Independent Noise Working Group

Wind Turbine Amplitude Modulation & Planning Control Study

Work Package 2.2 - AM Evidence Review

Author: Sarah Large MA(Cantab) MSc Dip (IoA) MIOA

Reviewed by Mike Stigwood

CONTENTS

Abbreviations

AM	Amplitude Modulation
EAM	Excessive (Enhanced) Amplitude Modulation DBJRG
IoA	Institute of Acoustics
IoA GPG	Institute of Acoustics Good Practice Guide
NAM	Normal Amplitude Modulation
OAM	Other Amplitude Modulation
RUK	RenewableUK, the wind industry trade association
SCADA	Supervisory Control and Data Acquisition

1 Executive Summary

1.1 This review focuses primarily on audible amplitude modulation (AM). This typically relates to AM from around 80Hz and up to around 800Hz - 1000Hz, with the higher frequencies being more dominant in earlier studies, smaller turbines and / or near field measurements. There is evidence supporting the prevalence of lower frequency AM and AM in infrasonic frequencies, including that which does and does not relate to blade pass frequency, which is discussed elsewhere but is beyond the scope of this work package.

1.2 Audible AM generated by wind turbines has been researched and documented since the late 1990s and more formally researched as a distinct topic from around 2002. Those working on behalf of government agencies have highlighted the need for AM control since around 2006.

1.3 There is a wealth of international research identifying either by measurement or written report, AM and / or specific features of noise that are characteristic of AM. AM is commonly found to impact residents in the far field most often from around 400m from the nearest turbine. Whilst there is a characteristic 'shape' of AM evident in the majority of data presented below, as measured using dB(A) and plotted with reference to time, the manifestation of AM can vary from site to site and even within sites.

1.4 The data described below is conclusive that AM exists and it shows AM is being generated by the majority of wind energy developments. It also shows that AM can be generated by all turbines regardless of size, model or type. AM is not rare but is prevalent and whilst meteorology may not be the sole determinant, under certain meteorological conditions adverse AM can occur for long periods of time.

2 Scope

2.1 This work package deals only with audible excess amplitude modulation (EAM). It looks primarily at measurements of AM in support of its existence and prevalence. It looks secondly at reports of AM, which is a limitation of this review as it relies on anecdotal evidence and presumes accuracy in the description of acoustic characteristics which has been highlighted as a potential issue in studies.[1] There is much research and theoretical discussion of the cause and prediction of AM. Such studies have not been included in this review but are covered to some extent in other work packages, see for example WP1, WP2.1 and WP5.

2.2 This work package is not intended to be a discursive document but simply as a collation of evidence with a brief resume of the AM noted in the relevant study or research project. The majority of studies, research papers and AM measurements are open access.[2] The Cotton Farm Wind Farm permanent monitoring station provides a wealth of information and source material on AM and is also open access.[3]

[1] See for example the DTI study which investigated low frequency noise but found that complaints related primarily to AM.

[2] MAS Environmental measurements at wind farm sites can be heard with interactive noise graphs online, see: http://www.masenv.co.uk/listening_room

[3] See: http://www.masenv.co.uk/~remote_data/plot.php

3 Introduction and methodology

3.1 This work package looks primarily for evidence of audible amplitude modulation noise. Amplitude modulation (AM) can be defined as the regular (cyclic) variation in noise level, usually at blade passing frequency, which exhibits a change in the noise character of the wind farm noise as the decibel level rises and falls. AM is further investigated and defined in WP1 and WP5.

3.2 ETSU-R-97 did foresee the generation of some AM from wind turbines. AM is described as blade swish, a 'rhythmic swishing sound' typically found in the region of 800Hz-1000Hz. ETSU-R-97 reports that AM is most apparent when close to a wind turbine, within 50m of the base, and with an A weighted modulation in the order of 2-3dB(A). It was expected that any AM character would diminish with distance and that as the higher frequency swish noise was attenuated and turbine sound level reduced, the background noise would provide sufficient masking to reduce any subjective impact. Thus AM was not expected to cause adverse impact in the far field.

3.3 AM as it typically occurs from modern wind turbines is commonly referred to as excess or enhanced amplitude modulation (EAM). This refers to AM that is considered unreasonable and in excess of that envisaged by ETSU-R-97. EAM is commonly found in the far field and is characterised by peak to trough levels of up to 10-13dB, commonly 3-8dB(A), and with a mid and lower frequency range, 160-400Hz. In this work package AM is used as a generic term to describe all audible amplitude modulation noise from wind turbines including EAM.

3.4 The importance of character features such as AM were identified in research at an early stage. Persson Waye and Öhström (2002) found that the perception of annoyance was well related to 'lapping', 'swishing' and 'whistling' turbine sounds. 'Lapping' and 'swishing' are indicative of AM. An ETSU report detailing wind turbine noise measurements published in 1999 identified 'rhythmical beat' and 'very strong swishing noise' in measurements of wind farm noise.[4] Modulation was recorded but found to be dominant upwind and in the 1 kHz and 2 kHz third octave bands, much higher in frequency than AM now most commonly observed in the far field. Clear modulation was not usually found by this report in a downwind and crosswind direction. Whilst the measurements were made within the near field of the turbine, and so cannot be considered representative of the type of sound experienced in the far field, it provides an early indication of AM awareness.

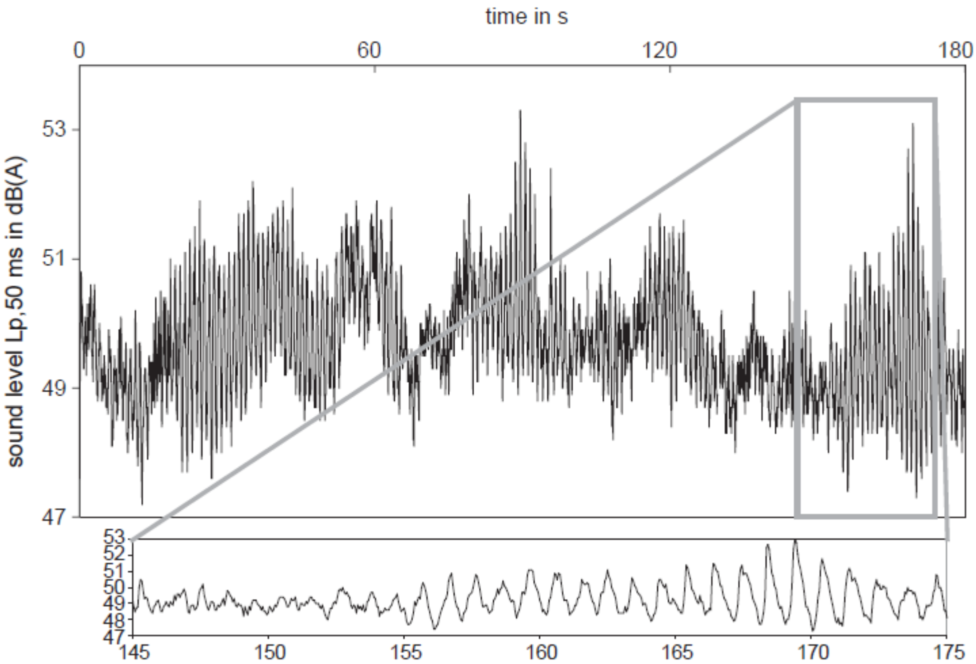
3.5 This work package presents a brief review of AM research and data and so provides evidential support that AM is not rare but is a common effect of wind farm noise.

[4] Wind Turbine Measurements for Noise Source Identification ETSU W/13/00391/00/REP

4 Review of AM 2004 - 2006

4.1 **Effects of the wind profile at night on wind turbine sound. Van den Berg (2004).** Van den Berg has pioneered much research in to wind turbine noise and amplitude modulation, particularly the influence of atmospheric stability. Van den Berg measured AM from the Rhede Wind Park at 400m and 1500m from the turbines. It was found that measured noise levels were louder at night time under certain atmospheric conditions than originally predicted and that turbines produced a lower frequency thumping sound (amplitude modulation). This was described as an impulsive noise character and part of the cause of residents' complaints. An extract from the measurements taken from the Rhede Wind Park is given below. It shows a typical amplitude modulation noise trace.

Figure 1: Sound pressure level near dwelling 750m from nearest turbine



4.2 **Perception and annoyance due to wind turbine noise - a dose response relationship. Pedersen and Persson Waye (2004).** A study of five areas comprising 16 wind turbines, either in isolation or in groups, investigated annoyance from wind turbine noise both in terms of level and noise character. Wind farm noise with specific character features such as 'swishing', 'whistling' 'pulsating / throbbing' were concluded as increasing annoyance. Measurements of specific noise character features were not made and reliance was placed on reports and descriptions in questionnaires.

4.3 **Toora Wind Farm - Review of the Environmental Noise Monitoring Program. Fowler (2005).** Residents complained of noise from the Toora Wind Farm and measurements were undertaken to assess noise impact. Although noise levels were measured there does not appear to be any detailed measurements demonstrating AM. However, residents complained of rhythmic turbine noise and noted that the noise from the blade rotation was clearly discernible. This indicates the presence of AM.

5 Review of AM 2006 - 2008

5.1 **The Measurement of Low Frequency Noise at Three UK Wind Farms (2006).** The DTI appointed Hayes McKenzie Partnership Ltd to undertake a review of low frequency noise complaints from wind farms. Measurements were taken at three sites and aimed at corroborating residents' complaints of low frequency noise. The report found that the common cause of complaints was not low frequency noise but audible amplitude modulation noise particularly at night. The level of AM measured was greater than any AM noise characteristic identified by ETSU-R-97. The report noted that whilst levels were not necessarily of sufficient decibel level to cause awakenings once awoken at night residents may have difficulty returning to sleep as a result of the wind farm AM.[5] The report highlighted the need for further research in to the occurrence of AM.

5.2 The DTI report provides evidence of three wind farm sites in the UK which in 2006 caused AM noise complaints. The report also highlights the difficulty in relying on resident's description of noise who as non acoustics experts may not be able to identify the intrusive noise with the same terminology expected by experts.

5.3 Freedom of Information requests surrounding the DTI report revealed additional commentary relating to AM in a 3rd draft of the report, which was edited or removed from the final report. The 3rd draft of the DTI report recommended revision to the night time noise limits set in ETSU-R-97 and notably stated *"...aerodynamic modulation is a clearly audible feature within the incident noise, it is recommended that a means to assess and apply a correction to the incident noise is developed".* Whilst the need to identify and control AM was highlighted at this early stage the onus to address AM impact was removed from the final report and has been buried, neglected and denied by industry and government until the last couple of years.

5.4 **Research into Aerodynamic Modulation of Wind Turbine Noise (2007).** The report undertaken by Salford University followed on from the results of the DTI study. AM was investigated by surveying local authorities to identify complaints and potential problem sites. The survey found 27 out of the 133 wind farm sites operational at the time of the survey had caused noise complaints. AM was found to be a factor of the noise complaint in four sites and possibly in an additional eight sites. It was estimated using meteorological data that AM would prevail at the four sites identified between about 7-15% of the time. The study concluded that the incidence of AM was rare.

5.5 The Salford study was heavily criticised for missing wind farm sites from which complaints had been received. Freedom of information requests and re-analysis of the data found that 15-16% of sites identified in their study were likely to be causing complaints. Again, there were difficulties in correctly identifying AM due to the descriptors used by residents and local authority officers. Further freedom of information requests indicate that around 25% of wind farms led to complaints to the local council.

[5] Note: This was the view of the report's author and was not based on research relating to sleep disturbance. Sleep disturbance and health effects are discussed in more detail in WP3.2.

5.6 The four sites identified in the Salford study as causing AM complaints were not named but are believed to be Bears Down (first site), Askham (second site), Deeping St Nicholas (third site) and Llyn Alaw (fourth site).[6]

5.7 **Auralization and Assessments of Annoyance from Wind Turbines. Legarth (2007).** Noise from five different wind turbines was measured at a distance of 1.5 and 3 times the hub height of the turbine; as such they are primarily near field recordings. However, swishing sound (AM) was identified in the recordings and is evidence of AM in the near field.

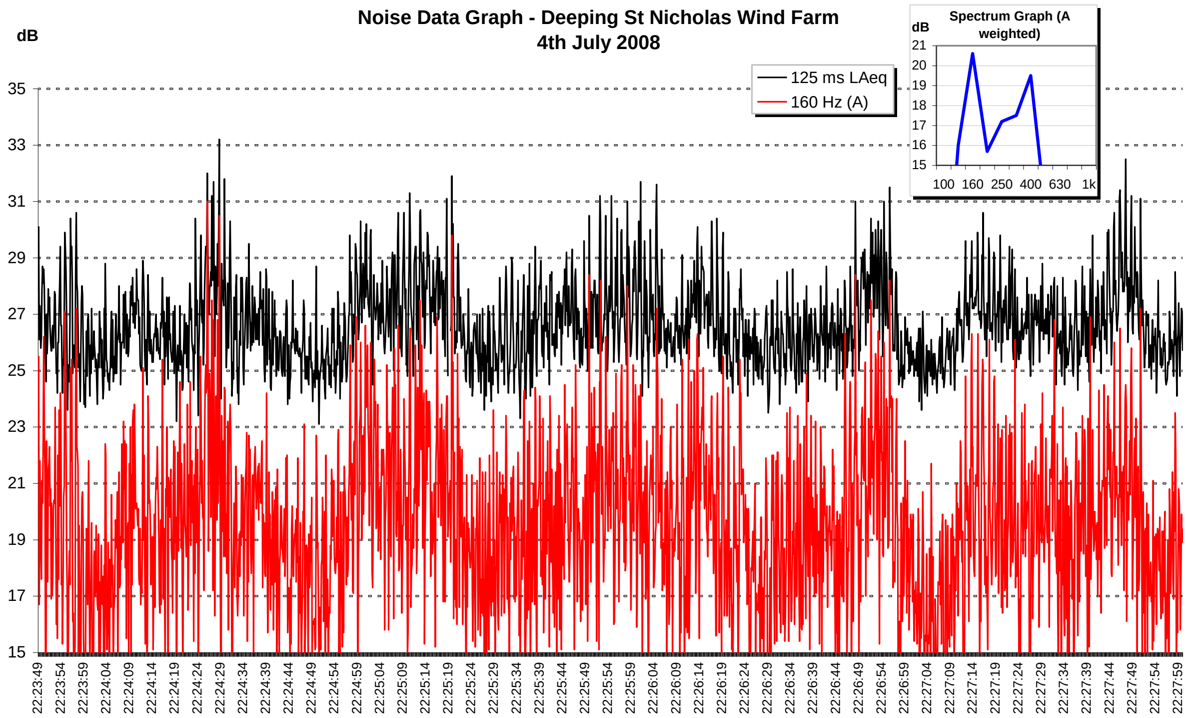
5.8 **Wind turbines - low level noise sources interfering with restoration? Pedersen and Persson Waye (2008).** Twelve areas in Sweden where there was at least one wind turbine with a rated power of 500kW or more were studied. Descriptions of the wind turbine noise indicated the occurrence of AM and were identified as an annoying feature of wind turbine sound. Wind turbine noise described as 'swishing', 'whistling', 'resounding' and 'pulsating / throbbing' were found to be highly correlated with annoyance.

