Validation of Measurements from a ZephIR Lidar

Peter Argyle, Simon Watson
CREST, Loughborough University
Loughborough, United Kingdom
p.argyle@lboro.ac.uk

ABSTRACT

Historically wind speed measurements for wind resource assessment have been made using tall meteorological masts. The development of remote sensing techniques, in particular Doppler lidar (light detection and ranging) now enables these measurements to be made from the ground, without the costs of erecting a met mast. This work compares measurements from a ZephIR 300 continuous wave lidar against measurements from an IEC compliant 91m mast, concluding the lidar data to be at least as good as the mast data and with a higher availability rate.

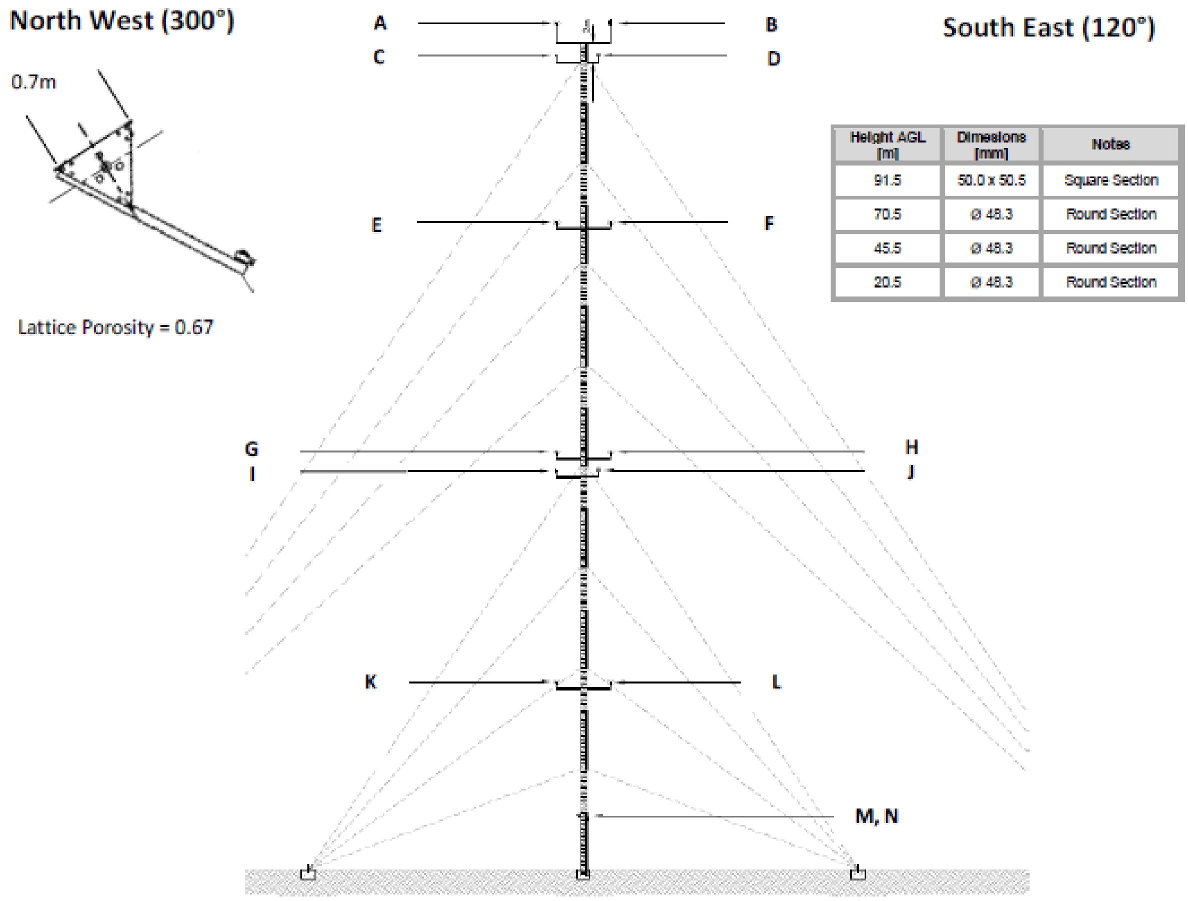
INTRODUCTION

Accurate measurements of wind speed and direction are increasingly important for a number of industries, particularly the wind energy industry. Building a large wind farm usually requires evidence that the project will provide a significant financial return on investment. Remote sensing techniques such as Lidar (Light detection and ranging) have been noted for their usefulness compared to traditional tall meteorological masts, especially where the local flow is likely to vary within the farm boundaries, such as in complex terrain [1]. Therefore, as Lidar data are becoming a more widely accepted alternative to traditional measurements from a mast, they are being tested under an increasing number of varied conditions, such as floating offshore and freezing ice conditions [2] [3] [4]. Their flexibility to be redeployed to different locations or measure at different heights as a result of preliminary findings can be useful to reduce errors in computer simulations or provide greater understanding of developing boundary layers offshore. As with any rapidly developing technology, however, regular reviews of its capabilities and accuracy are required. This is highlighted by [5] who observed calibration issues under mist and fog conditions, although they stress that an updated algorithm to address this exact problem had been available during their experiment.

By comparison to cup anemometry techniques, Lidars are capable of simultaneously measuring wind conditions at greater heights, without restrictions from the mast structure such as mast shadow effects or the necessity for guide cables and foundations. As wind turbine diameters become larger, the sampling of met conditions through a conical volume becomes more relevant than traditional sampling at a localised point. Reference [6] concludes remote sensing techniques should still undergo individual field calibrations against mast measurements. Whilst calls for more data are frequent in the scientific environment, they should not be ignored, especially to investigate possible variations in results. This is highlighted by differences associated with high wind shear observed by [7] but not by [5]. The data used in this work come from a field calibration test site where multiple Lidar are simultaneously tested against high quality mast measurements.

