Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect

Work Package D (WPD) - Measurement and Analysis of New Acoustic Recordings

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Audit Sheet

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EXECUTIVE SUMMARY

In the light of the expected key characteristics of Other AM (OAM) noise, and in particular the notable differences between OAM and Normal AM (NAM), the present project has involved targeted measurements across three separate wind farm sites in order to attempt to measure OAM and to confirm its expected characteristics. The measurements undertaken at the three separate sites adopted a very different approach in order to attempt to extract different information:

- **At Site A** measurements were undertaken at residential dwellings where AM noise issues had been reported by the residents. Noise measurements were undertaken at two dwellings in the absence of any other operational data from the wind farm and the data obtained used to test the AM metric routine developed;
- **At Site B** detailed measurements of noise at multiple locations around the test turbines, meteorological conditions and turbine operational data were undertaken on a wind farm site. The opportunity was provided for the switching on and off of various turbine combinations, but no control was provided for manually varying the operational parameters of the turbines.
- **At Site C** multiple noise measurements were undertaken around a test turbine (located within an operational wind farm) together with turbine operational data. The opportunity was provided to manually control the blade pitch settings of the test turbine away from its optimal design setting such that the effects on noise output of inducing full or partial stall could be established.

When present, the presence of OAM was able to be detected and rated effectively using the techniques developed in other parts of the current project. More general time-averaged metrics based on a 10-minute interval analysis, which are generally used to assess overall levels of wind turbine noise could not effectively discriminate the presence of modulation.

Based on the various measurement results, and particularly those at Site B, it has been concluded that the general characteristics of other OAM noise are consistent with the expected directivity and spectral characteristics of transitory stall noise, thus exhibiting a significantly increased effect in the downwind direction from the wind turbine.

In the far-field, instances of clear OAM were associated with the downwind direction and were reduced in the cross-wind direction. The effects in the near-field were more difficult to discern, although the expected presence of NAM was clearly characterised by higher modulation depths of up to 5 dB in the cross-wind direction.

The instance of OAM levels in the far-field were strongly variable and did not seem to be simply associated with the existence of certain meteorological conditions. In terms of the various hypotheses that have historically been as possible causal mechanisms for other AM, whilst the results could not generally rule out any of these as potential contributory factors, they did confirm the ability of OAM to exist in situations where the factors are known not to contribute. In summary, significant OAM was positively identified under conditions of:

- low wind shear;
- low wind veer;
- uniform turbulence;
- single operational turbines (i.e. no interaction effects);
- on both flat and hilly sites;
- turbines with high tower to rotor diameter ratios.

The only positively identified association between the occurrence of OAM and the operational characteristics of the turbines was that, in the detailed measurements undertaken at site B, OAM only occurred when active power generation was occurring, and it also appeared to be sometimes exacerbated during periods when changes in the estimated relative angle of attack of the blades also occurred.

Other source mechanisms may be at play. It is conceivable that particular blade designs could experience partial blade stall in certain conditions without the influence of non-uniform inflow conditions to trigger it. For example, aero-elasticity effects may vary the blade geometry in such a way that it departs significantly from its design conditions. There is, however, very limited information available to study this in the current state of knowledge.

1 INTRODUCTION AND SCOPE

1.1 Introduction

1.1.1 The work presented in this report is part of project funded by RenewableUK and entitled 'Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect'. The project comprises a total of six separate work packages. The outcome results of each of the work packages have separately resulted in their own dedicated final reports. A seventh work package, WPF, has produced an overarching final report in which the key findings across the separate work packages have been collated and discussed.

1.1.2 This is the final report of Work Package WPD: 'Measurement and analysis of new acoustic recordings'.

1.1.3 Wind turbine aerodynamic noise, by which is meant the noise produced by the rotating wind turbine blades, includes a steady component as well as, in some circumstances, a periodically fluctuating, or amplitude modulated (AM), component. However, AM may take different forms. One form of AM, commonly referred to as 'blade swish', is an inherent feature of the operation of all wind turbines. It can be explained by well understood mechanisms, it being the result of the directivity characteristics of the noise created by the air flowing over a turbine blade as it rotates. Because this type of AM is an inherent feature of the operation of wind turbines, whose origin can be explained and modelled, the present project adopts as its definition the term 'normal amplitude modulation' (NAM). The key driver for the project, however, is the recognition that some AM exhibits characteristics that fall outside those expected of NAM. Such characteristics include a greater depth of modulation, different directivity patterns or a changed noise character. For this reason the present project adopts as its definition the term 'other amplitude modulation', or 'OAM', for all observations of AM that lie outside that expected of NAM.

1.1.4 In recent years public concern has grown about the potential annoyance from wind turbine OAM noise. This concern has resulted in an increased interest to establish how AM, and in particular OAM, occurs, how it can be better defined and measured, and how it is generally perceived and responded to. It is the answers to these questions that the present project seeks to address.

1.2 Scope

1.2.1 Based largely on the outcome of other Work Packages, a programme of measurements was derived in order to collect supplementary acoustic and audio data. The aim of this data was to supplement the data already available from the database developed under Work Package C, as well as to provide detailed supporting information of the type that has been observed as often being lacking from the previously available data obtained from other sources. It was the conclusion of the research group that a more extensive measurement survey and a detailed (but indirect) study of on-blade generation mechanisms was necessary to reach firmer conclusions.

1.2.2 The scope and methodology of this part of the project evolved significantly with time. It was initially conceived, at the project outset, that additional measurements would be undertaken as part of Work Package D at up to seven separate sites, the original aim being to collect additional recordings to those of work package C, but using an essentially similar approach. However, as the project progressed, it was determined that, rather than simply acquire more examples of AM audio recordings in the far-field, more detailed supporting information, such as better defined meteorological information and turbine operational information was crucial to obtaining an improved understanding of the subject. This was because recordings acquired to date were not sufficient to prove or disprove the different mechanisms identified.

1.2.3 It has also been the experience of the project team that, even at those wind farm sites where AM has been reported or identified to be an issue, its occurrence may be relatively infrequent (see WPC). Thus, the capture of time periods when subjectively significant AM occurs may involve elapsed periods of several weeks or even months.

1.2.4 The approach adopted was therefore to focus on a more limited number of sites but to undertake more extensive and detailed measurements than originally envisaged at each of these sites, using a variety of strategies and taking into account the findings of other work packages.

1.2.5 One of the benefits of the originally envisaged approach to the measurements to be undertaken under work package D was that recordings could be taken at any accessible location without necessarily the need for approval from any involved parties. However, the downside to this approach was quickly recognised to be the subsequent inability to access relevant supporting information. The revised approach required the direct involvement of wind farm operators if the necessary supporting information was to be made available. The benefits of the revised approach were determined to far outweigh any drawbacks, although it had to be accepted that one of the drawbacks was the significantly extended time required to arrange site access and to adequately address confidentiality considerations. Also, many logistical and technical challenges were associated with the more detailed and innovative nature of some of the measurements proposed, some of which required working in close collaboration with wind turbine manufacturers in addition to the wind farm operators. This led to some delay to the overall project programme but, as previously stated, the value of the additional measurements which were undertaken were deemed to more than outweigh any adverse timing issues.

1.2.6 It was also therefore not expected that the measurements undertaken as part of this work package would offer more evidence into the frequency of occurrence across the country of the phenomenon, but it was considered preferable to focus on acquiring further insight on the characteristics of 'other AM' and its potential causes.

1.2.7 A staged approach was taken in which different approaches were employed at different sites in order to achieve separate aims, as summarised below.

1.2.8 **Site A** involved measurements that were most similar to wind turbine noise immission (far-field) measurements, as generally undertaken following the guidance of ETSU-R-97. However, in accordance with the expected requirements for the measurement of any modulation, high-resolution data including audio recordings were also collected as part of these works. Recordings were made at two residential properties neighbouring a wind farm site for which residents at the measured properties had been complaining about the noise from the wind farm, with investigations currently underway (by others) to assess the complaints further. Access was granted to the two properties which enabled detailed measurements to be made at suitable external locations over a period of several weeks.

1.2.9 **Site B** comprised a location where the existence of OAM had been positively identified. Efforts were therefore focused on undertaking a detailed series of measurements, allowing a study of conditions in which varying levels of AM were experienced and at different locations relative to the turbines. This also involved capturing detailed anemometry measurements and turbine operational data at a high resolution. The schedule and requirements of the measurement campaign were based on the theoretical considerations and requirements outlined in the WPA2 report, in as much as practical and budgetary conditions reasonably allowed. These measurements were significantly more detailed than those generally undertaken for immission measurements of wind turbine noise but were nevertheless still limited to some degree through practical constraints.

1.2.10 **Site C** involved targeted measurements on an operational wind farm site using novel techniques to investigate the influence of turbine operational parameters on the character of the AM noise produced, as informed by the results of the other work packages in this project. In particular, the hypothesis raised in WPA1 and WPA2 that partial blade stall may lead to increased levels of modulation at large distance downwind warranted particular investigation. Considering this, the influence of a turbine's pitch regulation system was considered a crucial element to be tested. Designing a measurement campaign capable of addressing the foregoing issues required detailed cooperation with turbine manufacturers, especially as a detailed knowledge of the blade geometry and control system operation of commercial wind turbines is generally not freely available due to confidentiality considerations. It was agreed with the turbine manufacturer to undertake tests in which the pitch of the turbine was controlled directly in order to attempt to trigger detached (stalled) flow on the blade, and to assess the relative impact on far-field noise, and in particular the potential for varying pitch angles to induce or control amplitude modulation. The project team is not aware of such investigations having been undertaken previously.

1.2.11 Each of the measurements surveys undertaken and associated results will then be described in turn.

2 SITE A – MEASUREMENT AT RESIDENTIAL LOCATIONS

2.1 Introduction

2.1.1 This phase of the measurement was most similar to wind turbine noise immission (far-field) measurements generally undertaken in current practice, following in particular the guidance of ETSU-R-97. However, in accordance with the expected requirements for the measurement of any modulation, high-resolution data including frequency and audio data were collected as part of these works.

2.1.2 These recordings were made at two residential properties neighbouring a wind farm site: referred to herein as locations 1 and 2. We understand that residents at these properties had been complaining about the noise from the wind farm and that investigations are currently underway to assess this further. Access was granted to the two properties for measurements to be made at suitable external locations over a period of several weeks.

2.1.3 The aim was to collect additional audio recordings of AM if at all possible. The limitations of such an exercise were recognised amongst the project team, particularly in terms of the potential for detailed investigations of the causal mechanisms of AM. It was nonetheless thought useful on balance to attempt to collect additional recordings, even in the absence of detailed supporting operational and meteorological data, as this would add to the current database of work package C and provide further data, this time from a wind farm with an alleged noise issue, on which to implement some of the techniques discussed in other parts of the project.

2.1.4 Recordings were made at an external location within the curtilage of each residential properties. No detailed turbine operational or meteorological data was available, but reference was made to observations made by residents, as well as the broad meteorological conditions available for the area from public sources.

2.1.5 The surveyed properties were situated less than 1km from the nearest turbines of a relatively large wind farm site. This site comprises more than 10 turbines which have a rotor diameter in excess of 80m. The turbines are located on a plateau, amongst a generally hilly terrain, with the surveyed residential properties located in a valley situated lower down. Due to the hilly nature of the area it was thought unlikely that the level of atmospheric wind shear would be high, although the terrain itself will provide a level of shelter from the wind. The area was rural and fairly isolated with low levels of traffic noise or other ambient sources. Each location experienced varying amounts of shelter from the wind, with location 1 situated further down the valley than location 2, the latter of which was more elevated by approximately 40m relative to the former and therefore tended to experience stronger winds.

2.2 Survey set up and description

2.2.1 Measurements were undertaken for slightly less than 3 weeks at free-field locations chosen, in consultation with the residents, to minimise the impact of reflections from building surfaces as well as noise from water-courses located in the area which would tend to mask the noise from the turbines.

2.2.2 At each of the survey locations, the noise measurements system used were capable of monitoring overall noise levels and could also provide periodic audio recordings. The chosen noise measurement system was one based around a 01dB Blue Solo sound level meter used in conjunction with a low power embedded computer running the 01dB “dBTrig” measurement software. This sound level meter system accords with the requirements of a Type 1 sound level meter. The sound level meter and computer were housed in an environmental enclosure and included a battery back-up power supply with a low voltage charge fed from the mains electricity supply.

2.2.3 The measurements system recorded data correctly during the entire survey period, except for the second system which stopped recording audio samples for a period of 4 days partly through the survey, due to a software fault. The microphone system was mounted on a pole attached to the side of the environmental enclosure with an installed microphone height of 1.2 m. A two layer windshield system was used to reduce wind induced noise on the microphone. The system comprised a 01dB BAP21S outdoor microphone protection system which incorporates rain protection and a small diameter foam wind screen. The secondary windshield (the second layer of the two layer arrangement) was custom made from open cell foam approximately 25 mm thickness formed as a domed cylinder 170 mm diameter and 300 mm high. A lower disc of 40 mm thick open cell foam formed total enclosure of the primary windshield. The outer windshield was designed following the guidance given in the report Noise Measurements in Windy Conditions [1] which indicates that the insertion loss of this type of windshield assembly is likely to be less than ±1 dB between 50 Hz and 5 kHz and so not a significant factor on the measured results.

2.2.4 The measurement system was set to log continuous and contiguous periods of both L_{Aeq} and L_{AF}, the 'A' weighted, 'Fast' time weighted sound pressure level, as well as filtered 1/3 octave band levels between 20 and 20kHz, every tenth of a second. From these logged values, longer term indices values may be calculated by a post-processing procedure in the 01dB dBTrait software. In addition the system was configured to provide regular audio recordings of two minutes duration with each recording start spaced at intervals of ten minutes and with an audio sampling rate of 25.6 kHz (10 kHz audio bandwidth). The clock on the computer was set to disable 'daylight saving' and synchronised with Greenwich Mean Time (GMT) using a global positioning system receiver.

2.3 Measurement analysis – introduction

2.3.1 In a preliminary phase, the review of notes provided by the resident at location 1 focused the analysis on some periods in which 'other AM' may have been experienced. Some of the likely relevant descriptions included "(loud) whooping", "(deep) thumping", "beating". Indications were that these periods often seemed to correspond to situations when the location was downwind of the wind farm. At other times descriptions included "rumble" or "roaring" which seemed less relevant to the analysis of AM and may represent more general wind turbine noise.

2.3.2 Figure 2.1 below shows a graph of the variation of the measured short-term $L_{Aeq,100ms}$ levels for a sample day-time period of less than 2 minutes in which the influence of noise from the turbines, including AM, was identified. Some short periodic patterns of relatively regular modulation of noise at a rate of slightly less than 1 Hz are visible in the trace of A-weighted levels as a function of time. One such AM period is highlighted in red, with a period with reduced modulation marked in blue, and a period of likely reduced wind turbine noise marked in green (denoted "background", although a residual influence of the wind farm could not be excluded). These descriptions were reinforced by a subjective review of the audio sample recorded for this period.

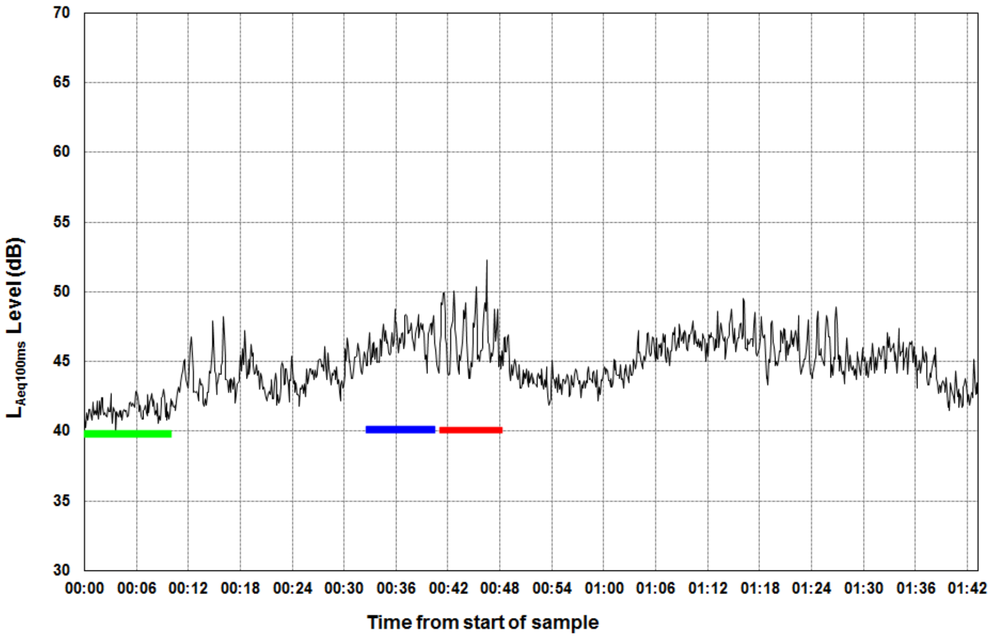

Figure 2.1– Sample AM period identified at location 1 as part of a preliminary analysis: evolution of $L_{Aeq,100ms}$ (dB) with time (min:sec) – colour bars highlight the periods analysed in Figure 2.2

2.3.3 The corresponding average spectra are then shown in Figure 2.2 using the same colour reference for the periods highlighted, along with instantaneous spectra corresponding to a clear peak and trough of the modulation. It can be seen that the modulation itself is dominated by the region between 300 Hz and 1 KHz. The slight “dip” observed in this region at 500Hz could be caused by interference due to ground reflection and/or propagation effects (see WPA2) which would therefore be location-specific. A similar but stronger dip is observed around 200 Hz, with some modulation energy between 80 and 160Hz: these frequencies would be characteristic of the presence of stall according to WPA1 [2]. The 1/3 octave band frequencies dominating the A-weighted modulation spectrum were at 315, 400 and 630Hz.

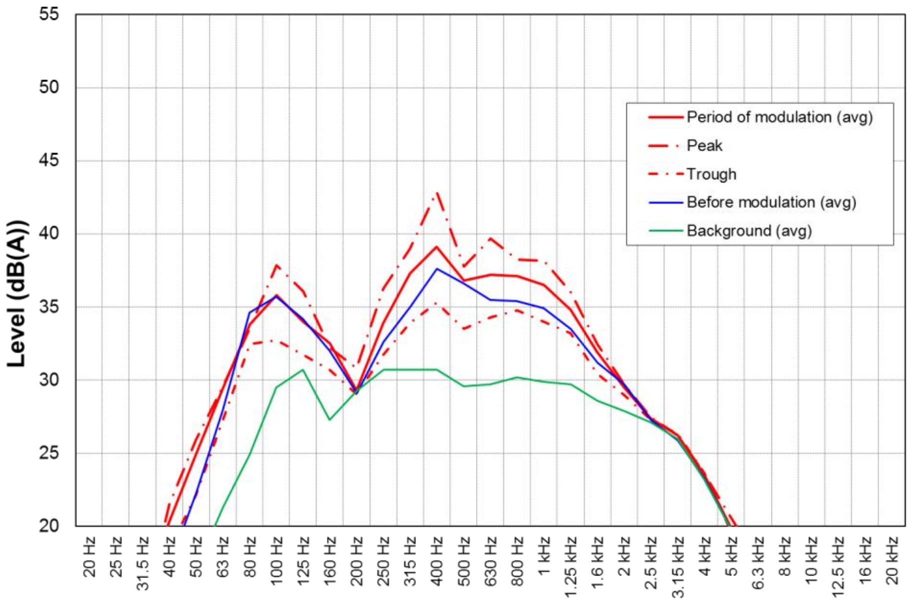

Figure 2.2– A-weighted average spectra corresponding to the periods highlighted in Figure 2.1, as well as the spectra of the modulation peaks and trough (average of several instances).

2.4 Towards a systematic analysis

2.4.1 Whilst, for some periods such as the one shown in the above Figure 2.1, the evolution of the short-term A-weighed levels exhibit a clear pattern during periods of audible modulation, this is not always the case. WPF discusses further the difficulties associated with the subjective interpretation of such short-term variations in levels. Even such a “visual” identification of periods of modulation was not possible without ambiguities or risk of subjective interpretations. The systematic review of the time-history of levels, in no more than 5 or 10 minute periods at a time, would not really be feasible in practice, particularly when considering the often sporadic and intermittent character of the AM, as well as the strong dependence on weather conditions and the potential influence of extraneous noise at typical noise sensitive receiver distances.

2.4.2 The variability of the short-term levels and modulation levels, for other periods, is illustrated by the following figure showing the evolution of 100ms L_{Aeq} levels. Even during periods in which audible modulation tended to be noted, periods of clearer modulations often lasted for periods of typically only a few (5 to 10) seconds. Any subjective review of $L_{Aeq,100ms}$ or similar may therefore miss such short modulation periods. A systematic analysis using the Fourier analysis techniques such as those described in WPB1 and WPF, which automatically and more objectively identify modulation at the expected modulation frequency, therefore seems to offer a preferred approach.

2.4.3 Furthermore, the modulation may not be so clearly apparent from the A-weighted levels because of noise from other sources either masking the variations on A-weighted or creating complex patterns in which regular variations at blade passing frequency may not be evident (see below). As discussed in WPB1, filtering the input signal into more restricted range in which the wind turbine modulation is considered likely to dominate will assist in the analysis. The WPB1 report explains that the analysis in a restricted frequency band means the assumption of uniform “white” noise, on which the Fourier analysis is based, is then more representative. A potential practical downside to this approach, however, is that it requires more detailed information to be captured and analysed: this is considered in the next section.

2.5 Practical considerations

2.5.1 In a “best-practice” wind farm acoustic immission measurement set-up, 2 minutes of audio recording would often be made every 10 minutes, as this allows a tonal analysis to be made in accordance with ETSU-R-97. This sampling period will often not match a particular period of interest. See for example Figure 2.3, in which only the first 2 minutes had a corresponding audio recording, and which experiences varying levels of modulation. The difference between the $L_{Aeq,10min}$ and the $L_{A90,10min}$ for this period was 1.8dB(A), which is considered typical for wind turbine noise [3].

2.5.2 Even limiting the effective audio recording rate to 20% in this way: using a 25.6kHz audio sampling rate for a single channel represents about 1.7Gb of audio data per day of recording. Full audio recording would represent more than 8 Gb of data per day. This amount of data recording also increases the risk of hardware/software failure of the equipment. Even if the audio sampling rate is reduced significantly, this still represents significant technological and practical constraints.

2.5.3 Therefore a systematic analysis based on 1/3 octave band data appears more practical. Recording 1/3 octave band data at a 10Hz sampling rate should represent significantly less data requirements (less than 50Mb per day). This represents a practical way of implementing the techniques described in WPB1 and WPF.

2.5.4 Any audio recordings, if present, would then provide a useful way of subjectively evaluating the nature of particular events which are visible from the audio trace as part of verification procedures.

2.5.5 As a minimum, data with a sufficiently short time resolution (i.e. significantly less than the expected blade passing period of typically 1 Hz, thus indicating a data capture resolution of 8 times a second or more) should be recorded. This will not be the case for many standard integrating sound level meters which only record average and statistical indices over longer periods, but it was done for the present survey.

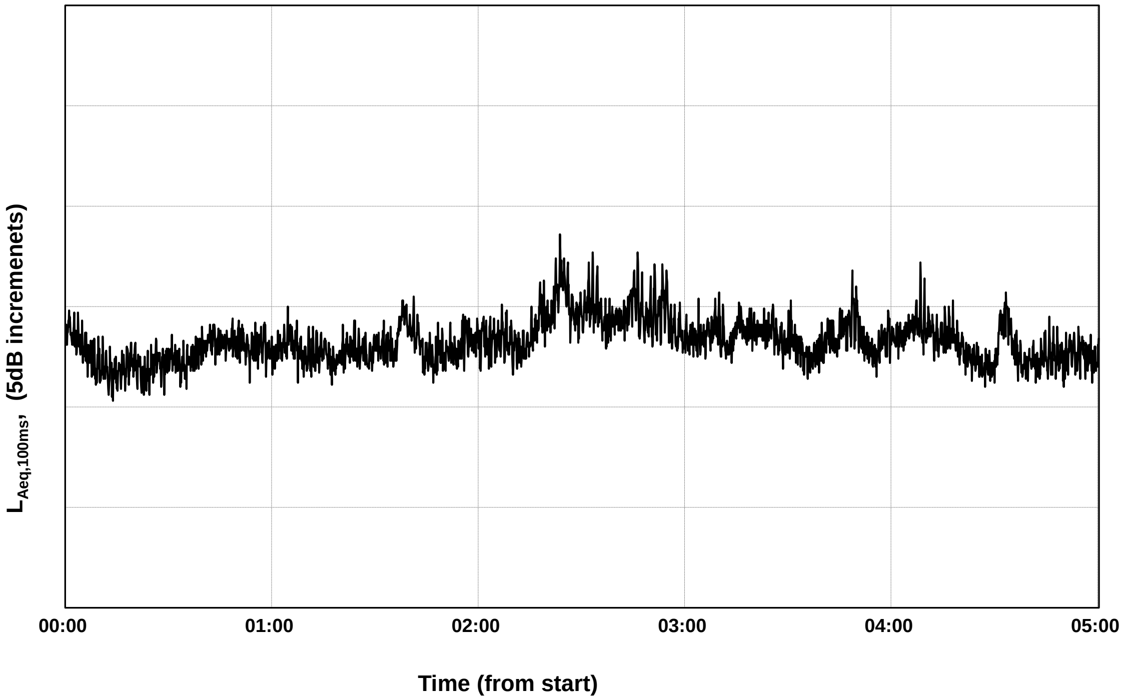

Figure 2.3 – sample time history (min:sec) of variation in short-term $L_{Aeq100ms}$ levels for a 5min measurement period

2.6 Automated AM analysis

2.6.1 An entire period of more than 24 hours measured at location 1 was systematically analysed, as descriptions by the resident seemed to suggest the presence of clear AM. This was made between 21:00 one evening to 24:00 the next day (27 hours in total).

2.6.2 This measured data was analysed using the main AM metric routine described in Work Package F (WPF), which is based on objective analysis techniques described in WPB1. The routine is based on a Fourier analysis of the noise signal envelope, either for the A-weighted signal or for a specific 1/3 octave band, implemented in the MATLAB software. WPF Annex C shows that using this implementation, the value of the peak in the modulation spectrum at the modulation frequency (in this case, the blade passing frequency of the turbine or BPF) results in a representative measure of the modulation magnitude. The normalisation used means that values are comparable to the typical peak-to-trough variation in short-term A-weighted levels (typically 1 dB lower, unless the analysis is restricted to a specific representative 1/3 octave band).

2.6.3 The MATLAB implementation of the main AM metric routine described in WPF was first applied to short-term A-weighted levels: the full set of recorded $L_{Aeq100ms}$ levels was separated into contiguous blocks of 10s of data which were then analysed. The modulation spectra obtained do exhibit evidence of modulation which is likely to be associated with the operation of the turbines, particularly during the quieter evening and night periods. During day-time periods, despite the relatively rural and isolated nature of the area, some spurious sources of noise appeared to affect the analysis.

2.6.4 For example, the evolution of the modulation spectrum with time between 09:00am to 12:00am is shown in Figure 2.4. A spectral peak at a fundamental modulation frequency close to 0.8 Hz is apparent as expected, but at times modulated signals at lower frequencies appear on the graph, but these are unlikely to be related to the operation of the turbines. The worst-case peak appears for block 622 (10:43:30), and a review of the measurements at this time show this is caused by a short squeal/whistle noise (around 3kHz).

2.6.5 In cases such as these, spurious signals influence the spectrum of a large range of "modulation" frequencies, and so even if only the spectral peaks close to the expected modulation frequency (in this case 0.8Hz) are retained, the values may not always be representative of actual wind turbine modulation except in quieter conditions. Nevertheless, the potential for false negatives remains relatively low compared to methods involving a visual inspection of $L_{Aeq100ms}$ levels.

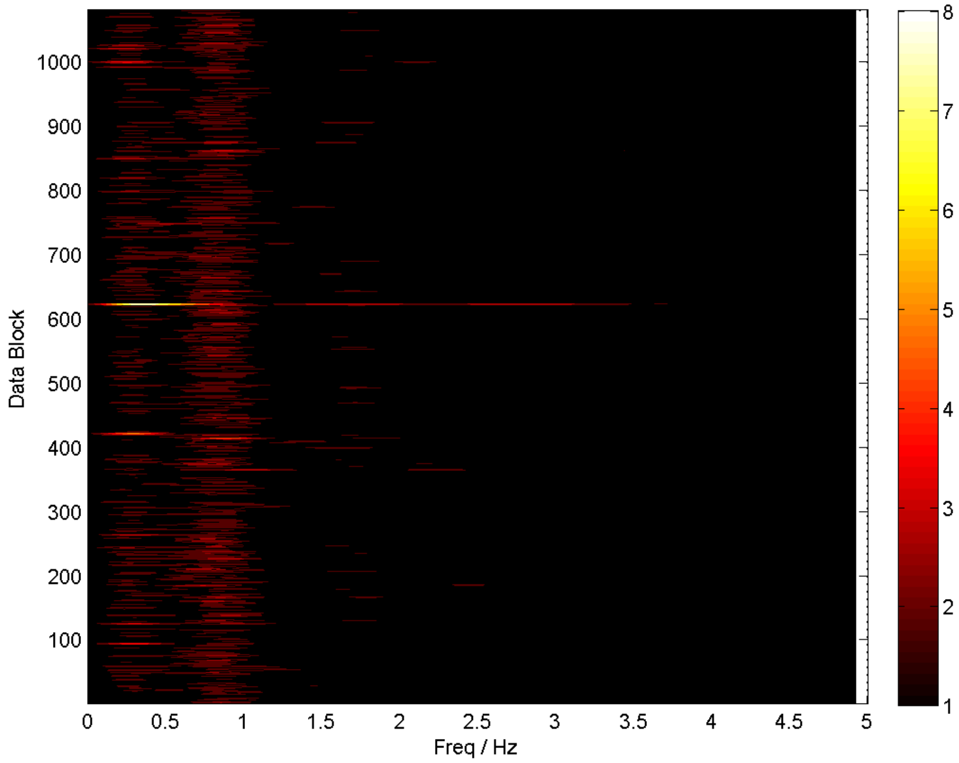

Figure 2.4 – Evolution over a period of 3 hours (09:00 to 12:00) of the calculated modulation spectrum based on the $L_{Aeq100ms}$ levels (for contiguous 10s data blocks) at location 1

2.6.6 The same analysis was therefore applied to the measured time history of the 315Hz 1/3 octave band (with a 100ms resolution). The analysis of each block of 3 hours of data for this single 1/3 octave band took less than 5 minutes using a PC with a 64-bits 2.7GHz processor with the MATLAB software, and this could probably be optimised further. This therefore represents a feasible analysis method even for large sets of data, particularly as reports from residents and analysis of any available complaint diaries can often assist further in refining the analysis period, in line with the approach described in ETSU-R-97.

