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Multi-MW wind turbine power curve measurements using remote sensing instruments – the first Høvsøre campaign

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National Laboratory for Sustainable Energy

Multi-MW wind turbine power curve measurements using remote sensing instruments – the first Høvsøre campaign

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Risø-R-1679(EN)

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February 2009

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Abstract (max. 2000 char.):

Power curve measurement for large wind turbines requires taking into account more parameters than only the wind speed at hub height. Based on results from aerodynamic simulations, an equivalent wind speed taking the wind shear into account was defined and found to reduce the scatter in the power curve significantly. Two LiDARs and a SoDAR are used to measure the wind profile in front of a wind turbine. These profiles are used to calculate the equivalent wind speed. LiDAR are found to be more accurate than SoDAR and therefore more suitable for power performance measurement. The equivalent wind speed calculated from LiDAR profile measurements gave a small reduction of the power curve uncertainty. Several factors can explain why this difference is smaller than expected, including the experimental design and errors pertaining to the LiDAR at that time. This first measurement campaign shows that used of the equivalent wind speed at least results in a power curve with no more scatter than using the conventional method.

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Contents

Preface

This report documents our first attempt at improving the accuracy of wind turbine power curves by utilising the profile information available using remote sensing instruments. The experimental work was carried out at the National Test Station for Large Wind Turbines at Høvsøre in western Jutland, Denmark in the spring of 2008. We express our gratitude to the technical team at Høvsøre, Bjarne Sønderskov and Anders Vestergård for their capable and always good humoured assistance. It is also appropriate here to thank the two anonymous wind turbine manufacturers who allowed us access to their wind turbines and their data.

The work was performed as a task under Work Package 6 of the European Union's Sixth Framework Programme (FP6) Upwind project. This report is a formal deliverable (D5) in that context. Rozenn Wagner is supported by the Marie Curie ModObs Network MRTN-CT-2006-019369.

1. Introduction

A measured power curve conventionally consists of the 10 minutes mean turbine electrical power plotted against the wind speed at hub height. Such a plot usually shows a significant spread of values and not a uniquely defined function. The origin of the scatter can mainly be grouped to three categories: the wind turbine components characteristics, sensor error and the wind characteristics. Within the last group, the standards stipulate to measure the mean wind speed and air density at hub height at a distance of 2 to 4 rotor diameters upstream [1]. However, other wind characteristics can influence the power production; for example: the wind shear and the turbulence.

The wind shear influence for the intermediate load range was shown with simulations by Wagner et al. in [2]. In order to take shear into account in the power curve production, an equivalent wind speed based on wind profiles was defined. The use of such a wind speed reduced the scatter. In this report, this exercise has been repeated but this time using the complete range of hub height wind speeds required to produce a power curve. Based on both sets of results, it is expected that wind profile measurements in front of the wind turbine would improve the power curve measurements. A mast mounted with cup anemometers at different heights seems then to be required. However, for large wind turbines the hub height exceeds 80m, and the installation of such a high mast takes time and is expensive. Therefore ground based remote sensing systems like LiDARs and SoDARs appear to be a good alternative. Indeed such devices enable us to measure wind profiles up to 150m and are easy to install. The second part of this report concerns power curve measurements made using two LiDARs and a SoDAR, installed in front of two wind turbines. The remote sensing devices were measuring at different heights within an area corresponding to the swept rotor areas.

First we revise the concept of equivalent wind speed and explain the simulations results. Then we describe the measurement campaign: the setup and the way each instrument operates, as well as their accuracy. The accuracy analysis of the SoDAR is the subject of a separate part where it is compared to a LiDAR. Finally, LiDAR wind speed profiles measurements are discussed and used to make power curve measurement using the equivalent wind speed method.

For reasons of confidentiality, all the numbers presented here are normalized. However it is fair to say that the data are representative of a modern, multi-megawatt wind turbine.

2. Preliminary work: Aerodynamic simulations

First of all, simulations of a wind turbine subjected to different forms of wind shear were carried out with an aerodynamic model. The following section describes the model.

2.1 Aerodynamic simulations

A simplified version of the aeroelastic model HAWC2, the HAWC2Aero code [3], is used in the analysis. It contains the same aerodynamic and wind modules as the full HAWC2 code and can be considered as a Blade Element Momentum model operating in the time domain, thus capable of including turbulence and non linear effects from aerodynamics as well as influence of the turbine controller. The turbine is a variable speed, pitch-regulated turbine.

The main wind related inputs to the model are the mean wind profile and the turbulence intensity. The Mann model of turbulence [4] is used to simulate the wind fluctuations which are added to the mean wind speeds field, and the wind is assumed horizontally homogeneous. For each profile, 10 simulations (implying 10 different turbulent fields) were carried out in order to map the statistical variation in normal turbulence fields expected over a turbine rotor.

The main output is 10 minutes time series of the power produced by the turbine, but also time series of the free wind at 5 different points regularly distributed along a vertical line within the rotor plane: one at hub height and 4 others at symmetrical positions above and below see Figure 1. The data point height is located at the average height of the segment.

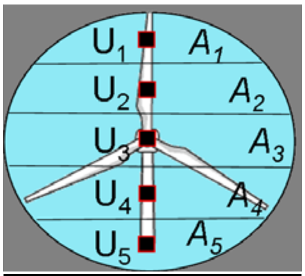

Figure 1 *Swept rotor area divided in 5 segments of area A_i;*
the wind speed in the middle of the i^{th} area is U_i.

2.2 Preliminary study results

Profiles measurements from the combination of two met masts (one 116.5 m high and the other 160 m high) over a one year period were binned according to the wind speed at hub height (2m/s bins). For each bin, 10 different profiles were chosen in order to cover the whole wind shear range observed for this range of wind speed at hub height. Each set of profiles are normalized so they have the same wind speed at hub height. Examples of normalized profiles are shown in Figure 2. The simulations were carried out using these normalized profiles as input.

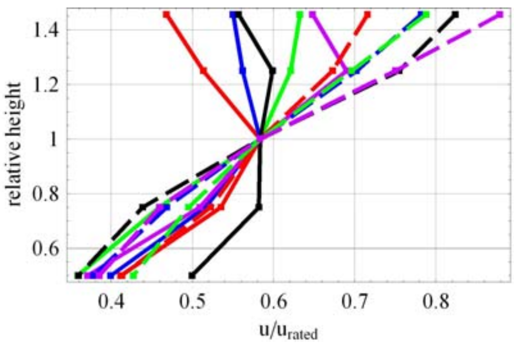

Figure 2 *Example of 10 measured wind speed profiles (10 minutes average values) normalized so they all have the same wind speed at hub height (relative height = 1).*

In Figure 3, 10 minutes averages of the power output are plotted against the 10 minutes average of the wind speed to give the power curve. The dataset derived from the conventional hub height wind speed is shown with the blue dots. Since for each set of input profiles, the hub height wind speed was the same for all the profiles, the points are aligned vertically, but do not merge into one point (they have different ordinate). This means that even though the wind speed at hub height is the same, the wind turbine power production varies; and these variations are due to the wind shear.

In order to take the wind shear into account when measuring the power curve, an equivalent wind speed was defined as the average of the wind speed at different heights weighted by the area of the corresponding segment of the swept rotor area [2]

$$U_{eq} = \frac{1}{A}\sum_i \overline{U_i} \cdot A_i \qquad (1)$$

where $\overline{U_i}$ is the 10 minutes mean wind speed at the ith height, A_i is the area corresponding at the specific data point height and A the swept rotor area. We chose that definition for the equivalent wind speed because it is the one showing the best results in [2]. Figure 1 shows an example for the swept rotor area divided in 5 segments. The data point height is located at the average height of the segment.

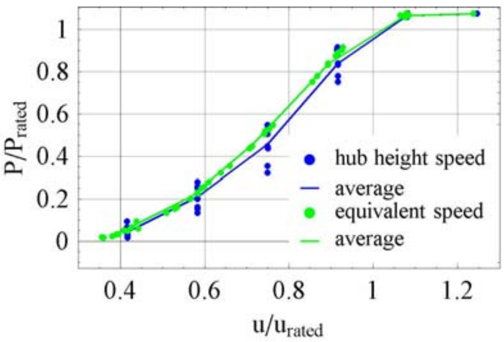

Figure 3 *Simulated power curves. Blue: power as a function of the wind speed at hub height. Green: power as a function of the equivalent wind speed calculated from profiles.*

The power curve obtained with the equivalent wind speed, calculated according to (1), is displayed in green in Figure 3. As the power values are the same (only the wind speed definition change between the two cases), plotting them as a function of the equivalent wind speed instead of hub height wind speed shifts the points to the right when $U_{eq} > U_{hub}$ and to the left when $U_{eq} < U_{hub}$. Plotted as a function of the equivalent wind speed, the points are almost aligned with a curve (the green line), corresponding to a power curve independent of the wind shear; and the power fluctuations (due to wind shear) around the average curve are reduced in comparison to the points plotted as a function of hub wind speed.

The difference between the two mean power curves (represented by full lines in Figure 3) is not due to any error but to the fact that these curves are obtained with different wind speed definitions. Indeed, the definition of a power curve is somewhat arbitrary. For example, if we plotted the power as a function of the wind speed at 0.75h_height, the power curve would mainly be shifted to the left, because the wind speed at this height is usually lower than the wind speed at hub height and the power output of the turbine is the same.

From these simulation results, profile measurements in front of the turbine and the use of an equivalent wind speed are expected to improve power curve measurement. As high met mast installations are expensive, ground based remote sensing systems like LiDARs and SoDARs appear to be a good alternative. Thus a measurement campaign including three remote sensing devices was set up. This is described in the next section.

