

# SITE EXPERIENCE WITH WIND TURBINE NOISE AM ANALYSIS

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## 1 INTRODUCTION

The publication in 2016 of the IOA Method for rating amplitude modulation (AM) in wind turbine noise<sup>1</sup> has allowed long term analysis of AM from wind turbines to be carried out at various sites. Most of these sites are existing wind farms without planning controls in respect of AM and therefore, although an agreed assessment method is available, the data can be presented in different ways. More recently, a planning condition has been proposed<sup>2</sup>, and while some debate of the shape of the penalty curve remains (as discussed at this conference<sup>3</sup>) our thoughts must also turn to how such penalties can be applied in practice. This paper will present examples of AM data analysis at different sites and the observations which resulted from this analysis.

### 1.1 Background

An initial strategy for applying penalties to AM in wind turbine noise as proposed in a report<sup>4</sup> by WSP / PB for the Department of Energy and Climate Change (DECC) now Department for Business, Energy & Industrial Strategy (DBEIS). This stated:

- *The AM condition should cover periods of complaints (due to unacceptable AM); and,*
- *A decibel penalty added to the overall average noise level during periods of unacceptable AM should lead to a breach of the planning condition for the overall average level of wind turbine noise, and subsequent action to reduce the noise level to bring the site back into compliance; and,*
- *Analysis should be made using individual 10-minute periods, applying the appropriate decibel 'penalty' to each period with subsequent wind speed analysis.*

The wind speed analysis would normally be done using integer wind speed bins but there was no further information provided. It is important to note however, under the ETSU-R-97 analysis method, some degree of averaging of measure  $L_{A90}$  values would be applied. Therefore, after penalties are applied to "individual 10-minute periods" as suggested, the resulting noise levels (with the penalties) would be averaged. It was not proposed to average the AM values and then apply the penalty as this could give rise to different results. The report by DECC did not include a planning condition wording. This was however provided in an article<sup>2</sup> in Acoustics Bulletin from Nov/Dec 2017. The relevant part states:

*"For each 10-minute interval for which an AM assessment is required this shall be performed in accordance with The IOA Metric. The value of AM for each ten-minute period shall be converted to a penalty in decibels in accordance with the graph below and the penalty shall be placed in the appropriate data sub-set and wind speed bin. Where a penalty is zero it should be placed in the bin in the same way. "*

Generally, compliance with noise limits is evaluated in downwind conditions since wind turbine noise levels tend to be greater. The relevant Supplementary Guidance Note<sup>5</sup> to the IOA GPG suggests evaluating the downwind condition  $\pm 45^\circ$ , although the range can be wider where more than one turbine contributes. Often, the analysis focusses on the night-time periods to avoid the additional corruption of noise data during the daytime. In such cases, the turbine noise level can be compared with the daytime limits.

However, the prevalence of AM during the night can be different during the day and AM has been found in upwind and crosswind conditions. Moreover, the principle put forward in the WSP/PB report is to assess AM during the periods of complaints.

These factors can result in the need to assess other periods and other wind directions and there continues to be some debate about how this can be done in practice. In the Nov / Dec 2017 article we explained:

*The proposed condition has therefore been drafted on the basis of aggregating the AM penalties obtained, and applying this to the overall noise levels. This is considered to be a pragmatic way to represent the frequency/intensity of AM typically observed in relevant weather conditions. The condition explains that this averaging should only be done in relevant subsets of conditions which are determined in each case based on the observed complaints (if relevant), data analysis results or practitioner judgment. Analysis in wind direction bins, or plotting the amplitude modulation as a polar plot may be important in determining the appropriate subset.*

To illustrate these points, some examples of AM analysis are given below.

## 2 SITE A – NARROW AM ARC

In this example, downwind directions correspond to the range of 40-100 degrees for the different turbines, and an interval centred on approximately 68 degrees from north. The Plot is shown in Figure 1. Figure 2 shows the average penalties calculated across wind direction bins of various widths centred on the downwind direction. In this analysis, the penalty is calculated as per the suggestion of the WSP report<sup>4</sup>. Table 1 shows results of a more systematic binned analysis, with the data split in bins of 30 degrees for wind direction and 1 m/s for wind speed.

