Validation of Measurements from a ZephIR Lidar

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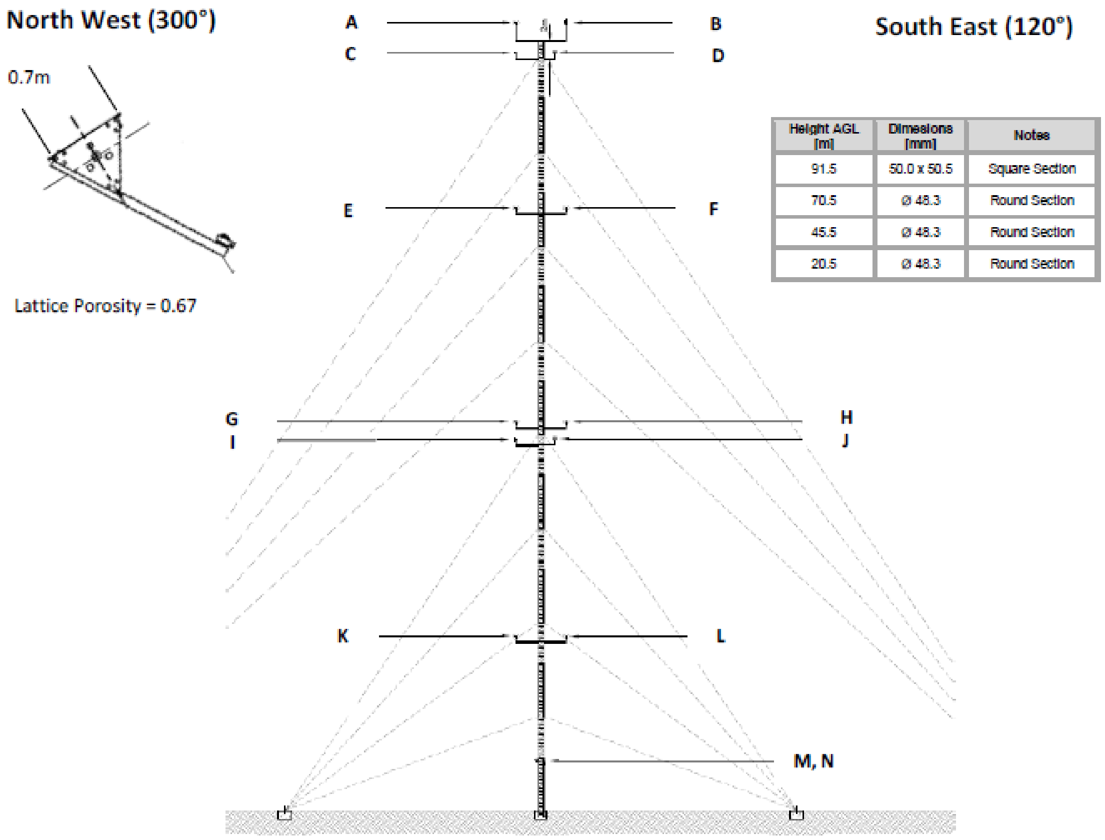
INTRODUCTION

Wind farm construction projects require a large amount of capital expenditure (CAPEX) with long return periods before the investment generates any profit. This is especially true of large offshore wind farms. A significant quantity of the CAPEX is related to long periods of resource assessment, involving the on-site measurement campaigns required to convince financial bodies that the project will produce attractive returns. Historically, measurements of wind speed (and thus the wind farm's potential yield via the P50, P75 and P90) have relied on the industry standard cup anemometer cup anemometer and thus the construction of at least one very tall meteorological mast on site. Erecting each mast requires specialist skills and may require unique designs to cope with unique locations – especially offshore. A Lidar by comparison is significantly cheaper and unlike a mast is highly portable allowing flexibility within a measurement campaign even after it has begun. Another Lidar advantage over standard meteorological masts is the height at which they can measure. Masts become increasingly more expensive with size and thus rarely extend above the planned farm's hub height, a Lidar by comparison can collect data throughout the whole atmospheric boundary layer (ABL), enabling measurements which can be used to validate the atmospheric flow within computer simulations of large wind farms.