2.6.7 The evolution with time of the modulation spectrum derived from the 315Hz data, for the first three hours (21:00 to 00:00), is shown in Figure 2.5. A clear peak at a fundamental modulation frequency close to 0.8 Hz is apparent, as well as (more faintly) the first harmonic at 1.6 Hz at times. Sometimes faint peaks at lower or higher modulation frequencies are apparent, but these spurious peaks are relatively less prominent than for the A-weighted data.

2.6.8 The consistent presence of such a peak in the spectrum, over long-term periods, is characteristic of wind turbine noise as:

- the modulation frequency is consistent with the expected rotational speed of turbines, in particular those of three-bladed machines of the size present at site A;
- this type of noise is relatively constant in time, over periods of minutes or hours in response to general wind conditions, as opposed to short-term spurious sources which might influence the spectrum for only brief periods or at specific times of the day.

2.6.9 On this basis, the analysis procedure determines the amplitude of peaks in the modulation spectrum at frequencies close to the assumed typical blade passing frequency (BPF) of 0.8Hz: the time evolution of this metric for the full analysis period is shown in Figure 2.6.

2.6.10 The resulting statistics of the prevalence of occurrence of periods of relatively high modulation is stated in Table 2.1, for the entire 27 hour period.

	Location 1
>3dB	6%
>4dB	1%
>5dB	0.3%

Table 2.1– proportion of 10s analysis period, over the entire 27h period of Figure 2.6, for which the calculated AM rating at BPF exceeded set values (315Hz 1/3 octave band)

2.6.11 A sample check of some of the relatively high values identified from this systematic analysis confirmed that they corresponded to periods of clear modulation likely to be associated with the wind farm: see for example Figure 2.7, which corresponded to the period (23:02) associated with the highest value determined over the entire period shown in Figure 2.6. The difference between the $L_{Aeq,10min}$ and the $L_{A90,10min}$ for this period was 3dB, but it can be seen from Figure 2.7 that the L_{Aeq} is influenced by spurious sources such as gusts of wind. For the period of highest modulation (23:01 to 23:02), which appears dominated by wind turbine noise, the difference between $L_{Aeq,1min}$ and the $L_{A90,1min}$ was 2.3 dB, which is typical of general wind turbine noise [3].

2.6.12 The values of AM rating obtained for the 315Hz 1/3 octave band were generally higher than for the A-weighted analysis only, by about 1 to 1.5dB, which is comparable to the analysis shown in WPF for a series of artificial stimuli. This analysis showed that, for the representative AM stimuli used in WPB2, the dB values obtained from the main AM metric routine were comparable to those determined from the variations in short-term L_{Aeq} (and labelled “MD” in WPB2): approximately 1dB lower when using the A-weighted signal envelope, and similar values when considering the dominant 1/3 octave band (315Hz).

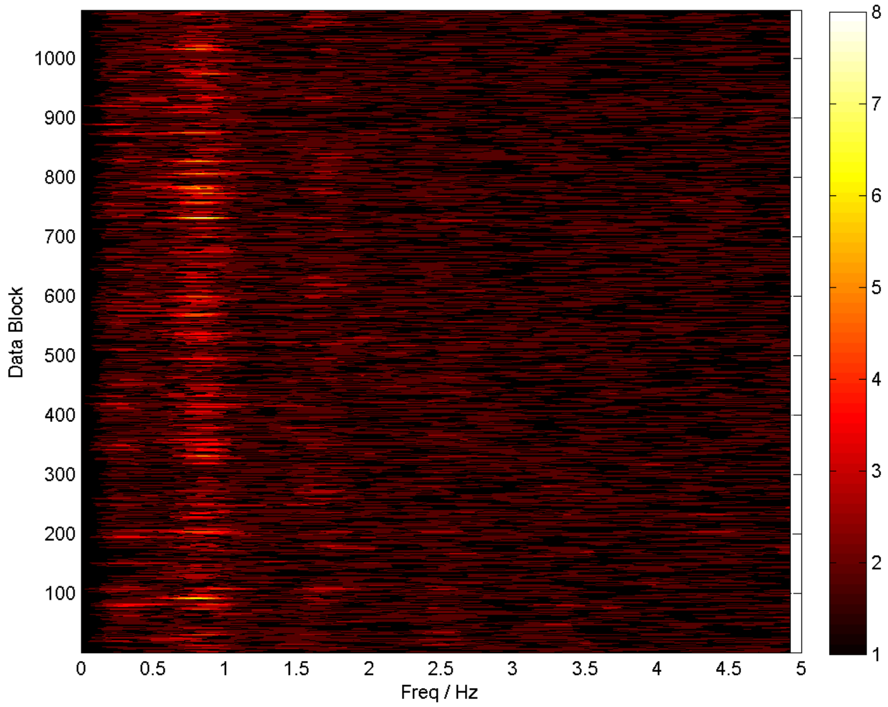

Figure 2.5 – Evolution over a period of 3 hours of the calculated modulation spectrum based on the 315Hz 1/3 octave band (for contiguous 10s data blocks) at location 1

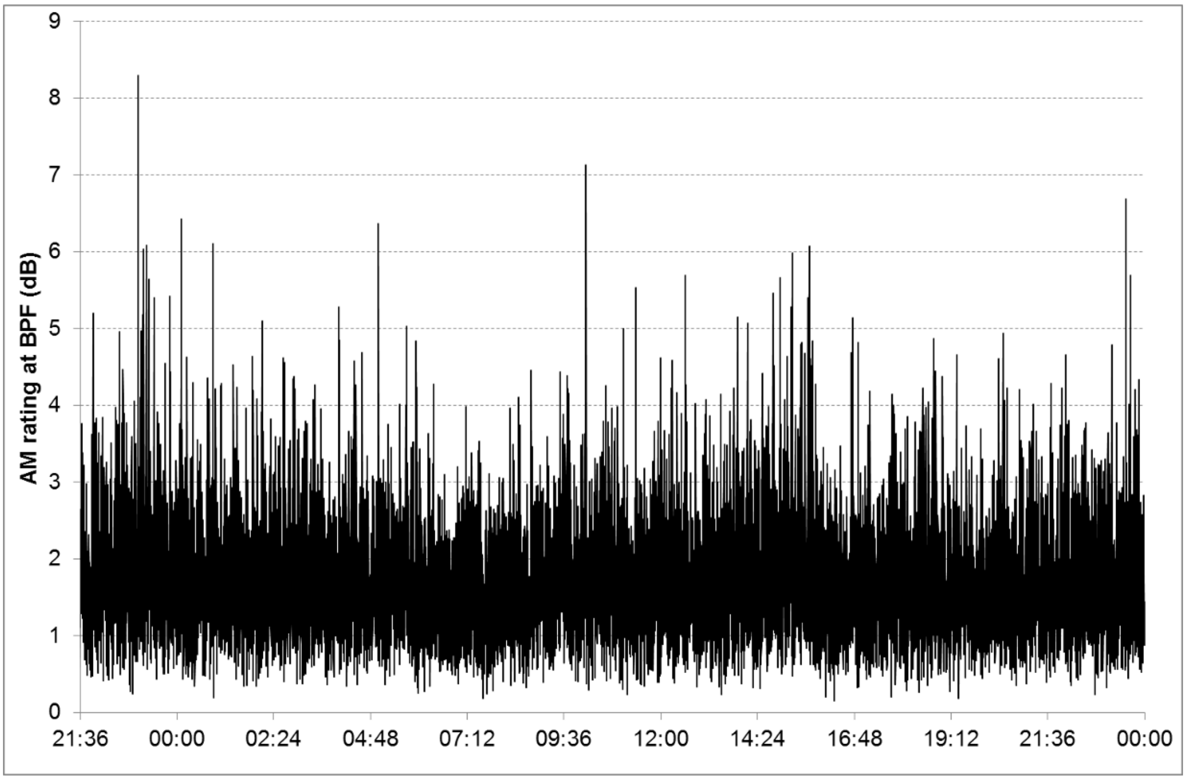

Figure 2.6– Evolution over a period of more than 24h of the calculated AM peak close to BPF based on the 315Hz 1/3 octave band at location 1.

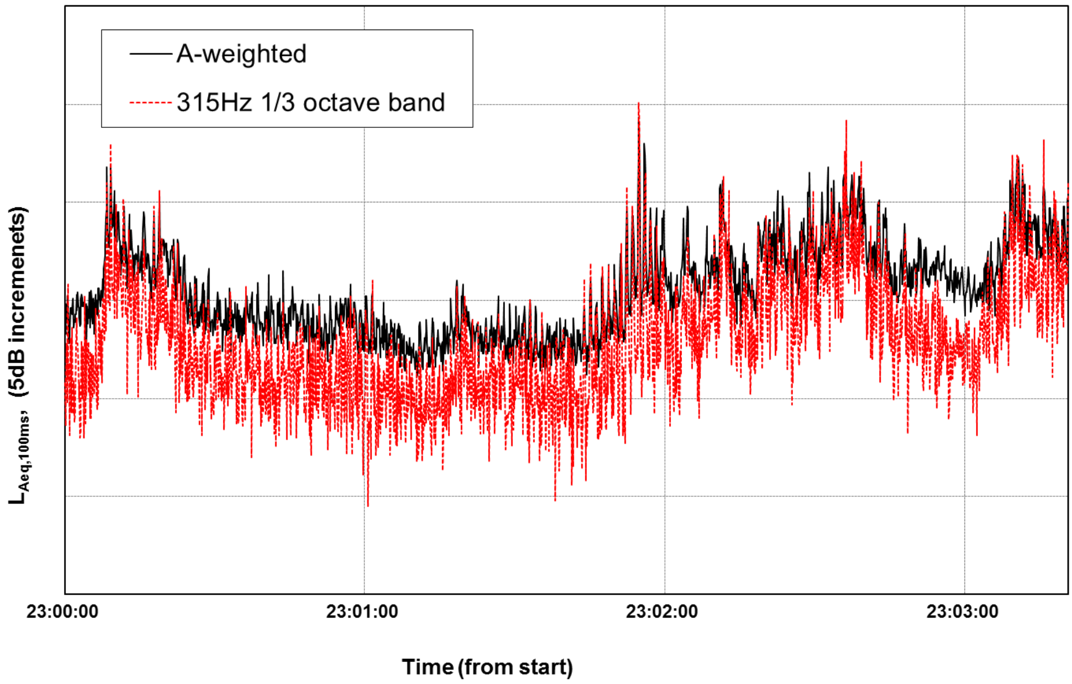

Figure 2.7–time history of variation in short-term $L_{Aeq100ms}$ and 315Hz 1/3 octave-band levels at location 1 for a period identified from the worst-case peak shown in Figure 2.6.

2.7 Comparative analysis

2.7.1 The analysis was also conducted for another octave band for comparison purposes: this was done for 630Hz following the analysis presented in Figure 2.2. As illustrated in Figure 2.8, comparable or lower values of modulation were obtained for this frequency band, and the analysis made for 315Hz is therefore considered to be more representative.

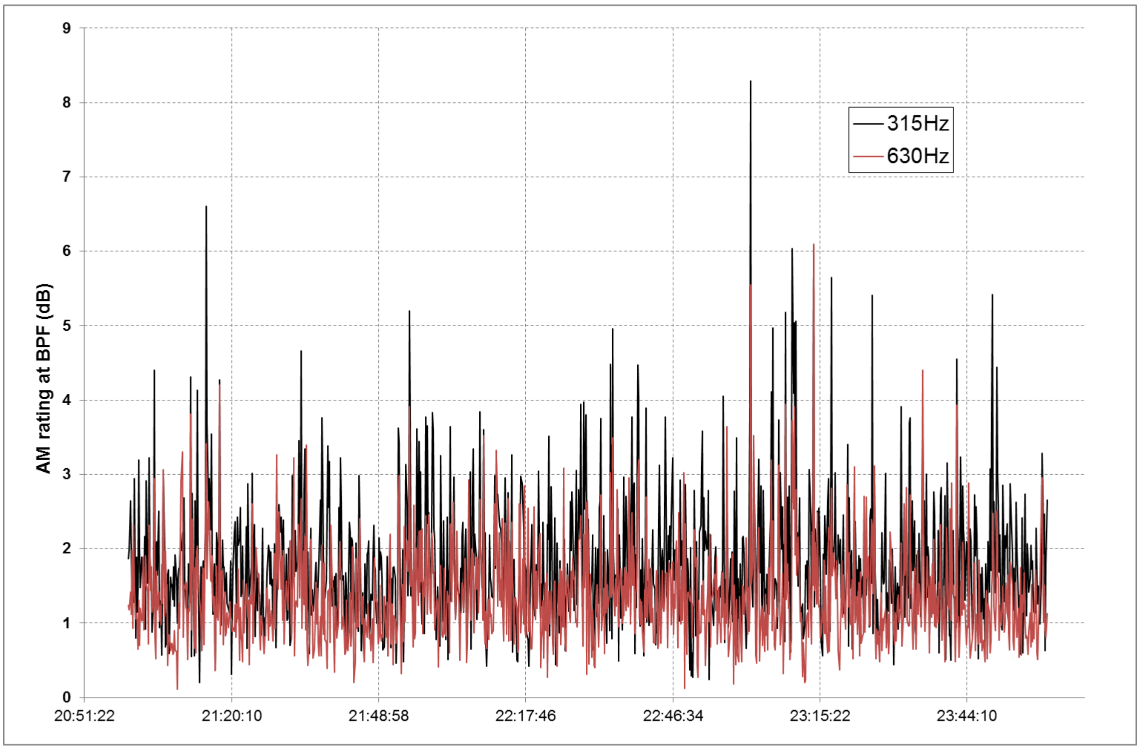

Figure 2.8 –Evolution over a period of 3 hours of the calculated AM peak close to BPF based on the 315Hz and 640Hz octave band at location 1.

2.7.2 As suggested in WPB1, this type of Fourier analysis could usefully be conducted over a wider range of 1/3 octave bands in parallel, such as in the work of Vos [4], or for narrow-bands as in WPB1 or the work of Lee *et al.* [5]. It may then be desirable to combine the individual results using a weighting function (such as A-weighting). This will naturally tend to reinforce modulation occurring at similar frequencies over a range of frequency bands. This was not implemented in this work due to timescale constraints, but the analysis above shows that implementation on a well-chosen octave band is representative and minimises the influence of background sources.

2.7.3 Finally, we can compare the analysis for the first three-hour period made at location 1 to the period measured simultaneously at location 2: see Figure 2.9. Table 2.2 shows the associated relative proportion of the 10s samples analysed for which the calculated modulation rating exceeded set values. Both illustrate that the effective modulation was reduced at location 2, which is consistent with its more exposed character as the increased masking from the wind will tend to mask the wind turbine noise and periods of AM, as was observed on site.

2.7.4 It can also be seen from Figure 2.9 that some periods of clear modulation were experienced at location 2 and not location 1, and this was verified by the review of such periods: see Figure 2.10 below, which highlights short periods of modulation which correspond to isolated peaks of Figure 2.9. This suggests the potential influence of propagation effects, as both locations are more than 400 m apart.

	Location1	Location2
>3dB	9%	5%
>4dB	2%	1%
>5dB	1%	0%

Table 2.2 – proportion of 10s analysis period, over the three-hour period of Figure 2.9 (21:00 to 00:00), for which the AM rating at BPF exceeded set values (315Hz 1/3 octave band)

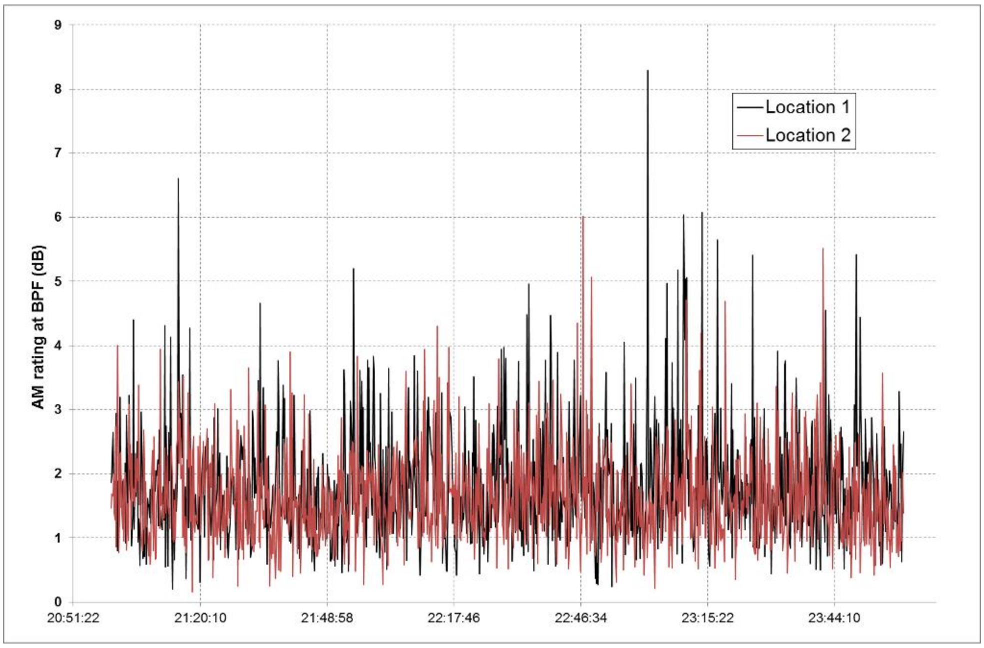

Figure 2.9 – Evolution over a period of 3h (21:00 to 00:00) of the calculated AM peak close to BPF based on the 315Hz 1/3 octave band, for locations 1 and 2.

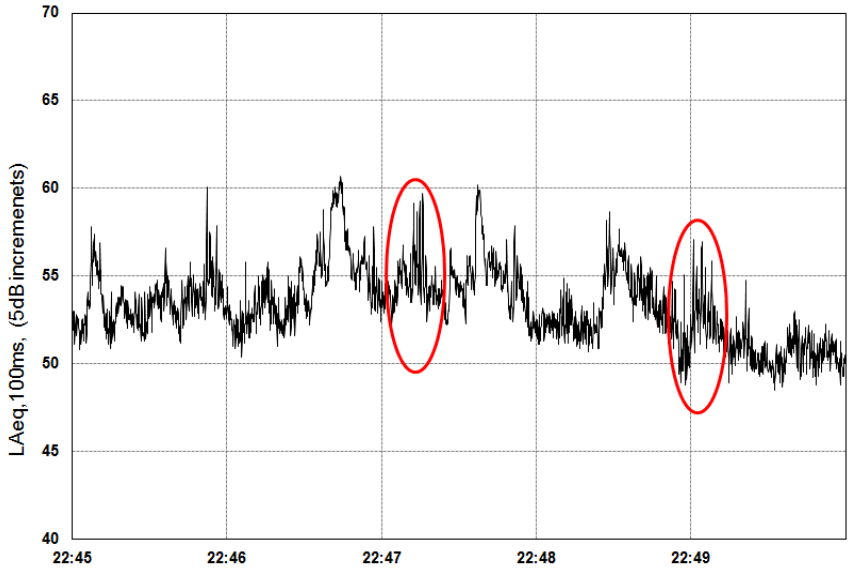

Figure 2.10- time history of variation in short-term $L_{Aeq100ms}$ levels at location 2 for two periods identified from peaks near 22:46 in the graph of Figure 2.9.

2.8 Analysis in reported "quieter" conditions

2.8.1 The next period analysed was for a day which was described as "quiet", in which the locations were thought to be upwind of the turbines, but conditions were not completely calm. A similar analysis of the 315Hz 1/3 octave band data was undertaken for a period of 9 hours (between 03:00 and 09:00). The full history of the value of modulation peaks close to 0.8Hz is shown in Figure 2.11.

2.8.2 The "modulation" values are generally very low, and the isolated "peaks" visible on the graph can be associated with spurious sources, most likely due to short term events from, for example, machinery or vehicle noise. This is most clearly visible if the full modulation spectra are considered: see for example Figure 2.12. This can be confirmed through the available audio records. There is no clear, consistent modulation trend here in the data (in comparison with Figure 2.5 for example) and periods of elevated levels are isolated and not consistent with the expected pattern from the wind turbines. This analysis is therefore consistent with the subjective reports from the residents.

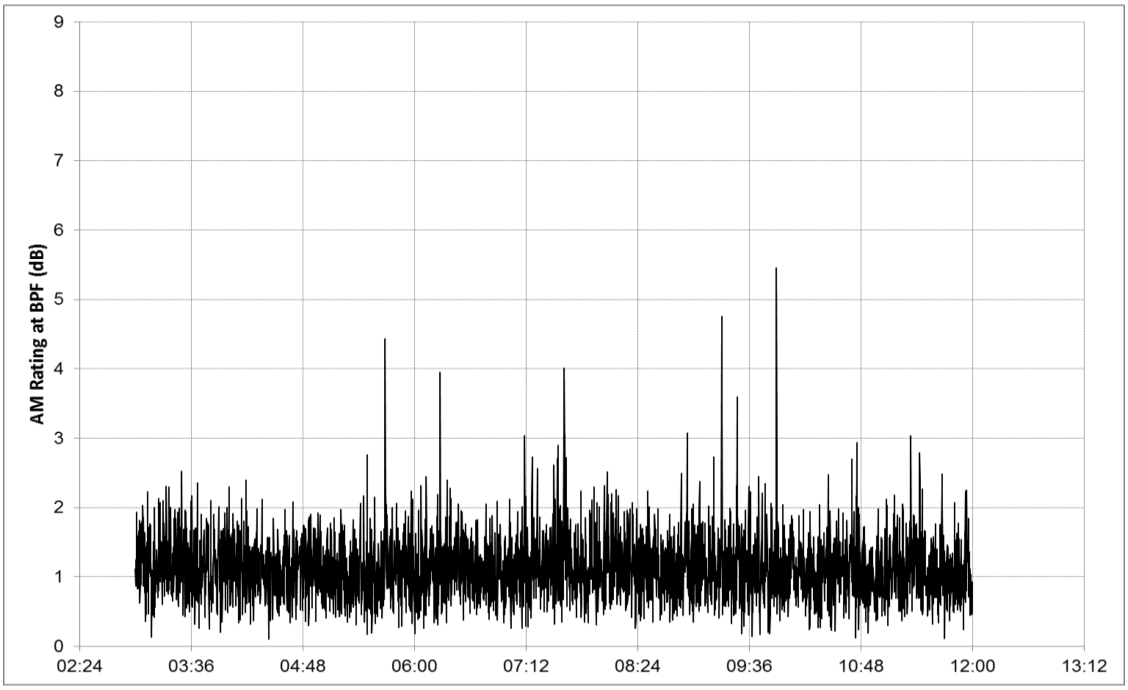

Figure 2.11 – Evolution over a period of 9h on a "quiet" day of the calculated AM peak close to BPF based on the 315Hz 1/3 octave band at location 1.

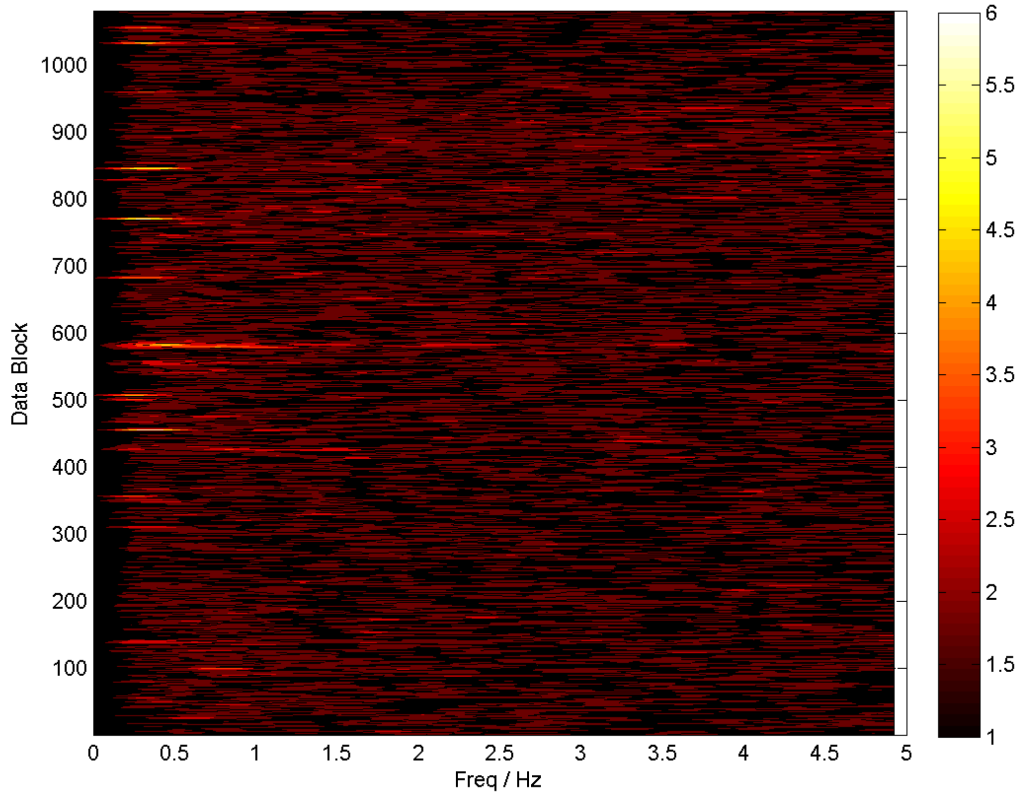

Figure 2.12– Evolution of the calculated modulation spectrum over a period of 3 hours (06:00 to 09:00) for the period shown in Figure 2.11

2.9 Site A - Conclusions

2.9.1 Although not exhaustive, the analysis undertaken suggests that varying levels of ‘other AM’ can be experienced at the locations surveyed when situated broadly downwind of some of the nearest turbines.

2.9.2 The analysis has shown that AM analysis techniques such as those described in WPB1 and WPF can be meaningfully applied to large datasets and can detect and characterise the measured AM even in complex rural environments in which wind turbine noise can often be difficult to detect (let alone characterise in detail). The use of measured data in specific 1/3 octave band characteristic of the modulation allows most spurious sources to be efficiently excluded from the analysis, without the excessive practical difficulties involved with continuous audio recordings.

2.9.3 These techniques have been shown to identify clear levels of AM through the consistent presence of a characteristic peak in the modulation spectrum corresponding to the blade passing frequency. The evolution of the amplitude of the peak in the spectrum has been shown to be representative of the depth of the modulation over the analysis period (10s intervals). This metric is also consistent with subjective response as assessed in WPB2. As shown in WPF Annex C, for simple signals the levels obtained with a dominant 1/3 octave band are similar to measures of peak-to-trough levels determined from short-term L_{Aeq} levels.

2.9.4 This then allowed a statistical analysis of the variability of AM at different times, which was done for some example representative periods of more than 24 hours. The analysis undertaken at the second location identified that the AM was less significant because of the location’s more exposed character, this being consistent with subjective impressions gained by the project team whilst on site. In “quieter”, upwind conditions, the characteristic peak in the spectrum was not present with the rated peak AM levels consistently lying below 2 or 3 dB.

3 SITE B – DETAILED IMMISSION AND PROPAGATION MEASUREMENTS

3.1 Introduction

3.1.1 Measurements were made at a site were 'Other AM' was experienced. Efforts were therefore focused on undertaking a detailed series of measurements, allowing a study of conditions in which varying levels of AM were experienced in different conditions and at different distances from the turbines. This also involved capturing detailed anemometry measurements and turbine operational data at a high resolution.

3.1.2 The schedule and requirements of the measurement campaign were based on the theoretical considerations and requirements outlined in the WPA2 report, in as much as practical and budgetary conditions reasonably allowed.

3.1.3 These measurements were significantly more detailed than those generally undertaken for immission measurements of wind turbine noise, both in current practice and in the literature, but were nevertheless still limited to some degree through practical constraints.

3.2 Survey set up and description

3.2.1 The wind farm site comprised more than 5 turbines, which are pitch-regulated, variable speed machines located in a relatively flat landscape. Due to the flat nature of the area, this site was known to experience elevated (although not atypical) levels of wind shear during evening and night-time periods due to atmospheric stability levels. Despite its rural nature, the area nonetheless experienced higher levels of background noise sources than site A, such as distant traffic noise and occasional agricultural activity, particularly during day-time periods.

