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Directivity noise attenuation values for large wind turbines – Research based on long term measurements

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Summary

Directivity of wind turbine noise at noise sensitive receptor distances is a crucial parameter in the design process of wind farms. It allows better predictions of cumulative noise impacts and can also inform the design of mitigation strategies tailored to specific wind directions. Real noise sensitive receptors are considered in this study and locations very close to wind turbines (ie. IEC 61400-11 measurement position) are not considered. In the case of wind turbine noise assessments, noise sensitive receptors are typically residential houses, located at distances over 400 meters, from the nearest wind turbine. Considering such distances outdoors, the propagation path is often complex and measurements are influenced overwhelmingly by background noise, especially as wind speed increases. Such complexity requires that extensive data sets are collected to try to establish a strong correlation of propagation from source to receiver for all wind directions. This study provides an overview of the current literature on the subject of wind turbine noise directivity, puts forward a methodology to establish directivity attenuation values from long term measurements at noise sensitive receptors, and presents the findings from long term measurements at one site.

1. Introduction

The noise emissions of a wind turbine are not equal in all wind directions; a person listening downwind of a wind turbine would be expected to experience higher noise levels compared to a person listening upwind of a wind turbine at the same distance. This investigation of directivity of wind turbine noise aims to quantify the differences in noise levels between downwind, upwind, cross winds but also in other more refined positions. When undertaking a wind resource analysis, or considering low noise modes, it is common practice to consider twelve "wind sectors". The differences in wind turbine noise between twelve different positions spread 30º apart in every direction (all at the same distance ~400m to 500m) around a large wind turbine are therefore the focus of this study. To report directivity attenuation values in a standard way, a polar coordinate system is used. As a convention, polar coordinate 0º is considered upwind, 90º cross wind, 180º downwind and 270º cross wind (on the other side). In this study, polar coordinate 180º (downwind) is the reference as it is expected to have the highest observed noise level, and noise levels in other positions are compared to it. For this reason, polar coordinate 180º downwind will always show 0dB directivity attenuation, and other polar coordinates are expected to show observations of directivity in excess of 0dB attenuation (i.e. lower noise levels are expected in other directions).

The need for accurate directivity attenuation values

When undertaking noise predictions for a wind farm, propagation models use as an input sound power levels valid for downwind predictions [1] and therefore downwind propagation is usually assumed, as a worst case prediction. However, in a cumulative context, for situations where

one receptor can not realistically be downwind of two wind farms (i.e. receptor between two wind farms) directivity attenuation values are used to adjust the downwind noise predictions to provide more realistic, lower predictions. Figure 1.1 and Figure 1.2 illustrate two situations when directivity attenuation should be considered to predict noise in an environmental noise impact assessment.

Figure1.1: Illustration of the use of directivity, basic upwind-downwind situation

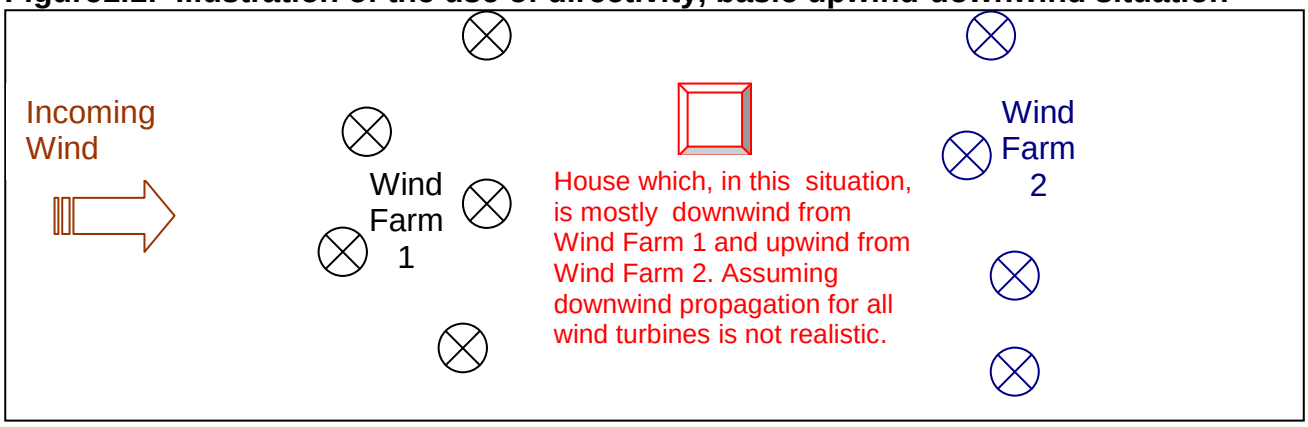
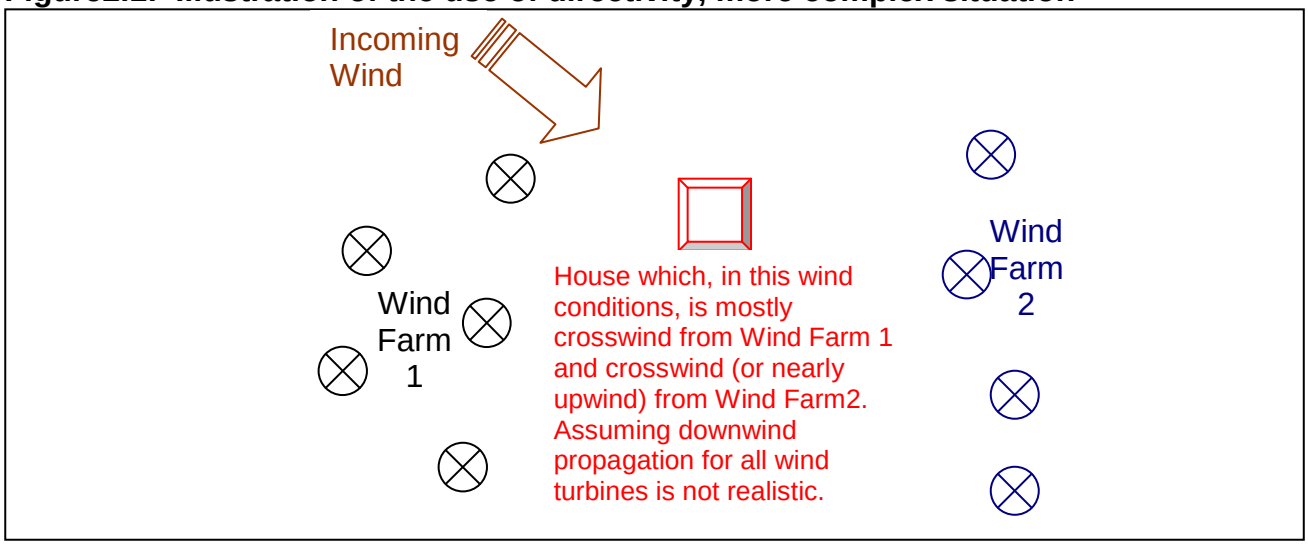


Figure2.1: Illustration of the use of directivity, more complex situation



Furthermore, directivity attenuation values are also required when undertaking noise predictions aimed at evaluating or designing mitigation measures for particular wind speeds and wind directions, where for example the noise limits are predicted to be breeched in full/standard operational mode. In establishing mitigation measures based on noise predictions, these have an impact on the power generation of a wind farm. Once a wind farm is consented, developers typically enter into negotiations with turbine manufacturers in order to find the turbine which offers the best financial return. If a chosen model shows marginal exceedence to the noise limits in full/standard operational mode, developers may evaluate the impact of low noise modes for specific wind speeds and specific wind directions. This targeted use of low noise modes may only incur a marginal overall power loss and therefore such mitigation measures are very important and are standard practice nowadays. The end result of the noise prediction exercise is to design an operational mode strategy, which will maximise the power output whilst meeting the noise limits. Figure 1.3 is an example of full/standard mode noise predictions over the classic 12 wind sectors whilst Figure 1.4 shows an example of the corresponding suggested operational mode strategy, usually designed by a noise consultant with the help of the developer and the turbine manufacturer who can inform on other non acoustic constraints to ensure it is not overly complicated and can be implemented in practice.

