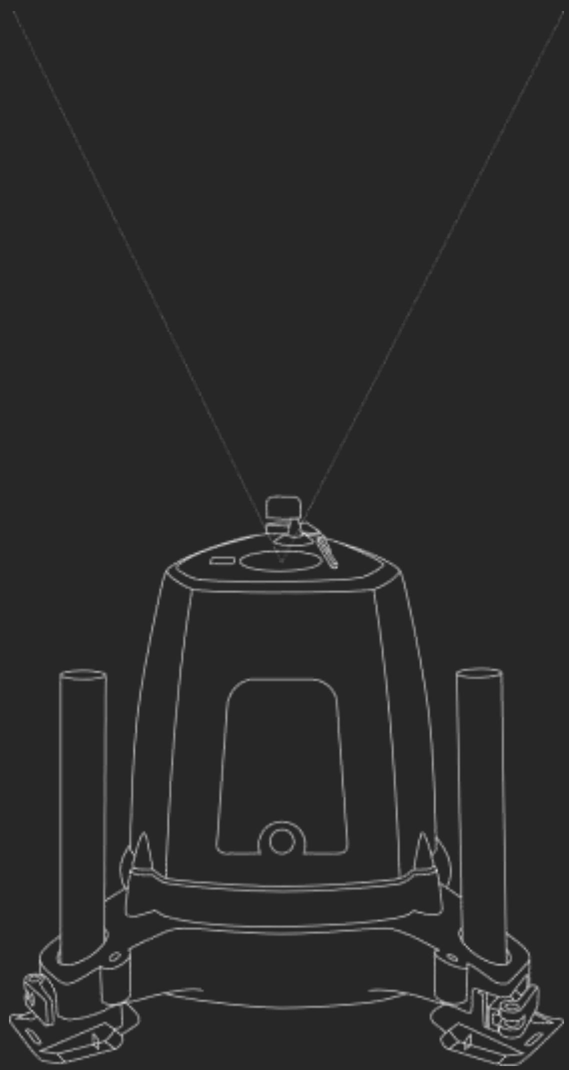
REPEATABILITY OF ZEPHIR PERFORMANCE

DEMONSTRATED ACROSS A SAMPLE OF MORE THAN 170 IEC COMPLIANT VERIFICATIONS



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June 3rd 2014

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TABLE OF CONTENTS

1 INTRODUCTION

This report presents the results from a sample of over 170 performance verifications 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 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 1.

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

Table 1: Uncertainty resulting from calibration of ZephIR 300.

Noteably, 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. Unlike many other remote sensing devices, no changes or performance tuning are made to the calibration parameters.

The long-term stability of this calibration process has been well documented following an unbroken 40 month campaign where the pre- and post- performance verification, as described below, showed no change in accuracy during the period [4].

3 PERFORMANCE VERIFICATION

ZephIR performance is verified against a 91.5m mast at the UK's Remote Sensing Test Site. The mast has been constructed to conform 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 benign 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 between 3m and 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 are shown in Figure 1 below.

