EVALUATION OF ZEPHIR

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Summary
Since the end of the year 2005 a first series model of QinetiQ's laser based wind measurement system, the ZephIR, is on the market. Detailed testing of one of the first series models has been performed by Deutsche WindGuard in the frame of a collaboration with QinetiQ. The measurements with the ZephIR have shown a very good agreement with state-of-the-art cup anemometer measurements at 65m height above ground. At 124m measurement height the ZephIR tends to underestimate the wind speed, while improvements of the accuracy at large measurement heights are under development. The ZephIR has shown a high rate of valid data between 96 % and 100 %, despite harsh weather conditions during the test campaign.

1 Introduction

Wind measurements for the wind energy industry by the application of meteorological masts become more and more impractical due to the large hub height of modern wind turbines. Thus, the wind energy industry is seeking since a long time for an accurate and reliable remote sensing technique for wind measurements [1]. A laser based measurement system (lidar=LIght Detection And Ranging) developed by the British company QinetiQ has shown promising results at the tests performed by the Risoe National Laboratory, Denmark over the last 3 years [2]. A first series model of QinetiQ's lidar, the ZephIR, has been introduced in late 2005 [3]. Field testing of one of the first series models has been performed by Deutsche WindGuard in the frame of a collaboration with QinetiQ.

2 The ZephIR

The ZephIR applies a continuous wave laser with 1575 nm wave lengths. The laser light is reflected at particles in the air, and the reflected laser light has a Doppler-shift in the frequency proportional to the wind speed component along the laser beam. Due to the high sensitivity of the laser only 1 of 10^{12} photons must be reflected for a wind speed measurement. The measurement height is defined by focussing the laser at a certain distance to the light source. The measurement of all three wind speed components is realised by rotating the laser beam along a cone with an opening angle of 30°. Thus, in one height the wind speed is averaged over a circle with a radius of about 57.7 % of the measurement height. The wind speed is scanned at 50 azimuth positions along the circle, while at each angle a large number of spectra are averaged. A full rotation of the laser beam takes 1 second. The rotation is performed three times for one wind measurement. Thus, the system provides 3-second averages of all 3 wind speed components. After three rotations in one height, the system shifts the focus of the laser beam to the next measurement height for a new measurement. The ZephIR can be programmed to scan 5 measurement heights successively. A picture of the ZephIR is shown in Figure 1. A detailed description of the ZephIR is given in reference [4].

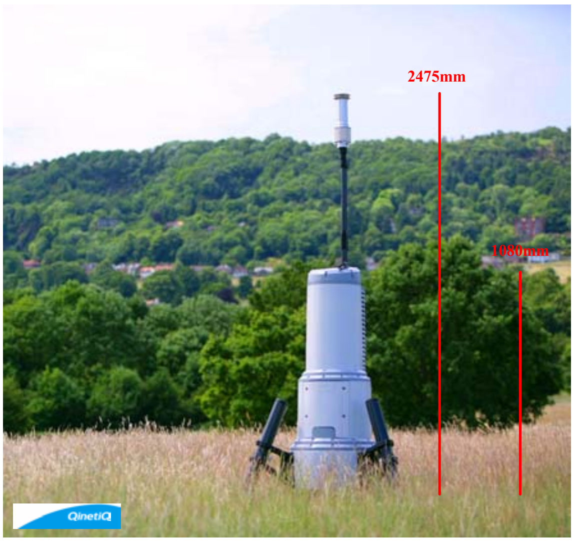

Figure 1: Photo of the ZephIR

3 Set-up of the Tests

Detailed testing of the ZephIR has been performed against high quality cup and sonic anemometers at different masts with 65 m height and 124 m height. Furthermore, a wind turbine power curve has been measured with the ZephIR and has been compared to the power curve determined with a met mast.
The 65 m mast was located in flat terrain near the German North Sea coast. The 124 m mast was located directly at the shore of the German North Sea coast. In the measurement sector, where the mast was exposed to free airflow, the wind came over the sea. The masts initially served for testing the power curves of prototype wind turbines of type Enercon E-70 E4 (65 hub height) and Enercon E-112 (124 m hub height).
The masts were equipped with cup anemometers of type Thies First Class, which were calibrated according to MEASNET [5] and DKD. The anemometers