3.2.2 The testing procedure focused on a group of three turbines (labelled T1 to T3), as represented on Figure 3.1. Other turbines were located at increasing distance from the instruments and did not generally appear to have a significant influence on the measurements. There was limited amount of vegetation surrounding the measurement locations, which were mostly located on bare agricultural land: therefore the impact of this type of wind-induced noise was limited.

3.2.3 The survey was conducted over a period of more than 6 weeks. It first comprised three free-standing sound level meters placed at different distances from the turbines: these were labelled P1 to P3 and are indicated on Figure 3.1. Part way through the survey, P3 was moved to a new location at an increased distance from the turbines (from location P3a to P3b on Figure 1). This move was possible following the relaxation of associated constraints on the measurement site. The layout was chosen to determine the propagation and directivity of the AM in different wind conditions, allowing for practical considerations. Two key wind directions are identified (Figure 3.1):

- In Wind Direction 1 (WD1), P1 and P2 are downwind of T1, and P3a/b is crosswind
- In Wind Direction 2 (WD2), P1 and P2 are crosswind, and P3a/b is downwind of T2/3

3.2.4 The measurement system used for locations P1 to P3 was one based around a Rion NL 52 sound level meter. This sound level meter system accords with the requirements of a Type 1 sound level meter and was housed in an environmental enclosure and included a battery power supply capable of running the system for at least two weeks. They included WS15 windshield systems which were designed to offer significant reduction of wind-induced noise. Each system was capable of logging overall noise levels, including in short time intervals of 100ms, over a period of many weeks. Periodic audio recordings were made, although this was limited to the space on the 32 GB memory card housed in the meter. The systems were configured to provide regular audio recordings of one minute duration, with each recording start spaced at intervals of ten minutes and with an audio sampling rate of 12 kHz (6 kHz audio bandwidth).

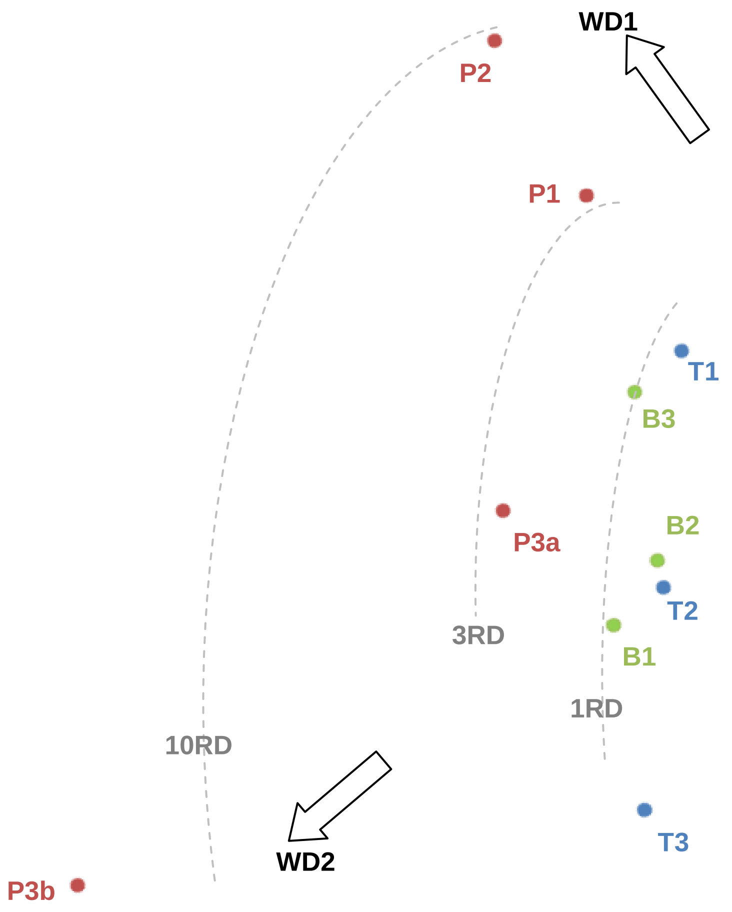

Figure 3.1– Diagram representing the layout of the measurements at site B (turbines in blue, sound level meters in red and ground-board systems in green)

	T1	T2	T3
P1	**302**	**613**	916
P2	**601**	**903**	1199
P3a	**299**	302	539
P3b		874	**845**
B1		82	
B2		44	
B3	77		

Table 3.1 – Distances (in meters) between the different turbines and sound level meters

3.2.5 In addition to these systems, additional sound level meters were placed in closer proximity of the turbines: labelled B1 to B3 on Figure 3.1. These comprised systems similar to those used for the measurements of site A but which were connected to ground-board mounted microphone and primary/secondary windshields. This was based on the advice of the IEC 61400-11:2003 standard [6] although the measurements were not strictly compliant with standard requirements: the aim was to identify relative source levels and character rather than undertake a formal sound power test. These systems included a mains-powered PC connected to a 01dB Blue Solo sound level meter, with large hard drive capacity. L_{Aeq} as well as filtered 1/3 octave band levels between 20 and 20kHz, were recorded every tenth of a second. In addition the system was configured to provide regular audio recordings of two minutes duration with each recording start spaced at intervals of two and a half minutes, with an audio sampling rate of 25.6 kHz (10 kHz audio bandwidth).

3.2.6 The measurements systems installed therefore covered three regions, which can be broadly characterised by comparing the distance with the turbine's Rotor Diameter (RD) as in WPA1:

- the near-field at ~1RD: locations B1 to B3
- the mid-field at ~3RD: locations P1/P3a
- the far-field at ~10RD: locations P2/P3b

3.2.7 A LIDAR (Light Detection And Ranging) remote sensing device was installed at a location which was approximately 100 m upwind of the turbines considered during all of the analysis periods, and was therefore thought to provide a reasonable representation of turbine inflow conditions. This remote sensing system measured wind speeds and directions at different heights representative of those covered by the turbine rotor, with a resolution of approximately 3s. This data could then be reduced in statistics for periods of 10 minutes as standard. Figure 3.2 illustrates the heights measured which were representative of those covered by the rotor (and above). This provided a significantly increased spatial resolution than that provided by the meteorological mast installed on the site which measured wind speed and direction at two heights only (hub and bottom).

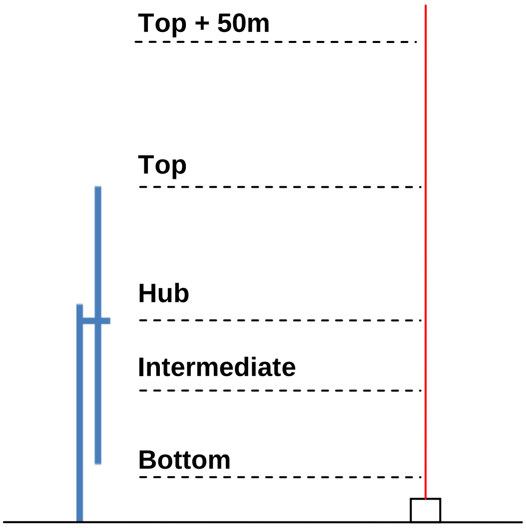

Figure 3.2 – Diagram illustrating the heights measured by the LIDAR scanning system (red line) in relation to the turbines

3.2.8 In addition, dedicated data loggers were prepared by HLA in order to capture turbine operational data with a resolution of 1 second. This is in comparison to the 10 minute resolution data otherwise generally available as standard from the turbines' Supervisory Control And Data Acquisition (SCADA) system. It was therefore possible for these three turbines to obtain data on their respective power generation, rotor/generator rotational speed, yaw (turbine orientation) and wind speeds (measured at hub height) with a 1s resolution. These were directly derived from the control system of turbines T1 and T2 using information supplied by the turbine manufacturer.

3.2.9 All HLA noise and turbine measurements systems were set to the same time reference by their synchronisation with Greenwich Mean Time (GMT). This was achieved through the use of a global positioning system (GPS) receiver. The synchronisation times were regularly verified during the site visits for data downloads and equipment calibrations as obtaining excellent time synchronisation was considered key to the measurements required in this instance.

3.3 Analysis approach

3.3.1 A preliminary analysis determined that some periods of other AM were experienced in conditions which were effectively downwind from the turbines studied. In lower winds, the turbines were operating very little or not at all, and in the windier periods the influence of wind noise represented a complicating factor despite taking reasonable precautions to minimise it. These considerations therefore restricted the analysis to medium wind speeds and certain key wind directions.

3.3.2 The analysis also focused on evening and night-time periods, where recordings were least likely to experience corruption from ambient sources of noise other than the wind farm, such as distant traffic or other human-related activities.

3.3.3 The chosen approach was to undertake a detailed analysis of five key periods, for which specific wind directions were experienced (typically within 15 to 20 degrees):

- **Wind direction WD1** (3 periods)
- **Wind direction WD2** (2 periods), for the latter part of the survey when the third sound level meter was moved from P3a to P3b.

3.3.4 For the latter case, this allowed a comparable analysis between the far-field locations P2 (crosswind) and P3b (downwind), as they were located at a similar distance from the turbines. Considering different wind directions also meant that the near-field locations B1-B3 experienced a range of different relative orientations of the wind turbine.

3.4 Metric analysis

3.4.1 As for site A above, a systematic analysis was undertaken using the AM analysis routine described, based on the measured $L_{Aeq,100ms}$ levels measured at locations 1 to 3, in blocks of 10 seconds. The technique used is the same as above and described in section 2.6. Analysis of filtered 1/3 octave band data was not possible because of equipment limitations, but as the analysis was restricted to quieter evening and night-time periods, the data contamination by spurious sources was limited, and a review of the calculated modulation spectra did allow the exclusion of short periods clearly affected by other sources.

3.4.2 Furthermore, it was possible to undertake a precise discrimination of the data through verification of the expected modulation frequency. The rotational speed of the turbine was measured in 1s resolution using a dedicated acquisition system, and therefore the expected modulation rate (at Blade Passing Frequency (BPF)) could be deduced from the turbine RPM by BPF = RPM x 3/60.

3.4.3 For each of the analysed 10 s periods, a local peak in the modulation spectrum was sought in the region 0.4 Hz to 1.2 Hz (based on the expected typical rotational rate for the turbine at site B). The corresponding frequency of this peak was then checked against the calculated BPF for the corresponding period as supplied by the logger on the nearest turbine, and rejected if more than 0.05 Hz apart. This tended to exclude periods of spurious low modulation, as for periods of high modulation the correct modulation rate was correctly identified. The modulation amplitude rating is then shown only for the points retained.

3.5 Wind direction 1 (WD1) – period 1 (evening)

3.5.1 An example of a period of relatively high modulation experienced at the two downwind locations (P1 and P2) is shown in Figure 3.4. The levels measured in the near-field on a ground-board at location B3, which was downwind of the turbine in this case, are also shown. A spectrogram analysis of the frequency content of the audio sample corresponding to this period is shown in Figure 3.5 to Figure 3.6. It should be remembered when comparing the various traces included on Figure 3.4 that the timescales are absolute and no compensation has been made for propagation delays between the various measurement locations.

3.5.2 It can be seen that a large variability in the modulation is experienced, even within the period above which representative of a typical worst-case in terms of modulation. The modulation at the far-field location (P2) was of increased depth compared to both the mid-field and near-field locations. The near-field modulation appears relatively constant in comparison to that measured at further distance from the turbine which varies significantly.

3.5.3 Although the general reduction in average levels between locations P1 and P2 was consistent with the increased distance from the turbines, the modulation peaks did not seem to have decreased in the same way. From the spectrograms below it appears that:

- the modulation in A-weighted levels at locations P1 and P2 was generally dominated by frequencies between 200 and 600 Hz;
- the modulation peaks do attenuate in the same way as troughs between 300 m (approximately 3RD) and 600 m (approx. 10RD).

3.5.4 This could be due to a number of effects, or combination of effects, including the relative attenuation of these frequencies in the mid-field, the variable influence of source directivity with distance, or propagation effects. For instance, one possible explanation could be due to the so-called ground effect. The actual frequency of the ground effect dip, and its associated bandwidth and depth, will in practice depend on the actual ground conditions, and in particular the flow resistivity of the ground surface layer. However, based on a simple hard ground model, the path length difference between the direct and ground reflected propagation paths in this instance equates to a calculated ground effect dip at 300 Hz for the measurement at 300 m distance (P1): see Figure 3.3. In contrast, for the measurement at 600 m distance (P2), the ground effect dip is calculated to be approximately twice this frequency. Therefore, if the dominant modulation is occurring around 300 Hz, this could well explain the reduced modulation depth seen at 300 m when compared to that seen at 600 m, as the modulation peaks may then be attenuated.

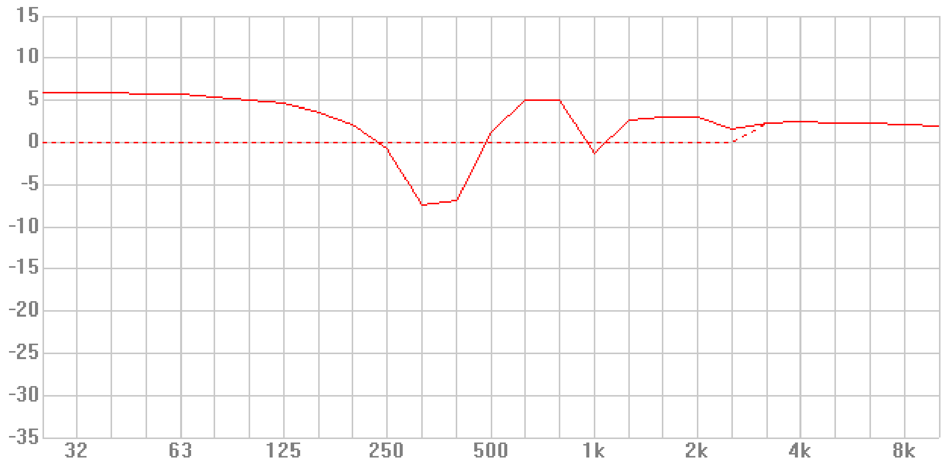

Figure 3.3 – Calculated typical propagation attenuation function, as a function of frequency based on a 1.2m receiver 300 m away from an elevated source, illustrating a “dip” in the 300 Hz region

3.5.5 Another interesting feature of the results shown in Figure 3.4 is the appearance of closely spaced ‘double peaks’ being quite evident in the 300 m and 600 m distance traces. It can be seen that, in some instances, these double peaks appear to drift apart with time and then drift back together to form a single peak. The presumption here is that these double peaks represent the amplitude modulated noise from two separate turbines, each having a slightly different rotational rate. In order to check this presumption, it is useful here to focus of the final 10 seconds of Figure 3.4 and on the measurement location P1. This data shows one of the double peaks being higher than the other. It is the higher peak that becomes increasingly delayed when compared with the occurrence of the lower peak. A check on the measured rotational rate of turbines T1 and T2 over this period reveals that it is T2 (i.e. the turbine more distant from the measurement location) that was rotating at the slightly slower rate. It therefore appears that the more distant turbine (located approximately 600 m from the measurement location) is resulting in higher levels of amplitude modulated noise than the turbine located approximately 300 m from the measurement location.

3.5.6 As the measurements made at ground levels on the board at B3 minimise the influence of ground reflections effects, they are considered further below.

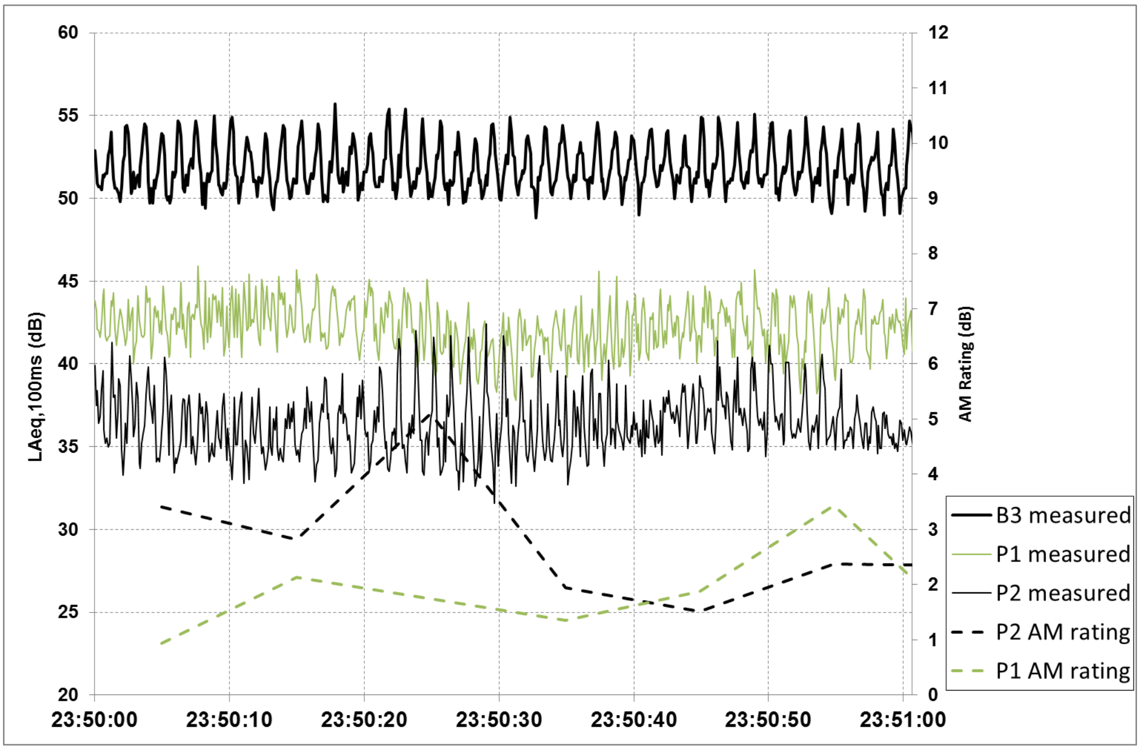

Figure 3.4 - Time history at locations P1, P2 and B3 for a 1-min period in period 1 (measured $L_{Aeq,100ms}$ and corresponding AM ratings for locations P1 and P2)

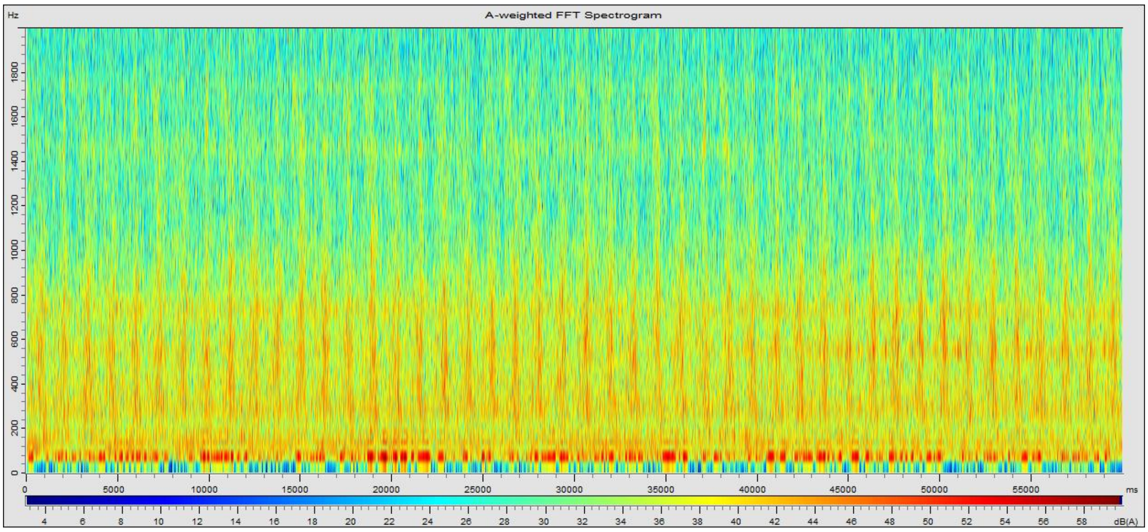

Figure 3.5 - A-weighted spectrogram of the audio recording corresponding to the 1min period shown in the above Figure 3.4: location B3 (~80m downwind) (arbitrary scale).

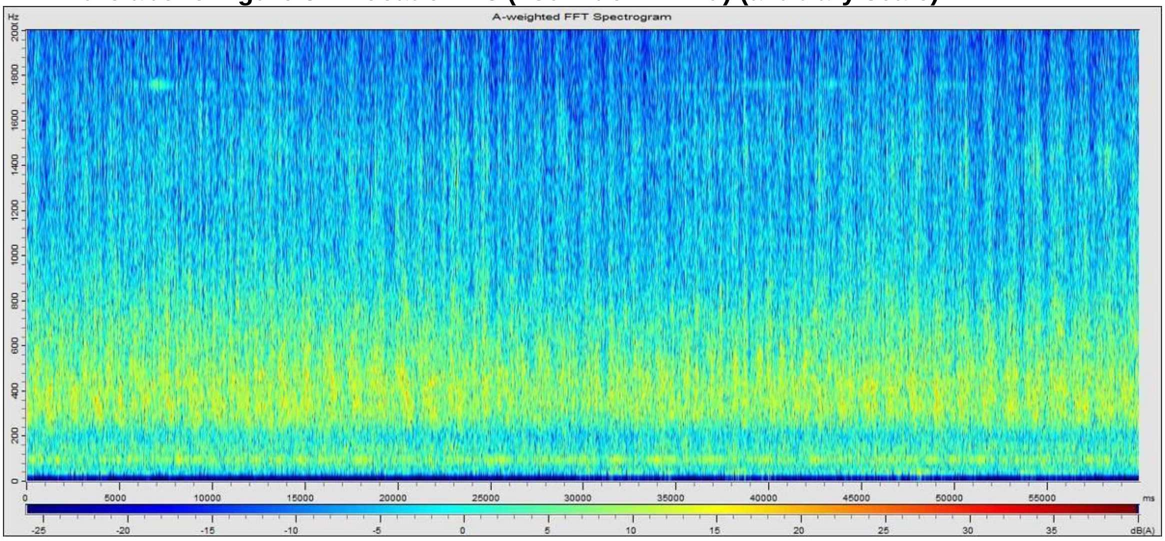

Figure 3.6 - A-weighted spectrogram of the audio recording corresponding to the 1min period shown in the above Figure 3.4: location P1 (~300m downwind) (arbitrary scale)

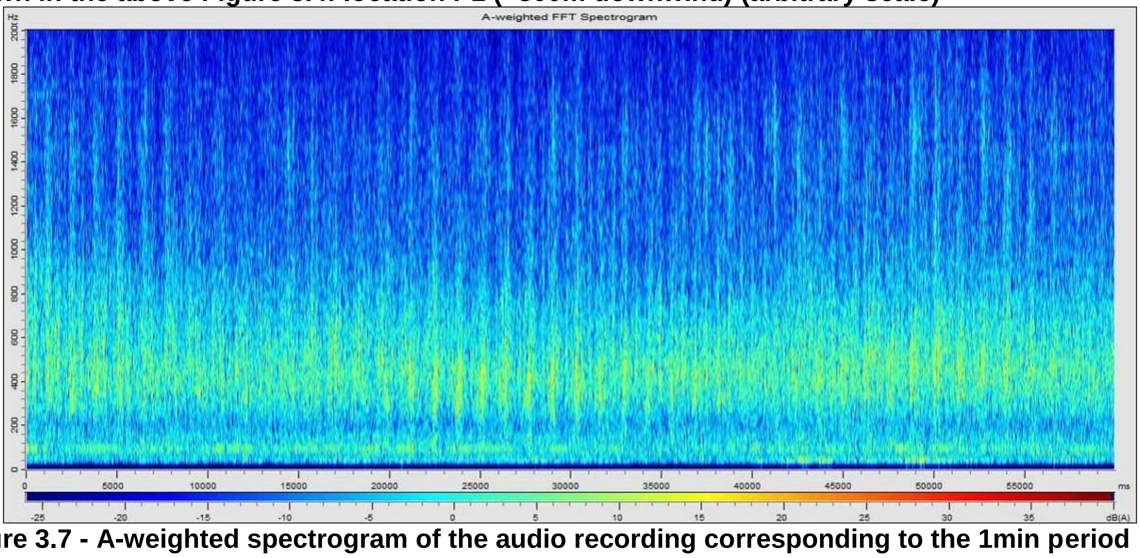

Figure 3.7 - A-weighted spectrogram of the audio recording corresponding to the 1min period shown in the above Figure 3.4: location P2 (~600m downwind) (arbitrary scale)

3.5.7 Earlier in the same evening, short-term phased shutdowns of the turbines were undertaken during which each of the three turbines studied was operated in isolation for periods of 5 minutes each with the 2 adjacent turbines switched off. This was done primarily to study if the interaction of the flow between the different turbines could be a potential factor in the modulation observed (although, for example, in the above conditions T1 was not directly downwind of T2 or T3). The shut downs additionally allowed for further analyses to be undertaken on the potential propagation effects between turbines and measurement locations at varying separation distances to be undertaken to supplement the observations already made in connection with the results shown in Figure 3.4.

3.5.8 Figure 3.8 below shows the calculated AM rating levels at both P1 and P2 locations, as well as those from the ground-board at B3 (cross-wind of T1 but down-wind of T2, see Figure 3.1). During this period, each of the three turbines studied was operated in turn for a period of 5 minutes, with the 2 adjacent turbines switched off. A period with T3 operating in isolation first occurs between 21:00 and 21:05 (this is known although no power output data was available to be shown on Figure 3.8), then T1 and T2 respectively, and this can clearly be seen in the latter case from the measured short-term operational data (generating power as a % of rated power).

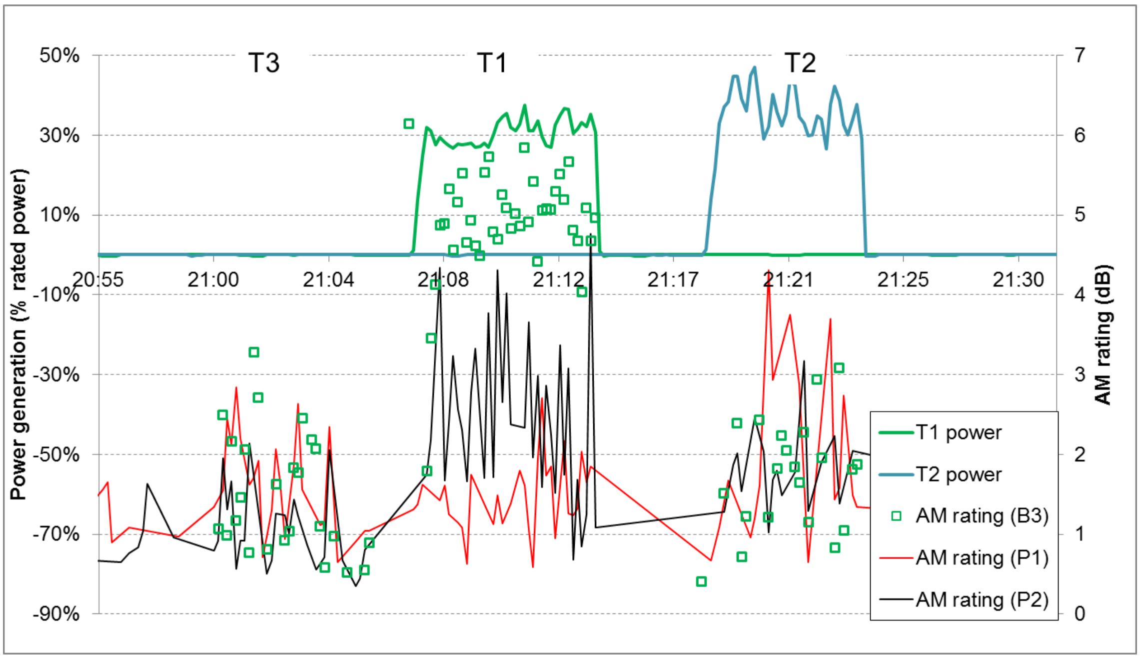

Figure 3.8 – Time history of AM ratings for locations P1 and P2 during a period of phased shutdown resulting in the isolated operation of Turbines T3, T1 then T2. Periods in which the modulation frequency returned from the FFT analysis method did not match the corresponding BPF were excluded. AM ratings for the ground-board location B3 (cross-wind of T1) are shown.

3.5.9 The following observations can be made:

- modulation rated at more than 3dB (similar to that of Figure 3.4) can occur with each turbine operating in isolation;
- the modulation experienced at P2 with T1 operating is comparable to that at P1 with T2: in both cases, the separation distance is similar (around 600m);
- the modulation was higher in the far-field than the near-field, and then reduced further with increasing distance: for example P2 is approximately 900m from T2 and modulation ratings were reduced from those at 600m (P1).
- For the period with T2 only operating, location B3 then represents ground-board measurements at a distance of 300m away, which can be compared to those obtained at P1 with T1 operating: marginally higher AM values are observed, although still comparably

lower than those observed at 1.2 m height at distances of 600 m in the other periods. Although the period is limited, this suggests the attenuation of the 300 Hz frequency region due to ground interference effects may not fully explain the lower levels of modulation observed in the mid-field.

3.5.10 The time histories of measured noise levels during the period of operation then the shutdown of turbine 1 is shown in Figure 3.9 in more detail. These results suggest a clearly dominant influence of separation distance on the amount of modulation experienced. Also, interaction of the flow between the turbines does not appear to be a dominant causal factor, as negligible flow interaction is expected with the adjacent turbines stopped. As above, increased levels of modulation are experienced with increasing distance from the turbine, with a peak in this instance at approximately 10 RD followed by a decrease thereafter. It is stressed, however, that based on this analysis it is not possible to confirm whether this is a general feature of this type of noise or a situation specific effect.

3.5.11 Similar results were obtained for a second shutdown period, although they are less clear as lower wind speeds led to reduced modulation levels.