3 Description of the measurement campaign

The experiment took place at Risø DTU's Test Station for Large Wind Turbines, located at Høvsøre, on the west coast of Denmark. The terrain is flat, surrounded by grassland and 1.7 km from the coast [6]. The main wind direction is from west, thus we considered wind directions included within the 90° sector delimited according to the IEC standards for performance testing [1] in order to avoid wakes from other turbines: 230°- 320°.

In this experiment, we wanted to measure the power performance of two of the five wind turbines located at Høvsøre. In this report, the two turbines of interest are named wind turbine A and B. On the west side of each wind turbine there is a mast, with the height of the turbine's hub and equipped with a top mounted cup anemometer used for power performance verification. For clarity, we call mast A and B the masts located in front of turbine A and B respectively.

A ZephiR LiDAR, a Windcube LiDAR and an AQ500 SoDAR were placed close to each other between the masts A and B, see Figure 4. Although the two wind turbines considered here do not have the same hub height, this setup enables us to measure the power curve with the remote sensing devices for both turbines in one campaign.

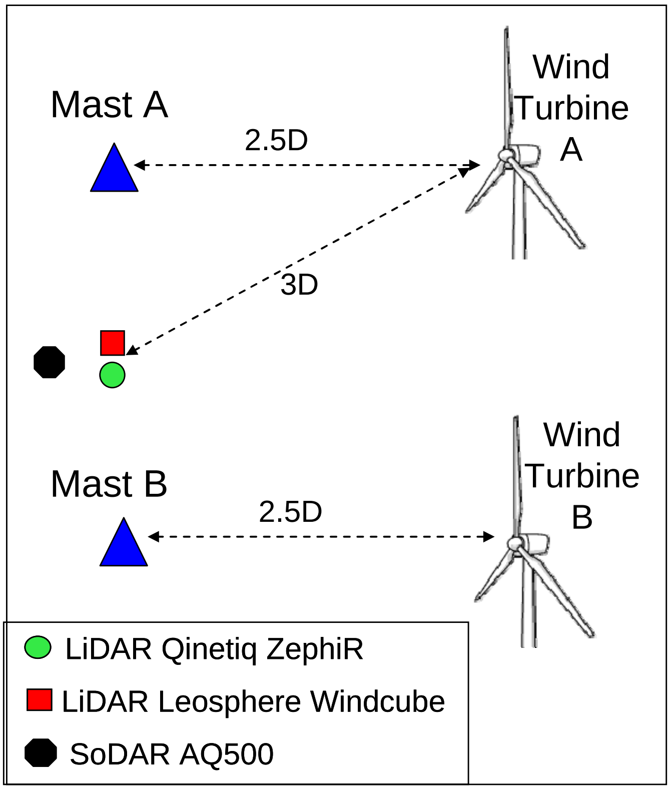

***Figure 4** Plan view of the measurement campaign with two LiDARs and a SoDAR in front of a large wind turbine (D is the rotor diameter).*

3.1 ZephIR LiDAR

The QinetiQ ZephIR is a continuous wave LiDAR scanning conically with an angle of 30 degrees from the vertical and with a sample frequency of 50Hz [5]. Different heights can be probed by varying the focus; however a consequence of the varying focus is that the probe length increases quadratically with altitude (about 6m at 50m and 23m at 100m for example). Each height is scanned for 3 seconds. Thus a radial wind speed is available every 7.2 degrees and a 3-D wind speed vector is computed from 150 radial speeds. The ZephiR LiDAR measured in this location for 6 weeks (from 07/02/08 to 14/03/08), at 5 heights corresponding to $0.5h_{hub}$, $0.75h_{hub}$, h_{hub}, $1.25h_{hub}$, $1.5h_{hub}$ for wind turbine A.

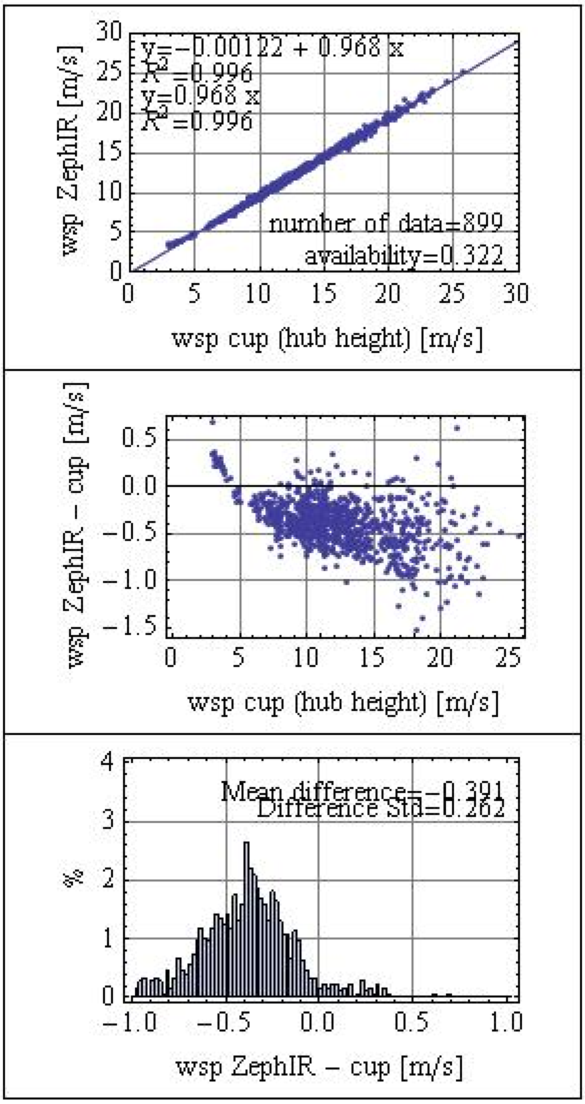

***Figure 5** Comparison of wind speed measurements at hub height A between the ZephIR LiDAR and the cup anemometer A. Top: regressions (firstly with an offset and secondly forced through zero); middle: Difference between wind speed measured by the LiDAR and by the cup anemometer at hub height as a function of (cup) wind speed; bottom: Distribution of the difference between the wind speed measured by the LiDAR and the cup anemometer.*

Figure 5 shows the comparison of the ZephIR measurement at hub height A compared to the cup anemometer of mast A. The data were selected for rain-free periods. In addition, low clouds can disturb wind speed measurements from the ZephIR LiDAR. Therefore we used a ceilometer to measure the cloud base height and the 10 minutes periods during which the cloud base was lower than 1600m in average were not taken into account. The latter filter removes a lot of data and is the main reason for the low availability (32.2%).

This ZephIR unit shows a quite low regression slope (96.8%) and a big negative mean error (-0.39 m/s), which is poorer than average for ZephiIR LiDAR.

3.2 Windcube LiDAR

The Leosphere Windcube is a pulsed LiDAR. The height discrimination is then inherently defined by the time taken by the backscatter to come back to the receptor. Unlike a focused system, the vertical probe length is constant with height and about 25m. The radial wind speed is measured at all heights simultaneously. Four line-of-sights at 30 degrees from the vertical (each separated by 90 degrees of azimuth) are sequentially scanned and a new wind vector is computed at the end of each scan, about every 1.5s. The Windcube LiDAR measured in this location for 3 months (from 25/02/08 to 20/05/08) at 10 heights chosen to match the five heights: $0.5h_{hub}$, $0.75h_{hub}$, h_{hub}, $1.25h_{hub}$, $1.5h_{hub}$ for each wind turbine.

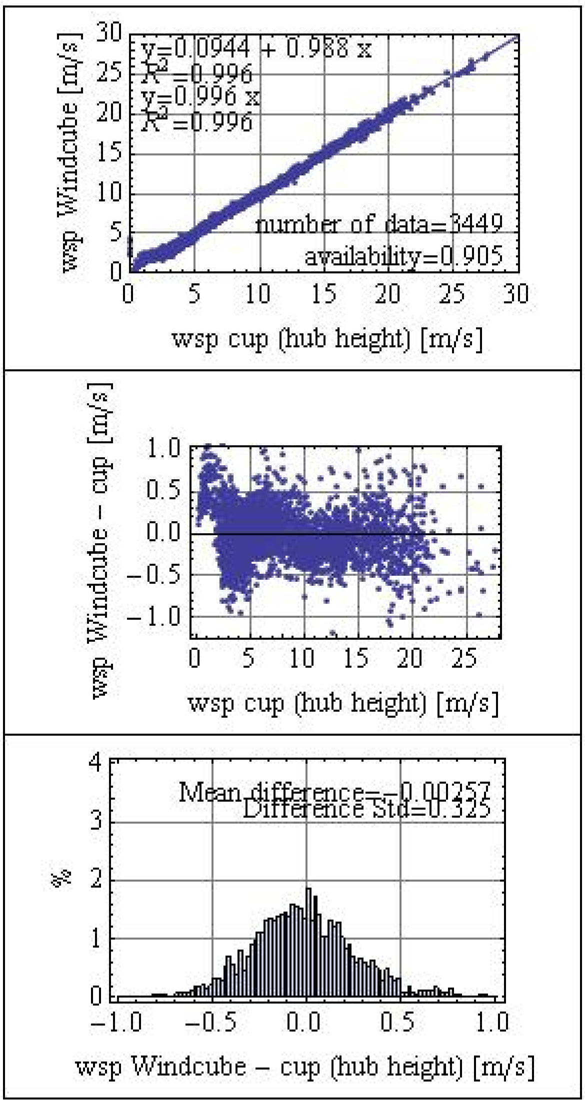

Figure 6 *Comparison of wind speed measurements at hub height B between the Windcube LiDAR and the cup anemometer B. Top: regressions (firstly with an offset and secondly forced through zero); middle: Difference between wind speed measured by the LiDAR and by the cup anemometer at hub height as a function of (cup) wind speed; bottom: Distribution of the difference between the wind speed measured by the LiDAR and the cup anemometer.*

Figure 6 shows the comparison of the Windcube measurement at hub height B compared to the cup anemometer of mast B. The data are screened in order to exclude the periods with rain. As it has been operating at this site for longer than the ZephIR LiDAR, the number of data is much higher. As it is a pulsed system, measurements are not affected by the low clouds, no screening is needed for clouds and the availability is very high (90.5%).

