



## Windcube + FCR test at Hrgud, Bosnia and Herzegovina

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# Windcube + FCR test in Hrgud, Bosnia & Herzegovina

## Final report

DTU Vindenergi  
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Rozenn Wagner, Jasmin Bejdić

DTU Wind Energy E-0039

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**Title:** Windcube + FCR test in Hrgud, Bosnia & Herzegovina -- Final report

**Institute:** DTU Wind Energy

**Resume (maks. 2000 char.):**

Velocity azimuth display (VAD) scanning lidars cannot measure the wind speed accurately in complex terrain because the fundamental assumption that the wind speed is horizontally homogeneous is violated. Leosphere provides an online correction, the Flow Complexity Recognition (FCR), in order to correct the effect of the terrain on the Windcube measurements. The aim of this project was to assess the accuracy of this correction by comparing the corrected lidar measurements to the uncorrected measurements and to simultaneous measurements taken by cup anemometers on a met mast. The measurements took place in a complex site, Hrgud, in Bosnia and Herzegovina, provided by ERS and where the reference met mast was erected and instrumented by COWI.

The lidar uncorrected wind speed was lower than that measured by the cup anemometer at the same height by about 4.1%. This deviation is sensitive to the wind direction and depends on the topography. The largest deviations were observed in the direction orthogonal to the hill on which the lidar and the mast were located, which is where the topography is the less homogeneous.

The FCR corrected wind speed on the other hand was higher than the cup anemometer by about 1.5%; but this deviation was fairly independent from the wind direction.

This measurement campaign also highlighted a couple of important technical points, such as the importance of well protecting the lidar power supply in order to avoid any damage of the instruments, due to lightning hits for example.

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# Peface

This project has been performed according to an agreement between DTU Wind Energy - Denmark, COWI - Denmark, ERS – Bosnia & Herzegovina, and Leosphere - France.

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# 1. Introduction

Ground based lidar profilers offer the opportunity to measure up to 200m with relatively easy logistics compared to a tall mast. The simple installation is particularly attractive in complex terrain. However, VAD scanning lidar cannot provide accurate measurement in complex terrain because the fundamental assumption that the wind speed is horizontally homogeneous is violated [1, 2]. Leosphere provides an online correction, the Flow Complexity Recognition (FCR), in order to correct the effect of the terrain on the Windcube measurements [3].

A wind study for a 48 MW wind farm at Hrgud, complex site in Bosnia and Herzegovina, has been performed by COWI for ERS. The planned wind farm will consist of 16 3 MW wind turbines with a hub height of 80m. COWI had installed a 77.5m mast at the site in order to perform the wind resource assessment as part of a larger feasibility study.

As part of an agreement between COWI, DTU, ERS and Leosphere, a Windcube v2 lidar with FCR was installed next to the met mast in order to supplement the original data with a wind speed measurement above the met mast. This measurement campaign was also used as an opportunity to assess the measurement accuracy of the lidar with and without FCR; this is the purpose of this report.

## 2. Measurement set up

### 2.1 Site description

The measurements took place at the complex site, Hrgud, Bosnia Herzegovina. The terrain is very complex with low vegetation (bushes). The mast was located on an oblong 100m high hill about 1.5km North of a 1000m deep and 2km wide canyon, as shown in Figure 1. The hill is about 1km long and 100m wide, oriented E-W. The site was a project under development and the mast position was selected to evaluate the project (and not to optimize the lidar comparison).



**Figure 1** Google topography map of Hrgud, Bosnia and Herzegovina. North is towards the top of the figure. The red cross shows the mast location.

## 2.2 Mast description

The mast was a guy wired triangular lattice tower of 75 m height. Wind speed measurements were taken at 30, 55, 75 and 77.5 m with Thies First Class cup anemometers. Direction measurements were taken at 53 m and 75 m with Thies Compact wind vanes; however the wind vane at 75m got broken during the measurement campaign, therefore the wind vane at 53m was used in the analysis (even for wind speed measurements at 77.5 and 75m). The 77.5m cup anemometer was top mounted. The other instruments were mounted on 2.7 m long booms. Most of them were oriented toward 144°. At 55 m, there were two anemometers, one on a boom oriented towards 144° and the other towards 319°.

## 2.3 Lidar

The lidar was a Windcube v2, equipped with the FCR [1]. Due to failure of the lidar caused by a lightning hit on the power supply during the measurement campaign, two lidar units were used. The first lidar unit (unit 196) was installed by Impro Impex, a subcontractor of COWI, on June the 14<sup>th</sup>, 2013. The lidar was placed 1.5m on the North side of the met mast. It was oriented so that the five lines of sight (LOS) avoided the mast and the surrounding guy wires [3]. It was configured to measure at 10 heights: 44, 54, 64, 74, 77, 79, 99, 119, 129, 159m. These heights were chosen accounting for the height of the lidar system itself, the emission of the beam was assumed to be one meter a.g.l. Therefore the actual measurement heights were one meter above the previous configured heights.

The power supply was directly connected to the local power line. On the 08-07-2013 the power line supplying the lidar was hit by a lightning which burned out the 220 V to 24 V converter and caused the failure of the lidar system. The lidar system had to be shipped back to Leosphere

and replaced by unit 174. The measurements taken with the two units have been analysed separately.

Unit 174 was installed on August the 22<sup>nd</sup> 2013. It was installed in the same configuration as unit 196.

The data were manually collected every time Impro Impex was visiting the site (about every two weeks) and transferred to DTU via an FTP server together with the mast data.

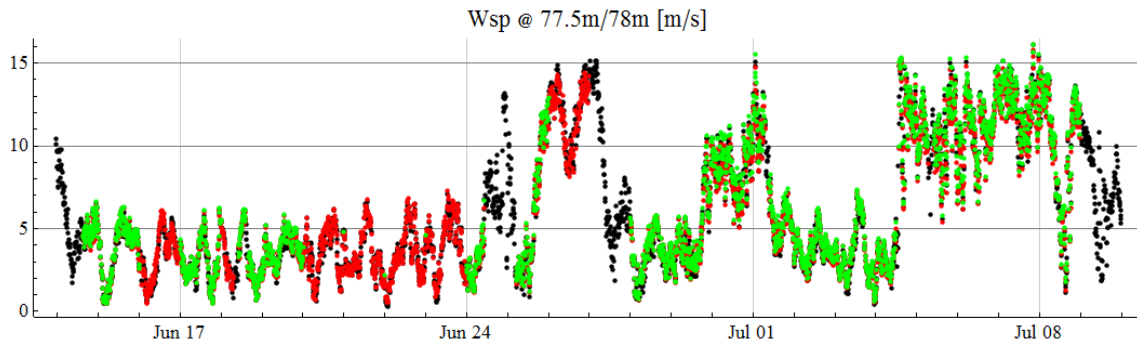


Figure 2 Picture of the lidar at 1.5m on the north side of the foot of the mast.