APPROACH

Measurement data of atmospheric conditions have been made available by the Lidar manufacturer ZephIR Lidar [8]. The measurements were collected using a ZephIR 300 wind Lidar (which collects finance grade measurements up to 200m and calibrated according to [9]) 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 91m mast, located less than 10m from the Lidar were also made available. A schematic of the meteorological mast is shown in Figure 1 and the instruments mounted are summarised in Table 1.



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

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. Data availability was then defined as the number of useable measurements divided by the number of ten-minute periods in a year. 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 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.

Table 1 Description of mast instrumentation

Label	Height (m)	Orientation (°)	Type	Manufacturer/Model	Instrument to mast centre (mm)
A	91.5	300	Cup Anemometer	Risø P2546A	1025
B	91.5	120	3D Sonic Anemometer	Metek USA1	1025
C	88	300	Direction Vane	Vector W200P	3700
D	88	120	Temperature/ Humidity	Campbell Scientific CS215	-
E	70.5	300	Cup Anemometer	Risø P2546A	3700
F	70.5	120	Cup Anemometer	Vector A100LM	3700
G	45.5	300	Cup Anemometer	Risø P2546A	3700
H	45.5	120	Cup Anemometer	Vector A100LM	3700
I	43.5	300	Direction Vane	Vector W200P	3700
J	43.5	120	Temperature/ Humidity	Campbell Scientific CS215	-
K	20.5	300	Cup Anemometer	Risø P2546A	3700
L	20.5	120	Cup Anemometer	Vector A100LM	3700
M	6	-	Pressure	Campbell Scientific CS1000	-
N	6	-	Data Logger	Campbell Scientific CR1000	-

RESULTS

Analysis of wind direction measurements from the mast's two wind vanes at heights 45m and 88m found they are strongly correlated, although the wind roses in Figure 2 suggests systematic variation exists between the heights. By comparison, the lidar data show less variation between measuring heights and a good agreement with the mast's lower wind vane. Due the very nature of using multiple instruments, it is harder to ensure each vane is identically oriented whilst undesirable interactions with birds could alter their alignment over time. The lidar however only needs to be oriented once to ensure every measurement height is aligned correctly, and since this is done at ground level, the task does not involve the complexities of working at height.

