 23rd July 2012 at a distance of 630m. AM is consistently present although the peak to trough level varies.



Spectral analysis of a sample of the AM peaks confirms a changing dominance in frequency content of successive AM peaks between energy in the 250Hz, 315Hz, 400Hz, 500Hz and 630Hz third octave bands.



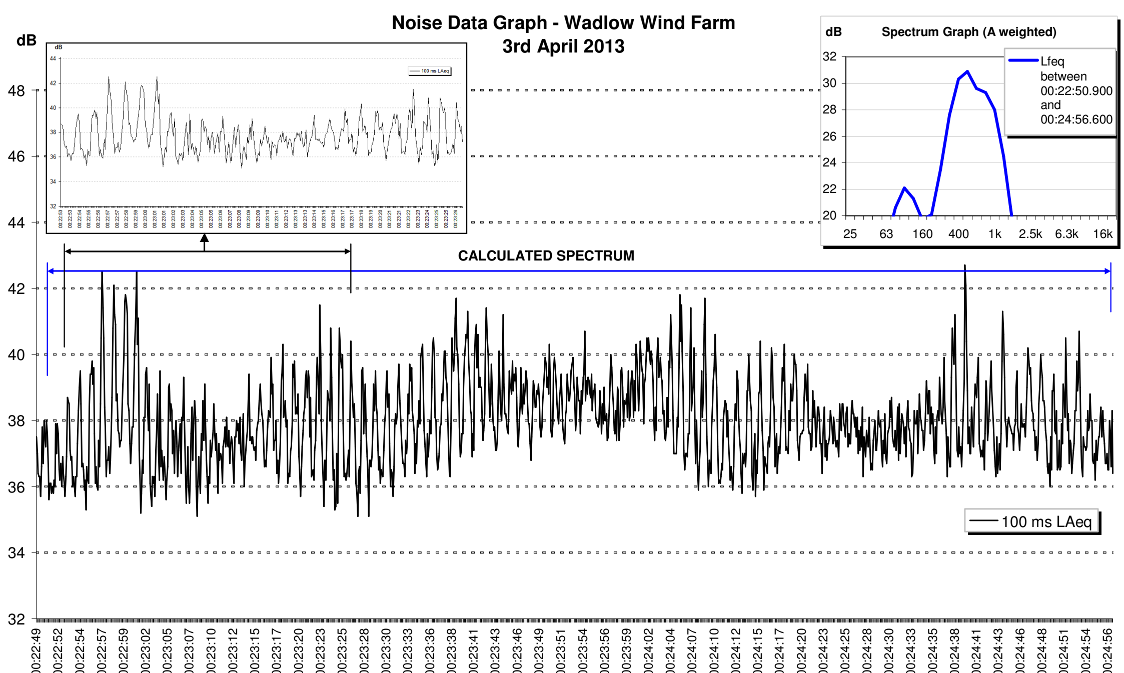
The first peak has higher frequency content in the third octave bands 400Hz and 630Hz. The second peak has some lower frequency content but is dominated by 630Hz third octave band energy. The fifth peak is equally dominated by 250Hz and

400Hz third octave band energy. Despite this sample of AM appearing to have a fairly uniform peak shape it is evident that the spectral content is complex and inconsistent resulting in noticeable changes in character. It can also be seen that where each event progresses through the rise and fall in sound energy there is a change in the dominant frequency. For example the middle peak highlighted is first dominated by 400Hz as the sound rises and 315Hz as it falls. Each peak differs in frequency content during the rise and fall in overall sound energy resulting in AM with a constantly changing character.

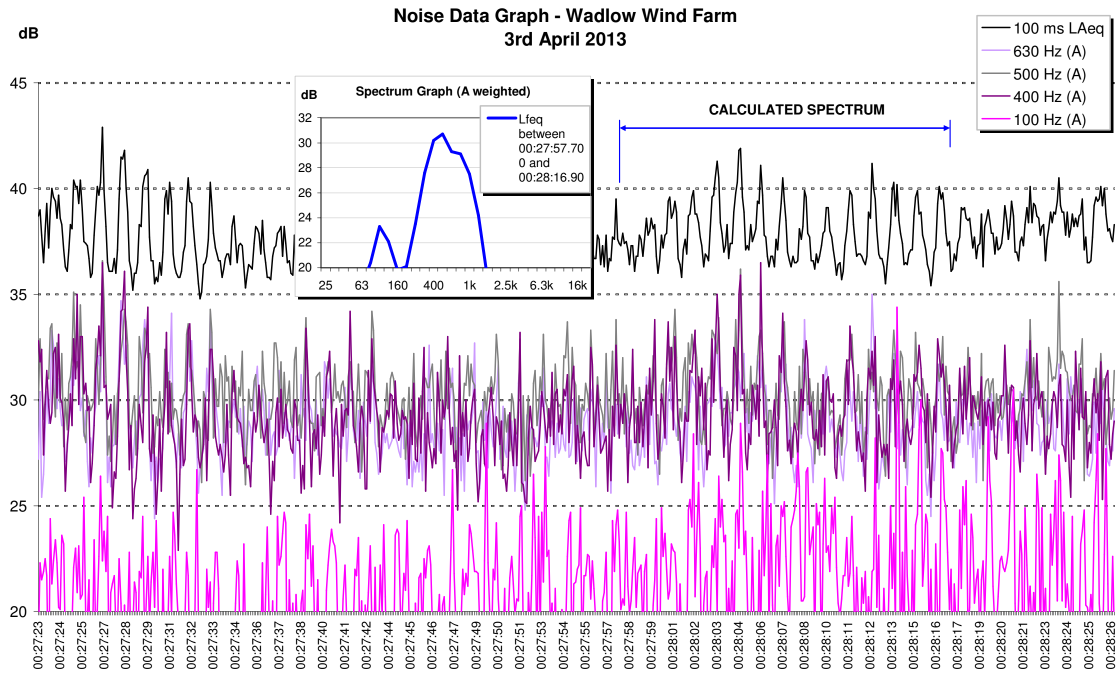
Wadlow Wind Farm, Cambridgeshire, England

Located close to the A11 road, when there is a westerly wind component the daytime noise levels in the vicinity of Wadlow Wind Farm are dominated by road traffic noise. At night time road traffic noise is minimal and there are few other sources of noise in the area. The site is located in eastern England, characterised by flat landscape. Measurements were taken approximately 1250m from the nearest turbine. The measurement location was 30 degrees clockwise from the downwind direction.

The chart below shows the 100ms noise trace for a 2 minute period. The AM peak to trough is generally 4dB with some differences of up to 6dB observed. The AM could be described as fairly clean. Peaks can be seen to phase in and out and this was the case fairly consistently for the 2 hour measurement duration. The inserted graph on the left of the chart below shows synchronicity of peaks at the beginning of the extract. Towards the end of the extract two pulses to the AM peak can be seen (and heard). The spectral content of the AM is generally dominated by energy in the 400Hz, 500Hz and 630Hz third octave bands. Sound at these frequencies generates a 'swish' or 'whoosh' sound.



On occasions a lower frequency thumping element to the AM sound is discernible with significant contribution from the 100Hz third octave band and which at times occurs as the peak subsides. Aural assessment of the sound in the field indicated that the higher frequency AM experienced arose mainly from a nearer turbine and the lower frequency AM was from a more distant turbine. The chart below shows the frequency content of a short extract of AM.