### 3. First measurement phase (Windcube unit 196)

Windcube WLS7-196 has been measuring at the site from the 14-06-2013 to the 08-07-2013.

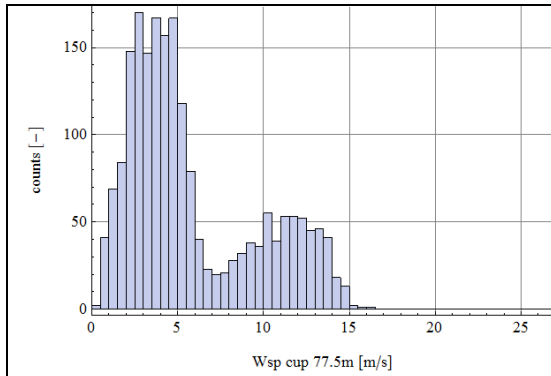


**Figure 3** Time series of the wind speed measured with the top cup anemometer at 77.5m (black), the lidar without correction at 78m (red) and the lidar with FCR correction (green).

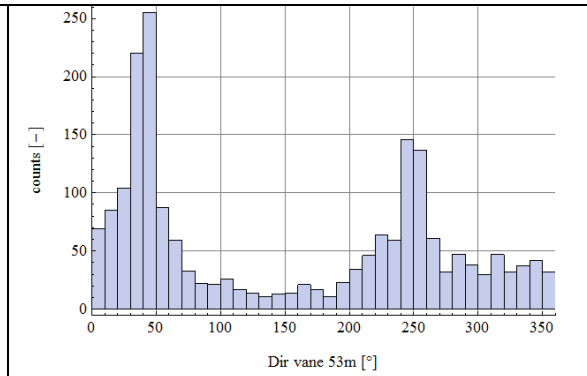
The lidar measurements were interrupted a couple of times because of power cuts. The FCR corrected data were missing for some periods of time, before the 28<sup>th</sup> of June. The reason for the missing data was probably due to an issue with the GPS synchronization (this was diagnosed later in the measurement campaign).

#### 3.1 Uncorrected lidar wind speed measurements

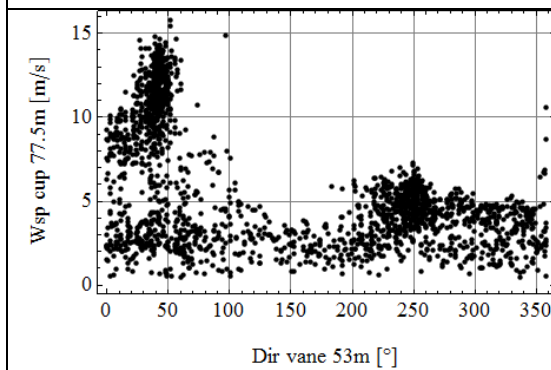
The dataset considered in this section include all the 10 minute periods for which the lidar provided uncorrected wind speed measurements. Figure 3 and 4 show the distribution of the wind speed and the direction, respectively, for this dataset. Mainly low wind speeds occurred during the first period of measurements (Figure 4) and two wind directions were largely prevailing: around 40° and around 250° (Figure 5). Figure shows that most of the wind speed above 7 m/s came from the NNE sector.



**Figure 4** Distribution of the wind speed measured by the cup anemometer at 77.5m (10 minute periods for which both the uncorrected lidar wind speed and the cup anemometer data were available: 3174 data).

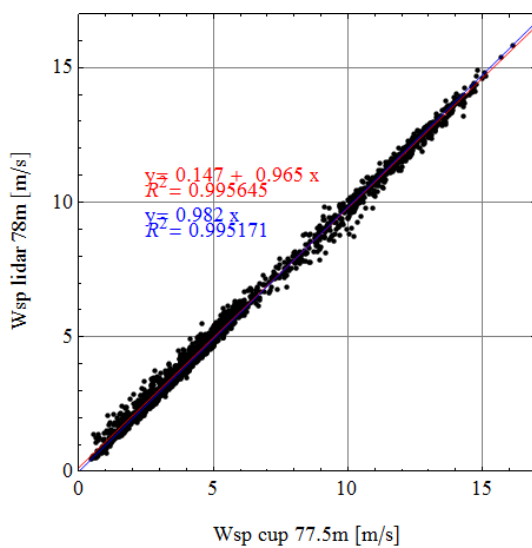


**Figure 5** Distribution of the wind direction measured by the wind vane at 53m (10 minute periods for which both the uncorrected lidar wind speed and the cup anemometer data were available).



**Figure 6** Cup anemometer wind speed at 77.5m vs wind direction (wind vane at 53m)

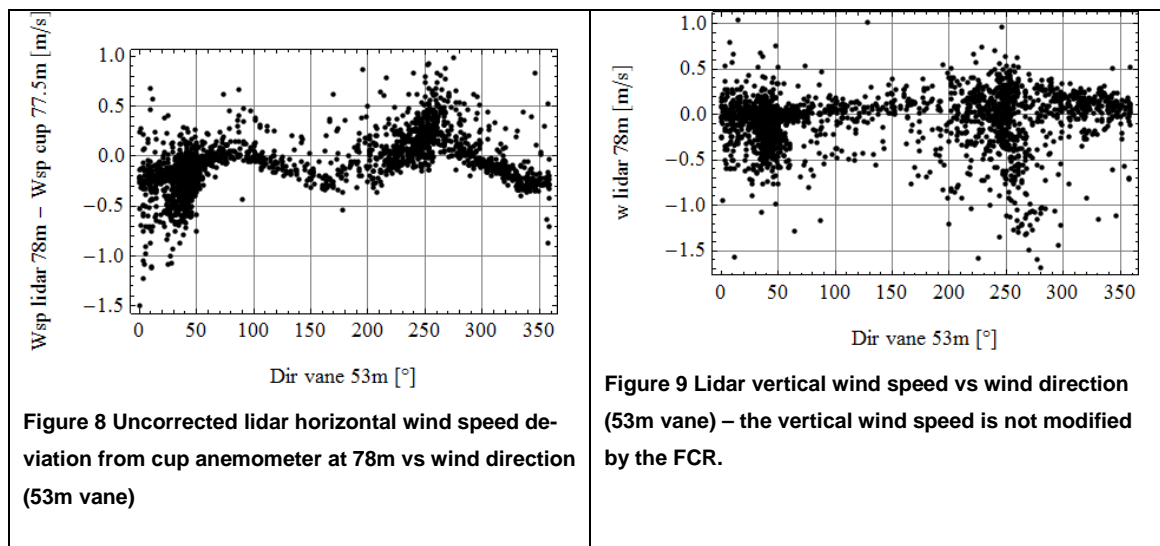
Figure 7 shows the comparison of the 10 minute mean wind speed measured by the lidar at 78m and the cup anemometer at 77.5m (top mounted cup anemometer). The lidar generally provides a lower wind speed than the cup anemometer by 1.8% on average.



