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Some studies of simultaneous measurements from side-by-side lidars

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Abstract:
Most testing of lidars occurs by comparing a single instrument with simultaneous measurements from a conventional meteorological tower close by. Lidars operating side-by-side can reveal useful information to supplement the mast data. We can directly test how nominally identical lidars measure the same wind and thereby achieve a better understanding of where the mast-lidar differences lie. Differences in measuring characteristics between two identical lidars can give an excellent indication of the maturity of the technology. Comparisons involving two different lidar designs can also be performed, telling us much about the relative benefits of the different concepts.

In this report, we examine three case studies involving the two prominent, commercially available lidars; the ZephIR and the Windcube. All three possible combinations (ZephIR-ZephIR, ZephIR-Windcube and Windcube-Windcube) are examined. The data are from periods spanning well over one year and during this time a considerable development has taken place and is still underway. We feel that it is inappropriate to perform detailed analyses of technically redundant data. Instead we have tried to draw attention to some of the underlying features.

Contents

STATUS, CONFIDENTIALITY AND ACCESSIBILITY							
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PL: *Project leader* **WPL:** *Work package leader* **TL:** *Task leader*

1. Introduction

Lidars are set to play an important role in the wind energy industry. As wind turbine sizes increase, the benefits of using lidars to replace conventional, mast based wind measurements become stronger. There are essentially two main arguments; eliminating expensive and logistically challenging mast structures on the one hand and providing more detailed and higher-reaching wind profile information on the other. The latter benefit enables us to move away from the simplistic paradigm of representing the wind turbine power (or wind resource) as a function of the hub-height wind speed only.

The first commercially available lidar profiler, the QinetiQ ZephIR ™, appeared on the market at the start of 2006. This is a constant wave, focused lidar. A year later the ZephIR was followed onto the market by the Leosphere WindCube ™, a radically different device based on pulsed laser technology. A description and comparison of these two devices can be found in [1] (Courtney, EWEC 2008). Extensive testing of both these systems has occurred within the context of the Upwind project (Work Package 6), notably at The Test Station for Large Wind Turbines, Høvsøre on the west coast of Denmark [2] (Courtney ISARS 2008).

An important task in the introduction of a new measuring technology is inter-comparisons with both existing measuring techniques and inter-comparisons amongst the new devices. This report is concerned more with the latter – inter-comparison of both nominally identical devices (e.g. two ZephIR's measuring simultaneously) and comparison of two different lidar devices (ZephIR and WindCube measuring simultaneously).

By looking at data from two supposedly identical devices, in particular by looking at the similarities and correlations of the errors in relation to mast measurements, we can gain a better understanding of the applicability and maturity of the new technology. This will give an idea about how repeatable two versions of the same device really are and therefore how much 'calibration' of individual systems is necessary. In the case of perfect repeatability, it would only be necessary to measure one example of a given design. Due to manufacturing differences and component tolerances, this will probably not be the case in practice.

With large differences in the measuring principles of the two currently available lidars, we do not expect them to perform identically in different meteorological conditions. For example, differences in the probe lengths at a given height will result in different wind speed observations in most wind shear cases (anything other than constant or linear variation). We will examine simultaneous ZephIR and WindCube measurements in order to gain an impression of the similarities and differences in relation to conventional mast measurements. Since significant modifications are still being regularly made to both designs, we will not be too exhaustive in this analysis since much of the relevance is probably only short-lived.

This report continues with sections describing the Høvsøre test facility and each of the lidar devices (ZephIR and WindCube). We then proceed to study 3 cases; a WindCube/WindCube inter-comparison, a ZephIR/ZephIR inter-comparison and finally a comparison of ZephIR and WindCube. In the Discussion section, we extract the lessons and implications of the data, reiterating the salient points in a Conclusion.

2. The Høvsøre test facility

In order to support the wind turbine industry and as a research venue for wind energy, Risø DTU has established the Test Station for Large Wind Turbines at Høvsøre in western Jutland, Denmark (Figures 1 and 2). This facility comprises a line of five test stands for MW class wind turbines, each stand with its dedicated upstream (westerly) measuring mast. Two technicians are permanently stationed at Høvøre in order to service the copious instrumentation and to assist with other research and development activities. There is excellent infrastructure including network over the entire site, offices, a workshop and meeting rooms.

The line of test stands is orientated N-S, parallel to the coastline and about 1.5km from the sea. At the southern end of the line, 200m from the closest wind turbine, there is an intensively instrumented meteorological mast (it can be seen in Google Earth at position 56.441045N, 8.150787E). It has a top-mounted anemometer at 116.5m and measuring stations with both cup and 3-D ultrasonic anemometers at 100m, 80m, 60m and 40m. The purpose of this mast is to supplement the wind measurements at the turbine test stands, to provide additional information about the climatology at Høvsøre and as a source of meteorological data for boundary layer research. The quality of the instrumentation is high both in terms of the mounting (< 1% flow distortion for dominant wind directions) and in respect of the sensor maintenance. Cup anemometers (Risø class 1 classification) are regularly exchanged for re-calibrated units and a rigorous QC is implemented.

Due to its height, intensity of instrumentation and high data quality, this mast is well suited for testing lidar profilers. Since there is no problem with backscatter from the mast structure (unlike fixed-echo problems with sodar testing), it is possible and indeed advantageous to place the profilers close to or directly beside the mast and thus improve the accuracy of the comparison. Wind speed measurements at 160m height (both cup and ultrasonic anemometers) are also available from a light beacon mast, some 300m north of the meteorological mast.

Høvsøre is located in very flat terrain but with somewhat inhomogeneous roughness. To the south is the lagoon ‘Nissum Fjord’, at the closest point, only 900m from the meteorological mast and 1.8 km to the west, the North Sea, separated from the land by a strip of sand dunes 10-20m high. The most homogeneous fetch is from the east – mostly open farmland. The presence of the five wind turbines to the north of the meteorological mast precludes testing with wind from the northerly sectors. Indeed, it is important to be constantly aware of the measuring volumes of the profilers and how these might be influenced by the inflow or wakes of the wind turbines or the mast itself. Most lidar testing makes use of wind from the sector 200-300 degrees. Wind from these directions is unaffected by the wind turbines, can be measured by the mast-mounted cup anemometers with less than 1% flow distortion and importantly, are very common.

In order to test remote sensing profilers in the context of power performance measurements, a test pad has been established between and upstream of two of the wind turbines at the test station. Here it is possible to place lidar and sodar profilers at distances from the wind turbines typical for power performance testing. Measurements from the profilers can be related both to the measured turbine electrical power and to the conventional mast-mounted cup and sonic anemometer measurements.