APPROACH

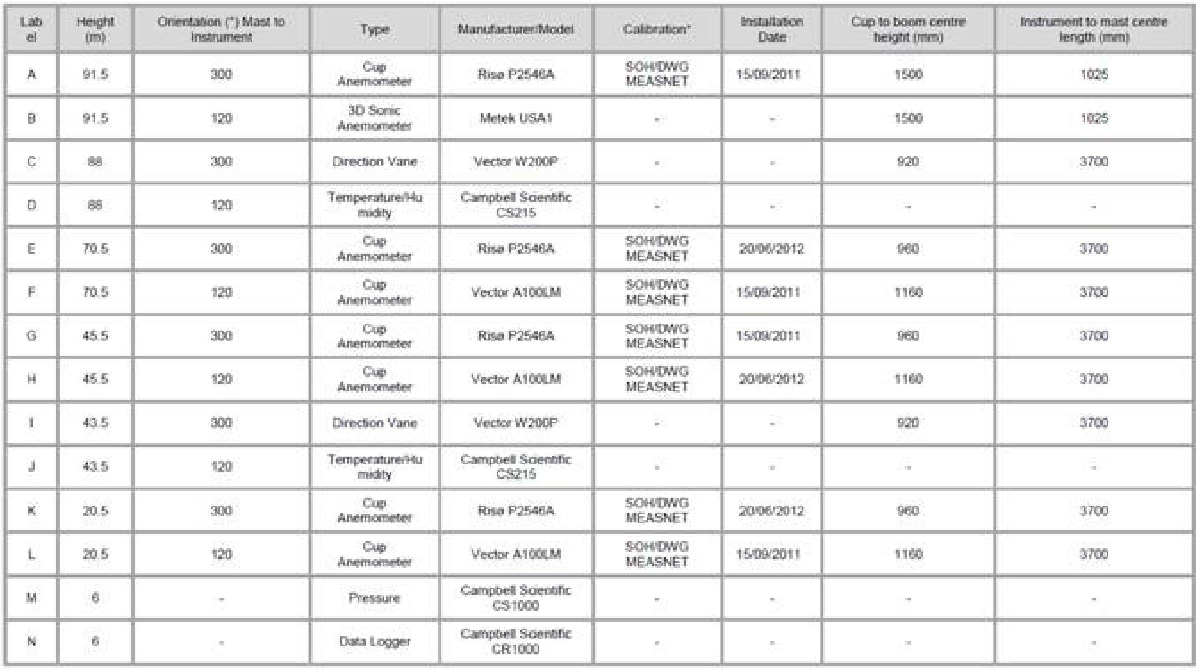
Measurement data of atmospheric conditions have been made available by the Lidar manufacture ZephIR Lidar [1]. The measurements were collected using a ZephIR 300 wind lidar (which collects finance grade measurements up to 200m) over a period of one year from November 2012 to October 2013 at their UK Remote Sensor Test Site (UKRSTS). For the purposes of validation, concurrent measurements from the site's IEC compliant 91 m mast, located less than 10 m from the Lidar were also made available. A description of the meteorological mast is shown in the figure and table below.



Height AGL [m]	Dimensions [mm]	Notes
91.5	50.0 x 50.5	Square Section
70.5	Ø 48.3	Round Section
45.5	Ø 48.3	Round Section
20.5	Ø 48.3	Round Section

Figure 1 Diagram of the UKRSTS meteorological mast

Table 1 Description of the instrumentaion used on the mast



Label	Height (m)	Orientation (°) Mast to Instrument	Type	Manufacturer/Model	Calibration*	Installation Date	Cup to boom centre height (mm)	Instrument to mast centre length (mm)
A	91.5	300	Cup Anemometer	Risø P2546A	SOH/DWG MEASNET	15/09/2011	1500	1025
B	91.5	120	3D Sonic Anemometer	Metek USA1	-	-	1500	1025
C	88	300	Direction Vane	Vector W200P	-	-	920	3700
D	88	120	Temperature/Humidity	Campbell Scientific CS215	-	-	-	-
E	70.5	300	Cup Anemometer	Risø P2546A	SOH/DWG MEASNET	20/06/2012	960	3700
F	70.5	120	Cup Anemometer	Vector A100LM	SOH/DWG MEASNET	15/09/2011	1160	3700
G	45.5	300	Cup Anemometer	Risø P2546A	SOH/DWG MEASNET	15/09/2011	960	3700
H	45.5	120	Cup Anemometer	Vector A100LM	SOH/DWG MEASNET	20/06/2012	1160	3700
I	43.5	300	Direction Vane	Vector W200P	-	-	920	3700
J	43.5	120	Temperature/Humidity	Campbell Scientific CS215	-	-	-	-
K	20.5	300	Cup Anemometer	Risø P2546A	SOH/DWG MEASNET	20/06/2012	960	3700
L	20.5	120	Cup Anemometer	Vector A100LM	SOH/DWG MEASNET	15/09/2011	1160	3700
M	6	-	Pressure	Campbell Scientific CS1000	-	-	-	-
N	6	-	Data Logger	Campbell Scientific CR1000	-	-	-	-