Figure 1.3 - Full/standard operational mode noise predictions over 12 sectors

Noise Assessment Location 01 - Exceedances of the noise limits in Full/Standard Mode																																				
Quiet Day Time																			Night Time																	
Turbine Nb	ws @10(m/s)	Limit(dB)	Wind Direction Sector												Turbine Nb	ws @10(m/s)	Limit(dB)	Wind Direction Sector											
			1	2	3	4	5	6	7	8	9	10	11	12				1	2	3	4	5	6	7	8	9	10	11	12
			0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°				0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
All turbines in the wind farm	3	35.0dB	-7.3dB	-5.6dB	-5.5dB	-5.5dB	-5.5dB	-6.1dB	-7.8dB	-11.9dB	-14.6dB	-15.1dB	-13.7dB	-10.1dB	All turbines in the wind farm	3	43.0dB	-15.3dB	-13.6dB	-13.5dB	-13.5dB	-13.5dB	-14.1dB	-15.8dB	-19.9dB	-22.6dB	-23.1dB	-21.7dB	-18.1dB
	4	35.0dB	-3.3dB	-1.6dB	-1.5dB	-1.5dB	-1.5dB	-2.1dB	-3.8dB	-7.9dB	-10.6dB	-11.1dB	-9.7dB	-6.1dB		4	43.0dB	-11.3dB	-9.6dB	-9.5dB	-9.5dB	-9.5dB	-10.1dB	-11.8dB	-15.9dB	-18.6dB	-19.1dB	-17.7dB	-14.1dB
	5	35.0dB	0.2dB	1.9dB	2.0dB	2.0dB	2.0dB	1.4dB	-0.3dB	-4.4dB	-7.1dB	-7.6dB	-6.2dB	-2.6dB		5	43.0dB	-7.8dB	-6.1dB	-6.0dB	-6.0dB	-6.0dB	-6.6dB	-8.3dB	-12.4dB	-15.1dB	-15.6dB	-14.2dB	-10.6dB
	6	41.0dB	1.2dB	2.9dB	3.0dB	3.0dB	3.0dB	2.4dB	0.7dB	-3.4dB	-6.1dB	-6.6dB	-5.2dB	-1.6dB		6	43.0dB	-0.8dB	0.9dB	1.0dB	1.0dB	1.0dB	0.4dB	-1.3dB	-5.4dB	-8.1dB	-8.6dB	-7.2dB	-3.6dB
	7	42.0dB	-1.8dB	-0.1dB	0.1dB	0.1dB	0.1dB	-0.6dB	-2.3dB	-6.4dB	-9.1dB	-9.6dB	-8.2dB	-4.6dB		7	43.0dB	-3.8dB	-2.1dB	-2.0dB	-2.0dB	-2.0dB	-2.6dB	-4.3dB	-8.4dB	-11.1dB	-11.6dB	-10.2dB	-6.6dB
	8	43.0dB	-4.3dB	-2.6dB	-2.5dB	-2.5dB	-2.5dB	-3.1dB	-4.8dB	-8.9dB	-11.6dB	-12.1dB	-10.7dB	-7.1dB		8	43.0dB	-3.3dB	-1.6dB	-1.5dB	-1.5dB	-1.5dB	-2.1dB	-3.8dB	-7.9dB	-10.6dB	-11.1dB	-9.7dB	-6.1dB
	9	47.0dB	-8.3dB	-6.6dB	-6.5dB	-6.5dB	-6.5dB	-7.1dB	-8.8dB	-12.9dB	-15.6dB	-16.1dB	-14.7dB	-11.1dB		9	47.0dB	-6.3dB	-4.6dB	-4.5dB	-4.5dB	-4.5dB	-5.1dB	-6.8dB	-10.9dB	-13.6dB	-14.1dB	-12.7dB	-9.1dB
	10	52.0dB	-12.3dB	-10.6dB	-10.5dB	-10.5dB	-10.5dB	-11.1dB	-12.8dB	-16.9dB	-19.6dB	-20.1dB	-18.7dB	-15.1dB		10	51.0dB	-10.3dB	-8.6dB	-8.5dB	-8.5dB	-8.5dB	-9.1dB	-10.8dB	-14.9dB	-17.6dB	-18.1dB	-16.7dB	-13.1dB
	11	56.0dB	-15.3dB	-13.6dB	-13.5dB	-13.5dB	-13.5dB	-14.1dB	-15.8dB	-19.9dB	-22.6dB	-23.1dB	-21.7dB	-18.1dB		11	54.0dB	-13.3dB	-11.6dB	-11.5dB	-11.5dB	-11.5dB	-12.1dB	-13.8dB	-17.9dB	-20.6dB	-21.1dB	-19.7dB	-16.1dB
	12	57.0dB	-18.3dB	-16.6dB	-16.5dB	-16.5dB	-16.5dB	-17.1dB	-18.8dB	-22.9dB	-25.6dB	-26.1dB	-24.7dB	-21.1dB		12	56.0dB	-17.3dB	-15.6dB	-15.5dB	-15.5dB	-15.5dB	-16.1dB	-17.8dB	-21.9dB	-24.6dB	-25.1dB	-23.7dB	-20.1dB

Figure 1.4 - An operational mode strategy designed to meet imposed noise limits

WT MODEL X (80m hub 2dB Uc) LOW NOISE MODE STRATEGY					
Low Noise Mode Names:	Full	Low Noise 1	Low Noise 2	Low Noise 3	Low Noise 4	OFF
Low Noise Mode Key:	Blank	LN1	LN2	LN3	LN4	OFF

Note1: The reported "ws@10" are wind speeds as standardised from hub to 10m height.
Note2: The reported "ws@hub" are wind speeds as measured at a hub of 80m.
Note3: A wind speed range "3.5-8.5" is a range starting at 3.5m/s and ending at 8.5m/s.
Note4: Each wind sectors are 30° wide and only the center value is given. As an example sector 1 center is 0° and is for the range 345° to 15° .

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Quiet Day Time																			Night Time																	
Turbine Nb	ws @10(m/s)	ws @hub(m/s)	Wind Direction Sector												Turbine Nb	ws @10(m/s)	ws @hub(m/s)	Wind Direction Sector											
			1	2	3	4	5	6	7	8	9	10	11	12				1	2	3	4	5	6	7	8	9	10	11	12
			0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°				0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
T1	3.5-8.5	4.9-11.8	LN3	LN3	LN3	LN3	LN3	LN3	LN3						T1	All	All												
T2	3.5-8.5	4.9-11.8			LN2	LN2	LN2								T2	All	All												
T3	3.5-8.5	4.9-11.8													T3	All	All												
T4	3.5-8.5	4.9-11.8	OFF	OFF	OFF	OFF	OFF	OFF	OFF						T4	4.5-7.5	6.3-10.4		LN3	LN3	LN3	LN3	LN3						
T5	3.5-8.5	4.9-11.8													T5	All	All												

As shown, accurate directivity attenuation values are used more and more to feed into noise propagations models. The accuracy of these can have a direct impact on the power generation of a scheme.