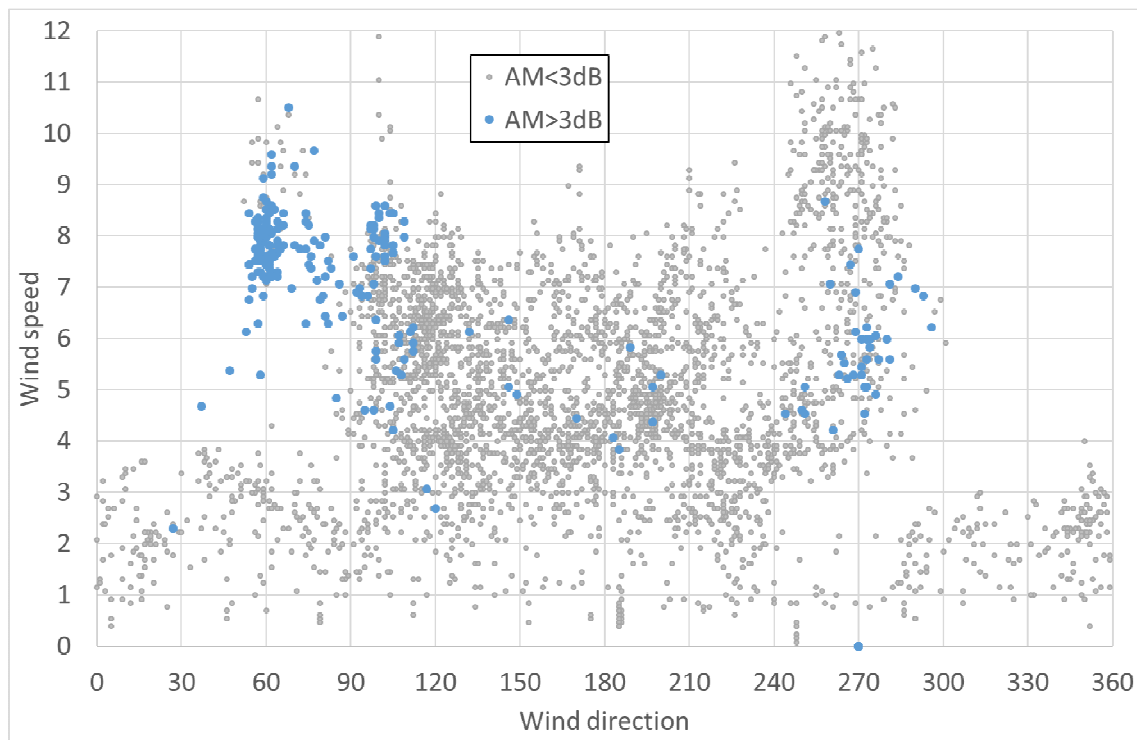


Figure 1 - Occurrence of 10minute periods showing broad AM rating (IOA method) distribution.

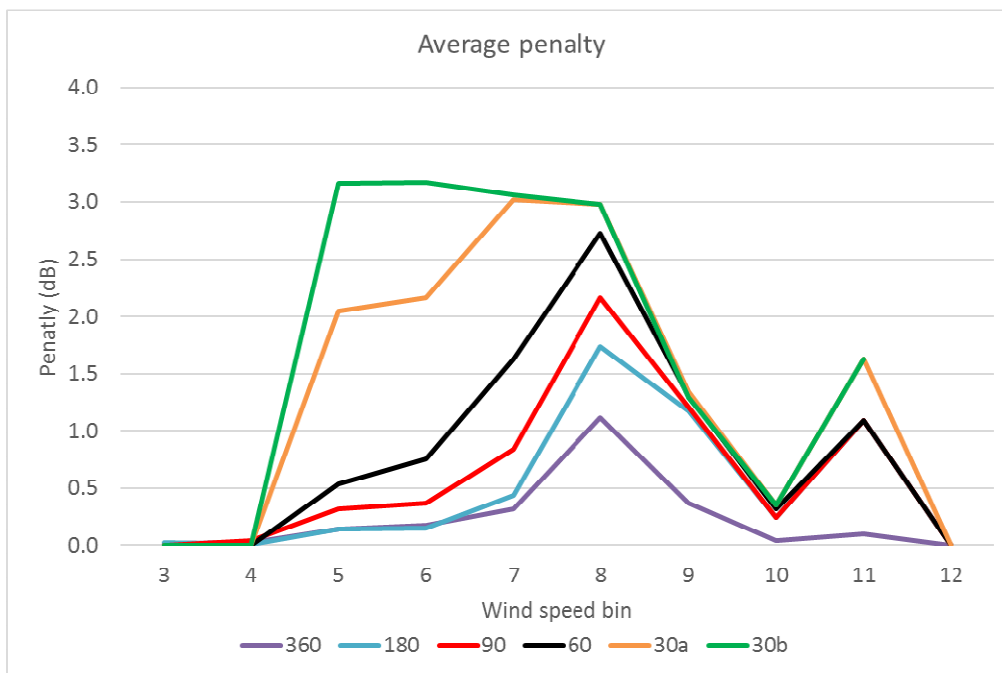


Figure 2 - Table of variation of calculated average AM penalty (WSP graph) as a function of the width (degrees) of the wind direction sector for averaging: 360 degrees = all directions, 180 = 180 degree sector centred on DW conditions, etc. 90 degrees is a “standard” downwind arc. “30a” is the 30 degree sector centred on the central downwind direction “30b” is that centred on 60 degrees and which corresponds to Table 1 below.

Table 1 Average AM penalty (WSP) in wind speed (1m/s) and wind direction (30°) bins

Wind speeds	Site A - Wind directions (bin centred on...)											
	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.1	0.0	
5		3.1	3.2	0.3	0.1	0.1	0.0	0.1	0.3	0.7	0.0	
6			3.2	0.2	0.1	0.0	0.0	0.0	0.0	0.9	1.1	
7			3.1	0.5	0.0	0.0	0.0	0.0	0.0	0.4	1.0	
8			3.0	1.5	0.2	0.0	0.0	0.0	0.0	0.1	0.0	
9			1.3	1.0	0.0			0.0	0.0	0.1		
10			0.4	0.0					0.0	0.0		
11			1.6	0.0					0.0	0.0		
12				0.0					0.0	0.0		

In this case, the binned analysis results in the “worst-case” 30 degree sector (“30b” in Figure 2) but this is more by chance as the opposite could well have been true depending on the data distribution. The binned analysis provides a useful systematic way of analysing the statistics of the data which may not be obvious from the first plot. Averaging over a wider range of wind directions than 30 degrees leads to great differences at some wind speeds, but this seems partly due to a relative lack of data in this case (5 periods or less in the 4-6 m/s wind speeds bins in the critical 150 degree wind direction bin). 10 degree-wide bins were also investigated but this resulted in data scarcity in many bins and excessive variability. It is also important to acknowledge that lack of data in some conditions does not mean that AM would not potentially be present in these conditions.

### 3 SITE B – EXAMPLE OF SPECIFIC WIND DIRECTION

When assessing AM as a consequence of complaint, there are benefits in the complainant keeping a log of their experiences. It is also of benefit for them to note when the sound is inaudible as well as when it is audible. Figure 3 below provides the assessed annoyance by a complainant in relation to the site averaged wind speed and direction. The complainant was asked to provide a rating between 0 (no noise annoyance) and 9 (significant annoyance) and time and date that it occurred. Comments took the form of identifying a period during the day, in their own words, i.e. (morning/afternoon/night), and an indication of how intrusive they found the sound. In Figure 4 it can be seen that periods of higher AM occur for the specific periods identified by the complainant. In this case the nearest upwind turbine is located at 271° (≈910m) and the next nearest is at 246° (≈ 980m).

