Repeatability of ZephIR 300 performance

Demonstrated across more than 240 IEC compliant verifications

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Author: Muhammad Mangat

wind speed at light speed

ZephIR 300

Document history

Author	Muhammad Mangat	01 March 2016
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Client Details	
Contact	
Client Name	ZephIR Lidar
Address	

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Local Office:

The Old Barns, Fairoaks Farm
Hollybush, Ledbury HR8 1EU
ENGLAND, UK
Tel: +44 (0) 1531 651 000

Registered Office:

ZephIR Limited
The Green House
Forrest Estate, Dalry,
Castle Douglas, Kirkcudbrightshire,
DG7 3XS

Company No. SC317594
VAT No: 2436926 48

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1. Introduction

This report presents the results from over 240 performance validations of ZephIR 300s conducted against the IEC compliant UK Remote Sensing Test Site (Pershore, UK), operated by ZephIR Lidar since 2010. Statistical analysis of the validation results robustly shows the repeatability and stability of the calibration that can be expected from the ZephIR 300 system.

2. ZephIR Calibration

Calibration of ZephIR 300 is performed at our production facility in the West Midlands, UK. The calibration process is detailed in [1], which identifies several contributions to the overall velocity uncertainty, outlined in Table 2.1

Table 2.1: ***Uncertainty resulting from calibration of ZephIR 300***

Total Uncertainty	
laser wavelength	0.07%
Doppler frequency	0.005%
wedge angle	0.30%
focus range	0.10%
Total	**<0.5%**

Notably, the calibration uncertainty of ZephIR 300 of <0.5% is less than the uncertainty typical associated to traditional cup anemometers. The cup classification class index [2] allows for ±1% deviations for Class 1 cup anemometers. However, double calibration of the same cups in two MEASNET wind tunnels have themselves shown differences in calibration results of order 1% [1].

Once the ZephIR 300s are calibrated in-house, the settings are fixed. Finally, each unit is validated against a tall IEC-compliant mast. No other changes to the calibration parameters are made.

3. Performance verification

ZephIR performance is validated against a 91.5m mast at the UK's Remote Sensing Test Site. The mast has been constructed to comply with the recommendations for mast anemometry in [2] and has been approved for use by technical and engineering services provider DNV-GL. The terrain in the vicinity of the mast is flat and covered with sparse low-growing vegetation. On a wider scale the site is surrounded by flat arable land that is devoid of any dense closed canopy forest. The terrain at the site is relatively benign with sparse low growing vegetation. The site meets the IEC requirements in [2] for maximum terrain variation in all sectors. Wind speed comparisons are carried out from ground-based ZephIR units, operating in their standard mode with the conical scan aligned vertically, at 4 heights: 91.5m, 70.5m, 45.5m and 20.5m. The units are located 3m - 8m from the base of the mast.

3.1. Horizontal wind speed

The lidar performance verification process for horizontal wind speed is based on the slope of the forced regression line for 10-minute average values obtained over a timescale of at least 7 days. The ZephIR data is processed using standard filters (applied automatically in customer deployment) with an additional calm filter of 3m/s. Mast filters are also applied to eliminate invalid cup data. A minimum of 400 valid concurrent data points from each unit deployment is required for the comparison. A successful verification requires that the regression slope at all 4 heights lies within ±2% of unity, with a correlation coefficient R^2 greater than 0.970. As an example, results from verifying the performance of a ZephIR 300 lidar over a period of 2 weeks in January 2011 are shown in Figure 3.1.

Statistics from the tests of lidar versus mast at Pershore can be compiled to investigate consistency of lidar performance. We have analysed over 240 ZephIR 300 performance verifications, and the results are summarised in Table 3.1 and Figure 3.2. A statistical analysis of regression slopes shows a standard deviation of <1% at all heights. As the verifications included in this analysis are not confined to any particular conditions, the effects of any seasonal changes are part of the analysis. Hence we conclude that the calibration consistency for ZephIR 300 demonstrably lies well within ±1% of the mean value, in agreement with the theoretical and laboratory analysis presented in [2].

Data availabilities are presented in Table 3.2 and Figure 3.3. ZephIR 300 shows very consistent data availability at all heights, >94%. Most significantly, because of continuous wave lidar's constant sensitivity with height for ranges of interest to the wind industry, ZephIR 300 retains high data availability at typical hub heights and beyond.