**Figure 7** Uncorrected lidar wind speed at 78m vs cup anemometer wind speed at 77.5m. Dataset including uncorrected wind speed data with an availability of 100%. Red: two parametric linear regression; Blue: one parametric linear regression forced through 0.

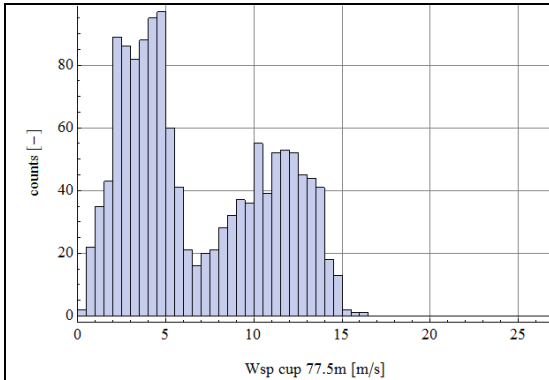
However the deviation between the lidar and the cup anemometer measurements varies strongly with the wind direction as shown in Figure 8. The lidar wind speed is lower than the cup anemometer in the N and S sectors corresponding to the directions of the strongest slope around the mast and the lidar. For these directions we can therefore expect the largest inhomogeneity in the flow sensed by the four lidar LOS since the flow inclination is expected to vary (from positive to negative) as the flow moves from one side to the other of the mountain.

A positive deviation is observed around 250° with a large scatter. In this direction the terrain may be slightly downhill (towards the lidar) however it would hardly generate a negative flow inclination that could explain this deviation. Figure 9 shows the vertical wind speed measured by the lidar vertical beam. Larger vertical wind speeds are observed towards NNE and SWW, which correspond to the sectors with the largest scatter in Figure 8. These directions also correspond to the prevailing wind direction of this measurement period. The large scatter around 250° is possibly due to the shadow effect of the lightning rod on the top cup anemometer, this is further discussed in section 4.1.

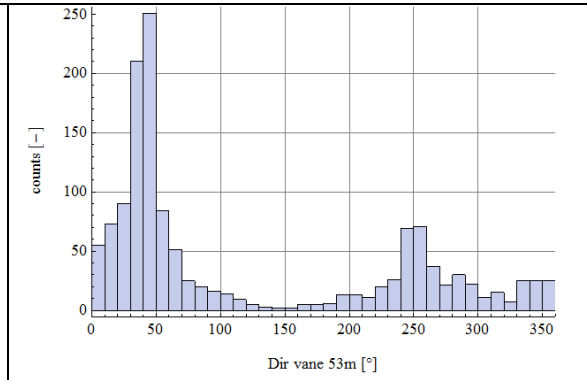


### 3.2 Measurements with FCR correction

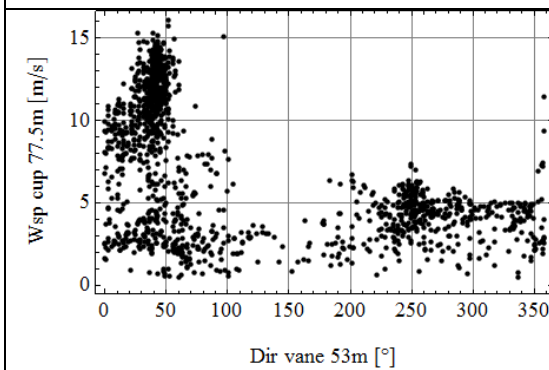
As mentioned above, FCR data were missing. In order to make a fair comparison between uncorrected data and FCR corrected data, only the 10 minute time periods for which the FCR corrected data were available are considered here. Figure 10 to Figure 12 show the distribution of wind speeds and directions for the considered dataset.



**Figure 10** Distribution of the wind speed measured by the cup anemometer at 77.5m (10 minute periods for which both the FCR lidar wind speed and the cup anemometer data were available: 2269 data).

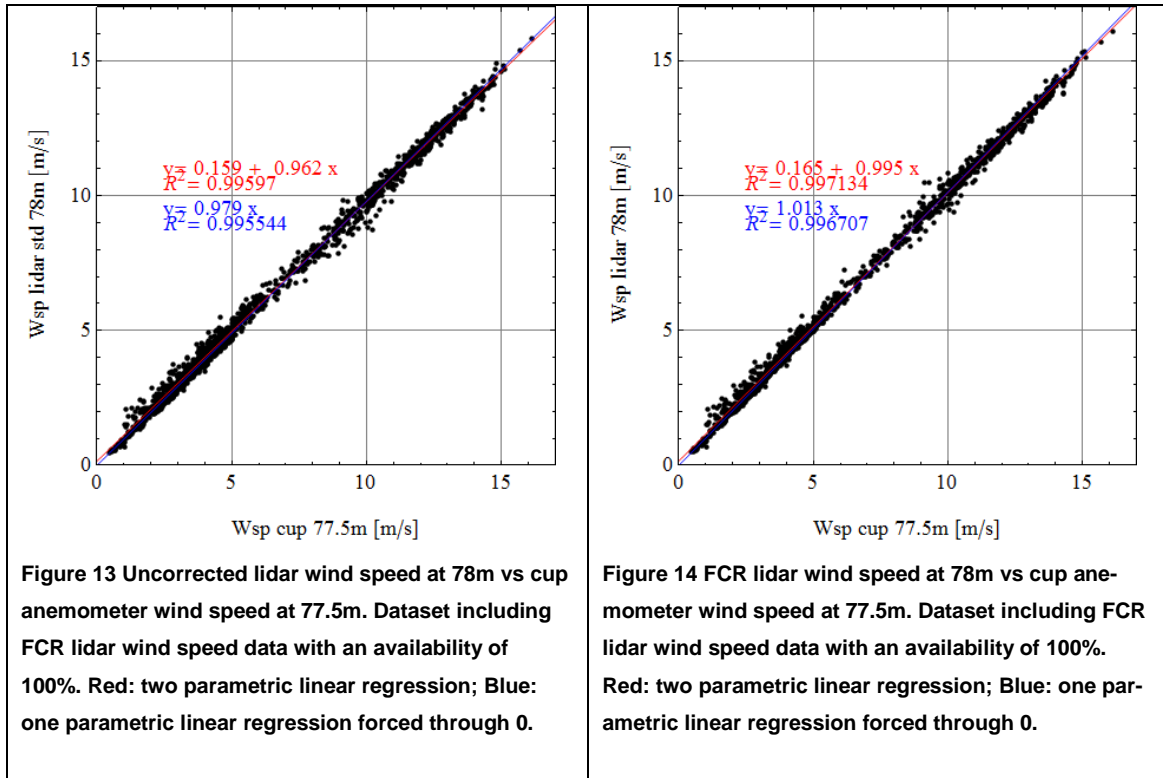


**Figure 11** Distribution of the wind direction measured by the wind vane at 53m (10 minute periods for which both the FCR lidar wind speed and the cup anemometer data were available).

