Lidar calibration and performance validation process

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Topic: Resource Assessment

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Biography: With a background in the development and marketing of innovative data recording and analysis systems, Tony Rutherford is currently responsible for Natural Power's worldwide sales of the ZephIR laser anemometer. During the preceding ten years he managed the commercialisation of a wide variety of novel technology solutions, including several lidar-based applications, across various divisions of QinetiQ UK.

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Learning Objectives: The presentation will describe recent advances in calibration of wind lidars for resource assessment. The sources of calibration uncertainty will be evaluated, and lidar performance statistics against a 91.5m mast will be analysed. The presentation will show: that lidar has achieved excellent agreement with conventional anemometry in a wind tunnel over a large range of speeds; that calibration uncertainty in lidar speed of order 0.1% is routinely achieved; and that, for ground-based operation, agreement in mean wind speed with a tall mast to better than 0.5% is obtained across a batch of 24 production lidars at all heights tested.

Extended Abstract

Introduction

Use of lidars is increasing in the wind industry across a wide range of activities, such as power performance measurement, turbine control, and resource assessment (both onshore and offshore). Remote sensing offers significant advantages for resource assessment in comparison to conventional methods of anemometry, including reduced administration costs, ease of use, flexibility of location, and data collection from near to the ground up to hub height and beyond. The value of lidar data is increased considerably when it is accepted as bankable; this typically requires accurate and controlled calibration processes, and demonstrable performance against an IEC-approved tall mast.

This paper describes recent advances in the calibration and performance verification of lidar units for wind measurement, in particular continuous-wave (CW) coherent laser anemometers; Natural Power's ZephIR is used as an example throughout this paper. ZephIR emits approximately 1 Watt of eye-safe (laser Class 1) infra red radiation in a conical scan pattern, allowing wind speed direction and turbulence to be measured at heights ranging from 10m to 200m above the unit. The design exploits advances in optical components developed during the telecommunications boom, the first commercial model being launched in 2004. The results presented here have been obtained with the most recent ZephIR300 model, introduced in 2011.

The velocity calibration accuracy is analysed, followed by an experimental demonstration in a high-performance wind tunnel. Other potential sources of calibration error relating to the focus range and conical scan are examined, and the possibility of significant drift in calibration is shown to be negligible. The performance of ZephIR300 units is then examined against the 91.5m mast at Natural Power's remote sensing test site at Pershore in Worcestershire, U.K. The results are used to verify the calibration of each ZephIR300 unit; statistics are compiled to illustrate the level of performance consistency.

Velocity calibration and verification in wind tunnel

We first consider the lidar velocity calibration: this depends directly on the laser wavelength and scaling of the digital signal processing (DSP). The contributions to the uncertainty from these two elements are independent and can be considered separately.

The measured line-of-sight velocity is given [1] by:

$$V_{LOS} = \nu_D \times \lambda/2 \quad (1)$$

Where ν_D is the measured Doppler frequency and λ is the laser wavelength. This simple relationship ensures that the velocity calibration depends only on the stability of the laser wavelength and frequency scaling. Notably, ZephIR's velocity calibration does not depend on the stability of an intermediate frequency (IF) oscillator; neither is it susceptible to frequency chirps brought about through non-linear optical processes within the optical fibres.

The absolute laser wavelength is defined by the manufacturer's specification to lie within a range ±1nm of the nominal wavelength (1565nm). We can hence derive the contribution to velocity uncertainty from wavelength variation to be 1/1565 = ±0.07%. Note that this describes the variability from laser to laser; each individual laser has higher stability. Wind speeds in ZephIR are determined from Doppler frequency spectra. Each spectrum is calculated in a dedicated DSP board embedded within the ZephIR unit. The analogue signal from the detector is sampled at 100 MHz by an analogue-to-digital converter. Any instability of this sampling rate translates directly and proportionally to an uncertainty in wind velocity. The sampling rate is controlled by a quartz clock/oscillator. The manufacturer's specification of clock stability is within ±50ppm for jitter and short-term drift, including any effect at temperature ranges exceeding those that are experienced in an operational ZephIR unit. The manufacturer's specification for aging is much smaller, at 5ppm per year.

