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Remote Sensing (UpWind WP6)
QinetiQ Lidar Calibration Report

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Abstract: This report summarises the development of calibration methods for lidar systems, particularly the QinetiQ wind lidar ZephIR^{TM}. These methods have been tested in the laboratory and developed in order to allow *in situ* field calibration of the main lidar performance parameters, including wind speed, direction, sensitivity and measurement height.

Contents

STATUS, CONFIDENTIALITY AND ACCESSIBILITY									
Status				**Confidentiality**				**Accessibility**	
S0	Approved/Released	x		**R0**	General public			Private web site	x
S1	Reviewed			**R1**	Restricted to project members	x		Public web site	
S2	Pending for review			**R2**	Restricted to European. Commission			Paper copy	
S3	Draft for comments			**R3**	Restricted to WP members + PL				
S4	Under preparation			**R4**	Restricted to Task members +WPL+PL				

PL: *Project leader* **WPL:** *Work package leader* **TL:** *Task leader*

1. Introduction

In order to reduce costs associated with the siting of tall masts, the wind energy industry needs methods such as sodar and lidar for remotely obtaining accurate wind profiles. However, widespread acceptance by the industry requires that these techniques be extensively validated for a wide variety of terrain and atmospheric conditions. One of the main objectives of Work Package 6 (“Remote Sensing”) is the evaluation of new wind lidar technologies - with a view to gaining greater acceptance of these methods in the wind energy industry, and then formal certification of lidar methods and their introduction into existing standards. QinetiQ, as the manufacturer of the ZephIR lidar used extensively by the partners in this Work Package, provides the required expertise on lidar principles and technology. QinetiQ’s contributions include updated reports on the lidar measurement process [1] and cloud removal algorithms [2]. The present report similarly provides more detail about calibration methods and is an updated version of [3].

2. Calibration methods for lidar

This is a report on progress towards a calibration method for lidar in the field. Methods have been devised that permit *in situ* calibration of the main performance parameters of the QinetiQ ZephIR lidar:

1. wind speed
2. wind direction
3. sensitivity
4. measurement height.

The first three parameters are conveniently checked with a moving belt that should be placed as close as possible to the lidar window (in order to minimise the belt size required). For example, a belt placed 10 cm above the centre of the window must have dimensions exceeding 20 cm by 20 cm if the beam is not to spill over the sides of the belt during the conical scan (see [1], Section 2.5). The velocity and reflectivity of the belt are characterised in the laboratory. Calibration of the three parameters is then easily checked in a procedure lasting only a few minutes. The belt mimics the behaviour of a uniform airflow, and a figure-of-eight plot ([1], Figure 5) is obtained from which the usual information on wind speed and direction is derived. This test is insensitive to the focus setting of the lidar. The values derived by the lidar can then be compared with the known value of belt velocity and orientation.

Maintaining lidar sensitivity is important to ensure high availability of wind data. The sensitivity is easily checked by measuring the spectral peak height of the Doppler-shifted return from the moving belt, after a suitable time average over many speckle fluctuations. The peak height gives a direct measure of lidar sensitivity, from which can be derived a value of minimum detectable backscatter ([1], Section 4.7).

The calibration of focal distance (corresponding with measurement height) is conveniently performed with two additional items of equipment:

1. 45-degree mirror, in order to rotate the conical scan axis from vertical to horizontal.
2. Running machine target (or equivalent).

The mirror (Figure 1) must be of very high quality to avoid beam distortion (flatness to less than one wavelength over the beam area is desirable). Since the scan cone is now aligned horizontally, the beam spot moves approximately vertically over small regions at the sides of the cone. The running machine is placed a suitable distance away (at least 40 m), in one of these regions; it must provide a moving belt with area of order 1 m x 1 m, inclined at 30 to 45 degrees from vertical (Figure 2).

Figure 1: Mirror clamped at 45-degree angle to the ZephIR optics pod for focus calibration.

Figure 2: Moving belt target positioned 58m from ZephIR lidar.

A pulse of signal is then detected in the real-time output of the lidar. The method has been evaluated down a long corridor at QinetiQ Malvern. The range from lidar to target was 58.0 m, corresponding to a height setting of 50 m when the cone angle is taken into account. The pulse duration in this arrangement is 5.7 ms, corresponding to the time for the scanned beam to traverse the moving belt.

Alternatively, the pulse can be displayed by connecting an oscilloscope to the analogue output of the ZephIR system (Figure 3).