Figure 1The Høvsøre Test Station as seen from Google Earth. The distance from the met mast to the coast to the west is 1.8 km. The site's UTM coordinates are 56.441045 N, 8.150787

Figure 2 The row of wind turbines at Høvsøre with the 116.5m meteorological tower in the foreground. The picture is taken from a low flying aircraft to the south-west of the mast..

3. Commercial lidar profilers

3.1 The QinetiQ ZephiR

After several prototype versions, one of which had previously been tested at Høvsøre [3], the English company QinetiQ presented the first commercial lidar profiler at the beginning of 2006. Known as the 'ZephiR', this is a continuous wave system with height discrimination achieved by varying focus. Five different sensing heights can be chosen. Each height is scanned for 3 seconds before the lidar re-focuses to the next height in the sequence. Figure 3 shows a ZephIR on test at the Høvsøre test facility.

The laser light is emitted through a constantly rotating prism giving a deflection of 30 degrees from the vertical and making one complete rotation per second. Backscattered light mixed with the local oscillator is sampled at 100MHz. The unit is able to transform blocks of 512 time series scans to power spectra in real time. The 200000 spectra per second are block-averaged 4000 at a time to give highly noise-suppressed Doppler shifted spectra at 50Hz. A centroid method is used to obtain the frequency of the 'peak', the radial speed (i.e. in the laser beam direction) being directly proportional to this frequency. Thus 50 radial velocities, one for every 360/50=7.2 degrees are available from each rotation.

Unlike pulsed systems, constant-wave lidar systems do not inherently 'know' the height from which backscatter is being received. We are obliged to assume (or rather, hope for) a sensibly flat vertical profile of aerosol concentration, in which case the backscattered energy is from the focused volume, weighted according to the appropriate Lorentzian function centered at the focus distance [4]. The obtained radial wind speed distribution in this case is dominated by the signal from the set focus distance.

The assumption of vertical aerosol homogeneity unfortunately fails completely in the fairly common case of low level clouds (under 1500m). Here, the relatively huge backscatter from the cloud base can be detected even though the cloud is far above the focus distance. The resulting Doppler spectrum has two distributions – one corresponding to the radial speed at the focused height and a second corresponding to the (usually) higher speed of the cloud base. Unless corrected for, this will introduce a bias to the wind speed measurement. For this reason, the ZephiR has a cloud-correction algorithm. An extra three second scan at 300m is inserted into the height cycle. The spectra measured at 300m are used in an attempt to remove the influence of the clouds at the desired measuring heights.

Since the ZephIR does not apply a frequency offset to the Doppler shift, it is not possible to determine the direction of the radial velocities. This fact introduces an ambiguity in the polarity of the parameter pair wind direction and vertical velocity. For this reason, the ZephiR independently senses the wind direction using a sensor mounted on a short mast fixed to the top of the lidar. Assuming that the lowest remotely-sensed wind direction will be closest to the directly-sensed value immediately above the lidar, the ambiguity is resolved for the direction and hence also for the vertical speed.

Figure 3 A ZephIR lidar on test 40m from the meteorological mast.

3.2 The Leosphere Windcube pulsed lidar.

With the recent (December 2006) introduction of the French company Leosphere's 'Windcube', there are now two contrasting lidar profilers on the market. The Windcube, shown in Figure 4, is a pulsed lidar with a fixed focus. Like the ZephiR, it has a 30 degree prism to deflect the beam from the vertical but here the prism does not rotate continuously. Instead, the prism holds still whilst the lidar sends a stream of pulses (5000-10000) in a given direction, recording the backscatter in a number of range gates (fixed time delays) triggered by the end of each pulse. Having sent the required number of pulses, the prism rotates to the next azimuth angle to be scanned, each separated by 90 degrees. A full rotation takes about 6 seconds.

During the rotation and before the next stream of pulses can be sent, the recorded data are processed. For each range gate, the time series from each pulse are Fourier transformed to power spectra which are block-averaged. Due to the short recording duration (200 ns), the resulting spectra have poor frequency resolution. Instead of using a centroid to obtain the frequency of the peak, Leosphere have developed a mathematical model [5] including the most important parameters affecting the shape of the expected Doppler spectrum. This model is fitted to each block-averaged power spectrum in order to obtain the Doppler shift to a much higher resolution than could otherwise be expected. At each direction step, the Windcube combines the four most recent radial speeds at each height in order to obtain the horizontal and vertical speed and wind direction.

In contrast to the ZephiR, the Windcube uses an acousto-optic modulator (AOM) to add a precise frequency offset to the local oscillator which is mixed to and beats with the returning Doppler shifted backscatter. Backscatter from a fixed target, introducing no Doppler shift, appears shifted in the resulting power spectrum. Thus the polarity of the radial velocity is available and there is no ambiguity regarding the wind direction.

Figure 4 Four Leosphere Windcubes on simultaneous test at the base of the meteorological mast.

4. Results

4.1 Inter-comparison of two ZephIRs

In this section we will compare data from two ZephIR lidars operating simultaneously at the Høvsøre test station. Data are presented for the four week period 12 September 2007 to 8 October 2007. For this test, the lidars stood beside each other at the side of the road to the north of the 116m meteorological tower. The distance between the lidars and the mast was about 40m whilst the (centre) distance between the two lidars was about 2m.

Since sensitivity to cloud backscatter is a major issue for constant wave, focused lidars such as the ZephIR, a ceilometer (Vaisala CL31) was placed close to the two ZephIRs. This instrument continuously detects the cloud base height from the aerosol concentration profile.

We have chosen to present only the data measured at 116m since, because the cup anemometer at this height is top-pole mounted, the available measuring sector is much larger (60-300°). The complete set of filtering conditions are:

- Wind direction 60° – 300°
- Wind speeds > 4 m/s (as measured by the 116m cup anemometer)
- No rain
- ‘turbulence parameter’ < 0.1
- ‘points in fit' > 100
- For ‘no low cloud’, Cloud base > 1600m

4.2 Results for all cloud conditions

Scatter plots of lidar and cup anemometer speed, lidar error (lidar speed – cup speed) and histograms of the lidar error distribution are shown in Figure 1. This is for a dataset containing all cloud conditions. Data for the ZephIR unit 102 are shown in the left column, data for the ZephIR unit 103 on the right.