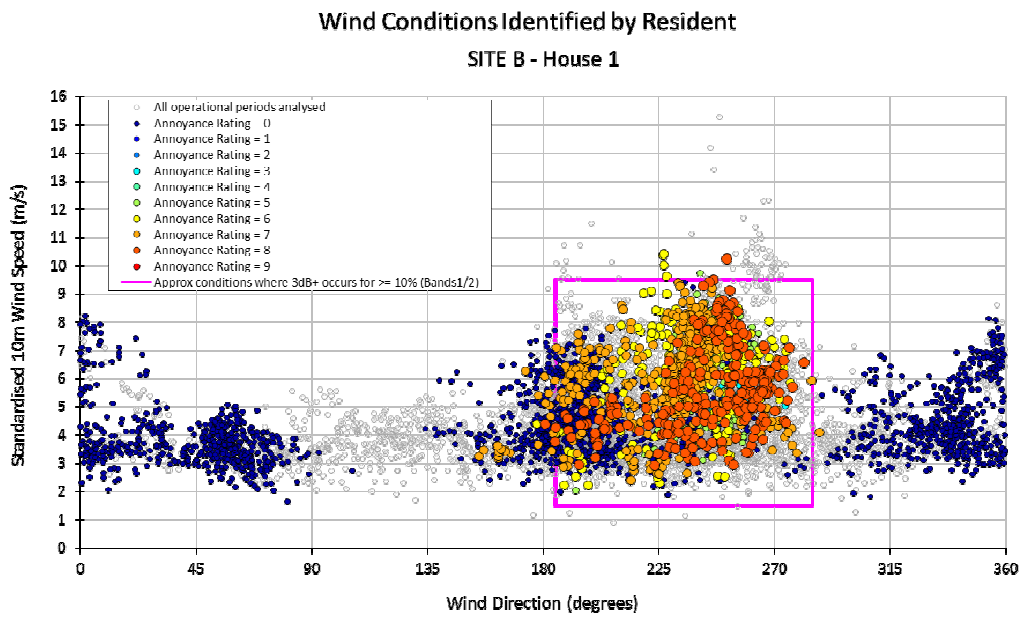


Figure 3 – Site B - Wind Conditions and Annoyance Ratings Identified by Resident

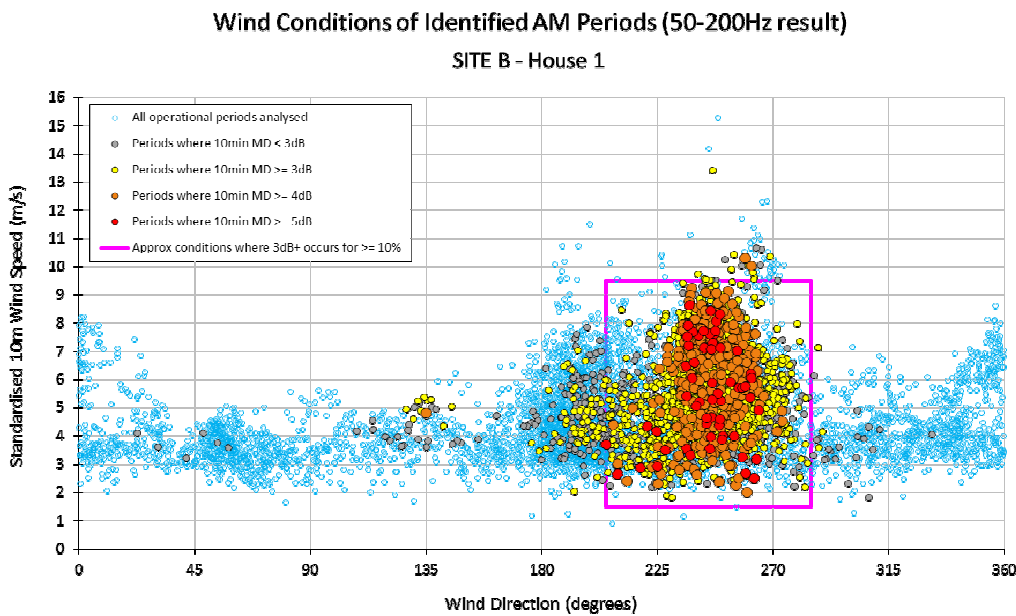


Figure 4 – Site B - IOA AM Ratings

Table 2 below shows the average penalty ratings in 30° bins.