MAIN BODY

To ensure an accurate comparison between data collection techniques, the cup anemometer data set has been appropriately cleaned to remove the effects of mast shadowing. Measurements taken by the mast instrumentation on the North West side were screened for events where the wind occurs from between 75° and 165° whilst events were screened between directions 275° and 325° for instruments on the South East side. Having filtered for mast shadow, the availability of wind measurements where the mast has two cup anemometers (heights 20m, 45m and 70m) was 76.2% whilst at the mast top, where there is only one cup anemometer, the wind data availability was 75.3%. By comparison, the availability of lidar wind measurements (number of measurements divided by the number of ten-minute periods in a year) ranged from 92.4% at 20m to 93.7% at 91m, with similar levels of data availability above the mast comparison heights up to 200m and the potential to measure at even greater heights.

Analysis of measurements from the mast's two wind vanes at heights 45m and 88m found they have are strongly correlated although the wind roses in Figure 2 suggests systematic variation exists between the heights. By comparison, the lidar data shows greater variation with height at individual events which may result from faster response times and thus the incorporating variation due to turbulence, though the results in Figure 2 show minimal variation between lidar measurement heights. Figure 2 also shows strong agreement between directional measurements by the lidar and mast for each sector except between 75°-165° where the mast data has been reduced by screening to remove mast shadow effects.