5.9 **Deeping St Nicholas Wind Farm, Lincolnshire England (2006 - 2009).** As noted above, Deeping St Nicholas is thought to be one of the sites listed in the Salford study as causing AM and associated complaints. MAS have measured AM internally and externally at a complainant's dwelling just over 1000m from the nearest turbine. Significant AM has been measured from the site and sound energy in the lower frequency range was found to be prominent (100Hz - 200Hz).

5.10 The data shown on the chart below was measured internally, with a window partly open and just over 1000m from the nearest turbine. 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.

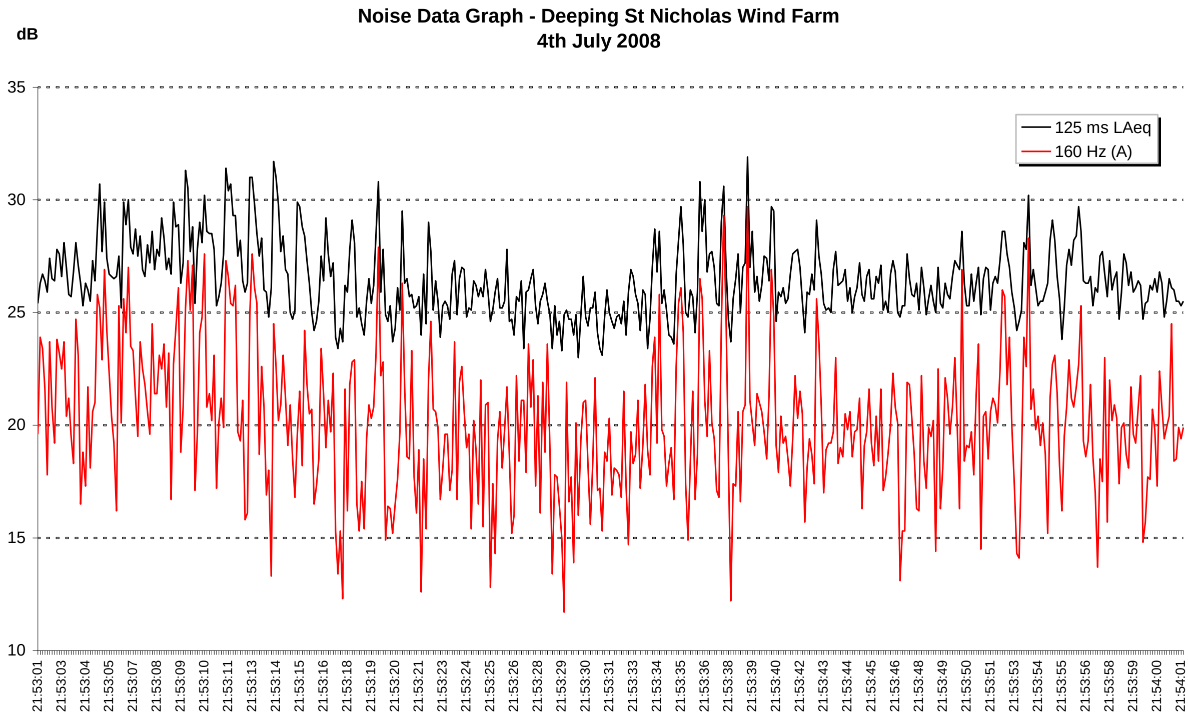
[6] http://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=5&cad=rja&uact=8&ved=0CDoQFjAE&url=http%3A%2F%2Fwww.ref.org.uk%2FFiles%2Fjc.lm.salford.data.comment.07.02.09.c.pdf&ei=5zTsVOqXMISwUcu_gbgO&usg=AFQjCNH3WQDHAScxERJ3xH8b_ROnzt3AYg&bvm=bv.86475890,d.d24

Figure 2: Internal sound pressure level at dwelling approximately 1km from nearest turbine



5.11 The chart below shows measured noise levels earlier in the same evening and demonstrates 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 lower frequency fluctuation.

Figure 3: Internal sound pressure level at dwelling approximately 1km from nearest turbine



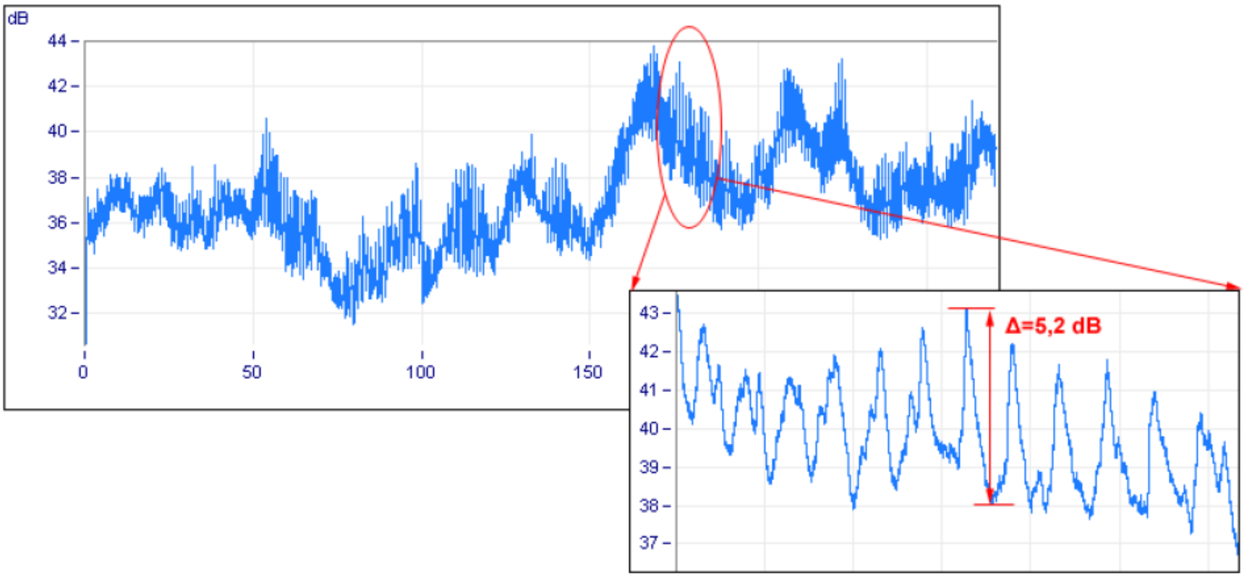
6 Review of AM 2009 - 2012

6.1 **An estimation method of the amplitude modulation in wind turbine noise for community response assessment. Lee (2009).** This paper deals largely with assessment of AM once measured using fast Fourier transform. Two sample measurements of AM from a turbine were gathered; however, both measurements are within close proximity of the turbine rather than a far field measurement of AM as would impact receivers.

6.2 **Response to noise from modern wind farms in The Netherlands. Pedersen et al (2009).** A study of all areas in The Netherlands in which there were at least two wind turbines of at least 500kW within 500m of each other was made to investigate sound level, sound character and annoyance. 'Swishing / lashing' was the most common descriptor of wind farm noise and it was asserted that this might enhance annoyance of wind turbine noise.

6.3 **Wind turbine noise in a small and quiet community in Finland. Di Napoli (2009).** Measurements from a single wind turbine in Finland revealed different noise character features from the turbine including AM noise. AM was found in one recording to change in sound level by 12dB. An example of the AM trace measured at the site is given below.

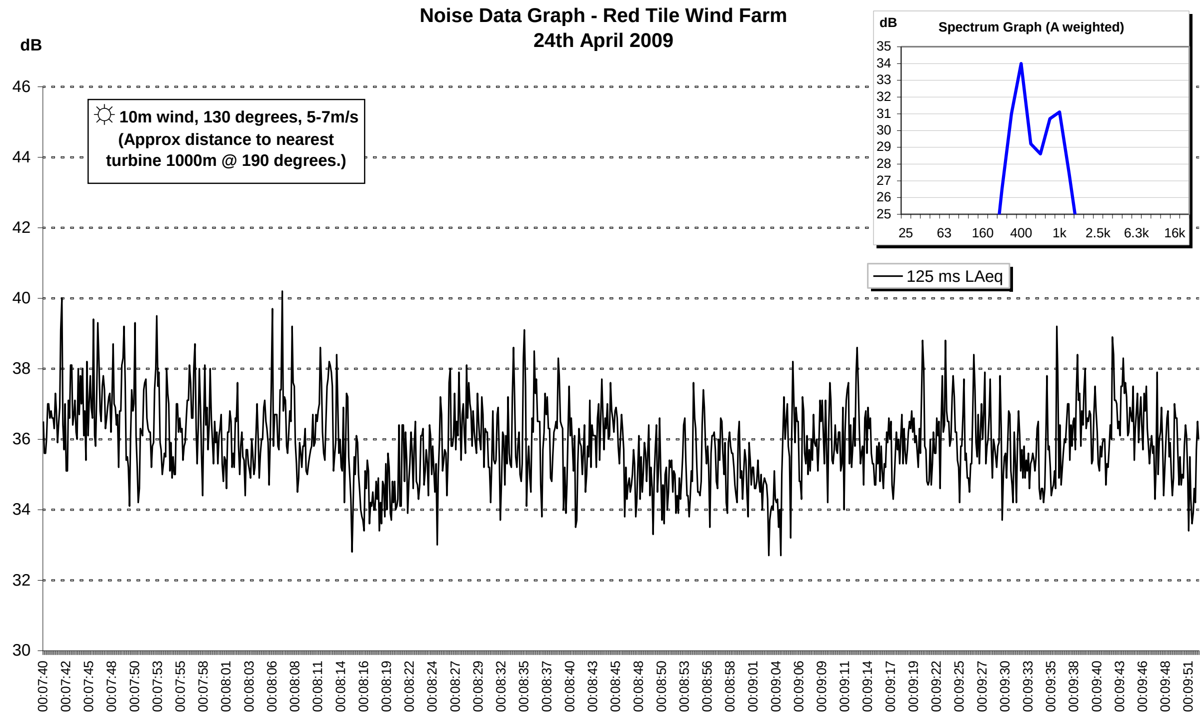
Figure 4: AM measured 530m away from the turbine



6.4 **Red Tile Wind Farm, Cambridgeshire (2009).** Red Tile Wind Farm is located on a flat site in eastern England. Measurements were made approximately 1000m from the wind farm. Noise complaints were received from a nearby resident.

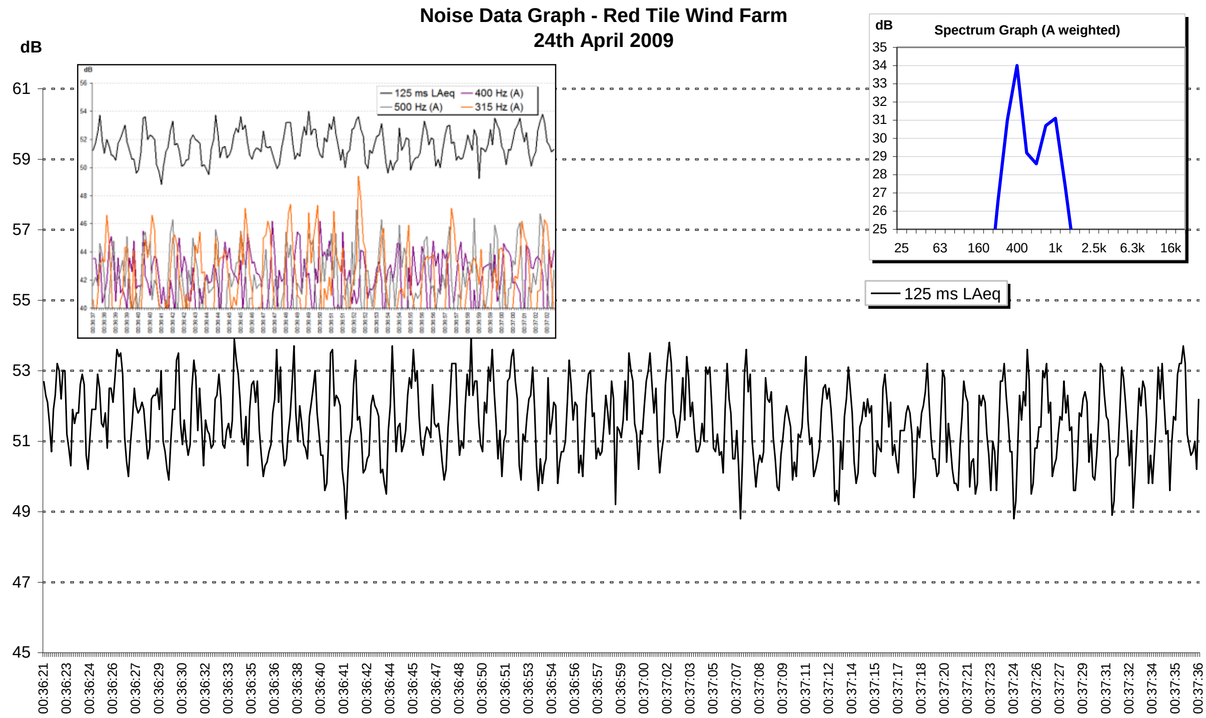
6.5 The example AM trace shown here is erratic both in peak level and shape. AM peak to trough is typically 4-5dB. Sound energy is focused in the 400Hz third octave band with some contribution from the 1 kHz third octave band.

