Can Lidars Measure Turbulence? Comparison Between ZephIR 300 and an IEC Compliant Anemometer Mast

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Abstract

A significant body of work has been amassed in support of the ability of lidar systems to accurately measure wind speed for wind resource assessment. Lidar measurements at heights significantly greater than those achievable with industry-standard mast anemometry enable reduction of project uncertainties through direct measurement of resource at hub height and reduction of uncertainty in measured shear profiles. Measurement of turbulence intensity (TI) at hub height also plays a role in wind resource assessment methodologies, site classification and turbine selection studies. Presented are the results of a comparison of TI measurements from ZephIR 300 and an IEC compliant 91.5m anemometer mast. The data was collected over more than 5000 hours of operation at the U.K.'s only dedicated lidar and sodar test site, operated by Natural Power in Worcestershire. Turbulence intensity measured by ZephIR 300 at typical turbine hub height is shown to be in good agreement with that measured by industry-standard anemometry. This is maintained across the wind speed and turbulence intensity ranges encountered during the test period over a full calendar year. Maximum variation between ZephIR and mast mean TI values of less than 15% is observed with variation in atmospheric stability conditions and measurement height for a typical one month deployment across the year. This is of the order of reported accuracy for industry-standard cup anemometry in the measurement of wind speed variance and demonstrates the ability of ZephIR 300 to measure TI values in flat terrain to an accuracy suitable for use in wind energy applications.

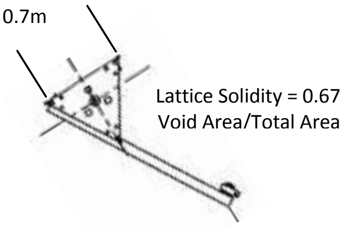
1 Introduction

A significant body of work has been amassed in support of the ability of lidar systems to accurately measure wind speed for wind resource assessment [1],[2]. Lidar measurements at heights significantly greater than those achievable with industry-standard mast anemometry enable reduction of project uncertainties through direct measurement of resource at hub height and reduction of uncertainty in measured shear profiles [3]. Measurement of turbulence intensity (TI) at hub height also plays a role in wind resource assessment through the estimation of energy losses due to turbine wake effects and variation in turbine performance [4],[5]. As well as having a role in energy yield studies, TI information is also a key component of site classification and turbine selection studies [5],[6],[7],[8]. Where lidar data is to be used as an input to established methodologies for wind resource assessment in place of mast data, consideration of the performance of lidar systems in measuring turbulence intensity with respect to industry-standard mast anemometry is of relevance. Data recorded during 34 ZephIR 300 deployments at the Pershore test site totalling in excess of 5000 hours of operation and spanning an entire calendar year has been compared with data from the mast. Results of the comparison are presented in terms of overall performance as well as seasonal variation for a typical deployment in the context of atmospheric stability at the test site.