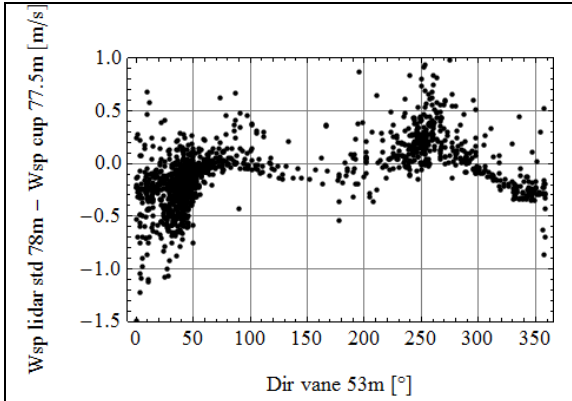


**Figure 12** Cup anemometer wind speed at 77.5m vs wind direction (wind vane at 53m)

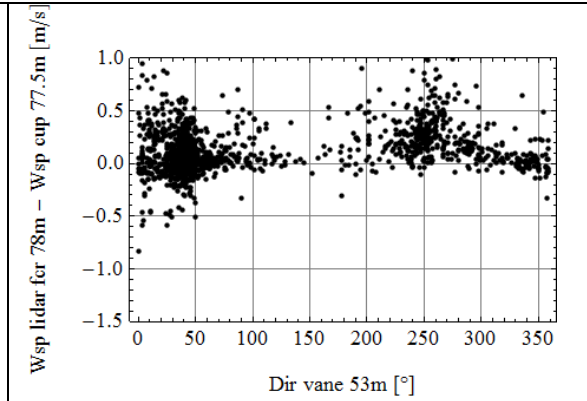
Figure 13 and Figure 14 show the comparison between the cup anemometer and the uncorrected lidar measurements and the FCR corrected lidar data, respectively, for the same dataset. The uncorrected lidar wind speed measurement underestimate the cup anemometer, by 2.1% on average. The FCR corrected lidar wind speed measurement overestimate the cup anemometer, by 1.3% on average. The coefficient of determination is higher for the FCR corrected data than for the uncorrected measurement.



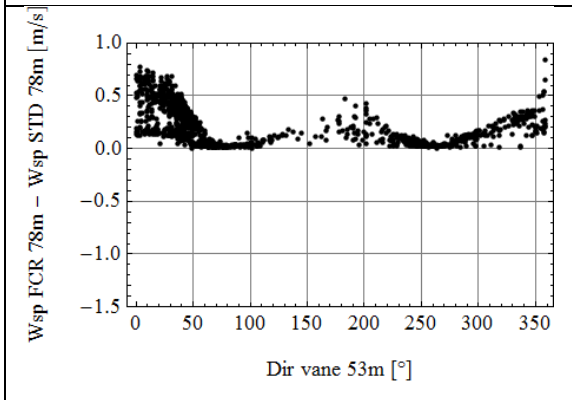
By comparison to Figure 15, the sinusoidal trend was attenuated by the FCR but the large scatter around NNE and SSW remained, see Figure 16. The largest overestimations occur for these directions. As seen in Figure 17, the largest correction was applied around N and S, whereas almost no correction was applied around W and E.



**Figure 15** Uncorrected lidar horizontal wind speed deviation from cup anemometer at 78m vs wind direction (53m vane)



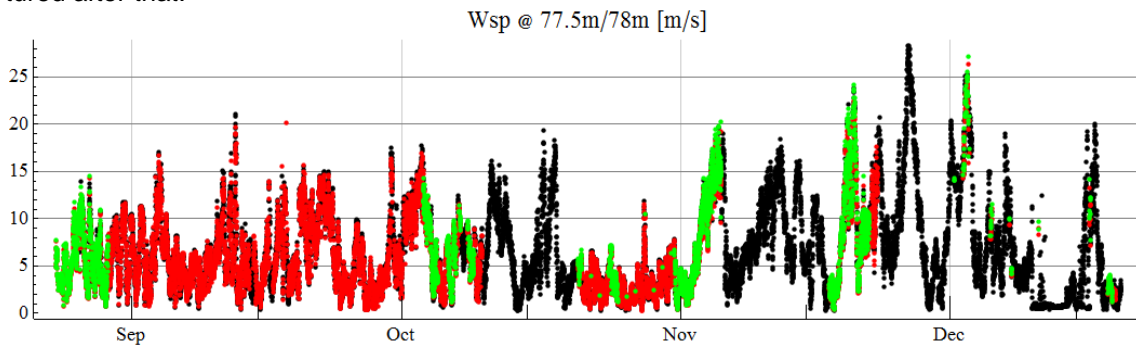
**Figure 16** FCR lidar horizontal wind speed deviation from cup anemometer at 78m vs wind direction (53m vane)



**Figure 17** Difference between FCR lidar wind speed and uncorrected lidar horizontal wind speed at 78m vs wind direction (53m vane)

## 4. Second measurement period

Windcube WLS7-174 was at the site at the site from the 23-08-2013 to the 19-12-2013. The time series of the wind speed measured with the top cup anemometer at 77.5m and the lidar with and without FCR at 78m are displayed in Figure 18. The lidar measurements were interrupted several times. The main events causing interruption in the measurements are summarized in Table 1. On the 05-11-2014, a lightning hit the power line to which the lidar was connected and as with the previous unit, the 220V to 24V converter burnt out. Once it was replaced (on the 17-11-2014), we realized that the EDFA has been damaged resulting in lowering the laser power and resulting in low CNR values. Only periods with very high aerosol loads were captured after that.



**Figure 18** Time series of the wind speed measured with the top cup anemometer at 77.5m (black), the lidar without correction at 78m (red) and the lidar with FCR correction (green).

**Table 1** Malfunctioning lidar time line

Beginning	End	Explanation
29-08-2013	03-10-2013	FCR accidentally turned off
09-10-2013	20-10-2013	Power supply damaged by lightning
20-10-2013	23-10-2013	Complete std data files, but incomplete FCR files (only 1 value/day); lidar GPS synchronization problem
25-10-2013	30-10-2013	Complete std data files, but incomplete FCR files (only 1 value/day); lidar GPS synchronization problem
05-11-2013	17-11-2013	Power supply damaged by lightning
22-11-2013		End of reliable measurements; lidar system damaged by lightning

Since much more lidar uncorrected wind speed data (non-corrected for the terrain effect) were collected than FCR corrected data, the analysis has been performed in two steps:

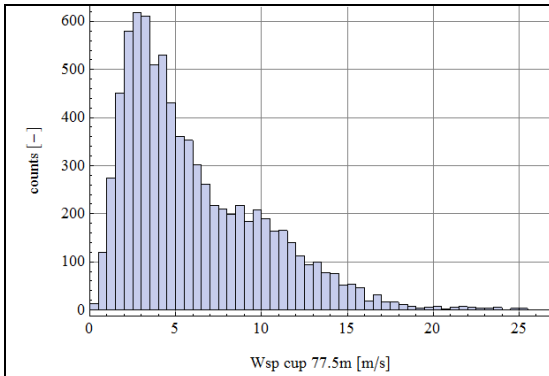
1. all the available uncorrected lidar data;
2. the FCR corrected dataset (with the simultaneous uncorrected data).