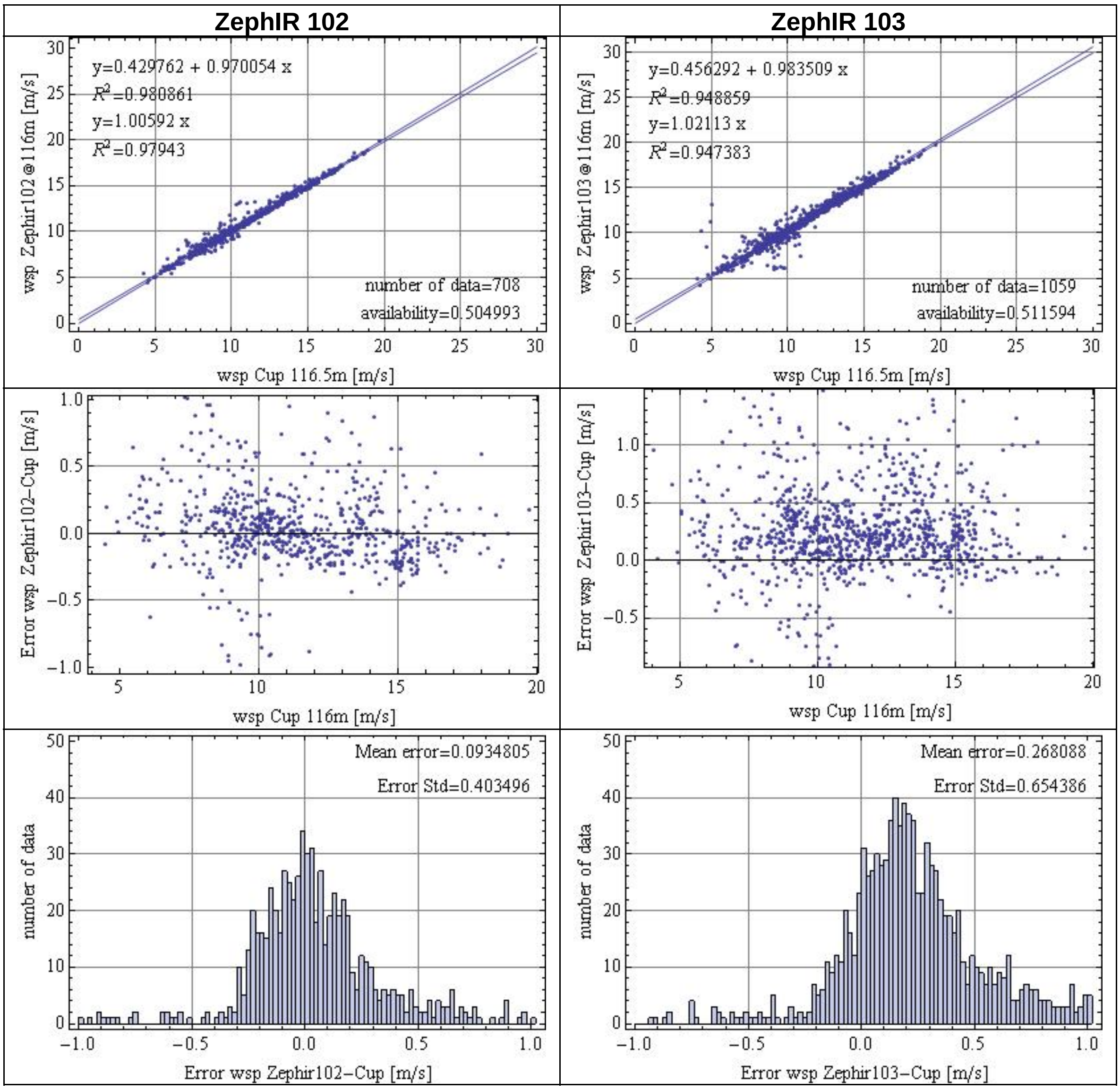

Figure 5 ZephIRs unit 102 (left) and unit 103 (right) vs cup anemometer windspeed at 80m (top row). Lidar error (lidar speed - cup speed) vs wind speed (middle row). Histogram of lidar errors (bottom row). All cloud conditions.

Results for periods without low clouds

Here we take a subset of the data shown in the previous section, namely those for periods without low clouds (cloud base > 1600m). Scatter plots of lidar and cup anemometer speed, lidar error (lidar speed – cup speed) and histograms of the lidar error distribution are shown in Figure 2. Data for the ZephIR unit 102 are shown in the left column, data for the ZephIR unit 103 in the right.