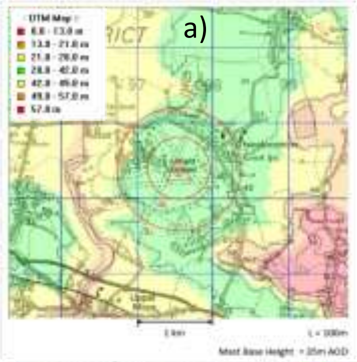
2 Description of the Measurements

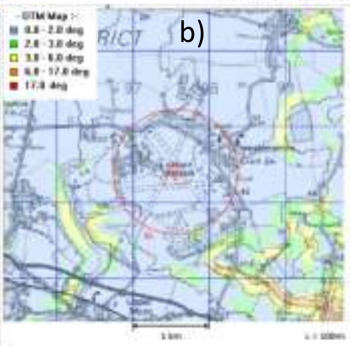
2.1 Test Mast

Natural Power Ltd. operate the U.K.'s only dedicated lidar and sodar test site at Pershore in Worcestershire, England. The test mast at Pershore has been constructed to be compliant with the current edition of IEC 61400-12-1 [9] and the terrain of the site falls within requirements for power curve testing without a site calibration. All cup anemometers installed on the mast are class 1A instruments as defined by [9] and have undergone individual rotor specific MEASNET calibration [10]. Boom and upright dimensions have been determined using the lattice porosity and mast dimensions in compliance with [9] to operate within a maximum flow distortion of 0.5%, Figure 1. Three different instrument types for the measurement of wind flow are installed on the mast. On the North-Western side of the mast Risø P2546A cup anemometers are installed at 20.5m, 45.5m, 70.5m and 91.5m above ground level (AGL). These instruments are used for comparison of ten-minute average and mean wind speed measurements. On the South-Eastern side of the mast Vector A100LM cup anemometers are installed at 20.5m, 45.5m and 70.5m AGL. These instruments are classified as fast-response cup anemometers and are used for comparison of measurements of standard deviation and turbulence intensity. A METEK USA1 3D ultrasonic anemometer is installed at 91.5m on the South-East side of the mast. This instrument is used for fine-grained investigation of standard deviation and turbulence measurements, atmospheric stability and vertical wind flow. The specification and installation of the instrumentation at Pershore is such that all instruments are suitable for use in wind speed verification in unshadowed sectors. Standard deviation and turbulence intensity measurements are restricted to the Vector A100LM and METEK USA1 anemometers due to the poorer dynamic response and sampling performance of the Risø P2546A anemometers. The analysis of turbulence intensity presented in this paper has therefore been carried out against the instruments on the South-East side of the mast only, in unshadowed sectors. The wind climate at Pershore as measured by the South-Eastern instruments on the mast over the period covered by this analysis is shown in Figure 2.



Height AGL [m]	Dimesions [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





Label	Height (m)	Orientation (°) Mast to Instrument	Type	Manufacturer/Model	Calibration*	Calibration Date	Cup to boom centre height (mm)	Instrument to mast centre length (mm)
A	91.5	300	Cup Anemometer	Risø P2546A	SOH/DWG MEASNET	07/2011	1500	1025
B	91.5	120	3D Sonic Anemometer	Metek USA1	-	-	1500	1025
C	88.0	300	Direction Vane	Vector W200P	-	-	920	3700
D	88.0	120	Temperature/Humidity	Campbell Scientific CS215	-	-	-	-
E	70.5	300	Cup Anemometer	Risø P2546A	SOH MEASNET	06/2010	960	3700
F	70.5	120	Cup Anemometer	Vector A100LM	SOH/DWG MEASNET	07/2011	1160	3700
G	45.5	300	Cup Anemometer	Risø P2546A	SOH/DWG MEASNET	07/2011	960	3700
H	45.5	120	Cup Anemometer	Vector A100LM	SOH MEASNET	06/2010	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 MEASNET	06/2010	960	3700
L	20.5	120	Cup Anemometer	Vector A100LM	SOH/DWG MEASNET	07/2011	1160	3700
M	6.0	-	Pressure	Campbell Scientific CS1000	-	-	-	-
N	6.0	-	Data Logger	Campbell Scientific CR1000	-	-	-	-

Figure 1 : Pershore 91.5m IEC Compliant Anemometer mast Specifications and Environment
a) Local Deviation from Plane*, b) Local Slope*.