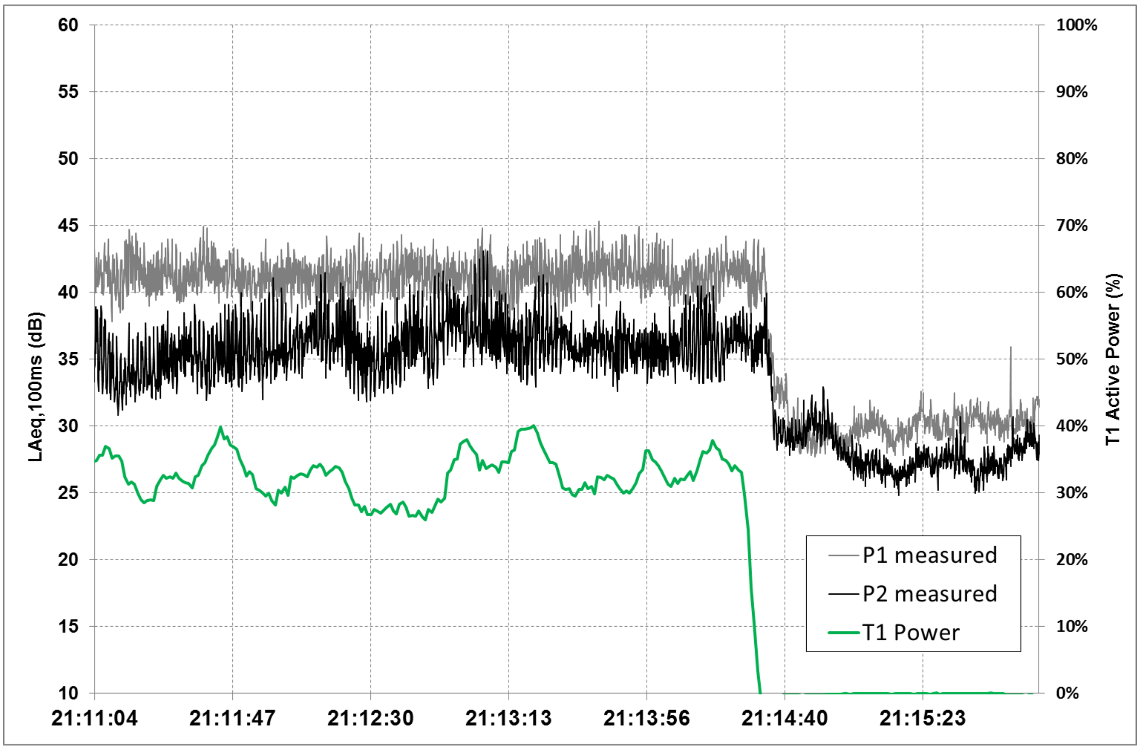

Figure 3.9 – Time history of $L_{Aeq,100ms}$ for locations P1 and P2 for a period of shutdown of T1 operating in isolation (illustrated by active power time history).

3.6 Wind direction 1 (WD1) – period 2 (evening)

3.6.1 A longer period of variable modulation experienced downwind at the far-field at location P2 can be studied in further detail. On this day, a systematic analysis was undertaken in the evening between 19:00 and 23:00. The evolution of the modulation spectrum for the entire period is shown in Figure 3.10 for each of the 10s blocks of the analysis. This illustrates the varying presence of modulation at an evolving rate (close to 0.8Hz) and harmonics at multiples of this frequency. Some spurious periods are identified through the presence of peaks at lower frequencies but this does not appear to excessively affect the results.

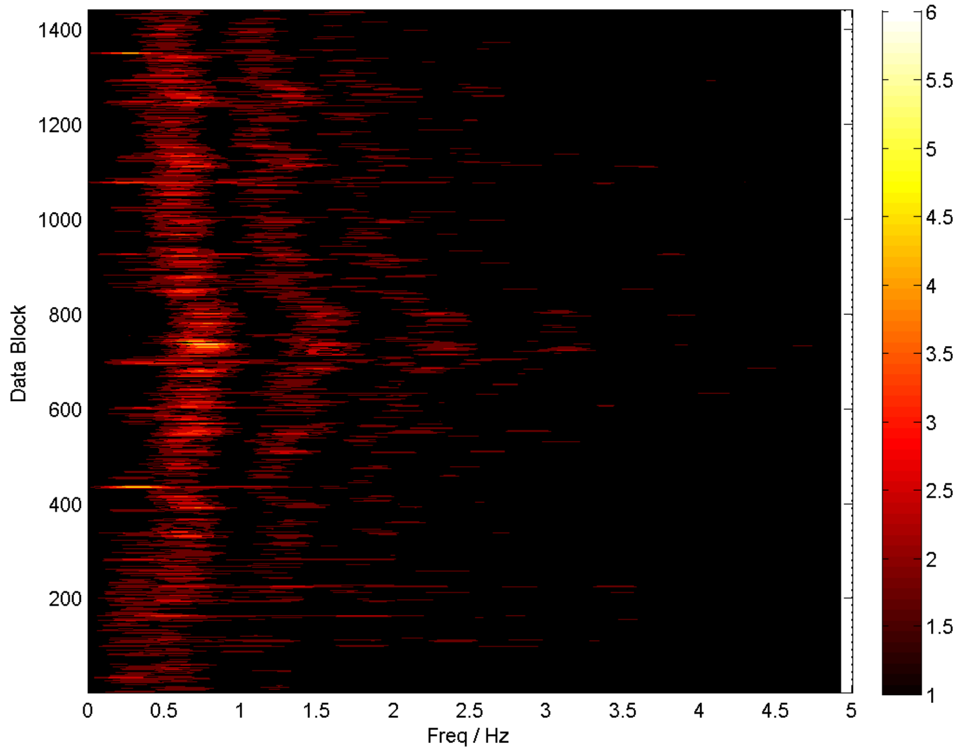

Figure 3.10 – Time history of the modulation spectrum amplitude determined for location P2 from the automated procedure for period 2(vertical axis represent the 10s blocks analysed).

3.6.2 Figure 3.11 illustrates the result of the subsequent filtering process. This process has retained the determined modulation rating from the automated metric analysis only when the resulting rate corresponds to the known actual rate, as determined from the rotational speed of the nearest turbine (T1) on a 10 second by 10 second basis with a permitted tolerance of 0.05 Hz prior to rejection of the sample. It can be seen that the resulting modulation frequency is consistently accurate within the resolution of the analysis undertaken which was 0.04Hz, which represents an impressive performance for the procedure.

3.6.3 The modulation frequency determined from the average turbine rotational rate from the 10 minute data is seen to capture the correct data trend, but does not capture short-term variations occurring within individual minutes, and a coarser tolerance would be required when considering such data. In this case, the minimum and maximum rate within each 10 minute period was provided by the SCADA system, which allows a finer analysis. However, a slight time offset is visible and this highlights the crucial importance of time synchronisation for such measurements.

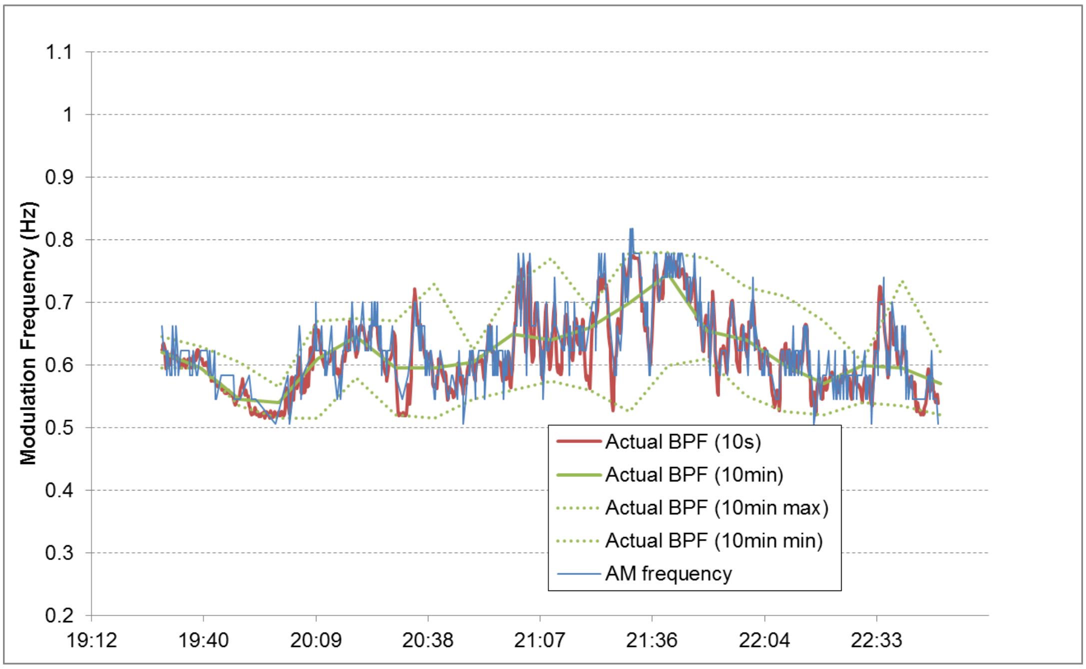

Figure 3.11 – Time history of the modulation frequency determined for location P2 for period 2, using the automated procedure after filtering.

3.6.4 Finally Figure 3.12 shows the excluded frequency values, as well as the resulting modulation rates, both with and without filtering. It can be seen that the excluded values overwhelmingly corresponded to period of low or spurious modulation, whereas for high modulation the correct frequency was generally accurately determined from the clearer signal. It was verified that the resulting periods of highest modulation indicated did correspond to period of clear AM.

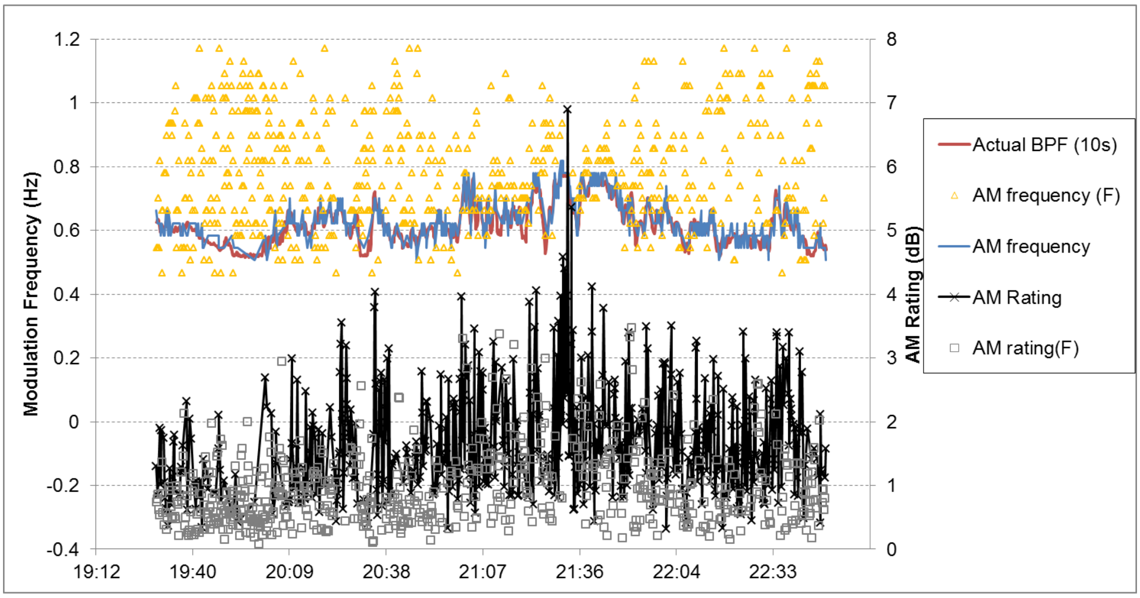

Figure 3.12 – Time history of the modulation frequency and amplitude for location P2, also showing the filtered values (F) which were excluded as their frequency was erroneous.

3.6.5 The variation in the determined AM rating parameter over this period (after filtering) can be examined in relation with different meteorological and operational parameter to assess the likely significance and relation with the varying levels of modulation experienced in the far-field.

3.6.6 First of all, the evolution of wind shear across this period can be visualised either through the wind speed profile at different heights or the corresponding shear exponents[1]. The heights refer to those defined in Figure 3.2. It is striking from Figure 3.13 that the period of elevated modulation is associated with a period of reduced wind shear.

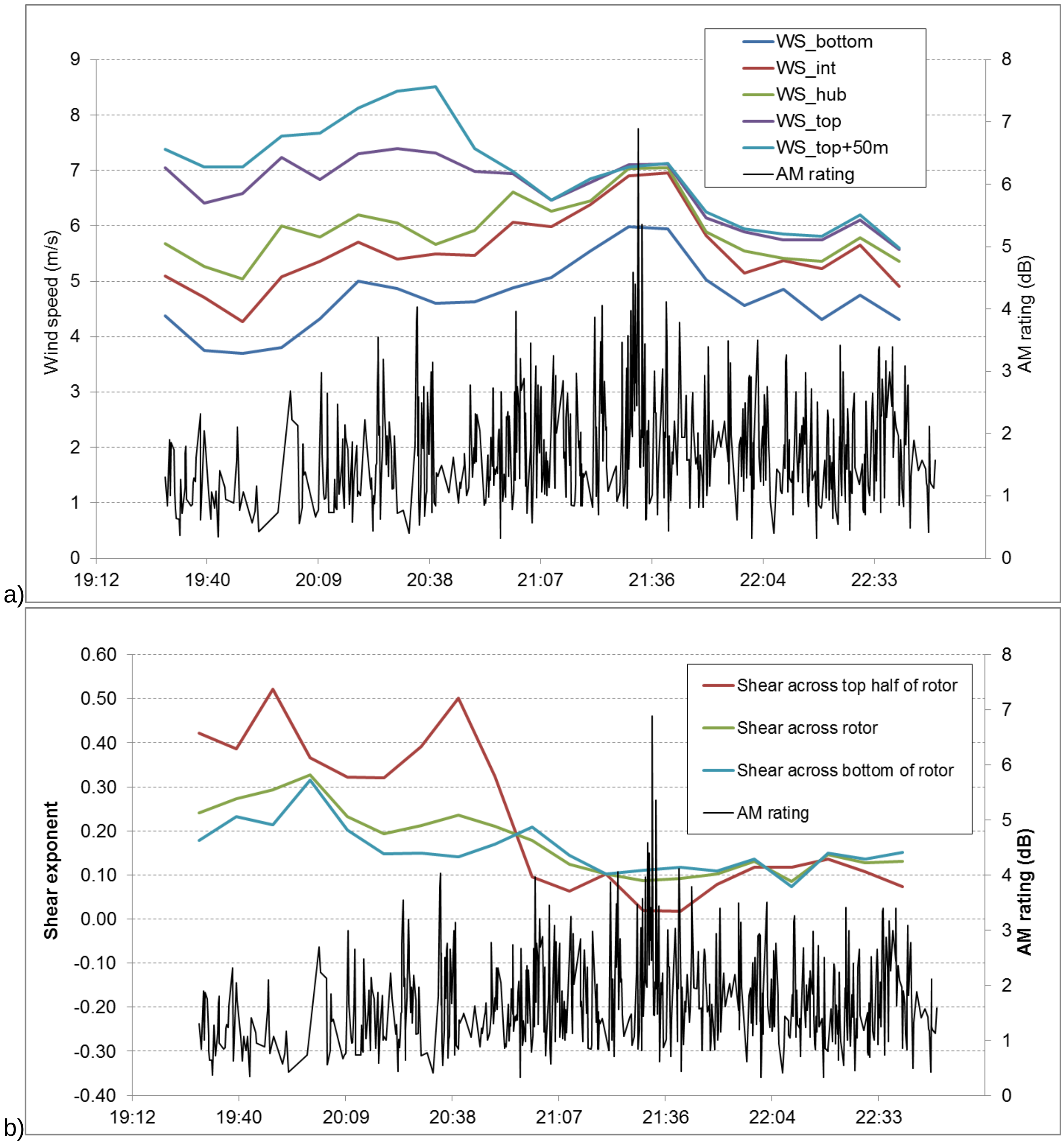

Figure 3.13 – Time history of the AM rating for location P2, in parallel with either: a) wind profile evolution at different heights and b) associated shear exponent coefficient.

[1] The shear exponent m represents a measure of the wind shear using this model: $U = U_{ref} \cdot \left[\frac{H}{H_{ref}}\right]^m$

3.6.7 Similarly, Figure 3.14 shows the variation in wind veer across the rotor with time. In this instance the wind veer is defined as the measured difference between the wind direction at different heights compared to the wind direction at the hub height.

3.6.8 Figure 3.15 then shows how turbulence levels, defined as the ratio (%) of the 10-minute standard deviation and mean wind speed, vary with height across the turbine rotor.

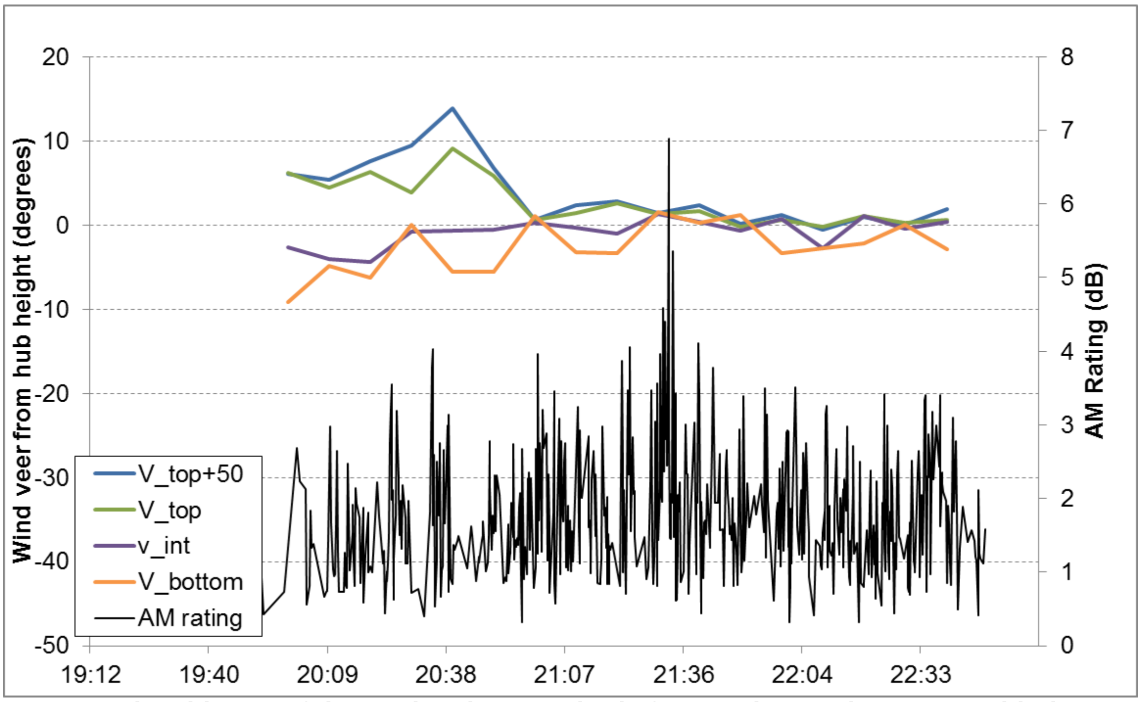

Figure 3.14 – Time history of the modulation amplitude for location P2, in parallel with the variation in wind veer at different height.

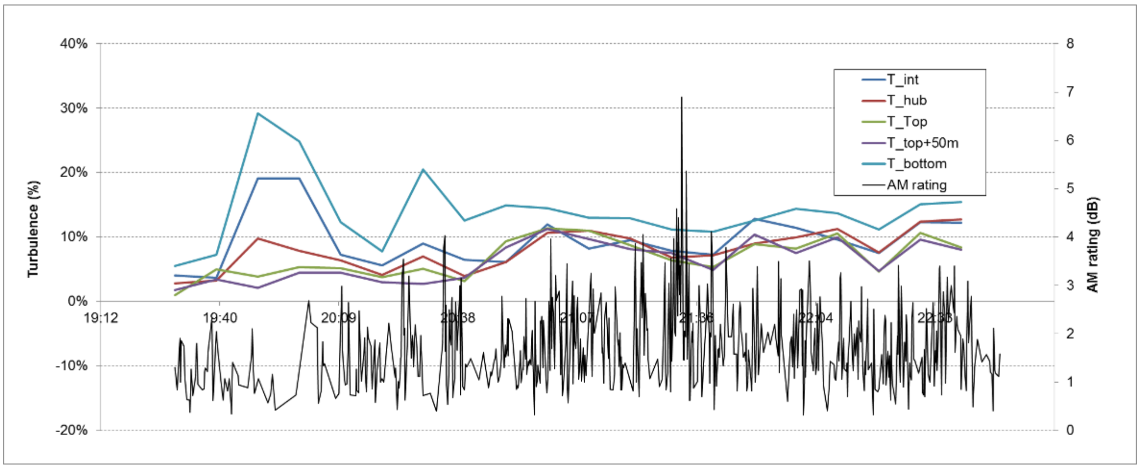

Figure 3.15 – Time history of the modulation amplitude for location P2, in parallel with the variation in turbulence at different height.

3.6.9 Figure 3.16 is more instructive as it shows the variation in the turbine generating capacity, and it can be seen that the turbine T1's power generating output (as measured in short timescales) broadly correlates with the amount of modulation experienced in the far-field: at the beginning of the period, although wind shear, veer and the gradient of turbulence are relatively high, there is little modulation. As the wind speed (Figure 3.17) increases, the amount of turbulence, wind shear and wind veer decrease, but the power output increases and so does the amount of modulation in turn.

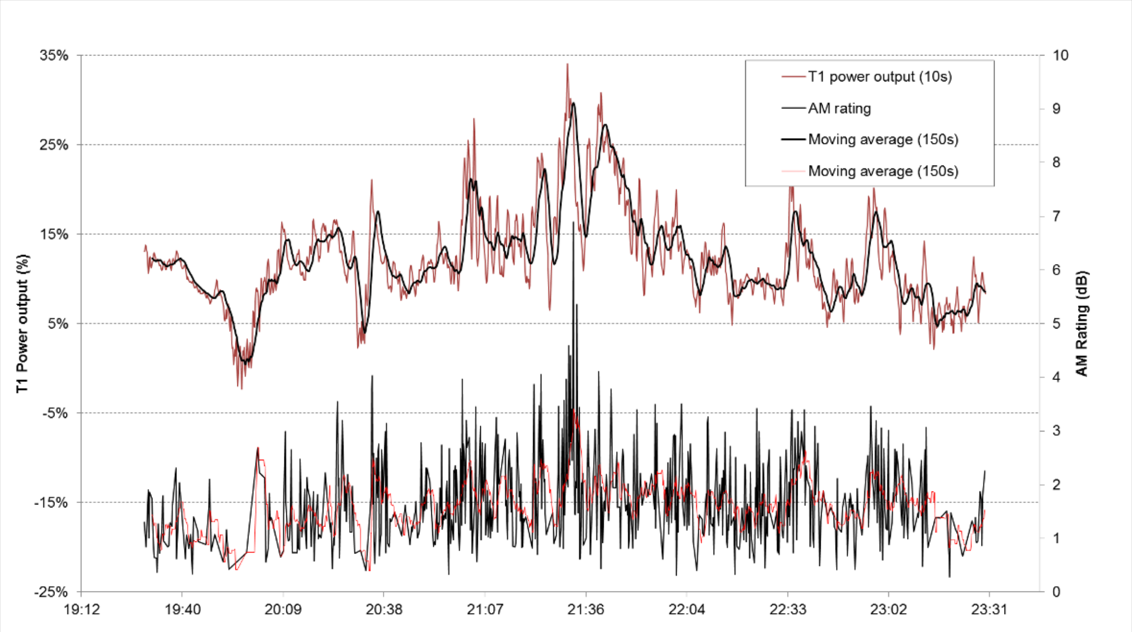

Figure 3.16 – Time history of the modulation amplitude for location P2, in parallel with the variation in T1 generating power (as a percentage of rated power, 10s resolution).

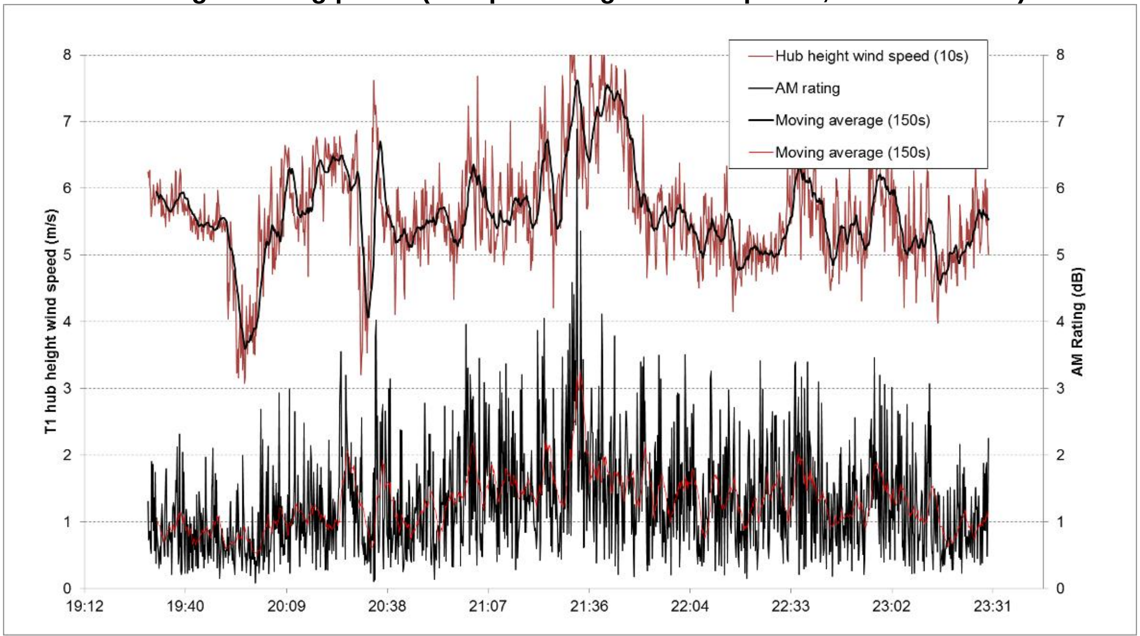

Figure 3.17 – Time history of the modulation amplitude for location P2, in parallel with the variation in T1 hub height wind speed (10s resolution).

3.6.10 When examining the time history in further detail, it can be seen that the short period of relatively highest modulation rating values visible in these graphs, at around 21:30, is not directly associated with the high wind speeds or generating power, as it is immediately followed by similar conditions but without the same AM in the far-field.

3.6.11 As the turbines at Site B are variable-speed, pitch-regulated machines, the interaction of rotational speed, incident wind speed and power regulation is complex and determined by the turbine's control system. As discussed in the Annex to this report, for evaluation purposes, it can be interesting to estimate the potential changes in the angle of attack of the flow on the blades corresponding to different conditions. Determining this precisely would require a full knowledge of the blade geometry, flow conditions, *etc.*, or it can be measured using dedicated on-blade sensors, as reported in some experiments by others [7], but this was not possible within the scope of the current measurements.

3.6.12 A “relative” angle of attack (“alpha”) can be estimated based on the rotational speed, incident wind speed and pitch adjustment for each 10 s period, to represent a reasonable estimate of the likely variation of the incident flow character with time. This is shown here in Figure 3.18. This suggests that the period of elevated modulation coincides with a rapid increase in the effective angle of attack on the blades, during a period when the turbine is generating significant power (>15% of its total rated power).

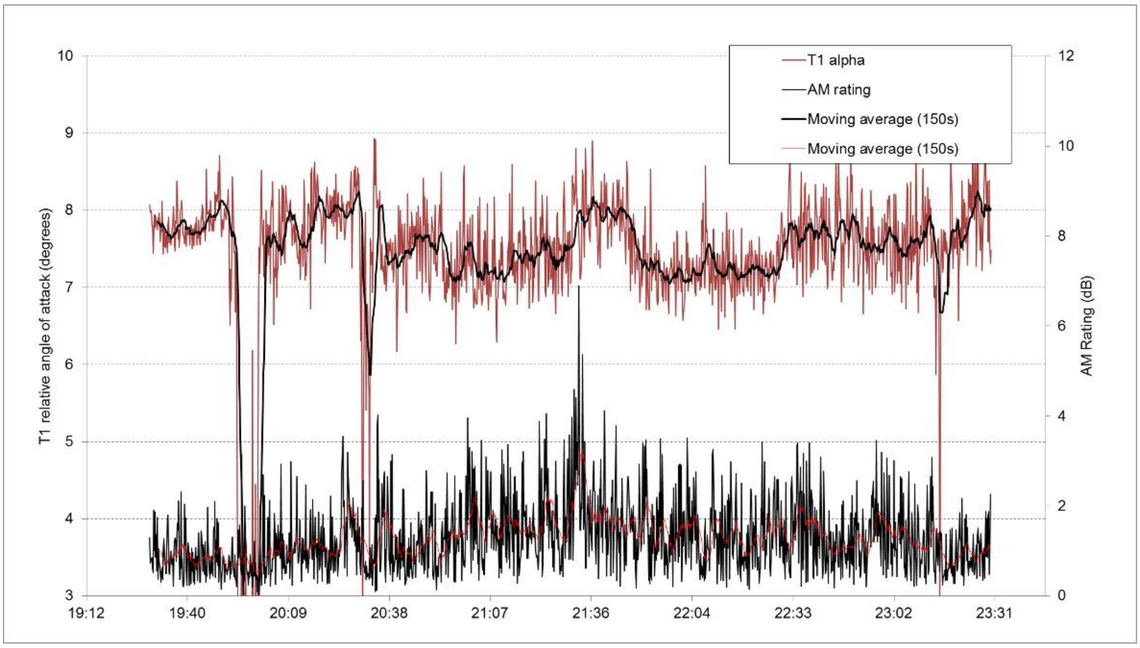

Figure 3.18 – Time history of the modulation amplitude for location P2, in parallel with the variation in T1 relative angle of attack (10s resolution).