The regression slope is rather good (98.8%) and the mean error is very small.

However, during that measurement campaign, a significant non-linearity was identified. This manifested itself as a rapidly varying wind speed dependant error that was particularly severe in the 5-10 m/s wind speed range. Subsequent investigations have shown that the error was due to a problem determining the peak position in the Doppler spectra. This has since been eradicated by the Windcube manufacturer.

Both the ZephIR and the Windcube are extensively described and compared in [6].

3.3 AQ500 SoDAR

The AQ500 SoDAR is a 3-beams monostatic SoDAR. A pulsed sound signal is sent in 3 directions using parabolic dishes to direct the beams with a beam angle of 15 degrees from the vertical. As for the pulsed LiDAR, the probe length is constant but about 20m. The AQ500 SoDAR has been measuring at this location for about a year, but for comparison purpose we reduce this period to when at least one of the LiDAR systems were measuring at the same place (from 07/02/08 to 20/05/08).

The SoDAR measurement accuracy is addressed in the following section.

4 SoDAR measurement

4.1 SoDAR measurements at hub height

The SoDAR AQ500 was located 5 m west of the LiDARs (see setup Figure 4). From the 25/02/2008 (start of Windcube measurement) to the 15/04/2008, the SoDAR was measuring the wind speed at every 5 m (from 0.5 hub height A). Figure 7 shows the results of the measurements from remote sensing instruments compared to the cup anemometer A for that time period. Both datasets (from the AQ500 SoDAR and the Windcube LiDAR) contain the same 10 minutes periods, therefore the cup anemometer values are the same.

The main result from this comparison is that the SoDAR error (difference between SoDAR and cup wind speeds) is larger than the LiDAR error. Particularly the standard deviation of the error (the scatter in the x-y plot at the top left corner of Figure 7 is worryingly large). In an attempt to reduce this uncertainty, on the 15/04/2008 we decreased the SoDAR spatial resolution, assuming that this would result in a longer pulse length, thereby improving the signal to noise ratio. After this change the SoDAR height resolution was 15m with the lowest measuring point at 0.55 hub height A. The results obtained with this new configuration are displayed in Figure 8.

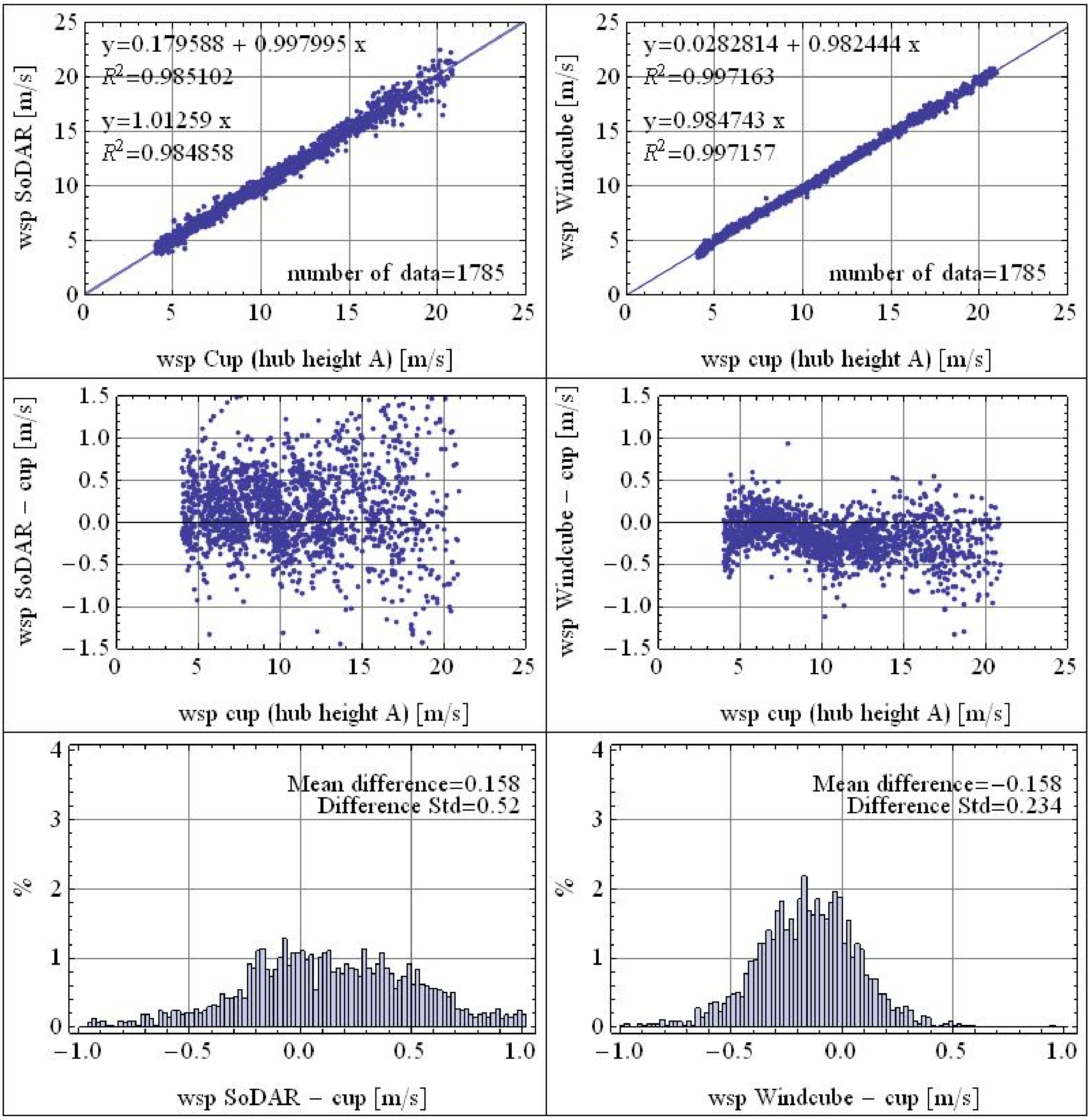

Figure 7 *Comparison of remote sensing measurements at hub height to simultaneous cup anemometer measurements. Left: SoDAR AQ500 (with 5m resolution); right: Windcube LiDAR. Top: Regression of 10 minutes mean wind speed measurements from remote sensing instrument against cup anemometer measurements; middle: Difference between remote sensing wind speed and cup anemometer wind speed as a function of the (cup) wind speed; bottom: Distribution of the difference between remote sensing wind speed and cup anemometer wind speed.*