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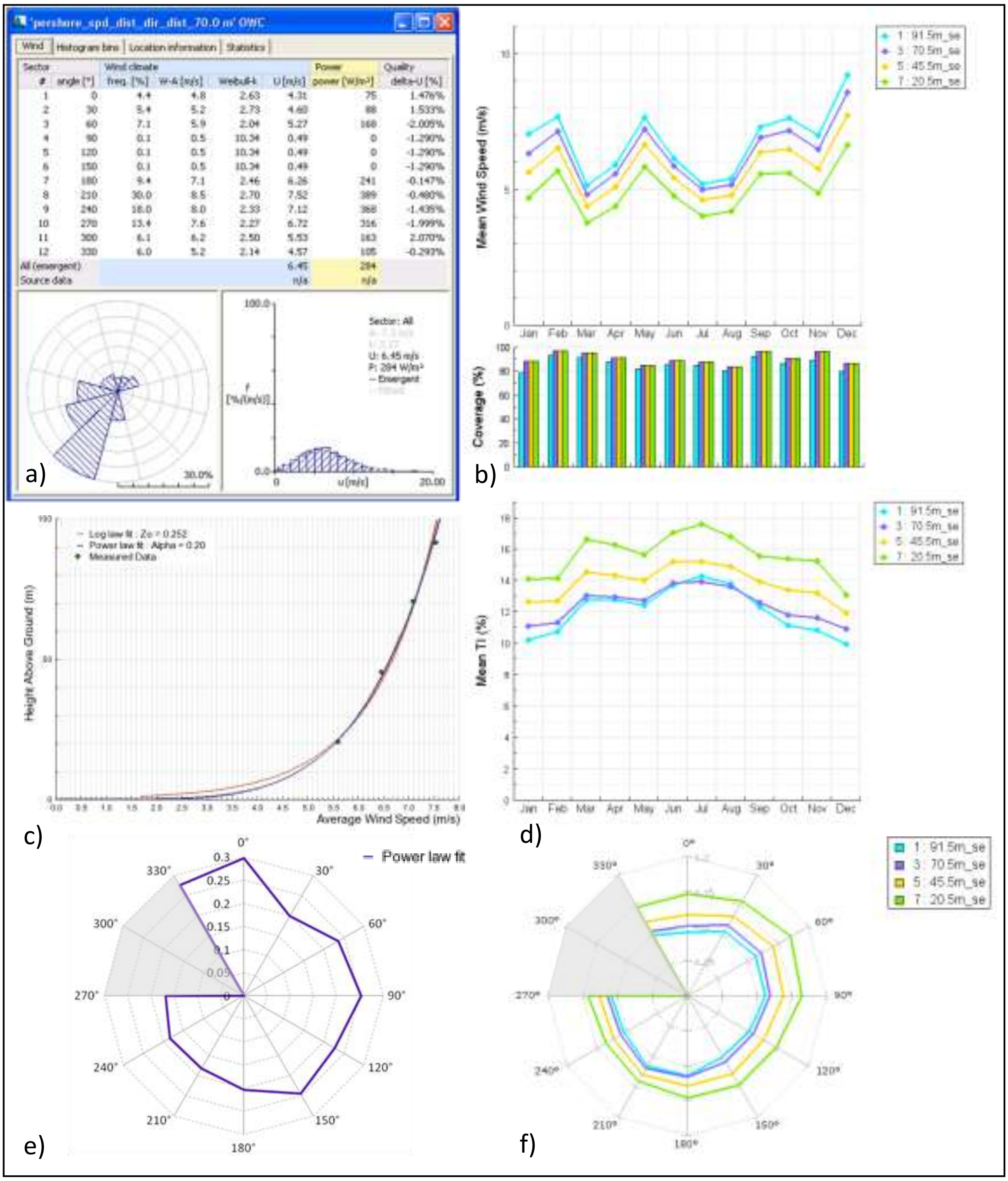


'pershore_spd_dist_dir_dist_70.0 m' OWC

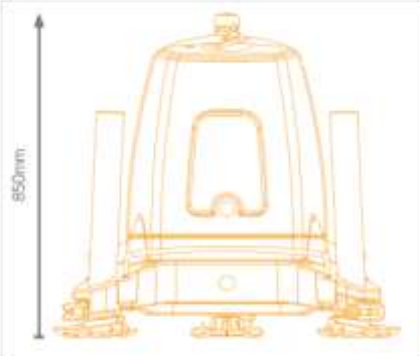
Sector		Wind climate				Power	Quality
#	angle [°]	freq. [%]	W-A [m/s]	Weibull-k	U [m/s]	power [W/m²]	delta-U [%]
1	0	4.4	4.8	2.63	4.31	75	1.476%
2	30	5.4	5.2	2.73	4.60	88	1.533%
3	60	7.1	5.9	2.04	5.27	168	-2.005%
4	90	0.1	0.5	10.34	0.49	0	-1.290%
5	120	0.1	0.5	10.34	0.49	0	-1.290%
6	150	0.1	0.5	10.34	0.49	0	-1.290%
7	180	9.4	7.1	2.46	6.26	241	-0.147%
8	210	30.0	8.5	2.70	7.52	389	-0.480%
9	240	18.0	8.0	2.33	7.12	368	-1.435%
10	270	13.4	7.6	2.27	6.72	316	-1.999%
11	300	6.1	6.2	2.50	5.53	163	2.070%
12	330	6.0	5.2	2.14	4.57	105	-0.293%
All (emergent)					6.45	284	
Source data					n/a	n/a	