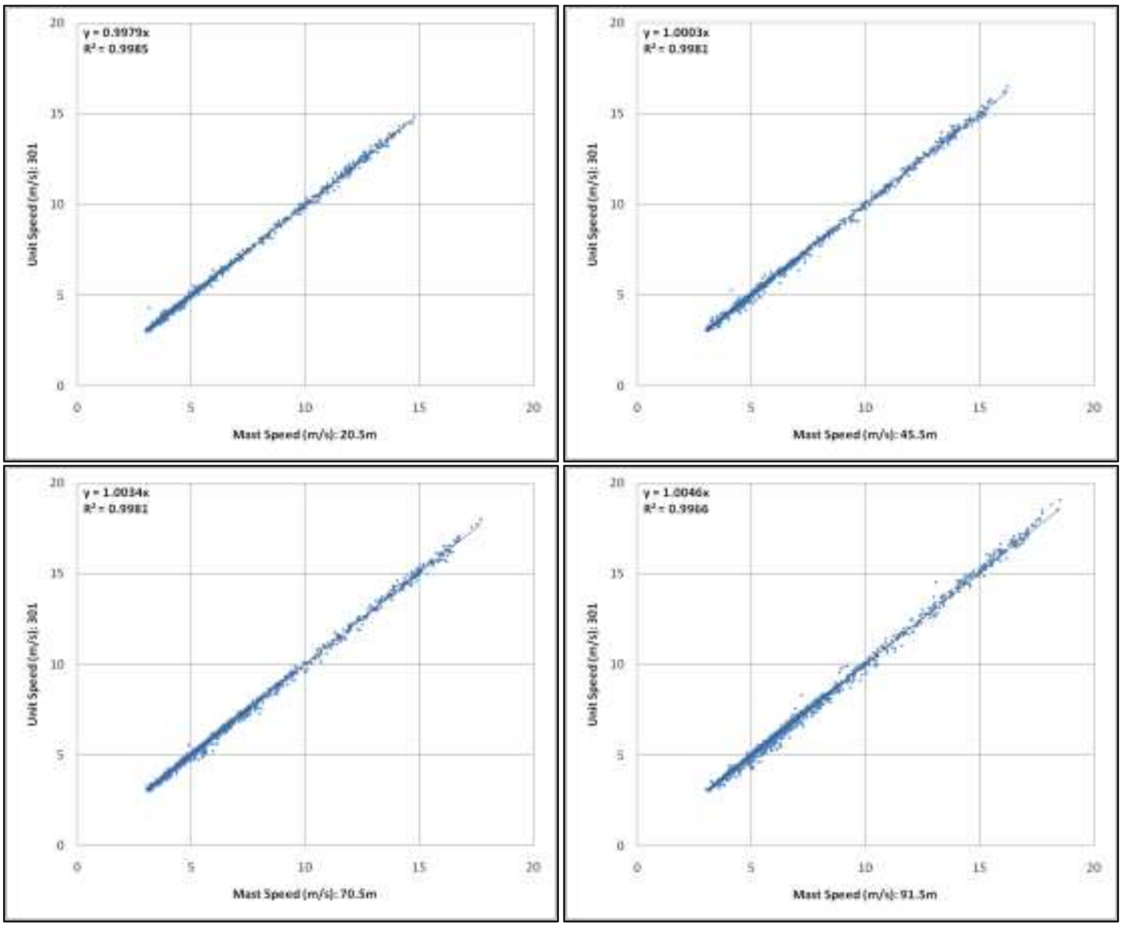


Figure 3.1: *Correlation plots of 10-minute averaged horizontal velocity, ZephIR speed versus mast speed. Data are shown from the 4 measurement heights ranging from 20.5m up to 91.5m.*

Table 3.1: *Statistical analysis of more than 240 ZephIR 300 performance verifications from an IEC compliant test site.*

Combined results from >240 ZephIR 300 performance verifications Horizontal wind speeds				
Height	Gradient		R^2	
(m)	Mean	Std Dev	Mean	Std Dev
91	1.004	0.007	0.989	0.005
70	1.001	0.005	0.992	0.004
45	1.000	0.005	0.992	0.005
20	0.998	0.005	0.992	0.004