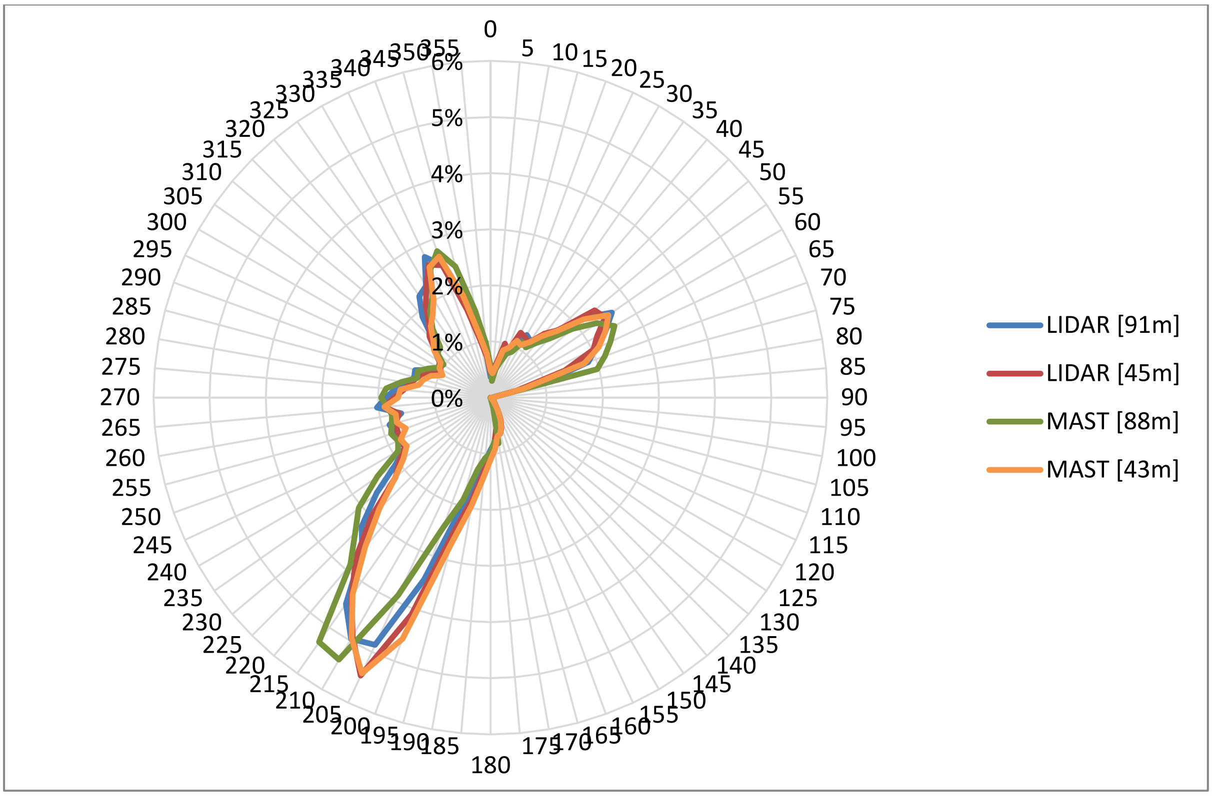


Figure 2 Wind Roses for UKRTS measured by Mast and Lidar at multiple heights, scale is percent of ten minute events

Due to the nature of their rotational inertia, mechanical cup anemometers can under-report at low wind speeds and incur a slight delay in observing changes in speed. Figure 3 and Figure 4 below compare wind speeds measured by both the mast anemometers and the lidar, across all direction sectors. Figure 3 shows that measurements can be modelled by a classic Weibull wind speed distribution at each of the four cup anemometer heights, and this is matched by the lidar results. There are slight differences between the measurements, with the lidar consistently 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 minimal scatter around the trend line. Although there is a lower correlation between techniques when comparing the standard deviations of measured wind speeds within each ten-minute period, the average values agree well from the gradient shown.