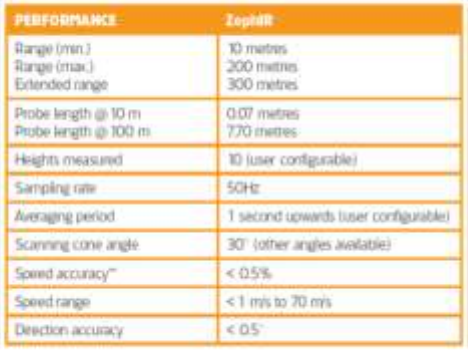
Sector: All
U: 6.45 m/s
P: 284 W/m²
— Emergent

Figure 2 : 2011 Wind Climate at Pershore Measured by South-Eastern Mast Instruments.
a) 70m TAB File, b) Seasonal Wind Speed Profile and Coverage, c) All sector shear,
d) Seasonal TI Profile, e) Shear Rose, f) TI Rose. Grey sectors shadowed.

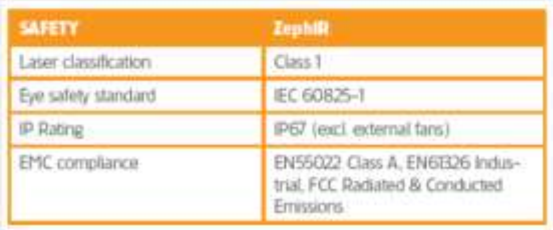
2.2 ZephIR 300

ZephIR 300 is the next generation of all-fibre continuous wave laser remote sensing wind profilers (lidar) produced by ZephIR ltd. [11]. Banks' Engineers recommend ZephIR onshore and offshore to both complement and replace traditional masts. ZephIR has proven performance across 450 lidar deployments globally including extreme conditions from -40 Celsius to +50 Celsius. System features include remote profiling of horizontal and vertical wind speed, turbulence intensity and wind direction across 10 user defined heights from 10 metres (33 ft) to 200 metres (656 ft), Figure 3.





PERFORMANCE	ZephIR
Range (min.) Range (max.) Extended range	10 metres 200 metres 300 metres
Probe length @ 10 m Probe length @ 100 m	0.07 metres 7.70 metres
Heights measured	10 (user configurable)
Sampling rate	50Hz
Averaging period	1 second upwards (user configurable)
Scanning cone angle	30° (other angles available)
Speed accuracy**	< 0.5%
Speed range	< 1 m/s to 70 m/s
Direction accuracy	< 0.5°



SAFETY	ZephIR
Laser classification	Class 1
Eye safety standard	IEC 60825-1
IP Rating	IP67 (excl. external fans)
EMC compliance	EN55022 Class A, EN61326 Industrial, FCC Radiated & Conducted Emissions

OPERATIONS	ZephIR
Temp range (min.) Temp range (max.)	-40°C +50°C
Power consumption	69 Watts
Power input DC	12 V
Weight	55 kg

Figure 3 : ZephIR 300 Specifications.

Since the introduction of the original ZephIR 150 model in 2004 independent verification studies have demonstrated the capability of ZephIR to produce accurate and reliable measurement of wind resource at hub height and beyond. [12],[13],[14]. As part of the commissioning process for ZephIR 300 the performance of each system is verified at the Pershore test facility.