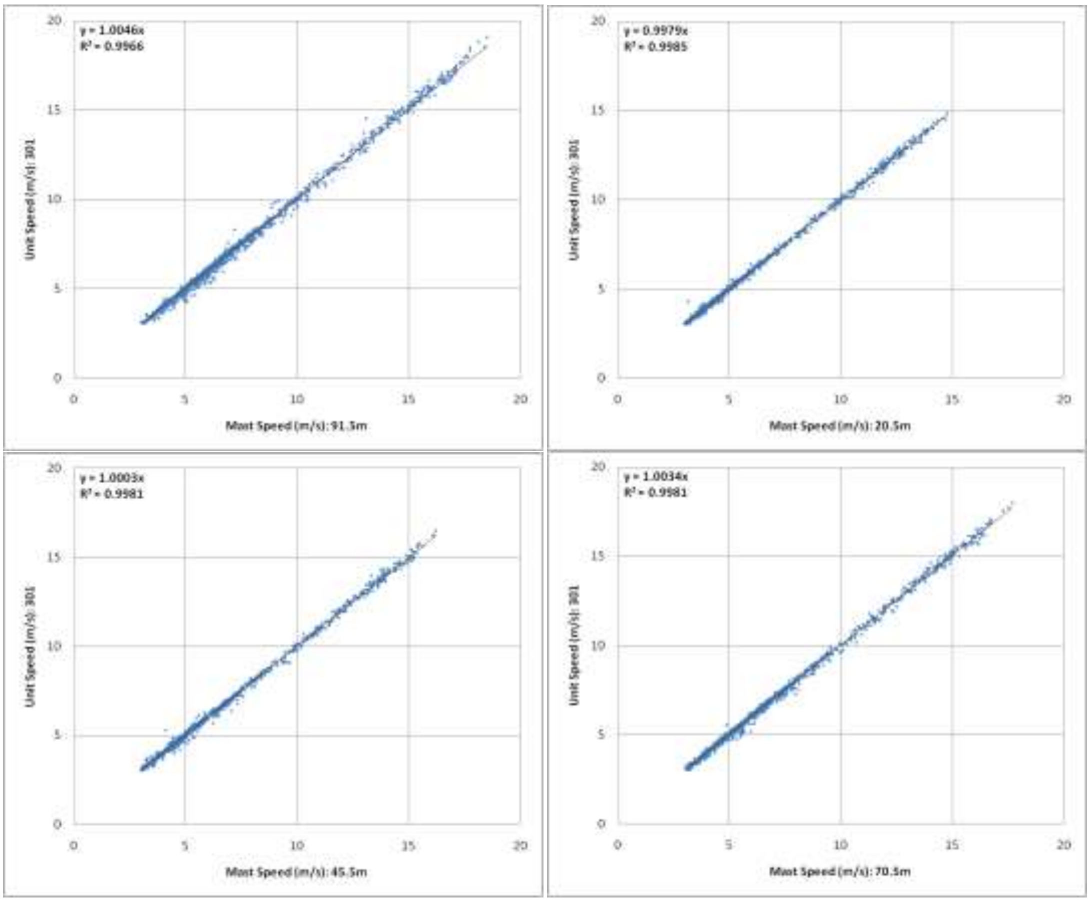

Figure 1: Correlation plots of 10-minute averaged horizontal velocity, ZephIR speed versus mast speed. Data are shown from the 4 measurement heights ranging from 20.5m up to 91.5m.

Statistics from the tests of lidar versus mast at Pershore can be compiled to investigate consistency of lidar performance. We have analysed a sample of 170 ZephIR 300 performance verifications, and the results are summarised in Table 2. A statistical analysis of regression slopes shows a standard deviation of <1% at all heights. Note that the tests are not concurrent; therefore this variation also includes any effects of differing weather conditions in addition to lidar and cup calibration effects. 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].

Combined results from >170 ZephIR 300 performance verifications Horizontal Wind Speed						
Height (m)	Gradient		R^2		Avail (%)	
	Mean	Std	Mean	Std	Mean	Std
91	1.004	0.007	0.988	0.007	96.66	2.61
70	1.002	0.005	0.991	0.008	97.20	2.22
45	1.002	0.004	0.991	0.006	97.37	2.10
20	0.999	0.005	0.992	0.005	97.15	2.66

Table 2: Statistical analysis of more than 170 ZephIR 300 performance verifications from an IEC compliant test site.

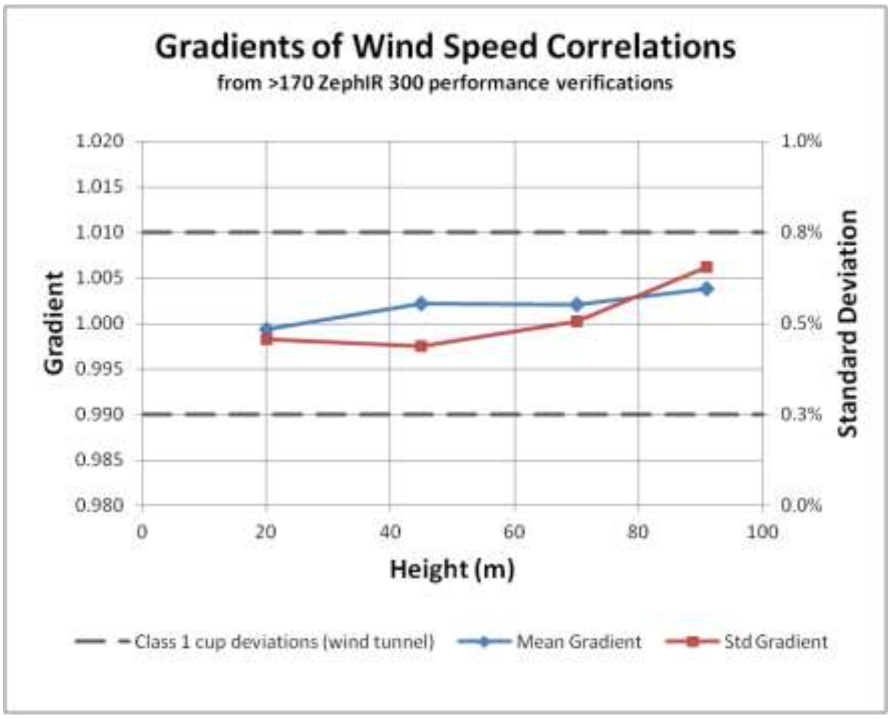

Figure 2: Statistical analysis of more than 170 ZephIR 300 performance verifications from an IEC compliant test site.