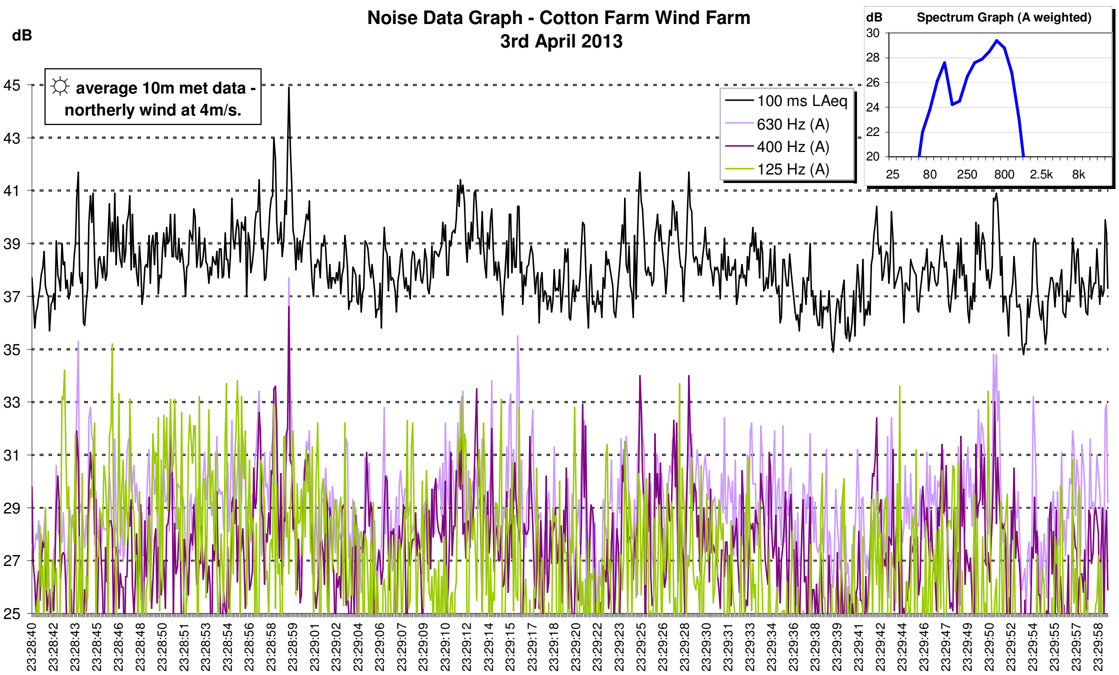


The spectrum graph for the period indicated on the chart above shows a dominant peak in the average frequency content around 500Hz; however, a secondary peak is evident within the 100Hz third octave band. With reference to the main chart and the 100ms traces for dominant third octave bands, whilst the 400Hz, 500Hz and 630Hz third octave bands modulate at a fairly consistent level and range, the 100Hz trace is more variable. Towards the end of the period the 100Hz third octave band noise can be seen to dominate certain AM peaks.

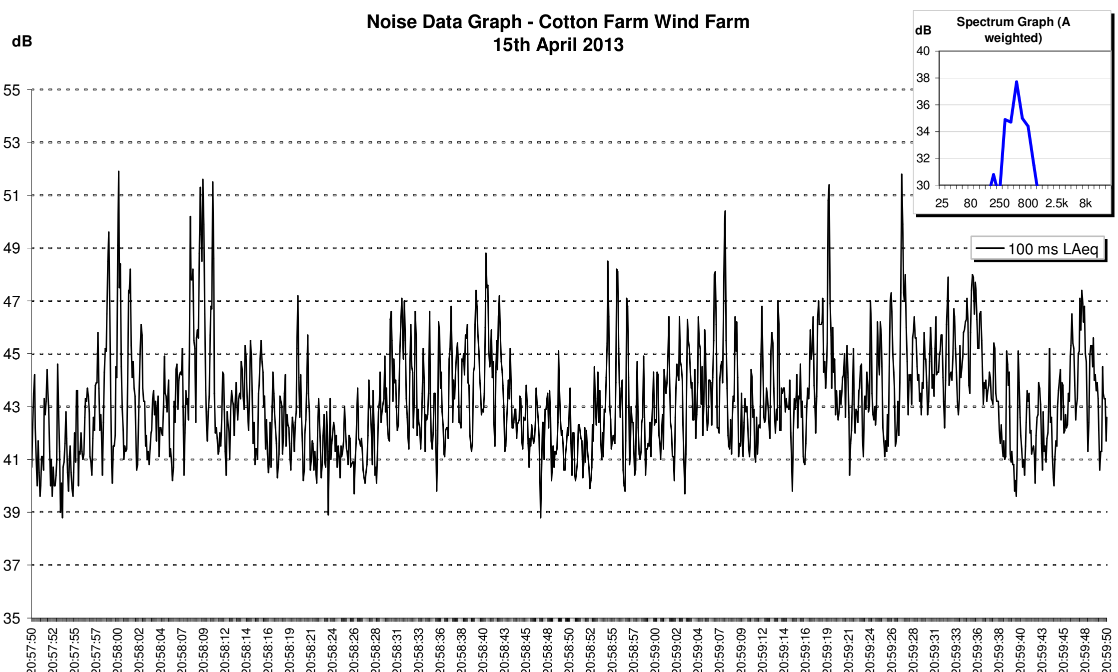
Cotton Farm Wind Farm, Cambridgeshire, England

AM has been measured from Cotton Farm on two occasions, the wind farm has only recently become operational. On 3rd April 2013 AM was measured to the west of the turbines under downwind conditions at a distance of 1200m from the nearest turbine. Temperatures during the daytime had not been particularly high, but there had been a relatively cloudless day and evening before the measurement period leading to increased wind shear. Not all turbines were operating during the measurement period. Although wind turbine noise was dominant in the area, some distant road traffic noise was also audible. The AM measured and heard did not pulsate as clearly as is the case with other measurements and results with a 'dirty' noise trace. AM peak to trough was typically 2-4dB and up to 6dB on occasions. There is a clear 125Hz third octave band component to the AM.

Frequency dominance within the peaks varied such that there were periods of 125Hz third octave band dominated peaks followed by 630Hz and 400Hz third octave band dominance. The random change in sound energy spectrum from one peak to another was a significant factor in the character of the AM. The change in sound energy character here is more distinct than the example from the Kessingland turbines examined above.