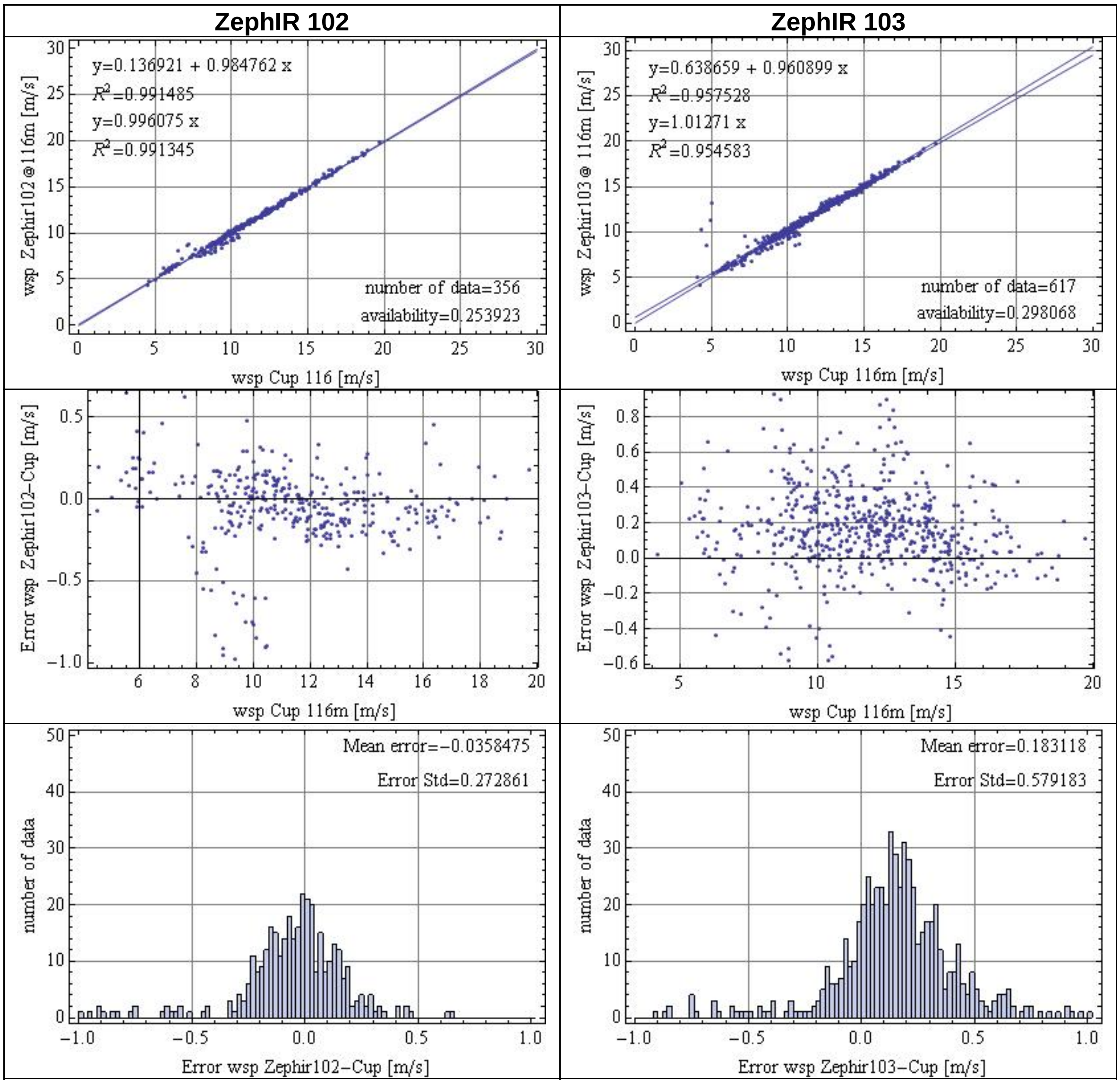

Figure 6 ZephIRs unit 102 (left) and unit 103 (right) vs cup anemometer windspeed at 80m (top row). Lidar error (lidar speed - cup speed) vs wind speed (middle row). Histogram of lidar errors (bottom row). High cloud only (cloud base > 1600m)

Correlation of lidar-lidar wind speeds and errors

Here (Figure 7) we present direct comparisons of the simultaneous wind speeds measured by the two ZephIRs. As before, we have chosen to study all cloud conditions first (the left column) and then only look at data for periods without low cloud (cloud base > 1600m). Underneath the scatter plot of lidar speed we have shown a scatter plot of the simultaneous speed error (lidar speed – cup speed) for each of the ZephIRs.

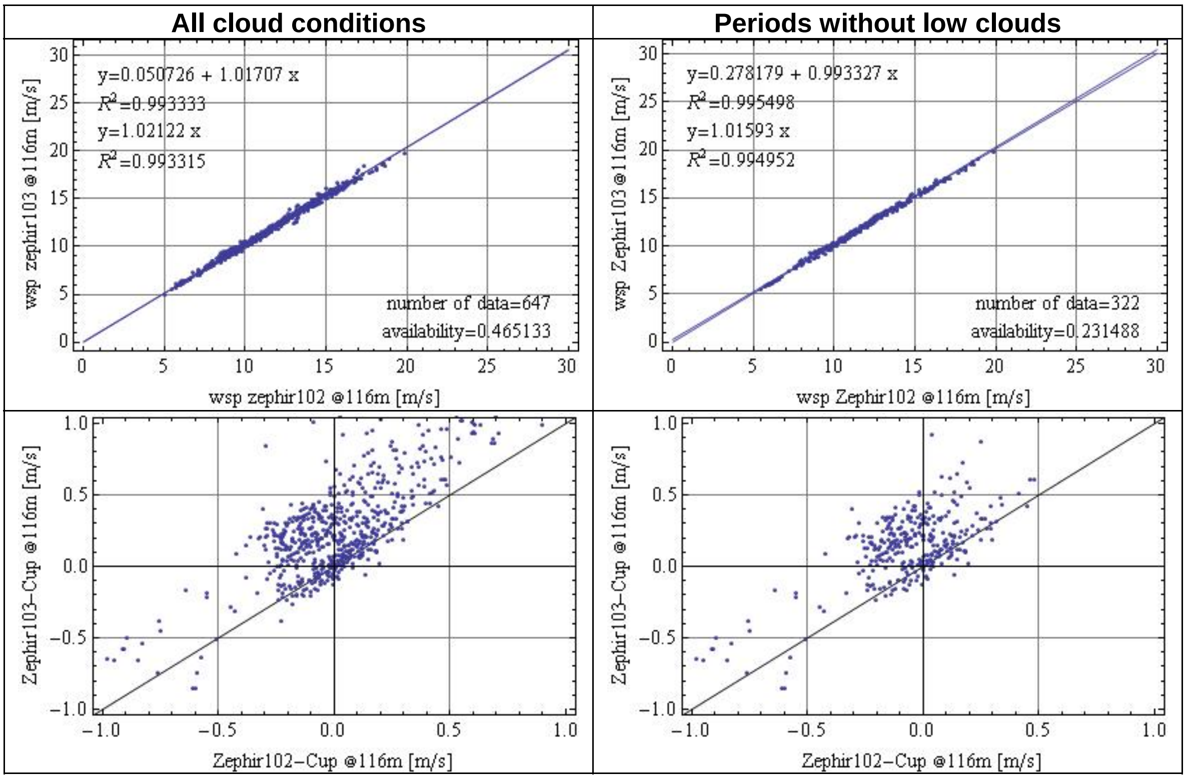

Figure 7 Scatter plots of simultaneous Zephir unit 102 and unit 103 wind speed (top row) and speed error (bottom row). The left column is for all cloud conditions, the right column is for periods without low clouds (cloud base > 1600m)

Discussion of ZephIR/ZephIR inter-comparison

Before removing periods with low clouds, the data from both ZephIRs is severely degraded, as seen in Figure 5. It appears that ZephIR 103 is worse affected than 102, this reflected in the larger mean and standard deviation of the lidar error. An explanation for the different cloud sensitivity between the two ZephIRs is probably to be found in different optical sensitivities.

The ZephIR can be operated with an internal cloud-correction algorithm. We have chosen not to bring cloud-corrected data here since the first version of this algorithm was found to negatively bias data in clear sky conditions and has now been updated.

Inspecting periods with no low level clouds (cloud base > 1600m), the performance of the two ZephIRs improves significantly (Figure 6). This again underlines perhaps the biggest drawback of the CW, focused design. Even with low clouds detected by the ceilometer removed, there are still periods when the ZephIR's apparently underestimate the wind speed significantly. Our suspicion is that these errors arise in conditions where there is a thin layer of mist beneath the measuring height. A thin mist layer at such a low height is not always detected by the ceilometer.