Figure 5: AM measured at Red Tile Wind Farm



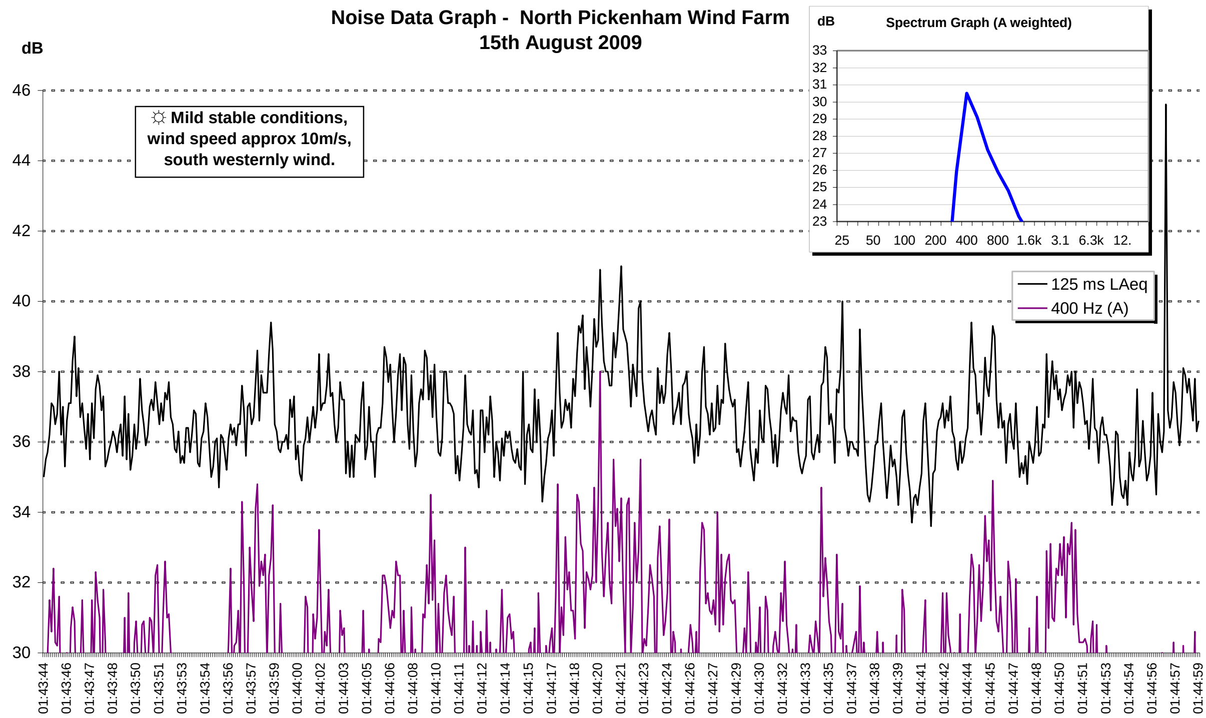
6.6 There is rarely any synchronisation in third octave bands and the phasing is consistently different, reflected in the multiple peak character of the AM. The AM has a sweeping tonal characteristic, which is most likely generated by the non simultaneous contribution of different third octave band sound energy to the AM peaks over time.

Figure 6: AM measured at Red Tile Wind Farm



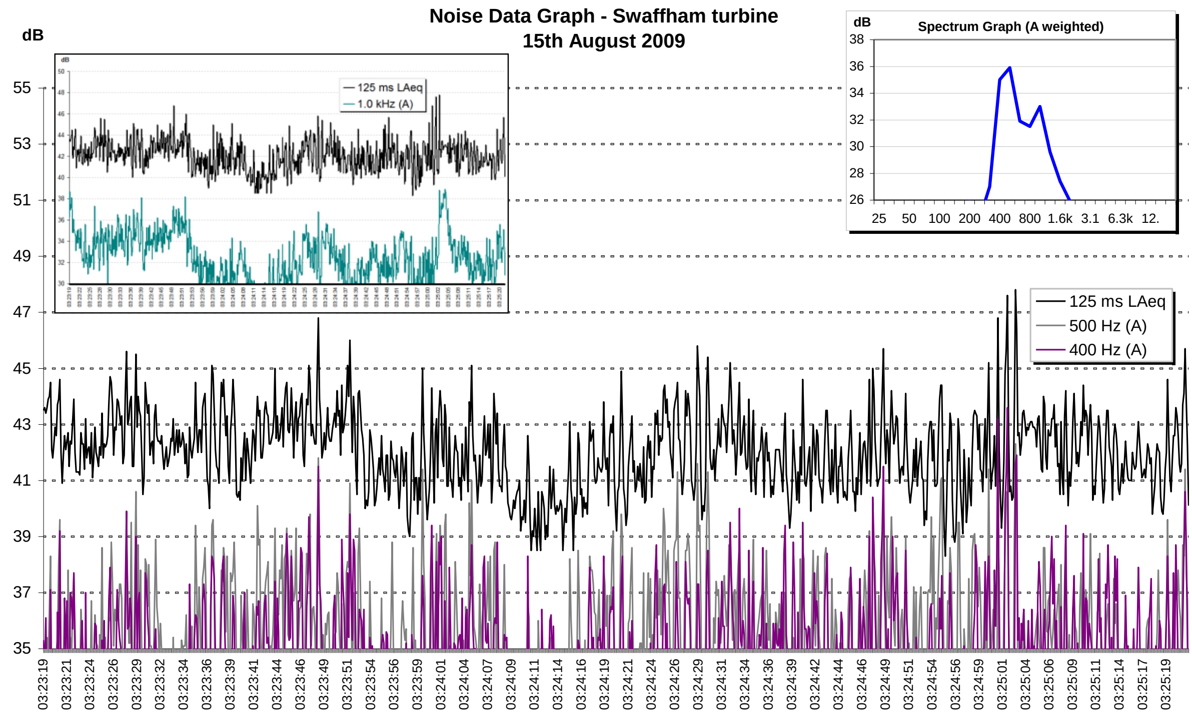
6.7 **North Pickenham Wind Farm, Norfolk (2009).** AM was measured approximately 1km from the nearest turbines. The noise trace is more erratic than measured at other sites and could be due to the measurement location, which was at varying angles to the turbines due to their geographical spread. The extract below contains noise that could be considered 'general' wind farm noise as well as lower frequency thump elements of AM.

Figure 7: AM measured at North Pickenham Wind Farm



6.8 **Swaffham Wind Turbine, Norfolk (2009).** Measurements from this single turbine were taken at a distance of approximately 320m. 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.

Figure 8: AM measured at Swaffham turbine



6.9 **Long Distance Amplitude Modulation of Wind Turbine Noise. Di Napoli (2011).** Measurements from a five turbine wind farm in Finnish Lapland revealed that significant AM was generated by smaller, older turbine types and could be measured approximately 2km away from the nearest turbine. Three examples of AM at increasing distances from the wind farm are given below.

Figure 9: AM measured downwind at 630m

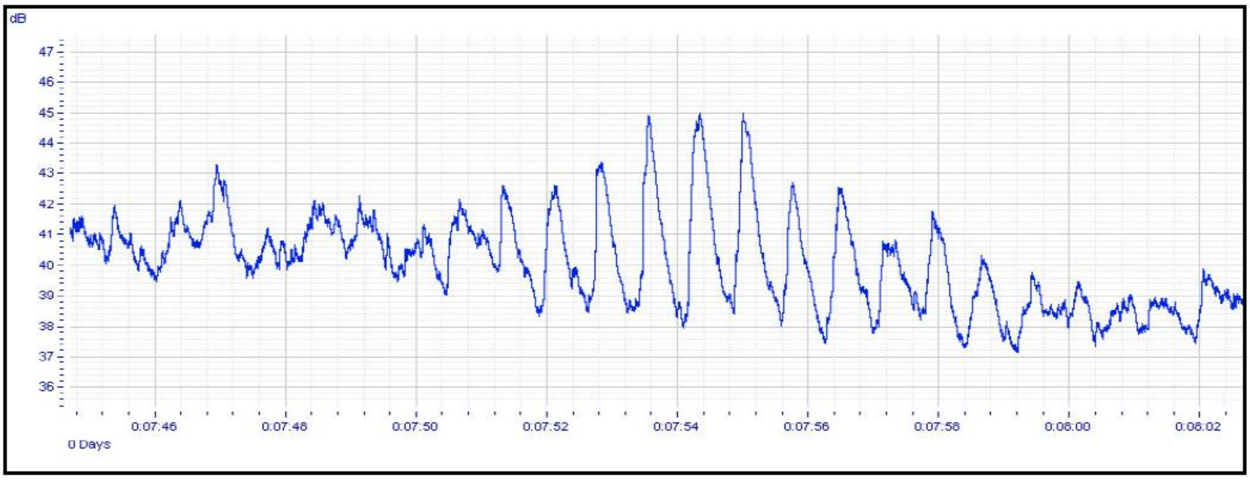


Figure 10: AM measured downwind at 1000m

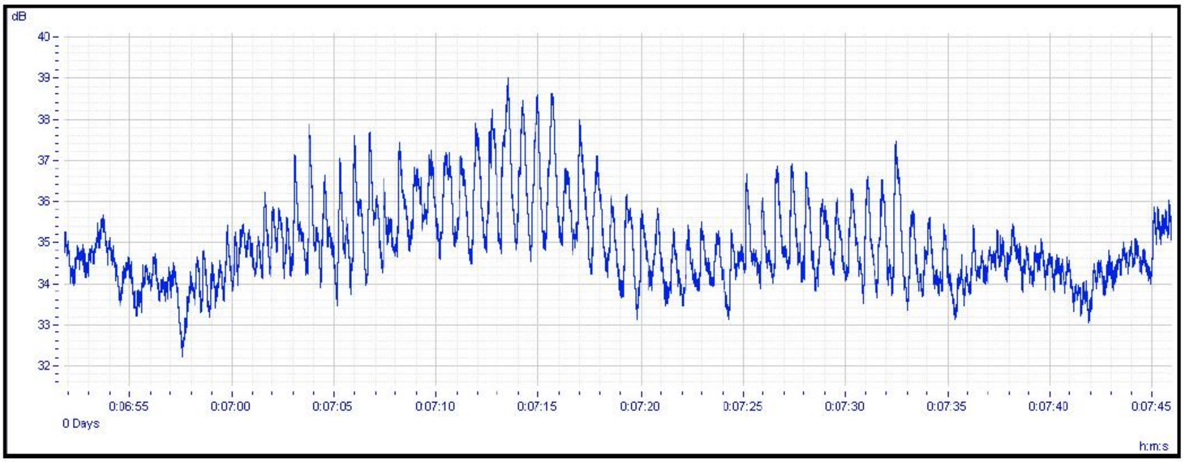
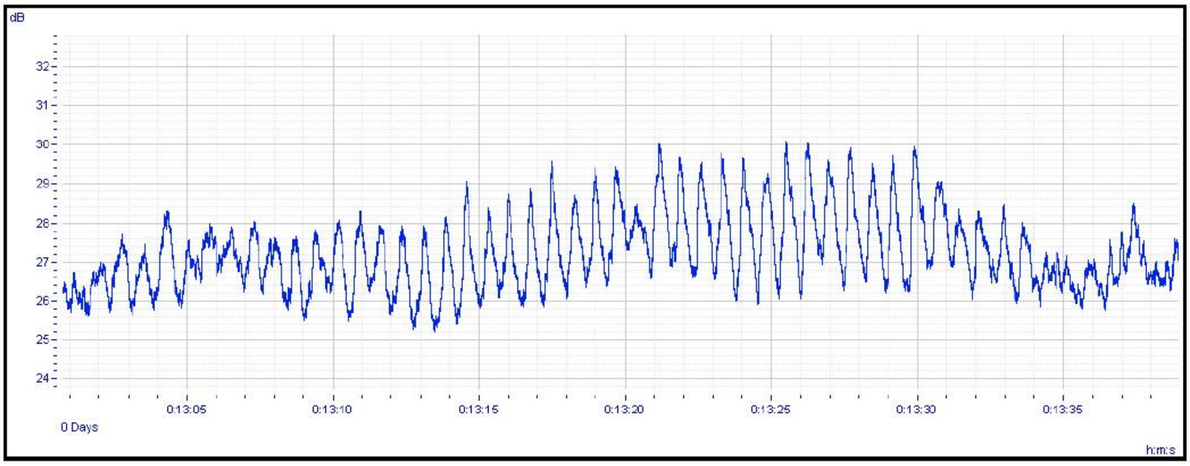
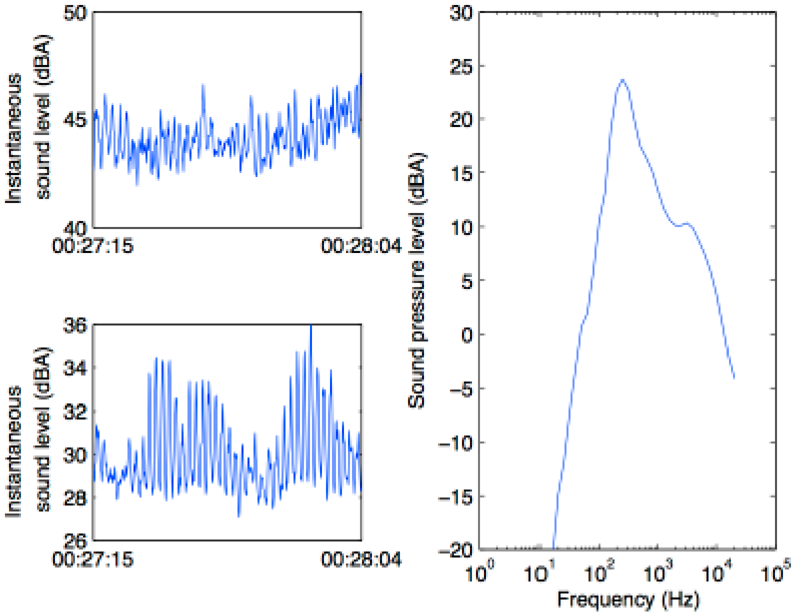


Figure 11: AM measured downwind at 2000m



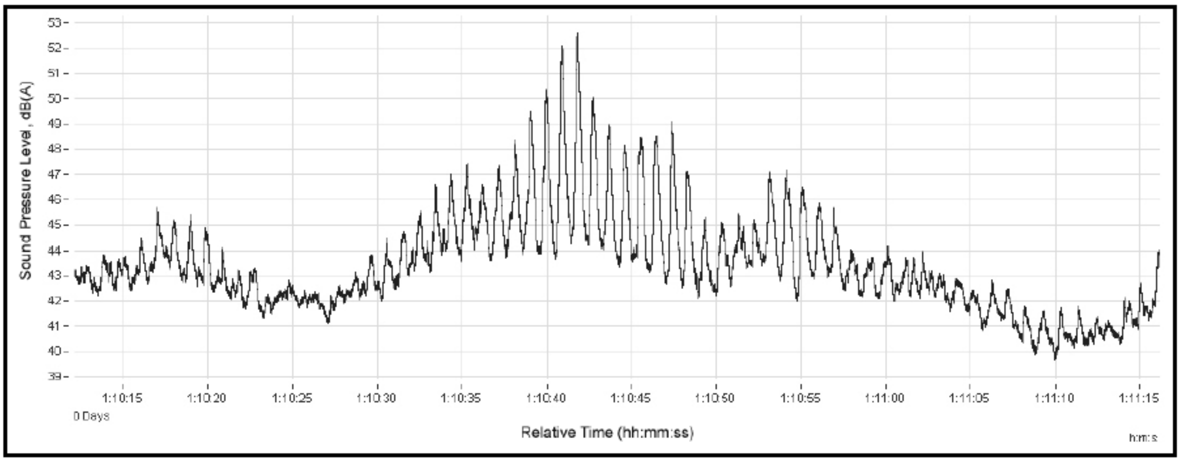
6.10 **Variations of sound from wind turbines during different weather conditions. Larsson & Ohlund (2012).** Long term measurements from two wind farm sites in Sweden found that received noise levels were extremely dependent on meteorological conditions and could vary by 6-14dB(A) depending on ground conditions and refraction. AM was measured from both sites and meteorological conditions were again found to be influencers of received sound. AM was estimated to occur for approximately 30% of the time at 400m and 10% of the time at 1km from the nearest turbine.