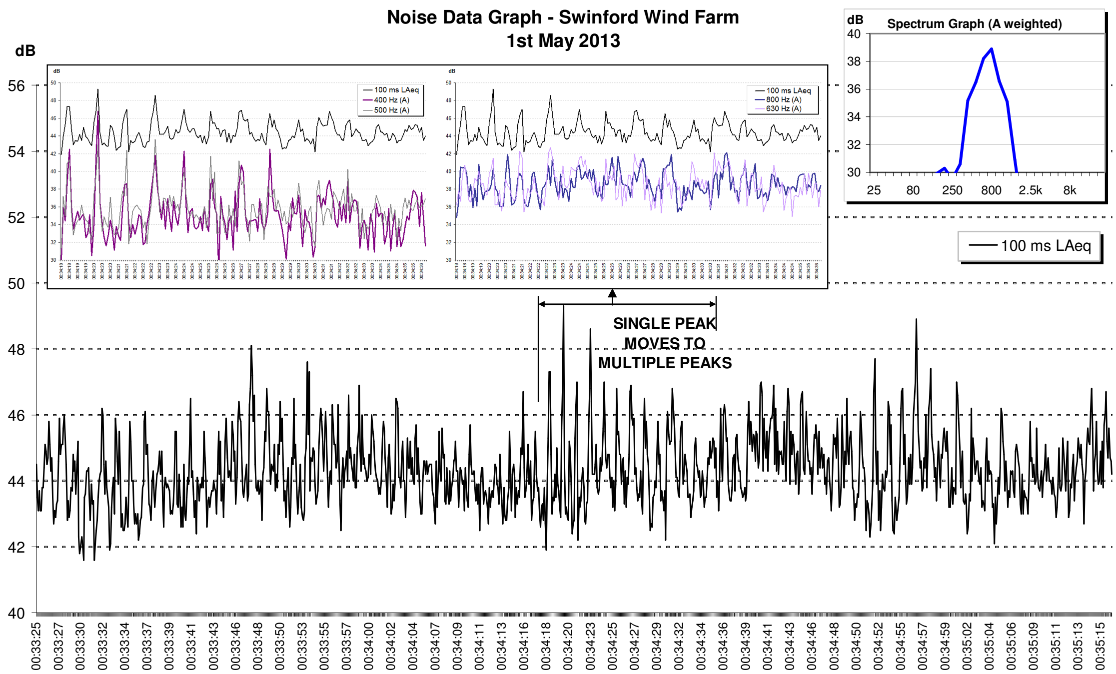
On 15th April 2013 measurements were taken to the east of the turbines at a distance of 800m from the nearest turbine.



AM was much clearer, though still erratic in occurrence, and peak to trough differences of typically 6dB and up to 8-10dB were measured. On this occasion low frequency noise was less prominent within the data and the dominant sound energy was focused around the 500Hz third octave band.

Swinford Wind Farm, Leicestershire, England

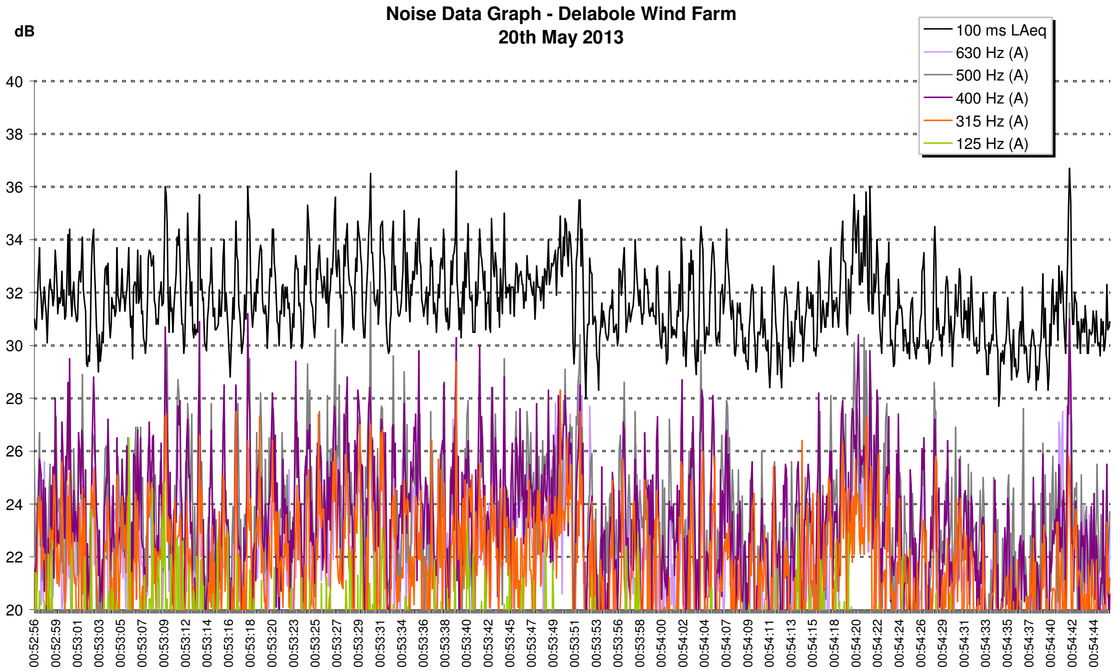
The weather conditions during the evening measurements at Swinford Wind Farm were not ideal for generating AM. There was high atmospheric pressure and wind energy speeds were continuing to fall and change direction throughout the period. The distance to the nearest turbine was approximately 750m. AM with peak to trough values typically of 3-5dB were measured and the dominant frequency content was focused in the mid frequencies around the 800Hz third octave band.



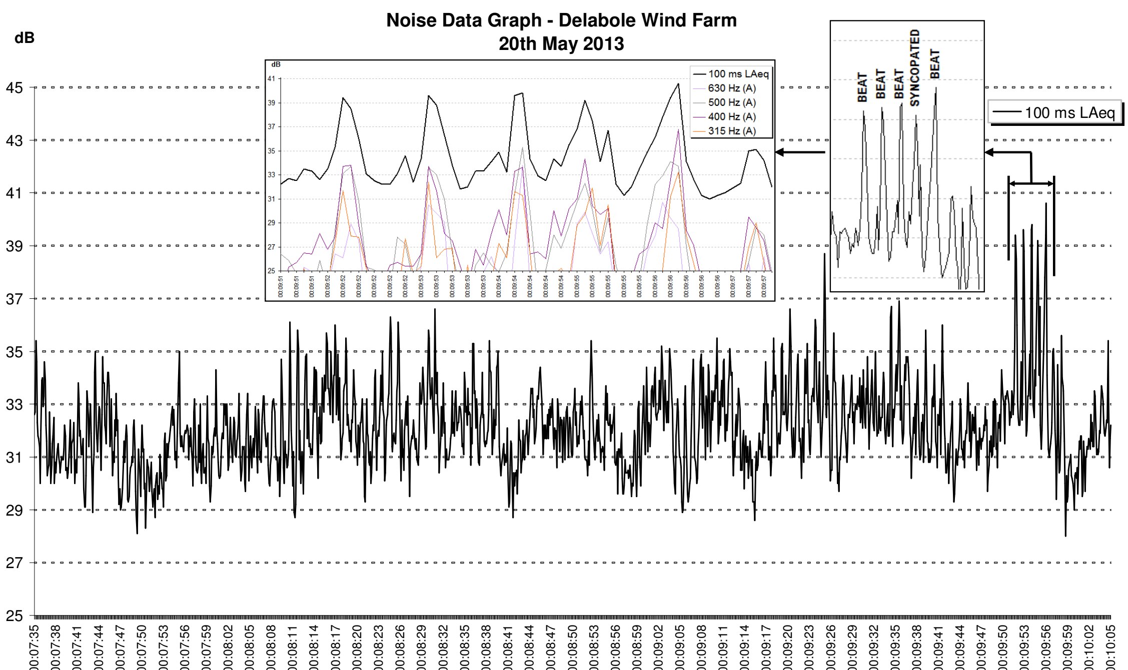
The graphs inserted in the chart above show the average spectrum on the far right hand side, and to the left a more detailed frequency analysis of the highlighted period. The period shows clear defined AM peaks which can be seen to move to less distinct AM with multiple peaks. The left hand side frequency analysis shows energy in the 400Hz and 500Hz third octave bands. The middle frequency analysis shows energy in the 630Hz and 800Hz third octave bands. The 400Hz and 500Hz third octave band energy fairly consistently peaks together, although the peaks disappear towards the end of the extract. The 630Hz and 800Hz third octave band energy peaks coincide at the beginning of the extract with the 400Hz and 500Hz third octave band energy. However, they quickly shift out of phase creating multiple less well defined peaks. Thus, the distinct peaks of AM during this period occur when dominant frequencies are synchronised. The clarity of the AM appears to be lost firstly due to phase shift in 630Hz and 800Hz third octave band energy and then towards the end of the extract due to less modulation in all four dominant third octave bands.