With the cloud degradation removed, it is easier to compare the relative performance of the two systems. It can be seen that there is a difference in regression slope (for the fit forced through zero) of about 1.5%. This difference was not atypical for different ZephIR systems at this time. Much of the slope differences have since been identified as due to variations from the ideal prism angle. Prisms are now individually measured and the actual rather than nominal value used in the internal software.

4.3 ZephIR and Windcube inter-comparison

Here we will look at data from a period during which a ZephIR (unit 107) and a Windcube (s/n 002) operated within a few metres of each other. The measurements took place at the Høvsøre Test Station, on a rented patch of ground midway between the upstream measurement masts for stands (wind turbine test pad) 2 and 3. We are concerned with a 3 week period from 25 February until 14 March 2008.

For this inter-comparison, the reference meteorological mast is the stand 2 mast, 150m to the north of the instruments. This mast is instrumented for power curve measurements on the wind turbine at stand2 which has a hub-height of 80m. For this reason, the highest cup anemometer on the mast is top-pole mounted at 80m and this is the reference instrument for this comparison. Note that the instrument-mast distance is considerably greater than for our normal measurements at the 116m meteorological mast and this will lead to lower lidar/cup correlations than we have previously seen.

During this campaign, the ZephIR is operating without cloud-correction. Data have been retrieved by streaming spectra directly to a local pc. The spectra are then loaded to a database and Risø DTU software used to extract the horizontal wind speed using an algorithm very close to that used by the ZephIR internally. The Windcube software was a version implemented before the speed-dependant non-linearity (the ‘Courtney bump’) was identified and removed.

For the data analysis we have excluded conditions known to affect the quality and integrity of the data. The filtering conditions we have used are:

- Wind directions from 240-320° (avoiding wind turbine wakes)
- Wind speeds > 4 m/s (as measured by the 80m cup anemometer)
- No rain
- For the Windcube, availability (per 10 min period) = 100%
- For the ZephIR, ‘turbulence parameter’ < 0.1 and ‘points in fit' > 100

All the data presented together with the values of the filtering parameters are 10 minute mean values.

Results for all cloud conditions

Scatter plots of lidar and cup anemometer speed, lidar error (lidar speed – cup speed) and histograms of the lidar error distribution are shown in Figure 1. This is for a dataset containing all cloud conditions. Data for the ZephIR are shown in the left column, data for the Windcube in the right.

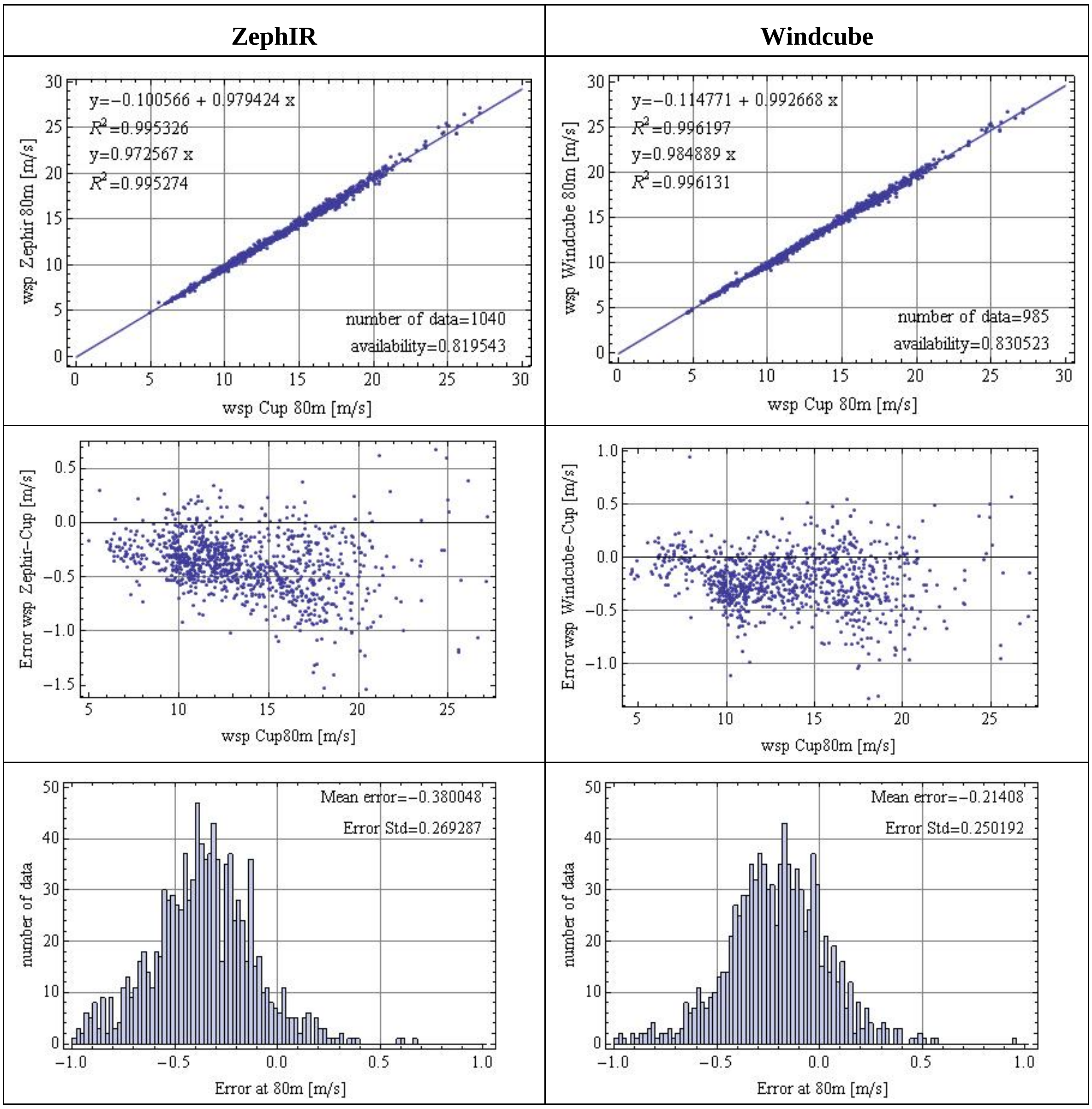

Figure 8 ZephIR (left) and Windcube (right) vs cup anemometer windspeed at 80m (top row). Lidar error (lidar speed - cup speed) vs wind speed (middle row). Histogram of lidar errors (bottom row). All cloud conditions.

