Offshore Compression zone measurement and visualisation

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The determination of the length of the compression zone in front of a wind turbine is critical to obtaining accurate power curve tests. Compression zone length defines the minimum distance where a meteorological mast can be installed for power curve testing.

Conventionally it is recommended that meteorological masts are installed between 2 and 4 (and preferably 2.5) rotor diameters away from the wind turbine to be tested. However, research has indicated that this may not be adequate and that meteorological masts may be reading compression zone affected wind speeds.

To investigate this, SgurrEnergy has conducted a comprehensive measurement campaign where Galion Lidar units have been installed on an offshore wind turbine, recording data in a mode whereby the Galion Lidar is measuring the incoming wind speed. Two different configurations were used, the first one provides a simplified visualisation of the incoming wind speed profile, whereas the second configuration is a contour plot showing how wind speed varies across the horizontal plane at hub height and along a distance of 1 km in front of the rotor.

In both cases, results show that at 2.5 rotor diameters the compression zone is still evident with wind speed reading varying between 1-3% from the free stream wind speed. In addition, the influence of the compression zone may extend until approximately 3.5 rotor diameters depending on the wind speed.

Therefore, it is possible that current power curve calculation methods are leading to an overestimation of annual energy yield prediction.

1 INTRODUCTION

The measurement of wind conditions within offshore wind farms presents a technical challenge that is difficult to overcome with traditional measurement techniques such as using meteorological masts equipped with wind vanes and anemometers. As the height of modern wind turbine generators (WTGs) increases, new techniques for measuring the wind conditions are required to ensure that large WTGs are designed to be fit for purpose over the entire wind farm life and optimised for maximum power output and efficiency.

One of the key objectives of these new measurement techniques should be to ensure that the power curves of large WTGs are accurately measured. The interaction of the rotor with the incident wind resource in the immediate vicinity of the rotor is of key interest, yet this has not been measured adequately due to the limitations of traditional instrumentation and the difficulty of installing sensors in situ in this region. These problems are obviated by the use of Lidar remote sensing.

1.1 COMPRESSION ZONE DEFINITION

The compression zone is defined as the distance upstream of a WTG where the wind speed is less than that of the free stream wind speed. Therefore, the compression zone defines the maximum distance ahead of the WTG rotor (denoted as x in Figure 1) where upstream wind speed is affected by the interaction with the WTG rotor.

$$V_{\text{compression zone}} < V_{\text{free flow}} \quad [1]$$

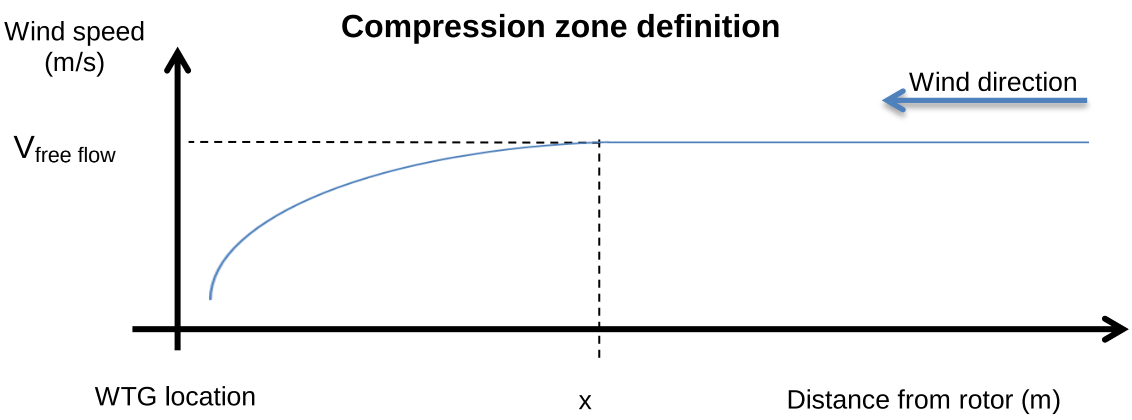

Figure 1: Definition of compression zone

2 BACKGROUND TO MEASUREMENTS

There is increasing concern that WTG power curves used for wind resource assessment studies are not representative of onsite commercial performance. This may lead to discrepancies between forecasted and achieved energy yields, which in turn has direct implications on the financial performance of a wind energy project.