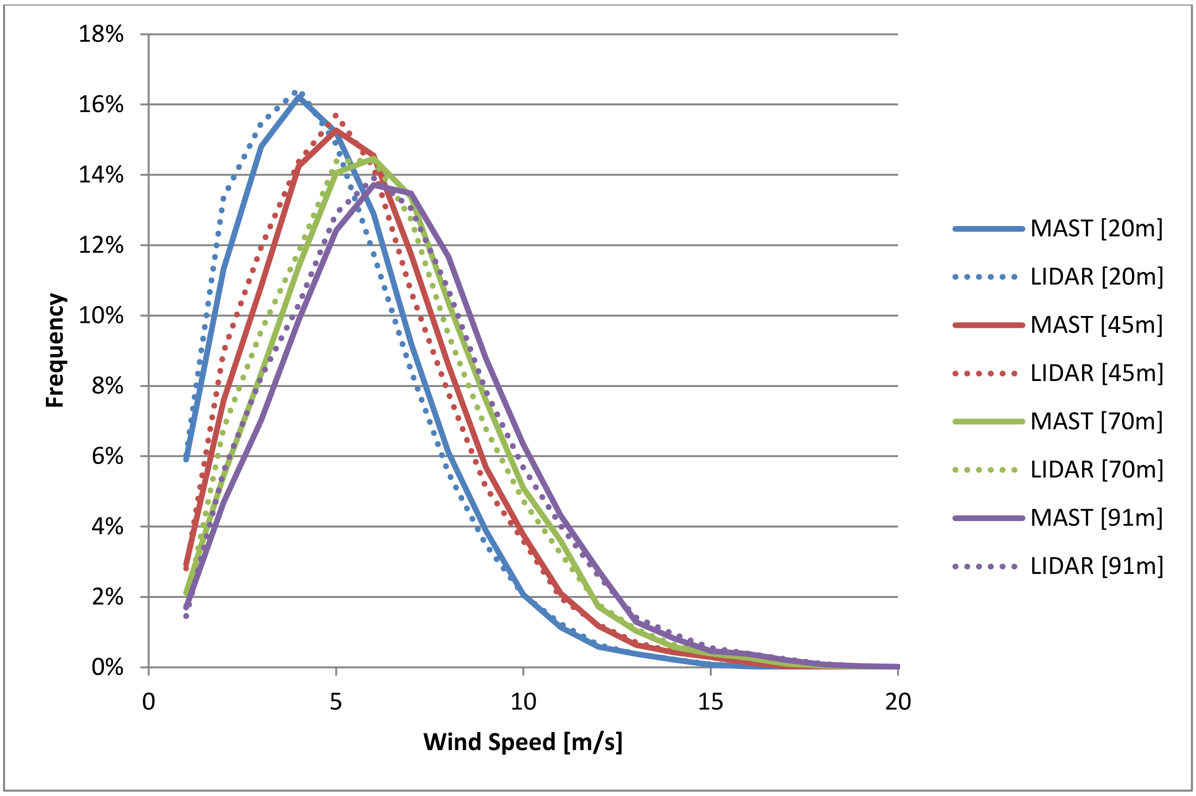


Figure 3 Wind speed frequencies as measured by mast and lidar

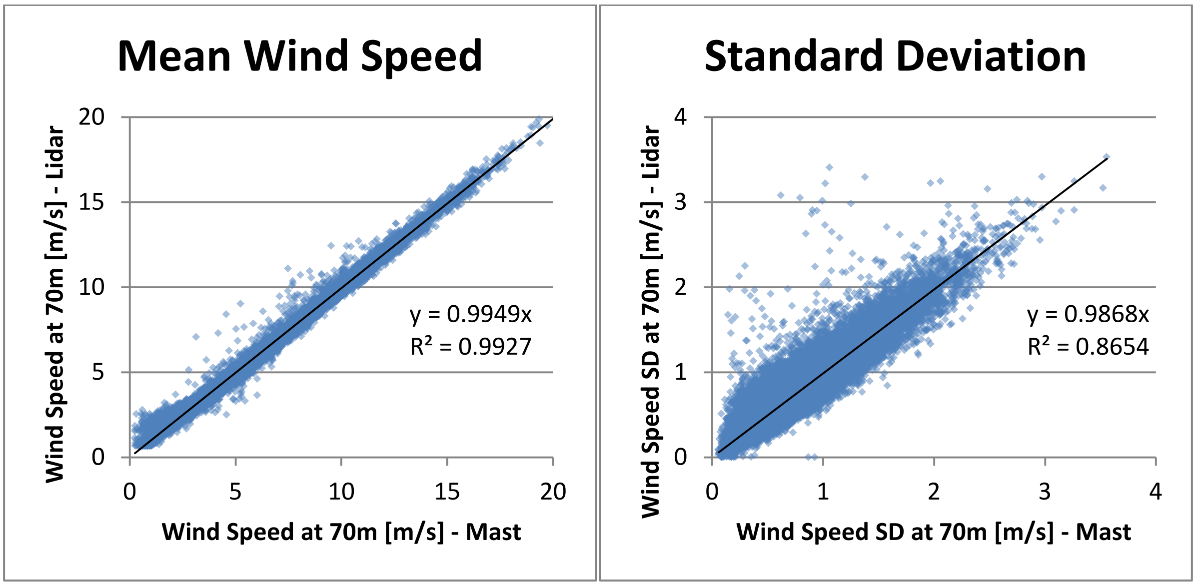


Figure 4 Comparison of 70m mean wind speed (left) and standard deviations (right) as measured by cup anemometers on the mast and by the lidar