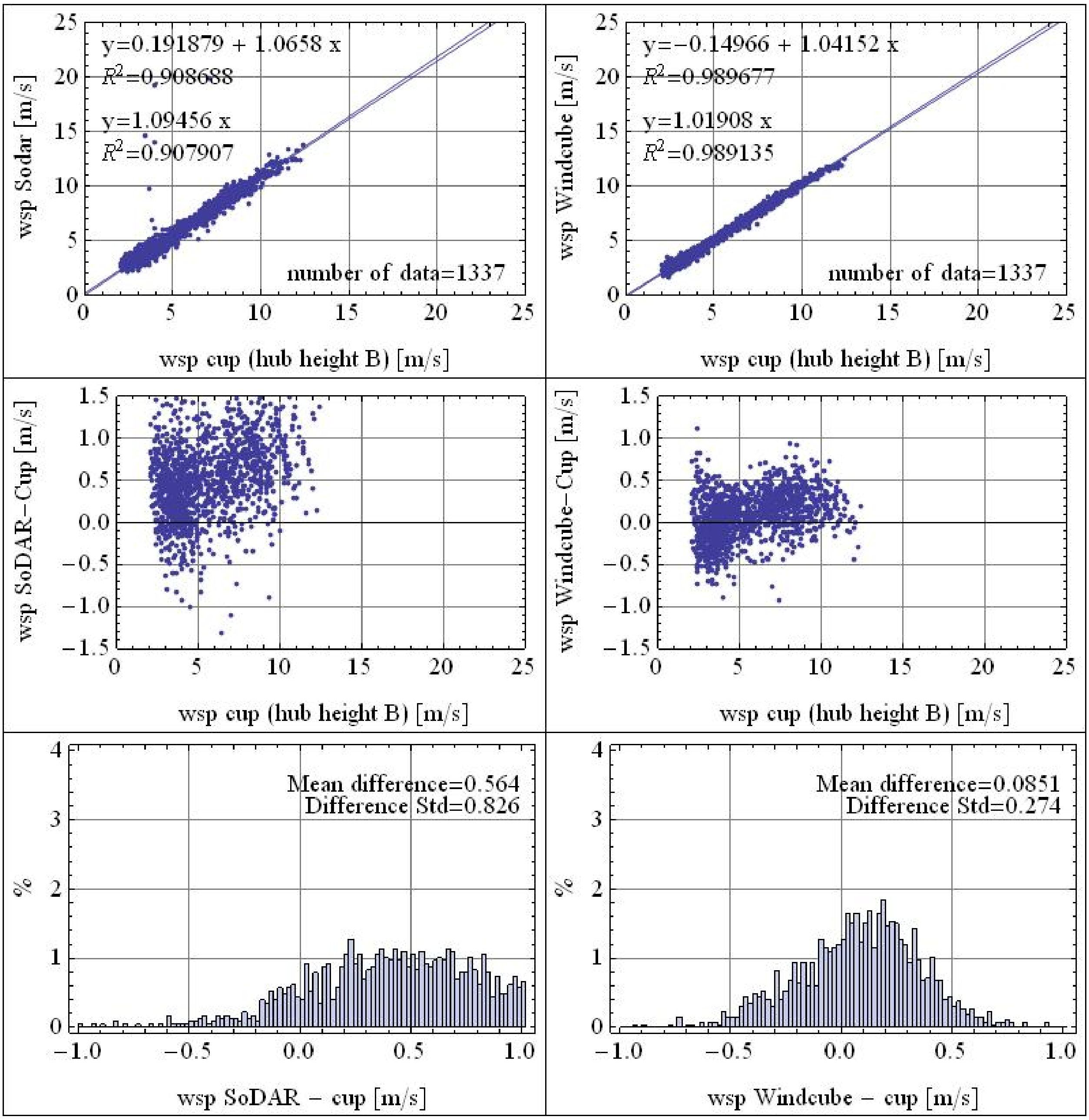

***Figure 8** Comparison of remote sensing measurement at hub height to simultaneous cup anemometer measurement. Left: SoDAR AQ500 with 15m resolution; right: Windcube LiDAR. Top: Regression of 10 minutes mean wind speed measurements from remote sensing instrument against cup anemometer measurements; middle: Difference between remote sensing wind speed and cup anemometer wind speed as a function of the (cup) wind speed; bottom: Distribution of the difference between remote sensing wind speed and cup anemometer wind speed.*

The results obtained for 5m and 15m resolution are not easy to compare as the wind speed distributions for the time periods are very different, and the second period contains only wind speed below 12m/s (see Figure 8). However we cannot observe any noticeable improvement. The explanation for this is that, as we have only recently ascertained, the change in spatial resolution did not result in a longer sound pulse, but only in less overlapping range gates.

4.2 SoDAR wind speed profile measurements

The consequence of the large scatter is that the wind speed profiles measured by the SoDAR are often distorted and unreliable for calculating an equivalent wind speed. In order to get an idea of this effect, Figure 9 shows some example of profiles measured by the SoDAR and the LiDAR (same place, same time). The SoDAR profiles are quite different from simultaneous LiDAR profiles: they are either globally over- or underestimating LiDAR profiles or they zigzag around the LiDAR profiles. We cannot observe any significant improvement with the 15 m resolution. Moreover, the bottom of Figure 9 shows simultaneous profiles from the LiDAR and the met. mast. The LiDAR profiles are generally very close to the mast profiles.

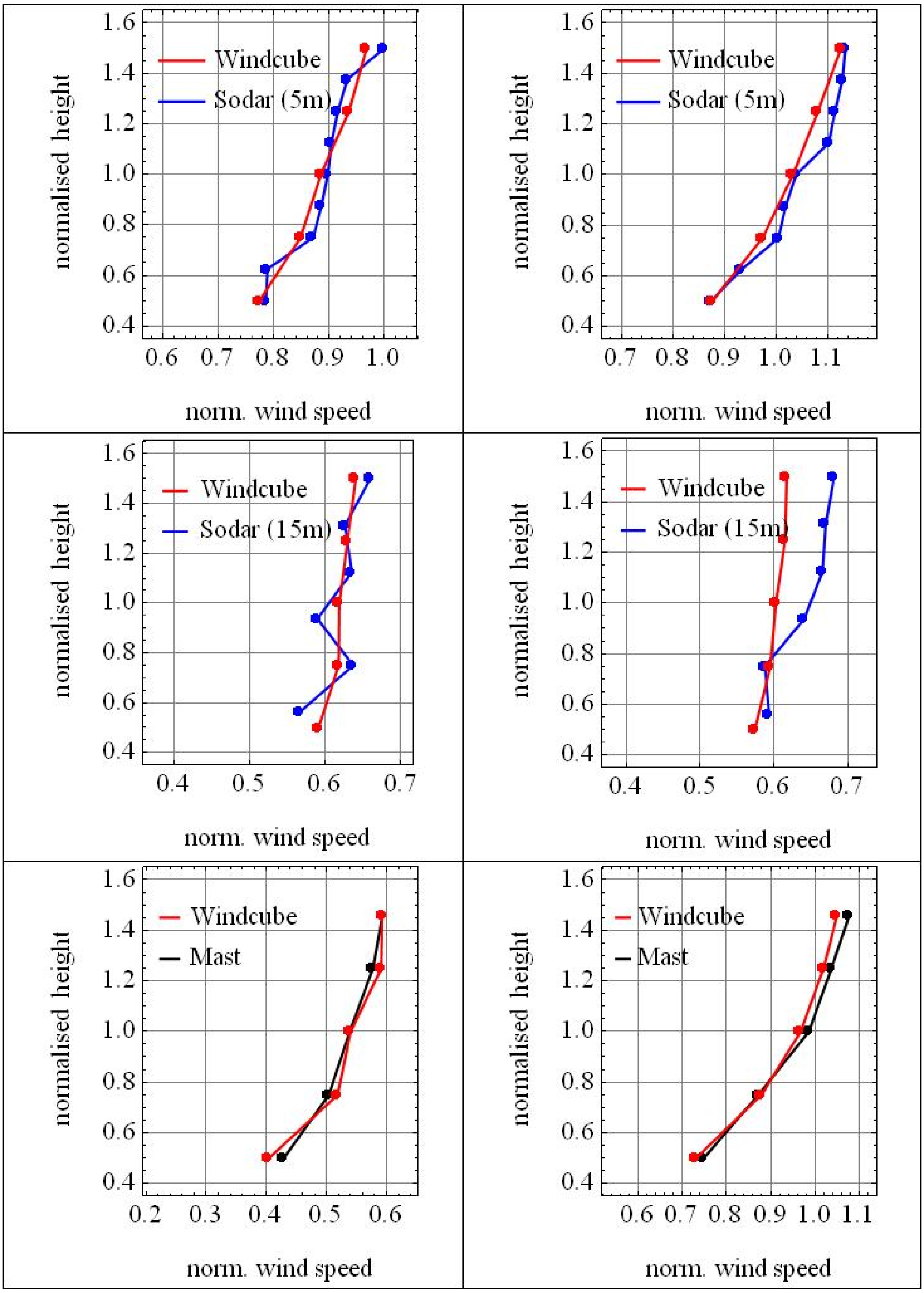

Figure 9 *Examples of comparison of 10 minutes average profiles measured by different instrument. Top: SoDAR with 5m resolution/Windcube LiDAR; Middle: SoDAR with 15m resolution/Windcube LiDAR; Bottom: Windcube LiDAR/met. mast.*

Figure 10.b shows the distribution of difference in wind speeds measured by the SoDAR and the Windcube LiDAR at five heights. For this plot we considered only the data when the Windcube was measuring at the same heights as the SoDAR. The difference of wind speed is the difference between the 10 min average wind speeds measured by both instruments at the same time. For comparison purposes, Figure 10.a shows the distribution of difference of wind speeds measured by the Windcube LiDAR and the cup mounted on the high met. masts located at the south of the Høvsøre site. These measurements were performed just before the start of the campaign described in this report. Figure 10 shows that the standard deviation of the difference of wind speed measurement between the AQ500 SoDAR and the Windcube LiDAR is larger than the standard deviation of the difference between the Windcube LiDAR and the cup anemometer. This shows that the accuracy of the AQ500 SoDAR on 10 minutes average wind speed is generally lower than the LiDAR accuracy.

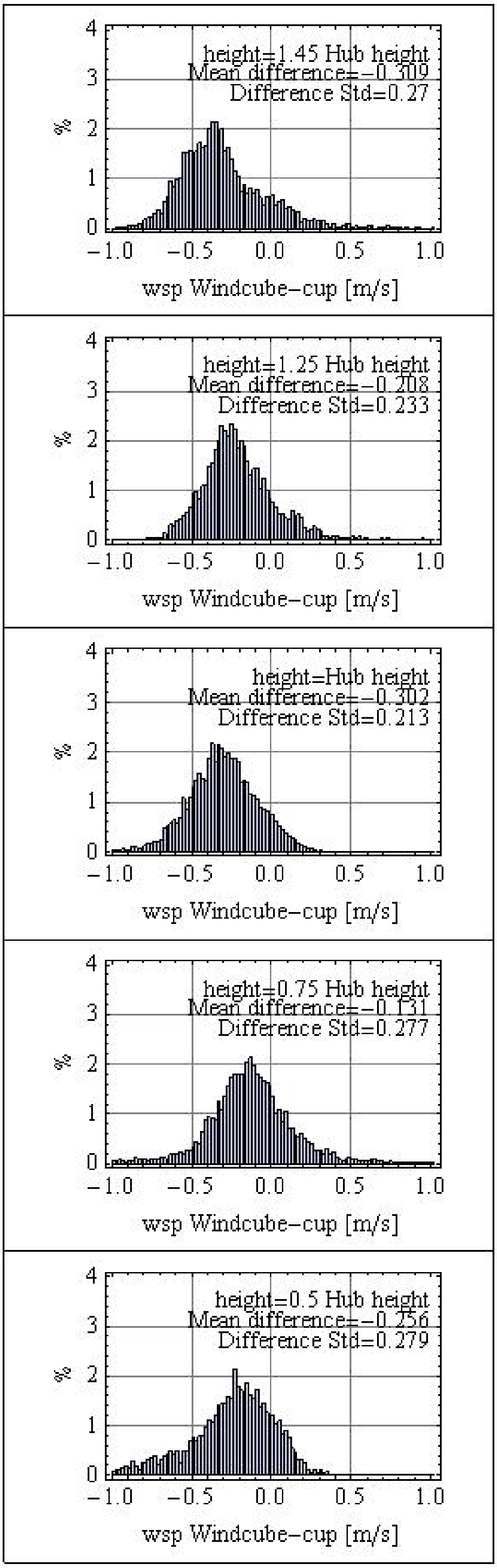

Figure 10.a *Distribution of differences of wind speed measured at various heights by the Windcube and the met. mast before the campaign (Early 2008)*