The calibration of the lidar was easily verified by programming the system to interrogate at three heights: 55 m, 50 m and 45 m. Correct focusing was confirmed by observation of the signal peak value as the heights are scanned. The signal behaviour should be nearly symmetric for small variations of focus around the peak at 50 m, and the signals derived from the lidar at 45 m and 55 m were identical to within experimental error. Once the equipment is set up, the focus calibration check is performed in only a few minutes.

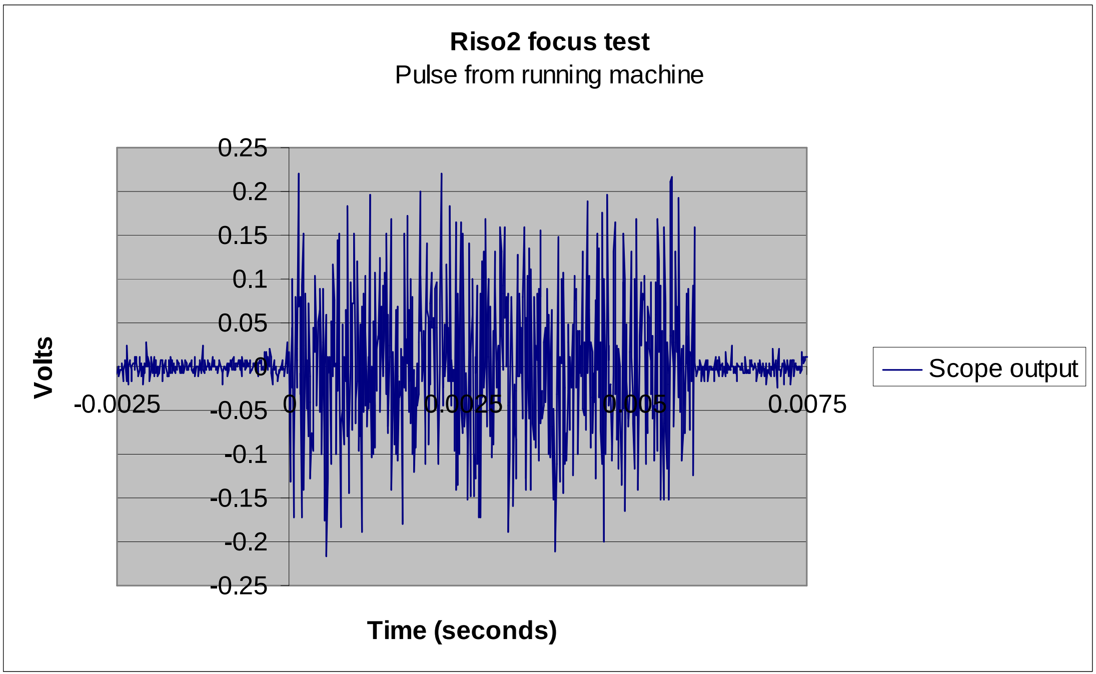

Figure 3: Signal pulse obtained on oscilloscope from analogue ZephIR output. The signal strength is calculated from the RMS value of the measured pulse (which exhibits fluctuations due to speckle effects).

The focus calibration technique described here has been used to check the focus of several ZephIR systems after extensive deployment by customers in the field. In all cases the focusing performance has been found to be unchanged from its original calibration: this is a consequence of the design in which the focus position is set via a closed loop system, providing automatic checking for positional discrepancy. The ease of testing has also permitted a number of tests confirming that the design goals have been met, and that the focusing has no measurable dependence on temperature

3. Current ZephIR calibration process

Currently, the clearest demonstration of validity is provided by direct side-by-side comparisons between the lidar system and a fully instrumented IEC-compliant meteorological mast of suitable height. Rigorous comparisons must be carried out with great care to avoid a number of problems associated with cup anemometers. A lidar/mast comparison is commonly used to provide a validation of lidar performance, and the lidar can then be used as a traceable reference for comparison with other units.

Lidar systems are normally calibrated in the laboratory before shipping. Routine checks on the calibration of units on their return to base provide confidence of long-term stability. As an example, the calibration process currently undertaken for a ZephIR lidar is outlined below. This consists of three stages:

- Velocity and direction check against a calibrated moving belt. The process provides a direct check of laser wavelength and scanner cone angle, each of which affects the velocity calibration.
- A focus range calibration is carried out at the factory with a moving target located at a distance of 100 m from the lidar. The closed loop positioning system ensures no drifts over time. An example of the output data from a subsequent focus calibration check is plotted in Figure 4.
- Finally, each unit undergoes an outdoor test to measure wind speed at several heights side-by-side against a reference unit. The reference unit has been checked against a tall mast to provide traceability. Figure 5 shows an example correlation plot of 10-minute average horizontal wind speed, obtained over a period of 7 days.