The IEC standard 61400-12-1 states that meteorological masts should be installed at a distance between 2 and 4 RD of the WTG. Usually a distance of 2.5 RD is recommended as a compromise between achieving a good correlation of wind speed with WTG power output and minimising the compression zone effect. This recommendation assumes that the compression zone influence is negligible at 2.5 RD. If this is not the case, met masts will record lower wind speeds for a given power output, thus inducing a positive bias to the power curve. This would suggest that WTGs are performing better than is really the case.

SgurrEnergy is working towards determining the length of an offshore compression zone and understanding whether the current recommendations mean that power curve tests are affected by compression zones in the manner that they are currently performed. Offshore compression zones are expected to manifest themselves more clearly than the onshore equivalents due to the lack of obstructions and low surface roughness.

3 CAMPAIGN DESIGN

The focus of the campaign was to measure wind speeds within an operational offshore wind farm in the North Sea (Alpha Ventus). For the measurement campaign three G4000 Galion units were installed on an AREVA Wind M5000 WTG, two on the nacelle and one on the transition piece. The Galion Lidar's flexibility as an all sky scanning Lidar allowed unique measurements to capture radial Doppler up to 4km, which could then be transformed into a wind speed measurement over a large spatial area.

Figure 2 below shows the layout of the Alpha Ventus offshore wind farm. The Galion Lidar units are mounted on the WTG encompassed by a green diamond, which is referred to as Alpha Ventus 7 (AV07).

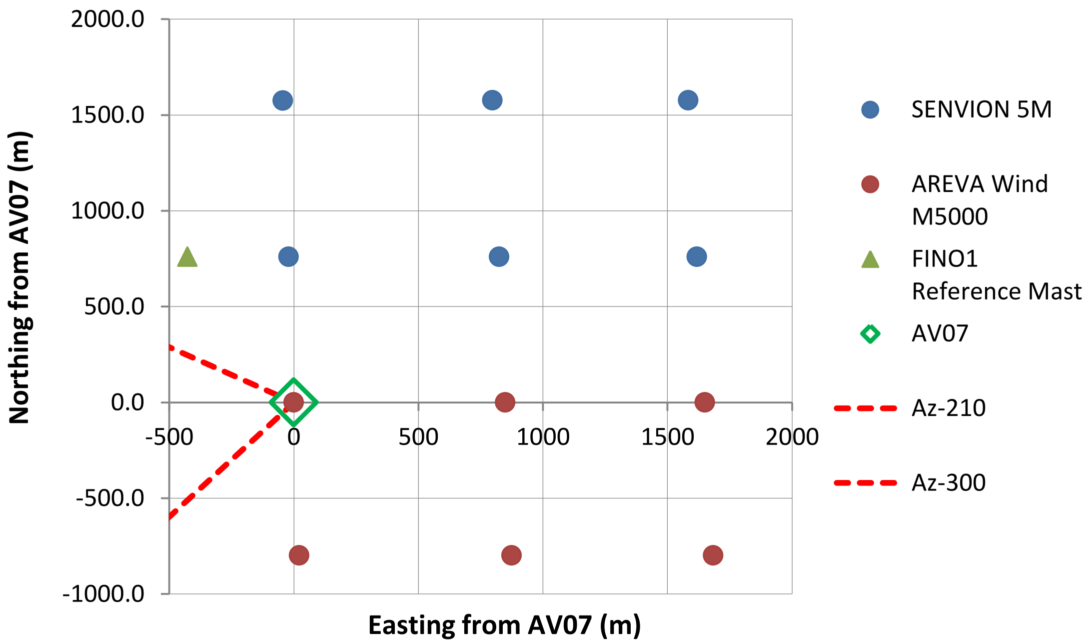

Figure 2: Free stream sector of Unit 24 readings

3.1 SCAN GEOMETRIES

Of the two devices mounted on the nacelle, the forward pointing Galion was used to undertake measurements of the incoming wind in order to observe the onset of the compression zone. The forward staring Galion was used under two different configurations:

1. Singe beam scan; and,
2. Horizontal arc scan, which is effectively a single beam scan with azimuth variation.

The first configuration was used to provide a simplified visualisation of the incoming wind speed profile, whereas the second configuration was analysed to produce a horizontal plane contour plot showing how wind speed varies across the width of the rotor and along a distance of 1 km in front of the rotor.