The trend lines in Figure 4 show strong correlation between the instruments, similar to those reported by [2]. The greater quantity of scatter above the trend line in the right hand graph but not below the line is probably due to the Lidar observations not being subject to the same angular momentum as the cup anemometer measurements. Averaged across ten minute periods, this effect is insignificant for measurements of mean wind speed but may prove significant when calculating turbulence intensity using methods described in the IEC standard [10].

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 wind 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 measured standard deviation increases linearly with wind speed and that there is little variation between the standard deviation of standard deviation values with increases in mean wind speed.

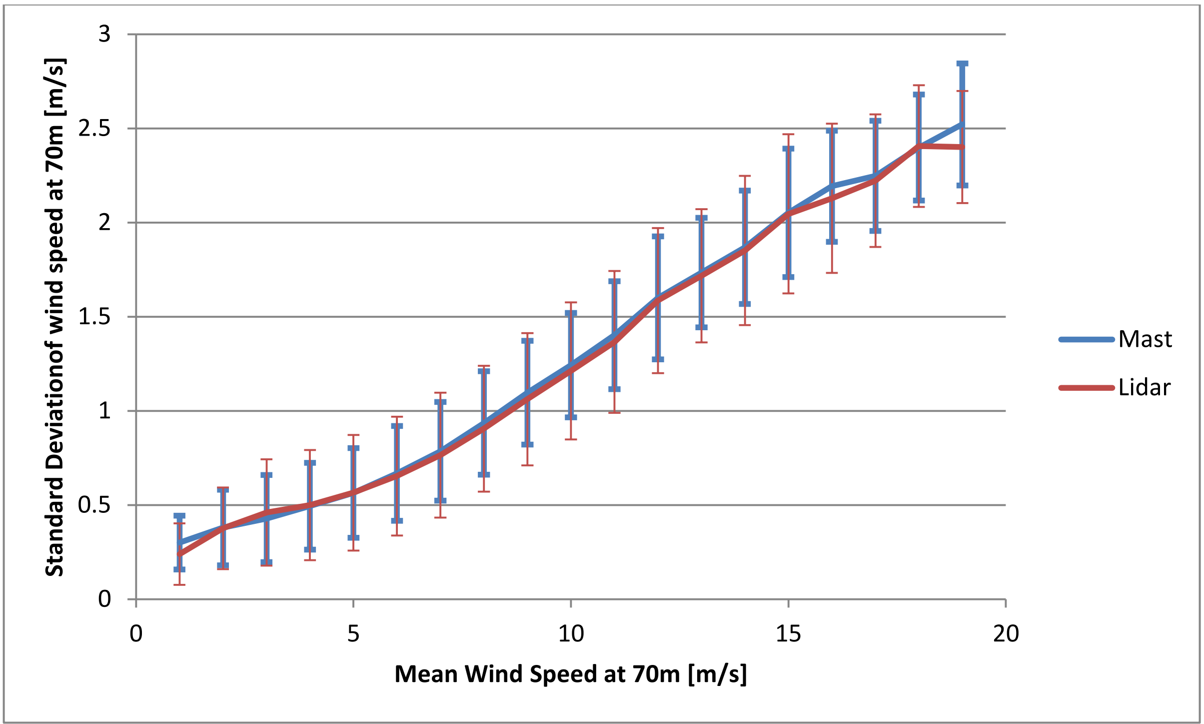


Figure 5 Comparison of measurement standard deviation within each wind speed bin

As atmospheric stability has been shown to affect the available wind resource for large farms [11], a short investigation has been undertaken into using lidar measurements to approximate the stability conditions. 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 [10], it would also prove helpful for validating computer simulations of large wind farms [12]. This work calculates the gradient Richardson (Ri_G) number according to equation (1),

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

where g is the gravitational acceleration, T is absolute temperature, z is the height above ground and u is the horizontal wind speed. The calculation of Ri_G used T values from 43m and 91m and u values from 45m and 91m with the resulting values of Ri_G converted into the stability classes used by [11] shown in Table 2. Any event outside the range $-1.28<Ri_G<0.19$ was considered a NULL stability event outside of Richardson number theory. As Figure 6 clearly shows this to be true for more than half of the events, it is therefore recommended that other methods of calculating atmospheric stability are developed.