Each of the three tests above gives information on the sensitivity of the unit. For deployments in “clean” air, it is important to ensure this aspect of performance is fully optimised and has not deteriorated; otherwise there is a risk of reduced data availability.

It is important that no adjustments are performed during validation trials, or afterwards for as long as the lidar remains a traceable reference unit. The certification process outlined above has been defined in collaboration with industry experts including Garrad Hassan and provides the traceability that is a key element of formal energy prediction reports used by the financial community.

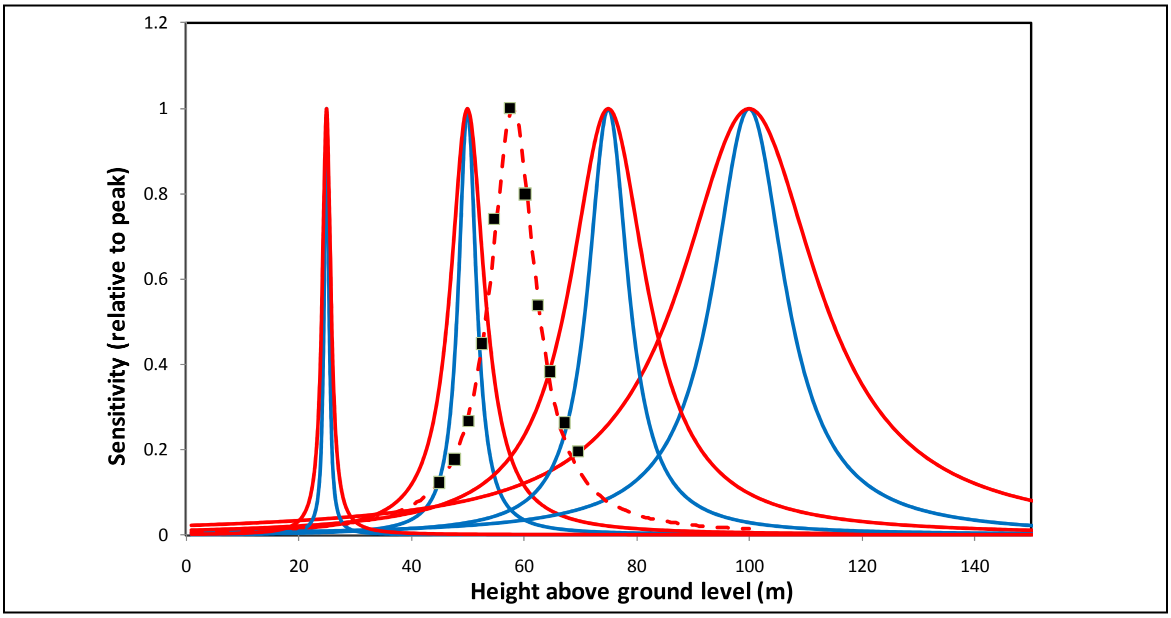

Figure 4: Theoretical lidar sensitivity curves at focus heights 25 m, 50 m, 75 m and 100 m for the two cases with beam radius A = 20 mm and 28 mm, corresponding to respectively the original (red curve) and current (blue curve) ZephIR designs. The peak is normalised to unity in each case; the absolute peak value decreases as the inverse of height squared, so that the area under each curve (representing the overall sensitivity) is always the same. This illustrates a useful feature of focused CW coherent lidar: in uniform scattering, the signal-to-noise ratio is independent of focus height. Calibration data (black squares), obtained for a target at range R = 68 m and adjusted for varying focus, are in close agreement with the corresponding theoretical values (dashed curve) at the equivalent height 58 m (= 68 m × cos30º).