The timeline of the scan geometries employed for the measurement of the compression zone is shown below in Table 1.

Table 1: Timeline of scan geometries

Scan Geometry	Galion Unit Position	Start date	End Date	10 minute samples
Single beam	Unit 24 Nacelle Fore	13/03/2013 02:50 11/07/2013 12:00	27/03/2013 16:50 19/08/2013 00:50	66,878 208,914
Horizontal Arc	Unit 24 Nacelle Fore	20/08/2013 00:00	27/09/2013 11:10	1,719,074

4 ANALYSIS METHODOLOGY

4.1 SINGLE BEAM SCAN FROM UNIT 24

4.1.1 DATA FILTERING

During the measurement periods, the standard deviation of the yaw reading from the WTG SCADA was checked. Should the 10 minute value of the standard deviation be higher than 10°, these values were filtered out as they indicate that the WTG has yawed significantly in order to match changing wind direction over the course of that 10 minute period. The application of this filter was designed to ensure that the Galion Lidar unit is consistently measuring the incoming wind.

Timestamps with data availability less than 50% were also filtered out. The aim was to ensure reliable wind readings were used in the compression zone analysis. It is noted that the 50% availability filter is lower than data availability figures used for other Galion Lidar analyses (approximately 98%). However, data availabilities of that high level were not possible due to the interference caused from the WTG blade passes to the Galion Lidar signal during WTG operation.

4.1.2 ASSESSMENT OF THE FREE STREAM SECTOR

The dataset was filtered to select measurements coming from the free stream direction, that is, the sector where there is no mast shadowing or wake effects from nearby WTGs. Figure 2 also presents the free stream sector used at 210º - 300º relative to true north and denoted with a red dashed line.

4.1.3 WIND SPEED NORMALISATION

In a conventional power curve test a meteorological mast would be installed at a distance of typically 2.5 rotor diameters from the WTG. The rotor diameter in this measurement campaign is 116 metres, therefore the met mast would be installed at a distance of 2.5 * RD = 290 metres. The Galion Lidar measures wind speeds in bins of 30 m starting from 15 m. As a result, the nearest Galion range gate to 290 m is the one at 285 m. Consequently, for each timestamp the integer wind speed at 285 metres distance is labelled as the reference wind speed.

$$\text{Wind\_speed}_{\text{reference}} = \text{Integer}\ [\text{Wind\_speed}\ (285)] \qquad [2]$$

This reference wind speed is then used to group the timestamps into bins of integer wind speeds. In addition, the wind speed readings for each distance along each scan are normalised to their equivalent reference wind speed.

$$\text{Wind\_speed}_{\text{normalised}}(x) = \frac{\text{Wind\_speed}\ (x)}{\text{Wind\_speed}_{\text{reference}}} \quad [3]$$

Where x is defined as the horizontal distance from the WTG rotor.

4.2 Horizontal arc scan

The horizontal arc scan effectively represents an arc scan with zero elevation. This geometry enables the measurement of wind speeds across the surface of a horizontal circular sector.

Figure 3, below, is an illustration of the horizontal scan configuration. The blue box denotes the nacelle top with the right hand side being the rotor side. It is highlighted that the nacelle will not be shown in the resulting final plots and that in all plots the WTG rotor always faces horizontally to the right. The sign convention of x and y is also shown in black.

The green box represents the area over which the wind speeds were measured and interpolated to form the plots shown in Section 5.2. The box is 1000 metres long and 800 metres wide. The red solid lines are the two extremities of the horizontal scan (± 42° from centre line). The Galion emits beams in that angle range in 3° increments (some of which are shown in dashed lines for illustration purposes), leading to a total of 29 wind measuring beams per 10 minute individual scan. Finally, the black box shows the location of the reference point.