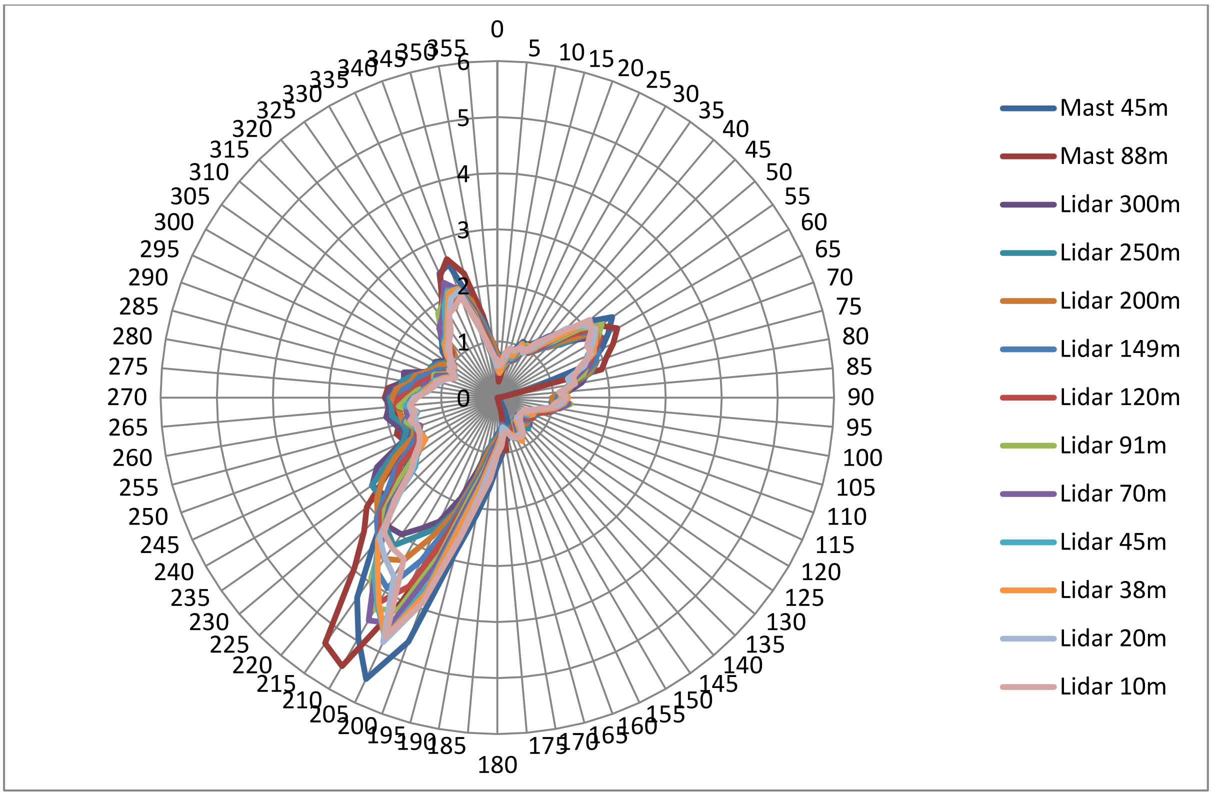


Figure 2 Wind Roses for UKRSTS at multiple heights, scale is percent of 10 minute recorded events

Due to the nature of mechanical cup anemometers often under-reporting at low wind speeds, the two figures below compare wind speeds measured by both the mast instrumentation and the lidar, over all directional sectors. Figure 3 shows a classic Weibull wind speed distribution is measured at each of the four cup anemometer heights, and this is matched by the lidar results. There is a slight difference between the measurements, with the lidar tending towards higher velocities. However this is small and within the range of cup measurement error and so the measurements are statistically identical. The two graphs in Figure 4 show the two measurement techniques are directly comparable with an offset well within the cup anemometer's margin of error. Although there is a lower correlation between techniques when comparing the wind speed standard deviation, the gradient is still exceptionally high and it is natural to expect a lower correlation for this parameter as cup anemometers take longer to react to changes in wind speed than lidar.