fulfil all requirements of latest standards for power curve testing [6]. At the 124 m mast, also a 3D-sonic anemometer of type Gill Windmaster was available at a height of 122m above ground. The ZephIR has been placed very close to the met masts, such that both were exposed to the same wind conditions and that the lidar beam did not interfere with the met masts. The ZephIR has been programmed to measure periodically four times at the target height of 65 m/124 m and one time at 300 m height.
The test contains 195 h of data from the 65 m mast and 270 h of data from the 124 m Mast. The measurements have been performed in winter 2005/2006. During the campaign very mixed weather conditions were present, from sunny whether to rain, snow, icing conditions and fog.
For the comparison of the measurements performed with the ZephIR and the met masts only such wind directions, where the ZephIR and the mast were exposed to free wind conditions have been evaluated. Furthermore, only wind speeds above 4 m/s have been considered for the comparison, because this is the most relevant wind speed range in wind engineering and because at low wind speeds also cup anemometer measurements show higher percentage uncertainties.

4 Results

4.1 Availability of the ZephIR

The ZephIR has reached a rate of valid data of 99.7 % at 65 m measurement height and 96.1 % at 124 m measurement height in respect to the horizontal wind speed component (wind speed and wind direction). This is a remarkable result for a remote sensing technique, taking into account the partly bad weather conditions during the measurement campaign. Normally, even data periods with rain or snow had not to be filtered out. Also under icing conditions the system performed in general well.
However, during periods with rain or snow, the measurement of the vertical wind speed component is invalid. Thus, in respect to the vertical wind speed component the ZephIR reached an availability of 71.8 % at 124 m height.

4.2 Cloud Correction

In periods with high cloudiness, an overestimation of the wind speed occurred due to too high cloud backscatter (Figure 2). This problem has been solved by applying a so-called cloud correction. For the cloud correction one of the 5 measurement heights of the ZephIR is set to 300 m, a measurement height well above the target measurement height. The spectrum gained from 300 m focussing height is then more or less subtracted from the spectrum measured at the target height. This cloud correction can be applied online or by after processing the measurement data.
After application of the cloud correction, the time series of the horizontal wind speed component as measured by the ZephIR and by the cup anemometer agree well even in periods with dens cloudiness (Figure 2).

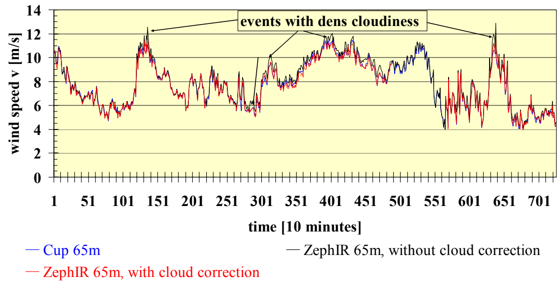

Figure 2: Time series (10-minute averages) of wind speed measured at 65 m height by the ZephIR without cloud correction and by the cup anemometer. The cloud correction has been after-processed on the data of the ZephIR (red line).

4.3 Comparison at 65 m Measurement Height

At 65 m measurement height, the horizontal wind speed component measured with the ZephIR agreed excellent with the cup anemometer measurements, when the cloud correction was applied (Figure 3). The squared correlation coefficient in terms of 10-minute averages of both measurements is higher than 0.99, the average deviation is -0.04 m/s, and the standard deviation of deviations is 0.18 m/s. This result is the more remarkable, as no filtering of the ZephIR-data has been applied, and partly bad weather with rain is included in the data.