3.6.13 The difference between the $L_{Aeq,10min}$ and the $L_{A90,10min}$ for the period of relatively elevated modulation (around 21:30) was approximately between 2 and 3 dB.

3.6.14 Finally, whilst the above analysis focused on the far-field location (P2), it can be useful to compare the relative level of modulation experienced at the other locations. Figure 3.19 shows a comparative plot of the filtered AM amplitudes between the different locations. This first confirms that, in the downwind direction, the modulation in the far-field (P2) is higher than in the mid-field (P1). This also shows that mid-field modulation is comparable between P1 (downwind) and P3a (cross-wind), but that the latter tends to be lower.

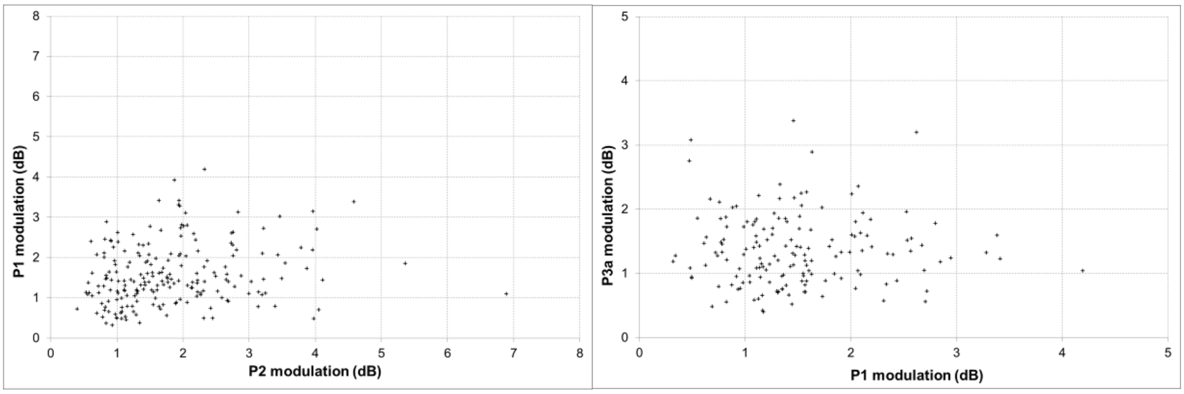

Figure 3.19 – Comparison of the filtered modulation amplitudes measured at locations P1, P2 and P3a for period 2 (20:00-22:00).

3.7 Wind direction 1 (WD1) – period 3 (evening and following morning)

3.7.1 A longer period of variable modulation experienced downwind in the far-field at location P2 can be studied in further detail. On this day, a systematic analysis was undertaken in the evening between 21:00 and 01:00 and 04:00 to 07:00 the next morning. The evolution of the modulation spectrum for the entire period is shown in Figure 3.20 for each of the 10s blocks of the analysis. The entire analysis took less than 10 minutes using a PC with a 64-bits 2.7GHz processor with the MATLAB software, which means that a systematic data analysis is feasible in practice.

3.7.2 A clear pattern of modulation at a varying frequency close to 0.8Hz, as well as several harmonics, is visible for most of the periods. Narrow, horizontal lines represent artificially high values across the entire modulation spectrum which are caused by short-term spurious sources, for example early morning bird call noise towards the end of the period. As these occur across the modulation spectrum, they may not be eliminated by the filtering procedure above, but it is a straightforward procedure to exclude them manually.

3.7.3 In this case as well, the metric analysis can be filtered using the known rotational speed of the turbines at any one time. The resulting evolution of modulation frequency is shown Figure 3.21 and a very good performance is again achieved, consistently, with the pattern of Figure 3.20. As previously, the differences between the $L_{Aeq,10min}$ and $L_{A90,10min}$ did not deviate significantly from typical values of 1.5 to 2.5dB.

3.7.4 The variation in the AM metric is then shown alongside a range of parameters as previously: Figure 3.22 and Figure 3.23. Values of wind shear/veer are generally more elevated than for period 2 considered above, but again no clear association is evident from these graphs, which in fact again suggest that AM increases occur following reductions in wind shear.

3.7.5 The turbulence data is similar to that of Figure 3.15, with a relatively uniform distribution across the rotor, and values of less than 10%, for the periods of more significant modulation. This can be compared to theoretical considerations (WPA2) which suggest that a 10-fold increase in turbulence amplitude would be required to correspond to the variations in source levels of the right order of magnitude.

3.7.6 Figure 3.25 shows the evolution of the relative angle of attack “alpha”. These results are not conclusive but suggest that the turbine generating output and an increased angle of attack represent key associated factors for the associated AM in this case.

3.7.7 Finally, Figure 3.26 shows the measured wind profile at different representative times (see time history in Figure 3.22) which illustrates the actual wind shear across the rotor. The measured wind speed above the rotor tip height is compared with that extrapolated using an exponent shear profile across the rotor. This was done following the suggestion of McLaughlin [8] that low-level jets may be present and affect source levels or propagation, However, the observed wind shear profiles did not highlight the presence of such a jet.

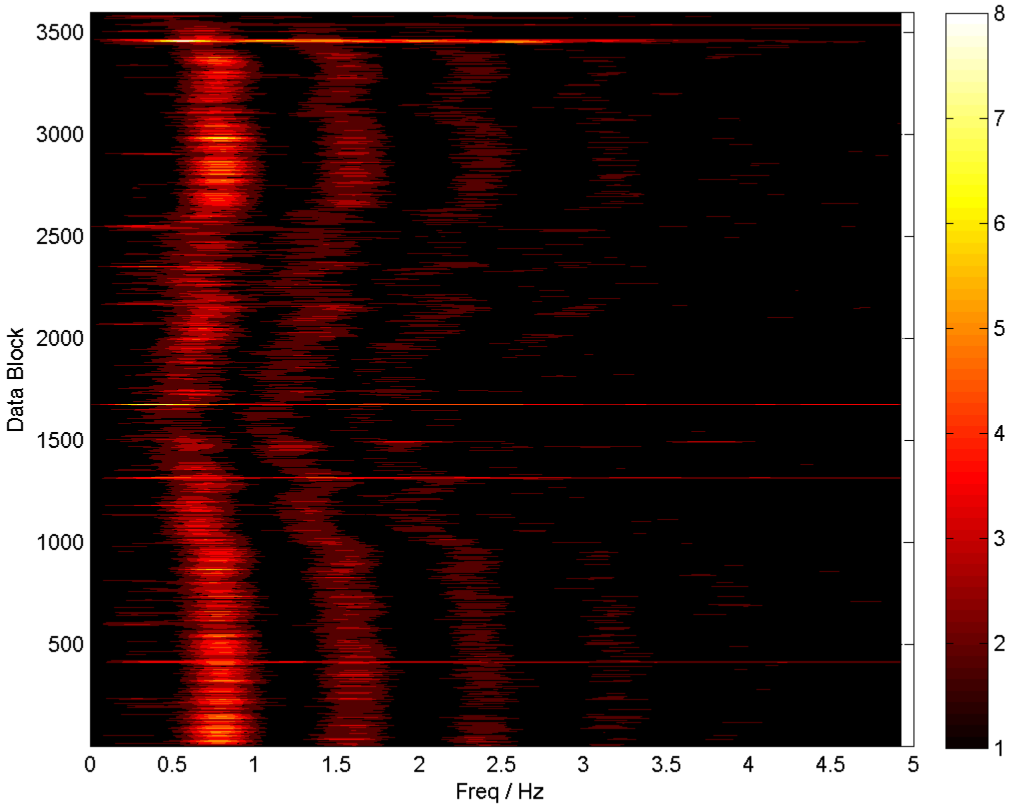

Figure 3.20 – Time history of the modulation spectrum amplitude determined for location P2 from the automated procedure for period 3 (vertical axis represent the 10s blocks analysed).

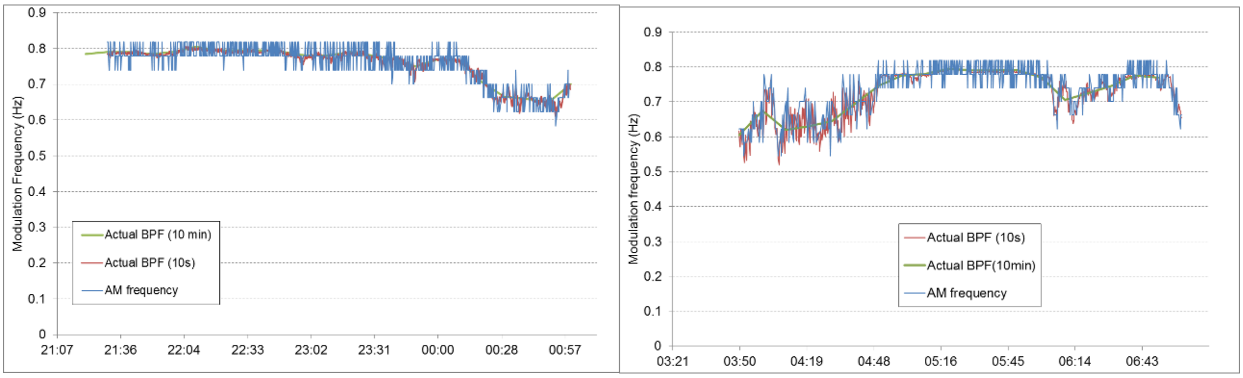

Figure 3.21 – Time history of the modulation frequency determined for period 3, location P2 from the automated procedure, after filtering. The residual variations observed are similar to the frequency resolution of 0.4 Hz in the analysis.

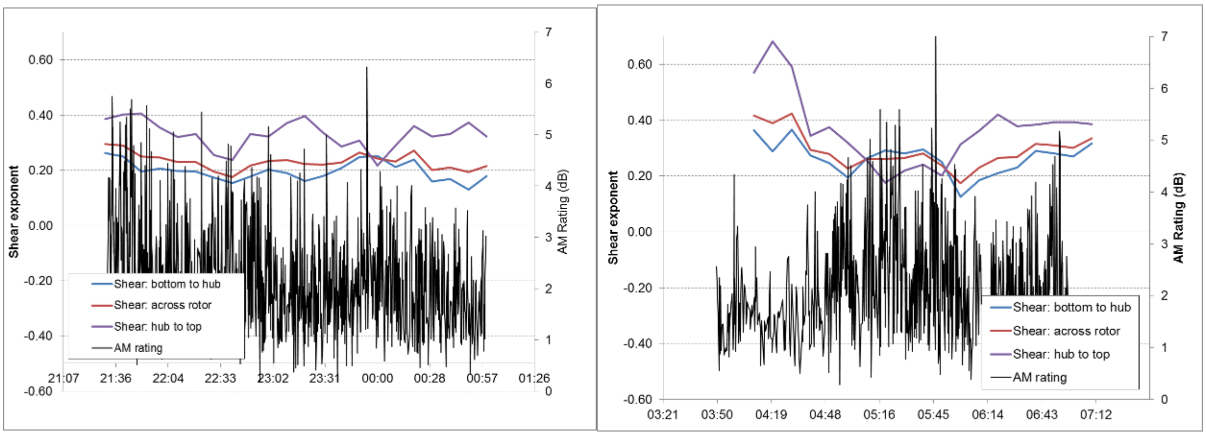

Figure 3.22 – Time history of the modulation amplitude for location P2, in parallel with the associated shear exponent coefficient at different heights, for period 3.

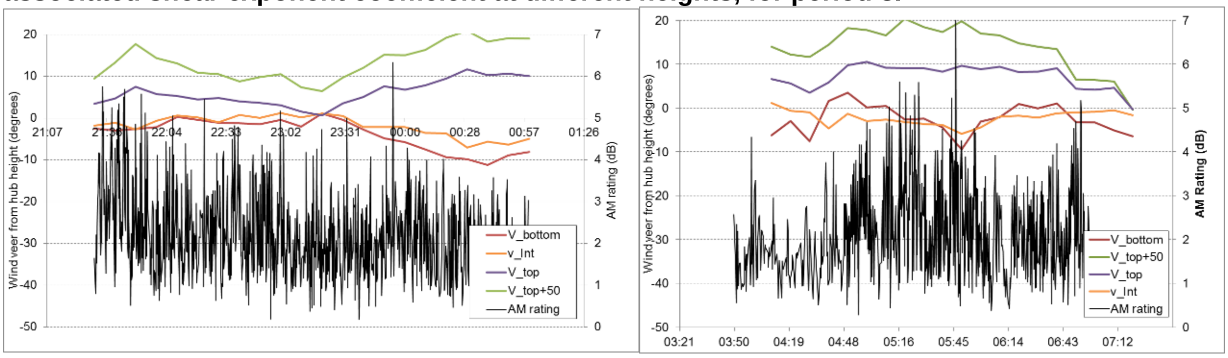

Figure 3.23 – Time history of the modulation amplitude for location P2, in parallel with the variation in wind veer at different heights, for period 3.

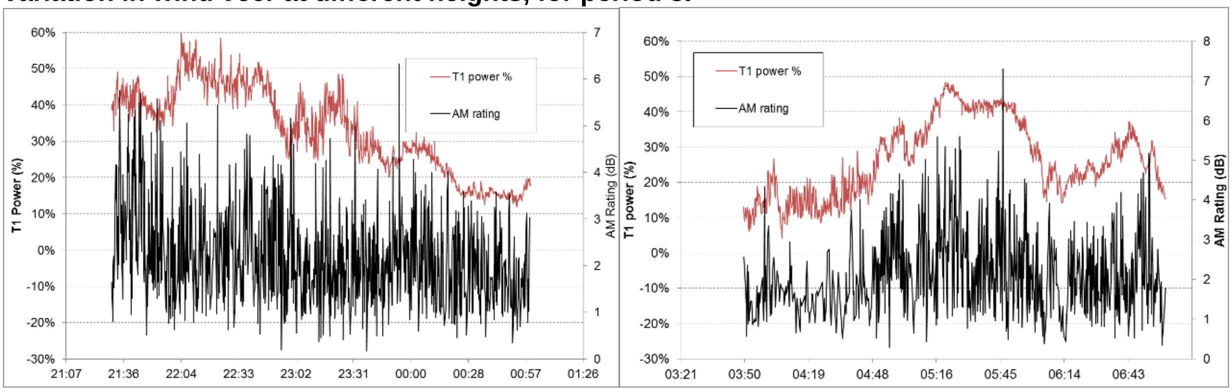

Figure 3.24 – Time history of the modulation amplitude for location P2, in parallel with the variation in T1 generating power (as a percentage of rated power, 10s resolution), period 3.

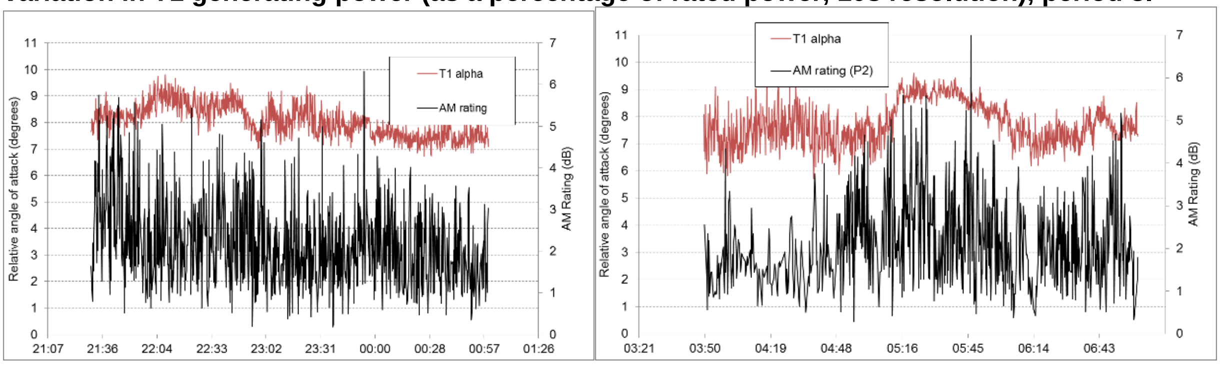

Figure 3.25 – Time history of the modulation amplitude for location P2, in parallel with the variation in T1 relative angle of attack (10s resolution), period 3.

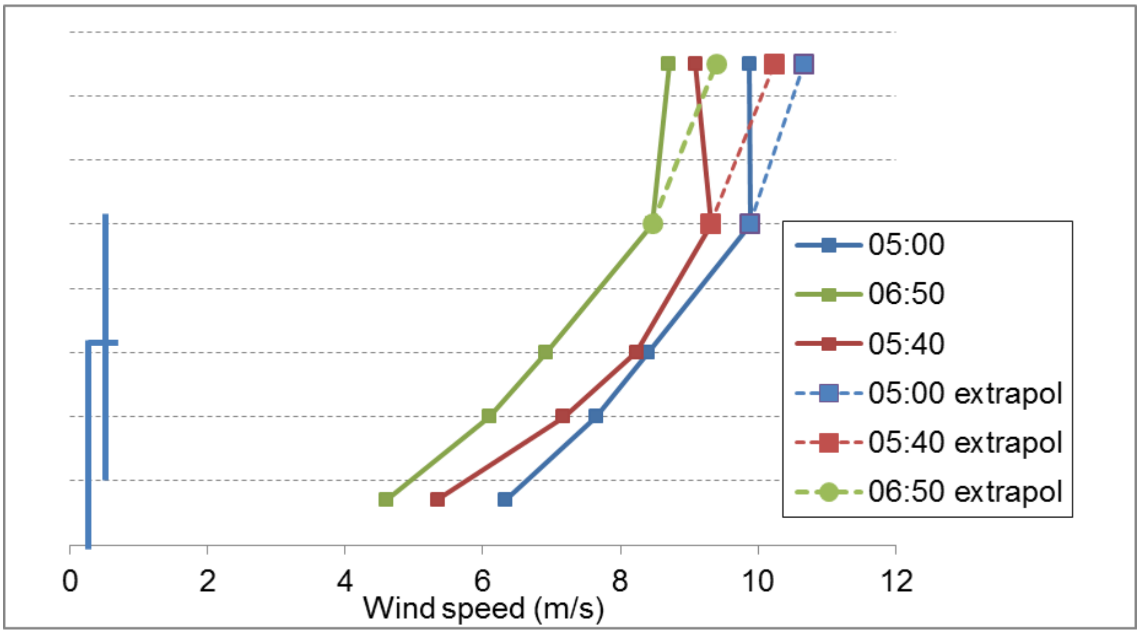

Figure 3.26 – Example of measured wind speed profiles (10 min. average wind speed) variation with height at different times of period 3, compared with that extrapolated above tip height based on an exponent model.

3.8 Wind direction 2 (WD2) – period 4 (morning)

3.8.1 In the last phase of the survey at site B, the system at location P3a (mid-field) was moved further away from the turbines to location P3b. This allowed a study of the propagation of the modulation noise in a second wind direction (WD2) for comparative purposes: see Figure 3.1. This also allowed a direct comparison between two far-field locations: P3b (downwind) and P2 (crosswind in this case).

3.8.2 By the time of this phase of the measurements, the LIDAR sensor had been decommissioned and so reference was made to the remaining, less detailed meteorological information from the wind farm's SCADA system.

3.8.3 The first of the two periods of suitable weather conditions identified was an early morning period in which variable levels of modulation were experienced. The resulting modulation spectra evolution for the period is shown Figure 3.27. It can be seen that similar modulation features can be observed in this wind direction in the far-field as that observed at comparable distances at location P2, which was downwind for the periods experiencing WD1. The modulation frequency is relatively constant across this period which is consistent with the measured rotational rate, with a similar filtering as above having been applied.

3.8.4 For this period, P2 is located cross-wind and the modulation magnitude experienced at both far-field locations is compared in Figure 3.28. It is clear from this analysis that the far-field (~10RD) cross-wind location experienced significantly less modulation than the downwind one.

3.8.5 The wind shear across the bottom half of the rotor was available for this period and is shown in Figure 3.29 along with the filtered AM magnitude. This suggests again a weak negative correlation of AM rating with the amount of wind shear.

3.8.6 In Figure 3.30 and Figure 3.31 the change in generating power and relative angle of attack is displayed. T2 is then used as a reference because of its relative proximity. It can be seen that the AM generally varies broadly in line with the power output of the turbine, and that elevated AM rating values can be associated with periods of variation in the angle of incidence.

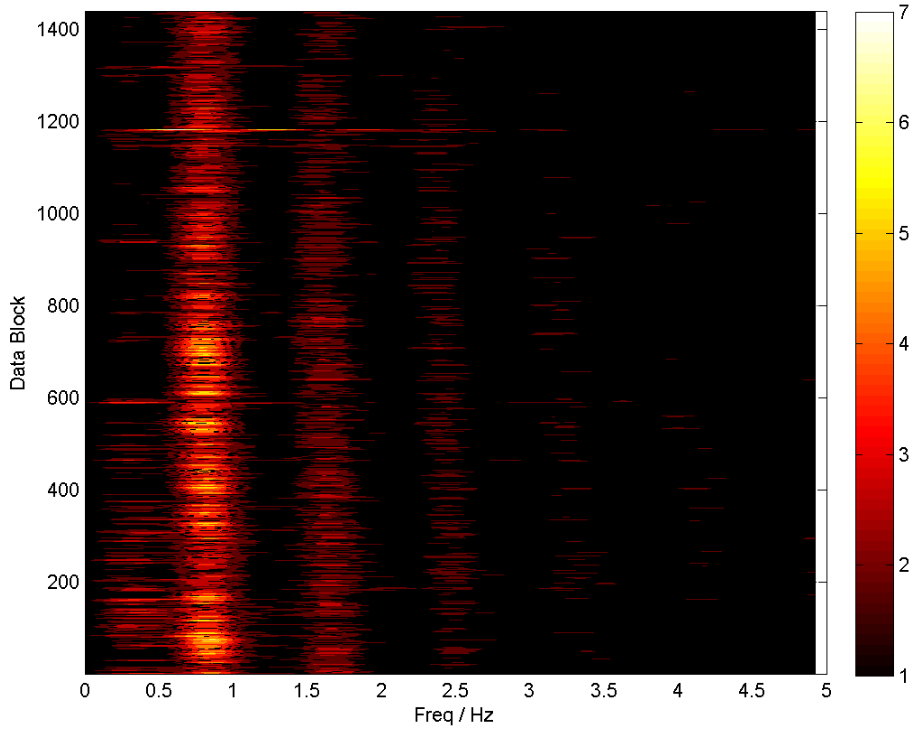

Figure 3.27 – Time history of the modulation spectrum amplitude determined for location P3b from the automated procedure for period 4 (vertical axis represent the 10s blocks analysed).

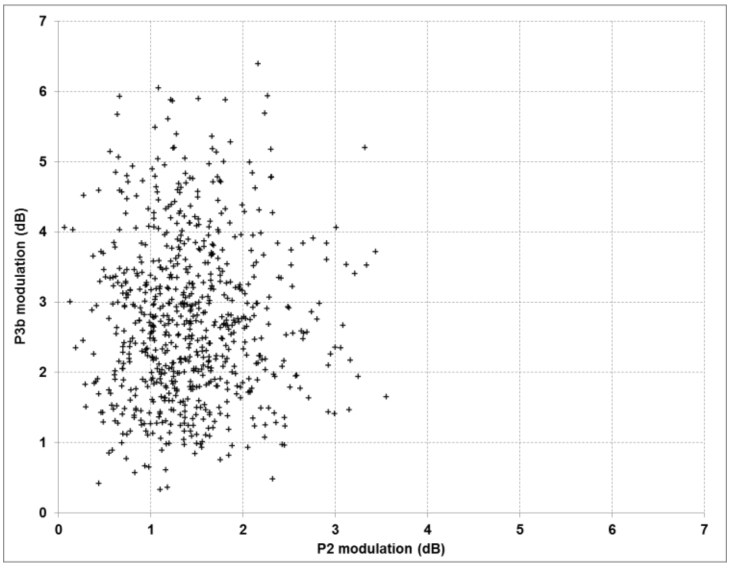

Figure 3.28 - Comparison of the filtered modulation amplitudes measured at P3a (downwind) with that measured for the same period at location P2 (cross-wind).

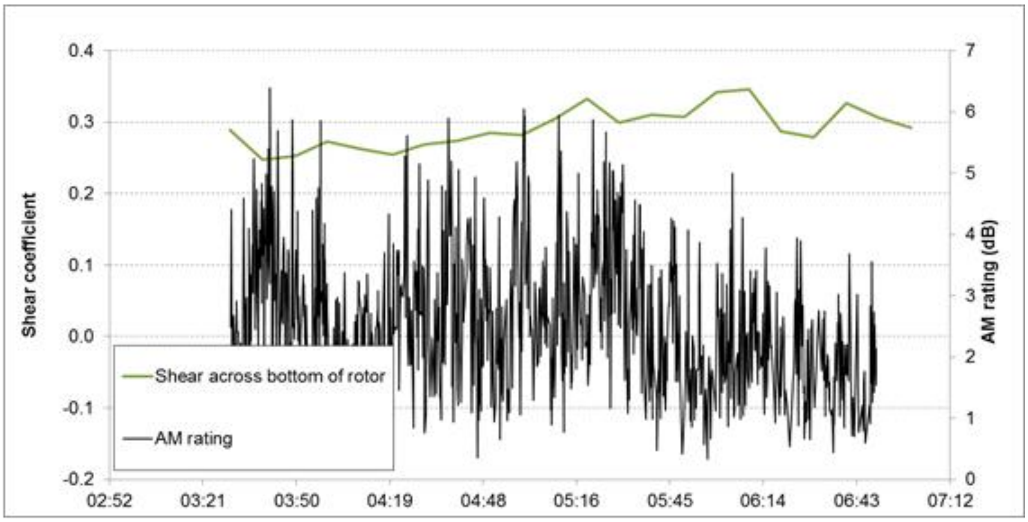

Figure 3.29 – Time history of the modulation amplitude for location P3b, in parallel with the associated shear exponent coefficient, for period 4.

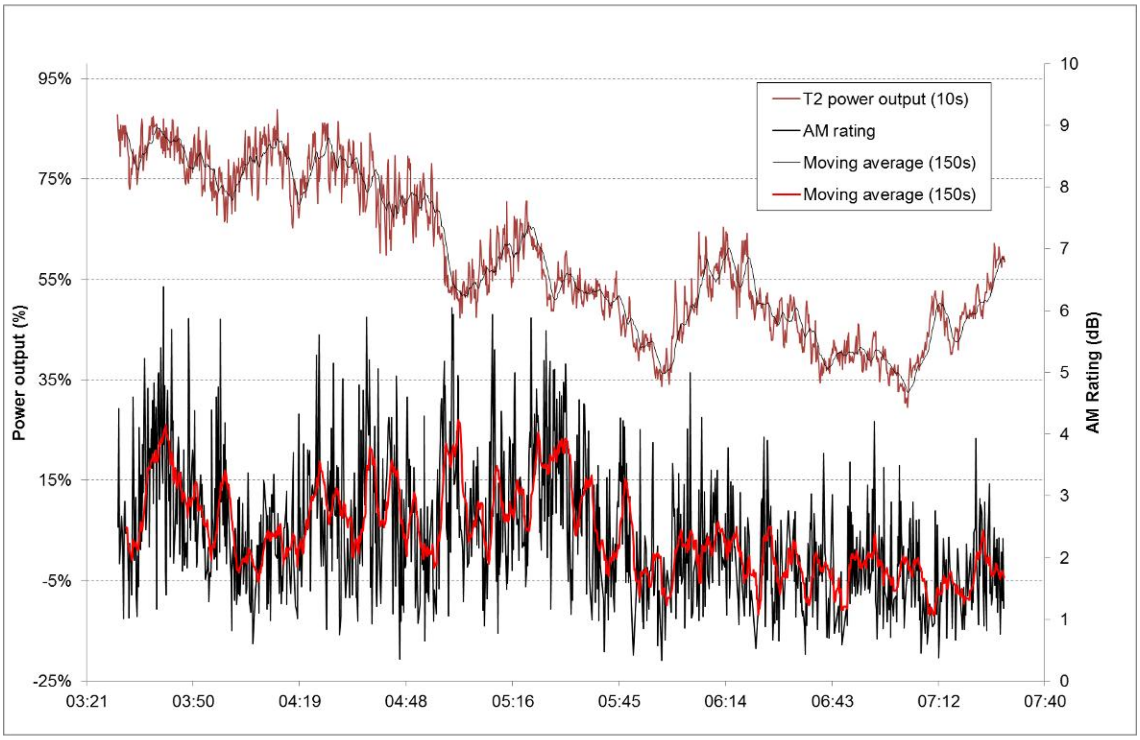

Figure 3.30 – Time history of the modulation amplitude for location P3b, in parallel with the variation in T2 generating power (as a percentage of rated power, 10s resolution), period 4.