Hence we conclude the overall velocity uncertainty resulting from these two sources is of order 0.1% or less. In an experimental investigation by LM Windpower, Risø DTU and NKT Photonics, a ZephIR300 system was configured to stare directly along the flow in a high-performance wind tunnel. The results reported below were obtained with no seeding. The measurement range was set to 3.3m, positioning the probe volume a few cm above the aperture of a pitot sensor mounted in the centre of the test section. This very short range illustrates one of the strengths of CW lidar, namely its ability to operate from very close ranges (1m or so) out to 200m and beyond. Lidar wind speed measurements were obtained at a rate of 50 Hz; the mean wind speed was integrated over a succession of 2 minute periods (during which the tunnel speed was highly stabilised) to allow comparison between the lidar and pitot measurements. The results showed very good agreement with the wind tunnel instrumentation across a speed range of 5 to 75m/s (figure 1). The correlation was extremely high ($R^2 > 0.9999$), and the gradient of the comparison plot differs from unity by less than 0.5%, comparable to the expected accuracy of the pitot sensor.

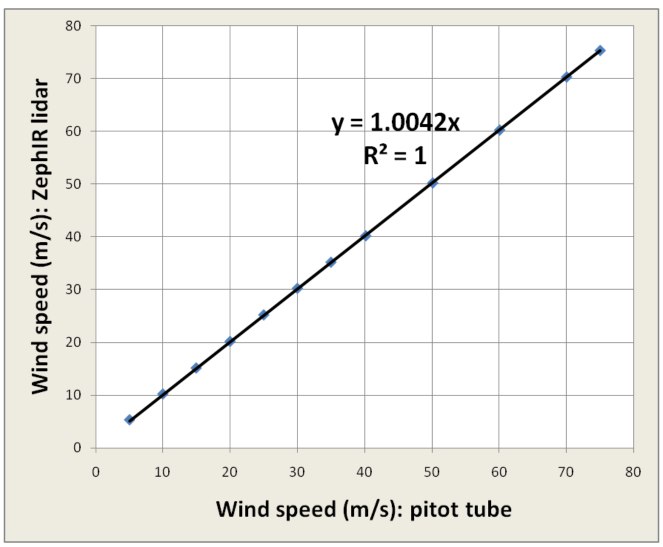

Figure 1: Speed comparison between lidar and wind tunnel instrumentation. The gradient and correlation coefficient indicate near-perfect agreement, considering the measurements are not made at the exact same point in space.

Other calibration factors

For a field-deployed ZephIR, employing its standard scanning mode for resource assessment, the wind speed measurement depends on several other parameters. Positioning of the beam in space is determined by the scan cone angle and the focus range. The calculation of horizontal wind speed depends directly on the sine of the cone angle; this in turn is determined by the wedge angle of a silicon prism that deflects the beam by 30.4 degrees from the vertical. The manufacturing tolerance on this angle is 0.1 degrees, which contributes ±0.3% to the uncertainty in horizontal wind speed. The wedge angle can be verified to higher accuracy in tests where the scanned beam illuminates a uniform moving belt, whose speed has been calibrated to <0.2%. The speed returned by the lidar is then compared with that of the moving belt, allowing precise calibration of the wedge angle to ±0.2%. For correct lidar operation in conditions of low atmospheric backscatter, it is essential that high sensitivity is achieved and maintained. The signal-to-noise ratio from the moving belt tests is used to ensure the performance closely approaches the theoretical limit of sensitivity; this is later verified in extended tests at the Pershore test site. Additionally, the belt test permits rigorous checks on scan rate and linearity, and wind direction accuracy.