2. Review of relevant standards and studies

2.1 Wyle project and NASA Technical paper 3057 in the USA - 1988-1990

NASA commissioned a number of studies on wind turbine noise in the late 1980's and a number of reports were published in 1989-1990. The report "Wind Turbine Acoustics"[2] includes a section "Directivity of the source" which only relate to close distances. Another section of the report called "Directivity consideration for a Wind Power Station" report computed directivity pattern (in Figure 7-30 of the report) for a site with 5 rows of 31 turbines. The results are from a computer model, and no details are provided on how the calculations were made and little data is presented. The Wyle Research Report [3] provides measurements results based on a loud speaker suspended in the air to simulate a wind turbine. The report is not specific to directivity. Only a handful of data points are used to draw conclusions. Measurements were made in upwind and crosswinds and estimation is made that in upwind conditions no attenuation due to directivity is expected up to distances of 5.25 times the turbine hub height.

2.2 JOR3-CT95-0091 (Joule Project) in Europe - 1998

The contract JOR3-CT95-0091 "Development of a wind farm noise propagation prediction model"[4], often referred to simply as the Joule Project, was a research project funded by the European Commission. The project started in 1996 and the report, called "Final Report" dates

May 1998. The report presents the results of a series of measurements made with a loud speaker suspended between 15 and 30meters above local ground level, emitting a constant sound power level of 113 dB(A). Different topography were tested. The measurement results are compared to various prediction models and a recommendation is made that ISO 9613 Part 2 should be used and provides realistic results. No data, figures or graphs are presented, only final recommendations are included and the report concludes that conference presentations would follow. It has not been possible to trace presentations relating to directivity under this project. The focus of the 1998 report was not on directivity and there was no directivity attenuation values presented however it transpires from the IOA GPG [5] dated May 2013 that evidence from this project was later used to estimate directivity patterns. At the time of writing, there are no known reports which present the detail of such evidence.

2.3 Presentation and papers by HMP and HLA in the UK - 2007- 2009

Dr Andy McKenzie from Hayes Mackenzie Partnership (HMP) and Mark Jiggins from Hoare Lee Acoustics (HLA) gave a presentation called 'Wind Turbine Noise – Cumulative Impact Assessment' [6]; at the Institute of Acoustics Wind Turbine Noise Conference in 2007. It discusses the issues of cumulative noise impact assessment and presents a number of potential directivity attenuation which could be used when undertaking cumulative predictions. There are no details on how these values were calculated. Four tables, found in the presentation, includes values for a "pessimistic" assumption, two "less pessimistic" and one "much less pessimistic". Hoare Lea Acoustics also presented a paper at the 2009 International Meeting on Wind Turbine Noise in Aalborg, Denmark. The paper looks at the accuracy of assuming downwind propagation in the prediction model to ensure that it is not "overly conservative", as it may penalise wind farm implementation and renewable energy generation. The paper presents measured data and focuses on downwind measured data at receptor distances, whilst also showing measured data upwind. Directivity attenuation of 6 to 7dB for upwind conditions were observed on one site at 754m from a turbine by comparing two data sets of 90 degree width, one with downwind data and one with upwind data. A regression analysis on each data set was the basis of the comparison. The conclusions of the study were:
"ISO 9613 offers a robust means of determining the upper turbine immission levels that may occur in practice under favourable, downwind propagation conditions. ….Further study of directional propagation effects would be beneficial given their relevance to large wind farm site and cumulative impacts."

2.4-Paper by Evans and Cooper in Australia – 2012

Tom Evans and Jonathan Cooper reported in a paper in November 2012 [7] estimations of "propagation loss" which were in turn used to estimate directivity attenuation for upwind and crosswind. LA90 1min measurements at three measuring locations in line at 120m, 500m and 1000m (from the nearest turbine in a large row of wind turbines) for two weeks formed the basis of the study. The topography in the propagation path included terrain features such as "a slight valley". The methodology was based on comparing noise levels at two measurement locations in the same direction but at different distances. The measurement of reference for the comparison was the 120m measurement location which is an IEC 61400-11 position for the wind turbine considered.

2.5 IEC61400-11:2012 International standard - 2012

IEC 61400 Part 11**[**Error! Bookmark not defined.**]** is the standard used to measure and characterise the noise emissions of a wind turbine, inclusive of sound power levels for each 1/3 octave band, tonality and as an option, directivity. The standard's main aim is to establish sound power levels of a single wind turbine for a range of wind speeds. To achieve a good signal to noise ratio (reduce the influence of background) the measurement position recommended is relatively close to the turbine to be measured, for a large modern 80m hub and 90 rotor wind turbine the distance is approximately 125m distant from the base of the turbine. Measurements are required to be undertaken under downwind conditions (+-15 degree from downwind) at the main position. There are alternative measurement positions at different

angles (same distance) which are optional for the assessment of directivity and a number of studies [8][9] have reported directivity on the basis of measurements in close proximity. The directivity attenuation values from studies reporting directivity at close proximity have not been reported in this review, as it was assumed that directivity at further distances is different (based on study [3] and guideline [5]).

2.6 Institute of Acoustics Good Practice Guide (IOA GPG) in the UK - 2013

The IOA GPG [5] is the current reference of good practice for wind farm noise in the UK and provides references to past studies. The guide suggests potential values which can be considered. Section 4.4.2 states that:

"Based on evidence from the Joule project ... current practice suggests that for a range of headings from directly downwind (0°) up to 10 degrees from crosswind (80°), there may be little to no reduction in noise levels; once in crosswind directions (90°) then the reduction may be around 2 dB(A); and when at sufficient distance upwind the reduction would be at least 10 dB(A)."

Section 4.4.2 also specifies that in order to use directivity attenuation values, the source to receiver distances should be between 5 and 10 turbine tip height. As an example, for a 100 turbine tip height this would be at least 500 meters. Other values are also provided in section 4.4.3 in a graphical form and referring to the work undertaken for NASA in the US in 1989-1990. It should be noted though that the two graphs included in section 4.4.3 are not found in the quoted references and therefore the values have possibly been interpreted.

2.7 Paper from Okada et al. from Japan - 2014

The study "A field measurement of the directivity characteristics of wind turbine noise" [9] focuses on very close measurements at 50m from a single 1.5MW wind turbine, but also expands the findings with additional measurements at one location up to 200m from the turbine. Whilst the distance is less than the typical receptor distances (typically >400m), this study shows interesting results with regards to data analysis methodology. The findings indicate that correlating noise levels with power output or rotation per minute (RPM) could provide better characterisation compared to the typical correlation with wind speed. Their results are therefore based on using power output and RPM, and not wind speeds.

2.7 Summary of literacy review

Table 2.1 summarises the above relevant studies reporting directivity at distances over 400m, Table 2.2 and Figure 2.1 present their reported directivity attenuation values.