Table 2 Definition of atmospheric 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	$0.17<Ri_G<0.19$

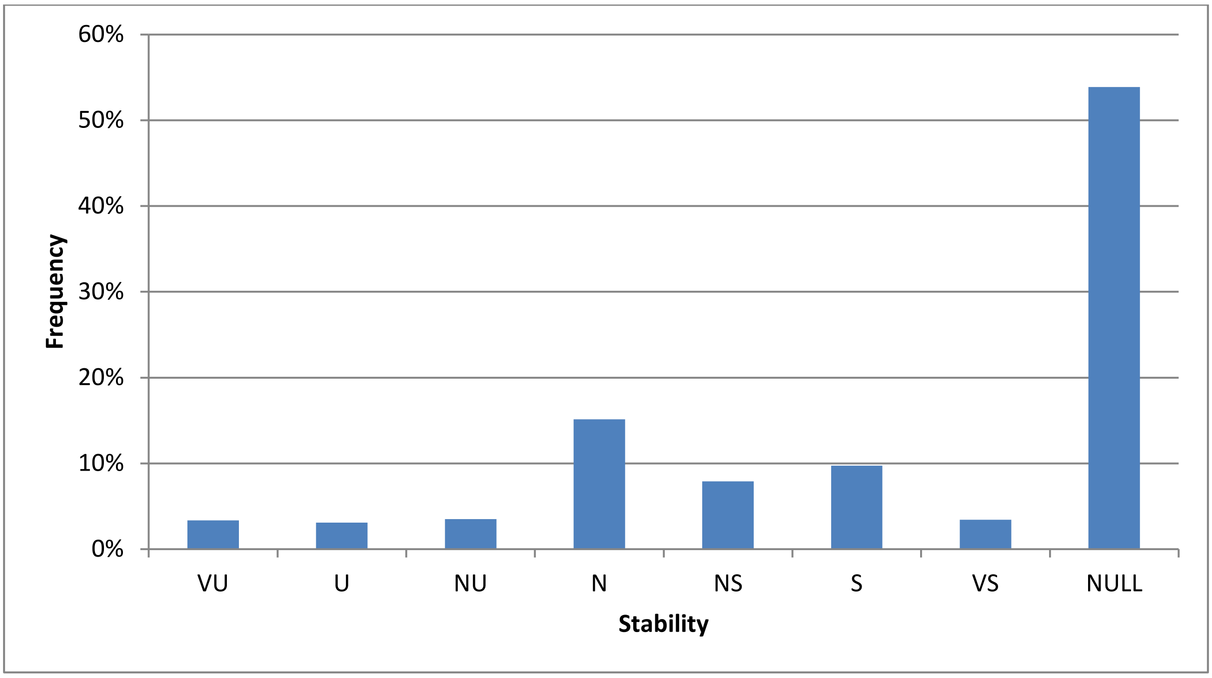


Figure 6 Frequencies of each stability class at UKRSTS

It is not unusual for stability calculations based on Ri_G to return a large proportion of "NULL" events [12]. 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 both the lidar and mast) vary according to Ri_G. It also shows primarily that the lidar's capability to measure wind speed accurately is not compromised by atmospheric stability conditions. Figure 7 suggests a relationship between stability and speed, where at common turbine hub heights, on average, the fastest events exhibit neutral conditions (where $Ri_G \approx 0$) whilst increased values of $|Ri_G|$ appears to be linked to a decrease in average hub height wind speeds. This is as might be expected as mechanical mixing will tend to dominate over thermal buoyancy effects as wind speed increases.