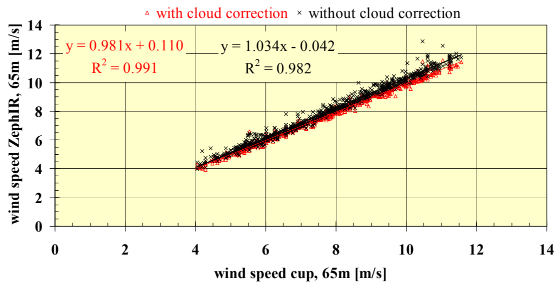

Figure 3: Comparison of 10-minute averages of horizontal wind speed component measured with the ZephIR and with a cup anemometer at 65 m height.

The power curve of the Enercon E-70 E4 prototype has been evaluated on the basis of wind measurements performed by the ZephIR and by the met mast (65 m hub height). The power curves agree very well with a difference in respect to the annual energy output below 2 % (Figure 4).

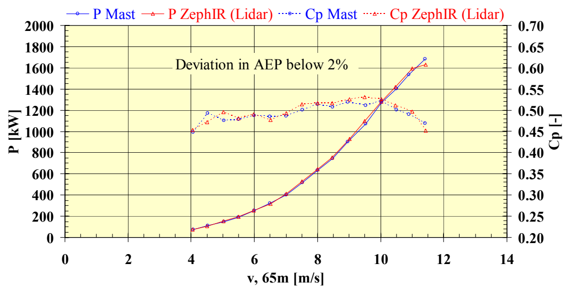

Figure 4: Power curve of the Enercon E-70 E4 prototype as measured with the ZephIR and with a met mast

4.4 Comparison at 124 m Measurement Height

At 124 m height, a relatively large scatter of the data points is seen, when the horizontal wind speed components gained from the ZephIR and the met mast are compared and no cloud correction for the ZephIR-data is applied (Figure 5). The outlier data almost disappears by the application of the cloud correction. Then, again a high correlation of the measurements is seen (squared correlation coefficient almost 0.99). However, the wind speeds measured with the ZephIR at 124 m height underestimate the wind speeds measured by the cup anemometer on average by 0.39 m/s. The standard deviation of deviations is 0.30 m/s at 124 m height. Interestingly, the regression slope between the ZephIR measurements and the cup anemometer measurements is nearly identical at about 0.98 at 124 m measurement height and 65 m measurement height (see Figure 3).

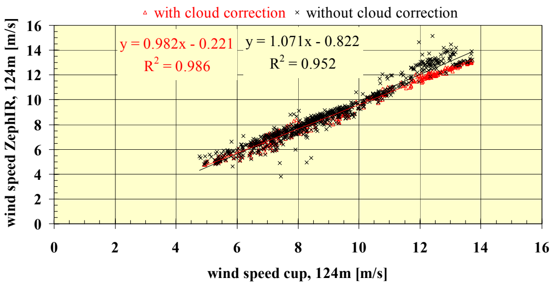

Figure 5: Comparison of 10-minute averages of horizontal wind speed component measured with the ZephIR and with a cup anemometer at 124 m height.

In order to find out the origin for the underestimation of wind speeds at 124 m measurement height, it has been analysed, which variables influence the deviation between the measurements of the ZephIR and the cup anemometer measurements. This investigation has been performed with the data of both measurement sites. Only a dependency of the wind speed difference on the vertical wind shear has been found at 124 m measurement height (Figure 6). It is assumed that this dependency is due to the limited focussing of the laser beam in this height range. The so called probe length, which is the effective half width of focussing, increases from about 5 m at 65 m measurement height to more than 30 m at 124 m measurement height. The large extend of the probe lengths at 124 m measurement height leads to a measurement error, if the vertical wind speed increases non-linearly with the height above ground within the probe lengths, or if the backscatter density within the probe lengths is uneven (e.g. due to uneven particle density). Remarkably, in Figure 6 the regression line between the percentage measurement error and the vertical wind shear crosses the zero line at zero wind shear. Thus, at the absence of vertical wind shear, the measurement error vanishes.