Table 2.1 – Summary of literature review

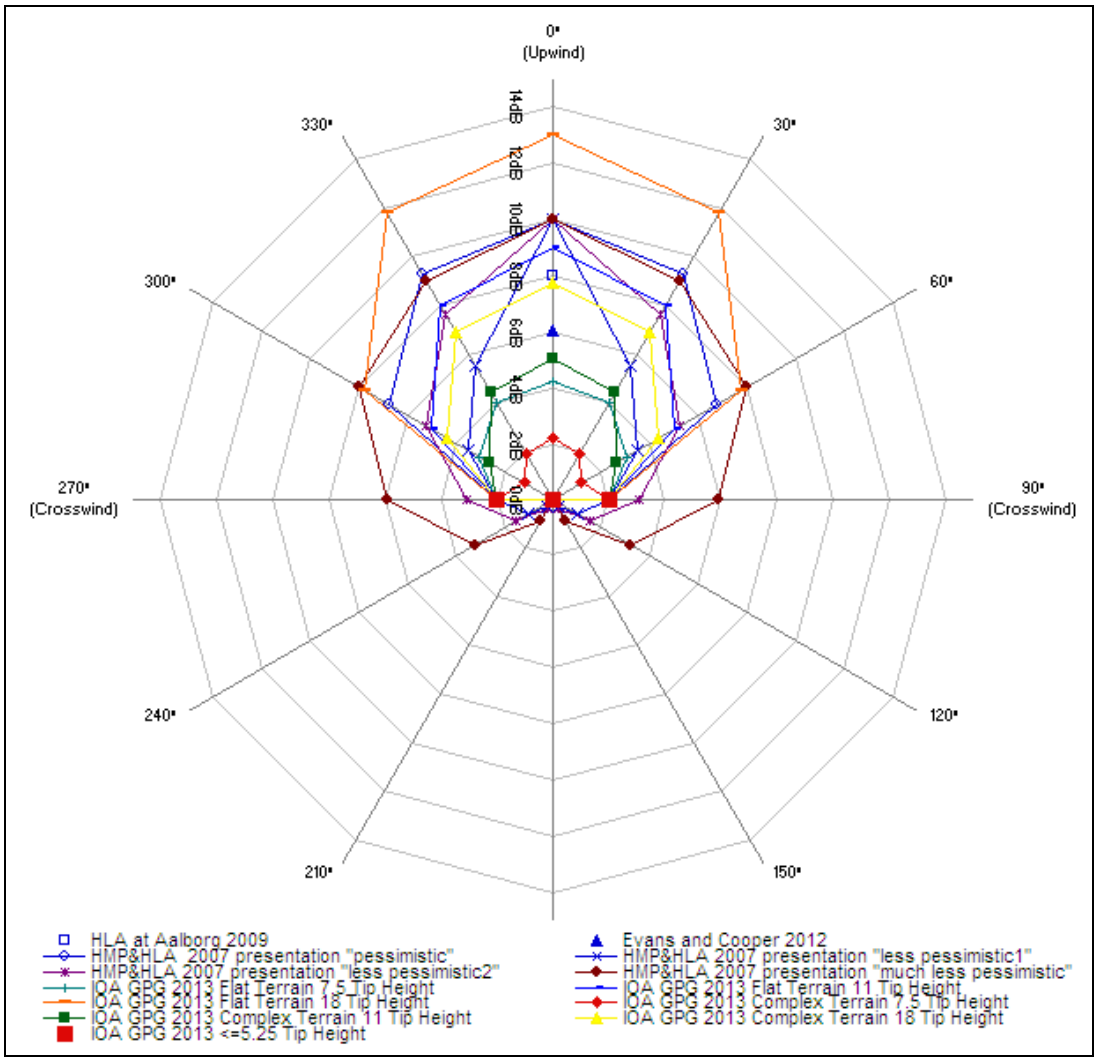
Reference name	Type of terrain	Distance of application	Wind speed of observations	Method used to obtain the values
HLA at Aalborg 2009	Flat, no vegetation, peat bog (G=0)	~757m	9-13m/s at hub	Measurements at one location at 754 split into bins 90° wide, for downwind and for upwind. Followed by regression analysis.
Evans and Cooper 2012	Complex (with slight valley)	~500-1000m	Above cut in and& up to 12m/s	Measurements at three locations at three distances and comparison between the locations.
HMP&HLA 2007 presentation "pessimistic"	Not specified	>400m	Not specified	Estimated*
HMP&HLA 2007 presentation "less pessimistic1"	Not specified	>400m	Not specified	Estimated*
HMP&HLA 2007 presentation "less pessimistic2"	Not specified	>400m	Not specified	Estimated*
HMP&HLA 2007 presentation "much less pessimistic"	Not specified	>400m	Not specified	Estimated*
IOA GPG 2013 Flat Terrain 7.5 Tip Height	Flat	7.5 Tip Height	Not specified	Estimated**
IOA GPG 2013 Flat Terrain 11 Tip Height	Flat	11 Tip Height	Not specified	Estimated**
IOA GPG 2013 Flat Terrain 18 Tip Height	Flat	18 Tip Height	Not specified	Estimated**
IOA GPG 2013 Complex Terrain 7.5 Tip Height	Complex	7.5 Tip Height	Not specified	Estimated**
IOA GPG 2013 Complex Terrain 11 Tip Height	Complex	11 Tip Height	Not specified	Estimated**
IOA GPG 2013 Complex Terrain 18 Tip Height	Complex	18 Tip Height	Not specified	Estimated**
IOA GPG 2013 <=5.25 Tip Height	Flat &Complex	5.25 Tip height	Not specified	Estimated**

* no paper available presenting on how these have been obtained. It is possible that it is a mix of the estimations from NASA 1990 reports and professional experience.
** the NASA 1990 reports are quoted as the source but the data were not found within the quoted document. It may be an interpretation of the quoted reference.

Table 2.2 –Summary of directivity attenuation values found in literature

Position number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Direction (used as a convention for polar representation)	**0º** (Upwind)	**30º**	**60º**	**90º** (Crosswind)	**120º**	**150º**	**180º** (Downwind)	**210º**	**240º**	**270º** (Crosswind)	**300º**	**330º**
HLA at Aalborg 2009	6	n/a	n/a	n/a	n/a	n/a	0	n/a	n/a	n/a	n/a	n/a
Evans and Cooper 2012	6	n/a	n/a	0	n/a	n/a	0	n/a	n/a	0	n/a	n/a
HMP&HLA 2007 presentation "pessimistic"	10	9.3	6.7	2	0	0	0	0	0	2	6.7	9.3
HMP&HLA 2007 presentation "less pessimistic1"	10	5.5	3.5	2	1	0.3	0	0.3	1	2	3.5	5.5
HMP&HLA 2007 presentation "less pessimistic2"	10	7.6	5.2	3.1	1.5	0.4	0	0.4	1.5	3.1	5.2	7.6
HMP&HLA 2007 presentation "much less pessimistic"	10	9	8	5.9	3.2	0.9	0	0.9	3.2	5.9	8	9
IOA GPG 2013 Flat Terrain 7.5 Tip Height	4.2	4	3	2	0	0	0	0	0	2	3	4
IOA GPG 2013 Flat Terrain 11 Tip Height	9	8	5	2	0	0	0	0	0	2	5	8
IOA GPG 2013 Flat Terrain 18 Tip Height	13	11.8	7.8	2	0	0	0	0	0	2	7.8	11.8
IOA GPG 2013 Complex Terrain 7.5 Tip Height	2.2	1.9	1.2	2	0	0	0	0	0	2	1.2	1.9
IOA GPG 2013 Complex Terrain 11 Tip Height	5	4.4	2.6	2	0	0	0	0	0	2	2.6	4.4
IOA GPG 2013 Complex Terrain 18 Tip Height	7.7	6.9	4.3	2	0	0	0	0	0	2	4.3	6.9
IOA GPG 2013 <=5.25 Tip Height	0	0	0	2	0	0	0	0	0	2	0	0

Figure 2.1 – Plot of directivity attenuation values found in relevant literature



The review of literature indicates that a number of directivity attenuation values exist for distances over 400 meter, but that supporting evidences, especially field measurements with large data sets are limited.