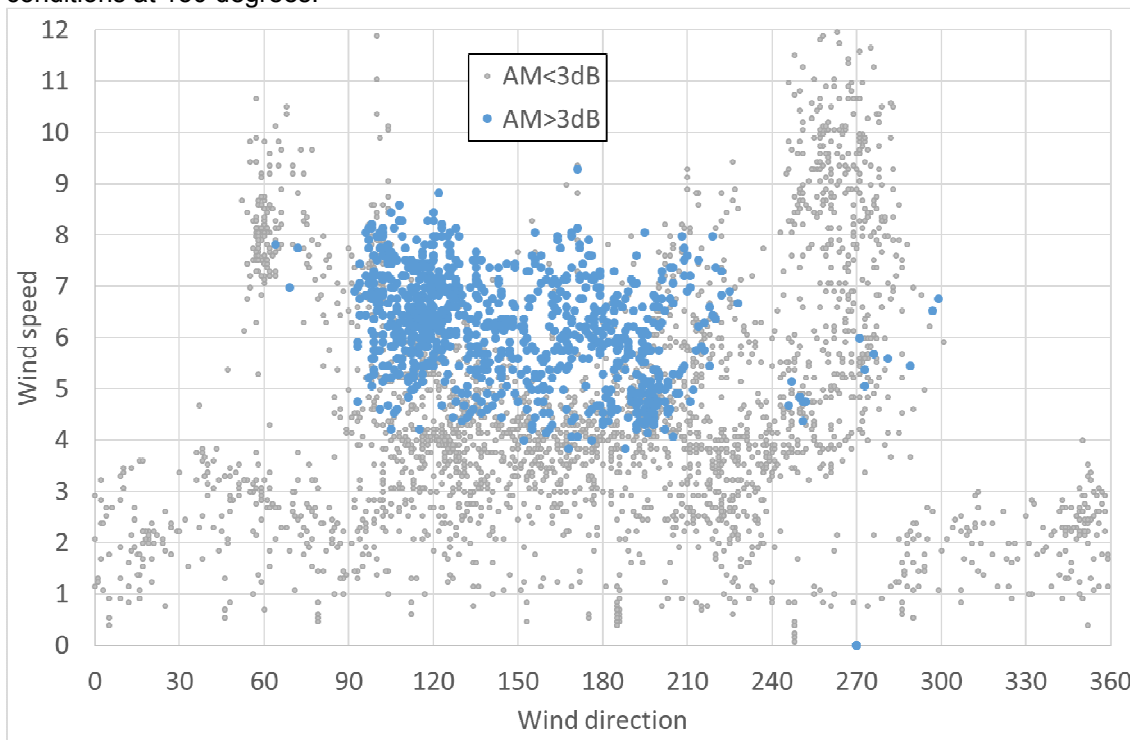
**Table 2 Average AM penalty (WSP chart) in wind speed (1m/s) and wind direction (30°) bins**

Wind Direction Bin Centre (degrees)	Standardised 10m Wind Speed Bin (m/s)											
	1	2	3	4	5	6	7	8	9	10	11	12
0°	#N/A	#N/A	0.0	0.0	0.0	0.0	0.0	0.0	#N/A	#N/A	#N/A	#N/A
30°	#N/A	#N/A	0.0	0.0	0.0	0.0	0.0	#N/A	#N/A	#N/A	#N/A	#N/A
60°	#N/A	0.0	0.0	0.0	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
90°	#N/A	0.0	0.0	0.0	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
120°	#N/A	0.0	0.0	0.0	0.6	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
150°	#N/A	0.0	0.0	0.0	0.5	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
180°	#N/A	0.3	0.0	0.1	0.0	0.1	0.1	0.0	0.0	0.0	#N/A	#N/A
210°	#N/A	0.2	0.4	0.4	0.4	0.2	0.1	0.2	0.0	#N/A	#N/A	#N/A
240°	#N/A	1.3	1.0	1.5	2.0	2.4	2.5	2.5	2.0	1.2	#N/A	#N/A
270°	#N/A	1.2	0.4	1.2	1.7	1.7	1.7	2.3	0.7	0.8	0.0	#N/A
300°	#N/A	0.0	0.0	0.0	0.0	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
330°	#N/A	#N/A	0.0	0.0	0.0	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

In this case the low penalty values at 210 compared to 240 should be noted. Averaging the penalties over a wider range of wind directions would reduce the effect. However, the WSP advice to assess the conditions causing complaint is important. It should be acknowledged that such detailed/specific information on complaint periods is often not available from residents, who are not always able to provide specific dates and times of complaints.

#### 4 SITE C – WIDE RANGE OF AM

In this case, AM is experienced over a wider range of conditions, broadly centred on upwind conditions at 150 degrees.



**Figure 5 – Occurrence of 10minute periods showing AM over a wider range of wind directions.**

In the same way as Site A, the average AM penalty (WSP graph) can be calculated in each wind speed bin for wind direction sectors of varying width.