Figure 12: Sound level measurements close and 3-4km from the wind turbines at Dragaliden site



6.11 **Assessing aerodynamic amplitude modulation from wind turbine noise. Di Napoli (2012).** Measurements were made from a single wind turbine in Finland as a result of a series of complaints at a dwelling approximately 470m away from the turbine. AM was measured typically in the region of 8-9dB modulation depth, near field modulation levels were typically not more than 5-6dB. An example noise trace is given below.

Figure 13: AM measured in the far field



6.12 **Site C, D & E (2012).** 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.

Figure 14: AM measured at site C

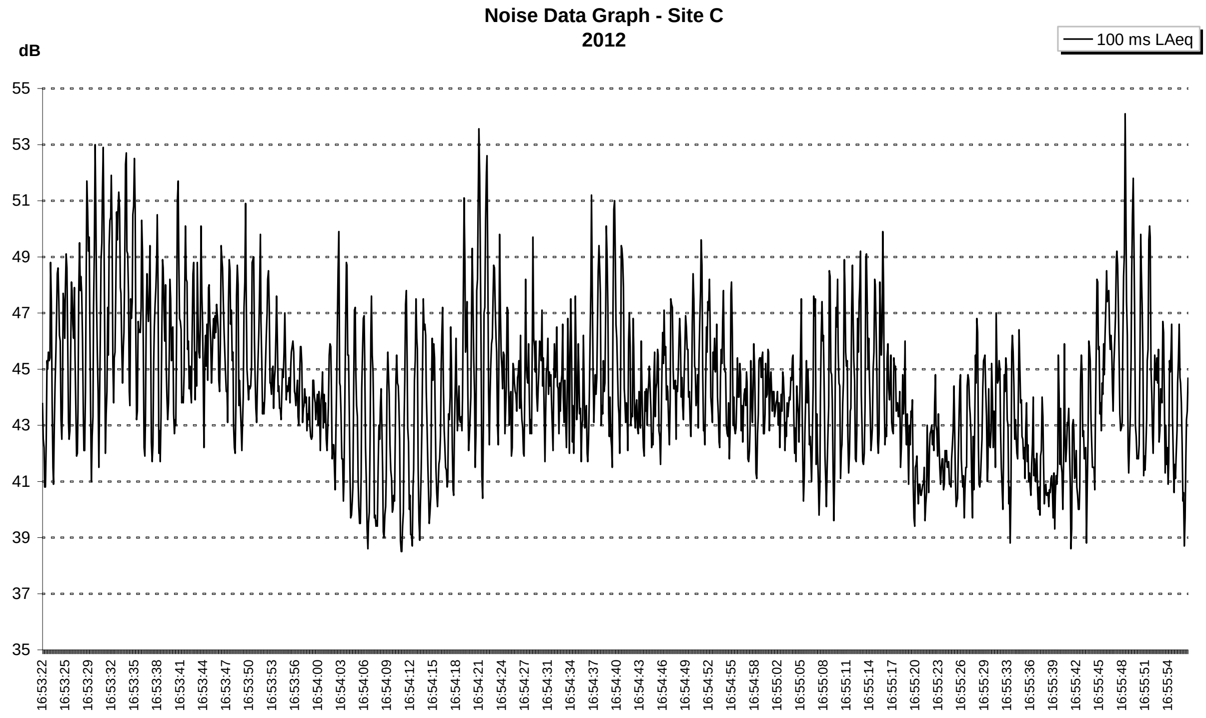


Figure 15: AM measured internally and externally at site D

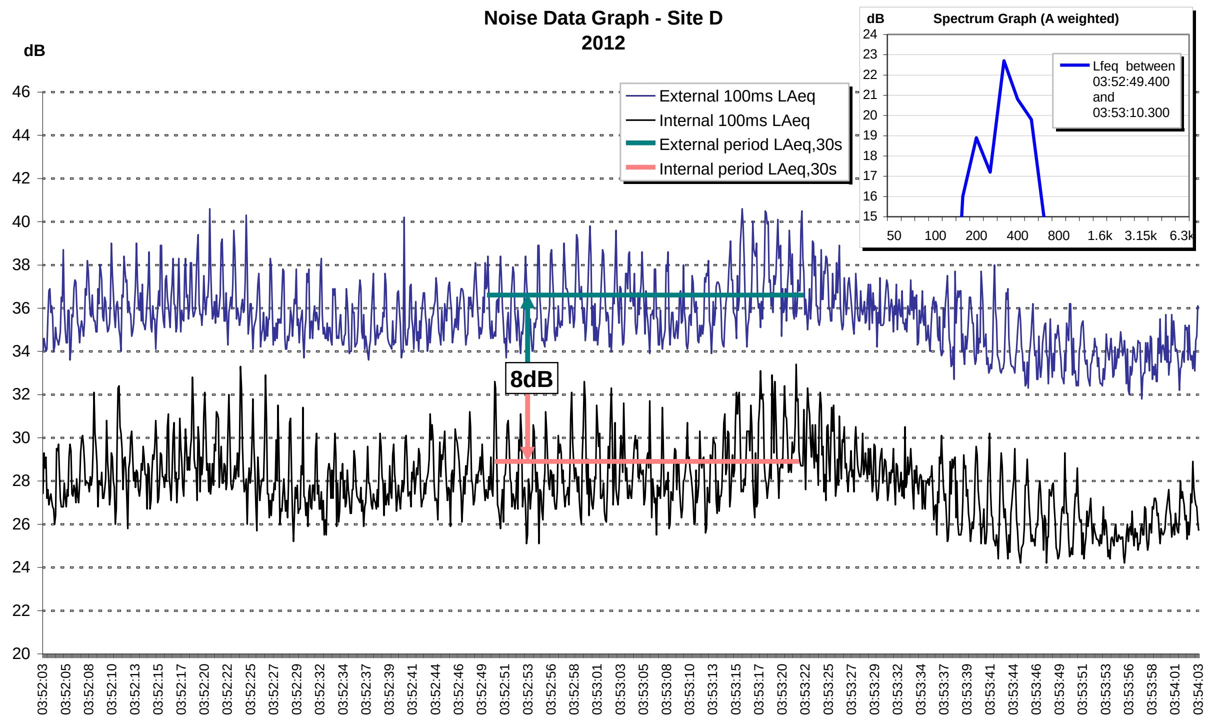
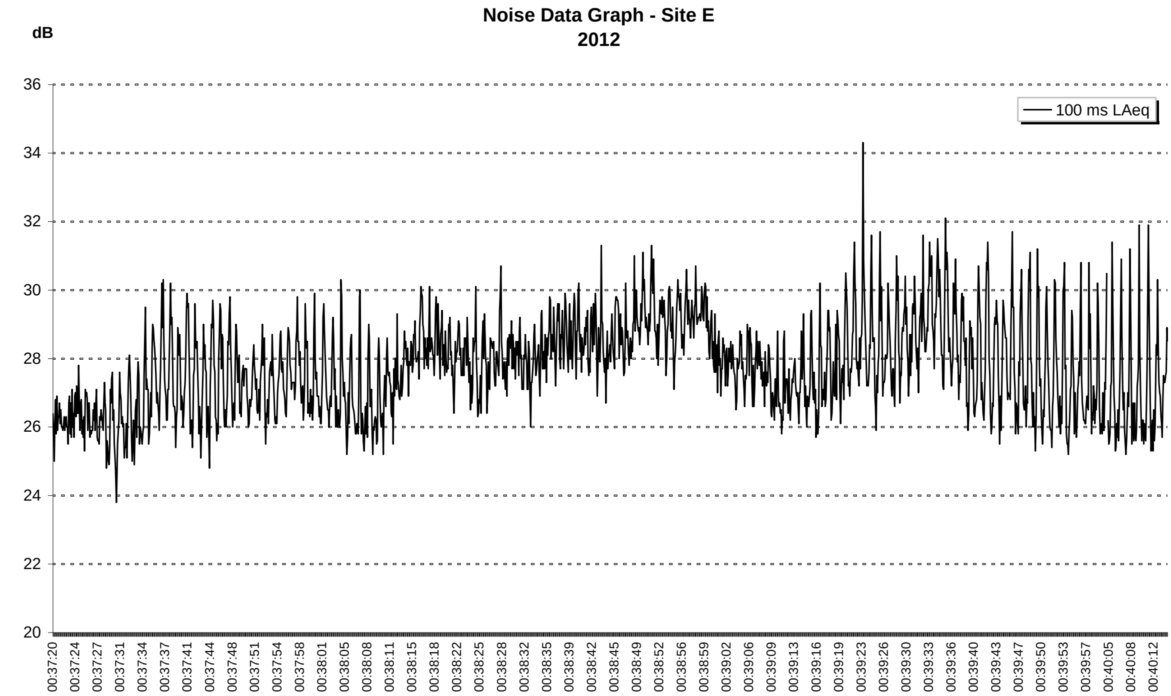
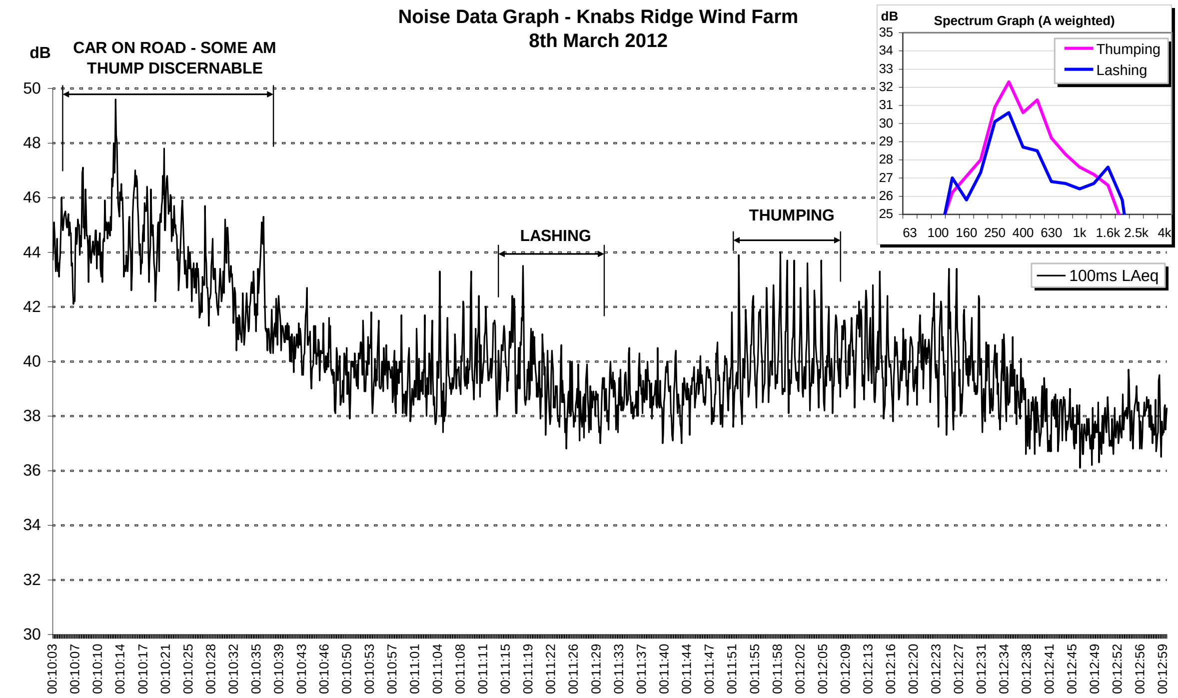


Figure 16: AM measured at site E



6.13 **Knabs Ridge Wind Farm, North Yorkshire (2012).** 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'.

Figure 17: AM measured at Knabs Ridge Wind Farm

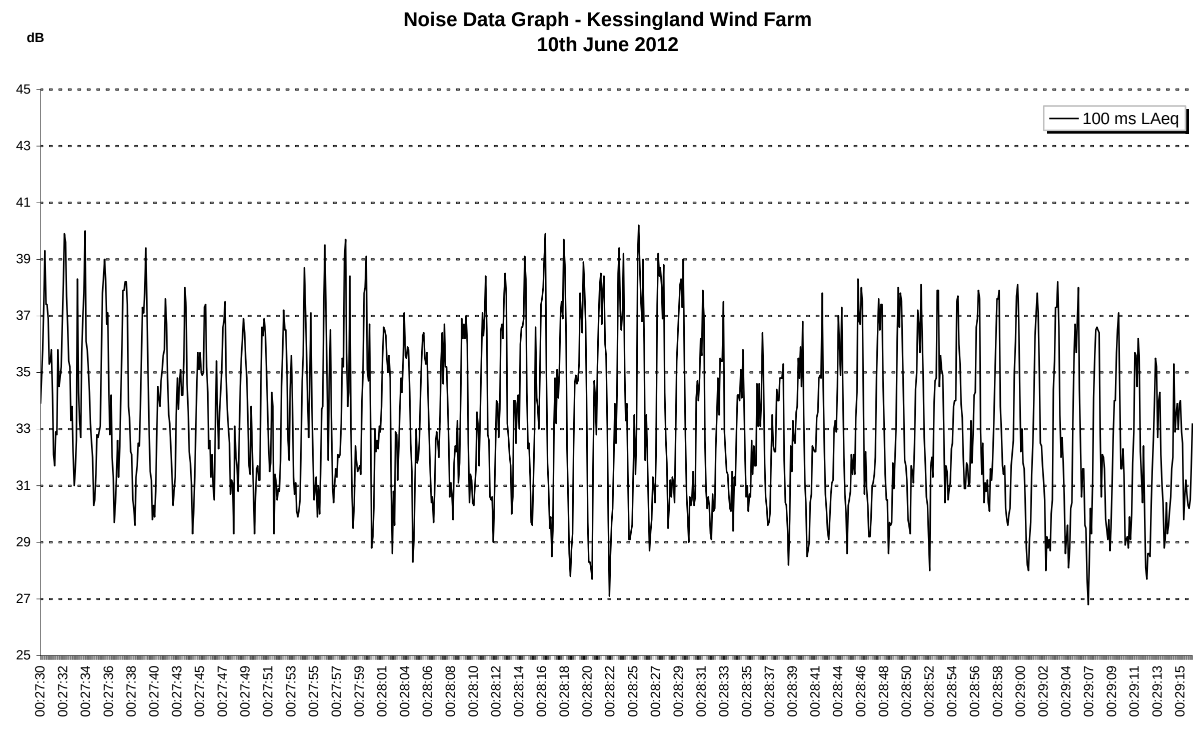


6.14 **The Perception and Effect of Wind Farm Noise at Two Victorian Wind Farms. Thorne (2012).** Measurements of wind farm noise were made as a result of complaints and were made in the vicinity of the Waubra Wind Farm and Cape Bridgewater Wind Farm in Australia. A detailed survey was not undertaken at Cape Bridgewater Wind Farm. At the Waubra Wind Farm residents complained of noise characteristics such as fluctuating, undulating, beating, rumble, repetitive, impulsive, thumping and annoying. These descriptors are indicative of AM.