Note: in the figures below, black dots represent 10 min average data, red dot represent bin averages (bin definition depends on the quantity displayed on the x-axis) and error bars represent +/- half of the standard deviation in the bin.

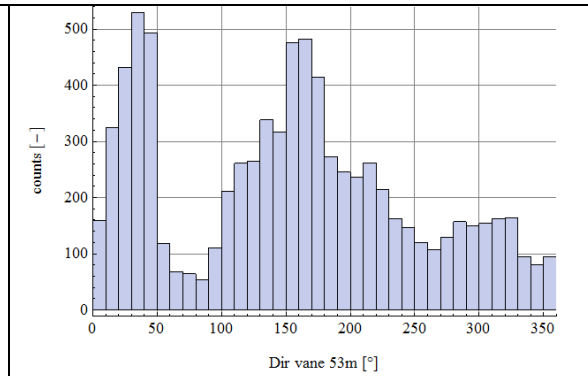
#### 4.1 Uncorrected lidar wind speed measurements

In this section all the available uncorrected lidar data are considered (independently of the availability of FCR data). The data with a 10 minute availability (parameter “available” given by the Windcube) lower than 80% were rejected. The remaining dataset counts 8065 data.

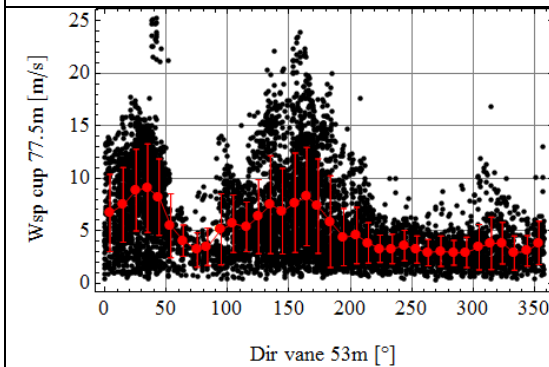
Figure 19 and Figure 20 show the distribution of the wind speed and wind direction for this dataset. This measurement period provided a better coverage of the wind speed and wind direction than the first measurement period. Mainly low wind speeds (mostly below 5 m/s) occurred for the wind directions between 50° and 90° and between 220° and 360° (Figure 21).



**Figure 19** Distribution of the wind speed measured by the cup anemometer at 77.5m



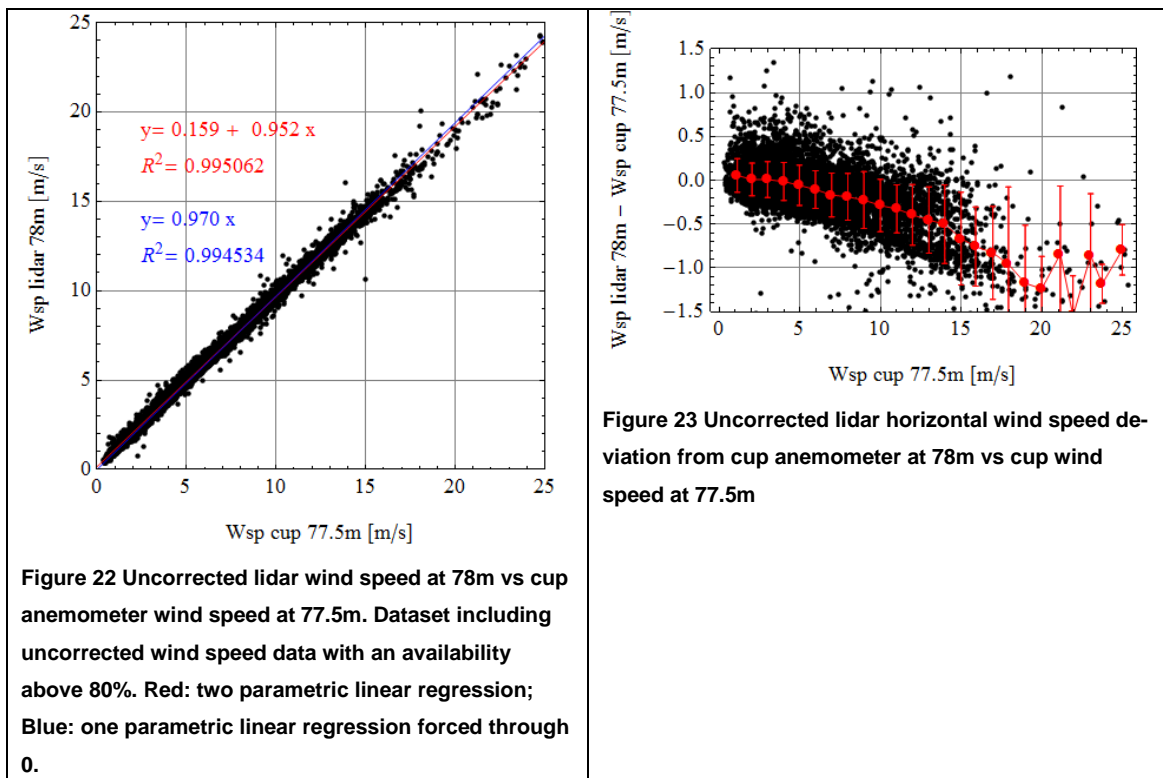
**Figure 20** Distribution of the wind direction measured by the wind vane at 53m



**Figure 21** Cup anemometer wind speed at 77.5m vs wind direction (wind vane at 53m)



Figure 22 shows the comparison between the lidar uncorrected wind speed at 78m and the cup anemometer at 77.5m. The uncorrected lidar wind speed measurements underestimate the cup anemometer by 3.0% on average. This deviation is larger than that observed with unit 196 which may be related to the larger number of data with high wind speed collected in the second measurement period, especially within the sector 120°-220°. As shown in Figure 23, the lidar wind speed deviation (difference between the lidar wind speed and the cup anemometer) is mainly negative and its amplitude increases with the horizontal wind speed.

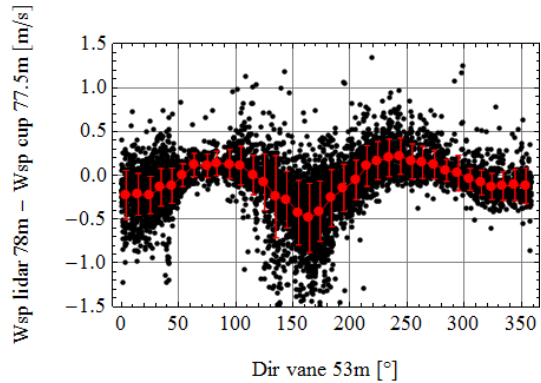


The variation of the lidar deviation appears clearly with this dataset, as shown in Figure 24. The largest negative deviation is observed between 130° and 190° and another clear negative deviation is observed between 330° and 30°. These two directions correspond to the directions of the largest slopes in the terrain surrounding the lidar within a radius of 1km. The fact that the deviation is larger in the 130°-190° than in the northern sector may be due to the very steep slope to the south of the site at 1 to 1.5km of the lidar location, whereas on the northern side the terrain is gently going down with inhomogeneity over about 3km [5, 5].