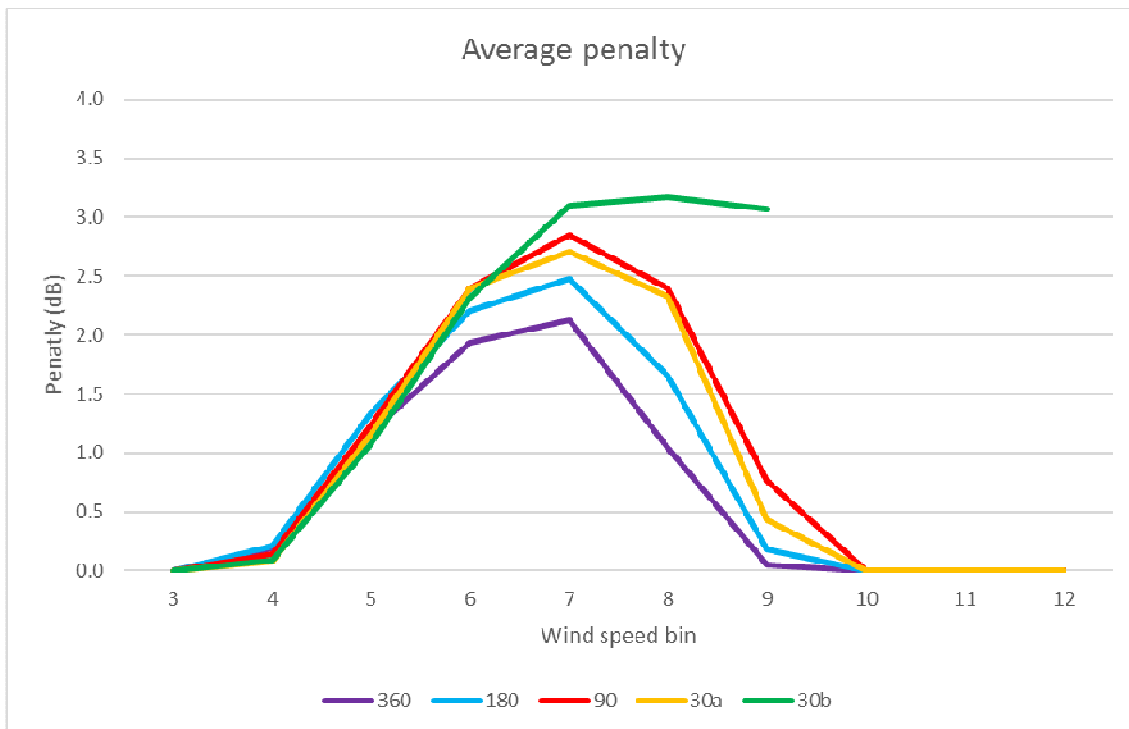


Figure 6 - Table of variation of calculated average AM penalty (WSP graph) as a function of the width (degrees) of the wind direction sector for averaging: 360 degrees = all directions, 180 = 180 degree sector centred on DW conditions, etc. 90 degrees is a “standard” downwind arc. “30a” is based on the 90-120 degree range which initially appeared to correspond to sustained elevated AM. But the binned analysis in Table 3 below suggests that wind direction bin centred on 120 degrees “30b” results in a marginally higher result (albeit with less data at high wind speeds).

As for Site A, the specific results obtained are to a certain extent an artefact of that particular data set; very limited data is available in some sectors at high wind speeds, but this is not uncommon.

Table 3: Site C AM penalty (WSP) in wind speed (1m/s) and wind direction (30 degrees) bins

Wind speeds	Wind directions (bin centred on...)											
	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.1	0.1	0.2	0.4	0.4	0.0	0.0	0.0	
5		0.0	0.0	0.9	1.1	1.5	1.4	1.6	0.4	0.2	0.6	
6			0.0	2.0	2.3	2.8	3.1	1.0	0.0	0.2	0.0	
7			0.1	2.1	3.1	3.1	2.9	1.5	0.3	0.0	1.0	
8			0.1	1.7	3.2	2.7	2.2	0.9	0.0	0.0	0.0	
9			0.0	0.0	3.1			0.0	0.0	0.0		
10			0.0	0.0				0.0	0.0			
11			0.0	0.0				0.0	0.0			
12				0.0				0.0	0.0			

## 5 SITE D – EXAMPLE OF AM DIRECTIVITY

Site D presents measurements for a property overlooked by a wind farm, with sound levels at the property dominated by a single wind turbine. For upwind and down directions, the average AM rating is similar but in the cross-wind direction (in the plane of the rotor) it was found that the downward blade resulted in AM but the upward moving blade resulted in little or no AM.

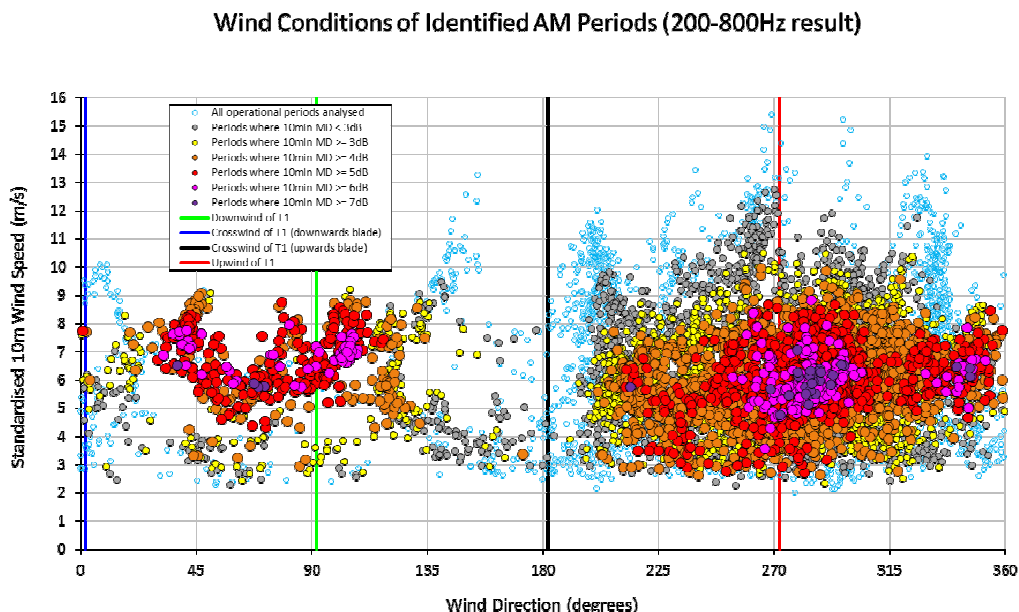


Figure 7 – Occurrence of 10minute periods showing AM over a wider range of wind directions

In this case the penalties are fairly consistent in the broadly upwind and downwind directions even though there is less downwind data.

Table 4: Site D AM penalty (WSP) in wind speed (1m/s) and wind direction (30 degrees) bins

Standardised 10m Wind Speed Bin	1	2	3	4	5	6	7	8	9	10	11	12
0	#N/A	#N/A	0.1	0.1	1.4	2.0	2.8	2.7	0.5	0.0	#N/A	#N/A
30	#N/A	#N/A	1.2	1.2	0.3	2.2	2.7	3.4	2.3	#N/A	#N/A	#N/A
60	#N/A	0.4	1.2	1.5	3.4	3.7	3.4	#N/A	3.4	#N/A	#N/A	#N/A
90	#N/A	#N/A	2.6	2.4	3.5	3.7	3.8	3.6	3.5	#N/A	#N/A	#N/A
120	#N/A	#N/A	0.5	1.8	2.6	3.1	3.1	2.6	1.6	#N/A	#N/A	#N/A
150	#N/A	#N/A	0.1	0.3	0.4	#N/A	0.9	0.9	0.1	0.0	0.0	#N/A
180	#N/A	#N/A	0.2	0.1	0.0	0.2	0.0	0.0	0.0	0.0	#N/A	#N/A
210	#N/A	#N/A	0.8	1.2	1.7	2.0	1.8	0.4	0.0	0.0	0.0	#N/A
240	#N/A	#N/A	1.5	2.0	2.9	3.1	2.3	1.6	0.8	0.1	0.0	0.0
270	#N/A	#N/A	1.5	2.8	3.1	3.5	3.5	3.3	1.8	0.7	0.0	0.0
300	#N/A	0.3	0.9	2.2	3.0	3.5	3.5	3.1	1.7	0.3	0.0	#N/A
330	#N/A	#N/A	0.7	1.3	2.4	2.7	2.0	1.1	0.6	0.3	0.0	0.0

## 6 SITE E

Site E relates to a property which neighbours a wind farm. The orientation of two closest wind turbines is indicated in Figure 8 below. High levels of AM present for a wind direction of around 345° were identified specifically by the residents as a period when AM was clearly audible and intrusive. It should be noted that for other periods when high levels of AM were found, no such comments were made but this may simply be the result of the residents not being at home at these periods.