Results for periods without low clouds

Here we take a subset of the data shown in the previous section, namely those for periods without low clouds (cloud base > 1600m). Scatter plots of lidar and cup anemometer speed, lidar error (lidar speed – cup speed) and histograms of the lidar error distribution are shown in Figure 2. Data for the ZephIR are shown in the left column, data for the Windcube in the right.

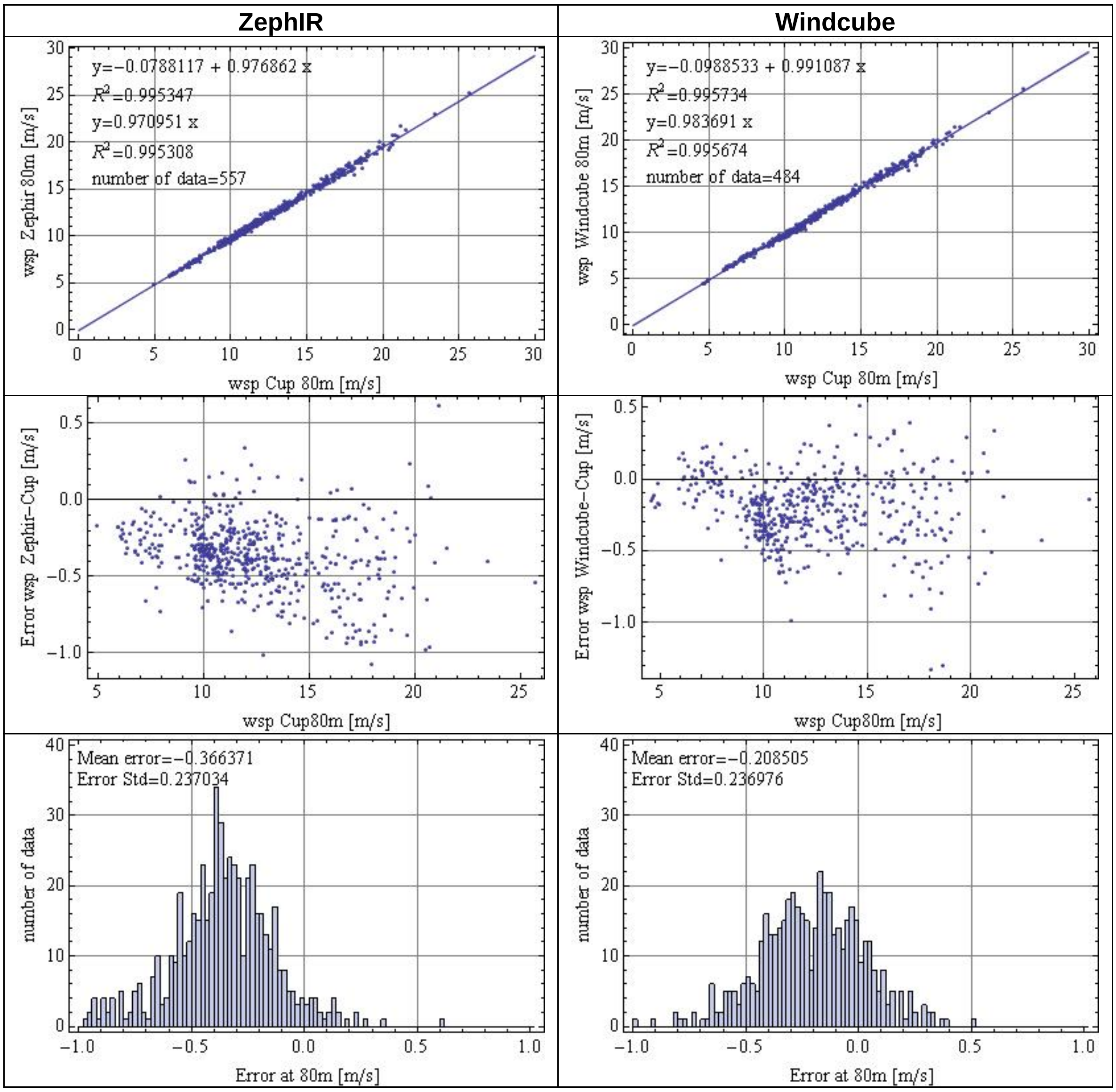

Figure 9 ZephIR (left) and Windcube (right) vs cup anemometer windspeed at 80m (top row). Lidar error (lidar speed - cup speed) vs wind speed (middle row). Histogram of lidar errors (bottom row). High cloud only (cloud base > 1600m)

Correlation of lidar-lidar wind speeds and errors

Here (Figure 3) we present direct comparisons of the simultaneous wind speeds measured by the ZephIR and by the Windcube. As before, we have chosen to study all cloud conditions first (the left column) and then only look at data for periods without low cloud (cloud base > 1600m). Underneath the scatter plot of lidar speed we have shown a scatter plot of the simultaneous speed error (lidar speed – cup speed) for the ZephIR and the Windcube.