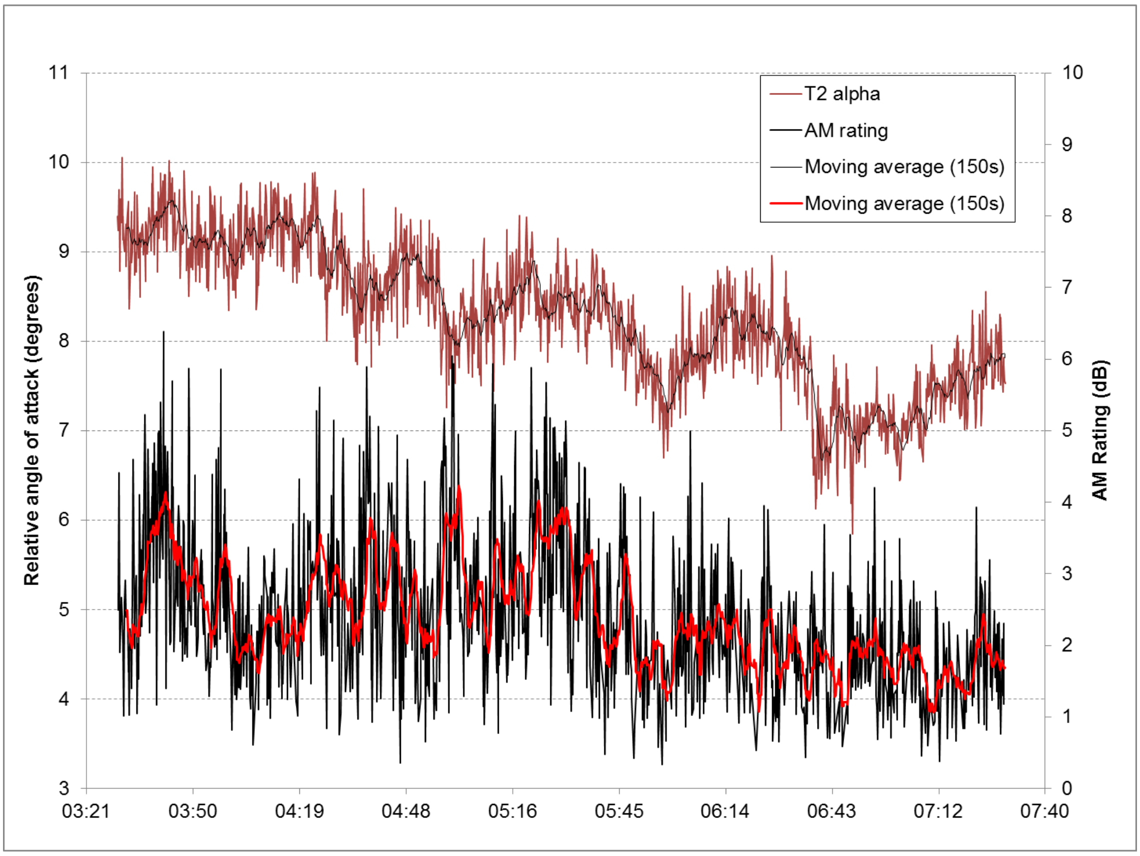

Figure 3.31 – Time history of the modulation amplitude for location P3b, in parallel with the variation in T2 relative angle of attack (10s resolution), period 4.

3.9 Wind direction 2 (WD2) – period 5 (morning)

3.9.1 Period 5 comprises another early morning period (04:30 to 07:30) which experienced similar wind directions (WD2) as period 4. A similar modulation pattern is observed, with some 10 second periods rated between 4 dB and 5 dB using the metric implementation for the data of P3b.

3.9.2 Figure 3.32 and Figure 3.33 illustrate that the algorithm performs well, even with a change in BPF of 0.6 to 0.8 Hz across the period, and that the subsequent filtering mostly eliminates some relatively low periods of modulation.

3.9.3 The measured shear exponent (over the bottom half of rotor) during this period slowly decreased from 0.5 to 0.3 across the measurement period, with little observable effect on the rate of far-field modulation.

3.9.4 Figure 3.34 and Figure 3.35 present similar data as for period 4, and similar observations can be made as for period 4 in terms of the relationships of AM rating with operational parameters.

3.9.5 Finally Figure 3.36 and Figure 3.37 present the time history for two periods of clear modulation observed in the far-field (location P3b), and compare the variations in $L_{Aeq,100ms}$ at this location with those obtained at a similar distance cross-wind (P2), showing reduced levels of modulation. Near-field measurements made on ground-boards closer to turbine T2 are shown: B1 and B2, representing both the down-wind and cross-wind directions. The latter experiences deeper modulation than the former, but in both cases the magnitude of modulation is higher in the far-field. Corresponding spectrograms are shown in Figure 3.38 Figure 3.39 respectively.

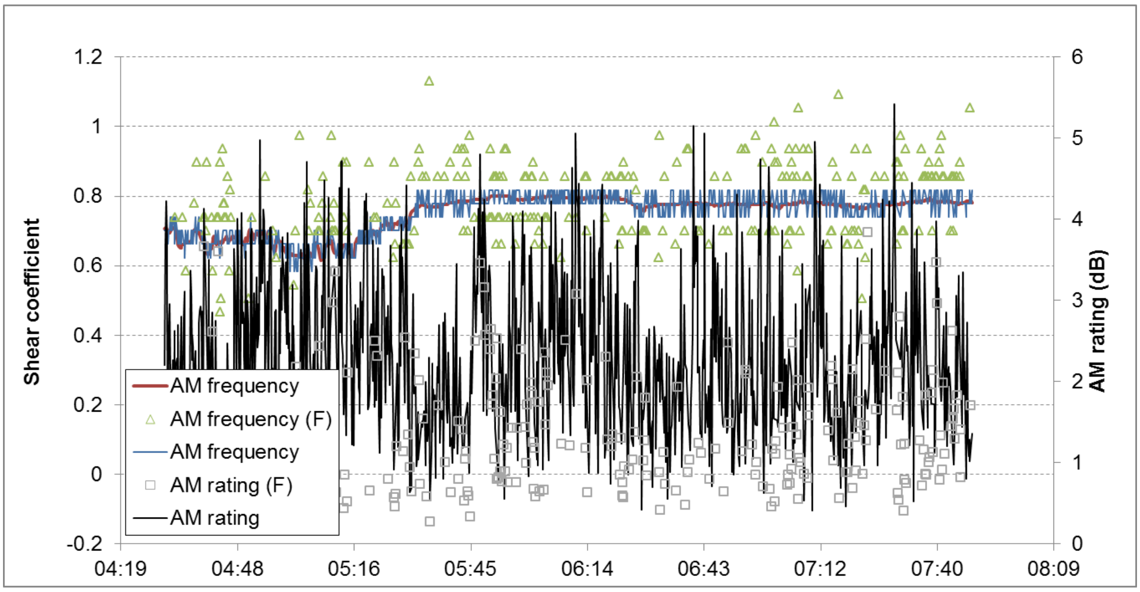

Figure 3.32 – Time history of the modulation frequency and amplitude for location P3b, also showing the filtered values (F) which were excluded as their frequency was erroneous.

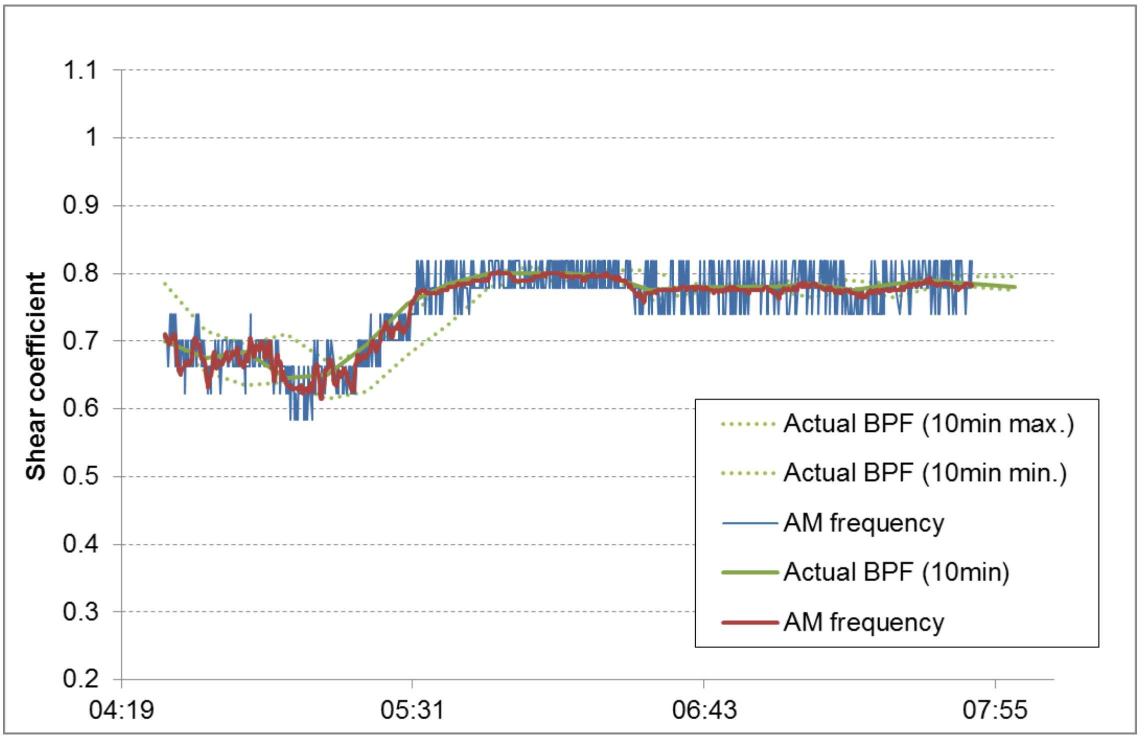

Figure 3.33 – Time history of the modulation frequency determined for location P2 for period 2, using the automated procedure after filtering.

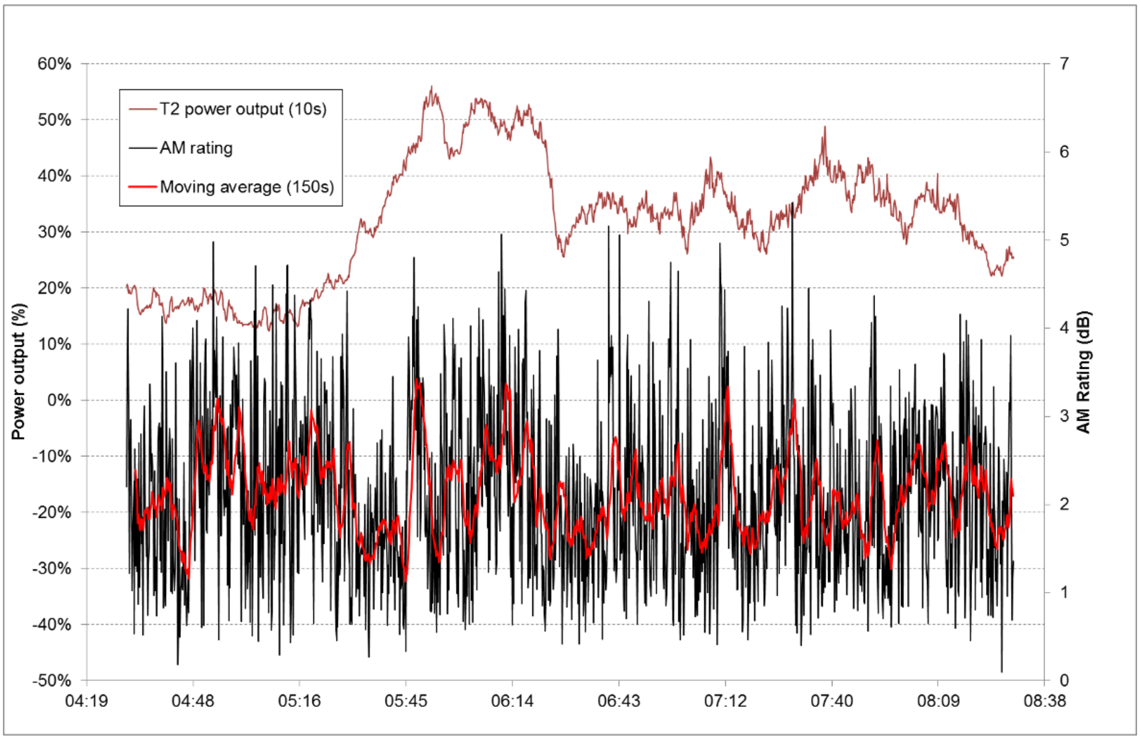

Figure 3.34 – Time history of the modulation amplitude for location P3b, in parallel with the variation in T2 generating power (as a percentage of rated power, 10s resolution), period 5.

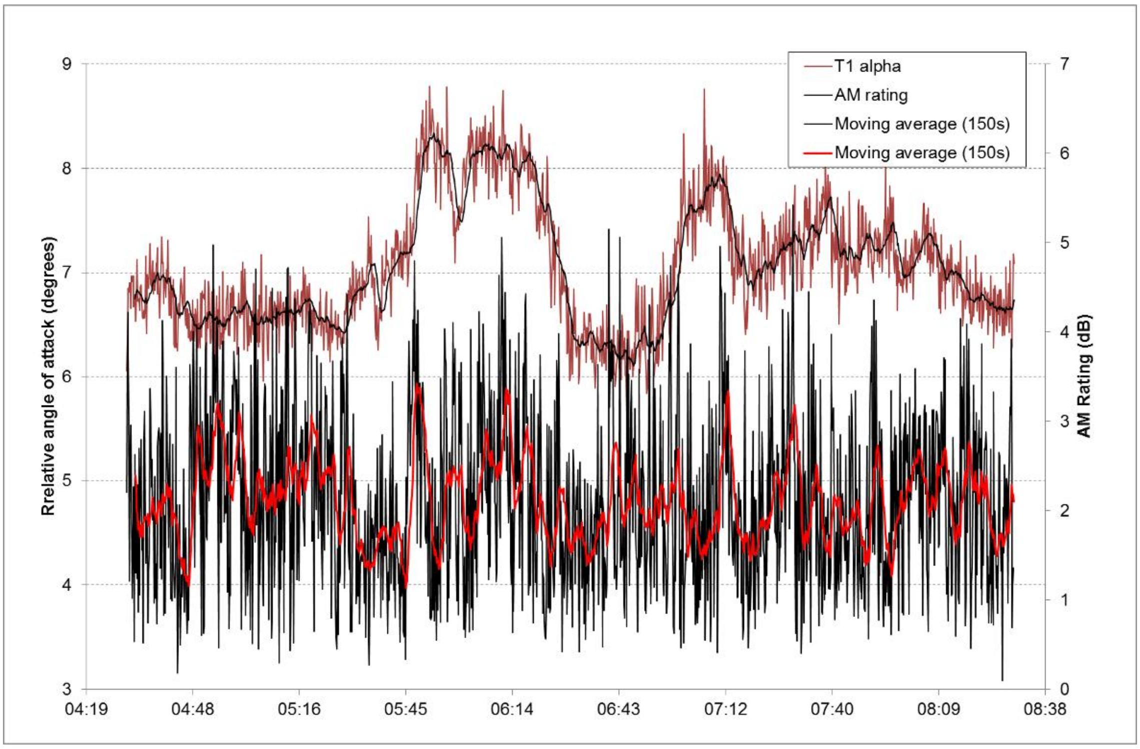

Figure 3.35 – Time history of the modulation amplitude for location P3b, in parallel with the variation in T2 relative angle of attack (10s resolution), period 5.

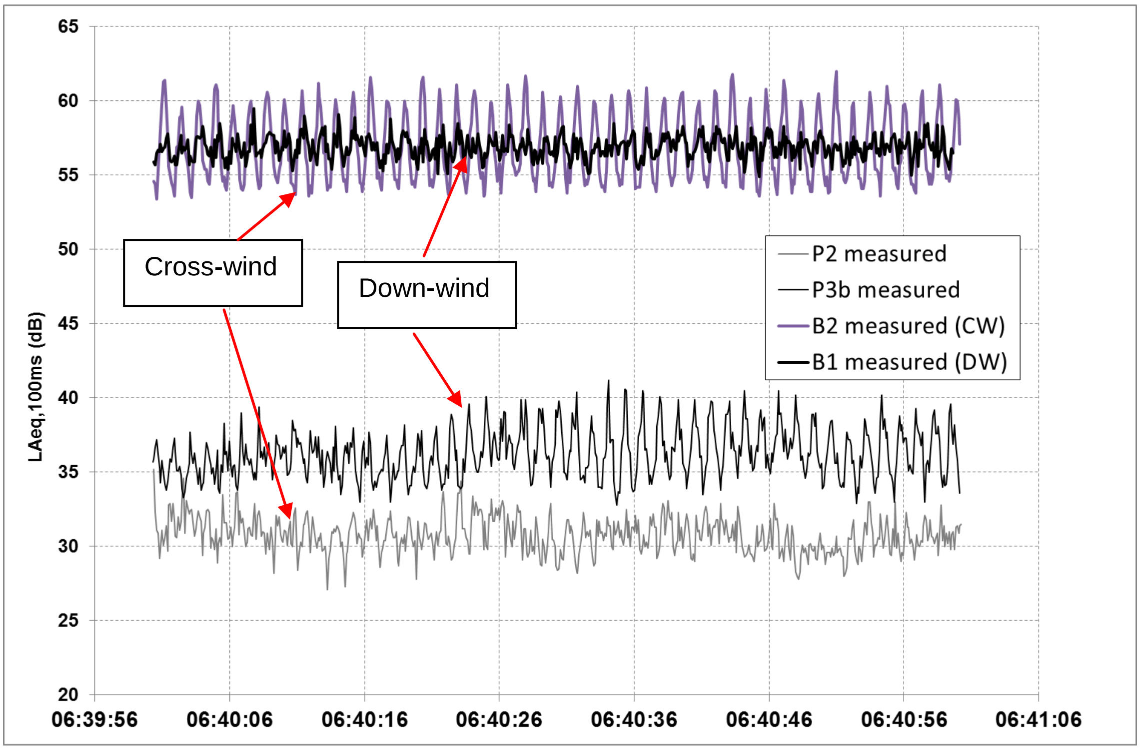

Figure 3.36 – Time history of measured $L_{Aeq,100ms}$ levels for a sample period showing: two far-field locations (P3b downwind and P2 cross-wind) and two near-field locations (cross- and down-wind)

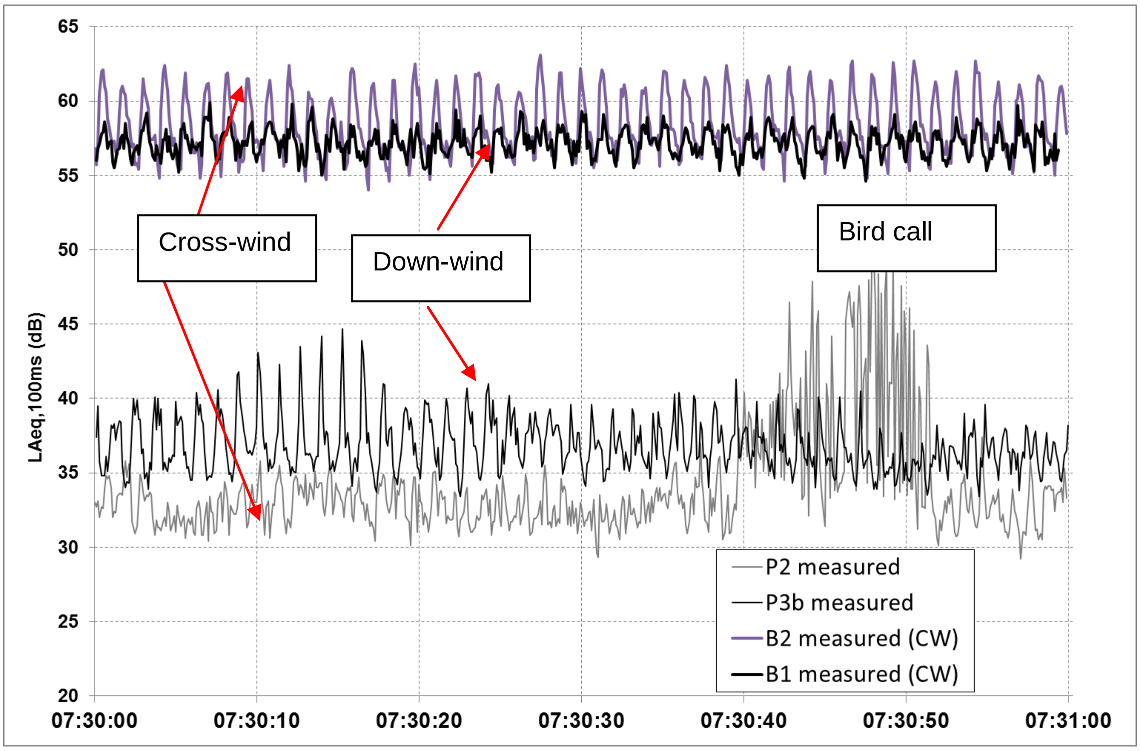

Figure 3.37 – Time history of measured $L_{Aeq,100ms}$ levels for a sample period showing: two far-field locations (P3b downwind and P2 cross-wind) and two near-field locations (cross- and down-wind). The elevated levels at P2 towards the end of the period correspond to bird noise, as can be seen on Figure 3.39.

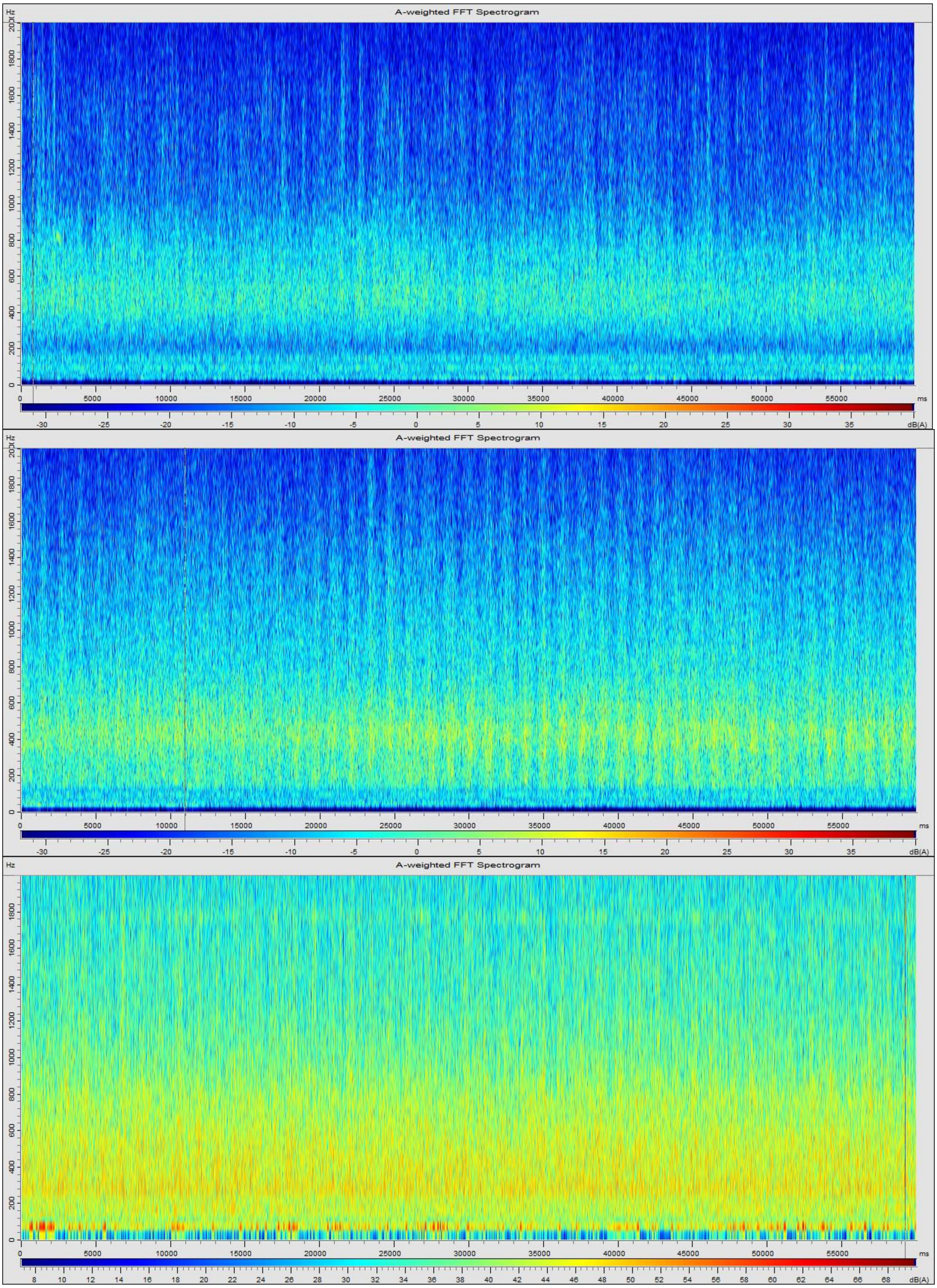

Figure 3.38 – A-weighted spectrograms for the modulation period shown in Figure 3.36: showing locations P2, P3b and B1 respectively (arbitrary scale).

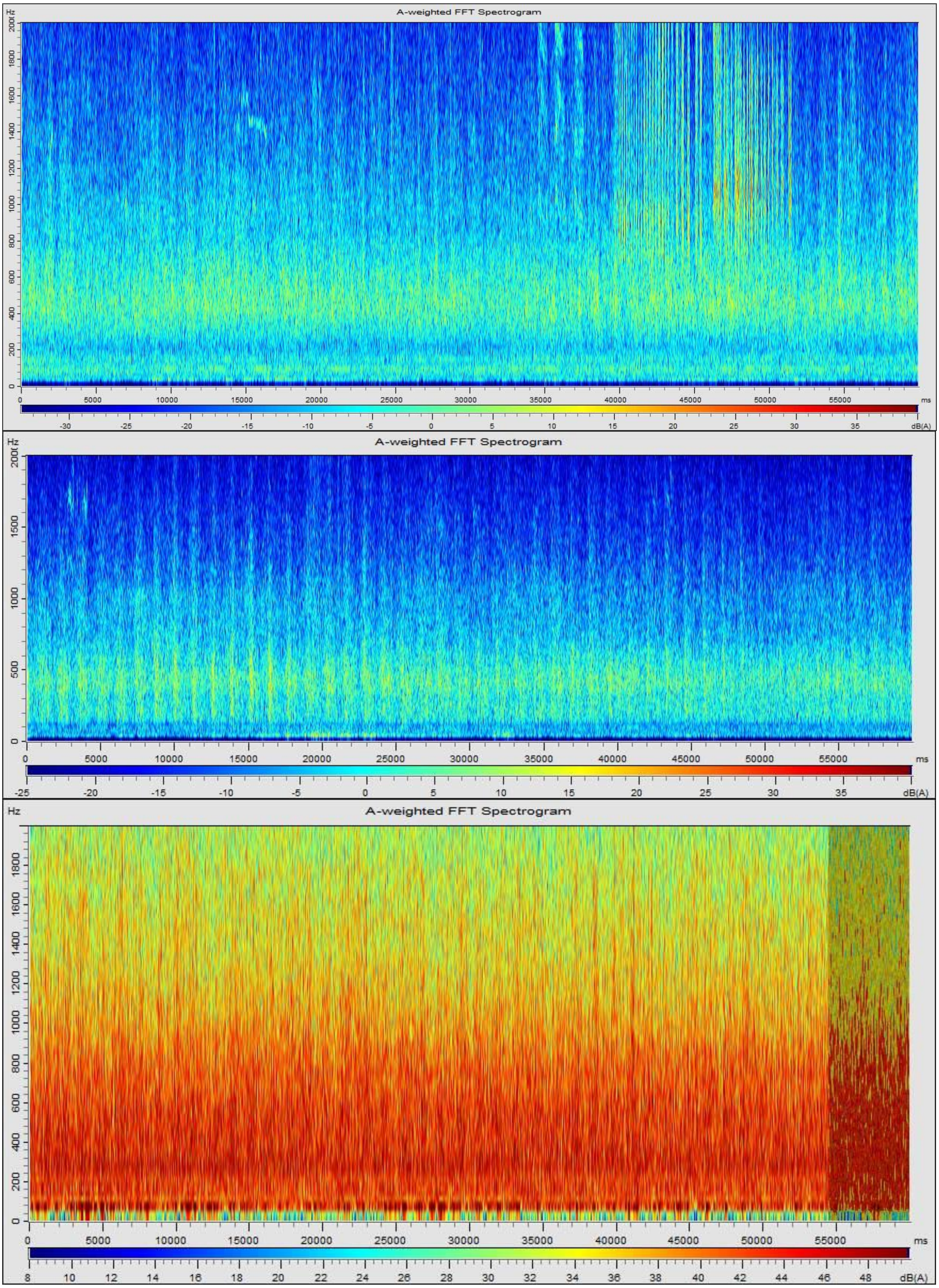

Figure 3.39 – A-weighted spectrograms for the modulation period shown in Figure 3.36: showing locations P2, P3b and B1 respectively (arbitrary scale).

3.10 Site B - conclusions

3.10.1 The measurement campaign undertaken at site B allowed a detailed study of the directivity and characteristics of 'other AM' noise. In the far-field, instances of clear AM were associated with propagation in the downwind direction and were reduced cross-wind. The effects in the near-field were more difficult to discern. Furthermore the AM levels in the far-field were strongly variable and did not seem to be simply associated with most of the operational or meteorological parameters considered. This suggests a strong influence of propagation effects. The AM increased downwind between the mid-field and far-field region, with a slight decrease further away (although the latter may be due to reduce signal strength). This is consistent with observations made by Di Napoli [9].

3.10.2 In addition to wind direction, the turbine generating output seemed the main associated variable related to the observed AM magnitude, in the sense that little modulation observed when the turbine was generating little (as could have been expected). In conditions of sufficiently elevated generation, rapid changes in the estimated relative angle of attack of flow on the blade did also appear to sometimes be a factor in enhanced AM depth, although the behaviour appeared complex.