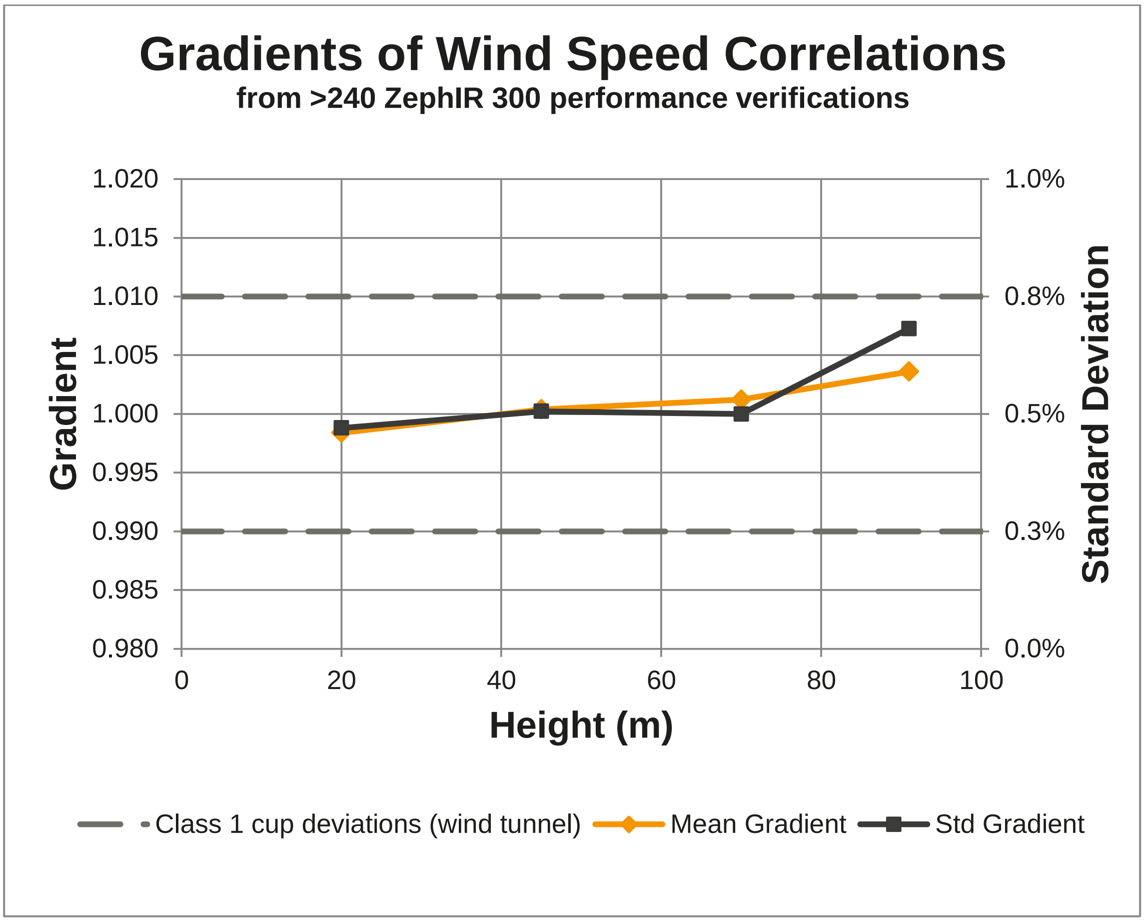


Figure 3.2: *Statistical analysis of more than 240 ZephIR 300 performance verifications from an IEC compliant test site.*

Table 3.2: *Statistical analysis of more than 240 ZephIR 300 performance verifications from an IEC compliant test site.*

Combined results from >240 ZephIR 300 performance verifications Data availability		
Height (m)	Mean (%)	Std Dev
200	94.5	3.2
149	95.5	3.0
120	96.2	2.7
91	96.7	2.5
70	97.3	2.1
45	97.5	1.9
38	97.3	2.1
20	97.3	2.4
10	98.3	1.5