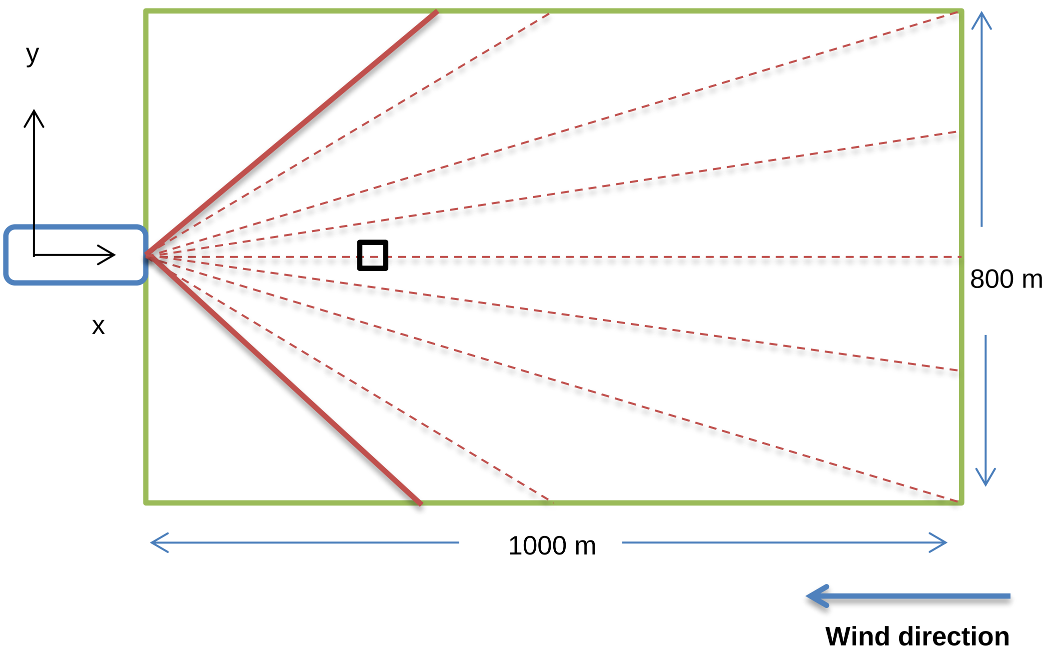

Figure 3: Visualisation of the horizontal arc scan interpolation

4.2.1 Data Filtering

A similar process was employed as mentioned in section 4.1.1, above.

4.2.2 Assessment of the free stream sector

A wind sector of 240º - 290º (in terms of yaw angle from true north) was applied as a precautionary measure to avoid interference from the surrounding obstructions (WTGs, FINO1 meteorological mast) and to ensure free stream wind measurements.

4.2.3 WIND SPEED NORMALISATION

Wind speeds in this configuration are a function of two variables which can be expressed as:

- Orthogonal Coordinates: $\text{Wind\_Speed}\ (x, y)$; or
- Polar coordinates: $\text{Wind\_Speed}\ (r, \theta)$.

Similarly to the "single beam" configuration described previously, the integer wind speed at 285 metres) and zero azimuth, hence polar coordinates notation, is labelled as the reference wind speed for each timestamp.

$$\text{Wind\_Speed}_{\text{reference}} = \text{Integer}\ [\text{Wind\_speed}\ (285{,}0)] \qquad [4]$$

This reference wind speed is then used to group the timestamps into bins of integer wind speeds. In addition, the wind speed readings for each longitudinal and transverse distance in each scan are normalised by their equivalent reference wind speed.

$$\text{Wind\_Speed}_{\text{normalised}}(x, y) = \frac{\text{Wind\_Speed}\ (x, y)}{\text{Wind\_Speed}_{\text{reference}}} \qquad [5]$$

where x is the distance ahead of the WTG rotor and y is the transverse distance from the nacelle centre line.

4.2.4 DATA INTERPOLATION

The processed data is then interpolated in order to create contour plot showing how wind speed varies in both x and y dimensions.

Due to the radial shape of the scan there are large gaps between data points at larger radii, leading to data interpolation over longer distances.

5 RESULTS

5.1 COMPRESSION ZONE MEASUREMENT (THROUGH A SINGLE BEAM)

As described in Section 4.1.3 above, wind speeds in Figure 4 are normalised to each scan's reference wind speed reading (wind speed at 285 metres), reflecting the current approach whereby meteorological masts are recommended to be installed at a distance of 2.5 RD from a WTG.

As stated previously, it is typically assumed that the compression zone effects do not extend to a distance of 2.5 RD. As a result, normalised wind speed values farther than this point should remain of a value of approximately 1, thus indicating that free stream wind speed has been reached.

Figure 4, shows the results of the analysis described in Section 4.1. It is observed that the measured wind speeds beyond the anticipated compression zone length (285 metres) are consistently 1-3% higher than the normalised wind speed indicating that the compression zone extends beyond 2.5 RD.