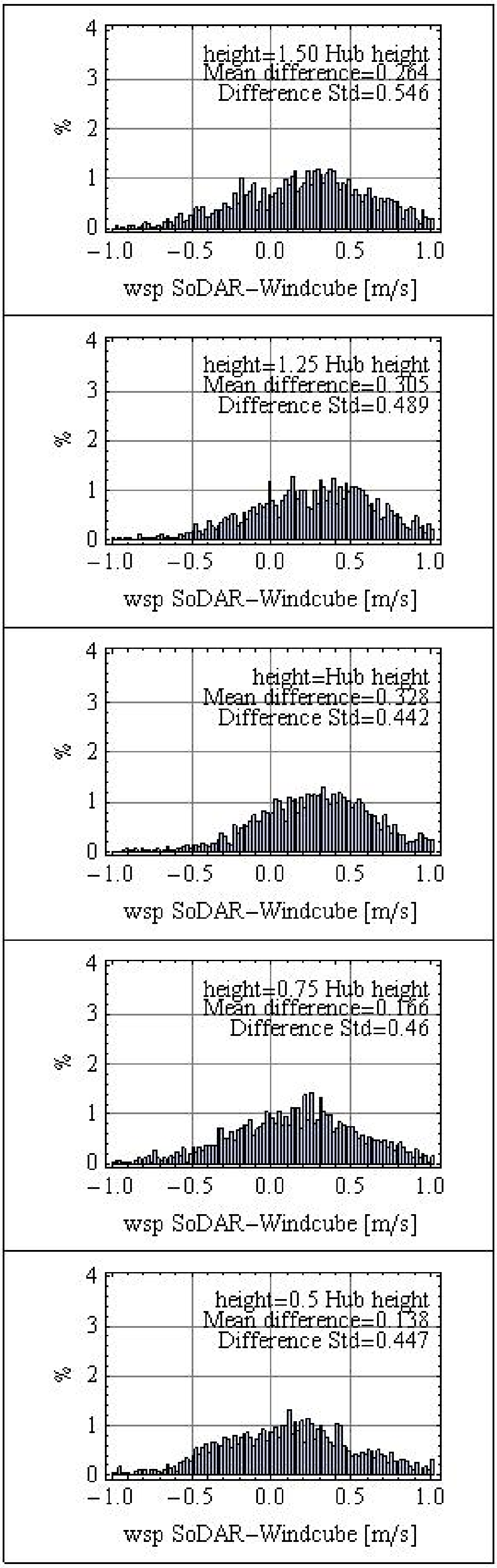

Figure 10.b *Distribution of differences of wind speed measured at various heights by the SoDAR and the Windcube during the measurement campaign (spring 2008)*

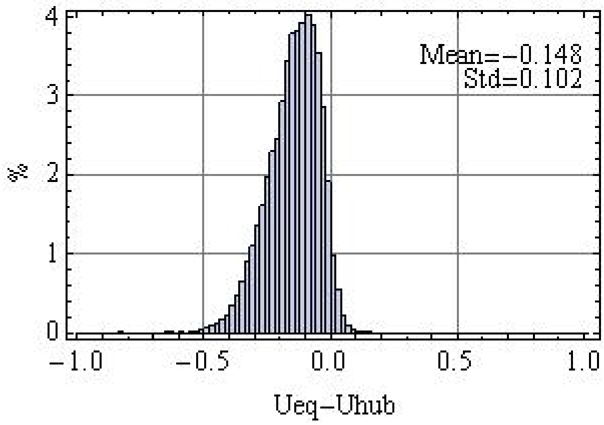

Figure 11 *Distribution of difference between the equivalent wind speed and the wind speed at hub height for an imaginary wind turbine of hub height 80m and rotor diameter 100m.*

In order to get an idea of the range of magnitude we are dealing with when calculating the equivalent wind speed, Figure 11 displays the distribution of the difference between the equivalent wind speed and the wind speed at hub height. The equivalent wind speed was calculated from wind speed profiles measured by the met. mast at Høvsøre instrumented with cup anemometers at 40m, 60m, 80m, 100m, 116.5m. To define a weight in order to apply the equivalent wind speed defined in (1), we imagine a wind turbine of hub height 80m and rotor diameter 100m.

This shows that the difference between the two kinds of wind speed is within a range of 0.5m/s, with a mean value of -0.148 m/s. Therefore, the wind speed profile measurements must be very accurate. The SoDAR seems then to be ill suited for this purpose and that is why we focus on LiDAR measurement in the rest of this report.

5 LiDAR profile measurements

5.1 Wind speed profile measurements

5.1.1 Necessity to measure above hub height

One could think that two wind speed measurements below or at hub height would be sufficient to evaluate the wind shear seen by the wind turbine. Indeed, it is then easy to reproduce a whole profile by fitting the two values to a model. The power law profile for example enables us to represent different wind shear with an exponent:

$$U(z) = U_r \left(\frac{z}{z_r} \right)^{\alpha} \quad (2)$$

where U is the wind speed, z the altitude, z_r a reference altitude and $U_r = U(z_r)$, and α the shear exponent. This procedure was applied to profiles measured by the high met. mast located at the south of the test site (see [6] for more details) with $z_r = 80m$ and $z = 40m$ to determine α. For some cases, this model fits the measured profile very well, but it cannot represent all kinds of profiles observed in Høvsøre. Figure 12 shows two examples of measured profiles and their corresponding modelled profiles.

The distribution of the error made by such an approximation is shown in Figure 13. We define the error as the difference of wind speed at 116.5m (top of the mast) estimated by the power law model and measured by the cup anemometer. Over a year of measurements, for a large wind sector 60 to 300 degrees (with predominant wind from west), 7% of the profiles show a wind speed error at 116.5m bigger than 10%. However we should keep in mind that all the anemometers are mounted on a boom except the top anemometer, and this can induce an error in the profile extrapolation to the top (116.5m).

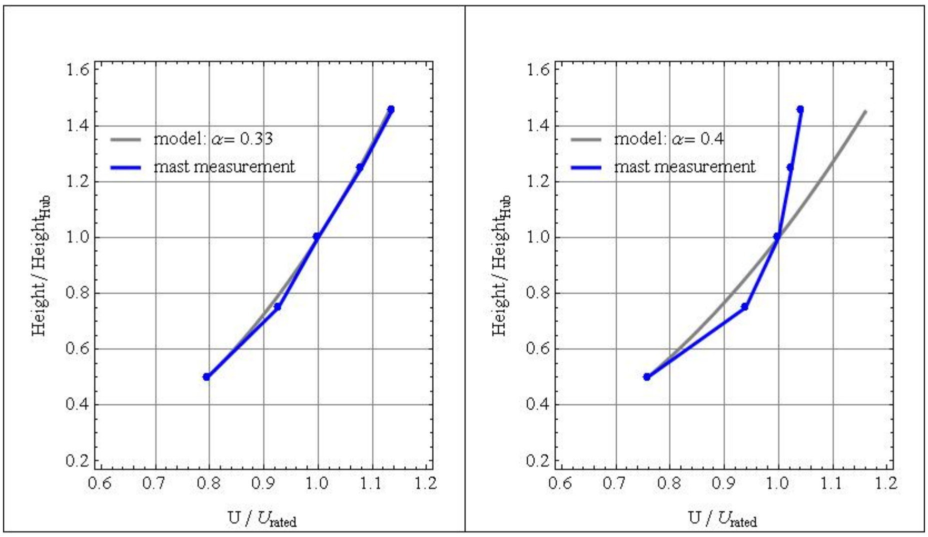

Figure 12 *Two examples of profiles and their fit to the power law model (using the wind speed values at 40m and 80m). The model fits very well the measured profile on the left, but it does not work for the profile on the right.*

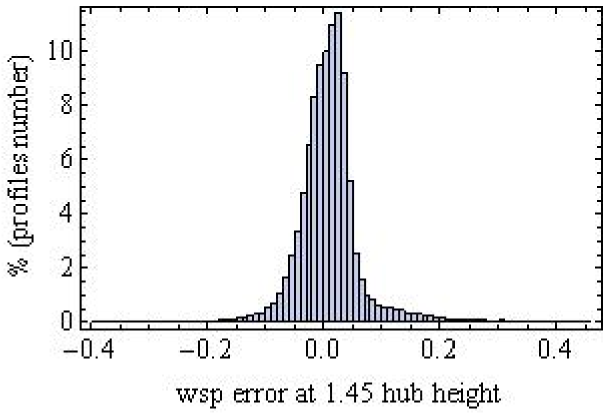

Figure 13 *Distribution of the error made on the wind speed at 116.5m height when assuming a power law profile with a shear exponent estimated with the wind speeds at 40m and 80m.*

As shown by the simulations presented in section 2, such an error in the wind speed profile can significantly affect the power curve. Therefore it is important to measure the wind speeds at several heights below and above hub height. This is where LiDARs become very interesting as they can measure up to 150m with a rather good degree of accuracy. LiDAR measured profiles are discussed below.