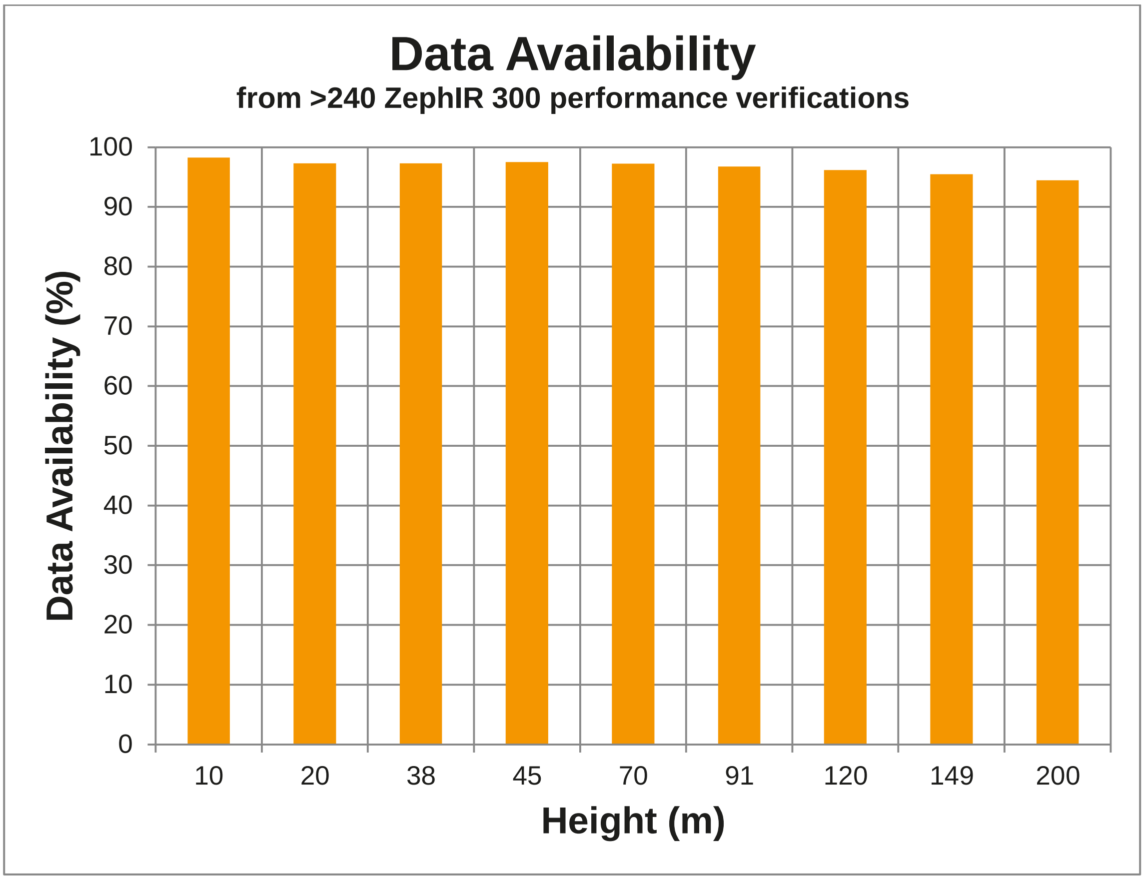


Figure 3.3: *Statistical analysis of a batch of over 240 ZephIR 300 performance verifications from the Pershore test site.*

3.2. Direction

Wind direction measurements are compared to wind vane measurements. Wind vanes are installed at 2 heights on the Pershore mast: 43m and 88m. The ZephIR lower (upper) 2 measurements are compared to the lower (upper) vane. The ZephIR measures wind direction relative to its own axis so the mean direction offset is dependent on correct orientation of the device during deployment. A summary of the correlation statistics is shown in Table 3.3.

Table 3.3: ***Statistical analysis of more than 240 ZephIR 300 performance verifications from an IEC compliant test site.***

Combined results from >240 ZephIR 300 performance verifications Direction				
Height (m)	Offset		RMSE	
	Mean	Std Dev	Mean	Std Dev
91	-2.93	4.51	2.68	3.15
70	-4.64	4.14	3.67	3.67
45	0.45	4.66	2.51	2.94
20	-0.96	4.42	3.75	3.15

The ZephIR and wind vane directions show very strong agreement as evidenced by the root mean squared error (RMSE) and associated small standard deviations. The accuracy of the wind vane in this analysis is ±3° for wind speeds greater than 5m/s, as quoted by the manufacturer.