The ZephIR lidar interrogates wind speed at a given height by focusing its emitted beam at that height. The focus is controlled by moving the position of an optical fibre with respect to the output lens. The focus range calibration is carried out with a moving belt target located at precise distances from the lidar. A closed-loop positioning system ensures the focus height is maintained during field deployment without the need for re-calibration. Focus uncertainty has been assessed by measuring the variations between independent calibration checks carried out on the same lidar unit over the short and long term. Statistical analysis of the results shows the uncertainty in focus height at 100m to be of order ±70cm.

Analysis of other contributions to uncertainty, such as stability of scan rotation rate, has shown that these are extremely small. The possibility of any drift of critical parameters (including laser wavelength, clock frequency, wedge angle) over time has also been considered. According to manufacturers' specifications this is negligible for each component. Similarly, analysis has been carried out of the magnitude of any variations with environmental conditions such as temperature extremes.

Performance verification at Pershore test site

All ZephIR lidars are routinely tested against a 91.5m mast at Natural Power'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 GL Garrad Hassan. 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 surrounding the tall mast at Pershore has been assessed in order to determine whether any sectors need to be screened from the mast data due to the orography of the site or local obstacles. 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. Data for lidar validation is provided by Risø P2546A cup anemometers on the North West side of the test mast and Vector A100LM cups on the South East side of the mast. Comparison of paired cups is used to provide a robust method for identifying any problems with the mast instrumentation. Direction data is taken from the Vector W200P wind vanes at the 88.0m and 43.5m levels. The cups are regularly re-calibrated; as an extra precaution in the most recent such exercise (August 2011), a set of 4 cups was sent for independent assessment in two different Measnet-approved wind tunnels. The two sets of calibrations revealed differences that varied from cup to cup, and with wind speed. These differences ranged from +0.8% to -0.6%; inconsistency between cup calibrations therefore imposes a limit on the achievable accuracy of lidar performance validation against the mast. The lidar speed uncertainty analysis and tunnel tests shown in figure 1 suggest that ZephIR has potential to resolve any such discrepancies between cup/tunnel calibrations.

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 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 testing the first ZephIR300 lidar over a period of 2 weeks in January 2011 are shown in Figure 2 below.