Delabole Wind Farm, Cornwall, England

AM from Delabole Wind Farm was measured at a caravan site approximately 400m from the nearest turbine. The measurement location was approximately 70 degrees counter clockwise to the downwind direction. Although AM was measured, weather conditions and the negative angle relative to the rotation angle were not conducive to typical worst case AM generation. Peak to trough was typically 4-6dB and as shown on the chart below dominant frequencies varied peak to peak but are mainly focused in the 315Hz, 400Hz and 500Hz third octave bands. Prevalence of 125Hz third octave band energy can be seen to vary throughout the period with most contribution at the beginning of the period.



A period from earlier on in the night presented below shows that the AM was slightly more erratic, with periods of AM of higher peak to trough differences phasing in and out.

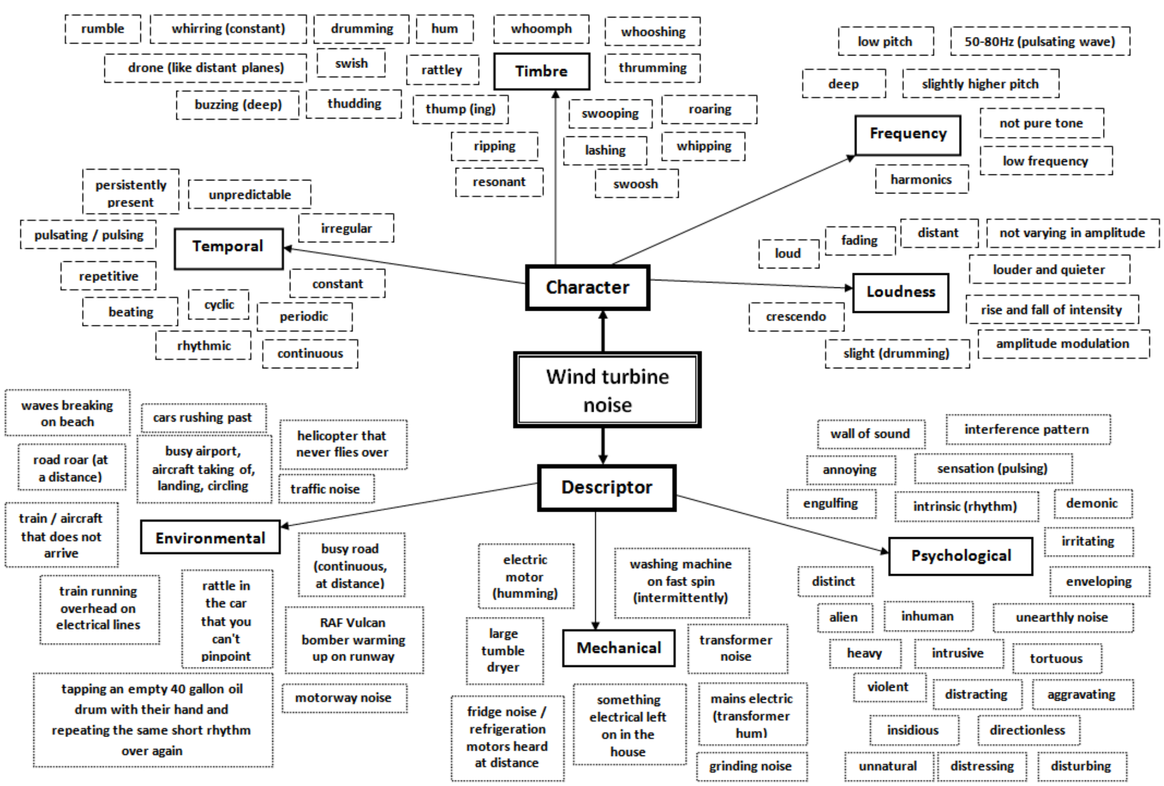


Towards the end of the period there are five AM peaks with a peak to trough difference of approximately 6dB. The peaks draw attention both due to their loudness and the rhythmic character. The first three AM beats are regular, the fourth is out of time in comparison to the first three beats and the fifth beat is perceived as in time with the original rhythm set up by the first three beats. With reference to the frequency content, it can be seen that the AM peaks that are perceived as in-time have synchronised peaks in the 315Hz, 400Hz and 500Hz third octave bands. The dominant frequencies in the syncopated beat are misaligned. This change attracts attention to the beats.

Psycho acoustical factors

Wind farm noise is widely acknowledged as more intrusive and more annoying at lower decibel levels than other types of industrial noise (Pederson & Waye, 2004). Although attitudes towards wind development have been noted as influencing perception of wind farm noise (Van den Berg, 2009) psycho acoustic factors have been little discussed or explored.

The word map below categorises some of the many terms used by affected residents to describe AM, including physical likeness of the sound and musical terms describing the character of AM.



"The assessment of sounds that vary in level and spectrum over long time periods requires continuous judgments" (Scharf, 1998, p. 1187). Whilst it is easy to provide a simplified acoustic description of AM through determination of an average decibel level, an AM peak to trough level or a dominant frequency component, such descriptors fail to relate to the auditory and psychological perception of the sound.

Indeed, rarely do the descriptions on the word map above consider an absolute overall decibel level or third octave band level and most aim to subjectively describe both the temporal and spectral character of the sound as it varies with time.

Our perception of sound will be influenced by cognition, by past experiences and associations with the sound (Hodges & Sebald, 2011). As Juslin and Västfjäll (2008) note "the perceptual system is constantly scanning the immediate environment in order to discover potentially important changes or events. Certain sound qualities are indicative of change, such as sudden or extreme sounds, sounds that change very quickly, or sounds that are the result of strong force or large size. Sounds that meet certain criteria (e.g., fast, loud, noisy, very low- or high-frequenced) will therefore produce an increased activation of the central nervous system" (p.564).

The musicologist Meyer theorised that our expectations of music (sound) govern our emotional response. Expectations of our environment and emotional response, based on sensory assessment, are a constant part of everyday mental processing. As Huron (2006) notes, accurate expectations benefit preparation for appropriate perception and action (p.3). Examining our environment for sensory changes and preparing for appropriate action requires varying and controlling our levels of attention and arousal accordingly. Emotion resulting from expectations reinforces appropriate reactions and promotes positive outcomes. For example, if something in our sensory environment changes we automatically pay more attention: our eyes focus on an object moving in the distance, a door slamming will quickly evoke a startle reaction. Although the door poses no threat, it is beneficial for survival to react as if danger were present, to become fearful and alert (Huron, 2006). Huron continues to discuss the uncertainties associated with expectations. Sounds and music can manipulate uncertainty regarding what and when certain sounds will happen, where and why sounds or music occur. These elements are manipulated by composers to illicit specific emotional reactions to music and sounds.