6.15 **A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin (Wisconsin report). Walker et al (2012).** This large research project involved the cooperation of four independent consultancies and extensive measurement of noise from the Shirley Wind project, Wisconsin, USA. The measurements focused on low frequency and particularly infrasound as a result of complaints from nearby residents specifically relating to adverse health effects including in the absence of any discernible audible noise. The report concluded that low frequency noise and infrasound are serious issues. The measurements and conclusions support the reported adverse health effects of neighbours. Whilst some noise measurements were made reporting audible noise levels this aspect appears to have been little investigated. The only reference to audible AM was the presence of a 'whoosh' sound seen in the higher frequencies from around 200Hz - 2kHz.

6.16 **Kessingland Wind Farm, Suffolk (2012-2013) (Site 3 WP5).** The majority of the local community have been complaining and campaigning for the turbines to be turned off due to adverse noise impact. Despite noise monitoring exercises being undertaken the noise issues have not yet been resolved. The measurements below were taken at a distance of approximately 550m from the nearest turbine.

Figure 18: AM measured at Kessingland wind farm (WP5 site 3)



6.17 Complaints are also made regarding internal noise impact and particularly lower frequency noise penetrating the bedroom. The figures below show an extract firstly with windows open and secondly with windows shut. AM is still clearly audible and visible in the recorded data and there is significant lower frequency noise.

Figure 19: AM measured at Kessingland Wind Farm - internal with window open (WP5 site 3)

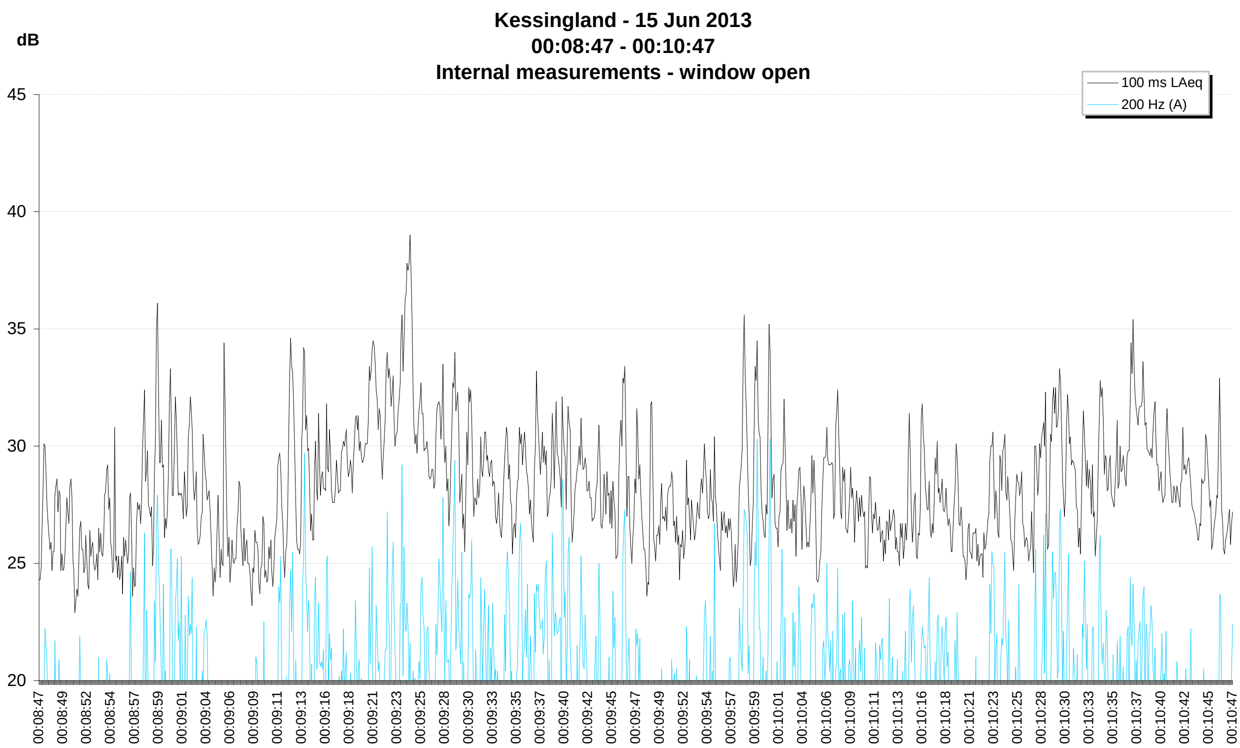
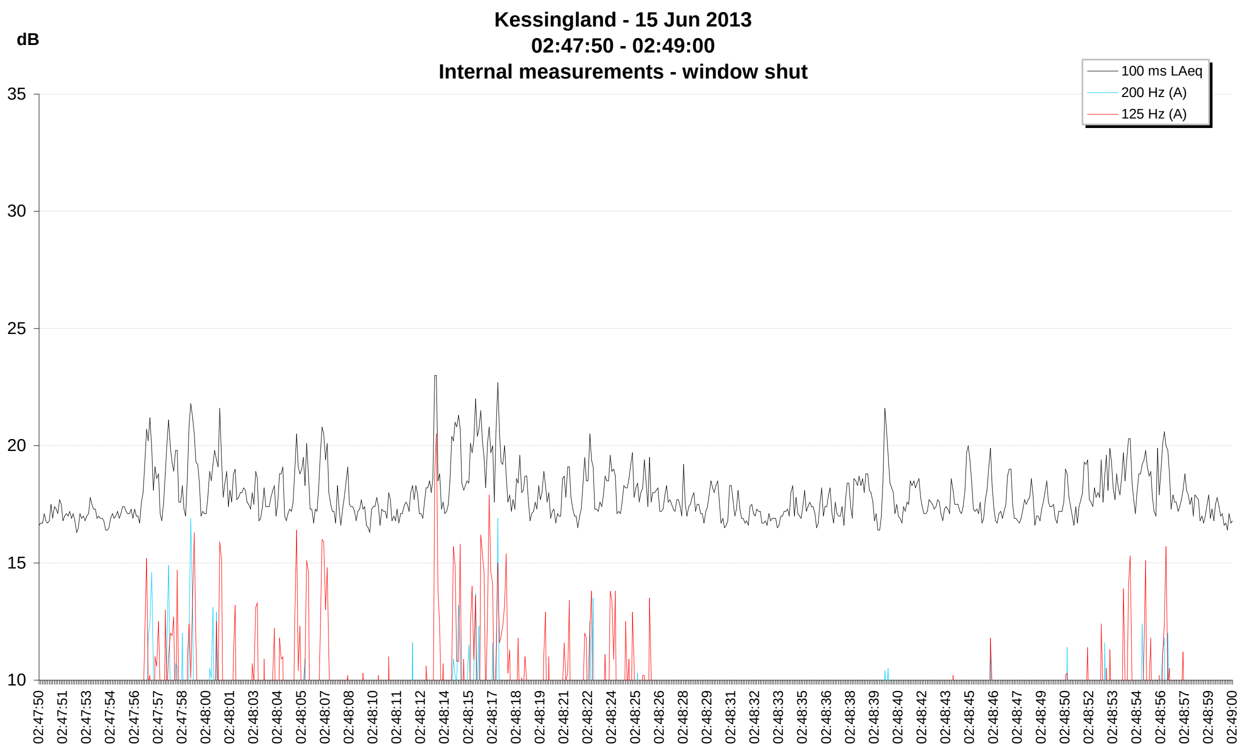


Figure 20: AM measured at Kessingland Wind Farm - internal with window shut (WP5 site 3)



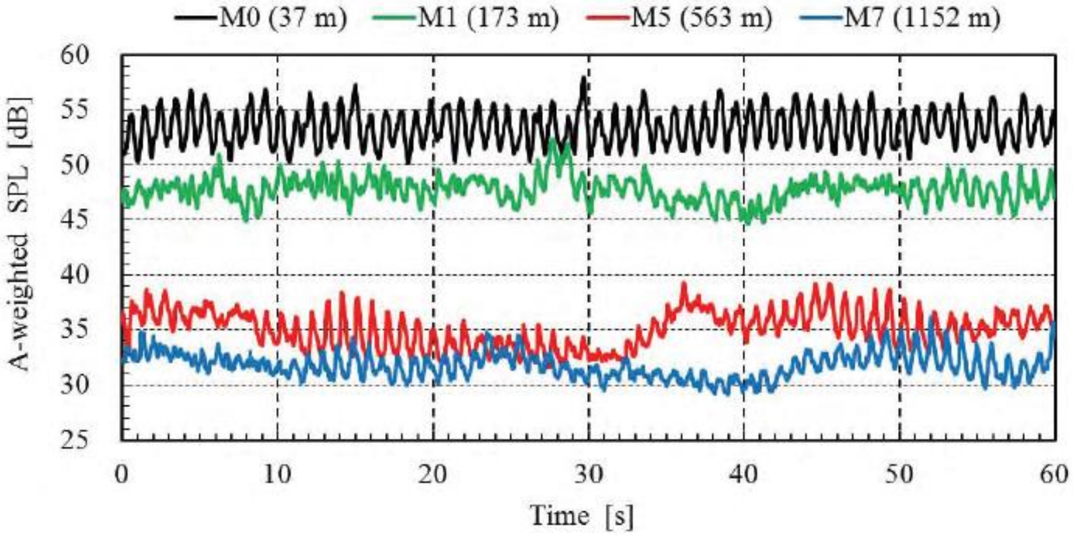
6.18 Measurements of AM and wind farm noise have also been made by those developing AM assessment tools and methods. Limited detail of the measured AM is provided in these papers as the primary focus of the paper is the algorithm or other means of AM assessment. See for example McLaughlin (2011),[7] McCabe (2011),[8] Nobbs, Coolan and Mereau (2012).[9]

[7] "Detection and Quantification of Amplitude Modulation in Wind Turbine Noise"
[8] "Measurement of amplitude modulation frequency spectrum"
[9] "Characterisation of noise in homes affected by wind turbine noise"

7 Review of AM 2013 - present

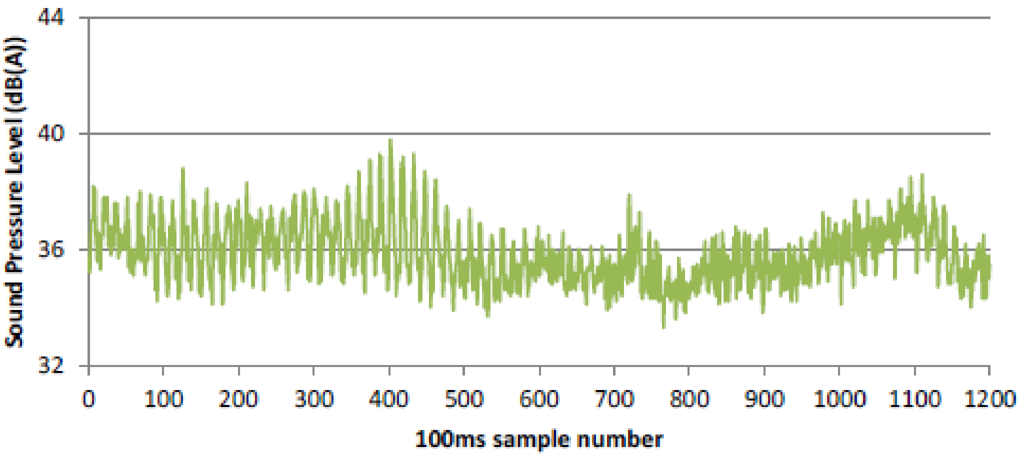
7.1 **Study on the amplitude modulation of wind turbine noise: Part 1 - Physical investigation. Fukushima et al (2013).** An extensive study in Japan measured noise from 18 wind farm sites. A method for rating AM was derived (DAM index). In other research subjective impression of AM was investigated and it was found that a fluctuation sensation begins at around 2dB modulation, equivalent to a DAM index of 1.7. The study found that AM fluctuation is sensible in approximately 75% of the measurement points investigated in the study. AM is stated as 'generally contained in wind turbine noise' and as causing serious annoyance. An example of the AM measured in a residential area at different distances from a wind farm is given below.

Figure 21: A weighted sound pressure levels measured at a reference point and in a residential area



7.2 **Automated detection and analysis of amplitude modulation at a residence and wind turbine. Cooper and Evans (2013).** This paper aims to develop an automated means for detecting AM. It is stated in the introduction that all wind turbine noise features AM. AM was measured at a residence to test the automated method described in the paper. An example of the measured AM is given below.

Figure 22: AM measured at the residence - "Measurement Period #1"

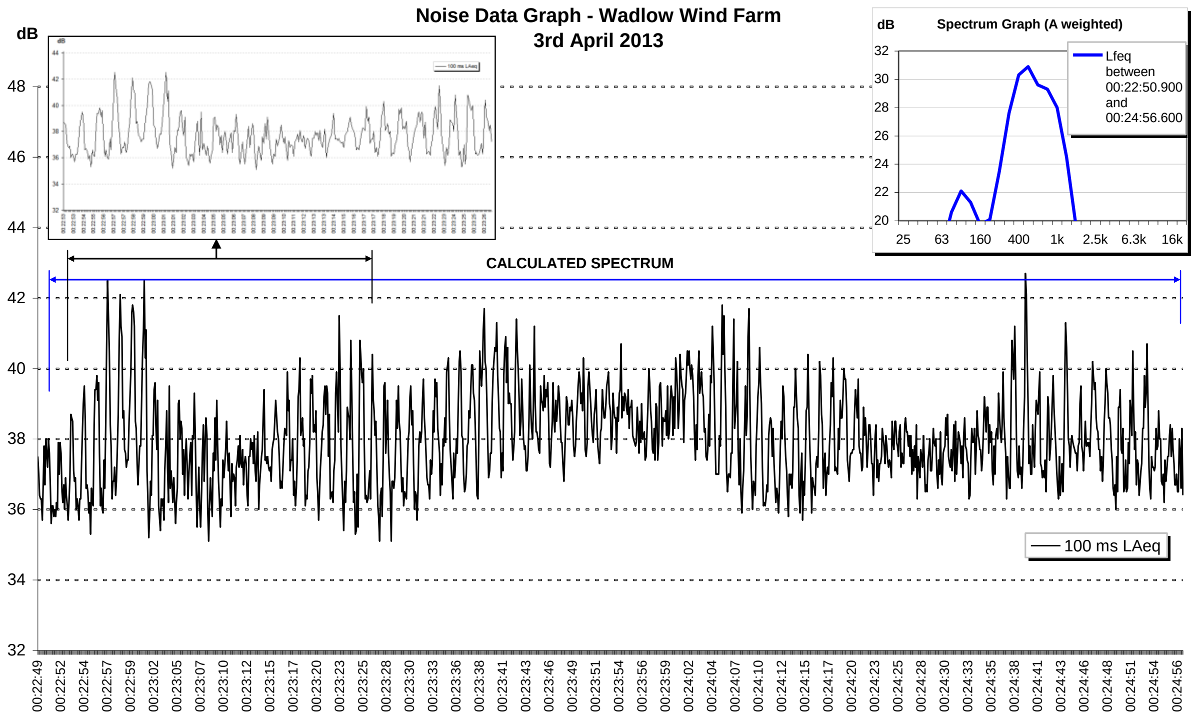


7.3 **Amplitude Modulation and Complaints about Wind Turbine Noise. Gabriel, Vogl and Neumann (2013).** Measurements of a nine turbine wind farm in northern Germany were taken in a village approximately 1500m from the wind farm. Questionnaires and complaints' documents were sought from local residents. The study found that it was not the loudness of the wind farm noise that caused complaints but the character of the noise, namely AM.