Along the 250°-70° directions along, there is no significant lidar deviation. This is probably related to the locally fairly homogeneous terrain along the N-S direction. However, according to the terrain topography considerations, these variations would have been expected to be shifted 20° west (i.e. largest underestimation for southerly winds and smallest deviation in the E-W direction).

Furthermore, it seems that the lidar measurements are mainly influenced by the topography of the terrain surrounding the lidar within a radius of about 500m, but the major feature of the to-

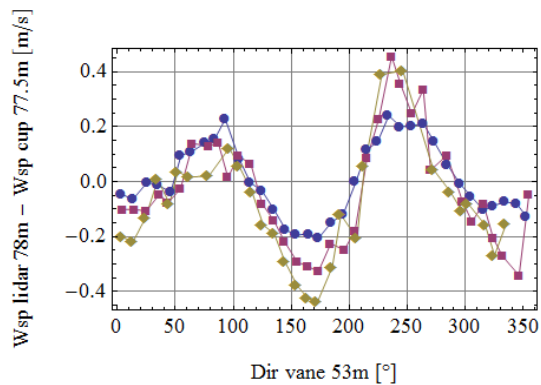
pography in a perimeter with a larger radius has also an influence. This could be more systematically investigated with numerical tools (e.g. CFD modeling).



**Figure 24 Uncorrected lidar horizontal wind speed deviation from cup anemometer at 78m vs wind direction (53m vane)**

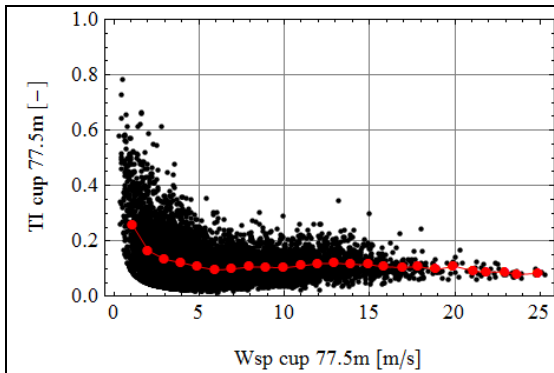
Figure 23 shows that the lidar deviation is sensitive to the wind speed and Figure 24 shows it is sensitive to the wind direction. However, the wind speed distribution is rather sensitive to the wind direction (see Figure 21). In order to identify the effect of the two parameters, the lidar deviation data were binned according to the wind speed and to the wind direction.

Figure 25 shows the lidar deviation as a function of the wind direction for three wind speed bins. Around 170° (where a large wind speed range has been covered), the amplitude of the deviation increases with the wind speed; whereas for the other directions, there is no clear pattern. Note that, in the directions above 230°, there were much less occurrences of wind speed above 5 m/s.

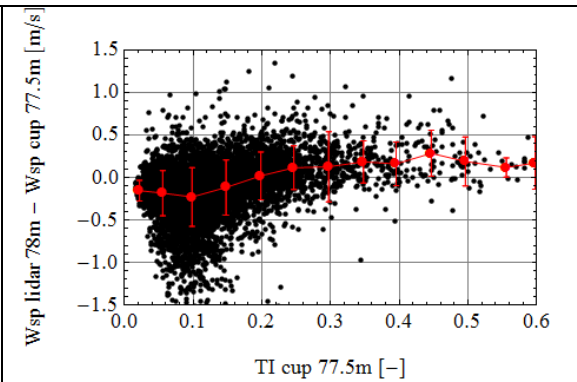


**Figure 25 Uncorrected lidar wind speed deviation from cup anemometer at 78m binned per wind speed (2m/s bins) and wind direction (10 degrees bins). Blue:  $3 \leq w_{sp} < 5$  m/s, red:  $5 \leq w_{sp} < 7$  m/s, yellow:  $7 \leq w_{sp} < 9$  m/s.**

The turbulence intensity was 12.7% on average, with larger values for wind speeds below 5m/s, as shown in Figure 26. Therefore the increase of lidar deviation with turbulence intensity observed in Figure 27 is mainly due to the effect of the mean wind speed. For high wind speeds, the lidar deviation is larger and the turbulence intensity is generally low.