On a very basic auditory level, aspects of AM sound may cause heightened attention or arousal, resulting in negative emotional states and focused cognitive analysis. The internal measurement of AM at Deeping St Nicholas Wind Farm demonstrates significant low frequency contribution. Low frequency sounds are often associated with large objects or objects with a lot of energy, which in turn are often related to feelings of uneasiness due to associations with danger. The association with threat is heightened when AM gets louder and peak to trough difference increases. A sound that gets louder is often gaining energy or getting closer, again environmental factors that may be associated with potential threat.

AM peak to trough is often unpredictable and higher peaks can arise suddenly and after periods of less modulation. See for example the chart for Site E. Towards the end of the period the AM fades, peak to trough is in the region of 2dB, and typical noise levels are approximately 28dB(A). Within a few seconds the sound changes to AM with peak to trough of 4-6dB and peaking above 34dB(A). The listener would likely be in a dark room without any visual clues. Arousal and attention are therefore focused on auditory clues. These changes represent a significant change to the sensory environment and as noted by Huron (2006) and Juslin & Västfjäll (2008) our body will react accordingly. This effect can also be seen in the Cotton Farm AM measured on 15th April, which displays erratic peaks in the region of 51dB(A) compared with the majority of peaks between 45dB(A) and 47dB(A). Changes in peak to trough difference are often accompanied by changes in spectral content or dominance and would add another varying factor to the auditory environment which could draw attention.

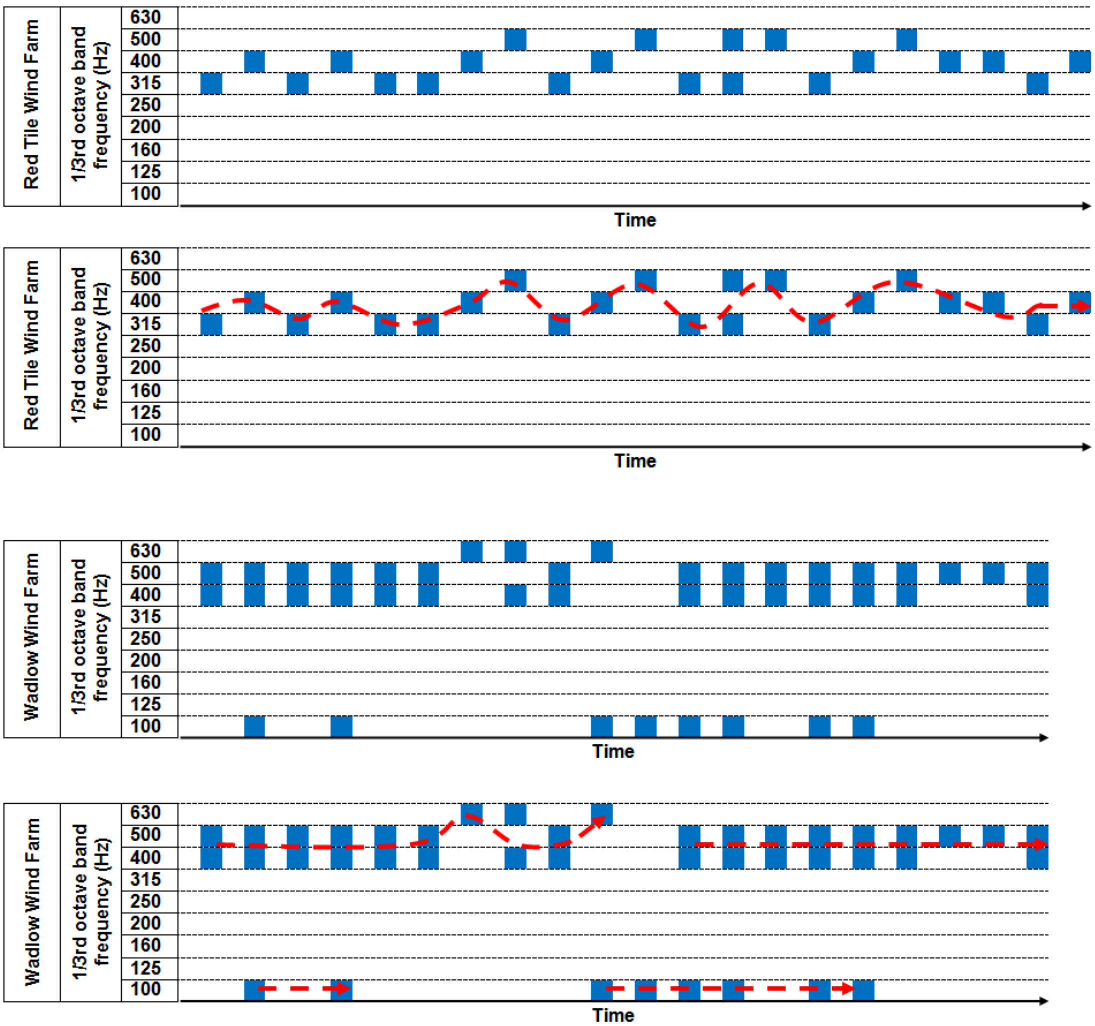
The discussion of theory and measurements can easily be related to the terms used to describe AM in the above word map. Terms such as 'distressing' and 'disturbing' may be related to fear or threat responses. 'Deep', 'heavy' and 'thudding' may be compared to musical features eliciting negative emotions[12]. Descriptors relating to our expectations of our environment include 'unpredictable' and 'train / aircraft that does not arrive' which may encourage prolonged attention.

In addition to basic mental processing and associations of sounds, our ears are also capable of highly complex analysis. Albert Bregman coined the term auditory scene analysis to describe the way in which the ear processes and organises sounds in to meaningful components as a way of understanding our environment. The ear searches the sound for clues including temporal, spectral, periodical and sequential relationships (Plack, 2005). Rises and falls in frequency may be segregated as separate streams depending on pitch proximity (Stevens & Byron, 2009). Sounds will also be grouped according to a perception of rhythm, beat or meter[13] (McAuley, 2010).

As indicated in the data presented above, AM is a complex sound consisting of varying frequencies, loudness and meter (pulses and beats). The noise data graph from Red Tile Wind Farm shows fairly equal but unsynchronised modulation of sound energy in 315Hz, 400Hz and 500Hz third octave bands. The sound energy is fairly close together in frequency (pitch) and also close together in time. The sound that is heard is sweeping and broadband. The different component frequencies have been grouped together in to a single sound stream by the brain. In contrast the noise data graph from Wadlow Wind Farm demonstrates two separate streams grouped by frequency (pitch) and to some extent time. The majority of energy is in the 400Hz and 500Hz third octave bands but, towards the end of the period some peaks are dominated by 100Hz third octave band energy. There is sufficient distance between the frequencies dominating the AM peak, and without intervening blurring frequencies, for these to be heard as two separate sounds. This is demonstrated on the image below with the red dashed lines representing the streamed sounds.