5.1.2 Wind speed profiles measured by a LiDAR

LiDAR measurements at a given height are generally not exactly equal to cup measurements at the same height. It is important to realise that a LiDAR measurement will always be different from a cup measurement because a LiDAR measures over a volume whereas a cup anemometer makes a point measurement. However over flat terrain such as at Høvsøre, it is fair to assume that the flow at a given height is horizontally homogeneous. We therefore expect LiDAR measurements to be in close agreement with a cup anemometer measurement. On the other hand, the LiDAR technology is still quite recent and a comparison to a cup anemometer can show some error such as the bad regression slope we observed for the ZephIR LiDAR (see Figure 5) and the non-linear error observed for the Windcube (see Figure 6). This can directly affect the power curve measurements; it is particularly obvious in Figure 15.a, top.

As we want to observe the relative uncertainty reduction when using an equivalent wind speed compared to the use of the wind speed at hub height, we would like not to get any interference of the possible LiDAR measurement error. A suggestion to take care of this eventuality is to use the LiDAR as a relative instrument together with a cup anemometer at hub height, considered as an absolute instrument. For each ten minutes average measurement, the wind profile measured by the LiDAR is shifted so the hub height wind speed from the LiDAR is equal to the cup measurement, see Figure 14.

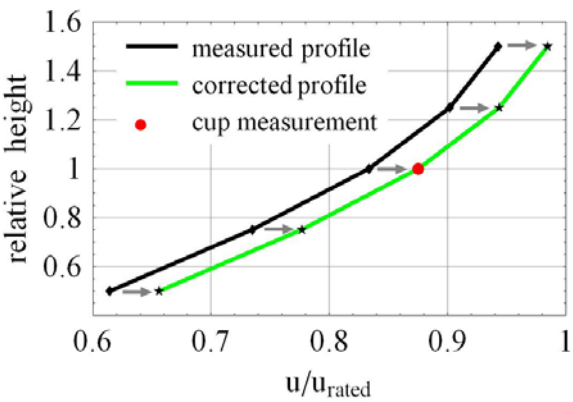

Figure 14 *The profile measured by the LiDAR is shifted so that the wind speed at hub height (relative height = 1) is the same as the one measured by the cup anemometer.*

5.2 Comparison of power curve measurement with IEC standards method and equivalent wind speed method

As we said before, the LiDAR systems used for this experiment were not operating during the same time periods. The overlapping period of time is rather short and does not give enough data to be statistically reliable. Therefore an intercomparison of measurements from the two LiDARs was not possible. Below, we present the results from two different datasets: one where the wind speed is measured with the ZephIR LiDAR and the power from turbine A (dataset 1) and the other one where the wind speed was measured by the Windcube LiDAR and the power from turbine B (dataset 2). All the results are compared to measurements obtained with a cup anemometer (cup A for dataset 1 and cup B for dataset 2).

For both datasets we show the results we obtain with direct measurements and with measurements corrected as described in 5.1.2. In both cases the power curve measurements obtained with a cup anemometer are displayed in blue as a reference (current standard procedure) for comparison purpose. Cup anemometer measurements are not affected by the profile correction. Then results obtained with LiDAR measurements at hub height are shown in red. Note that when we corrected the wind speed profiles as described in section 5.1.2, the wind speed of the LiDAR at hub height is the same as the wind speed measured by the cup anemometer. Therefore, in the power curve plot obtained with shifted profiles (Figures 15.b and 16.b), the LiDAR hub-height speed (red) lies exactly over the cup anemometer speed (blue). Finally results obtained with the equivalent wind speed are shown in green. The equivalent wind speed is calculated with the wind speed profiles measured by the LiDAR, un-shifted profiles in Figures 15.a and 16.a, shifted profiles in Figures 15.b and 16.b.

We observe that the results qualitatively agree with the simulations as the mean curve is slightly shifted to the left. Indeed, most of the profiles are not linear and present a smaller wind speed and a larger shear below hub than above. Consequently the equivalent wind speed is lower than the wind speed at hub height. Besides, for nose profiles, the equivalent wind speed is obviously smaller than the wind speed at hub height.

5.2.1 Results for dataset 1

This dataset combines the wind speed measured by the ZephIR LiDAR and the power produced by wind turbine A. It contains rather few data because the ZephIR system was available only for 6 weeks during that experiment, the data availability is consequently reduced by the screening on cloud height (see 4.1). Moreover the turbine setup was modified during these 6 weeks. We removed the data which were obviously obtained for a different set up. However the lack of information about the wind turbine testing by the manufacturer during our measurement campaign does not allow us to be completely sure about the constancy of the setup for the dataset shown here. The rather unusual shape of the power scatter plot obtained with cup anemometer (top of Figure 15.a, blue) increases the doubt about the constancy of the turbine settings.

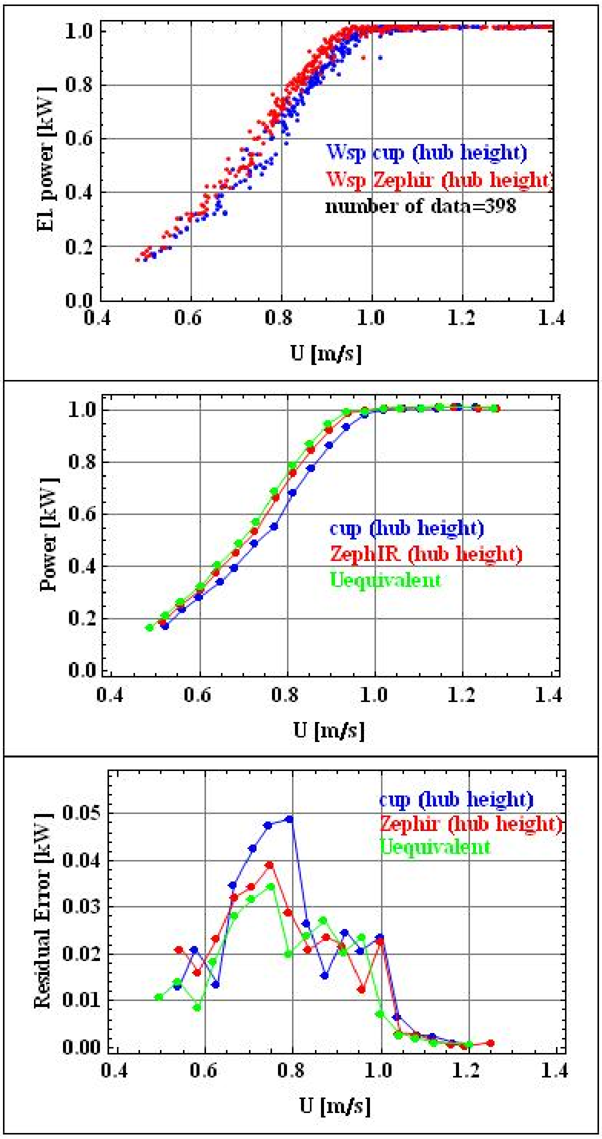

Figure 15.a *Turbine A _ ZephIR LiDAR without correction. From top to bottom: a) power curve scatter plot obtained with the cup and the LiDAR wind speed measurement at hub height; b) mean power curve obtained with the cup anemometer, the LiDAR at hub height and the equivalent wind speed; c)mean residual error per wind speed bin.*

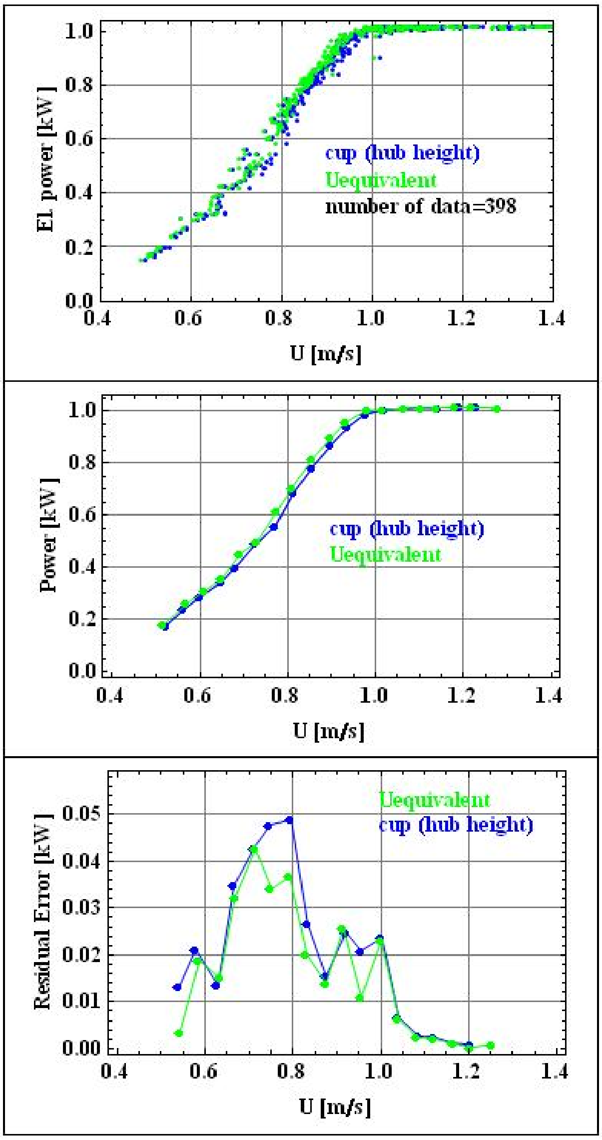

Figure 15.b *Turbine A _ ZephIR LiDAR with correction. From top to bottom: a) power curve scatter plot obtained with the cup anemometer and the equivalent wind speed after correction of the LiDAR profiles; b) mean power curve obtained with the cup and the equivalent wind speed; c)mean residual error per wind speed bin.*

Figure 15.a , top, shows the scatter plot of the power curve measured with the cup anemometer A (in blue) and with the ZephIR LiDAR at hub height (in red). The influence of the LiDAR error on the power curve measurement is very clear: the underestimation of the wind speed by the LiDAR shifts the power curve to the left. The bottom of Figure15.a shows that there is less scatter in the power curve measured by the LiDAR at hub height (in red) than in the power curve measured by the cup anemometer (in blue), especially around 0.75 u_rated, where cup anemometer the power curve scatter plot shows some erratic behaviour. Furthermore, the equivalent wind speed results (in green) show a small decrease of the scatter compared to the results from the LiDAR at hub height. Figure15.b shows the power curve results obtained with the cup anemometer (in blue _ same as Figure15.a) and the equivalent wind speed obtained with shifted wind speed profiles (in green). Our correction reduced the distance between the power curves due to the LiDAR error.