Wind speed reduction (gradient) is observed up until 3.5 RD, which corresponds to a distance of approximately 400 metres, although there still appears to be some compression beyond this distance.

There is a trend where the lower the wind speed bin the farther the distance before wind speed increase diminishes. This indicates that the compression zone length reduces as wind speed increases, which is consistent with our expectations since:

- The thrust coefficient tends to reduce in value at higher wind speeds; and

- The air carries more momentum, which would reduce the effect of the compression zone.

This is clearly shown via setting the colour scale of the data series to represent the value of the respective wind speed bin (ranging from light blue for smaller wind speeds to darker blues which indicate higher wind speeds).

In the low wind speed bins a number of peaks in wind speed are observed along the beam at approximately 1, 3.5 and 6.5 RD. In each of these wind speed bins there are a large number of counts which gives confidence that this is not noise or an effect of a low number of counts. However these structures are not fully understood and require further investigation, analysis of other datasets is ongoing to try and establish the nature of this structure.

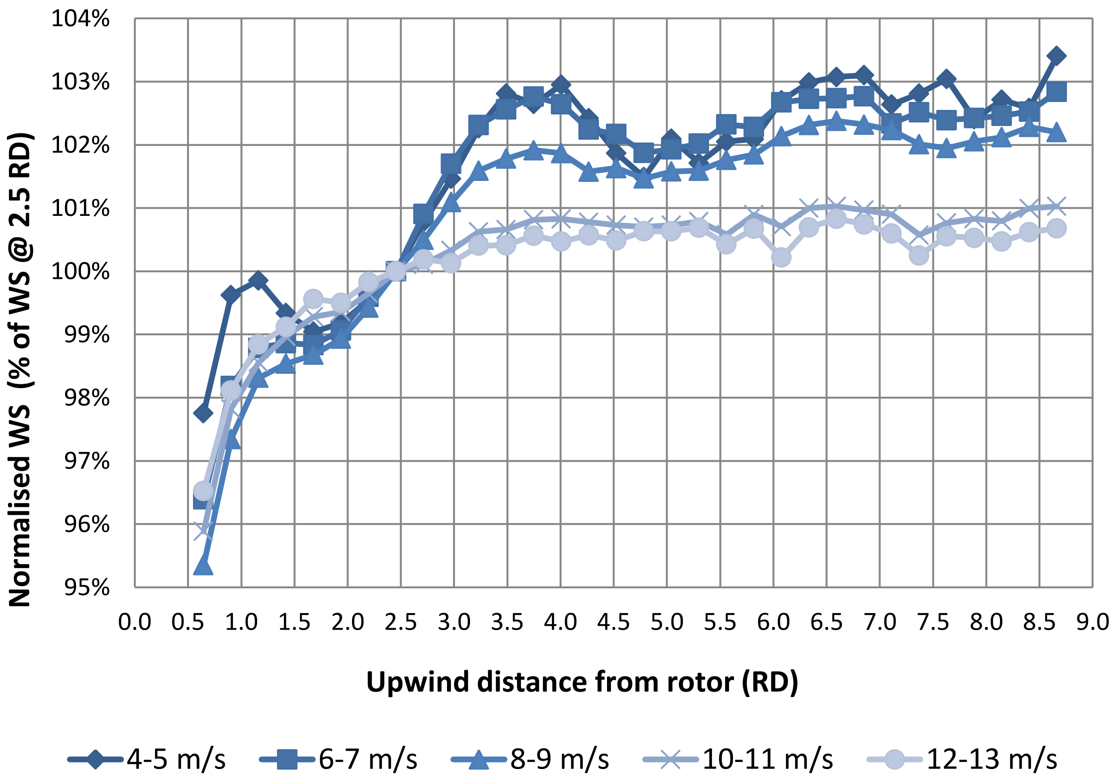

Figure 4: Single beam visualisation of compression zone

5.2 COMPRESSION ZONE SURFACE MAPPING (THROUGH A HORIZONTAL ARC SCAN)

Figure 5, Figure 6, Figure 7 and Figure 8 below, show the results of the analysis on the horizontal arc scans. Each figure is representative of a wind speed of 4, 5, 6 and 9 m/s respectively.

In all of the following figures the WTG is always positioned at (0, 0) looking horizontally towards the right side of each figure into the incoming wind (wind direction is from right to left). Effectively the figures show the horizontal surface area ahead of a WTG (at nacelle height).