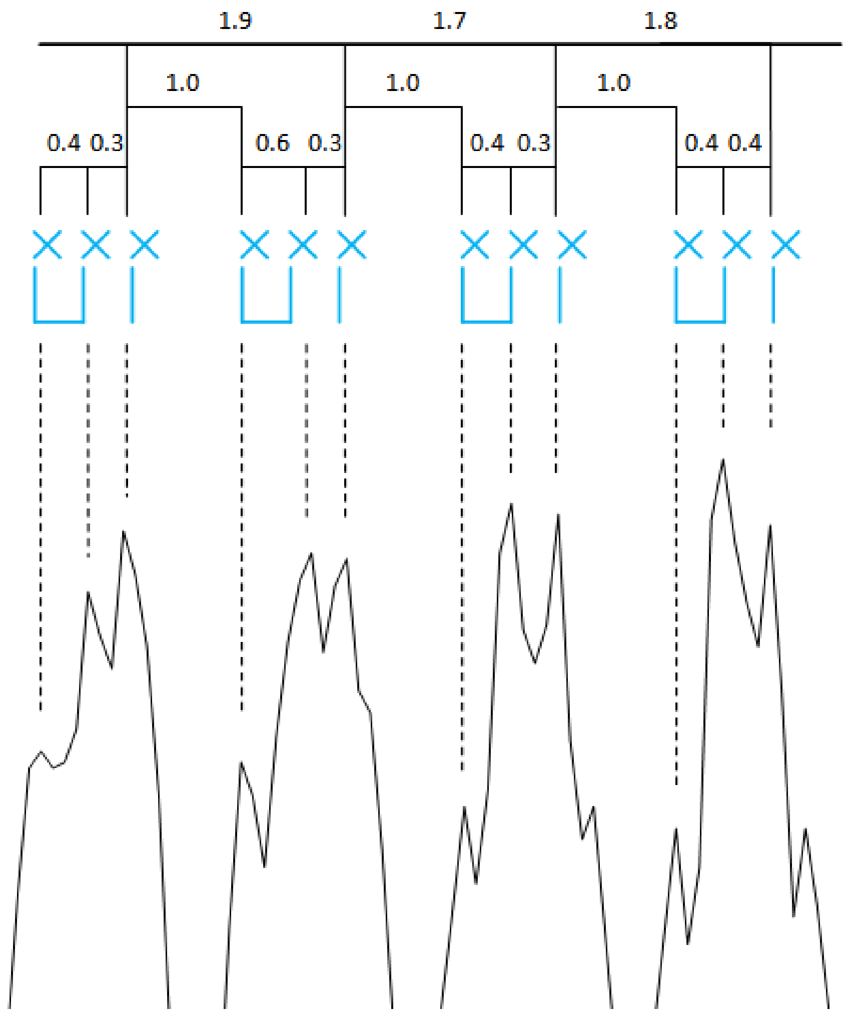
[12] Consider for example the theme tune to the film Jaws.

[13] A rhythmic element as measured by division into parts of equal time value. (http://dictionary.reference.com/browse/meter?s=t)



The discrepancies between how AM sounds from different wind farms or at different time from the same wind farm can be processed by the ear and may help to describe the disparity between descriptors in the word map above. Terms such as 'whirring (constant)' and 'repetitive' may fairly describe the AM at Red Tile Wind Farm whereas terms such as 'irregular' and 'thumping' may better describe the AM from Wadlow Wind Farm.

As well as pitch, rhythm and meter play a role in grouping sounds. Rhythmic aspects of AM regularly feature in descriptions of AM and can easily be observed in much of the data. The AM peaks at site C regularly occur at intervals of approximately 1s. In contrast the extract from Kessingland on 28th June has already been described in this paper as having a beat and 'echo' sequence' and AM consisting of two beats. The beat and 'echo' sequence is a good example of how the ear interprets sound with rhythmic hierarchies. In western music there is a preference to hear sound with meter, an alternation between strong and weak beats (Thompson & Schellenberg, 2002). As the AM often varies due to phasing differences our attention increases as we process the new rhythm or meter that results. The extract from Kessingland on 10th June shows a fairly constant period of AM with a regular periodicity of just under 2s. Each AM peak consists of a dominant double pulse; however, there is also a third weaker pulse before the main AM peak. Each pulse conforms to the meter. The weak pulses are separated by approximately 2 seconds, the first peaks are separated by approximately 2s and the second peaks are separated by approximately 2 seconds. The weak pulse and double peak AM form one rhythmical group. The timing between each group is 1s. The timing within each group, i.e. between the weak pulse and first AM peak and between the first AM peak and second AM peak, is just under half a second. Thus, a rhythmical hierarchy can be formed. See the image below which shows the time in seconds separating the constituent pulses of the AM and how this forms a rhythmic hierarchy



Although it is unlikely that on perception we will naturally develop this rhythmical hierarchy for AM, it shows that there are rhythmic relationships between the pulsing components that generate the AM trace which draw attention and have meaning.

Temporal entrainment also plays an important role in perception of sounds. Entrainment describes the interaction of two rhythmic processes combining to a common phase. Entrainment to rhythms is observed in humans from an early age (Trainor & Hannon, 2013) and there is evidence that biorhythms entrain to external rhythmic stimuli (Large & Jones, 1999, as cited in Stevens & Byron 2009; Schneck & Berger, 2006). With reference to the word map above, the description of AM as having an 'intrinsic (rhythm)' may relate to the entrainment between the AM beat and biorhythms. As noted above, the AM peaks at site C regularly occur at intervals of approximately 1s. This interval is not uncommon in the measured AM data. The timing between each AM group in the Kessingland data from 10th June is 1s and the timing within the group is approximately half a second. Fraisse (1982) (as cited in Thompson & Schellenberg, 2002) found that physiological processes, such as heart rate and walking pace, tended to occur at a rate 60-120 beats per minute. AM events occurring approximately once per second coincide with a rate of 60 beats per minute and as such AM entrainment, synchronisation between AM and our movements or heart rate etc, is likely to occur.

Information regarding a sound source can be determined by the process of localisation. This relates to the 'where' expectation discussed by Huron (2006). The ear can detect the direction from which a sound originates by comparing differences in timing and frequencies perceived by each ear (Pierce, 2001). This is a feature we have not been able at present to replicate in the Listening Room Experience (see below). The precedence effect describes the phenomenon by which we hear sound as originating from the direction where we first hear the sound, even if this changes or originates from two separate sources. As AM has been shown to regularly vary in both level, frequency content and timing, there may be difficulties in localising the source of AM due to contradicting or confusing auditory clues. With reference to the word map above this supports descriptions of AM as 'enveloping', 'wall of sound' and 'rattle in the car that you can't pinpoint'.