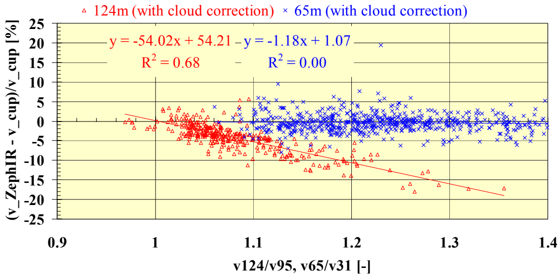

Figure 6: Percentage deviation between measurements of the horizontal wind speed component by the ZephIR and the cup anemometer at 124 m and 65 m height above ground as function of the vertical wind speed gradient. The vertical wind speed gradient is expressed as ratio of cup anemometer measurements at 124 m height and 95 m height, respectively 65 m height and 31 m height.

4.5 Comparison of Wind Direction Measurements

The wind direction measurements performed by the ZephIR and by vanes correlate well in terms of 10-minute-averages (Figure 7). It has been found, that within 3-second averages sometimes the detected wind direction is switched around by 180°.

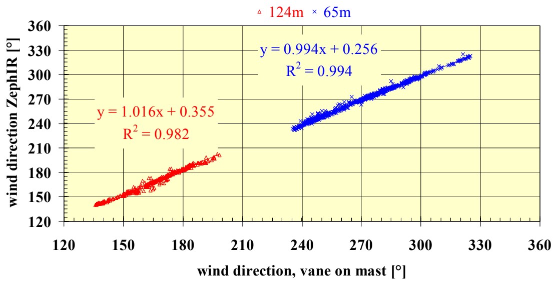

Figure 7: Comparison of wind direction measurement performed by the ZephIR at 124 m and 65 m height above ground and by a vane near the top of the met masts (10-minute averages).

4.6 Comparison of Vertical Wind Speed Component

The vertical wind speed component as measured by the ZephIR does not correlate well with the vertical wind speed component measured by a sonic anemometer of type Gill Windmaster (Figure 8). The reason for this has to be further investigated, also with data from complex terrain sites, where a larger and systematic vertical wind speed component is present. However, the average deviation of the vertical wind speed component measured by the ZephIR and by the sonic anemometer is only 0.06 m/s (standard deviation of deviations: 0.08 m/s), what is reasonable under consideration of the measurement uncertainty of the sonic anemometer.

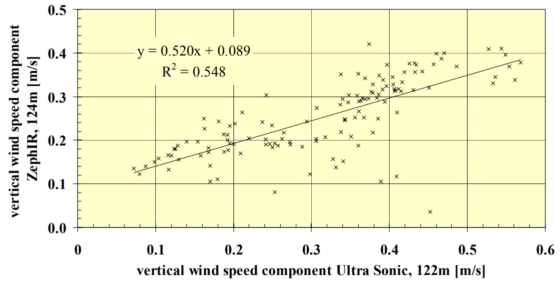

Figure 8: Comparison of vertical wind speed component measured at 124 m height above ground by the ZephIR and measured at 122 m height above ground by an ultra sonic anemometer (10-minute averages).

4.7 Comparison of Standard Deviation of Horizontal Wind Speed Component

The standard deviation of the horizontal wind speed component as measured by the ZephIR is smaller than measured by cup anemometers (Figure 9). This can be understood from the spatial averaging of the ZephIR (averaging over circle and probe lengths) compared to point measurements by cup anemometers and from the fact that in case of the ZephIR the standard deviation is calculated from 3-second averages of the wind speed, while in the case of the cup anemometers 1-second averages and 0.2-second averages have been applied in case of the measurements at 65 m and 124 m.

At 124 m measurement height, the underestimation of the wind speed standard deviation by the ZephIR is higher than at 65 m measurement height, due to the larger spatial averaging.

At this stage, the direct evaluation of the turbulence intensity form measurements of the ZephIR needs further investigation.