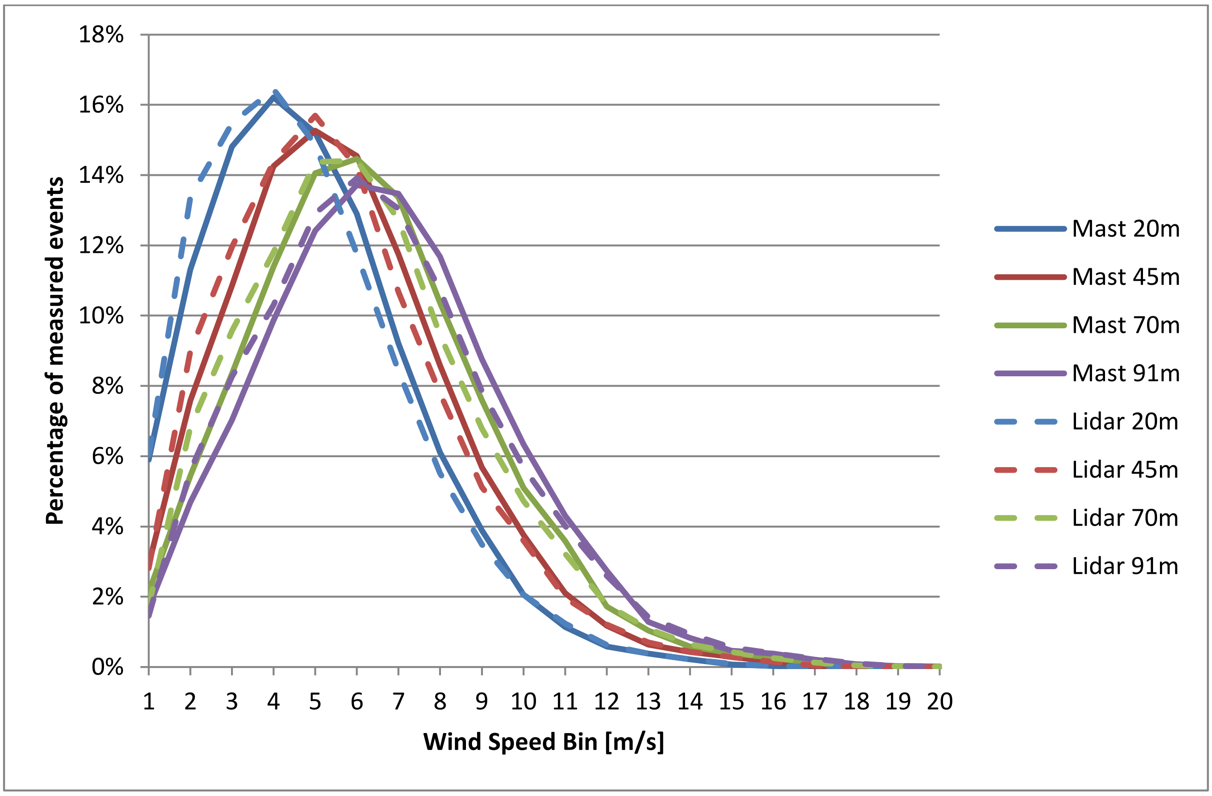


Figure 3 Wind Speed frequencies as measured by mast and lidar

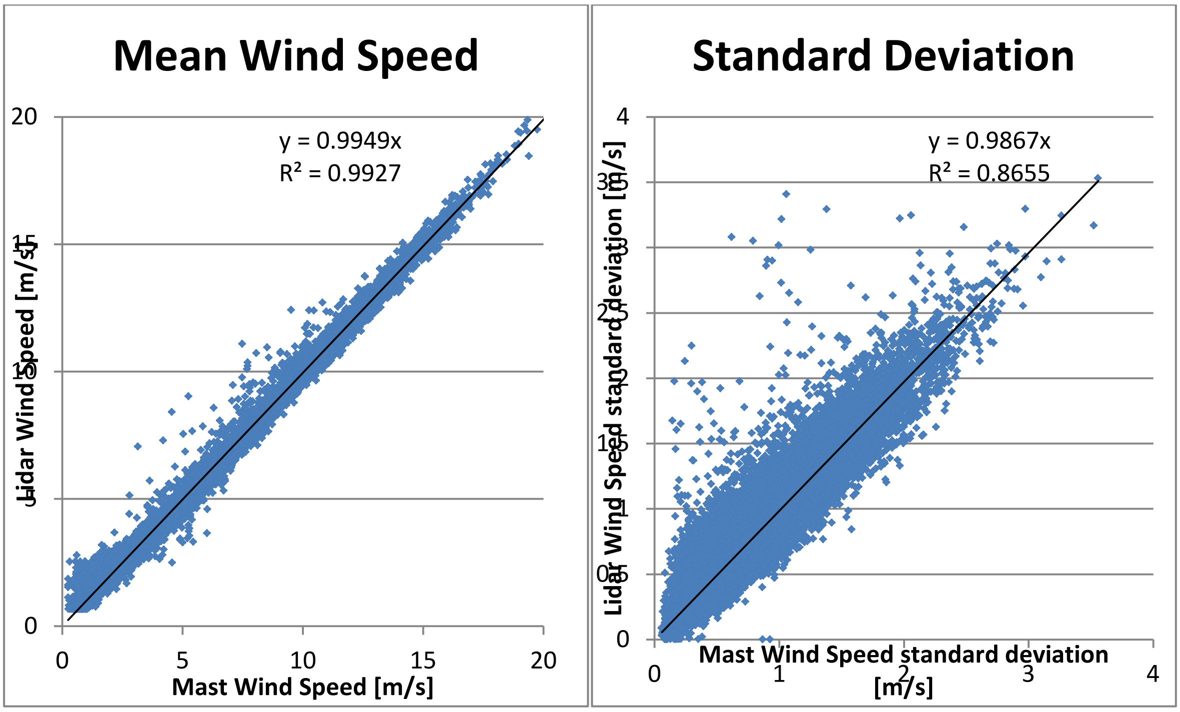


Figure 4 Comparison of 70m mean wind speed and standard deviations by mast and lidar

To further investigate how the two measurement techniques compare, Figure 5 below compares how the standard deviation of wind speed measurements changes with mean wind speed at 70m above the ground – a typical turbine hub height. The vertical axis shows the mean value of measurement standard deviation across the relevant 10-minute events where the 10-minute mean wind speed occurs within the wind speed bins on the horizontal axis, each 1ms^{-1} in size. The error bars are the standard deviation of the standard deviation values shown on the vertical axis. The figure clearly shows that statistically, the measurements of mean wind speed are the same whether measured by cup anemometers or by lidar. It is also of note that the mean value of measurement standard deviation increases linearly with wind speed.