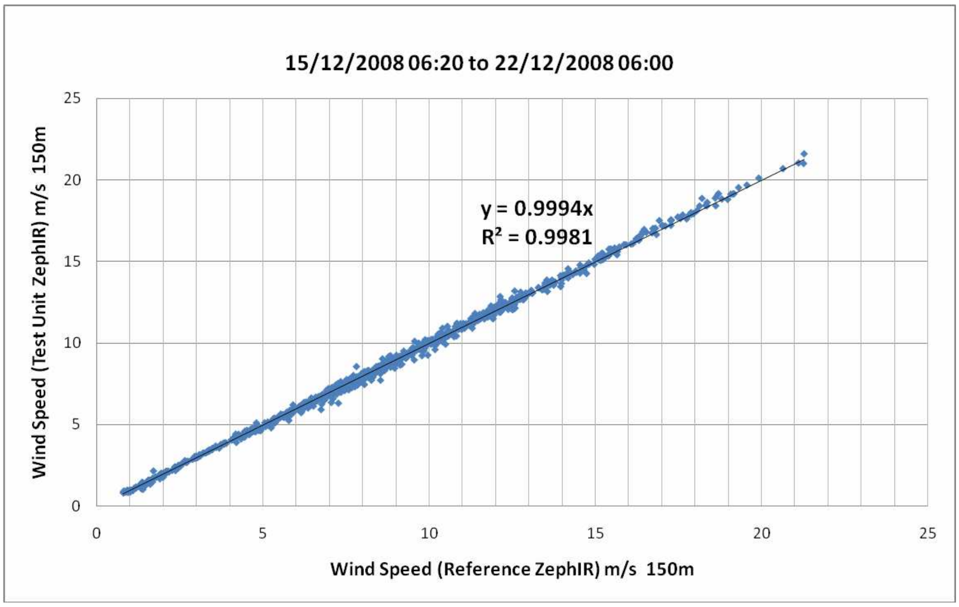

Figure 5: Comparison of a new ZephIR against the reference system, showing strong correlation and a gradient close to unity. This comparison has been carried out at 150 m height.

4. Recent improvements

Since the publication of the preliminary report on calibration [3], these ZephIR procedures have been further tested and refined for use outdoors and in the field.

We have noted that care is needed when choosing a "running machine" type of target, especially for focused beams. It will be seen from the descriptions above that a single large belt (area 1 m x 1 m) can be used for all the checks, or a smaller belt can be substituted during the short-range checks. For the focus checks we require only that the beam strikes the target during a brief part of each scan, whereas for the first three checks we require the beam to be continually on the target. Various rough-surface moving targets have been used in the history of lidar calibration; belt sanders, polystyrene plates and ground-glass plates have been popular. The commercial running machine with a flexible rubberised belt is inexpensive and surprisingly uniform in terms of reflectivity and velocity. It is quite satisfactory for many purposes, but when the illuminating beam spot is very small (millimetres rather than centimetres, say) the scattering statistics may no longer be reliably Gaussian. We should not expect a cheap commercial belt to show very good uniformity and reproducibility. Because the tolerances now being demanded of our wind industry sensors are very strict (better than 1% in many cases), it is sometimes necessary to choose a higher-specification Doppler target.

Recently, automated software has been developed that fits the near-Lorentzian shape of the sensitivity curve. The width of the curve is sensitive to both target effects and atmospheric turbulence effects which disturb the beam along its horizontal path just above ground level (see below). However, the position of the focus has been found to be very reproducible in tests carried out on different days, in different conditions, and before and after deployments. Calibrations are normally carried out at a standard range of 67 m; agreement of better than 1 m between the measured and programmed focus positions is routinely and reproducibly achieved.

In a recent technical note [4], Torben Mikkelsen remarked that measurements at Høvsøre with ZephIR suggest that the probe or focal volume is larger than theoretically expected, and he attributes this to "the different nature of hard target speckle statistics relative to diffuse atmospheric scatterers". We should probably clarify this by saying that the speckle statistics are very closely Gaussian for both hard and diffuse targets, *if* in each case we have the many independently phased scatterers that are generally assumed (e.g. when we appeal to the central limit theorem). The problem is that, in some circumstances and particularly with small tightly focused beams, the number of scatterers is not very large. Indeed at times the number may be 0 or 1, and then the statistics change completely.

This behaviour for scattering dominated by "a few" particles has been described several times in the literature, for hard targets and aerosol targets, and for free-space lidars and fibre lidars (see [5] and [6] and their References).

We can conclude that the standard expressions for CW heterodyne lidar focal volume (e.g. as in [7]) are correct, and are verified in calibration measurements with ZephIR, if a suitably fine-textured target is chosen so that the requirements of the central limit theorem are always satisfied.

We also note, in respect of the focused-beam measurements with a running-machine target, that care is needed when the lidar beam propagates through turbulent air. In ordinary operation, the ZephIR beam has a fixed elevation angle of 60 degrees; turbulence effects generally weaken rapidly with increasing height. However, calibration measurements are often made for convenience on optical ranges near ground level, with nearly horizontal beams, and then there is an increased risk that the size and position of the focal spot will fluctuate. This should be kept in mind even when the target range is only a few tens of metres, and it is of more concern as the range increases. So it is preferable to perform the focus checks in low-turbulence conditions, e.g. on an indoor range.

5. References

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