The areas coloured in white are areas beyond the azimuth range of the scan, therefore these are areas with no data.

The location of the assumed reference wind speed (with which all speeds are normalised) is shown with a small black square in each of the following figures. From this, it can be seen that the wind speed beyond the reference point radius continues to increase (the colouring changes from a dark yellow to red). This indicates that the compression zone is still present at the reference point.

It is noted that the figures below show the variation of axial wind speed as the wind approaches the WTG and not the full wind speed vector.

The wind speeds appear to increase up to a radius of approximately 4 RD, where the normalised wind speeds become more stable at a value of 1.03 approximately, which coincides with the results from the "single beam" configuration. This is shown most clearly in Figure 7.

These results show that the 2.5 RD (290 metres) distance is still within the compression zone. As a result, power performance readings would be affected by the compression zone if the meteorological mast was installed at 2.5 RD.

Due to the larger transverse distances between beams at greater distances, some inaccuracies in the interpolation process were observed. As a result, the following figures provide an overall illustration rather than an accurate metric of the compression zone.

Finally, it is observed that the compression zone appears to reduce in size with increasing wind speed bins, which is most clearly apparent in Figure 8.

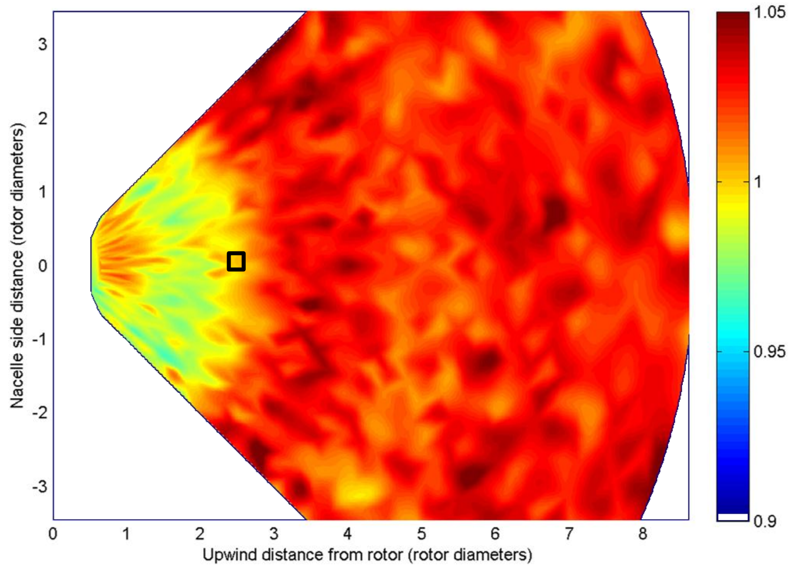

Figure 5: Compression zone visualisation (reference wind speed = 4 m/s)

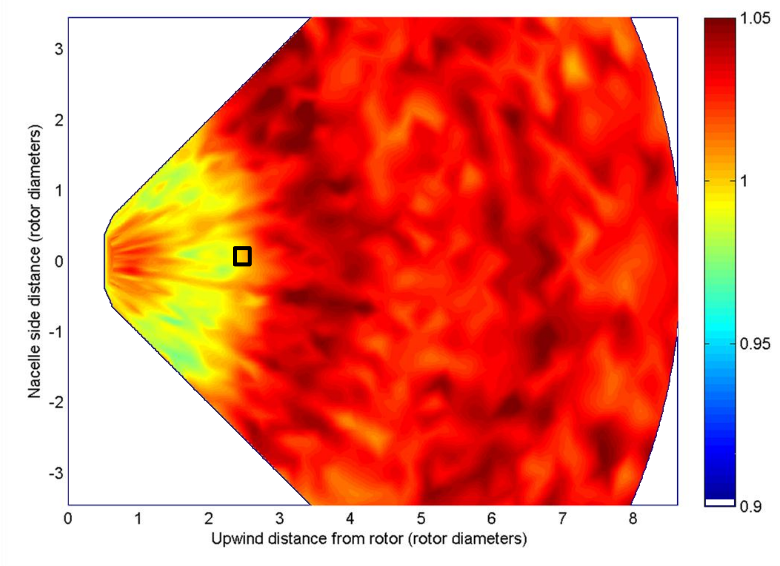

Figure 6: Compression zone visualisation (reference wind speed = 5 m/s)