3 Methodology

Following best practice siting recommendations for mast comparisons [15] all ZephIR deployments were located within 10m of the mast base, Figure 4. Data from the deployments listed in Figure 4 has been combined in this analysis to form a continuous data set spanning an entire calendar year. Linear regressions between ZephIR and cup/ultrasonic measured TI have been analysed at 4 heights from 20.5m up to the top anemometer at 91.5m. In addition analysis has been carried out to identify any dependency between deviation in TI measurements and wind speed. For adequate sampling of wind resource and quality parameters in wind energy projects it is generally accepted practice to deploy lidar systems for a period of no less than four weeks [15], [16]. A moving average analysis of the data for a one month deployment has been carried out to place bounds on the deviation in mean TI for a typical deployment with variation in atmospheric conditions at the test site across a full calendar year. The gradient of the Virtual Potential Temperature (VPT), calculated using a combination of temperature, pressure and relative humidity records from the mast, is used as a measure of atmospheric stability as a context in which to assess the results [17].

Deployment	Separation [m]	From	To
1	< 10	15/10/2010	08/11/2010
2	< 10	13/12/2010	01/01/2011
3	< 10	22/12/2010	25/03/2011
4	< 10	23/12/2010	27/01/2011
5	< 10	01/01/2011	08/02/2011
6	< 10	08/02/2011	23/02/2011
7	< 10	09/02/2011	14/03/2011
8	< 10	27/02/2011	17/05/2011
9	< 10	01/04/2011	08/04/2011
10	< 10	11/04/2011	11/05/2011
11	< 10	14/04/2011	03/05/2011
12	< 10	20/05/2011	06/06/2011
13	< 10	26/05/2011	23/06/2011
14	< 10	26/05/2011	21/06/2011
15	< 10	01/07/2011	08/08/2011
16	< 10	14/07/2011	22/07/2011
17	< 10	20/07/2011	30/08/2011
18	< 10	01/08/2011	16/09/2011
19	< 10	11/08/2011	24/08/2011
20	< 10	18/08/2011	17/10/2011
21	< 10	31/08/2011	28/09/2011
22	< 10	08/09/2011	20/09/2011
23	< 10	09/09/2011	21/09/2011
24	< 10	10/09/2011	21/09/2011
25	< 10	29/09/2011	11/10/2011
26	< 10	12/10/2011	21/10/2011
27	< 10	19/10/2011	09/12/2011
28	< 10	19/10/2011	07/11/2011
29	< 10	02/11/2011	18/11/2011
30	< 10	16/11/2011	09/12/2011
31	< 10	28/11/2011	14/12/2011
32	< 10	04/12/2011	13/12/2011
33	< 10	06/12/2011	17/12/2011
34	< 10	22/12/2011	19/01/2012

Figure 4 : ZephIR Siting and Deployments. ZephIR 150 (left) and ZephIR 300 (right).

4 Results

Figure 5 shows linear regressions of the ZephIR turbulence intensity measurements against measurements from the mast instruments at each measurement height.