3.10.3 These observations are not consistent with the "standard" modulation model, hence the use of the description "other AM". However, several of the observed features are consistent with some of the predicted outcomes of the detached flow theoretical model of WPA1. These are most notably that there is significant modulation in the far-field downwind (see WPA1 figures 19/21), the presence in some cases of a spectrum bias towards 200Hz and spectral differences between peaks and troughs. Although reduced modulation was observed in the mid-field, this may be attributed in part to ground reflection effects.

3.10.4 The observed far-field modulation was of a higher depth (more than 5dB(A) at times) than predicted in the standard model of WPA1, but it was noted that this prediction is highly dependent on the features of the detached flow source model (WPA1 figure 29) which was largely uncertain. The large modulation predicted in one cross-wind direction in the near-field (WPA1 figure 29), was also not observed (see Figure 3.4 for example), and this may again be a very specific feature of the particular model employed (turbine geometry etc.). Finally as noted in WPF, the model employed does not incorporate propagation effects and, because of the strong influence of such effects, it may be interesting to extend this model to include them, as in the work of Boorsma and Schepers [10]. Ground effects in particular may cause significant variations in response at varying source heights, receiver heights, separation distances and different ground types.

3.10.5 Because of the lack of detailed frequency measurements, the analysis was limited to evening and night-time periods, in which levels of human or bird-related activity decreased significantly, but these periods will also be those in which increased wind shear due to atmospheric effect will tend to be greater at this site, because of atmospheric stability effects. This was, however, clearly not a necessary condition as some periods of elevated modulation were observed as the wind increased and the wind shear decreased.

3.10.6 Thus other source mechanisms may be at play. It is also conceivable that particular blade designs could experience partial blade stall in certain conditions without the influence of non-uniform inflow conditions, as was assumed to trigger it in WPA1. For example, aero-elasticity effects may vary the blade geometry in such a way it departs significantly from its design conditions. There is, however, very limited information available to study this in the current state of knowledge.

3.10.7 It should be borne in mind that, on some sites, the impact of wind shear on effective modulation may be more important at (non-sheltered) residential location surrounded by vegetation. This is because increased wind shear will correspond to relatively reduced wind near the ground, and this will have an effect on the level of masking background noise which may otherwise reduce the effective modulation depth. The chosen monitoring locations were surrounded by negligible vegetation and therefore this effect was minimised in these measurements, but it likely represents a complicating factor in many other situations. This is because a lower signal-to-noise ratio will rapidly reduce the effective modulation measured.

3.10.8 As the effect of partial stall is posited and the effect of angle of attack of the flow appear significant for the study of “other AM”, the next section describes further tests which were undertaken at a site in which turbine pitch was directly varied and the effects measured.

4 SITE C – DEDICATED TRIAL MEASUREMENTS

4.1.1 This aspect of the project involved targeted measurements on a wind farm site using novel techniques to investigate the influence of turbine operation on the character of the AM noise produced, as informed by the results of the other work packages in this project.

4.1.2 In particular, the hypothesis raised in WPA1 that partial blade stall may lead to increased levels of modulation at large distance downwind warranted particular investigation. Considering this, along with the linked discussions in WPA2 and WPF, the influence of the turbine's pitch regulation system was considered crucial. In certain conditions the angle of attack of the flow on the blade may be such that stall occurs for part of the blade rotation. Although complex, this effect would be most sensitive to changes in the blade pitch, which would either increase or decrease the angle of attack and therefore affect the likelihood of stall.

4.1.3 Designing a measurement campaign capable of addressing the foregoing issues required detailed cooperation with turbine manufacturers. With this in mind, a meeting was organised in April 2011 with representatives of most of the major wind turbine manufacturers in Europe to present the preliminary results of the research undertaken to date. This was considered necessary in order to better understand and/or evaluate the functioning of the power-control and regulation mechanisms in modern wind turbines. It was also considered valuable to investigate in more detail the impact of modifications in the turbine operation on the character of the noise. A detailed knowledge of the blade geometry and operating condition is generally not available publicly because of commercial confidentiality considerations.

4.1.4 It was proposed to undertake tests in which the pitch of the turbine was controlled directly in order to attempt to trigger detached flow on the blade, and to assess the relative impact on far-field modulation. Similar manual pitch changes were undertaken in previous investigations [11], but these focused on overall sound power levels rather than modulation. The project team is not aware of such investigations having been undertaken previously.

4.2 Measurement description

4.2.1 The test site comprised a dozen pitch-regulated, variable speed turbines, located on a treeless moorland hill, amongst generally hilly terrain and valleys. The site was relatively isolated from any habitations, roads or settlements, and therefore exposed to relatively low levels of noise from human activity.

4.2.2 A single turbine was selected as a test turbine. It was selected as being relatively isolated from the rest of the wind farm, and at a location from which measurements could be undertaken at increasing distance downwind (under prevailing wind directions) whilst moving away from most of the wind farm site, thus minimising the need for extensive turbine shutdowns, which would have been more difficult to justify and secure.

4.2.3 Noise monitoring equipment was installed at seven locations surrounding the test turbine for the duration of the testing, focusing on the downwind direction, at distances of up to 1km from the test turbine. These locations are represented on Figure 4.1 and listed in Table 4.1.

4.2.4 01dB Duo integrating sound level meters with audio recording were used at six of the measurement locations (L2-L7). Two of these systems were installed at crosswind positions either side of the test turbine at a distance of approximately 1 RD (L6 and L7). Three more systems were installed at positions downwind of the test turbine at various distances of up to 1km (L2-L5). As shown in Figure 4.2, the most distant downwind location (L4) was located across a valley; it experienced the influence of noise from a water-course at the bottom of this valley. The remaining system (L5) was installed at a cross-wind location which was in a relatively sheltered location, which experienced partial terrain shielding from the test turbine.

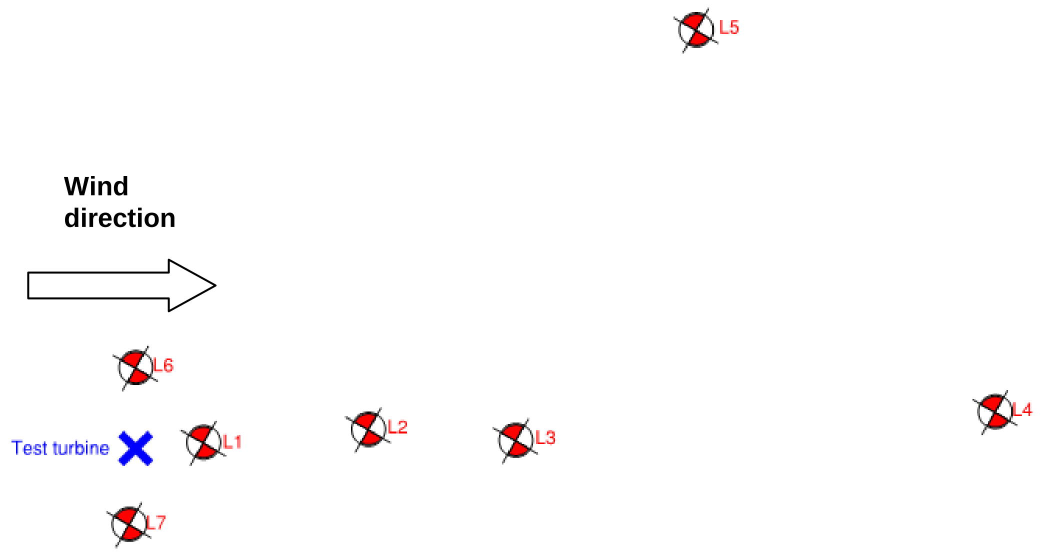

Figure 4.1 – Schematic representation of the different measurement locations at site C

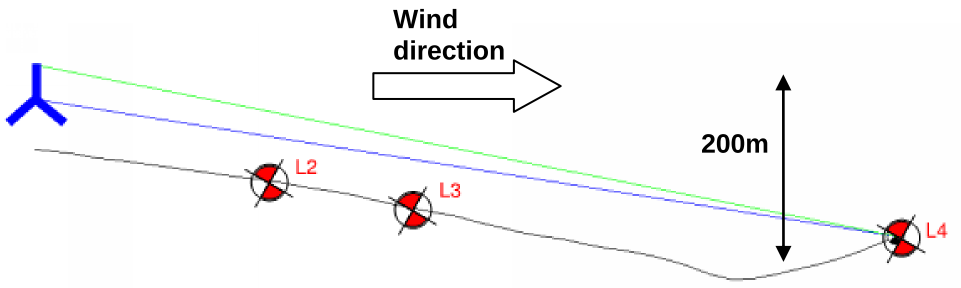

Figure 4.2 – Vertical ground profile between the test turbine and location L4 and altitude differences (schematic representation of turbine hub and tip height)

Location	SLM type	Serial number	Distance from test turbine
L1	01dB Blue Solo	61760	81m (down wind)
L2	01dB Duo	10346	271m (down wind)
L3	01dB Duo	10341	441m (down wind)
L4	01dB Duo	10345	1040m (down wind)
L5	01dB Duo	10340	815m
L6	01dB Duo	10374	96m (cross wind, upstroke)
L7	01dB Duo	10348	81m (cross wind, down-stroke)

Table 4.1 – noise monitoring locations installed

4.2.5 The Duo systems were mounted on tripods with the microphone height at approximately 1m from the ground. The microphones were fitted with primary and secondary wind shields. Each system was connected to a 12V external battery which was also used to weight down the tripod to avoid toppling in high winds. However due to a manipulation error, the system at location L7 did not record any data for the measurement period.

4.2.6 A final measurement system was installed downwind at location L1, approximately 1RD from the test turbine. This comprised a single 01dB Blue Solo sound level meter, configured in conjunction with a low power computer running the 01dB “dBTrig” measurement software and housed in an environmental enclosure. This location was used to conduct measurements of the effective turbine sound power levels, with reference to the guidance in the IEC 61400-11:2003 standard, although the latter was not strictly complied with. This system was configured with the microphone mounted on a circular ground board and was fitted with primary and secondary windshields. All sound level meter systems meet with the requirements of a Type 1 sound level meter. Each system was set up to undertake simultaneous and synchronised noise level recordings, including L_{Aeq}, L_{AF} and third-octave band frequency data between 6.3Hz and 20kHz, every tenth of a second, as well as near-continuous audio recording with an audio sampling rate of 12.8 kHz.

4.2.7 In addition to the noise monitoring equipment, a dedicated data logger was prepared by HLA, in consultation with the turbine manufacturer, in order to capture turbine operational data with a resolution of 1s. It was therefore possible to obtain data on the respective generating power, rotor blade pitch, yaw (turbine orientation) and wind speeds (measured at hub height) with a 1s resolution. Unfortunately data on the turbine rotational speed was not captured in this instance.

4.2.8 All HLA noise and SCADA measurements systems were set to the same time reference by their synchronisation with Greenwich Mean Time (GMT). This was achieved through the use of a global positioning system (GPS) receiver or the internal GPS receiver of the Duo systems. All equipment was set to run continuously so that tests could be conducted without delay once the required wind conditions occurred.

4.3 Test procedure

4.3.1 During testing, turbine engineers could use specifically-developed turbine operational modes to vary the pitch of the turbine blade at a range of integer pitch angles three degrees either side of the default standard pitch setting for the turbine. Note that, in the convention used in this case:

- the standard pitch setting during conditions present for most of the test was -1 degrees;
- decreasing the pitch (down to a minimum of -4 degrees) would mean increasing the relative angle of attack and therefore the likelihood of blade stall;
- increasing the pitch would tend to reduce the angle of attack, which is what is done at high wind speeds to regulate the power generation of the turbine.

4.3.2 It was expected by the manufacturer that the lowest setting would correspond to blade stall conditions. Due to the operating restrictions of the turbines and safety consideration, such tests could only be conducted during particular weather conditions. The main requirement was of not exceeding a certain wind speed threshold, above which the power regulation requirements would automatically over-ride any manual pitch settings entered in the control system. Of course completely calm conditions would not have been suitable either. It was also necessary to experience certain wind directions because of the practical constraints and measurement layout outlined above. The SCADA data analysis described in the Annex to this report suggested that this range of wind speed would be suitable to the pitch investigations as relatively high angle of attacks were calculated.

4.3.3 As a consequence of these requirements, the window of opportunity for conducting the tests was limited, with several abortive attempts to measure being made. This section of the report describes a test which was undertaken several months later, over a period in which conditions were anticipated to be more favourable. Strong winds were still dominant for most of the three days when the testing equipment was installed. It was nonetheless possible to undertake two measurement test sequences on the second day of the measurements. Although further testing may have provided useful supplementary data, this was not undertaken as this would have delayed the current project still further, the project already having been delayed to accommodate the tests reported herein that were undertaken on Site C.

4.3.4 Each test sequence consisted of successive periods of approximately 5 minutes in which the pitch angle was varied in steps of one degree. This was so that the full range of pitch angles could be tested before wind conditions changed significantly. During each test, the nearest two turbines to the one tested (located approximately 400m upwind) were switched off. This was done to minimise the influence of the rest of the wind farm at most locations, but at the most distant locations, such as L4 or L5, the separation distance from the test turbine was more comparable to that of other, operating turbines and a residual influence of these other turbines could not be excluded. For example, one turbine was operating at approximately 1.5km from location L4, compared to the distance of 1km from the test turbine.

4.4 General considerations

4.4.1 Due to the hilly nature of the terrain at the site, it was not considered likely to experience strong levels of wind shear. An analysis of the 10 minute wind speed data collected at two heights over a period of several months at the site's permanent meteorological mast showed that, even if excluding periods of negative shear, the shear exponent coefficients (defined in 3.6.6 and WPA2) averaged over different hours of the day did not typically exceed 0.2 (as compared with site B where values of up to 0.4 to 0.5 were experienced at times, see Figure 3.22).

4.4.2 The nature of the site means that it will tend to experience complex flow in certain conditions, although detailed turbulence data was not available. The test turbine was situated downwind of a hill as the ground climbed up to about 100 m more in the up-wind direction. Based on the analysis of WPA2, it was thought that these complex flow conditions may trigger blade stall at times, even in the absence of high wind shear conditions, particularly when the pitch of the turbine was decreased. Whilst undertaking measurements on site, sporadic 'thumps' were audible from some of the turbines at times, although these were quite rare: these observations may consistent with the occurrence of complex flow, or large-scale turbulence triggering blade stall.

4.4.3 As in previous sections, a systematic analysis of the modulation level measured at the different locations was undertaken using the same AM metric routine described above, with the MATLAB software. This was based on the recorded short-term history of measured noise levels at each of the noise monitoring locations. This systematic analysis was verified using a review of recorded levels and audio samples. The analysis was first done on the basis of the A-weighted levels $L_{Aeq,100ms}$, but excessive contamination from spurious sources was encountered, in particular at the most distant location (L4) which was affected by water-course noise. The recorded time-history of 315 Hz levels provided by the sound level meters was then used instead, as it was established that this provided a more accurate measure of the amount of modulation experienced at the different locations.

4.5 Test sequences

4.5.1 On the main day of testing, wind speeds at the site reduced sufficiently at times so that meaningful tests could be undertaken. A first test sequence was undertaken shortly after 15:00: with the pitch increased from -4 to +2 degrees in 1 degree steps. The recorded history of 1 second pitch values recorded by the data logger is shown in Figure 4.3. It can be seen that deviations from the proposed setting were experienced at times: this was due to gusts of wind increasing above the threshold meaning the turbine control system needed to override the settings.

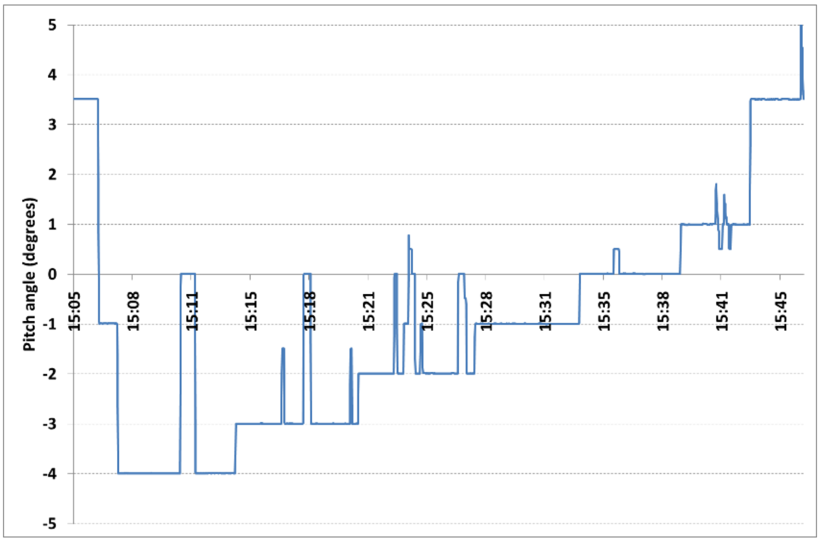

Figure 4.3 – Evolution of the pitch during the first test sequence

4.5.2 This test was aborted when the wind increased again. Even when rejecting the short excursions periods, it was difficult to exclude their potential effect in the analysis, particularly given the test duration. This meant that the results of this first test were not considered conclusive and they are therefore not considered further here.

4.5.3 A second test sequence was initiated remotely later this day: see Figure 4.4. The range of pitch values in this sequence was wider and more comprehensive, and the analysis will therefore focus on this period. Short deviations from the desired pitch setting and any disturbance in the measurement were excluded from the subsequent analysis.

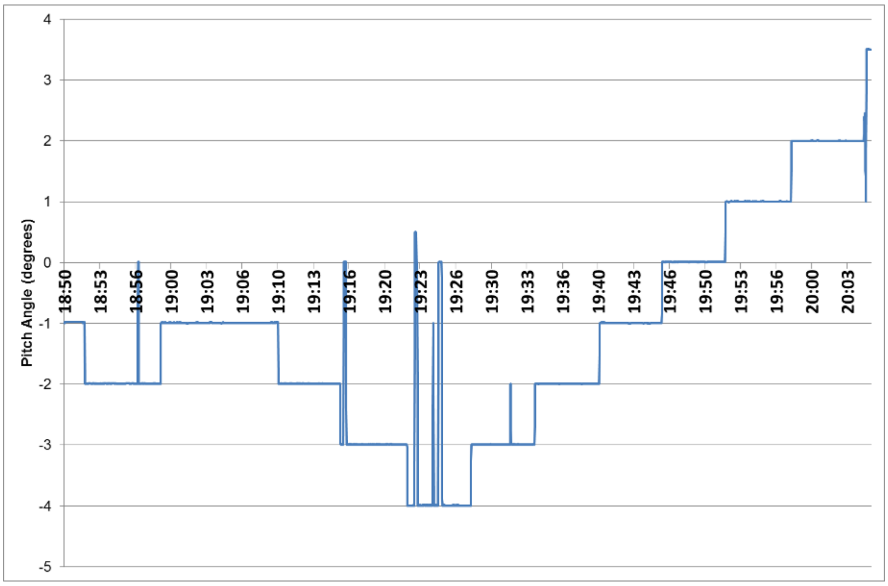

Figure 4.4 – Evolution of the pitch during the second and main test sequence

4.6 Relative sound power analysis

4.6.1 For the measurements undertaken on the ground-board mounted microphone at location L1, an apparent sound power was calculated from the measured L_{Aeq} levels by subtracting 6dB and correcting for the slant distance to the turbine. Although this was clearly done with reference to the IEC 61400-11 standard, the aim was to assess relative changes in the overall sound power of the turbine in different conditions, and not to undertake an assessment of the absolute sound power level of the turbine. Some effective deviations from the standard requirements were made, such as the distance from the turbine and the windshield system used, because of practical considerations.

4.6.2 The evolution of the apparent A-weighted sound power level (L_{wA}) with time is shown in Figure 4.5 below, both on a 1 second basis and for 1 minute averages (as suggested in IEC 61400-11). The corresponding evolution of the pitch setting is also shown, and this graph suggests that the lowest pitch setting tend to correspond to elevated values of L_{wA}. Significant variability is however visible, which can be explained by short-term variations in the hub height wind speed. This was established by calculating the wind speed from the generating power of the turbine using its power curve (in accordance with the IEC 61400-11 standard). If L_{wA} is plotted as a function of the 1 minute wind speed at hub height, standardised at 10 m height in accordance with the 61400-11:2003 standard, the relationship becomes clearer: see Figure 4.6.

4.6.3 This shows that elevated levels of overall noise were produced by the test turbine for the lowest pitch setting (-4 to -3 degrees in particular), which represents an indicator of the extensive presence of stall on the blades, as expected. This was also consistent with subjective impressions on site in a “roaring” type of noise when these settings were in place. It would therefore follow that increasing the level of pitch further may be conducive to *partial* blade stall, which (according to the model of WPA1) would correspond to elevated levels of “other AM”. For all pitch values of -1 and above, similar overall sound power levels are observed.

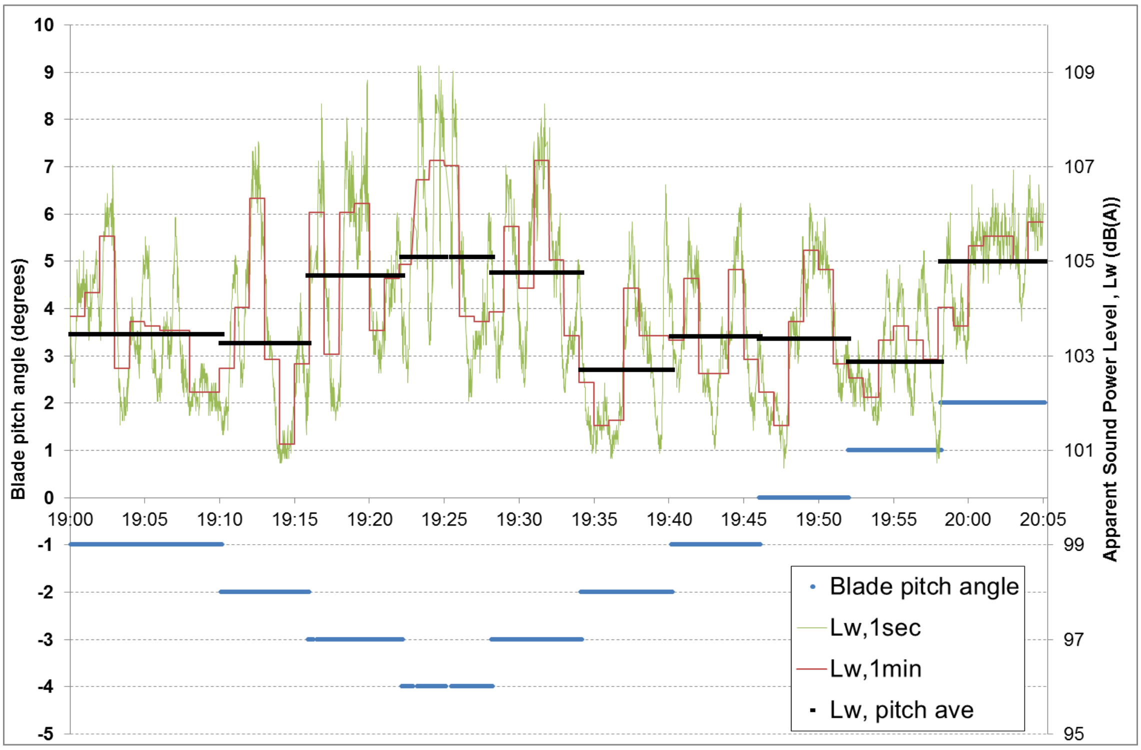

Figure 4.5 – Evolution of the pitch and apparent sound power level (in 1 second or 1 minute averages) during the main test sequence, with averages shown for each pitch step

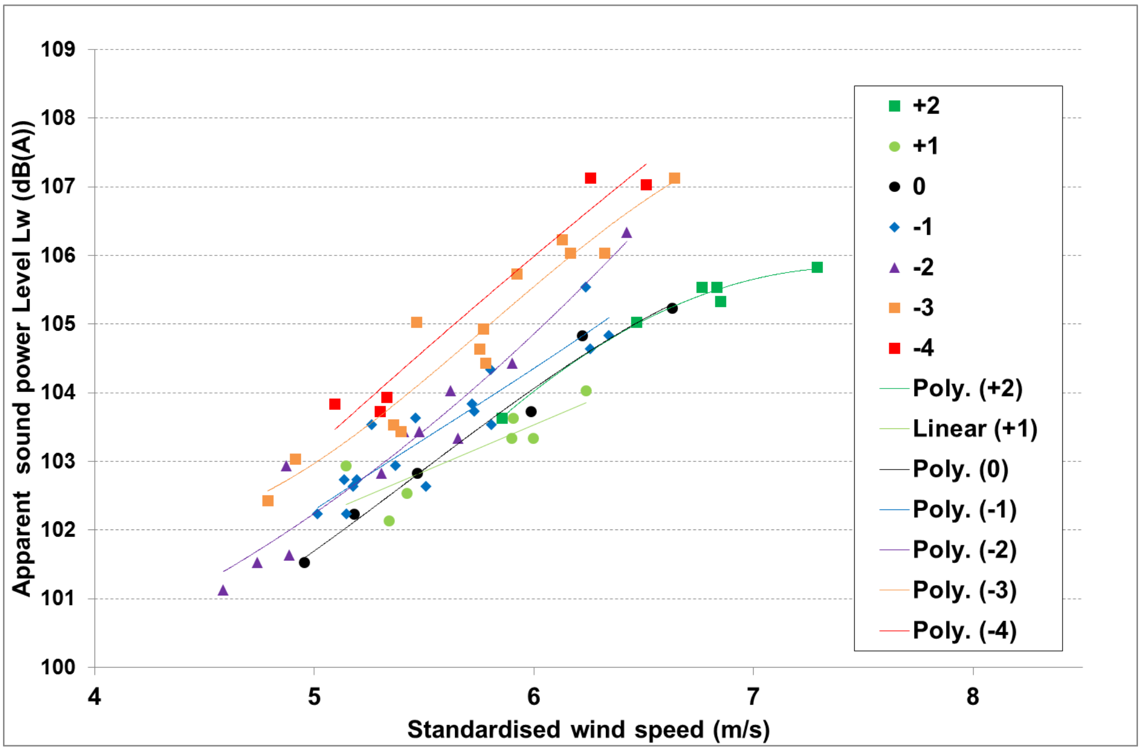

Figure 4.6 – Apparent sound power as a function of standardised wind speed for different pitch settings in the main test sequence, and trend-lines obtained by regression analysis

4.7 Modulation analysis

4.7.1 Figure 4.7 presents a comparative example of the analysis of AM for a three-hour period (which included the test period) at the most distant location (L4) based on either the A-weighted data ($L_{Aeq,100ms}$) or the 315 Hz 1/3 octave band levels (in 10s periods). The technique used is the same as above and described in section 2.6. This illustrates the effectiveness of the filtering in eliminating spurious sources from the analysis, most of which appear as horizontal lines in this plot, when all "modulation frequencies" are affected; sometimes the effect of spurious sources results in a more general masking effect which is more difficult to detect.

4.7.2 In this case, short-term turbine rotational speed data was not available to verify if the modulation frequency obtained was correct (as was done for site B), but the turbine's rotational speed was relatively constant during the test period, as can be seen on Figure 4.7. Furthermore, given the limited duration of the test, a manual review of the AM peaks identified could be undertaken to limit the amount of potential negatives.

4.7.3 The evolution of the values of AM ratings (for each 10s analysis period) are shown for the main test sequence, along with a graph showing the evolution of the pitch values during the test, in Figure 4.8 to Figure 4.12 for all measurement locations. An average was calculated of the AM rating values (dB) obtained for each of the 5-minute pitch stepping periods. To represent the incidence of the highest AM values, as obtained within each 5 minute step, the 90th percentile (top 10%) of the AM values are considered separately (in purple) and a separate average made.

4.7.4 Although some sporadic periods of high AM are recorded throughout, the prevalence of these events appears to increase significantly as the pitch decreases, particularly for "intermediate" values (-2 or -3 degrees). It can be noted that, for example in Figure 4.10, the trend appears broadly symmetric relative to the evolution of the pitch setting, which suggests a systematic effect. This would be consistent with an enhanced likelihood of partial blade stall caused by a progressive increase in the effective angle of attack of the flow, and triggered by complex flow events such as wind gusts or large turbulent structures.

4.7.5 The incidence of modulation did not appear to decrease significantly when the pitch angle increased further beyond 0 degrees. The picture is made more complex overall by the presence of sporadic AM at times, which may be caused by isolated events of non-uniform flow, caused by the complex flow present at the site. The influence of other turbines, situated further away, could also not be completely excluded and was observed at times whilst on site during the first test. The effect in the near-field (location L6, Figure 4.8) was more limited, as is predicted in WPA1, although a marked change was observed at the lowest pitch setting.