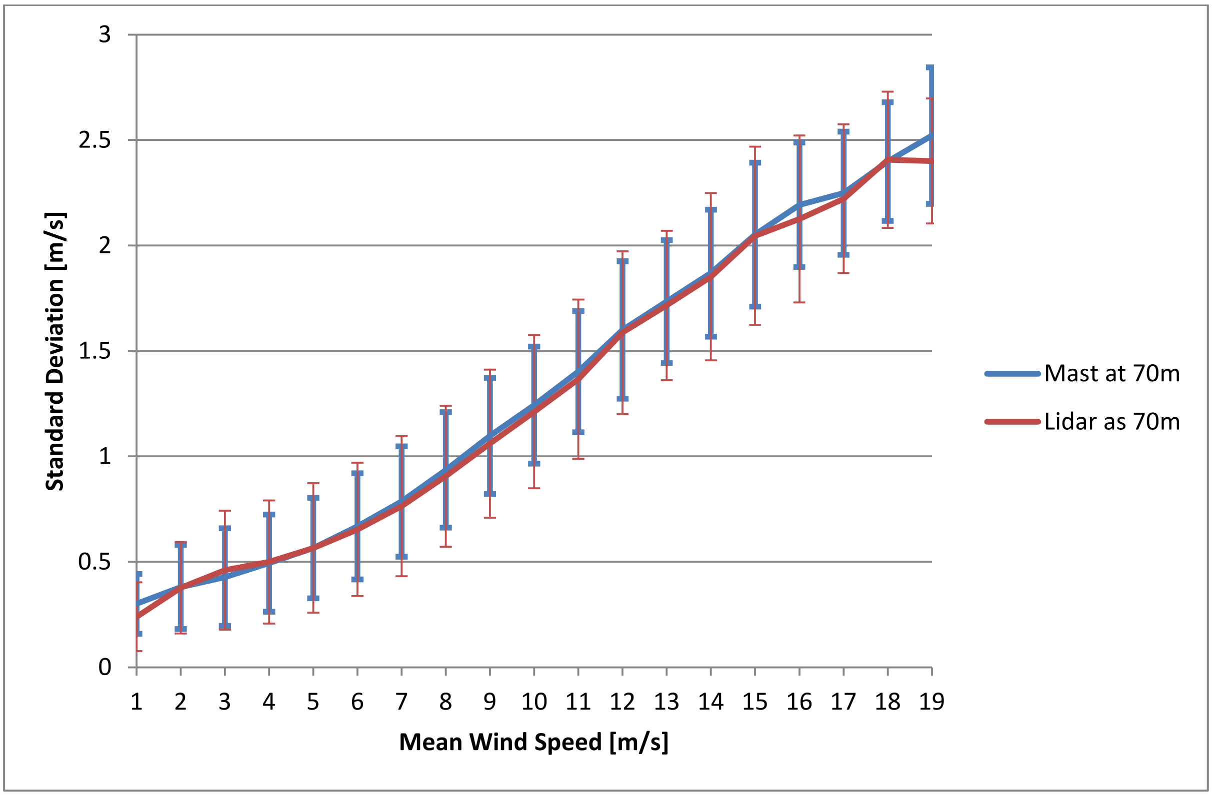


Figure 5 Comparison of measurement standard deviation within each wind speed bin for both measurement techniques

As atmospheric stability has been shown to affect the available wind resource for large farms [2], a short investigation has been undertaken into using lidar measurements to approximate the stability conditions. If successful, this could play a significant role in reducing resource assessment costs as farm applications in the UK are currently required to measure the stability conditions at development sites [3], it would also prove helpful for validating computer simulations of large wind farms [4]. This work calculates the gradient Richardson (Ri_G) number according to equation 1,

$$Ri_G = \frac{\frac{g}{T}\left(\frac{dT}{dz}\right)}{\left(\frac{du}{dz}\right)^2} \tag{1}$$

where g is the gravitational acceleration, T is absolute temperature, z is the height above ground and u is the horizontal wind speed. The resulting values of Ri_G are then converted into the stability classes used by [2]. The calculation of Ri_G used T values from 43m and 91m and u values from 45m and 91m with classes shown in table 2, with anything outside that range considered a NULL stability event outside of Richardson number theory and the distribution of events is shown in Figure 6.