3. Experimental design

3.1 Concept

Whilst IEC 61300-11 offers an option to measure directionality for wind turbines, it is only valid for representing directionality in close proximity of a turbine. In the context of environmental noise impact assessments, the interest of this study is to establish directivity attenuation values for a single large wind turbine and which are representative at typical noise sensitive receptor set back distances, approximately over 400 meter.

At noise sensitive receptor distances, usually over 400 meter, it can be difficult to obtain “clean data”, not influenced by background noise. This is one of the major difficulties when undertaking such work. It is appreciated from the onset that the influence of background noise will remain the main source of uncertainty and effort should therefore be made to minimise this as much as practicable. Another difficulty is that collecting useful data completely depends on the weather and it can take months to collect the desired data set. Finally, access to operational wind turbine data is another key constraints for such studies; it may be easy to install a noise monitoring kit in a garden near a wind turbine, but having access to the operational data could prove much more difficult. In this context, making the data anonymous is usually an associated requirement to such sensitive data.

A methodology has been developed for this study based on broadband 10min averaged noise levels recorded continuously over long surveys in proximity of operational wind farms. $L_{A90\ 10min}$ (UK, Australia), $L_{A50\ 10min}$ (France) and $L_{Aeq\ 10min}$ can be considered. It is suggested that as a

starting point, $L_{A90\ 10min}$ is used, as it is a good compromise between minimising the background noise influence and not removing completely all high recorded levels (which could be turbine noise). Such surveys in proximity of operational wind farms are typically undertaken as part of compliance monitoring surveys and it is anticipated that the methodology could be used to re-analyse data with the aim to establish directivity attenuation values for a single large modern wind turbine.

3.2 Data collection principles

Data such as wind speed, wind direction, operation timer (duration of normal operation in seconds for each 10 minute), rain as well as noise data at one Noise Monitoring Location (NML) are required. All data need to be recorded on the same time basis to allow correlation (i.e. what was the noise level, wind speed and wind direction at a given time and was the turbine actually operating). Careful selection of the wind farm site and the noise monitoring locations are considered to be the two most important parameters before undertaking any analysis of recorded data.

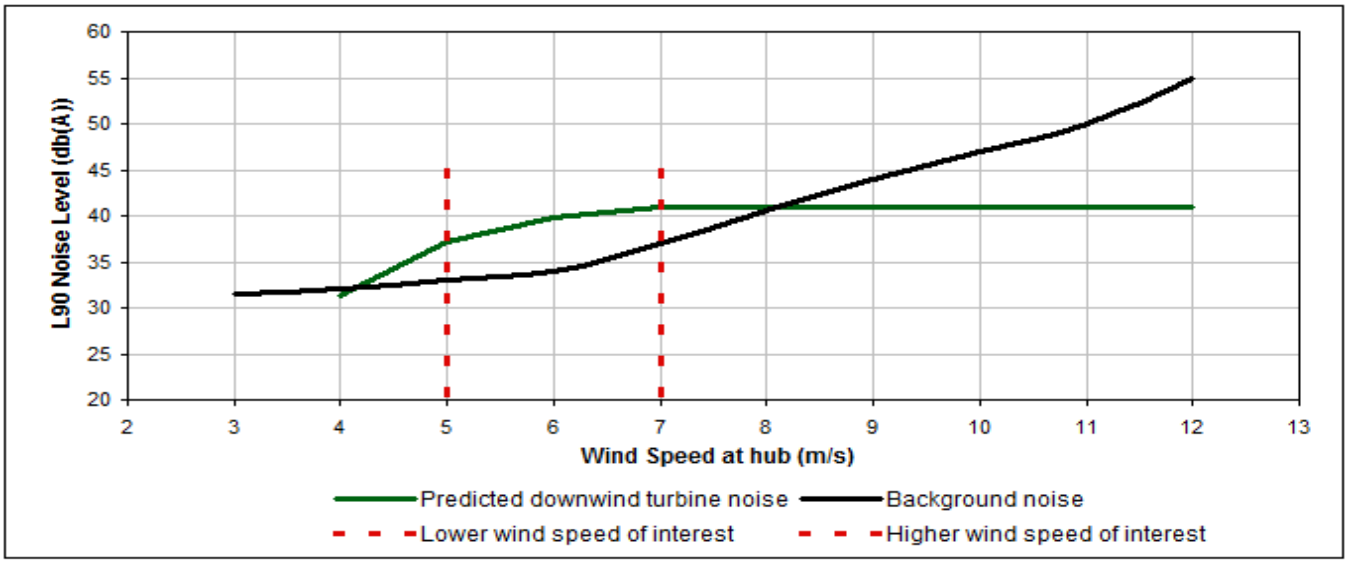
The site topography should preferably be flat in order to reduce the uncertainties associated with complex propagation and which may unduly affect the results. Whilst it may be desirable to also establish directivity attenuation values for complex sites, it would be preferable to first acquire as many robust data sets as possible reporting on sites with simple topography. For this methodology, a site with a single wind turbine is preferred but larger number of turbines (up to ~6) can be considered, preferably with square layouts and not layouts with rows of turbines. A quiet rural site with no major noise sources is preferable.

The noise monitoring location would ideally be in the middle of an empty field (no leafy vegetation) at approximately 400 to 500 meters as it is judged that noise sensitive receptors are rarely found under 400m distances and that between approximately 400m and 500m, the influence of background noise is already significant; and measuring at much further distances would be detrimental in this respect. Direct line of sight between the noise equipment and the wind turbines is essential. And finally, having a baseline, either from a previous background noise assessment (wind farm specific with wind speed correlation) or by collecting data with turbines switched off would be ideal to better appreciate the influence of background. If possible the raw data (ie. not only the resulting trendline) of the original baseline would be acquired so that it can be used for this specific analysis. It is recognised though that such data set may be dated or very difficult to obtain and it is therefore not a crucial part of this methodology, as long as a large number of NML selection criteria are met.

3.3 Data Analysis principles

It is suggested that realistic downwind noise predictions are undertaken in advance of the analysis and that the predicted wind farm noise levels are compared to the baseline, if available. Such comparison provides an indication before starting the survey about the wind speed range which should be investigated. It is expected that the wind speed range will be limited to a narrow 2 to 4 m/s wind speed range starting just after the wind turbine cut in wind speed. The reason is that background noise, beyond a certain wind speed, will exhibit similar if not higher noise levels than the specific wind turbine noise. This is illustrated in Figure 3.1.

Figure 3.1 – Example comparison of baseline and predicted levels



A wind speed filter should be applied, on the basis of the analysis performed as illustrated in Figure 3.1 above. The range 4-7m/s at hub height is expected to be the range of interest for most modern large multi mega watt turbines. All obvious exclusions should apply such as rain or removing periods when the turbines were not operating for 600 seconds out of 600 seconds according to the operation timer. It is recommended that a time filter is applied, to consider only data during the quietest periods, these are likely to be in the middle of the night. However, to avoid removing too many data points, especially those in rare wind directions, such filter should be used with care and with a certain degree of flexibility. It will be necessary to rotate the wind direction recorded in order to present the results in a standard way, on a polar coordinate system for which coordinate 0º is considered upwind, 90º cross wind, 180º downwind and 270º cross wind. The rotation to apply is calculated simply as 0º minus real upwind wind direction on the measurement site. As illustrated in Figure 3.1, for the example presented in this paper the real upwind condition on site occur during easterly winds (90º) therefore a rotation of -90º is applied to all 10minute data. It should be noted that this step greatly helps towards making the site anonymous (as long as the rotation adjustments in not provided in any reporting).