7.4 **Waterloo Wind Farm Environmental Noise Study (2013).**[10] As a result of community complaints and concerns noise monitoring around Waterloo Wind Farm, in Australia, was undertaken for a period of 10 weeks beginning in April 2013. Many of the complaints and concerns related to low frequency noise and so measurements were focused on this aspect of the noise. It is not clear whether impact from AM was specifically investigated and the means used to measure noise does not appear capable of providing a detailed study of this noise character. Whilst the residents' noise diaries identified sound features such as pulsing, thumping, pounding etc, which are indicative of AM, such features were reportedly not readily apparent in audio recordings.

7.5 **Wadlow Wind Farm, Cambridgeshire (2013).** 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 noise trace shown in the figure below demonstrates a typical feature of AM where there are periods of high peak to trough differences but that fade in and out during the period.

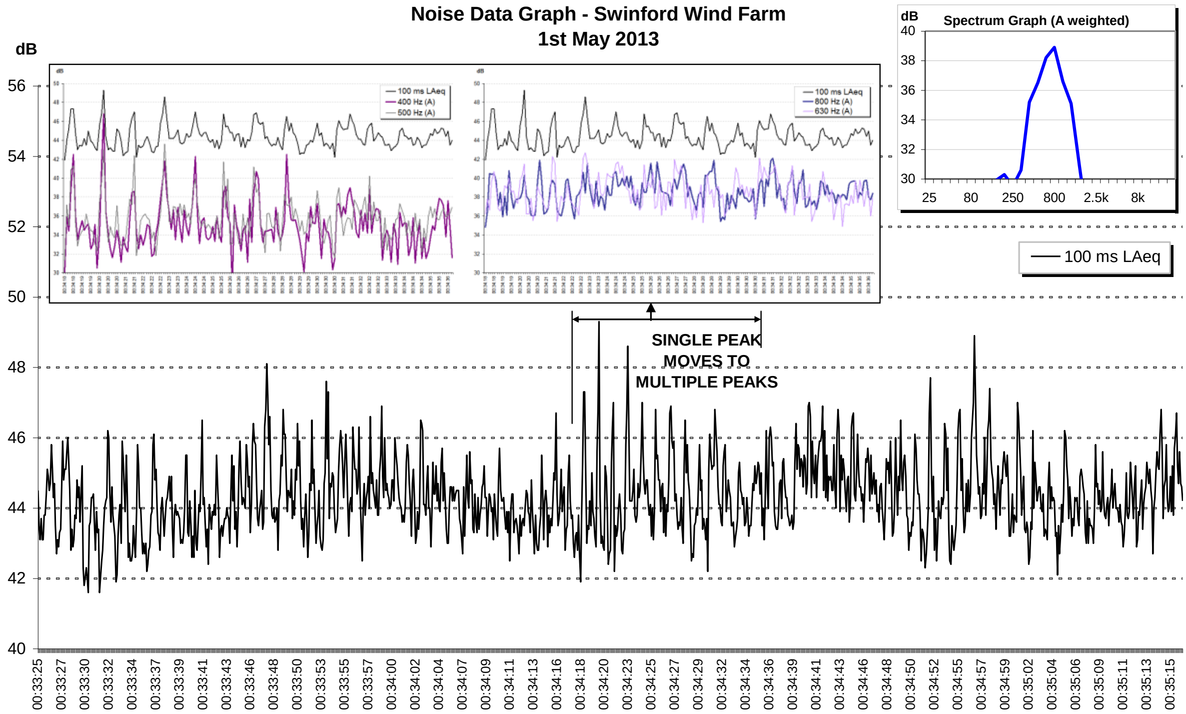
Figure 23: AM measured at Wadlow Wind Farm



10 http://www.epa.sa.gov.au/environmental_info/noise/wind_farms/waterloo_wind_farm_environmental_noise_study

7.6 **Swinford Wind Farm, Leicestershire (2013).** The distance to the nearest turbine was approximately 750m. The weather conditions during the evening measurements at Swinford Wind Farm were not ideal for generating AM as there was high atmospheric pressure and wind energy speeds were continuing to fall and change direction throughout the period.

Figure 24: AM measured at Swinford Wind Farm

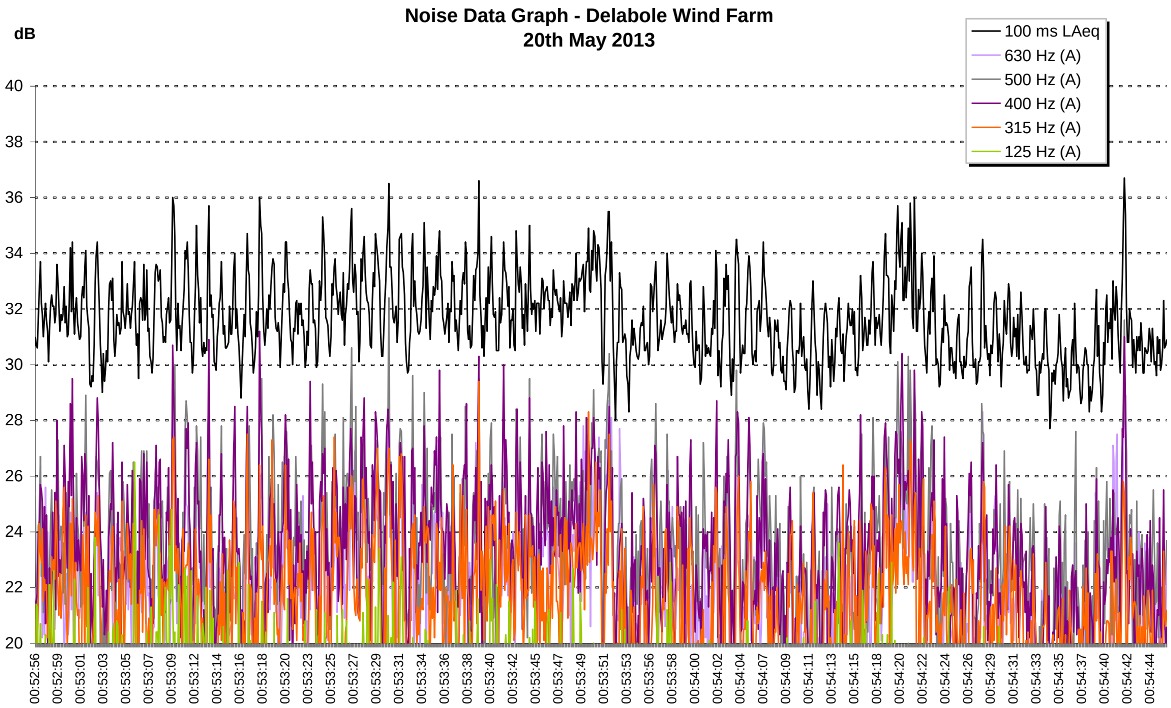


7.7 The AM is fairly erratic and shows different character features at the site including moving from one single 'beat' of AM to AM that has two distinguishable 'beats'.

7.8 **Delabole Wind Farm, Cornwall (2013).** 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.

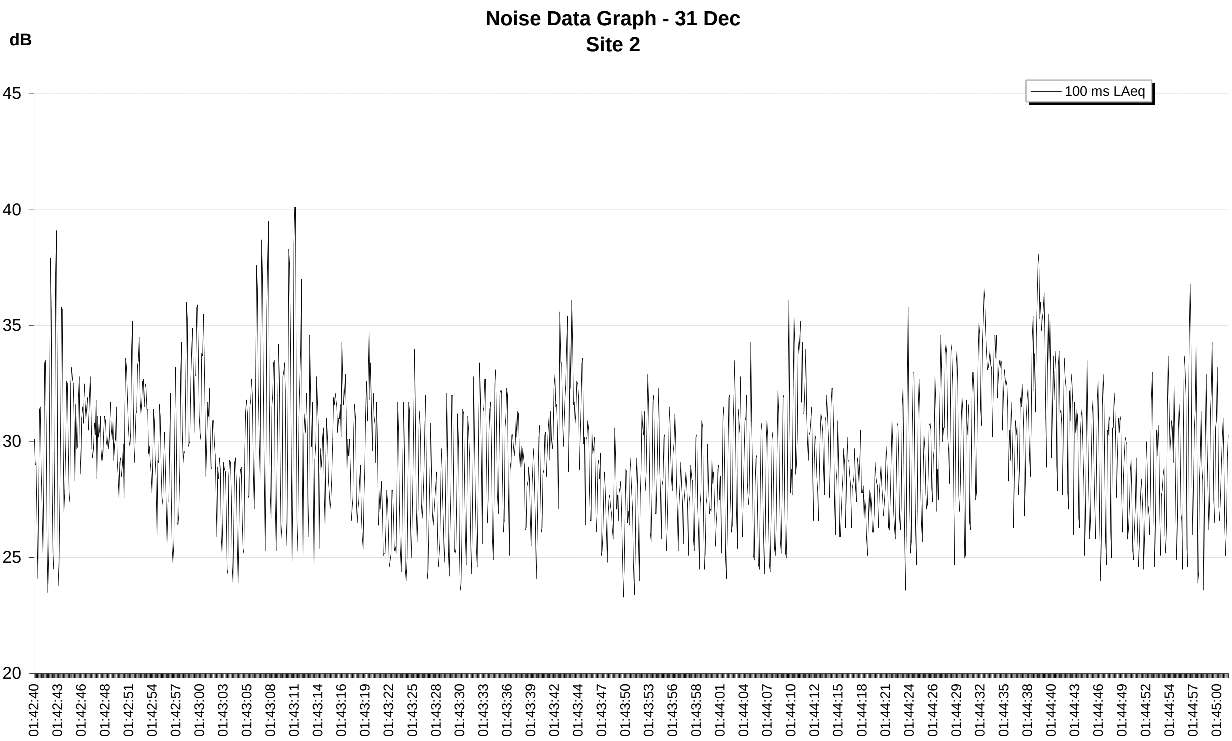
7.9 The AM measured in this case has a fairly broadband frequency content, though there are some periods of the modulation that are dominated by different third octave bands.

Figure 25: AM measured at Delabole Wind Farm



7.10 **Site F - 1 x 275kW turbine (2013-2014) (Site 2 WP5).** Site F remains anonymous due to potential nuisance action. It is a single 275kW turbine that operates in two different gears. An example of the turbine in the higher gear mode operation is given below.

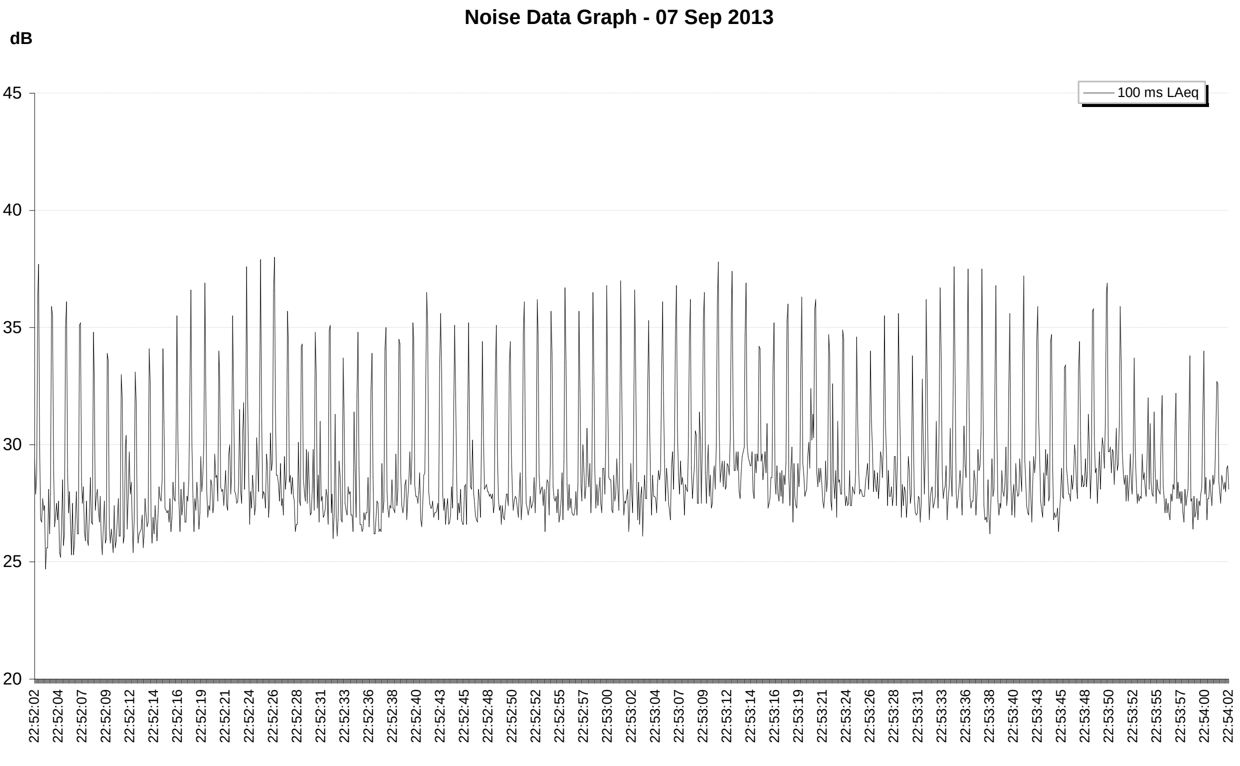
Figure 26: AM measured from Site F (WP5 site 2)



7.11 The turbine noise is highly tonal and an element of tonality is always present when the turbine is operating. When operating in the lower gear the turbine produces a humming noise which is mid frequency in pitch though there is also a quieter higher frequency tonal whine. In the higher gear mode the tonality of the turbine is much stronger and is better described as a dominant high pitched whine. The turbine also generates AM. In the lower gear blade swish modulates at a reasonable pace and has a more subdued character. The modulation of noise is much greater in the higher gear and this is caused both by variances in the tonality but also by a harsh whipping / scraping blade swish noise.

7.12 **Site N - single 50kW turbine (2013) (Site 1 WP5).** The turbine has caused complaints from nearby residents, who specifically complained of the noise character. The noise from the turbine is predominantly tonal and the modulation visible in the graph is caused by modulating tonality though there are some occasions were blade swish is also audible. An example is given below.