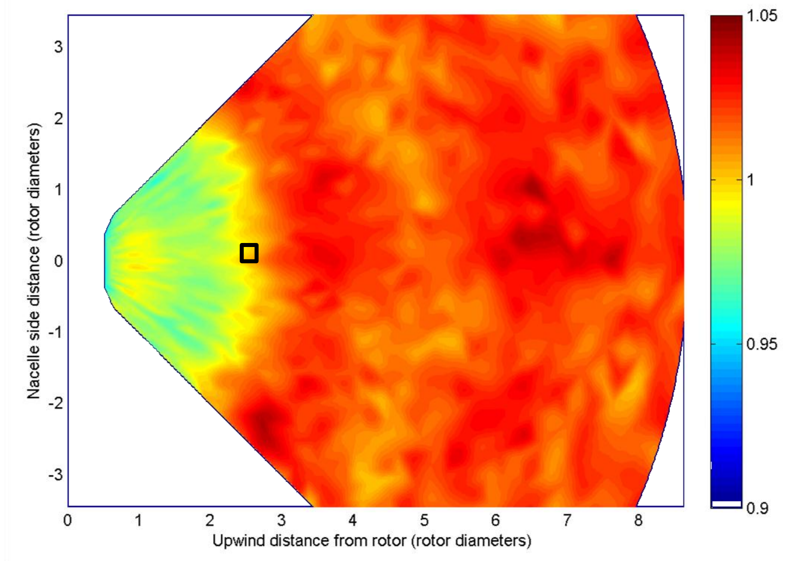

Figure 7: Compression zone visualisation (reference wind speed = 6 m/s)

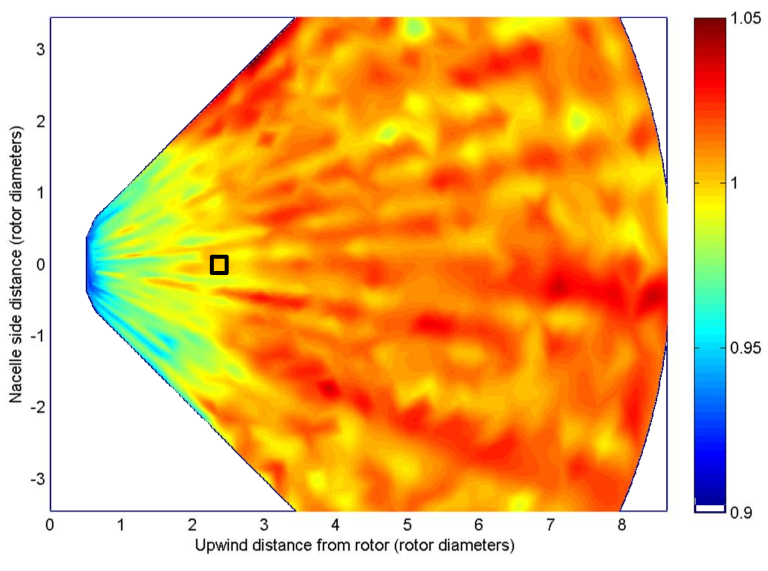

Figure 8: Compression zone visualisation (reference wind speed = 9 m/s)

6 CONCLUSIONS

SgurrEnergy undertook a comprehensive wind measurement campaign using Galion Lidar units installed on an offshore WTG in Alpha Ventus.

Results from the measurement campaign suggest that compression zone effects may be present up to a distance approximately 3.5 times the length of the rotor diameter. This is supported by both the single beam and horizontal arc scan campaigns.

These results indicate that current power performance test procedures may be affected by the compression zone, which would in turn affect energy yield prediction. There are three ways to address this issue:

- Meteorological masts could be installed at a greater distance from a WTG, namely at a range of 3.5-5 RD for offshore wind projects. Due to the reduced terrain effects in offshore wind projects it would be anticipated that the wind speed correlation between the mast and the WTG would remain strong;
- Met masts could be installed outside the measurement wind direction (diagonal to the WTG), provided that they are outside the lateral dimension of a compression zone; and
- Implementation of compression zone correction factors could be used to account for the compression zone effects.

It is noted that measurements have been made at an offshore site and further measurements at an onshore site are recommended to determine whether the same results are obtained.