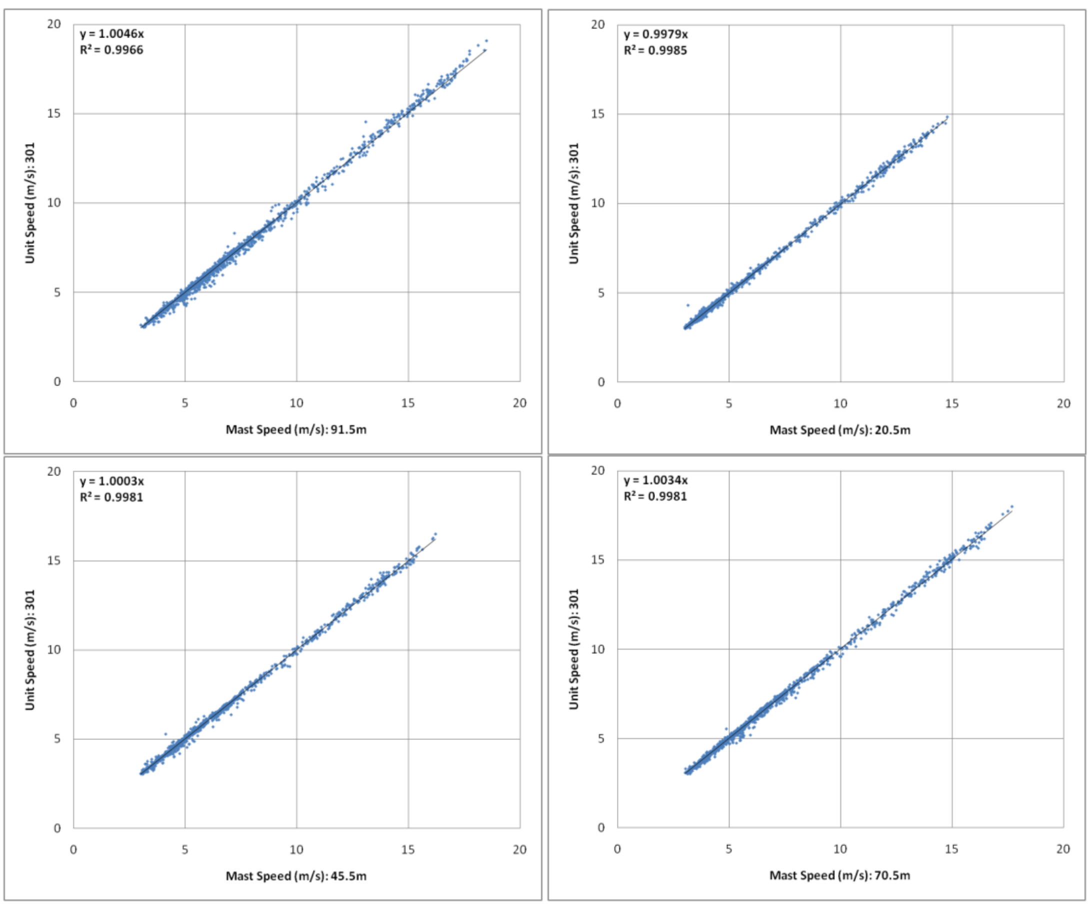

Figure 2: Correlation plots of 10-minute averaged horizontal velocity, ZephIR speed versus mast speed. Data are shown from the 4 measurement heights ranging from 20.5m up to 91.5m.

Statistics from the tests of lidar versus mast at Pershore can be compiled to investigate consistency of lidar performance. We have analysed the first batch of 24 ZephIR300 units, and the results are summarised in Table 1. A statistical analysis of regression slopes shows a standard deviation of <0.5% 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 ZephIR300 demonstrably lies well within ±0.5% of the mean value, in agreement with the theoretical and laboratory analysis presented earlier. The sensitivity of each lidar has also been assessed by comparing the wind signal strength to that from a reference unit over the same test period. This parameter has been averaged over all heights, and the results show a standard deviation of <10%. This is considered a very high level of consistency for a wind lidar system, as it includes random fluctuations resulting from changing atmospheric conditions during the test as well as transmission and alignment tolerances for all the optical components in the transmit/receive chain.

	Gradient		**Sensitivity**	
Height (m)	**Mean**	**StDev**	**Mean**	**StDev**
91.5	1.0038	0.0069	1.0350	0.0881
70.5	1.0039	0.0076		
45.5	1.0005	0.0054		
20.5	0.9967	0.0048		

Table 1: Statistical analysis of a batch of 24 ZephIR300 units. Results from the Pershore test site have been analysed to investigate consistency of lidar calibration. The sensitivity has been compared to that of a reference unit, defined to have a sensitivity of unity.

Conclusions

We have analysed the sources of calibration uncertainty in the ZephIR300 wind lidar using a combination of theoretical calculation based on manufacturing tolerances, experimental results from wind tunnel and calibrated moving belt targets, and final verification of multiple units against an IEC-approved tall mast. Hence we have shown that the overall variation in calibration for horizontal wind speed is less than ±0.5% across the first batch of 24 ZephIR300 units. The variation in sensitivity of the batch has also been analysed; this demonstrates standard deviation from unit to unit of better than ±10%. Any theoretical sources of drift in calibration during long-term deployment are shown to be negligible, and this conclusion is borne out by long-term and repeated tests at the remote sensing test site.

The repeatability and stability of the calibration of ZephIR300, as shown here, indicates lidar's potential as a powerful tool for bankable resource assessment, particularly in locations where regular recalibration is impractical. The extreme precision of continuous-wave lidar in staring mode suggests further potential for cross-calibration of wind tunnels without any requirement for seeding, as well as the potential for lidar technology to supersede cup anemometry as a primary standard.

References

[1] C J Karlsson, F Å A Olsson, D Letalick & M Harris, *All-fiber multifunction CW 1.55 micron coherent laser radar for range, speed, vibration and wind measurements*, Applied Optics **39** 3716-3726 (2000)

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