Figure 27: Tonal AM measured from site N (WP5 site 2)



7.13 **Renewable UK - Wind Turbine Amplitude Modulation: Research To Improve Understanding As To Its Cause and Effect (2013).** Work Package C of the project was aimed at collating and analysing existing acoustic recordings of AM. Many of the data sources used have been discussed above, though there are additional references to 'several long term measurements at a number of UK sites', data from wind farm sites in Australia and other unnamed excerpts available on the internet.

7.14 Work package D of the project outlines the findings of measurement campaigns at three different wind farm sites in the UK. Examples of AM from site A and site B are reproduced below. The work package notes that its aim was to further investigate the cause of AM (more specifically OAM as defined in the Renewable UK research) and that it was not seeking to quantify frequency and occurrence of AM around the UK. The analysis of AM at sites A, B and C was made primarily using the Renewable UK AM methodology based on an FFT analysis of the raw data. There are significant limitations with this approach including the occurrence of false negatives.[11] The limitations of this methodology are further discussed in WP5. Due to the flaws in the FFT methodology, it is expected that the occurrence of AM is greater than suggested in the report's findings.

Figure 28: Sample period of AM from site A (fig 2.1 in Renewable UK WPD)

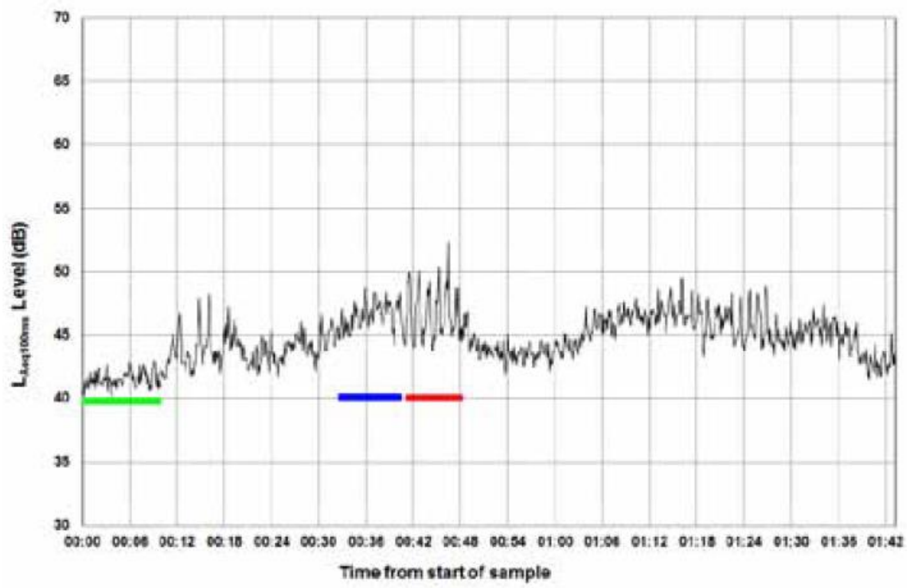
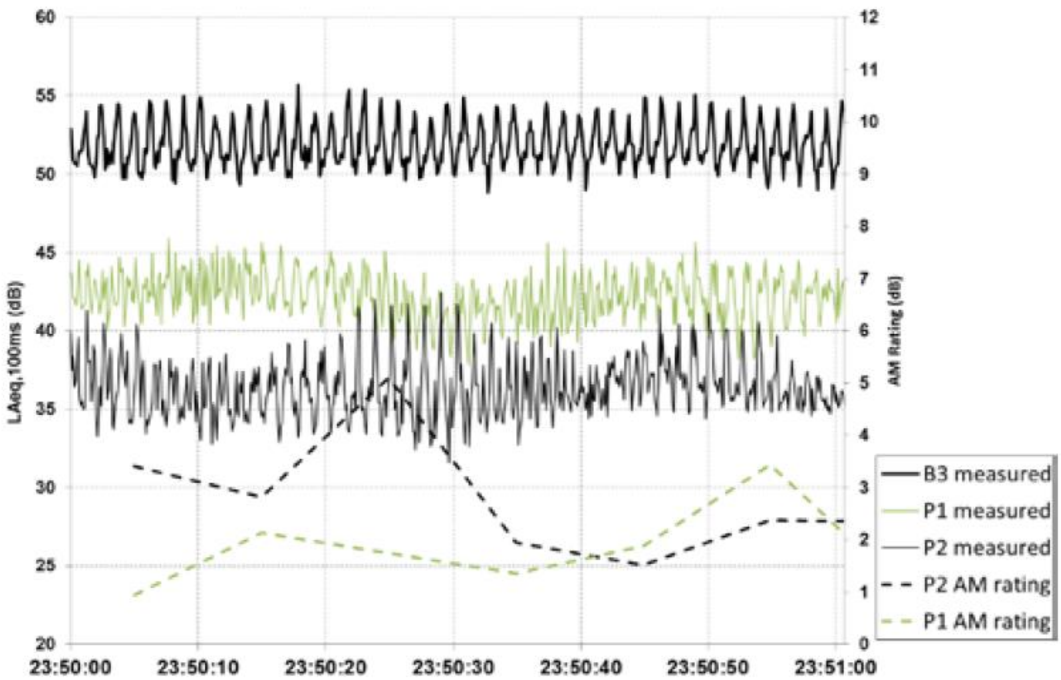


Figure 29: Sample of AM from site B (fig 3.4 in Renewable UK WPD)

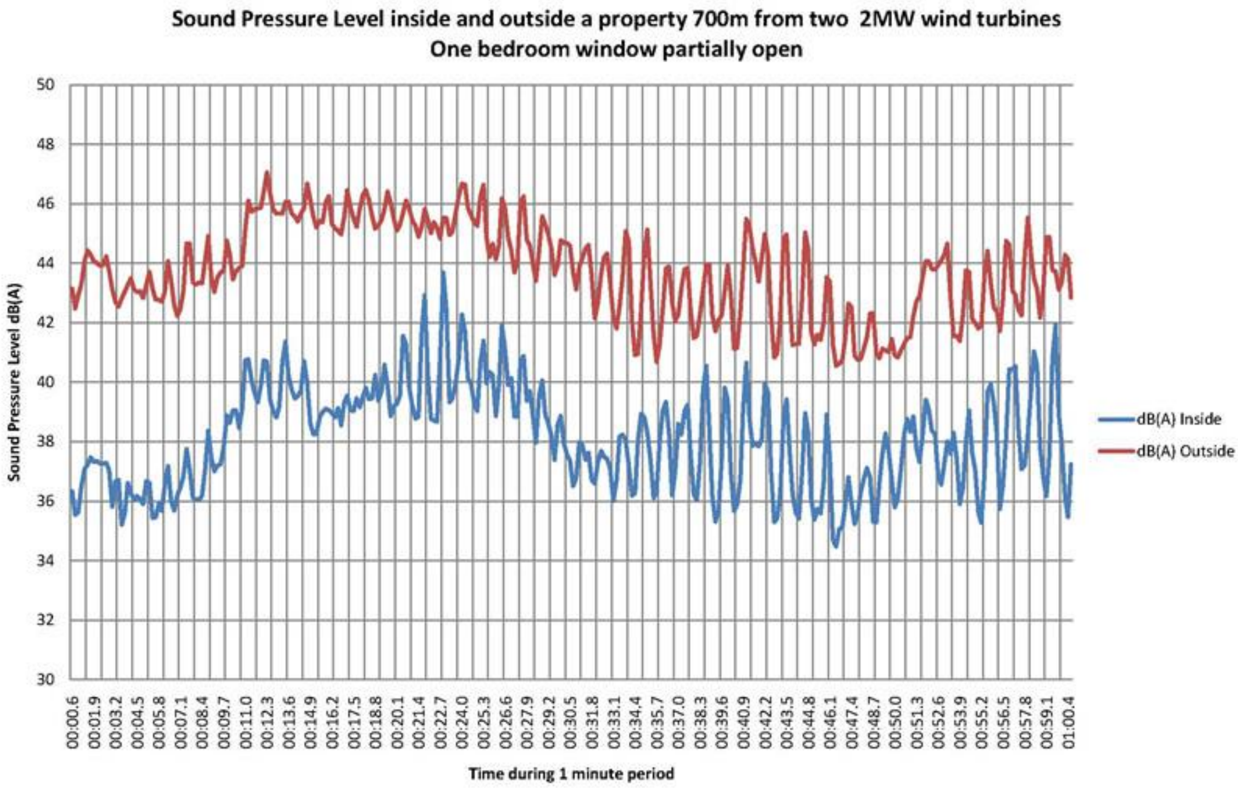


[11] Not identifying AM where there is AM.

7.15 **The Results of an Acoustic Testing Program - Cape Bridgewater Wind Farm. Cooper (2014).** A noise survey was undertaken at dwellings within 650m and 1600m of the Australian Cape Bridgewater Wind Farm as a result of ongoing complaints from residents. The study also looked at low frequency noise. Although AM was clearly identifiable within close proximity of the turbines it is unclear to what extent audible AM was present at the dwellings. The report notes that modulation at blade pass frequency was found at 31.5Hz at residential locations. This is a lower frequency AM than measured in many of the above preceding studies.

7.16 **Amplitude Modulation Case Study at the Leonards Hill Wind Farm, Victoria, Australia. Huson (2014).** Measurements of audible AM and infrasound were made at a dwelling approximately 700m from Leonards Hill Wind Farm. The data presented a number of interesting findings and included identification of AM both internal and external to the dwelling. An example is given below.

Figure 30: AM measured at Leonards Hill Wind Farm internal and external noise measurements



7.17 **Indoor noise survey at Knockglass Farm. Huson (2014).** Noise measurements were made at Knockglass Farm following noise complaints from residents. The source of complaints was suspected to be the Neilston Community Wind Farm in East Renfrewshire. Neilston Community Wind Farm has two 2.3MW turbines approximately 1000m away from Knockglass Farm. Both infrasonic and A weighted sound pressure levels were measured inside the affected property. AM variations of up to 20dB(A) peak to trough were measured and found to correspond to rotor rotation. Infrasound was also measured but found to have an inverse correlation with the A weighted sound levels. An example of the

A weighted and infrasound waveform is given below and following this a short extract of the A weighted noise level.

Figure 31: Infrasound pressure waveform on the upper trace and dB(A) on the lower trace

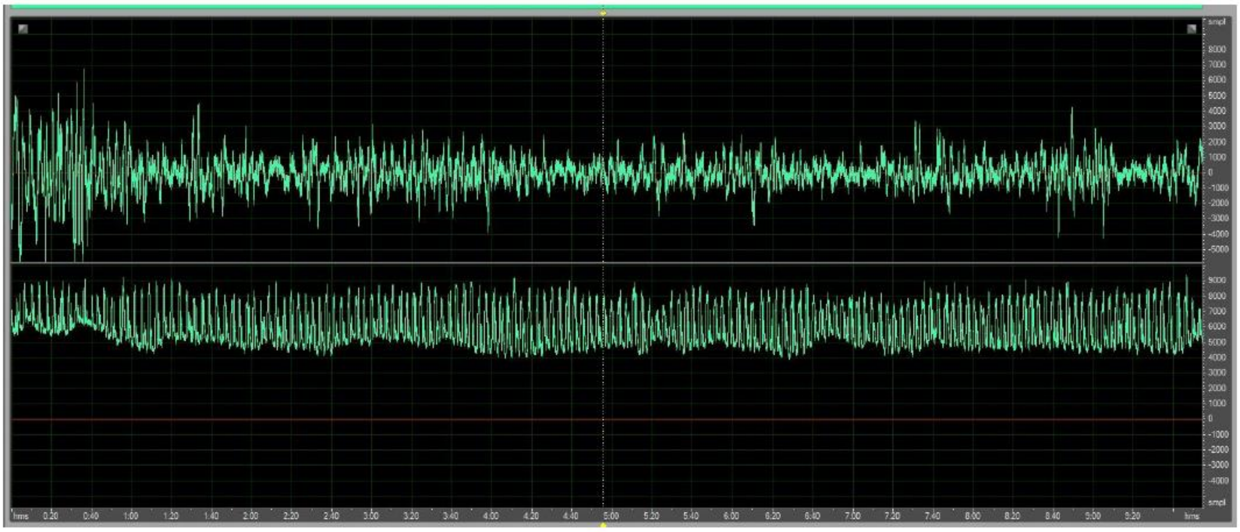
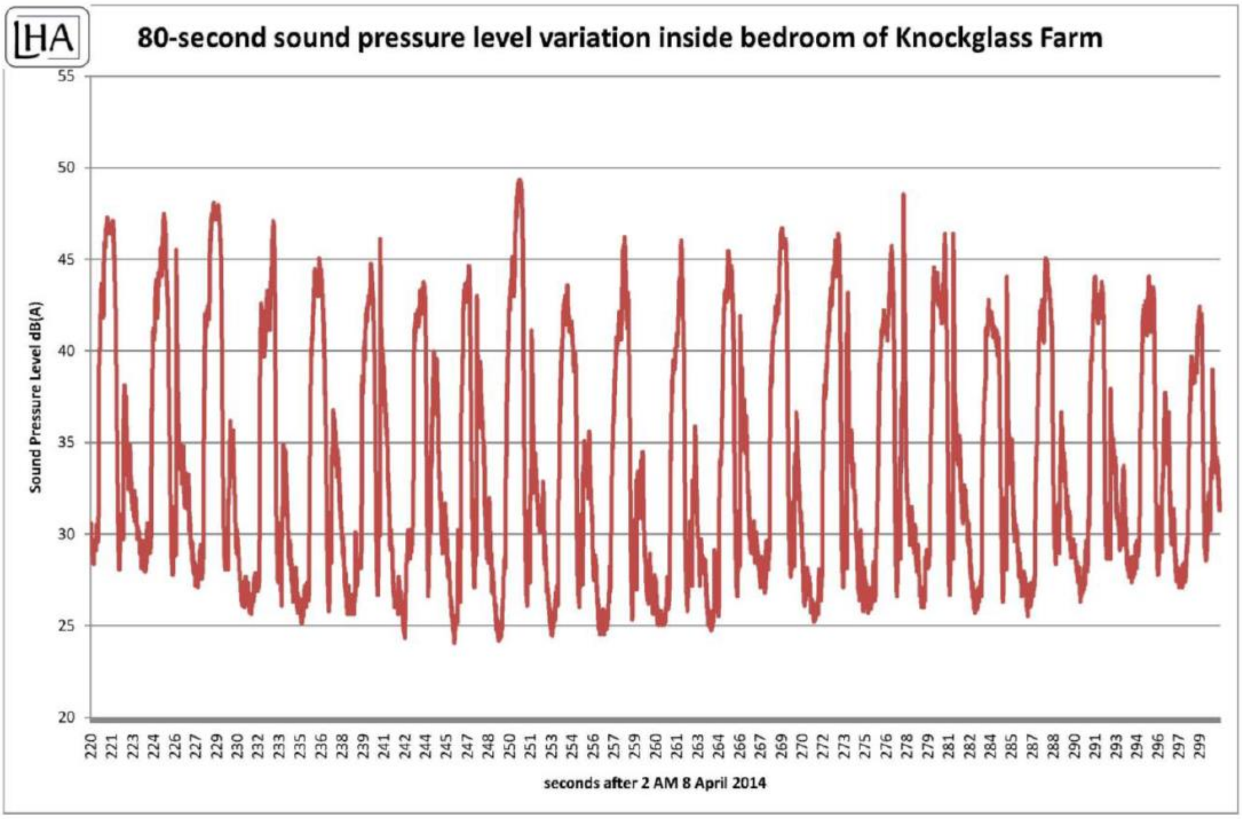


Figure 32: Example of A weighted sound level variation taken from Huson (2014)



7.18 **Cotton Farm Wind Farm, Cambridgeshire (2013 - present) (Site 5 WP5).** In March / April 2013 MAS Environmental started a long term research project in conjunction with residents surrounding the Cotton Farm Wind Farm. A permanent noise monitoring and weather station, funded by the residents, was installed in the village of Graveley Cambs. It is connected to the internet so that all can see the noise generated by the wind farm. The noise meter continuously logs 100ms noise, spectral, and statistical data along with audio and meteorological data. The station is at a residential garden 600m from the wind farm.