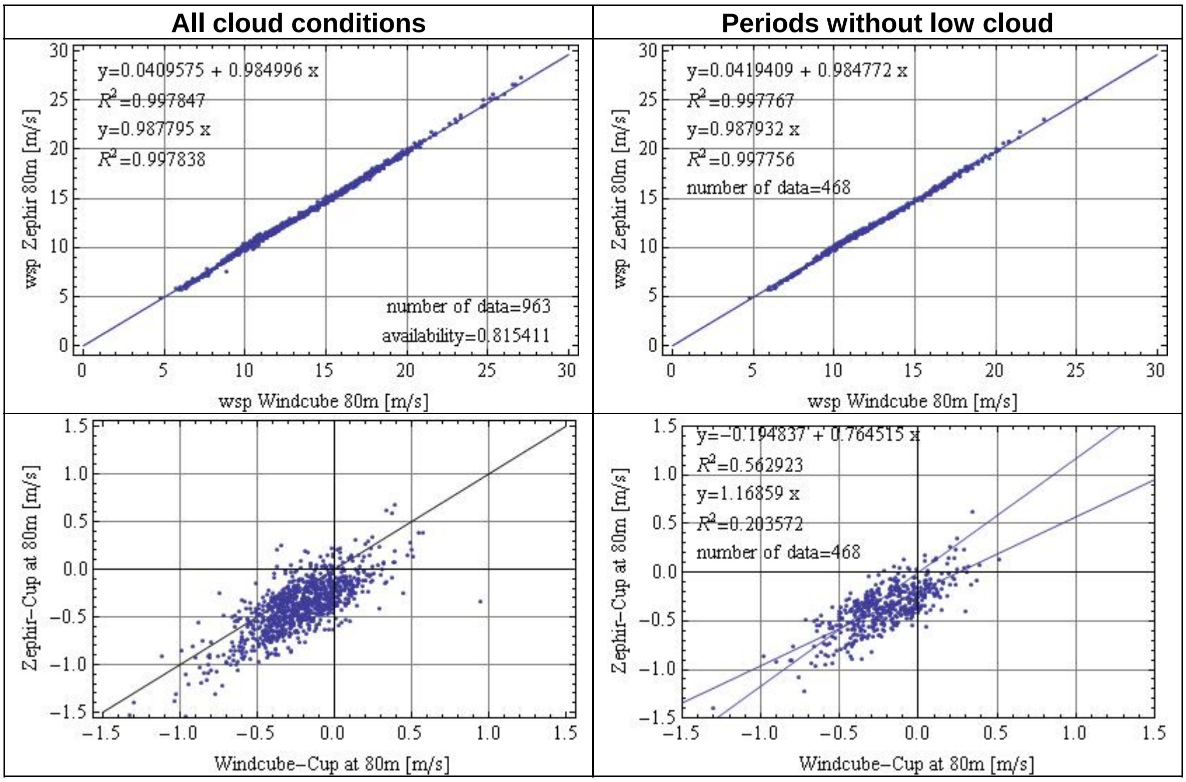

Figure 10 Scatter plots of lidar (ZephIR and Windcube) wind speed (top row) and speed error (bottom row). The left column is for all cloud conditions, the right column is for periods without low clouds (cloud base > 1600m)

Discussion of ZephIR/Windcube inter-comparison

In the dataset containing all cloud conditions (Figure 1), the performance of the two lidars is comparable. There is unusually little degradation of the ZephIR data due to cloud. Consequently the difference between this dataset and the following (Figure 2), where low cloud conditions have been filtered out, is not very large. The lidar-lidar scatter plots (Figure 3) show that the lidars are better correlated with each other than either lidar is correlated with the mast. Indeed, the scatter plots of lidar error show that many of the errors are correlated, indicating that they are primarily due to differences in measuring position and the differences arising from point (cup anemometer) and volume (lidar) measurements. A conclusion that we can draw is that to better see the more subtle differences between the instruments, it is necessary to move them closer to the reference mast. Indeed, at our usual test location, close to the 116m meteorological tower, the mast-lidar distances are much smaller.

4.4 Inter-comparison of two Windcubes

Here, we will present a fairly short period of data from two Windcubes operating side-by-side, close to the 116m meteorological tower at Høvsøre. The data are from the period 21 to 29 August 2008. Both Windcubes are placed about 8m to the north of the mast and are orientated such that the laser beams in 2 of the 4 shooting directions are just clear of the corners of the mast. This geometry maximizes the combined distance from the mast of the measuring volumes in all of the 4 directions and at the same time maximizes the correlation between the lidar and mast wind speed measurements.

Since we are primarily concerned with looking at how equally two nominally identical lidars measure we will only include the highest quality data and therefore perform the comparison with the top-pole mounted cup anemometer at 116m and the corresponding lidar measurements at this height. We are thus free of directionally dependant boom and mast effects on both the cup anemometer and lidar measurements. In addition we may employ wind from all directions from 60 to 300°. Other filtering conditions applied are exclusion of ten minute periods with rain and the requirement that the reported availability of the Windcube in each ten minute period is 100%. The complete filtering conditions are:

- Wind directions 60 to 300°
- No rain
- availability of the Windcube in each ten minute period is 100%

Lidar versus cup anemometer comparisons

Figure 4 shows salient details of the lidar/cup anemometer comparisons made using the simultaneous data from each Windcube. Scatter plots of lidar and cup anemometer speed, lidar error (lidar speed – cup speed) and histograms of the lidar error distribution are shown. Data for Windcube s/n 009 are shown in the left column, data for Windcube s/n 014 in the right column.