Table 2 Definition of stability classes

Stability Class	Acronym	Range of Ri_G values
Very Unstable	VU	$-1.28 < Ri_G < -0.64$
Unstable	U	$-0.64 < Ri_G < -0.32$
Near Unstable	NU	$-0.32 < Ri_G < -0.13$
Neutral	N	$-0.13 < Ri_G < 0.08$
Near Stable	NS	$0.08 < Ri_G < 0.12$
Stable	S	$0.12 < Ri_G < 0.17$
Very Stable	VS	$0.17 < Ri_G < 0.19$

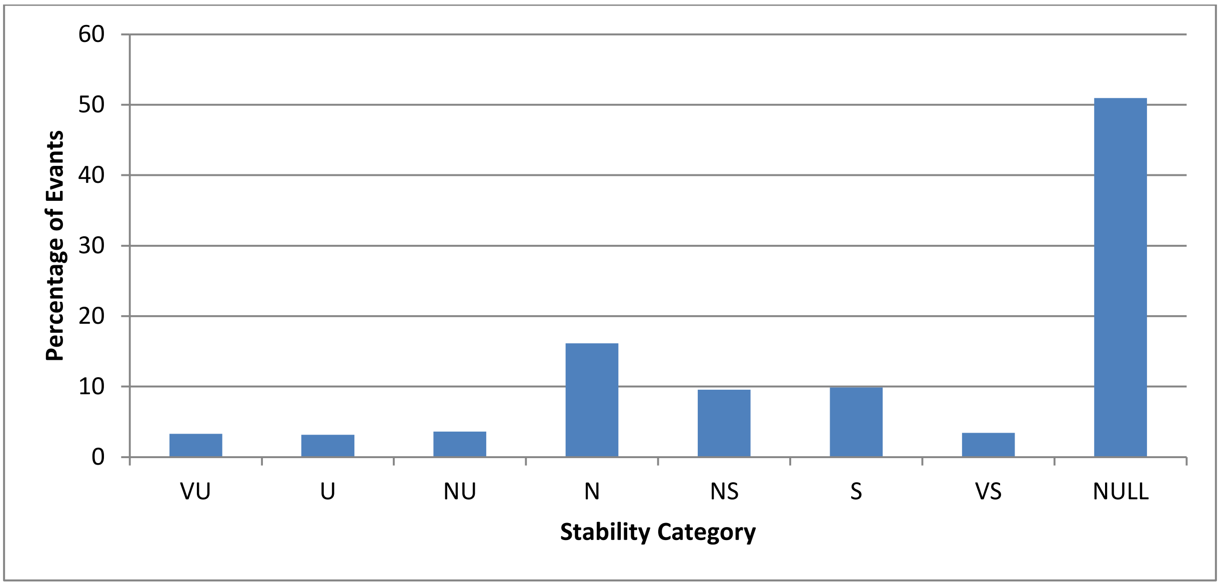


Figure 6 Frequencies of each stability class at the site

It is not unusual for stability calculations to return a large proportion of “NULL” events [4]. This is one reason why using lidar data, specifically wind shear measurements, as an alternative way to classify atmospheric stability conditions may prove wise. Below, Figure 7 gives an example of this, showing how velocity profiles (as measured by the lidar) vary according to the Ri_G calculated using mast measurements. It also shows that the lidar’s capability to measure wind speed accurately is not compromised by stability conditions.