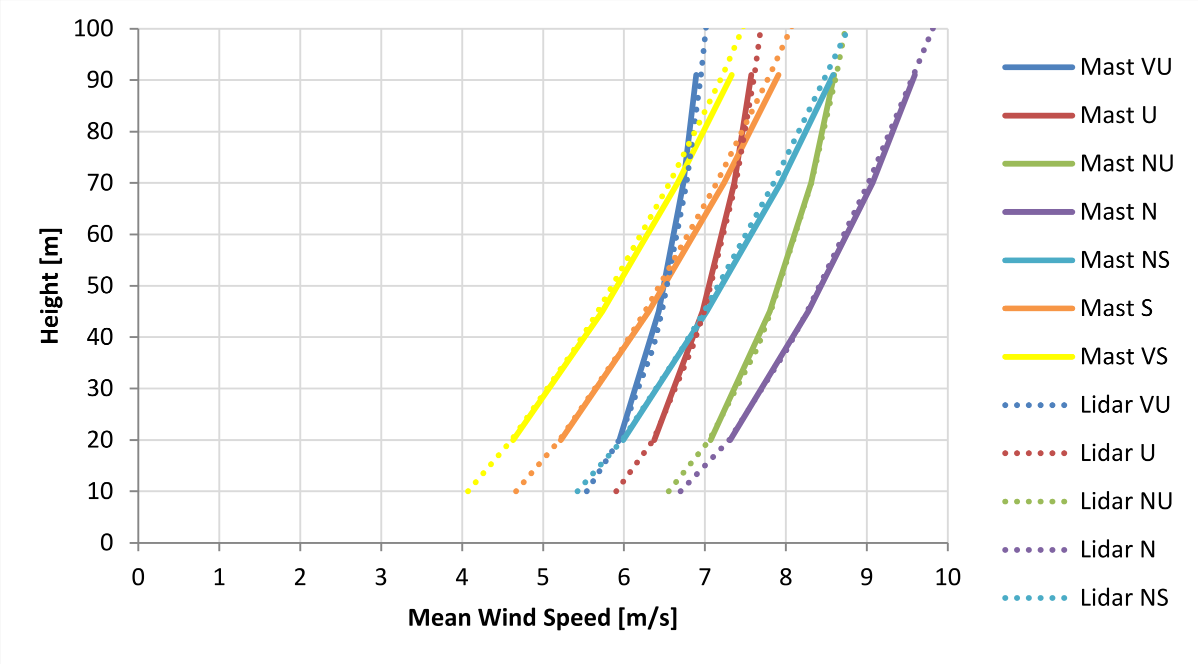


Figure 7 Average wind speed profiles measured by the mast and lidar, filtered by atmospheric stability

Since there is significant variation in the wind speeds displayed in Figure 7 between stability categories, even at a height of 10m, Figure 8 has been filtered to include only 10-minute events where the 70m mean wind speed is 8±0.5m/s. From this we can see there is a clear relationship between wind shear with height and the more unstable atmospheric stability categories, though not for the stable categories.