All data are binned into twelve wind direction bins, also called sectors. Bin 0º includes data from 345º to 15º, bin 30º includes date from 15º to 45º and so on. A regression analysis is performed for each data set to find the line of best fit. A statistical average could also be considered, however, the regression analysis is preferred as this requires the analyst to review all data points within the data set on a graph, providing valuable additional information and context; which is preferable in comparison to just an average number. The resulting lines of best fit (12 lines) are at this stage “Total Noise”. A background correction would preferably be applied to extract the “Specific turbine noise”. For such correction, a background representing wind speed for all wind directions could be used. In the absence of robust background levels for the correction, the careful selection of monitoring location and wind speed range should be considered very. To establish the directivity attenuation values, the downwind noise levels are used as a reference and all other directions (11) are compared to it. An arithmetic substraction downwind noise level minus other sector noise level provides the directivity attenuation value.

3.4 Checklist before proceeding to data analysis

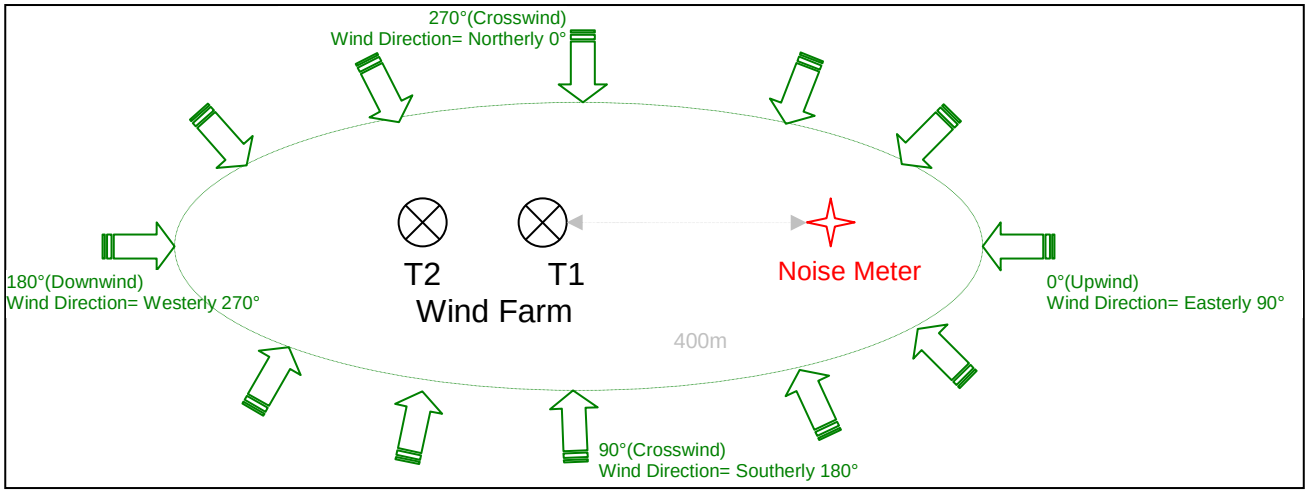
To help selecting an appropriate site and monitoring location, a checklist summarising the recommendations in sections 3.2 and 3.3 has been created. Table 3.1 below provides the checklist completed for “Site01_NML01”, the results of which are presented in the next section. Figure 3.2 illustrates the measurement set up.

Table 3.1 – Example of a checklist before proceeding to data analysis

Site ID and Noise Monitoring Location(NML) ID:	Site01_NML01

Criteria to check	Checked	Comments
NML near a large modern multi mega watt turbine? *Detail brand and model of the turbine(s) if possible in the comments.*	Yes	>2MW Turbine(s) on a 60m hub.
NML ~400-500m from the nearest turbine ?	Yes	
NML in a field, or has limited vegetation, or has limited nearby wind induced noise sources ?	Yes	Not in a field, but hardly any vegetation around.
Direct line of sight between NML and wind turbine(s) ?	Yes	
Quiet rural environment with no major noise sources ?	Yes	
Site topography is flat or not too complex ?	Yes	Gentle slope from turbine(s) to receptor,
The wind turbine(s) layout is a single turbine or small scheme ~6 wind turbines with square layout ?	Yes	Small scheme of 2 turbines
Operational data (10 minute averaged) is available? *This should include operation timer, wind speed and wind direction as a minimum.*	Yes	
Rain data (10 minute averaged) is available?	Yes	Recorded at or near NML by a tipping rain gauge placed on the ground.
Noise LA90 and LAeq 10 minute is available and the turbine(s) were audible above background noise during site visits? *Please include details about the noise meter in the comments.*	Yes	RION NL32, microphone placed vertically 1.5m above the ground fitted with a RION WS-03 wind shield.
A time filter to select the quietest periods of the days during the survey will be necessary? *Please include details in the comments.*	No	Site location is generally quiet with little variation of noise levels over the course of a day (i.e. No rush hour traffic etc…).
Background noise is available from past survey or by having switched off the turbine(s) **and** it can be used to correct results in all 12 wind direction bins ?_	No	Not available, good monitoring location chosen to mitigate the background influence as much as possible.
Wind speed of interest (due to low background influence) will be ~4-7m/s at hub **or** else based on comparison with predictions? *Specify detail in comments.*	Yes	4-7m/s used by default
The recorded entire data set has enough data recorded for the wind speed of interest in the majority of wind directions?	Yes	Extensive long term survey ~3 months, good amount of data available in all wind directions.
Analysis was undertaken to calculate a rotation adjustments (0º minus real upwind wind direction) ?	Yes	See Figure 3.1, upwind is in easterly winds for this specific site, therefore all data will be adjusted by -90º for the purpose of reporting directivity values.

Figure 3.2 – Noise Monitoring Location and the twelve wind directions



4.0 Field measurements results at one location

Preliminary results, from analysis of the data recorded at “Site01_NML01” (from Table 3.1 above) are presented in the following Figures and Tables.