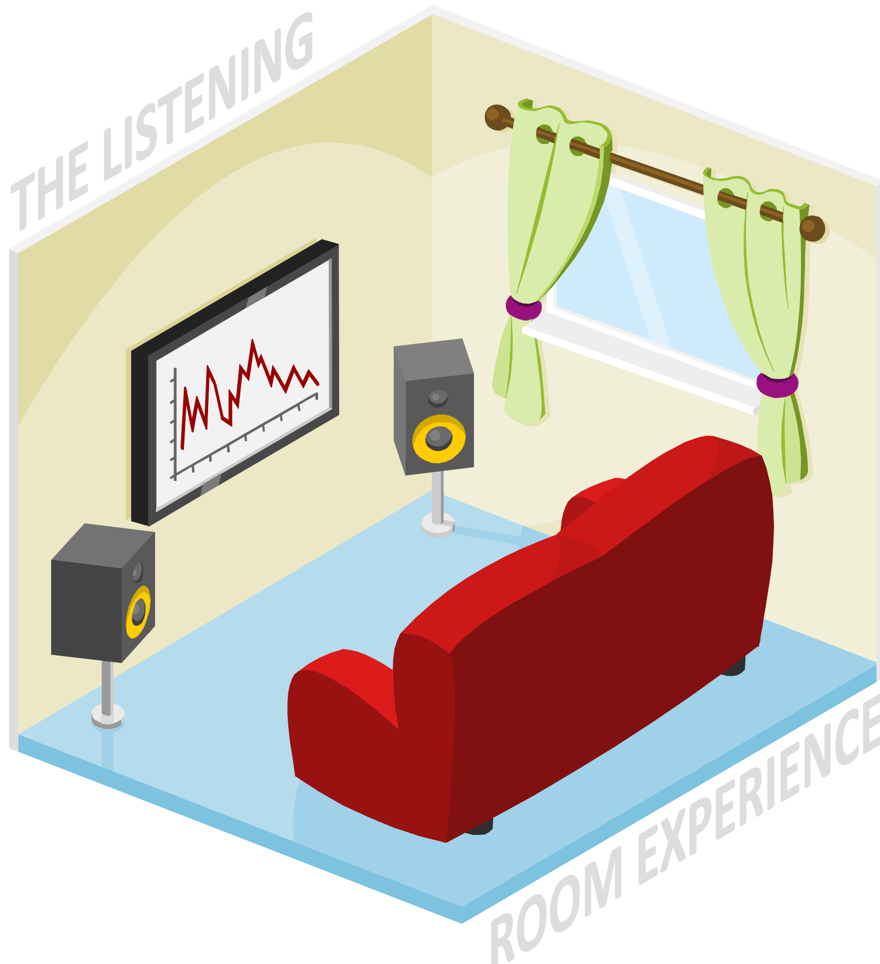
With a little consideration of the range and complexity of auditory processes used to assess our environment it is not surprising that AM evokes many different descriptors of the sound. The varying nature of AM necessitates constant reappraisal of our auditory environment and supports anecdotal evidence that AM is rarely a sound that can be pushed to the back of our consciousness. For these reasons it is considered inappropriate to try to categorise the boundary between acceptable and unacceptable AM by reference to a total or average sound energy level except when identifying circumstances where it is clearly intrusive if all other factors are equal. Instead, assessment should focus on the audible character of the noise, recognising that there are many manifestations of the sound which increase impact once discernible.

The Listening Room Experience

The Listening Room Experience is an exercise where wind farm noise is replicated as close as possible to that which is experienced in and around homes[14].

Acousticians are well aware of the problems associated with using the decibel level to convey how noise intrudes and the difficulty in deciding what levels of noise are acceptable when it exhibits varying characteristics. The lack of transparency in decibel parameters can be exploited and it is difficult for lay decision makers to appreciate the consequences of accepting or setting decibel limits, especially when two opposing acousticians present different arguments over acceptability.

[14] A typical playlist schedule is provided on our website along with some of the tracks used in the experience.



In UK courts it is normally open to either party to present the evidence of their choice. We have successfully used audio recordings on many occasions in the courts to convey the character of a noise; where defendants object it may lead the court to question why they do not want the court to hear the noise. In more recent cases we have attempted to accurately simulate the decibel levels in order to replicate the experience of the noise that the community actually experience. This is especially important for wind energy development where, as shown by our findings above, noise features such as AM have a distinct and intrusive character. Difficulty arises in the UK as planning decisions do not compel regulators to undertake a listening room experience even when one party request it.

Court room scenario

Problems also arise as the courtroom or inquiry hall is remote from the character of the bedroom, living room or garden of a rural residence. The background and ambient noise levels within a city courtroom are usually much higher than in a rural bedroom when there is a distinct lack of industrial or transport related noise sources. The state of mind of the listener is important, whilst on public display and studying technical evidence the listener is not attempting to relax in the same way as if they were in their own home. The perception of the impact clearly changes as a result.

We have sought to create a relaxed listening experience which is outside of the court room or inquiry building. Previously we have used a specialist listening room facility and a recording studio but found that it is best to run the exercise in a rural dwelling provided the background noise levels are low and unaffected by dominant manmade sources. The location should provide an environment where decision makers are not in front of the public, are sat in comfortable chairs in a living room type environment and allow relaxation perhaps even imagining trying to sleep with the noise. Experience suggests it is normally best to conduct the experience after dark, in the late evening when people are naturally preparing for the night and sleep. We consider it is important to replicate the conditions when impact arises as close as possible, especially low background noise levels. Background noise levels in rural bedrooms can typically be below 15dB(A) with windows open and below 8-10dB(A) with windows closed.[15] The room should reflect a rural bedroom / living room environment including typical reverberation times.[16]

Low-noise equipment

The use of microphones with a low noise floor to record both the source noise and background noise environment during playback is critical to ensure no artificial masking effects (usually from internal electrical interference) are present either in the recordings or at playback. Music or interview recording studios provide a good substitute for a rural living room / bedroom environment as generally they are designed to ensure background noise levels are around 15dB(A), to have low reverberation times and are normally devoid of daylight. Where such a facility is to be used, soft chairs and possibly curtains are needed to replicate a comfortable home situation as best as reasonably practicable.

The process and setup adopted

In most rooms external noise mainly enters through the window. The seating is therefore arranged in a “U” shape equidistant from and facing a window or mock window (or with one in view) and two powered monitor speakers with a flat response down to 40Hz placed either side of the window setup. A flat screen TV is used, either placed below the window or in the approximate direction for comfortable viewing. The set up enables levels at the seating to be within a couple of decibels of the actual levels experienced. Groups of 8-15 people are accommodated. For larger groups two rows of seating have been used, recognising levels are potentially slightly lower in the second row. The objective is not to perfectly replicate the sound energy levels, as this will change in different rooms and with different numbers of people but to provide a sound energy experience which is close to that experienced by wind farm neighbours.

During test playback the sound trace and spectrum are compared with the actual recordings to ensure a good standard of replication is achieved. This is also recorded during the final playback to demonstrate reasonable replication.

Each playback track is co-coordinated with an interactive graph of the decibel levels and spectrum. This software requires the audio to be converted to mp3 format so it is

[15] Many acousticians use microphones with a noise floor of 16-20dB(A). These are unsuited to recording AM inside dwellings or determining the internal background noise environment. A low noise microphone is always required.

then checked using audio processing software to ensure minimal distortion when compared to the original track.

The experience

Attendees are provided with an explanatory pack with a copy of each chart, some details about the wind farms, the piano scale to enable comparison with the spectrum and a playlist schedule. Interactive graphs are displayed on the TV screen. The experience lasts about 90 minutes and currently 16 clips are reproduced from 6 wind farms where AM has been recorded. The process is as follows:

1. External noise recordings in the vicinity of homes.
    a) Background noise is played to enable the hearing system to adjust to a low noise environment after travelling.
    b) Several late evening / early night time recorded AM incidents outside dwellings are replayed.
    c) Wind farm noise (devoid of AM) compared to periods when the wind farm was stopped for testing is played to enable comparison with turbine noise virtually devoid of character.
2. Internal noise recordings inside dwellings or simulated inside dwellings.
    a) Background noise is played again to enable the hearing system to adjust to the lower internal noise environment and provide comparison.
    b) Several recordings are played starting inside a car and then transferring inside different dwellings through the night.