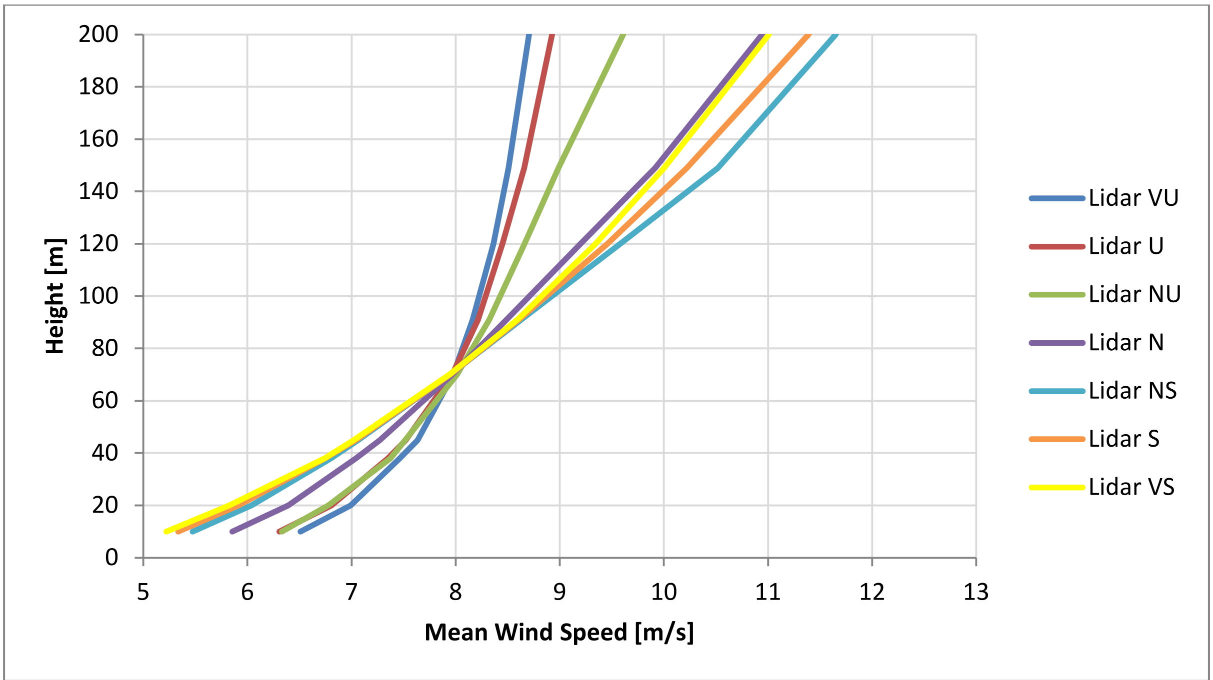


Figure 8 Average wind speed profiles measured by the lidar for each stability category, filtered for events where the wind speed at 70m was 8±0.5m/s

An important aspect to consider when comparing measuring techniques by stability category is that cup anemometers measure the wind speed at a point location whilst a lidar reports the average speed across a conical volume. This is significant for stability calculations as Equation (1) defines the value of Ri_G to be a function of wind shear. Under high shear conditions, or conditions where the shear is not linear with height through the lidar's sampling volume, it is possible that the two measurement techniques report different values for specific heights. This effect is just visible in Figure 7 but emphasised in Figure 9 below, which shows the differences between average lidar and mast wind speed values as a percentage of the mast measurements. The lidar reports higher average speeds than the mast in low shear (unstable) conditions but lower average speeds than the mast in high shear (stable) conditions. The difference increase with height, but at 90m, remains less than 1.2% which is within the measurement uncertainty of the cup anemometers, thus the values measured by lidar and mast are considered to be the same.

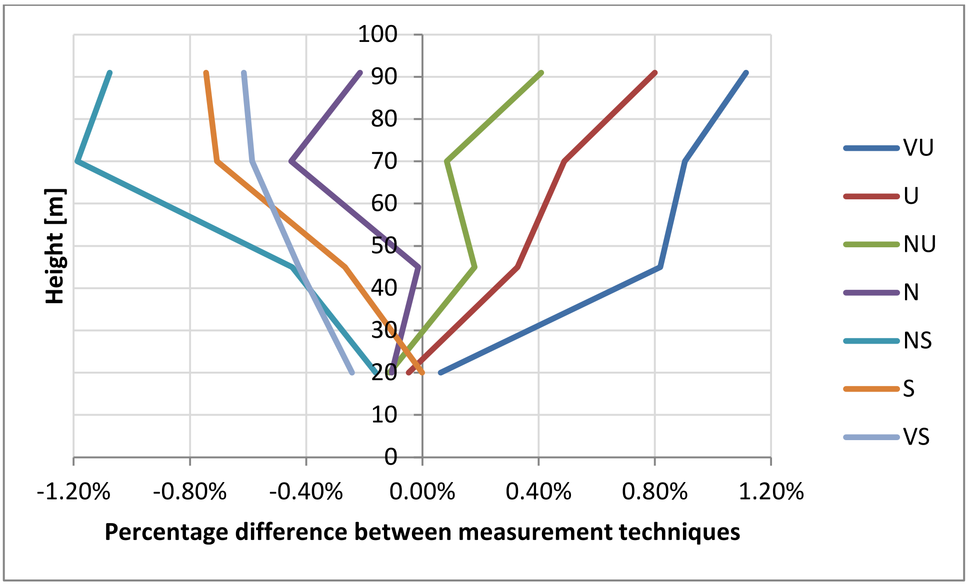


Figure 9 Percentage difference in values of average wind speed as measured with the lidar and mast with respect to the mast values, by atmospheric stability.

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 for 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 wind shear over the greater range of heights provided by a lidar compared with a typical mast suggest a reasonable proxy method to determine stability though more work is required to relate shear reliably to stability. There is seen to be some slight bias in wind speed measurement by the lidar compared with cups as a function of stability whereby the lidar records a higher wind speed than the cup anemometer in unstable conditions and vice versa in stable conditions. This effect increases with height though gives no more than +/-1.2% variation at typical hub heights (90m) and as it is systematic could easily be accounted for.

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