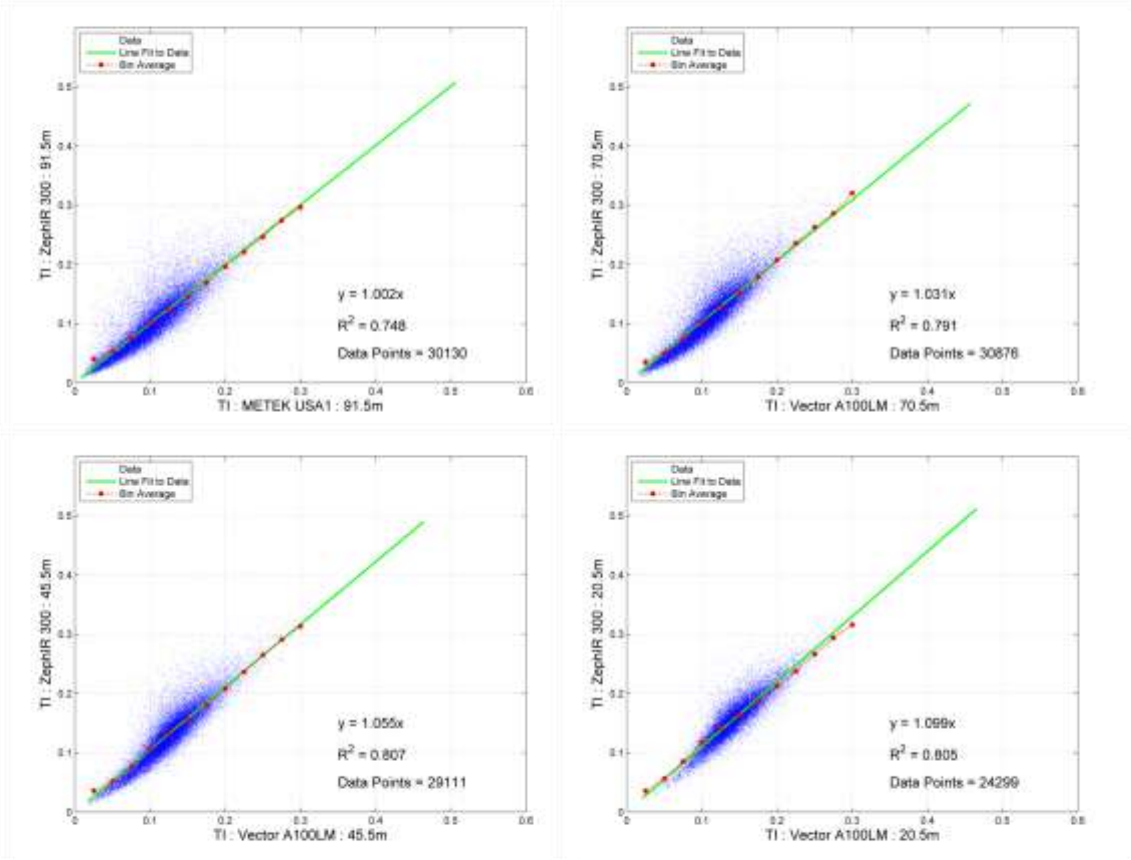


Figure 5 : TI Regressions : ZephIR vs Mast South-Eastern Instruments.

Although some scatter can be observed in the plots in Figure 5 the overall coefficients of determination for the data (R^2) are relatively high at around 0.75 and above for all measurement heights. The slopes of the regressions are within 10% of unity at all heights and within 5% of unity at heights greater than 60m that fall within the range used for the installation of modern wind turbines. The bin averaged data in these plots shows that a linear relationship exists between TI measured by ZephIR and mast that has no mean deviation with turbulence intensity.

Figure 6 shows the wind speed binned ratio of TI measurements from the ZephIR and mast at each measurement height. Mean TI measurements from the ZephIR can also be seen to show no significant or systematic deviation with wind speed.