Figure 9 shows analysis for different penalty schemes presented in the “Penalty Considerations” paper<sup>3</sup> and information of the distribution of the AM values by wind speed bins. The results obtained using the WSP proposed penalty are presented in Table 5. No application of a modulation frequency correction has been applied as the maximum modulation frequency was below 0.8 Hz.

Figure 9 also details an assessment of the potential variation in the penalty between the WSP scheme and the two arguments and an assessment of potential variation in penalty associated with three averaging methods: (i) N>30 Arithmetic, (ii) N<30 Arithmetic and (iii) N<30 Energetic average where N is the number of valid 10 second periods in each 10 minute sample block.

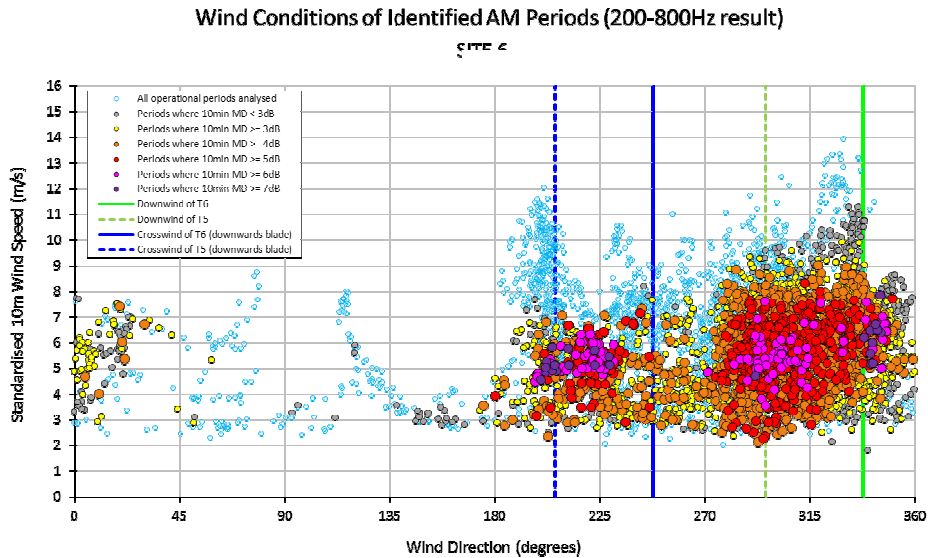


Figure 8 – AM Assessment for Site E

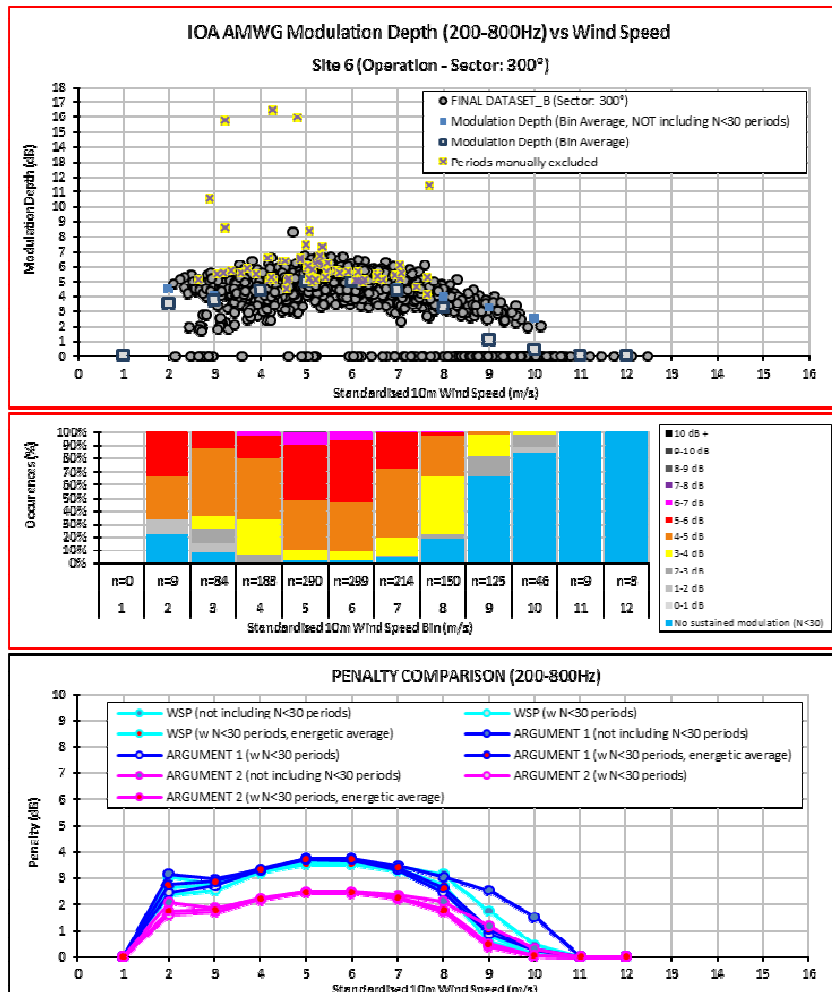


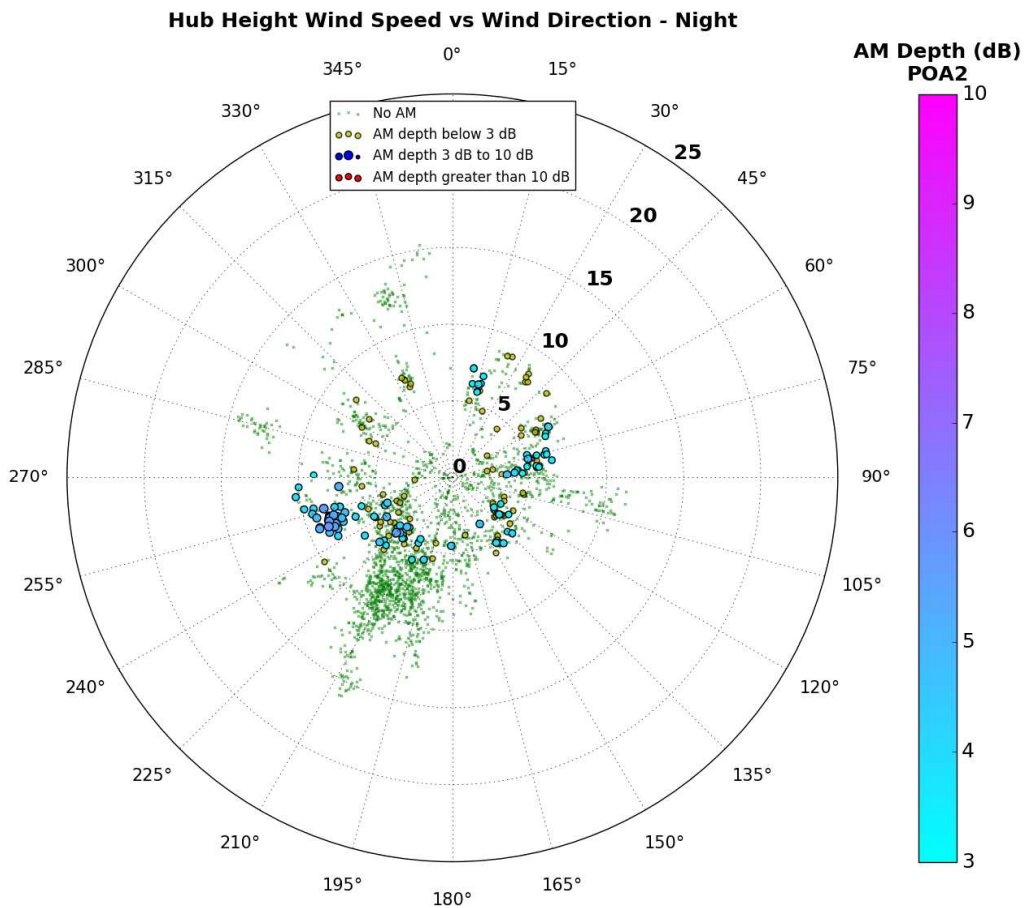
Figure 9 – Site E - Analysis for Different Penalty Schemes and Distribution of AM by Wind Speed Bin

**Table 5 - Site E - WSP Penalty Scheme – binned analysis of average penalties**

Standardised 10m Wind Speed Bin	1	2	3	4	5	6	7	8	9	10	11	12
0	#N/A	#N/A	0.5	0.6	2.8	2.5	1.8	0.7	#N/A	#N/A	#N/A	#N/A