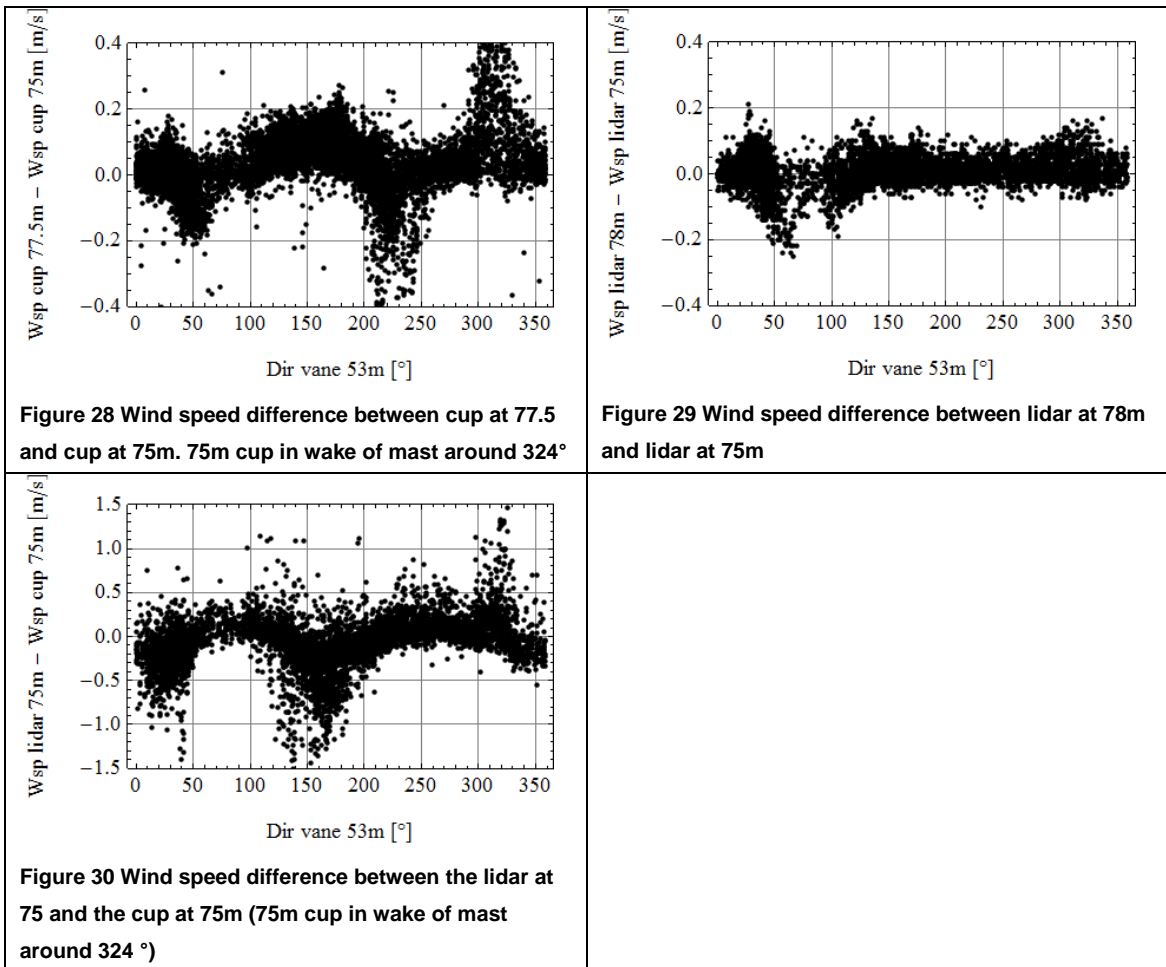


**Figure 26 Turbulence intensity vs mean wind speed from cup anemometer at 77.5m**



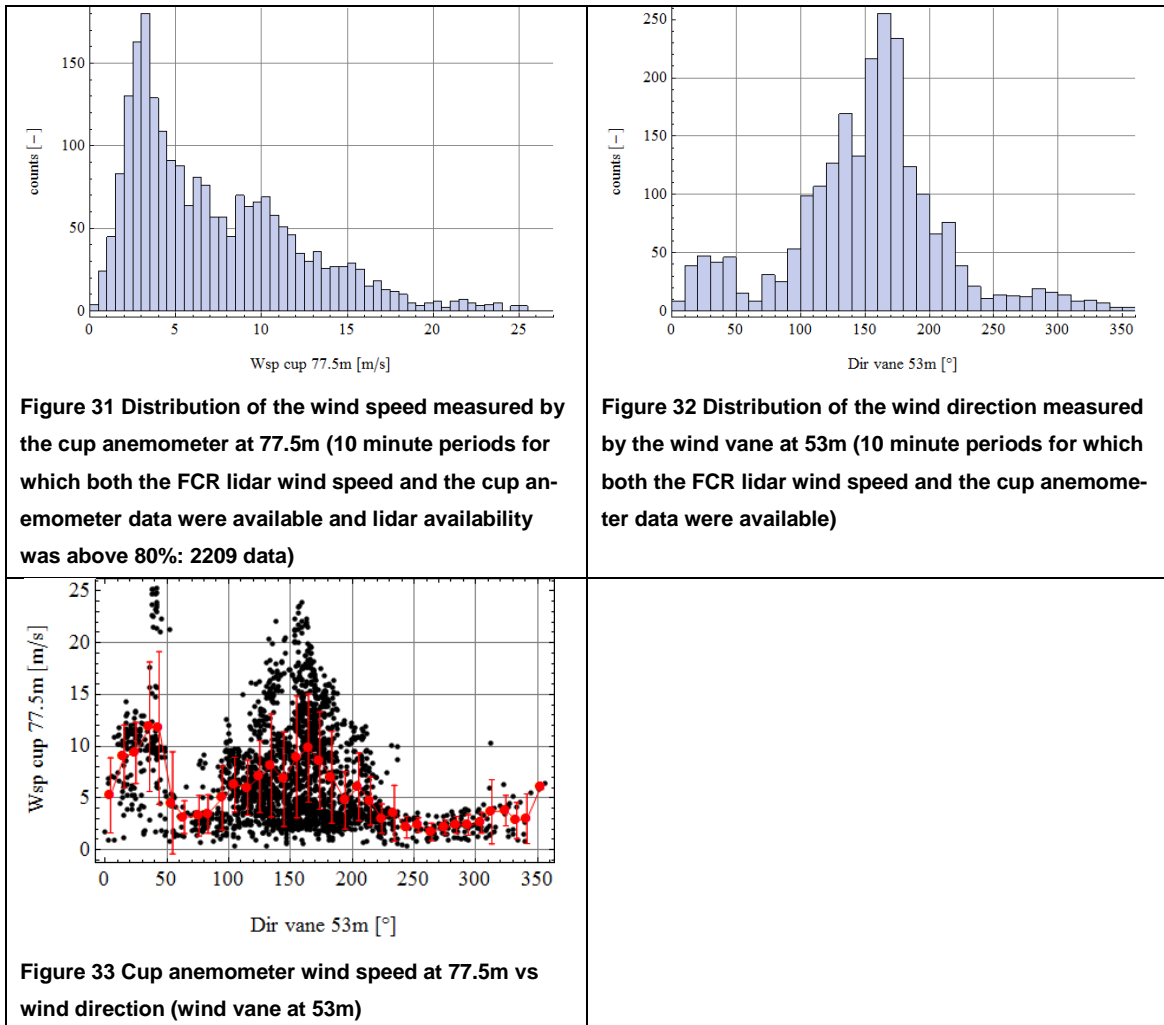
**Figure 27 Uncorrected lidar horizontal wind speed deviation from cup anemometer at 78m vs cup turbulence intensity at 77.5m**

Figure 28 shows the difference in wind speed measurement by the cup anemometers at 77.5m and 75m. The 75 m boom is oriented toward 144°, so the cup anemometer is in the wake of the mast for wind direction around 324°. The slight positive deviation around 150° could be due to the blockage of the mast decreasing slightly the wind speed at 75m. A negative deviation is observed between 200° and 250°, with a large spread. For these directions, the boom is perpendicular to the wind, the effect of the mast and the boom on the cup anemometer are therefore expected to be relatively low. Figure 29 shows the difference in wind speed measurement by the lidar at 78m and 75m and nothing particular appear for this sector. Moreover this deviation does not appear at 75m as shown in Figure 30. It therefore looks like something is influencing the top cup for the wind sector between 200° and 250°. One possible explanation could be the influence of the lightning rod. Although it is mounted on the west side according to the mast installation report, at the site visit, it appeared to be twisted. However the width of the sector affected is surprisingly large relatively to the size of the lightning rod. Nevertheless, this underestimation of the top cup anemometer could explain the slight positive lidar deviation observed between 200° and 250° in Figure 24.