3.3. Turbulence

The lidar measured turbulence [3] is also assessed compared to the cup measured turbulence. The assessment is based on the slope of the forced regression line for 10-minute average values obtained over a timescale of at least 7 days. Turbulence is defined by the wind industry as:

$$TI = \sigma/\bar{v}$$

ZephIR 300 calculates TI internally as:

$$TI = {}^{1}/_{C}\ (\sigma/\bar{v})$$

Where C is a height-dependent scaling factor required to convert the volume measured TI to a point-measured TI. The top-mounted instruments did not provide un-biased TI measurements. Combined results from over 240 ZephIR 300s at Pershore are presented in Table 5. A statistical analysis of regression slopes is summarised in Table 3.4. It shows a standard deviation of gradients of less than 5% at heights up to 70m.

Table 3.4: ***Statistical analysis of more than 240 ZephIR 300 performance verifications from an IEC compliant test site.***

Combined results from >240 ZephIR 300 performance verifications Turbulence intensity				
Height (m)	Gradient		R^2	
	Mean	Std Dev	Mean	Std Dev
91	#N/A	#N/A	#N/A	#N/A
70	1.036	0.048	0.756	0.076
45	1.010	0.035	0.777	0.068
20	1.005	0.019	0.773	0.066

4. Conclusions

This White Paper concludes that the ZephIR factory calibration process and repeatability in batch ZephIR manufacture, as demonstrated by validations at UK's Remote Sensing Test Site, delivers lidar systems well within the IEC criteria for wind measurement equipment for use in finance-grade energy assessments. The evidence is gathered across the largest single batch of lidar performance validations against an IEC compliant mast.

5. References

[1] Rutherford, A., Harris, M., Barker, W., Burin des Roziers, E., Pitter, M., Scullion, R., Slinger, C., *Lidar calibration and performance validation process*, AWEA 2012.

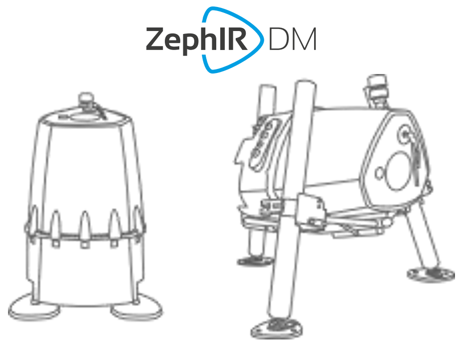
[2] IEC 61400-12-1: *Power Performance Measurements of Electricity Producing Wind Turbines*

[3] Barker, W., Slinger, C., Pitter, M., Burin des Roziers, E., Medley, J., Harris, M., *Lidar turbulence measurements for wind farm energy yield analysis*, EWEA 2013.

About Us

In 2003 we released the first commercial wind lidar, ZephIR®, pooling decades of fibre laser research from the science, security and energy industries. Designed specifically for the wind industry ZephIR has paved the way for many of the remote sensing devices seen in the market today. Our original lidar technology continues to innovate with world firsts such as taking measurements from a wind turbine spinner and being the first to deploy an offshore wind lidar, both fixed and floating. ZephIR has also now amassed more than 7 million hours of operation across 750+ deployments globally spanning a decade of commercial experience. Some of our proudest achievements are listed below; these are the earliest reported examples that we are aware of from open publications.

2003 - The first wind lidar to make upwind measurements from a turbine nacelle
2004 - The first and original commercially available lidar for the wind industry
2004 - The first wind lidar to investigate the behaviour of turbine wakes
2005 - The first wind lidar to be deployed offshore on a fixed platform
2007 - The first wind lidar to take measurements from a turbine spinner
2008 - The first wind lidar to be signed off against an industry-accepted validation process
2009 - The first wind lidar to be deployed offshore on a floating platform (SeaZephIR)
2010 - The first wind lidar to re-finance and re-power a wind farm
2011 - The first wind lidar to be proven in a wind tunnel
2012 - The first wind lidar to be used with very short masts and secure project financing
2012 - The first wind lidar to be accredited for use with no or limited on-site anemometry for project financing by DNV GL
2013 - The first wind lidar to provide true dual-mode functionality in one platform (ZephIR DM)
2014 - The first wind lidar to be subjected to more than 170 performance verifications against an IEC compliant test site
2015 - The first wind lidar to be deployed in dual configuration as standard on floating offshore platforms



Our Global Expertise

ZephIR Lidar delivers wind lidar solutions and supporting services globally for our clients, with offices and agencies across Europe, the Americas and Asia Pacific.

UK
Head Office > England
The Old Barns, Fairoaks Farm
Hollybush, Ledbury HR8 1EU
ENGLAND, UK

zephirlidar.com
sales@zephirlidar.com