Procedure adopted

The room is softly lit and this is switched off once the TV screen is switched on. Questions and commentary are kept to a minimum to enable relaxation. An interactive graph with a moving curser is displayed on the TV screen placed at the window location or where it provides for comfortable viewing. A clip between 1-3 minutes is played with minimal introduction. The clip is then replayed and the TV switched off to ensure very low light / near darkness and to remove visual stimuli. Attendees are encouraged therefore to focus merely on the sound. In our experience this replay has the most significant effect as attendees notice the different impact when not concentrating on the charts and paperwork. Clips range from those with regular 10dB peak to trough fluctuations to those smaller than 3dB and varying levels of low frequency noise. This process is repeated for the external and then the internal recordings. The final extract presents levels recorded in a bedroom where the impact had continued for about 4 hours. As before this is first played allowing study of the graphs and then repeated in darkness whilst considering if attendees could sleep. At the conclusion of the session discussion is encouraged with the lights on, without the TV screen on but the AM continuing. This has previously prompted requests to stop the noise and expressions of relief when it stops.

Use of headphones

Experience indicates the use of headphones is a poor substitute. Few headphones provide a flat response and therefore change the signature of the spectrum of the noise on playback. This distortion can change the experience significantly. Also, the recordings are monaural and therefore playback through headphones creates an unnaturally flat experience by removing time shift and directionality. Further, the mere wearing of headphones induces an artificial environment which can inhibit relaxation. Whilst the speakers do not reproduce sound binaurally, room effects and direction of the speakers gives a greater sense of reality in the sound.

Anechoic chambers

Whilst the noise floor of any anechoic chamber is normally good, the highly artificial situation in an anechoic chamber leads to an alien experience and so have not been used.

Equipment used and settings

- → Norsonic 140 Type 1 SLM.
- → 40HL Gras microphone.
- → Laptop with Adobe flash player and external sound card.
- → Rokit powered professional studio grade monitor speakers.
- → Flat screen TV (silent in operation including no high frequency tone).
- → Audio recording standard = 24 bit, 48Kz standard. 16 bit 44KHz still provides a reasonable reproduction.
- → Mp3 compression = 320 kbps for the listening room experience.

Variation in the room

In reality the rooms in which people live vary acoustically and it is unhelpful to try to set a standard for dimensions and reverberation time. The important requirement is that it is reasonably free of reverberation, which can easily be achieved by carpeting, soft furnishing and people. It is important that masking noise from ambient sources is at least 10dB(A), or as close to this difference as possible, below the reproduced source noise including the troughs in the noise data. Analysis of the background noise spectrum is recommended. The reproduced source already includes background noise. Difficulty can arise in mechanically ventilated buildings which produce significant levels of low frequency ambient noise from the mechanical plant.

Conclusions

Single wind turbines cause AM. This has been recorded by several researches and by us. It is also confirmed mathematically.

AM appears to occur in heightened noise zones, where levels are greater than at some other nearby locations. This means meter location and site observations need to reflect the appropriate conditions and careful analysis of localities at the time of AM impact is required. These zones can vary with wind direction, synchronicity and meteorology (especially wind shear) although certain locations appear to regularly experience higher noise and levels of AM than others.

Crosswind AM can arise at significant distances in excess of 400m.

A range of features in the AM are experienced. Typically AM will fluctuate with heightened peak to trough values for periods of a few seconds. The greater the atmospheric stability the less variance in the AM trace.

Under a wider range of atmospheric conditions the AM that commonly occurs has increases in peak to trough variations (fluctuating with periods of significant AM) for about 6-20 seconds which then gradually subside. In some circumstances the AM does not subside and continues with only minimal variation for periods of several hours. This appears to arise when there is a steady wind direction and wind strength as well as prolonged high wind shear.

The spectrum of the AM depends on the distance from the individual turbines but also meteorological effects, the extent of refraction, synchronisation of separate turbine emissions and the frequency content emitted in the direction of the receiver. This leads to a wide range of variations with increasing lower frequency dominance within the AM peaks at greater distances typically approaching one kilometre or more. Where there is an array of turbines you can experience different frequency AM from a nearer turbine and normally lower frequency AM from a more distant turbine either at the same time or in succession giving changes in the sound character that are highly variable and rarely the same. Some sound characteristics are commonly repeated, most likely due to the same range of recurring meteorological conditions.

Peak to trough values of overall A weighted levels at distances of 400m to over 1km can vary in excess of 10dB. This can involve sustained periods or AM varying by 10dB peak to trough but even when variation is less than 3dB the constituent frequency bands still modulate dramatically. This results in a changing noise character that is intrusive because they trigger a range of psycho-acoustic effects and associations. Individual third octave band levels will typically fluctuate far more than the A weighted levels with peak to trough values commonly in the order of 10-15dB and at times higher.

Coherence / synchronisation effects clearly arise where sound waves at particular frequencies reinforce at certain points for a short period and then diverge again. The divergence and partial coherence which changes over time leads to changing noise character increasing the noticeability, perception and impact of the AM peaks.

The complex change in spectral content over time is clearly a common feature of AM. The multitude of sound attributes results in AM that constantly changes in its noticeability and impact. Many of the characteristics do not manifest themselves within the overall A weighted variations with small peak to trough values still exhibiting significant change in noise character. It is also clear that changes in spectral content, peak to trough range and consistency will vary not just with distance and wind direction but with a complex interaction of meteorological conditions most likely including downward refraction resulting from changes in the sound speed gradient. The variations in location of impact and distance of impact from the turbines lead to changing periods of adverse noise at wind farm neighbours. These are again dependent on a complex interaction of meteorological factors.

The elements identified within AM and their psycho-acoustic characteristics show why reference to the A weighted decibel level is a poor basis for acceptability or unacceptability in a particular case. However, any measure of peak to trough variation that is identified is likely to reflect an unacceptably intrusive noise in most cases. The importance of subjective and psycho acoustic perception of AM is vastly underestimated in assessment of wind farm noise. AM displays many features that attract attention both on a basic and complex level of auditory processing.

Regulators and decision makers need to experience the effects of AM to fully understand wind farm noise impact and the limited relevance of average decibel controls in relation to the psycho-acoustical effects. As a substitute to living and experiencing wind farm noise impact at an affected dwelling, the Listening Room Experience provides a reasonable way of experiencing and understanding the impact.

Postscript

Measurements versus predicted levels

This paper has focused on the character and occurrence of AM identified in field measurements. A significant factor in the measurement of AM is the source speed gradient in the atmosphere and in particular temperature and wind shear effects leading to downward refraction.

Analysis of the sound speed gradient data in the work by Larsson & Öhlund (2012) effectively shows a 3-4dB increase in levels over those predicted when there is an increase in the sound speed with height or under high wind shear conditions. The increase in sound energy under these night time conditions has been found by a number of other researchers (van den Berg, 2005; Palmer, 2011). It follows that prediction methods ignoring the variable effect of refraction and sound speed gradients, may understate levels. Our own field measurements under stable atmospheric conditions or high wind shear conditions have similarly found levels are higher than predicted by 3-4dB(A).

Complaints of AM

Recent research Crichton et al (2013) and Chapman et al (2013) has suggested complaints arise as a result of pressure groups or because individuals are already opposed to wind farms. This is contrary to our own direct evidence where many communities and individuals either did not object to the development, positively supported the development or moved near to the wind farm in the belief that it would not adversely affect them. It also follows logic that people adversely affected may seek advice from pressure groups and it is not always clear which step occurred first.

One of the authors has experience of staying at affected locations and being woken by AM on more than one occasion though not prevented from returning to sleep either because the effects subsided or were masked by playing music. In all cases windows were kept closed.

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