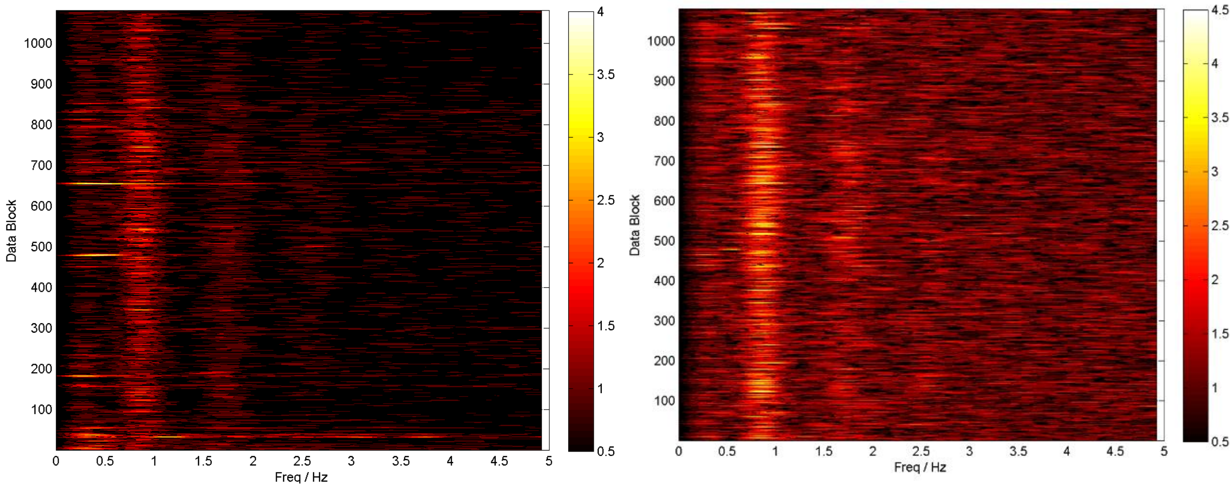

Figure 4.7 – AM Analysis for the data at location L4 (1km) for the period 18:00-21:00, based on the analysis of $L_{Aeq,100ms}$ levels (left) and 315 Hz 1/3 octave band levels (right)

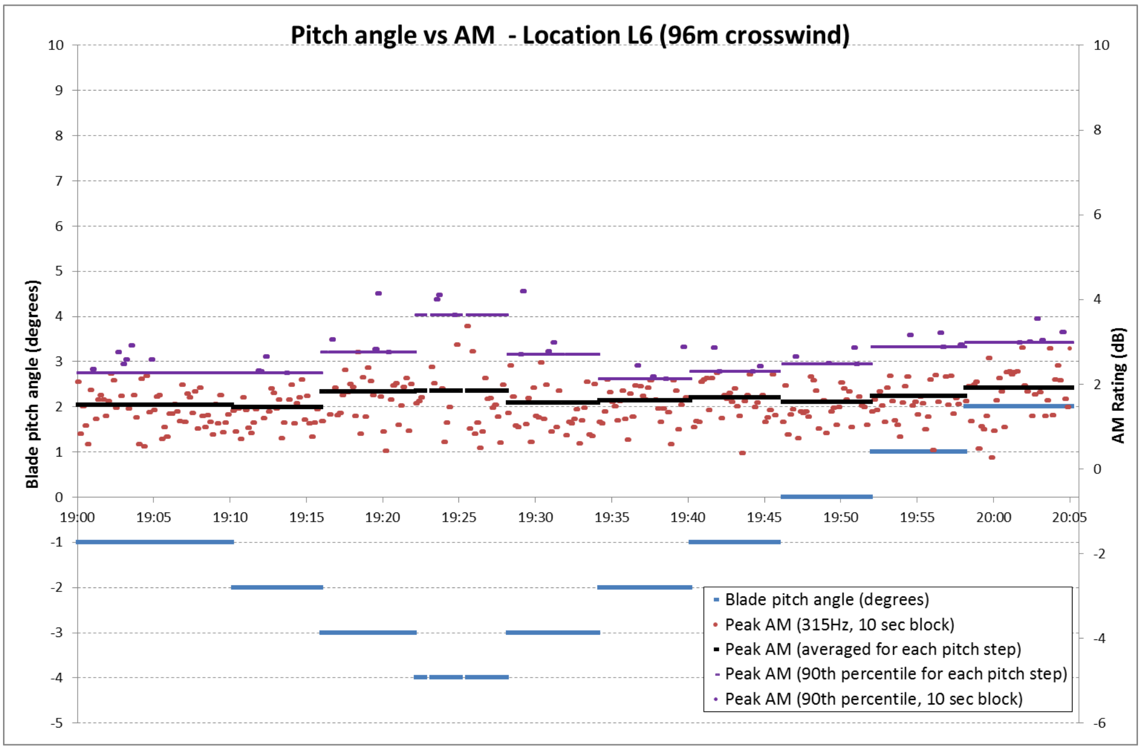

Figure 4.8 – Evolution of the AM rating (including top 10%) for each pitch step period – L6

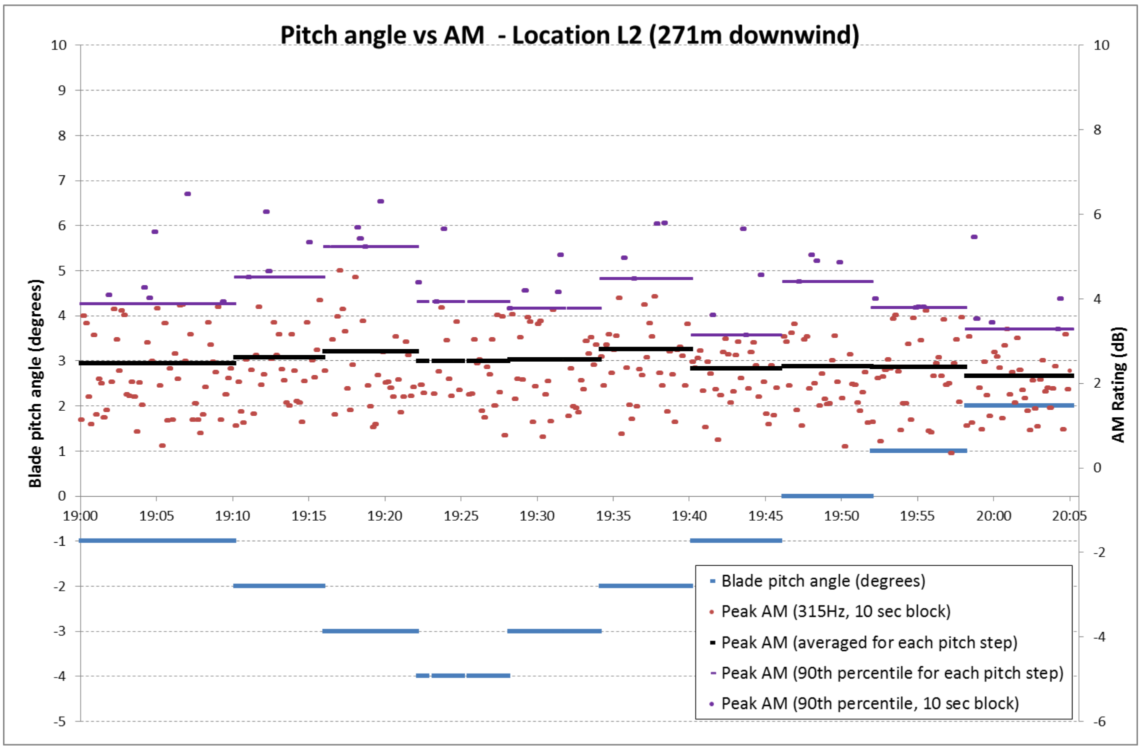

Figure 4.9 – Evolution of the AM rating (including top 10%) for each pitch step period – L2

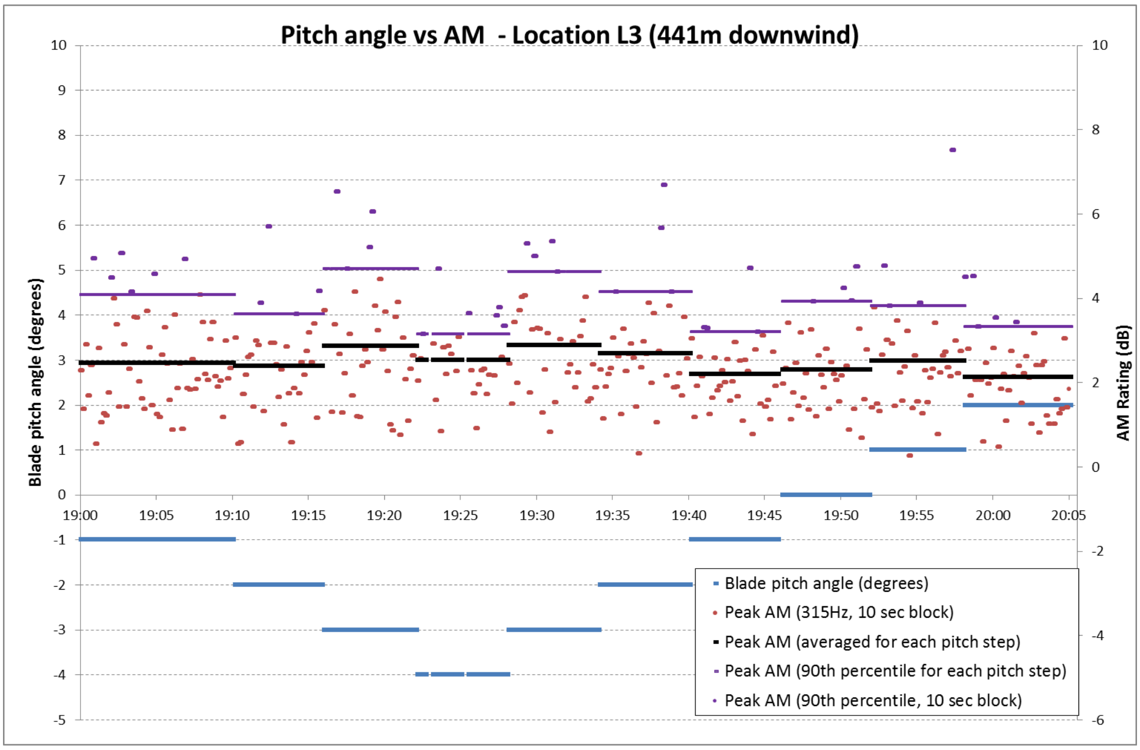

Figure 4.10 – Evolution of the AM rating (including top 10%) for each pitch step period – L3

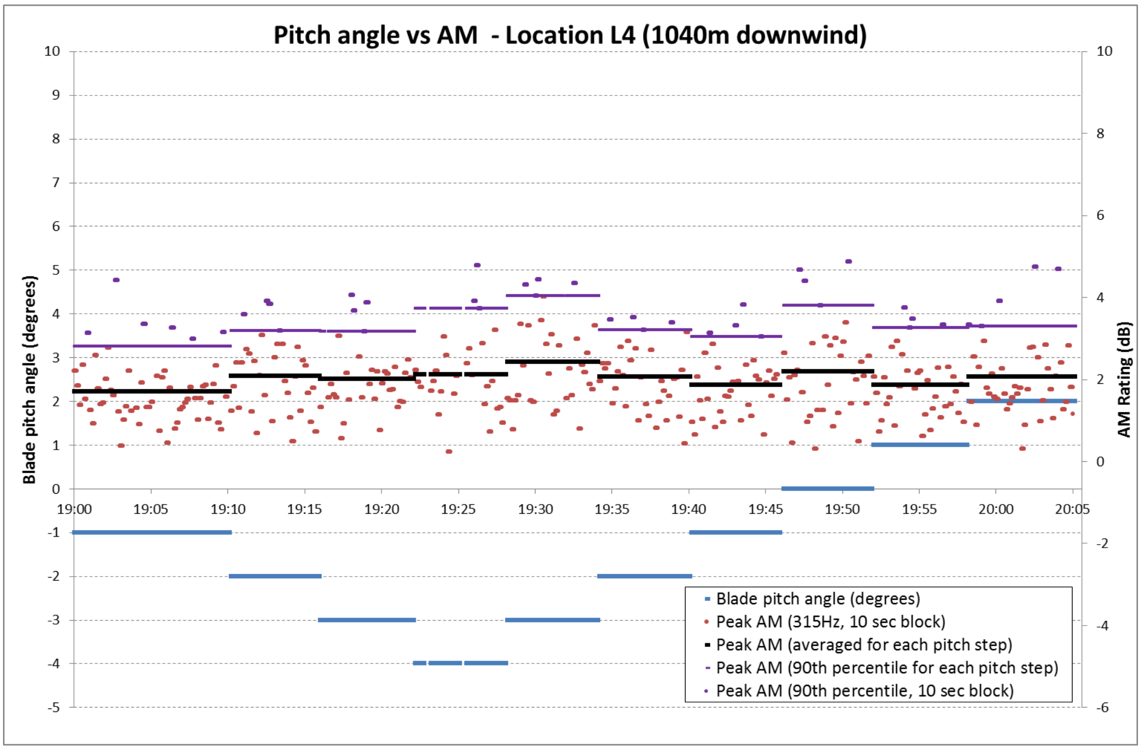

Figure 4.11 – Evolution of the AM rating (including top 10%) for each pitch step period – L4

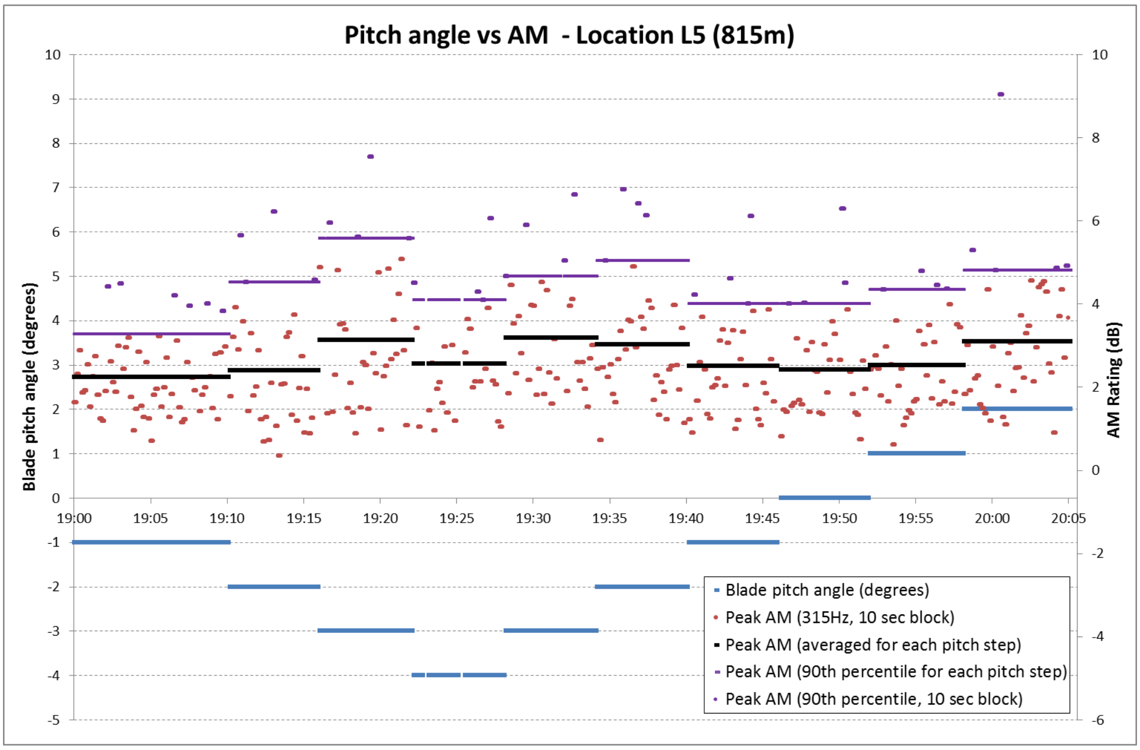

Figure 4.12 – Evolution of the AM rating (including top 10%) for each pitch step period – L5

4.8 Site C - conclusions

4.8.1 The measurements on Site C were undertaken in a highly targeted manner in an attempt to elicit information that could not be gained from the types of measurements undertaken at Sites A and B. The additional factor which was within the control of the project team (via the wind turbine manufacturers) at Site C compared with Sites A and B was the ability to control the pitch of the turbines away from their standard design settings. In this manner the effect of angle of attack of the turbine blades on radiated noise could be studied.

4.8.2 The primary aim at Site C was to confirm the hypothesis that separated flow (i.e. stall) would consistently result from too high an angle of attack. Further, it was desired to test the suggestion that, around the angle of attack where the transition between fully separated and attached flow occurs, there exists an increased likelihood of localised flow separation (transient stall) giving rise to an increased likelihood of other AM.

4.8.3 In order to positively test for the occurrence of stall, either in the form of totally detached flow or in the form of localised (transient) stall, ideally what is required would be pressure measurements or stall flags on the surface of the blades themselves. However, this was not possible within the scope of the project, so reliance had to be placed on the noise data in order to establish any changes to the radiated noise that may indicate stall. In order to achieve the foregoing aims, a test turbine was selected and installed with a high resolution data acquisition system which was set up to record the key turbine operational parameters at 1 second intervals. Audio recording and logging noise measurement systems were located at a total of 7 noise monitoring locations around the test turbine, at various distances ranging from approximately 80 m to 1000 m in both downwind and cross-wind positions relative to the test turbine.

4.8.4 Ideally the measurements would have been undertaken over extended periods such that more data could be obtained to enable a more complete statistical analysis to be undertaken on the measurement data. In this manner the significance of the relationship between potential causes and effects could have been better established. However, due to the need to avoid controlled blade pitching during conditions of higher wind speeds, it was only possible to undertake two runs of these tests during which the pitch of the blades was altered from +2 degrees to -4 degrees, as compared to the ideal design pitch for the test conditions which was approximately -1 degree.

4.8.5 Notwithstanding the practical limitations just described, the limited extent of the acquired data still allows a useful analysis of the effect of changing blade pitch. In terms of overall radiated noise levels, a systematic change in noise levels was measured as a result of re-pitching the blades away from their optimum design pitch. Negative blade pitching moved the blades closer to stall, and by the point at which the blades were pitched to -4 degrees the ‘roar’ of stall noise became subjectively quite apparent. This was reflected in the increased level of sound power which was measured under these same conditions when compared with optimally pitched or positively pitched blades. Around the ‘transition’ pitch angle of -2 to -3 degrees, the likelihood of the existence of intermittent AM noise (as opposed to the more continuous roar of stall noise) became subjectively more apparent. The increased prevalence of such AM noise under these same conditions was also confirmed by measurements. However, there was no single pitch setting in which a total absence of AM occurred. This may be due to the complexity of the site or, more likely, from AM arising from other operational turbines (other than the test turbine) which remained operational throughout the measurement period.

4.8.6 As a final conclusion and recommendation, the tests at Site C have confirmed the effect of blade pitch on the potential for inducing or reducing the chances of AM occurring. However, more extensive test measurements would be required, under much more closely controlled conditions, and ideally also including blade surface measurements, in order to positively identify when stall occurs and therefore to enable firm conclusions as to the use of pitch variations to positively control AM.

5 CONCLUSIONS

5.1.1 The objective of work package D was to undertake additional measurements to supplement the data available as part of the other work packages, and in particular work package C. As a consequence of the output of other work packages, it was decided that the best approach would be to undertake a series of measurements across three sites, with a very different approach to the measurements being undertaken at each site:

- At Site A measurements were undertaken at residential dwellings where AM noise issues had been reported by the residents. Noise measurements were undertaken at two dwellings in the absence of any other operational data from the wind farm and the data obtained used to test the AM metric routine developed under work package B1;
- At Site B detailed measurements of noise at multiple locations aroud the test turbines, meteorological conditions and turbine operational data were undertaken on a wind farm site. The opportunity was provided for the switching on and off of various turbine combinations, but no control was provided for manually varying the operational parameters of the turbines.
- At Site C multiple noise measurements were undertaken around a test turbine (located within an operational wind farm) together with turbine operational data. The opportunity was provided to manually control the blade pitch settings of the test turbine away from its optimal design setting such that the effects on noise output of inducing full or partial stall could be established.

5.1.2 The results obtained at all sites have reaffirmed the point that the measurement of wind farm noise, particularly in the far field, is made difficult because of the relatively low acoustic power of the source and the dependence on wind conditions, both in terms of propagation effects and background noise effects, both of which can reduce the signal to noise ratio and thus the consequent utility of the measured data.

5.1.3 However, the test results have also confirmed that the incidence of “other AM” was most readily detectable in the far-field locations. This therefore represents a significant additional challenge for detailed measurements studies, which is probably one of the main factor which has limited the progress made in the subject to date. Compared to the assessment made in the near to mid-field (such as for sound power testing or previous modulation studies [12]), assessments in the far-field are complicated by the dominance of propagation effects and the masking of other sources.

5.1.4 Notwithstanding these measurement challenges, analysis of the results obtained at all sites have shown that the type of analysis techniques which have been described and developed as part of other work packages of this project can be realistically and meaningfully applied to both detect and rate the levels of modulation in the far-field noise from wind turbines, even in complex rural environments in which wind turbine noise can often be difficult to detect (let alone characterise in detail). In particular, the main AM metric routine described in WPF was systematically used at each of the different sites and proved effective in both detecting and rating the magnitude of the modulation.

5.1.5 In particular, the use of measured data in specific 1/3 octave band characteristic of the modulation has been successfully demonstrated to enable most spurious sources to be efficiently excluded from the analysis, without the excessive practical difficulties involved with continuous audio recordings. But even using these techniques for a carefully filtered and scrutinised analysis of a real measured dataset in a typical rural environment will produce values of the AM rating metric of up to 2 dB (with a limited amount of sporadically higher values) even in the absence of any significant modulation. This is mainly due to residual noise, uncertainties associated with digital processing and the integration process used, and should be borne in mind when applying such techniques. Perhaps counter-intuitively, the differences between the longer-term L_{Aeq} and L_{A90} did not deviate significantly from values of 1.5 to 2.5dB typical of general wind turbine noise, and this cannot therefore represent a good indication of the presence of OAM.

5.1.6 Based on the various measurement results, and particularly those at Site B, it has been concluded that the general characteristics of other AM noise are consistent with the characteristics identified by WPA1 which assume the directivity and spectral characteristics of stall noise, thus exhibiting a significantly increased effect in the downwind direction from the wind turbine.

5.1.7 In particular, the measurement campaign undertaken at site B allowed a detailed study of the directivity and characteristics of 'other AM' noise. In the far-field, instances of clear AM were associated with propagation in the downwind direction and were reduced cross-wind. The effects in the near-field were more difficult to discern, although the expected presence of normal AM was clearly characterised by higher modulation depths, of up to 5 dB, in the cross-wind direction compared to reduced levels downwind. Furthermore the AM levels in the far-field were strongly variable and did not seem to be simply associated with most of the operational or meteorological parameters considered. This suggests a strong influence of propagation effects. The measured AM increased downwind between the mid-field and far-field region, with a slight decrease further away (although the latter may be due to reduce signal strength). This is consistent with observations made by Di Napoli [9].

5.1.8 The reported test measurements have also enabled the testing of various other hypotheses that have variously been proposed as possible causal mechanisms for other AM. Whilst the results cannot generally rule out any of these as potential contributory factors, they can confirm the ability of other AM to exist in situations where the factors are known not to contribute. In summary, significant other AM has been measured under conditions of:

- low wind shear;
- low wind veer;
- uniform turbulence;
- single operational turbines (i.e. no interaction effects);
- on both flat and hilly sites;
- turbines with high tower to rotor diameter ratios (see WPC).

5.1.9 The only positively identified association between the occurrence of other AM is that of power generation and changes in angle of attack (as per Sites B and C).

5.1.10 The tests at Site C have confirmed the effect of blade pitch on the potential for inducing or reducing the chances of AM occurring. It is therefore recommended that more extensive test measurements are undertaken, under much more closely controlled conditions, and ideally also including blade surface measurements, in order to positively identify when stall occurs and therefore to enable firmer conclusions as to the potential use of pitch variations or other mitigation solutions to positively control AM.

5.1.11 Other source mechanisms may be at play. It is conceivable that particular blade designs could experience partial blade stall in certain conditions without the influence of non-uniform inflow conditions, as was assumed in WPA1, to trigger it. For example, aero-elasticity effects may vary the blade geometry in such a way it departs significantly from its design conditions. There is, however, very limited information available to study this in the current state of knowledge.

5.1.12 It should also be borne in mind that, on some sites, the impact of wind shear on effective modulation may be more important at (non-sheltered) residential location surrounded by vegetation. This is because increased wind shear will correspond to relatively reduced wind near the ground, and this will have an effect on the level of masking background noise which may otherwise reduce the effective modulation depth.

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ANNEX – SCADA DATA ANALYSIS

In most cases, detailed information on the operation and power regulation of particular turbines will be proprietary and subject to commercial confidentiality considerations. A full analysis would also require a very detailed knowledge of the turbine and blade geometry, internal working, etc. This becomes particularly complex for pitch-regulated turbines

But a qualitative and outline analysis can be made, based on summary data typically available from the turbine Supervisory Control And Data Acquisition (SCADA) system. This may assist in evaluating the implications of different modes of operation of a turbine and assess the potential impact this could have on the effective angle of attack of the flow on the blade. This can be done in practice based on the 10-minute average data which is typically available from wind turbine SCADA system: this may highlight relevant trends, although this would of course miss short-term changes and be subject to additional variability.

As a simplification of the full assessment of inflow angle as detailed in WPA1 [2], we can consider a relative angle of attack of the flow on the blade, based on the ratio of the apparent rotational speed and the incident wind speed on the turbine rotor. Given the considerations in WPA1, it seems natural to consider evaluating this at a point on the blade rotation typical of where blade source noise emissions tend to be maximal and where any blade stall would be more likely to occur: at 75% of the rotor radius, at a distance of $d_{75\%} = 0.75\,R$, where R is the turbine Rotor diameter.

For each (10 minute) period i, if the rotor rotational speed is $RPM(i)$, the corresponding apparent wind speed $V_{75\%}$ due to the blade velocity at $d_{75\%}$ is given by:

$$V_{75\%}(i) = 2\pi \mathrm{d}_{75\%} \frac{RPM(i)}{60}$$

We can then consider this in relation to the incident wind speed, generally measured by the turbine at the hub height (HH): $V_{HH}(i)$. In practice, because the wind is slowed down by the rotor, the effective incident wind speed will be reduced according to a certain induction factor. As discussed in WPA1, there are some complex considerations there to take into account, but as a reasonable starting the purpose of an approximate analysis, a factor of $A = 0.2$ (corresponding to 20%) is assumed. If, for period i, the blade pitch $\mu(i)$ (in degrees) is also known, this can be taken into account. The relative estimated angle of attack $\alpha(i)$ would therefore be given by:

$$\alpha(i) = \ tan^{-1}\left(\frac{(1-A)V_{HH}(i)}{V_{75\%}(i)}\right)\frac{180}{\pi} - \mu(i)$$

Please note that the above assumes the convention that an increase in the pitch μ corresponds to a decrease in the angle of attack, which might not be the case for all control systems.

This effectively assumes that the incident wind speed on the rotor is uniform. To take into account the actual effects of non-uniform flow due to wind shear may be more realistic in some cases. If the wind shear exponent $m(i)$ is known by measurements or estimated based on long-term data, we can then consider, instead of $V_{HH}(i)$, the actual wind speed at $d_{75\%}$, when the blade is at top dead centre (TDC), as this will then be the worst case under this assumption. In the above equation, we would then replace $V_{HH}(i)$ by:

$$V_{75\%}(i) = V_{HH}(i)\left(\frac{HH + d_{75\%}}{HH}\right)^{m(i)}$$

And therefore this results in a modified angle:

$$\alpha'(i) = \ tan^{-1}\left(\frac{(1-A)V_{75\%}(i)}{V_{75\%}(i)}\right)\frac{180}{\pi} - \mu(i)$$

It can be useful to then consider the variation of *α* or *α'* as a function of the hub height wind speed or, for a variable speed machine, the turbine rotational speed (after exclusion of spurious periods such as those when turbines were not operating). This may highlight particular operating conditions in which the angle of incidence of the flow, and therefore the potential for partial blade stall, increases significantly. It should be noted that this analysis should be considered quantitative and relative, and that the calculated *α* values not necessarily directly indicative of actual flow angles, as the effects of blade geometry and twist and actual flow induction are not considered.

This represents the basis of the analysis undertaken in this report. An example is shown below, with or without incorporating wind shear effects: Figure A.

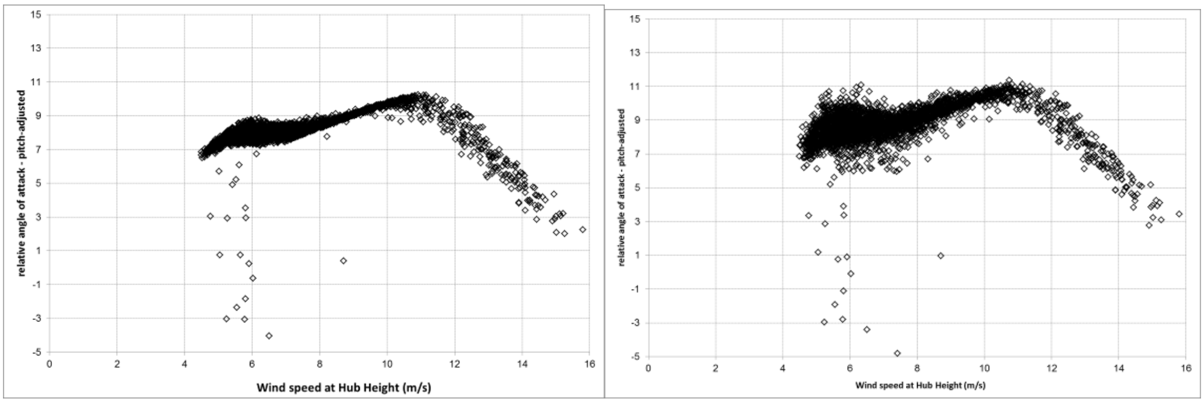

Figure A – example of calculated relative angle of attack calculated as a function of wind speed, with and without the inclusion of wind shear effects. This highlights in this example an effective increase of angle of attack at lower wind speeds.