Figure 4.1 – Wind conditions during the survey at Site01_NML01

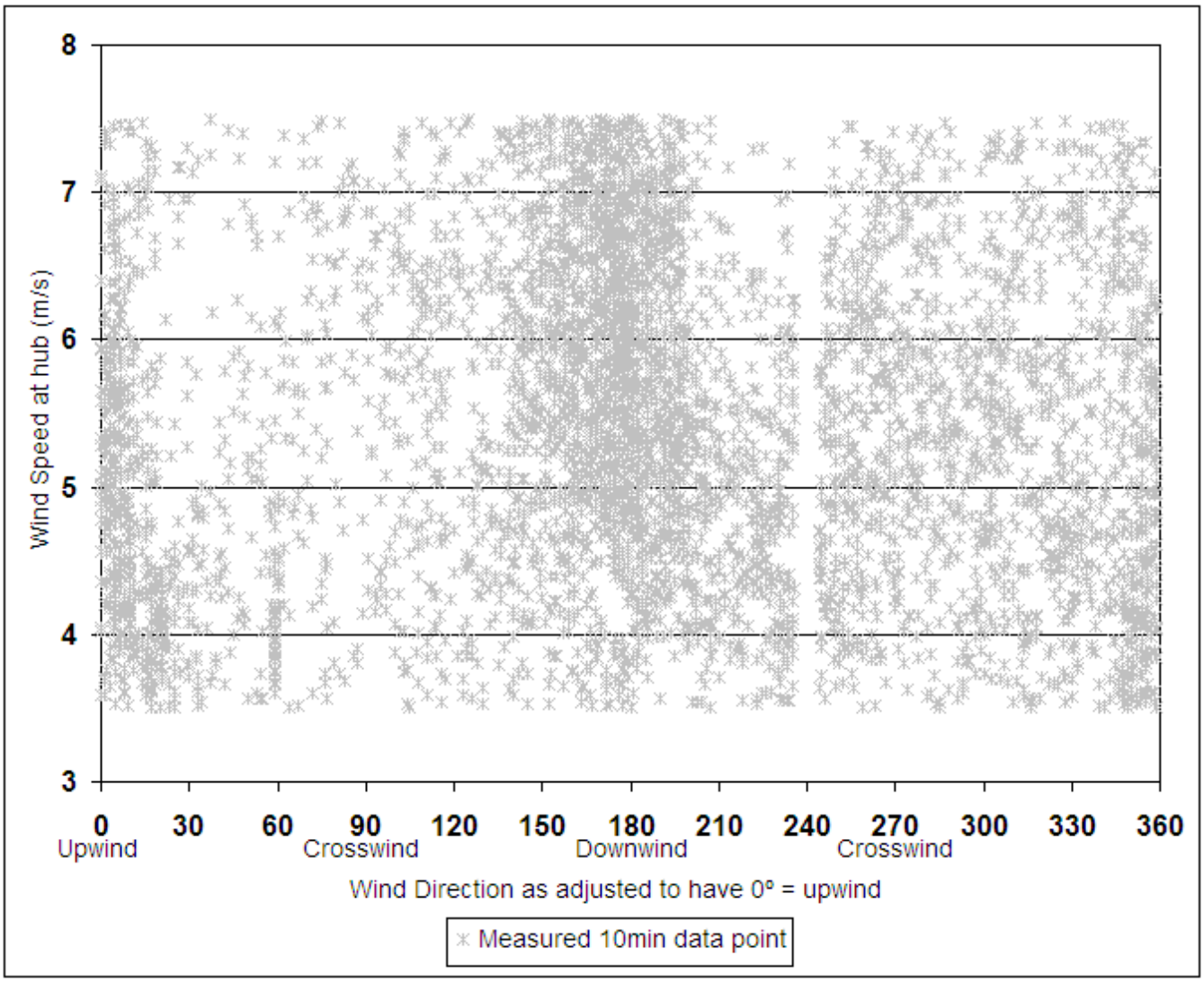


Table 4.1 – Number of data points included in the analysis of Site01_NML01

Wind Sectors		0° (Crosswind)	30°	60°	90° (Upwind)	120°	150°	180° (Crosswind)	210°	240°	270° (Downwind)	300°	330°	All Wind Directions
Wind Speed at hub (m/s)	4	234	139	57	35	52	69	118	97	105	63	72	83	1124
	5	196	50	40	24	56	151	323	167	103	107	101	101	1419
	6	155	12	26	38	64	201	353	97	60	117	91	67	1281
	7	80	27	22	40	41	161	333	48	22	74	47	63	958

Figure 4.2 – Regression analysis performed for each of the 12 sectors at Site01_NML01

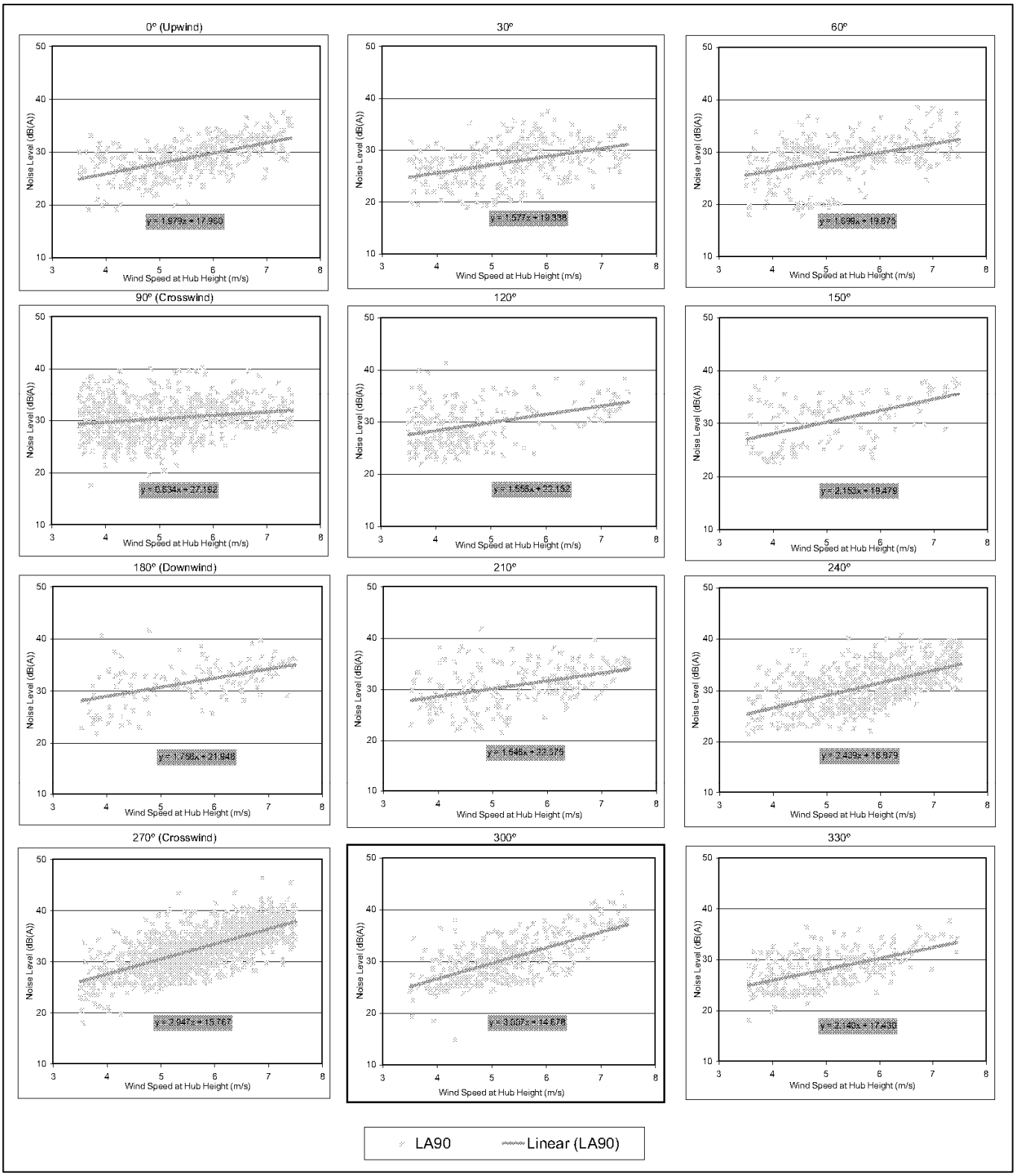


Table 4.2 –Directivity attenuation values measured at Site01_NML01

Wind Sectors		0º (Crosswind)	30º	60º	90º (Upwind)	120º	150º	180º (Crosswind)	210º	240º	270º (Downwind)	300º	330º
Wind Speed at hub (m/s)	4	-2.2	-0.8	-0.5	-1.4	-1.0	0.9	0.0	0.8	1.6	1.7	1.9	1.1
	5	0.1	0.6	0.3	-0.2	0.4	1.4	0.0	0.8	2.4	2.6	3.3	2.3
	6	2.5	2.0	1.1	1.0	1.8	1.9	0.0	0.7	3.2	3.6	4.6	3.6
	7	4.8	3.4	1.8	2.2	3.2	2.4	0.0	0.7	4.0	4.6	6.0	4.8