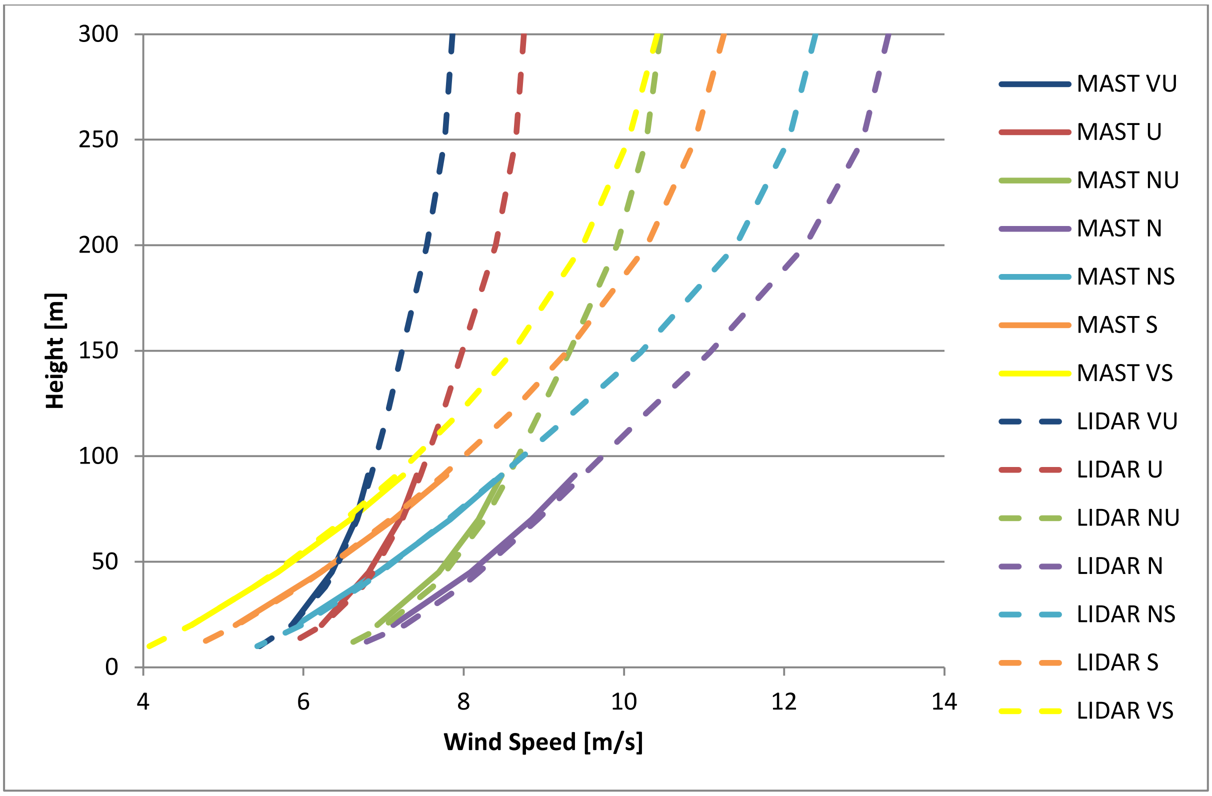


Figure 7 Wind speed profiles by atmospheric stability category

CONCLUSION

From the results presented in this work, it is clear that a ZephIR 300 wind lidar is capable of measuring the wind resource to at least the same standard as a met mast, with very comparable values of wind speed (both mean and standard deviation) and wind direction. Furthermore, the lidar data set was more complete with over 93% availability compared to the mast's 75% availability, more measurement heights – both within the mast's height range and also extending to over twice the mast height with potential for more. The lidar measurements of wind direction have been shown to be more reliable than using a wind vane on a mast, owing to the difficulty of aligning individual vanes and mast shadow effects. The availability of lidar directional measurements throughout the ABL is also useful validation purposes when considering the Ekman spiral in computational simulations, both for wind resource assessment and weather forecasting. Although lidars are unable to measure air temperature at height and therefore do not directly aid the calculation of atmospheric stability via thermal buoyancy, the observed variation in horizontal velocity above mast height with mast calculated stability category suggests it may provide a future substitute at considerable cost savings.

LEARNING OBJECTIVES

The primary objective of this work is to show that wind measurement data from lidar are at least as good as wind measurements from meteorological masts. This is demonstrated through a number of plots of mean and standard deviations of wind speed.

The Secondary objective is to investigate the potential for lidar data to be the basis of atmospheric stability calculations throughout the ABL and as a source of validation data for complex wind farm simulations.

Works Cited

[1] ZephIR Lidar, [Online]. Available: http://www.zephirlidar.com/. [Accessed 15 May 2015].

[2] P. J. Eecen, J. W. Wagenaar, N. Stefanatos, T. F. Pederson, R. Wagner and K. S. Hansen, "Final Report UpWind 1A2 Meteorology," ECN-E--11-013, 2011.

[3] *IEC Standard, 61400-1, Edition 3 + Amendment 1, 2010. Wind Turbines, Part 1: Design Requirements, BS EN 61400-1:2005 + A1:2010.*

[4] P. Argyle, *PhD Thesis: Computational Fluid Dynamics Modelling of Wind Turbine Wake Losses in Large Offshore Wind Farm, Incorperating Atmospheric Stability,* Loughborough University, 2015.