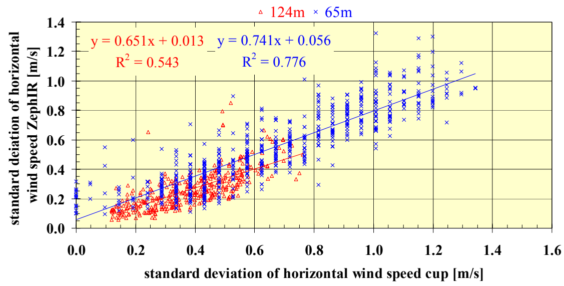

Figure 9: Comparison of standard deviation of wind speed within 10-minute periods as measured by the ZephIR and cup anemometers at 124 m and 65 m height above ground.

4.8 Comparison of Extreme Values of Horizontal Wind speed Component

The maxima of the horizontal wind speed component within 10-minute periods measured by the ZephIR are underestimated compared to cup anemometer measurements, while the minima are overestimated (Figure 10). The origin can again be seen in the larger spatial averaging of the ZephIR and the larger pre-averaging period of 3 seconds.

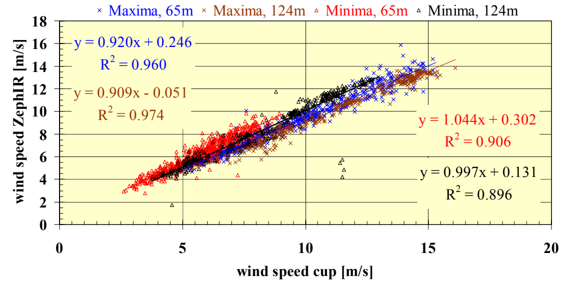

Figure 10: Comparison of extreme values of wind speed within 10-minute periods as measured by ZephIR and the cup anemometer at 124 m and 65 m height above ground.

5 Conclusions

The following conclusions can be drawn:

- The ZephIR has a high rate of valid data, even under harsh weather conditions.
- A cloud correction exists, which works effectively at high cloud backscatter.
- The ZephIR has a high accuracy in terms of the horizontal wind speed component at lower measurement heights.
- The ZephIR shows an underestimation of the horizontal wind speed component at large measurement heights (124m tested), which increases with increasing vertical wind shear.
- The ZephIR shows a high quality of wind direction measurements,
- The ZephIR shows an underestimation of the turbulence intensity and extreme values of the wind speed.
- Further investigation is needed in terms of measurements of the vertical wind speed component, of the turbulence intensity and of extreme values.

The following outlook can be given:

- There is likely room for improvement of the measurements by the introduction of more data corrections and filtering.
- Within the EC funded research project RESWIND it is intended to prepare the introduction of lidar measurements in international standards for wind turbine power curve testing.
- Measures to increase the accuracy at large measurement heights are under development.
- Further testing by Deutsche WindGuard is scheduled for the year 2007.

6 Acknowledgement

Thanks belong to Enercon to allow the use of the met masts for this work and for the permission to present results from the power curve measurements at the Enercon E-70 E4 and Enercon E-112 prototypes within this work.

7 References

[1] A. Albers, D. N. Asimakopoulos, C. Berteotti, F. Beyrich, J. Handwerker, C. G. Helmis, D. Kalaß, H. Klug, V. Mellert, A. Schomburg, M. Tombrou, H.-P. Waldl, U. Weisensee; SODAR for Siting and Operating of Wind Energy Converters, SOSOWEC, final report, (JOU2-CT93-0424), 1995

[2] D. A. Smith, M. Harris, A. S. Coffey, T. Mikkelsen, H. E. Jørgensen, J. Mann, R. Danielian; Wind lidar evaluation at the Danish wind test site in Høvsøre, proceedings of EWEC2004, London

[3] A. Albers; LIDAR, eine revolutionäre Methode zur Durchführung von Windmessungen mit Laser, Windstärke-Forum der Windenergieagentur Bremerhaven, Bremen e.v., HusumWind 2005

[4] D. A. Smith; Wind Speed at Light Speed Laser Radar (lidar), Windtech international, November 2004

[5] MEASNET, Cup Anemometer Calibration Procedure, 1997

[6] IEC 61400-12-1, WIND TURBINE GENERATOR SYSTEMS, Wind Turbine Power Performance Testing, 2005