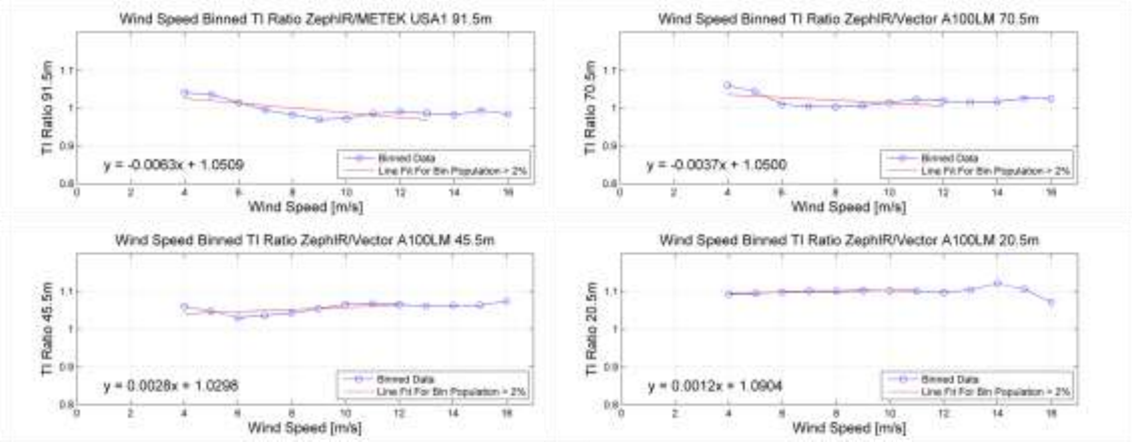
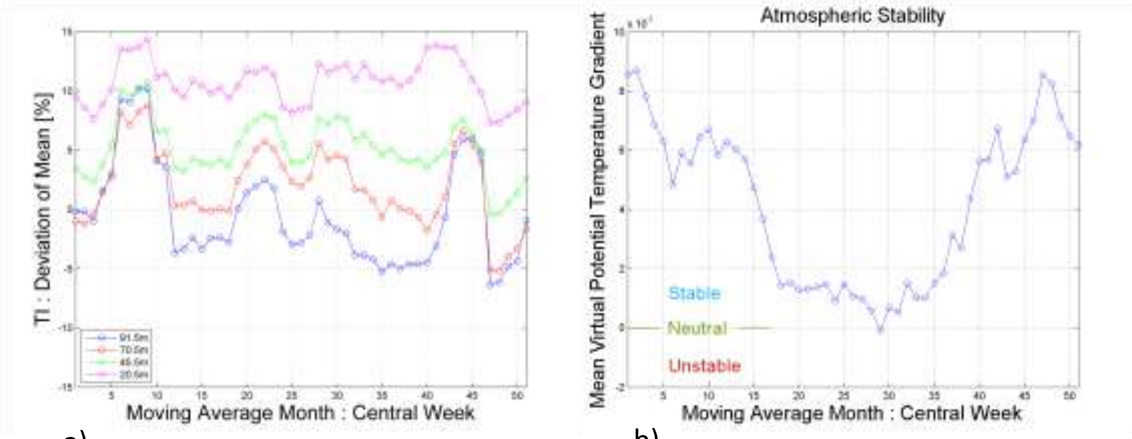


Figure 6 : Wind Speed Binned TI Ratio : ZephIR/Mast.

The variation in deviation in mean TI measured by the ZephIR and mast for a one month deployment at the test site across 2011 is shown in Figure 7 a). Mean and extremes of deviation are presented in table 1. The mean atmospheric stability at the test site as represented by the gradient of the virtual potential temperature is shown in Figure 7 b).



a) b)

Figure 7 : Monthly Moving Average TI Deviation Across 2011.
a) Deviation in Mean TI vs Central Week, b) Atmospheric Stability vs Central Week.

	Mean of Deviation [%]	Extremes of Deviation [%]	
Height	**-**	**Upper**	**Lower**
91.5m	-0.5	10.2	-6.4
70.5m	2.0	8.8	-5.2
45.5m	5.2	10.7	-0.5
20.5m	10.8	14.4	7.3

Table 1 : Mean and Extremes Monthly Moving Average Mean TI Deviation Across 2011.

The results place bounds on the maximum deviation in measured TI across the year of +15% and -7% across all of the measured heights. At typical hub heights in excess of 60m the results give an overall mean deviation of <= 2% with bounds on deviation of +10% and -7%. Although stability is known to have an influence on VAD scanning lidar measurements of turbulence no significant relationship between measurement deviation and the stability measure at the monthly mean level has been observed in the data.

5 Conclusions

Turbulence intensity measured by ZephIR 300 at typical turbine hub height is shown to be in good agreement with that measured by industry-standard anemometry. This is maintained across the wind speed and turbulence intensity ranges encountered during the test period over a full calendar year. Maximum variation between ZephIR and mast mean TI values of less than 15% has been observed with variation in atmospheric stability conditions and measurement height for a typical one month deployment across the year. This is of the order of reported accuracy for industry-standard cup anemometry in the measurement of wind speed variance [18] and demonstrates the ability of ZephIR 300 to measure TI values in flat terrain to an accuracy suitable for use in wind energy applications.

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