Figure 4.3 – Plot of directivity attenuation values measured at Site01_NML01

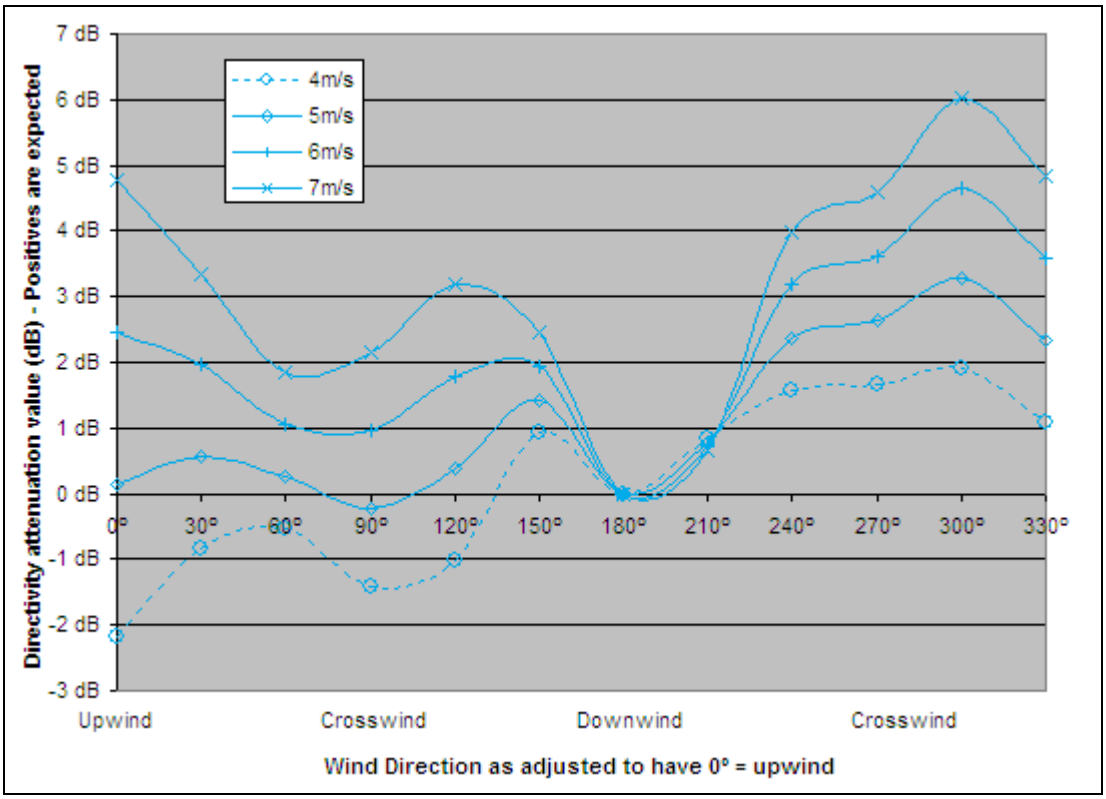
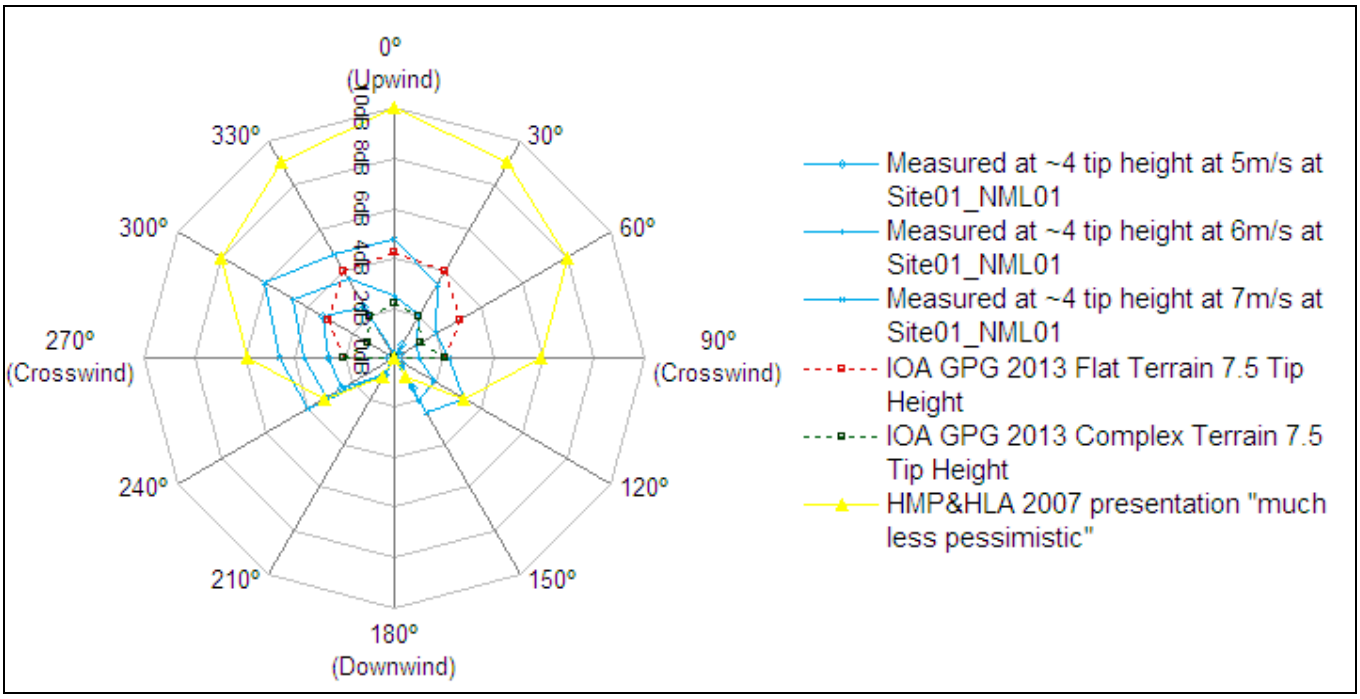


Figure 4.4 – Polar plot of directivity attenuation values measured



4.0 Discussion

The initial results from “Site01_NML1”, based on total noise show that:

- The 4m/s results are inconsistant. The potential cause could be that the turbine noise levels at this wind speed are not high enough in comparison to the background noise levels. This is a wind speed bin just after cut in and perhaps too early to measure turbine noise.
- The 5 to 7m/s results shows that with increasing wind speed, directivity attenuation seems to increase. In other words, the windier/noisier, the more directive the turbine noise becomes.
- The results either side of downwind (150º and 210º) show already 1 to 2dB directivity. This would imply that directivity patern are observed as soon as 30 degrees either side of downwind, and match broadly in downwind the values from the HMP&HLA 2007 presentation ”much less pessimistic”. .
- The results for 300º-330º shows much higher attenuation value compared to 30º-60º. Generally speaking the average noise levels (ie. regression analysis) will be more accurate in 300º-330º as these polar coordinates (used for reporting directivity) correspond to south westerly winds therefore more data is available. The difference observed could also be due to topography as it is not completely flat.

It may be beneficial to consider undertaking the analysis based on Power Outpout and RPM, and not based solely on wind speed. Also, it is envisaged that binning wind direction in lower resolutions to establish results over 8 or 4 wind direction bins for example would be usefull to include more data in each bins and compare the results. The methodolohy was developped to help identify suitable site and help to acquire a database of directivity attenuation results. As there is a large choice of values to choose from the litterature and even within current good practice guidelines, there is a need to establish a generic set of recognised values which can be applied for all wind speeds, and if possible at all noise sensitive receptors beyond 400 meters from a wind turbine.

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