5.2.2 Results for dataset 2

This dataset combines the wind speed measured by the Windcube LiDAR and the power produced by wind turbine B. Results for this dataset are shown in Figure 16.

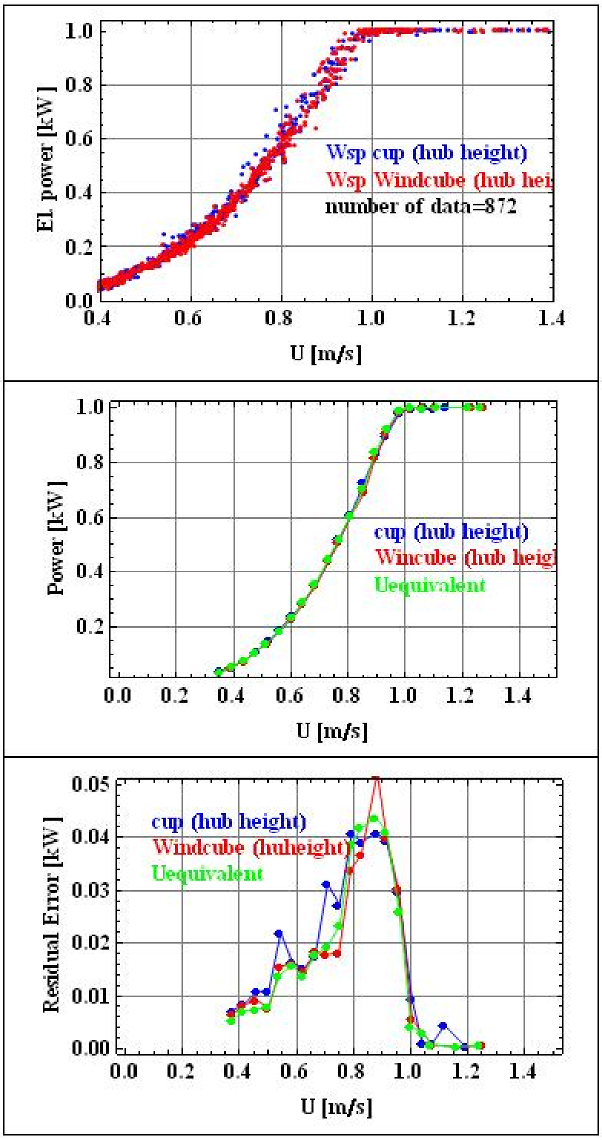

Figure 16.a *Turbine B _Windcube LiDAR without correction. From top to bottom: a) power curve scatter plot obtained with the cup and the LiDAR wind speed measurement at hub height; b) mean power curve obtained with the cup anemometer, the LiDAR at hub height and the equivalent wind speed; c)mean residual error per wind speed bin.*

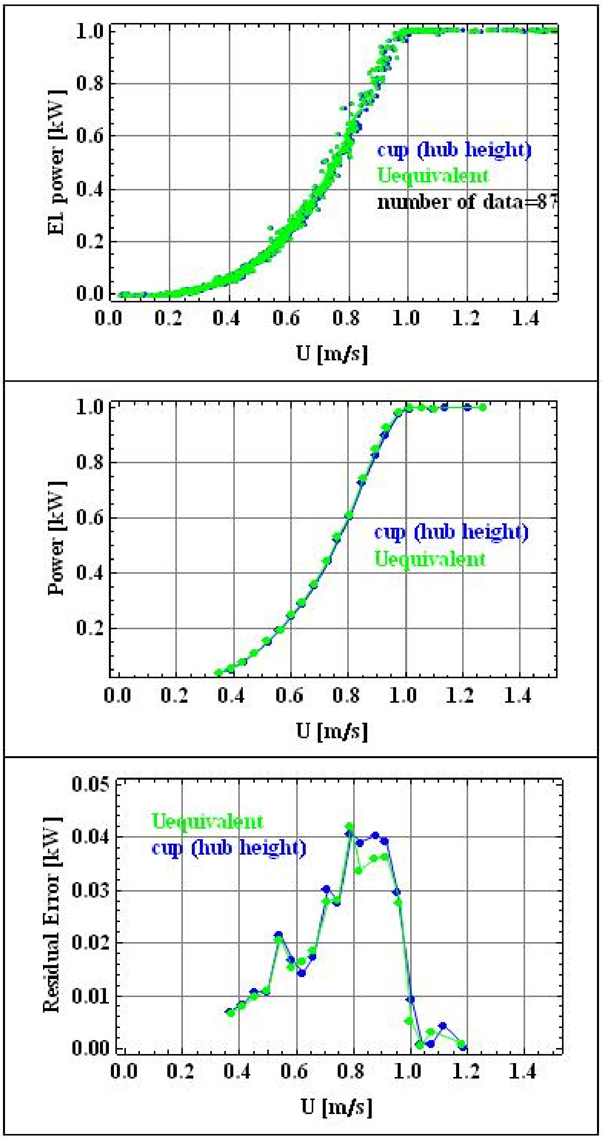

Figure 16.b *Turbine B _ Windcube LiDAR with correction. From top to bottom: a) power curve scatter plot obtained with the cup anemometer and the equivalent wind speed after correction of the LiDAR profiles; b) mean power curve obtained with the cup and the equivalent wind speed; c)mean residual error per wind speed bin.*

For this dataset, the error due to the LiDAR is not that obvious in the power curve plot (see Figure 16.a, top). We applied the wind profile correction anyway in order to be fair and analyse both datasets in the same way.

In the top of Figure 16.a, we can observe some outliers, when the power curve is measured with the cup anemometer (in blue), which do not appear in the datasets where the power curve is measured with the Windcube at hub height (in red). Further investigations showed that these outliers were appearing only for winds coming from North-West, see Figure 17. These outliers are probably the reason for the maximum peaks observed in the residual error plot both for the cup anemometer measurements and the LiDAR measurements at hub height (bottom of Figure 16.a).

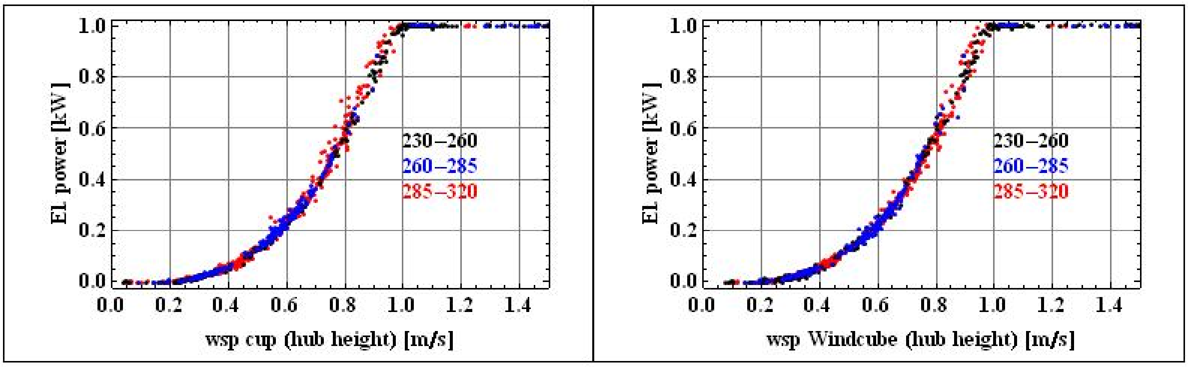

Figure 17 *Power curve scatter plot obtained with wind speeds measured at hub height with the cup anemometer (on the left plot), with the Windcube LiDAR (on the right plot). In both plots the points have been colored according the wind direction sector*

6 Discussion

6.1 Effect of wind profiles on large wind turbine power curve measurement

According to the aerodynamic simulations, profile measurements combined into an area-weighted equivalent wind speed can reduce the scatter in the power curve measurement. The power law profile cannot represent every profile encountered by a wind turbine even in flat terrain. That is why it is important to measure the wind speed in front of the turbine at several heights; not only below hub height but also above. Therefore remote sensing technology presents a great interest for that application.

6.2 SoDAR versus LiDAR

The standard deviation of the error of the AQ500 SoDAR used in this campaign are much larger than the Windcube LiDAR error in spite of the “bump” problem experienced by the Windcube during the campaign. The change in space resolution of the SoDAR measurement did not show any improvement. Within the Upwind WP6 EU project and the Danish EFP IMPER project, the AQ500 SoDAR has been tested against a met. Mast [7]. Intercomparison of wind speed measurements of this AQ500 SoDAR (which was already located at the same place as during this experiment) with cup anemometer measurements showed results very similar to those presented in this report: a rather good correlation slope but very broad scatter.