A tabulation of data availabilities are presented in Table 3. ZephIR 300 shows very consistent data availability at all heights, >94%. Most significantly, because 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.

Combined results from >170 ZephIR 300 performance verifications Data Availability		
Height (m)	Mean (%)	Std
200	0.95	3.22
149	0.95	3.04
120	0.96	2.88
91	0.97	2.61
70	0.97	2.22
45	0.97	2.10
38	0.97	2.33
20	0.97	2.61
10	0.98	1.66

Table 3: Statistical analysis of more than 170 ZephIR 300 performance verifications from an IEC compliant test site.

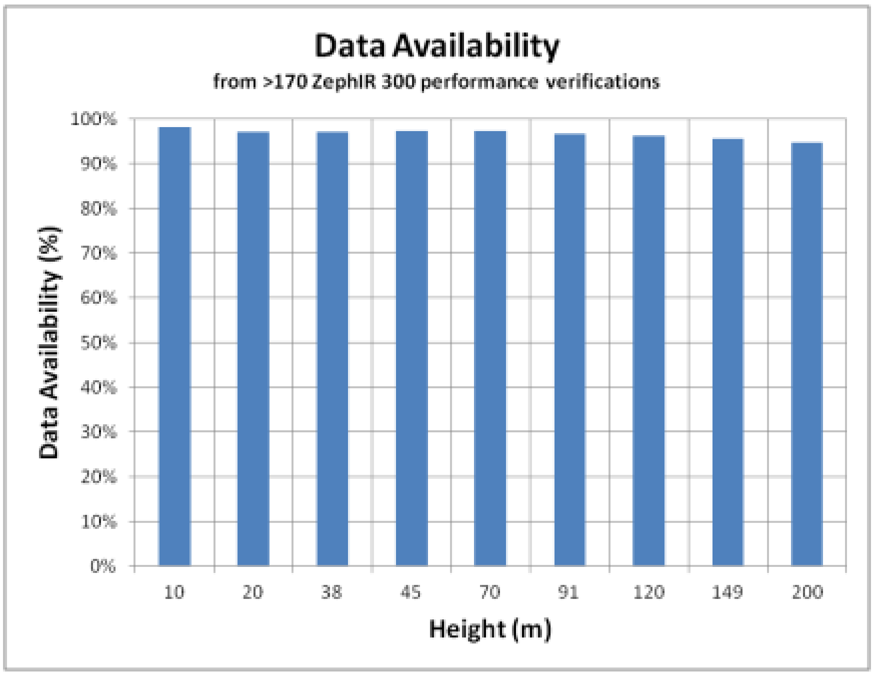

Figure 3: Statistical analysis of a batch of over 170 ZephIR 300 performance verifications from the Pershore test site.

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.

Combined results from >170 ZephIR 300 performance verifications Direction				
Height (m)	Offset		RMSE	
	Mean	Std	Mean	Std
91	-3.52	3.24	2.48	0.79
70	-5.34	3.20	3.44	0.79
45	-0.02	3.29	2.35	0.73
20	-1.49	3.22	3.58	0.66

Table 4: Statistical analysis of a batch of more than 170 ZephIR 300 performance verifications from an IEC complant test site.

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:

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

ZephIR 300 calculates TI internally as:

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

Where C is a height-dependent scaling factor required to convert the volume measured TI to a point-measured TI. TI is compared to Vector 100LM cups at 20.5m, 45.5m and 70.5m only. The top-mounted instruments did not provide un-biased TI measurements. Combining results from over 170 ZephIR 300s at Pershore are presented in Table 5. A statistical analysis of regression slopes shows a standard deviation of <4% at all heights.

Combined results from >170 ZephIR 300 performance verifications TI				
Height (m)	Gradient		R^2	
	Mean	Std	Mean	Std
91	0	0	0	0
70	1.036	0.050	0.731	0.105
45	1.011	0.037	0.756	0.092
20	1.005	0.021	0.753	0.094

Table 5: Statistical analysis of more than 170 ZephIR 300 performance verifications from an IEC compliant test site.

4 CONCLUSIONS

This White Paper concludes that the ZephIR factory calibration process and repeatability in batch ZephIR manufacture, as demonstrated by a sample of more than 170 verifications 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-type 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.

[4] Mangat, M, M, A., *ZephIR performance evaluation after 40 months of continuous operation*