7.19 Despite detailed evidence on AM presented at the appeal, the Cotton Farm Wind Farm was approved planning permission without any condition to control for AM. This was based on the recommendations of the applicant's noise consultant that AM was rare and highly unlikely to occur at the site. The evidence now provided by the Cotton Farm Wind Farm monitor completely discredits the expert evidence given on behalf of the applicant.

7.20 The measurements have recorded substantial periods of excess amplitude modulation including many periods of extreme AM. Analysis concentrates on periods where modulation depth is at or exceeding 5dB(A), referred to hereon as '5EAM'.

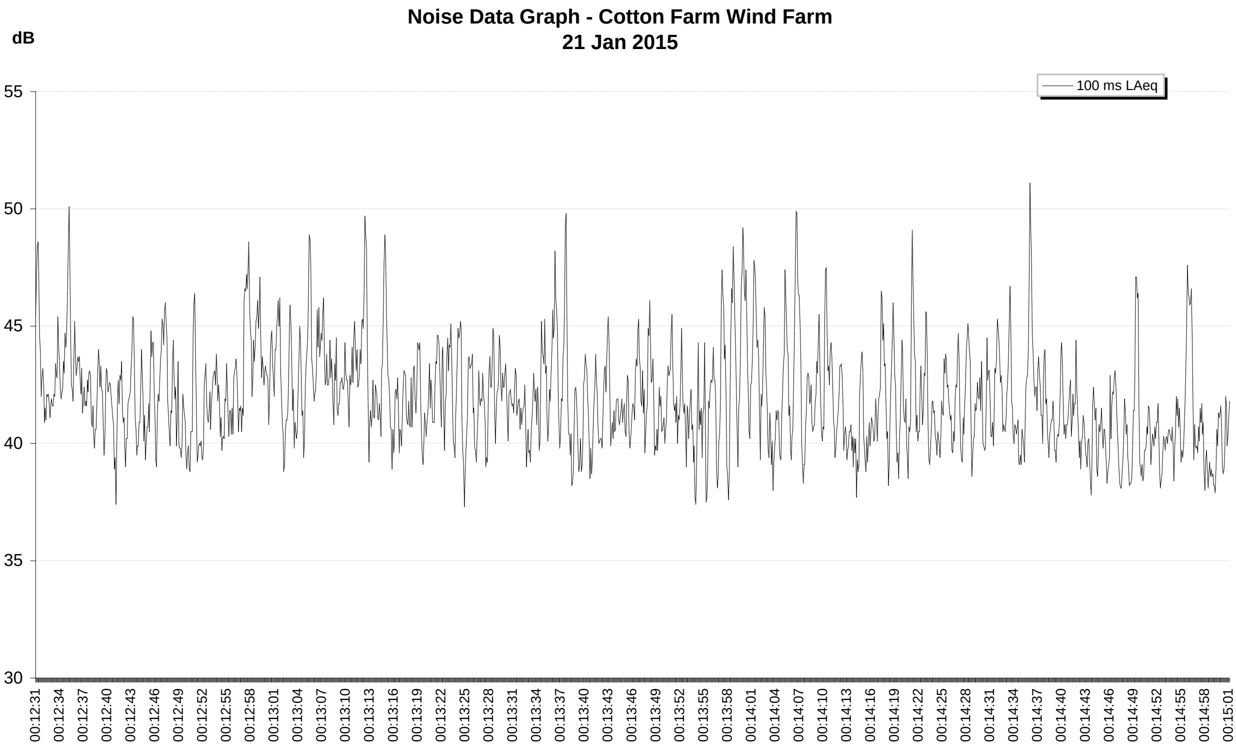
7.21 The data demonstrates the wide range of wind directions and wind speeds at which EAM greater or equal to 5dB(A) (5EAM) arises. It shows:

- → On average over 50% (about 54%) of all the intervals are affected by 5EAM.
- → Over 50% of nights are affected by 5EAM and EAM is extremely common.
- → In the case of December 2013 and January 2014, 82% of days were affected by 5EAM.
- → For certain wind speeds and directions every record included 5EAM i.e. 100%.
- → Modulation depth increases within certain wind directions and wind speeds.
- → EAM is more extreme under certain wind directions and wind shear conditions.
- → Broadly 5EAM of different character can be predicted for different meteorological conditions.
- → 5EAM increases significantly under high wind shear conditions.
- → Upwind 5EAM occurs in certain conditions and can be substantial in both sound energy and peak to trough variation.
- → EAM levels increased to a modulation depth of 13dB(A) at times.
- → The spectral content of the sound changes under different wind directions and meteorological conditions changes, sometimes significantly.
- → The character of the AM for this site is very erratic compared to that found at many sites. This is critical in relation to how the EAM is assessed. The erratic changes increase cognitive appraisal and re-appraisal but lead to reduced penalty levels when the Renewable UK condition metric is applied. [12]

7.22 An example of AM measured at the site is given below. The experience of those affected by the Cotton Farm Wind Farm development is further detailed in WP9.

[12] Renewable UK (2009). Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause and Effect. London: Renewable UK.
See also work undertaken in WP5

Figure 33: AM measured from Cotton Farm Wind Farm



7.23 There are many other reported cases of adverse impact caused by AM. These are summarised elsewhere but no empirical measurements have been made to date.[13] A full table is provided in appendix A and sites include Bicker Fen Wind Farm, Blaen Bowi Wind Farm, Darracott Wind Farm, Alltwalis Wind Farm, Delabole Wind Farm, Paul's Hill Wind Farm, etc.

7.24 Furthermore, there are other studies of wind farm noise and AM that have not been translated in to English. These provide another source of information on AM that has not been presented in this work package. The review of AM evidence is correct up until April 2015 and does not include information published after this date.

[13] See for example work WP3.1 which discusses the extent of noise impact from wind turbine noise following a survey of noise complaints reported to local authorities and WP3.2 which documents health effects, in particular sleep disturbance, linked with wind turbine noise and AM.

8 Conclusion

8.1 There exists an international history of evidence that documents the presence and regular occurrence of AM. Empirical data and subjective reports demonstrate that the manifestation of AM and the presence of AM within wind farm noise is effectively linked to increased annoyance.

8.2 The above review of AM research provides only a summary of documents and measurements from a single UK consultancy and open access papers. Access to papers published in subscription-only journals or to the resources available to larger consultancies can only be expected to increase documented cases of AM and provide further evidence supporting the prevalence of AM.

Appendix A - Wind Farm sites known to have caused complaints, including AM complaints.

Wind Farm	Location	MW per turbine	No. of turbines	Hub Height (m)	Reference
Aggregate Ind Newquay	Cornwall	0.5MW	1	59	Audio examined
Alltwalis	Carmarthenshire	2.3MW	10	65	Statement from complainant - clear case
Askham	Cumbria	660kW	7	40	Salford - clear case added
Site B	Banff and Buchan	ANON			Confirmed AM by resident - anonymous at moment
Bears Down	Cornwall	600kW	16	30	Salford - clear case added, recent complaints from residents
Bicker Fen	Lincolnshire	2MW	13	59	Statement from complainant - clear case
Black Law, Forth	South Lanarkshire	2.3MW	42	82	Reported by others
Blaen Bowi	Carmarthenshire	1.3MW	3	46	Salford - clear case but not added
Carland Cross	Cornwall	400kw	15	30	In ETSU-R-97 and Salford - now repowering and complaints received from residents
Cairnmore	Aberdeenshire	850kW	3	55	Information on complaints is second hand
Causeymire	Highland	2.3MW	21	60	In Salford but not added by Salford
Coal Clough	Lancashire	400kw	24	30	In ETSU-R-97 missed in Salford
Cold Northcott	Cornwall	300kw	22	25	In ETSU-R-97 - in Salford but not added by them
Coldham	Cambridgeshire	1.75MW	8	60	Statements from complainant matches AM
Conisholme	East Midlands	800kW	20	65	Evidence from others
Cregan Gate	Cornwall	50kW	1	25	Complaints from residents
Cotton Farm	East Anglia	2MW	8	80	MAS have measured EAM
Cruach Mhor	Argyll & Bute	850kw	35	45	Salford - but not added
Crystal Rig	Scottish Borders	2.3MW	51 + 9	60 + 80	Evidence from others
Dalswinton	Dumfries	2MW	15	80	Confirmed by the LA and affected resident
Darracott	Devon	850kW	3	50	Complaints by residents of AM clearly is AM
Deeping St Nicholas	Lincolnshire	2MW	8	59	In Salford and added, MAS confirmed
Delabole	Cornwall	2.3MW	4	99 (tip)	Direct complaints and advice of acoustician
Site C / D / E	ANON			64	MAS have measured EAM
Site F	ANON	275kW	1	55	MAS have measured EAM and significant tonality
Forestmoor, Bradworthy	Devon	1MW	3	48	Evidence of others
Four Burrows	Cornwall	300kW	15	30	In Salford - 'another' noise complained of
Fullabrook	Devon	3MW	22	65	Complaints by many residents of AM, post Salford
Gedney Marsh (Red House)	Lincolnshire	2MW	6	59	Indirect evidence

Wind Farm	Location	MW per turbine	No. of turbines	Hub Height (m)	Reference
Glens of Foundland	Aberdeenshire	1.3MW	20	46	In Salford but not added
Glyndebourne	Lewes District	850kW	1	44	Independent source - see also article in Private Eye No.1334
Hadyard Hill	South Ayrshire	2.5MW	52	60-70	In Salford, possible case, but no direct evidence
Hafoty Ucha	Gwynedd	850kW	1	39-44	In Salford, questionable case, but no direct evidence
Harlock Hill	Cumbria	500kW	5	35	In Salford, but no direct evidence
Hazlehead	Yorkshire	2MW	3	60	Indirect complaints from residents - developer undertaking monitoring
High Volts	Hartlepool	2750kW	3	60	Indirect evidence
Hill of Easterton	Aberdeenshire	850kW	3	45	Indirect evidence / information
Kessingland	Suffolk	2.05MW	2	80	Complaints and MAS measured, post Salford
Knabs Ridge	North Yorkshire	2MW	8	58	Complaints and MAS measured - post Salford
Lissett	Yorkshire	2.5MW	12	80	Controls introduced to reduce noise
Llandinam P&L	Wales	0.3MW	103	31	In ETSU-R-97
Llangwryfon	Ceredigion	0.85MW	11	40	Indirect information - complaints from residents
Llyn Alaw	Anglesey	600kW	34	31	In Salford and WAS added
Lowermoor Water Treatment Works	Cornwall	100kW	1	30	Direct complaint from resident
Lynch Knoll	Gloucestershire	500kW	1	42	In Salford but not added
Lynemouth	Northumberland	2MW	13	78	Indirect evidence / information
Mablethorpe	Lincolnshire	600kW	2	65	Indirect evidence
Michelin Tyre Factory	Dundee City	2MW	2	85	In Salford but not added
Moel Maelogen	North Wales	1.3MW	9	50	Indirect information, in Salford but not added
Mynydd Clogau	Powys	850kW	17	34	In Salford, possible case, but no direct evidence
Mynydd Gorddu	Ceredigion	0.5-0.6MW	19	34-35m	Indirect information
Site N	ANON	50kW	1	23.6	MAS have measured EAM and significant tonality
Newstead	Cuminstown	0.8MW	1	49	Multiple sources of evidence from residents
North Pickenham	Norfolk	1.8MW	8	80	MAS measured - residents not complaining officially
North Rhins	Dumfries	2MW	11	60	Indirect information
Parc Cynog	Carmarthenshire	720-850kW	5+6	60	When extended in size
Paul's Hill	Moray	2.3MW	24	60	AM confirmed by independent acoustician
Penrhyddlan & Llidiatywaun	Powys	300kW	103	45	Noise problems noted in ETSU-R-97
Red Tile / Warboys	Cambridgeshire	2MW	12	59	MAS measured and complaints - missed by Salford

Wind Farm	Location	MW per turbine	No. of turbines	Hub Height (m)	Reference
Roscarnick Farm	Cornwall	275kW	1	32	Reported by residents as 'thumpy', turbine off much of the time
Rhyd y Groes	Ceredigion	300kW	24	31	Noise problems noted in ETSU-R-97
Royd Moor	South Yorkshire	500kW	13	35	In Salford but not added, MAS heard
Site P - single turbine	Pembrokeshire	ANON			Confirmed by EHO
Six Penny Wood	East Riding of Yorkshire	2MW	10	80	Confirmed by residents, complaints to LA, compliance measurements
Skelmonae	Ellon, Aberdeenshire	0.8MW	4	64	Controls in place to reduce noise
South Sharpley	County Durham	1.3MW	2	65	Evidence from affected residents
St Breock	Cornwall	450kW	11	35	In Salford but not added
Swaffham	Norfolk	1.8MW	1	67	Complaints and MAS measured, missed by Salford
Swinford	Leicestershire	2MW	11	80	MAS have measured EAM
Taff Ely	South Wales	0.45MW	20	35	Indirect information
Tallentire	Cumbria	2MW	6	80	Direct complaint information
Tir Mostyn & Foel Goch	Denbighshire	850kW	25	49	In Salford but not added
Trysglwyn	Gwynedd	400kW	14	25	In Salford but not added
Wadlow	Cambridgeshire	2MW	13	80	MAS have measured and confirmed with direct observations
Walkway Wind Farm	Sedgefield District	2MW	7	69	Evidence from affected resident clearly identifies AM
Wharrels Hill, Bothel	Cumbria	1.3MW	8	76	Complaints by residents of AM, post Salford
Whittlesey	Cambridgeshire	1.8MW	1	80	Turned off at night
Site X	North East England	ANON	15+	ANON	Direct complaint evidence and measured data
Ysgellog	Anglesey	2.3MW	2	60-70	Correspondence from Council