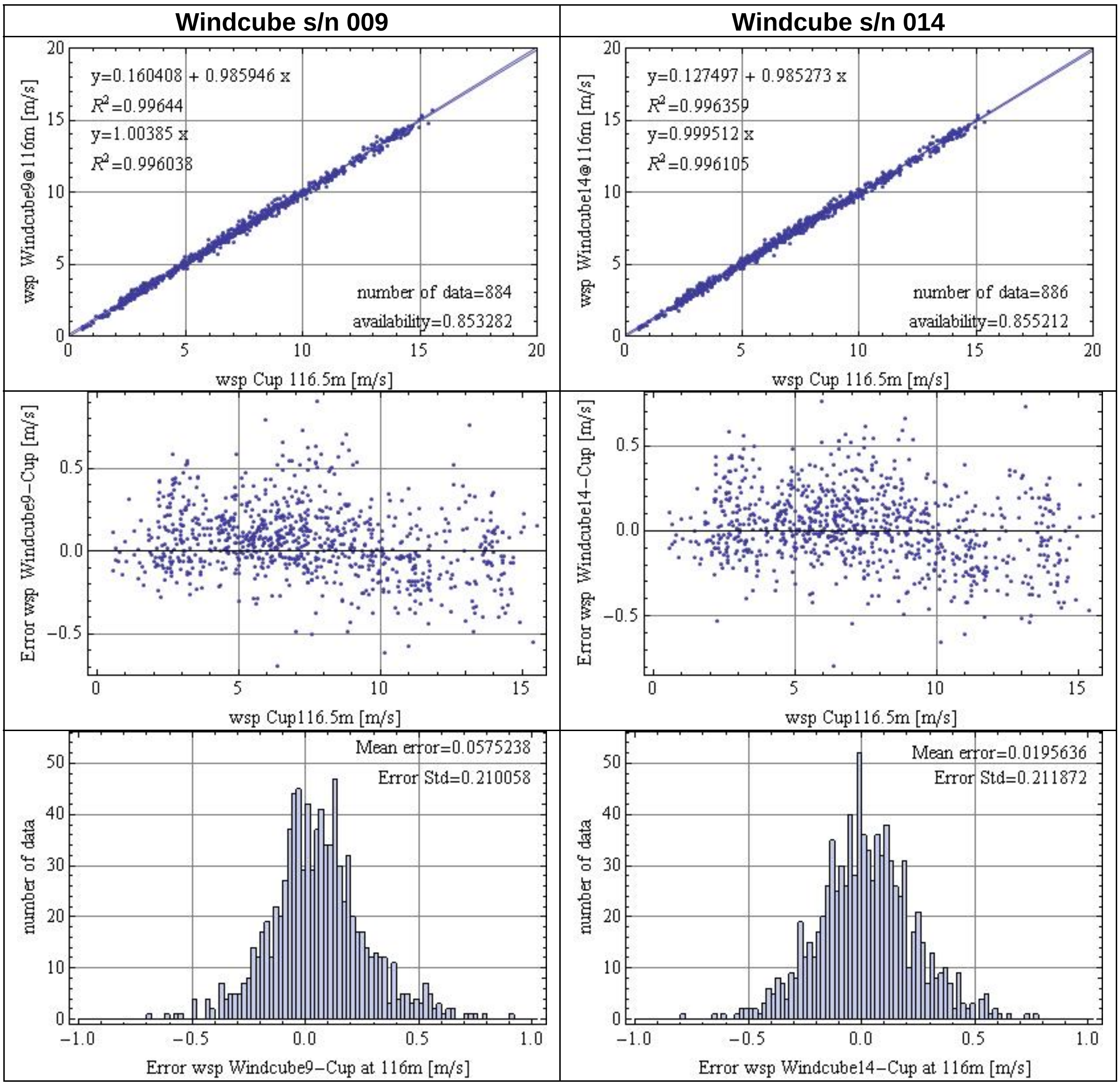

Figure 11 Lidar vs cup anemometer wind speed for simultaneous measurements at 116m height (top row), lidar error vs wind speed (middle row) and distribution of error (bottom row). All for Windcube s/n 009 (left) and Windcube s/n 014 (right).

Correlation of lidar-lidar wind speeds and errors

Figure 5 shows direct comparisons of the simultaneous wind speeds measured by the two Windcubes. Underneath the scatter plot of lidar speed we have shown a scatter plot of the simultaneous speed error (lidar speed – cup speed) for each of the Windcubes.

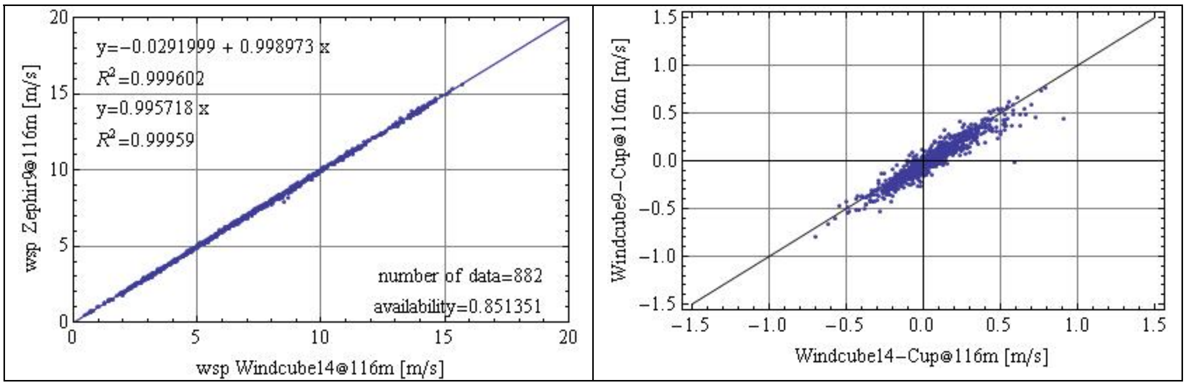

Figure 12 Scatter plot of simultaneous 10 minute wind speeds measured by two adjacent Windcubes (left) and scatter plot of the simultaneous errors (lidar speed - cup speed) for the two systems (right).

Discussion of the Windcube/Windcube comparison

The performances demonstrated by both Windcubes in the cup anemometer comparisons (Figure 4) are excellent. Both are highly correlated to the cup anemometer and there is no significant non-linearity. Values of the slope for the linear regression forced through zero are within 0.5% of unity for both systems (1.004 for s/n 009 and 1.000 for s/n 014). For these regressions, the R-squared values are 0.996 for the datasets from both the lidars.

The similarity of the scatter plots is confirmed by the error distribution histograms. Here the standard deviation of the error is also essential equal for both the Windcubes. The mean error for Windcube s/n 009 (0.06 m/s) is larger than for s/n 014 (0.01 m/s), reflecting the difference in the regression slopes. These are impressive values for a remote sensing system. Better lidar data has never been reported from Høvsøre.

Figure 5 shows a staggeringly high correlation between the two Windcube wind speed signals. This is also confirmed by the scatter plot of the error (lidar speed – cup speed) for each system. Most of the error of one of the Windcubes is shared by the other system. This suggests that most of the difference between a Windcube measured wind speed and that measured by the cup anemometer is due to differences in how the wind is sensed (spatial probing as opposed to a point measurement). Measurement errors due to noise in the measurement train do not appear to be significant since it is hard to imagine that such noise would be so well correlated between two separate instruments.

5. Conclusions

From studying the various lidar-lidar inter-comparisons we can draw a number of conclusions. The first ZephIR-ZephIR comparison shows us primarily that low-lying cloud can have a major impact on the performance of these systems. This was fairly early data and the effectiveness of the cloud-correction algorithm implemented at that time is no longer relevant and has not been reported. A newer, much improved version is now available and will be assessed as soon as we have sufficient data for this purpose.

The ZephIR – Windcube comparison at the Høvsøre stand2 test site showed similar performance for both systems. In this case, the ZephIR was surprisingly unaffected by low level cloud even though the cloud-correction algorithm was not employed. A feature of this comparison was the relatively large distance (150 m) to the reference meteorological mast. The de-correlation of the wind over this distance probably blurs many of the more subtle differences between the two different lidars and this is an important message. Successful lidar calibration and inter-comparisons require short distances between the lidar and the reference mast.

Finally we studied a more recent campaign in which two Windcubes were measuring simultaneously at the foot of the Høvsøre 116m mast. The ten minute wind speed data obtained from both the Windcubes was of high quality, with an apparent accuracy approaching that of a cup anemometer. Most significantly, there was a very high correlation between the lidar error (lidar speed – cup speed) for both the lidars. Indeed a large part of the error seems to be correlated, suggesting that the lidar-cup differences are due mainly to the drastically different probing methods (volume versus point) rather than random noise.

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[3] Courtney M.S.; Wagner R.; Lindelöw P., *Testing and comparisons of lidars for profile and turbulence measurements in wind energy. 14th International Symposium for the Advancement of Boundary Layer Remote Sensing, Roskilde, Denmark (2008).*