The large standard deviation of SoDAR error is observed at every height resulting in a general distortion of the profiles (zigzag around the Windcube profiles). As the mean SoDAR error is rather small (same as the Windcube LiDAR), the mean power curve obtained with a SoDAR measurements at hub height is very close to the mean power curve obtained with a cup anemometer LiDAR measurements at hub height. However the purpose of the work presented in this report is to investigate the reduction of the scatter in the power curve by using an equivalent wind speed. Therefore, the profiles measured by the AQ500 SoDAR were found to be unreliable and not suitable for equivalent wind speed calculation. It may be fair though to specify that the system used for the experiment includes versions of the software and hardware from 2005. SoDAR systems have probably evolved since then, but we did not have any opportunity to observe other SoDAR measurements. Fundamental differences in sampling rate and the extent of beam spreading makes it unlikely that a SoDAR will ever be able to provide sufficiently scatter free measurements to be appropriate for an equivalent wind speed without introducing more uncertainty than we are removing. Therefore we then focused on the LiDAR measurements.

6.3 Power curve measurement with LiDAR

The use of an equivalent wind speed as defined by equation (1) resulted in a small reduction of the scatter in the power curve in dataset 1 and no noticeable reduction in dataset 2 (regarding the un-shifted data). We suggested a profile correction, in an attempt to simplify the comparison of the cup anemometer measurement and the equivalent wind speed obtained from remote sensing measurements, but also in order to use the LiDAR as a relative instrument with a cup anemometer considered by the power performance measurement standards as the only absolute instrument. However the results, obtained after such a correction, are rather difficult to interpret, as a reduction in the scatter may then hide a result of the design of the experiment. For this reason, it is important to analyse the un-shifted data as well.

First of all, direct comparison of the remote sensing measurements to cup anemometer measurement at one height revealed a lot about the performance of the instruments. Both LiDARs used in this measurement campaign seemed to have some deficiencies. The ZephIR system showed a wind speed linear error larger than what is usually seen. Regarding the Windcube, a software problem created a non-linear wind speed dependant error. However this technology is evolving very fast and the Windcube software has been upgraded after the end of the campaign.

The power curve obtained with the un-shifted data revealed that the design of the experiment was not optimum. The remote sensing instruments were not located at the foot of the mast but at 100m and 150m away from the mast A and B respectively. The direction instrument-turbine was different from one instrument (for example: LiDAR) to another (for example: mast mounted with cup anemometer). According to the wind direction, the power curves measured by the two kinds of instruments presented different scatters. Indeed there might be a significant difference of wind speed between the mast location and the LiDAR location. If the wind direction was close to the direction defined by the mast and the wind turbine (West-East), the cup anemometer measurement was closer to the wind speed “seen” by the wind turbine than the LiDAR measurement and vice-versa if the wind direction was closer to the LiDAR-turbine direction (N.-W. – S.-E.). Moreover, in such a case, shifting the LiDAR profiles to coincide with the cup measurement might introduce larger scatter in the points, transferring possible cup anemometer de-correlation to the LiDAR dataset.

Another factor which must be taken into account is that measurements were limited to the westerly wind (to avoid turbines wake) and were for a few months only (because of wind speed and power measurements availability) whereas the profiles used for the input of the simulations were selected from a complete year of measurements from the east sector. The east (land) sector presents more variation in the wind shear than the sea sector. Most of the profiles measured during this campaign were logarithmic or close to a power law profile. For such profiles, the difference between the equivalent wind speed and the hub height wind speed is largely unaffected by the shear exponent The shape of the profile has more effect: it is usually wind speed profiles with a shape different from a power law profile that give unexpected power outputs and also a larger difference between equivalent and hub height wind speeds. Therefore the reduction observed was smaller than predicted from the simulations results.

We must note that both datasets were rather small considering the time the measurement campaign lasted. Indeed the restriction to westerly winds and the consistency of the turbine setup (as well as its normal operation) reduced significantly the number of data available for the analysis.

Although this experiment did not allow us to really conclude about the possibility of improving the power curve measurement with a LiDAR, we learned a lot from it. This enabled us to plan a new measurement for winter 2008/2009. This will focus on the power curve measurement of one multi-megawatt wind turbine. Two upgraded (no more non-linear wind speed dependant error) Windcube systems will be used simultaneously: one will be positioned at the foot of the mast west to the turbine (mast mounted with a cup anemometer at hub height, fulfilling the requirement of the IEC standards for power curve measurements); the second Windcube will be placed at the foot of the met. mast mounted with several cup and sonic anemometers at different heights, positioned to the south of the turbine, see Figure 18. Therefore we will be able to measure the power curve as required by the standards, compare the LiDAR profiles to a mast profiles, compare the profile from one location to the other, calculate an equivalent wind speed based on LiDAR profile measurements and analyse the stability conditions. Moreover this setup allows a larger wind sector, therefore more data and greater variety of wind profiles.

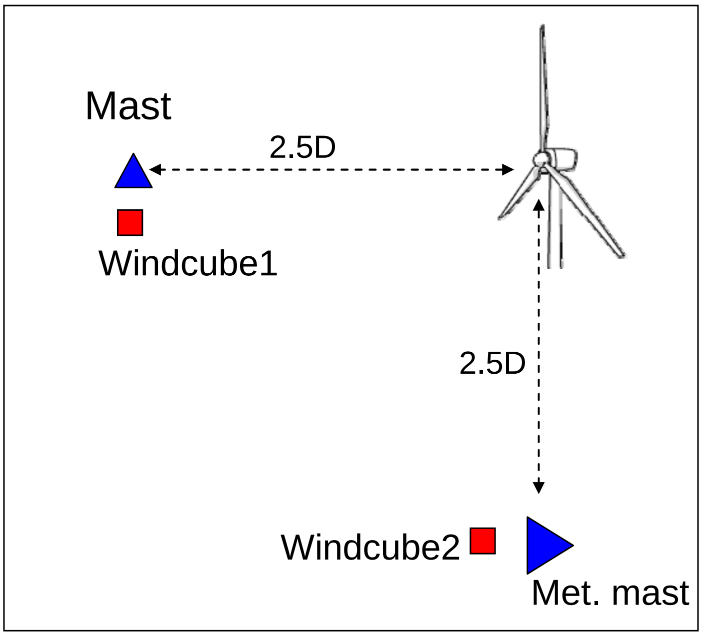

***Figure 18** Future measurement campaign focused on the power performance of one multi-MW wind turbine implying two Windcube LiDARs.*

Furthermore, in this investigation, each LiDAR system has been used as a relative instrument together with a calibrated cup anemometer, because the objective was to show the necessity of measuring profile instead of wind speed at hub height, and, for now, only the cup anemometer is considered as an absolute instrument. However LiDARs are expected to be used on their own at some point. In order to make this realizable, more research is being undertaken to fully understand the differences between a wind speed measurement from a cup anemometer and a measurement from a LiDAR [8]. Indeed, this difference is not necessarily an error from the remote sensing instrument. We must keep in mind that they measure over a volume whereas a cup anemometer measures at one point. The probe or pulse length, according to the system, implies a weighted average in the vertical direction, which is therefore influenced by the wind shear and the turbulence as well. This could actually be better for power curve measurement purposes since this volume averaged wind speed might be more representative of the wind speed over a rotor segment area A_i than the wind speed measured at a point in the centre of the segment.

7 Conclusions

Aerodynamic simulations have shown that wind turbine power production is influenced by the wind shear. The use of an equivalent wind speed, taking the wind shear into account, can reduce the fluctuation in power when plotting the power as function of this speed. Remote sensing instruments have the advantage of being able to measure wind speed profiles up to the upper tip.

The measurement campaign results did not enable us to make very strong statement about the improvement of power curve measurement using remote sensing instruments. However it enabled us to learn many things that should be carefully considered when investigating power curve measurement with remote sensing:

1- Power performance verification requires very accurate measurements. The SoDAR used during our experiment did not meet this requirement and it did not make sense to use the SoDAR measurements to estimate a wind speed average over the swept rotor area. On the contrary, the accuracy of LiDAR systems has been increasing very fast during the last 3 years. Therefore LiDAR can be considered as good candidates for future power curve measurements and their evolution should be followed with much attention.

2- However, the LiDAR technology is still recent and therefore a comparison to a met mast measurement is still required before using a LiDAR for power curve measurements (new error source inherent to the system may be discovered).

3- Comparing power curve measurement resulting from LiDAR measurements to the result obtained with a cup anemometer must be done carefully keeping in mind that the spatial correlation decreases with distance between the instruments. The comparison will be all the better that the instruments are positioned close to each other.

4- Although the cup anemometer only is accepted as a stand-alone instrument and it should be used as a reference for comparison, a correction of the LiDAR measurement to match the cup is not always a good solution.

5- Test turbines are used for many different testing purposes and we must be sure that the turbine set up remains the same during the power curve measurement and for long enough to get the minimum number of data required.

Although we saw no significant reduction in the power curve scatter when using the equivalent wind speed, the conventional and the equivalent wind speed power curves were at least as good as each other. This is what we would expect and desire for the power law and logarithmic (‘well behaved’) profiles that have dominated during the measuring campaign. We clearly require a further measurement campaign with an improved set up and improved remote sensing instruments, placed in a period of the year when we can expect more challenging profiles. Only then can we clearly demonstrate whether the equivalent wind speed reduces the power curve scatter as we hope. This campaign is currently underway.

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