30	#N/A	#N/A	#N/A	#N/A	0.3	0.8	1.4	#N/A	#N/A	#N/A	#N/A	#N/A
60	#N/A	#N/A	0.2	0.0	#N/A	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
90	#N/A	#N/A	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
120	#N/A	#N/A	#N/A	0.0	0.0	0.0	0.0	0.0	#N/A	#N/A	#N/A	#N/A
150	#N/A	#N/A	0.0	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
180	#N/A	#N/A	1.0	1.8	0.9	1.4	#N/A	0.0	0.0	0.0	#N/A	#N/A
210	#N/A	#N/A	2.0	2.5	3.0	2.0	0.5	0.0	0.0	0.0	0.0	#N/A
240	#N/A	#N/A	1.8	1.7	2.5	1.0	0.6	0.1	0.0	0.0	#N/A	#N/A
270	#N/A	#N/A	1.8	2.2	2.1	1.8	1.2	0.7	0.3	0.0	#N/A	#N/A
300	#N/A	2.4	2.5	3.2	3.5	3.5	3.3	2.6	0.6	0.1	0.0	#N/A
330	#N/A	#N/A	1.6	2.9	3.3	3.4	3.4	2.8	1.5	0.2	0.0	0.0

## 7 SITE F

For site F, the AM data can be presented as a polar plot for the night-time only but excluding the dawn chorus.



**Figure 10 - Site F - Polar Plot for Night-time Data**

In this case, the complainant’s property was broadly downwind of the turbines under northerly wind conditions, but limited AM was encountered for a crosswind condition. Since the property was in a quiet area, the AM analysis was expanded to include all data during the day and night. This is shown in Figure 11. The small green dots in this case indicate data samples without AM.

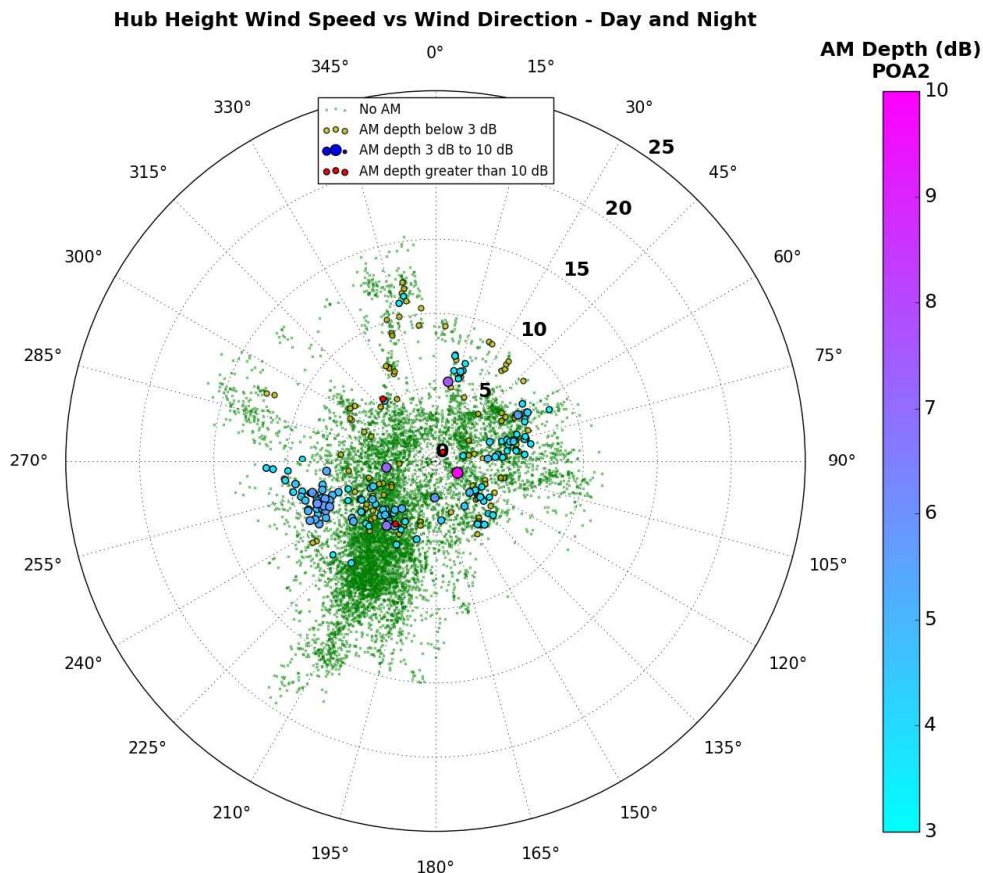


Figure 11 – site F – IOA AM analysis for day and night (all results)

The daytime analysis did not reveal any additional significant AM periods except for possibly some spurious samples, which are clearly atypical (no manual exclusions have been undertaken). The resulting penalty analysis is shown below.

Table 6 Site F WSP Penalty Scheme

		Average AM Penalty (dB, WSP graph) by Wind Direction Bins (Degrees re. North)											
		0	30	60	90	120	150	180	210	240	270	300	330
Wind Speed at HH (m/s)	5	1.1	0.7	1.0	0.0	1.0	0.1	0.2	0.8	0.4	0.3	0.0	0.0
	6	1.5	0.4	1.1	0.0	0.0	0.0	0.0	0.3	0.3	0.2	0.1	0.5
	7	1.1	0.5	0.8	0.0	0.0	0.0	0.0	0.0	1.6	0.0	0.0	0.4
	8	0.5	0.6	0.0	0.0	0.0	0.0	0.0	0.0	3.3	0.0	0.4	0.0
	9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2	1.6	0.0	0.0
	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0

## 8 CONCLUSIONS

The above examples have shown different approaches to the analysis that can be carried out with long term AM data. The IOA AM metric has proved invaluable in assessing AM using long term noise monitoring data. In some cases, very little manual filtering is required.

A binned analysis of the average penalty using 30 degree wind direction bins and 1 m/s wind speed bins represents a useful systematic approach, which could be applied in a first instance or in the absence of case-specific requirements, for example in an agreed noise monitoring scheme. However, this may not necessarily be consistent with the analysis of compliance with limits with ( $L_{A90,10min.}$ ) noise levels and/or tonal effects. The results obtained are also dependent on the data gathered during the survey and the results could be misleading if the worst-case AM conditions are not encountered. Extensive noise surveys may be necessary (over several months) to gather a wider range of conditions and improve the statistical analysis of all conditions.

Furthermore, whilst the binned analysis can be useful in identifying strong AM regions, filtering data in a relatively narrow range is not always justifiable. It is rare that complaint analysis is available in a similar basis. General advice for compliance analysis is to consider downwind conditions  $\pm 45^\circ$  or wider with multiple turbine sites. However, limiting the AM analysis to downwind conditions may exclude the worst-case AM conditions or reduced the significance by averaging lesser periods. Furthermore there will be an effect on the ETSU-R-97 compliance with widening or narrowing the wind direction range. The combined effect of the rating level ( $L_{A90}$  + penalties) of considering different averaging conditions should be investigated on a case-by-case basis, taking into account any available information on specific complaints logged by residents.

## 9 REFERENCES

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- 1 Institute of Acoustics (IOA) Amplitude Modulation Working Group, Final Report, A Method for Rating Amplitude Modulation in Wind Turbine Noise, June 2016.
  - 2 A Planning Condition for Wind Turbines, Andy McKenzie, Matthew Cand, Dick Bowdler, Mark Jiggins, Gavin Irvine, Michael Reid, Richard Perkins, Michael Lotinga, Malcolm Hayes and Andrew Bullmore. Institute of Acoustics, Acoustics Bulletin, Nov/December 2017
  - 3 Wind Turbine Noise Amplitude Modulation Penalty Considerations Dick Bowdler, Matthew Cand, Malcolm Hayes, Gavin Irvine. IOA Acoustics 2018, Cardiff.
  - 4 Review of the evidence on the response to amplitude modulation from wind turbines, WSP/ Parsons Brinckerhoff for Department for Business, Energy & Industrial Strategy. Wind Turbine AM Review, Phase 2 report, August 2016
  - 5 IOA Good Practice Guide, Supplementary Guidance Note 5 (SGN5): Post Completion Measurements.