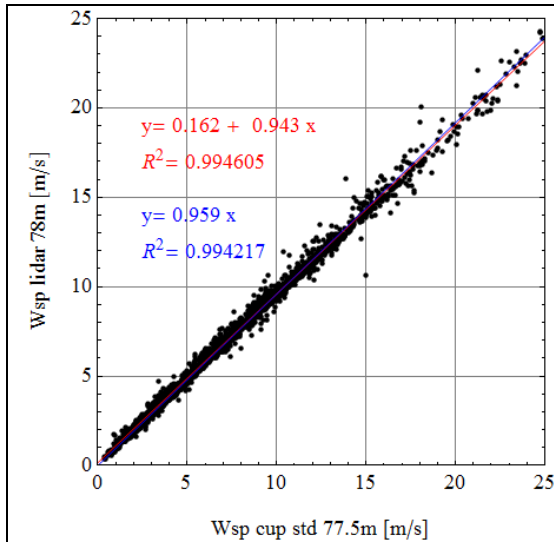
## 4.2 Measurements with FCR correction

In this section only the 10 minute time periods for which the FCR corrected data were available are considered. Data with a 10 minute availability lower than 80% were discarded. Figure 31 and Figure 32 show the distribution of wind speeds and directions for the considered dataset. Figure 33 shows the wind speed as a function of the wind direction. The average variation is similar to Figure 21. A large majority of data have a wind direction between  $100^\circ$  and  $200^\circ$ , which is the sector with the largest wind speed range.

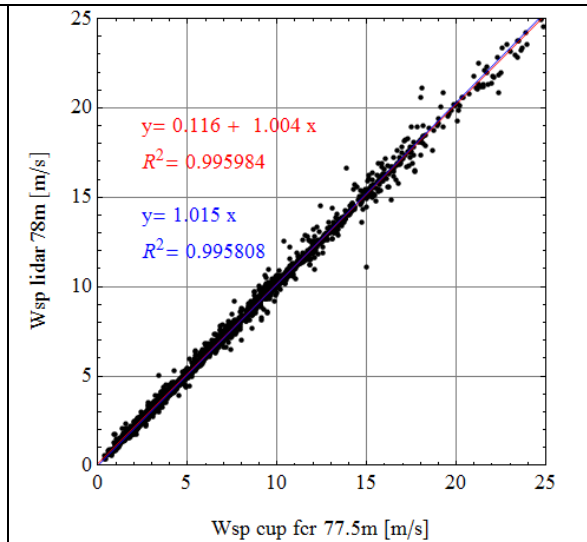


### 4.2.1 Measurements at 77.5m/78m

Figure 34 and Figure 35 show the comparison between the cup anemometer and the uncorrected lidar measurements and the FCR corrected lidar data, respectively, for the same dataset. The uncorrected lidar wind speed measurements underestimate the cup anemometer, by 4.1% on average; the average deviation is 1.1% larger than that observed in Figure 22. The FCR corrected lidar wind speed measurements overestimate the cup anemometer, by 1.5% on average. The coefficient of determination is higher for the FCR corrected data than for the uncorrected measurement.



**Figure 34** Uncorrected lidar wind speed at 78m vs cup anemometer wind speed at 77.5m. Dataset including FCR lidar wind speed data with an availability above 80% (Red: two parametric linear regression; Blue: one parametric linear regression forced through 0)

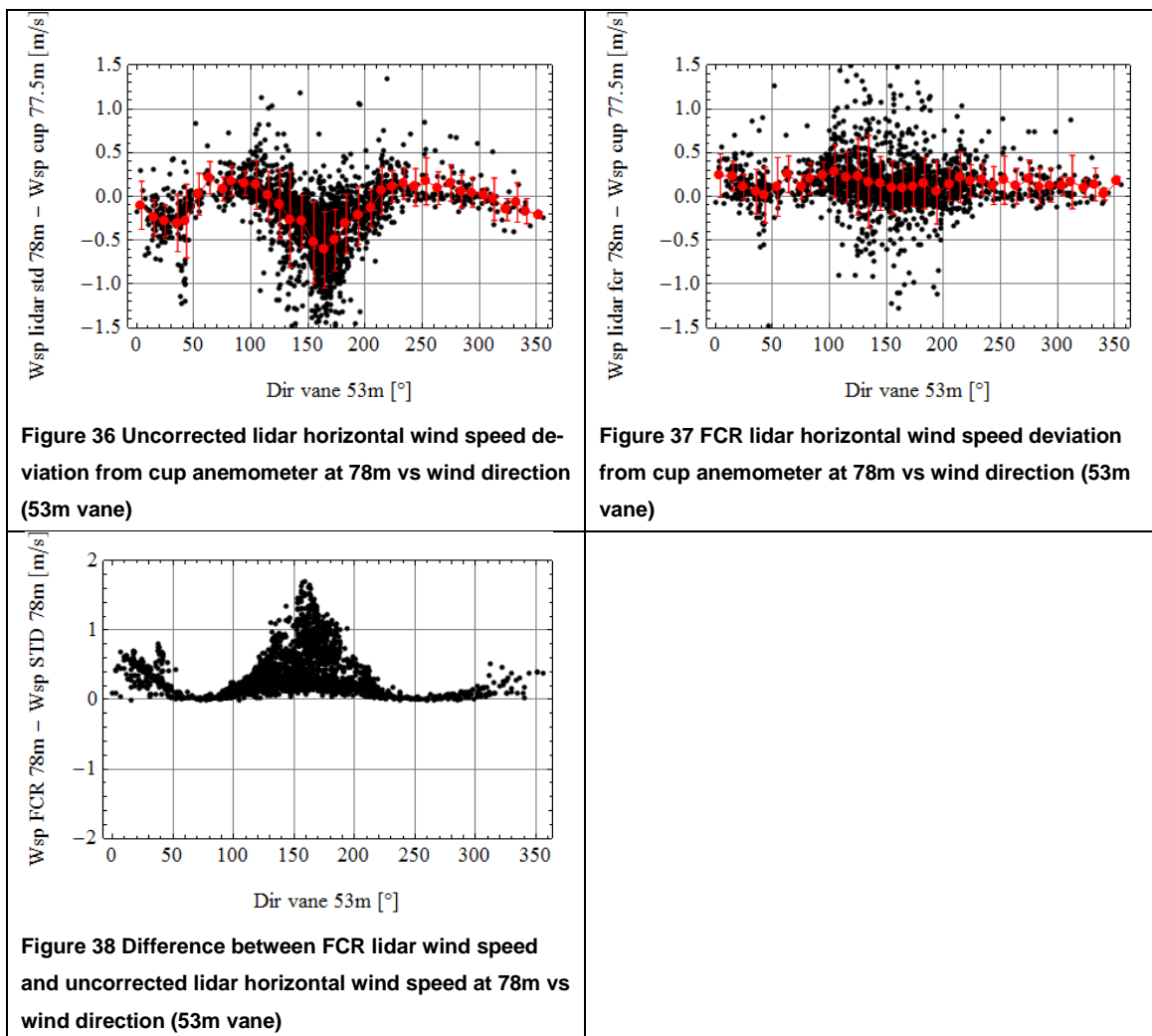


**Figure 35** FCR lidar wind speed at 78m vs cup anemometer wind speed at 77.5m. Dataset including FCR lidar wind speed data with an availability above 80% (Red: two parametric linear regression; Blue: one parametric linear regression forced through 0)

## Sensitivity to direction

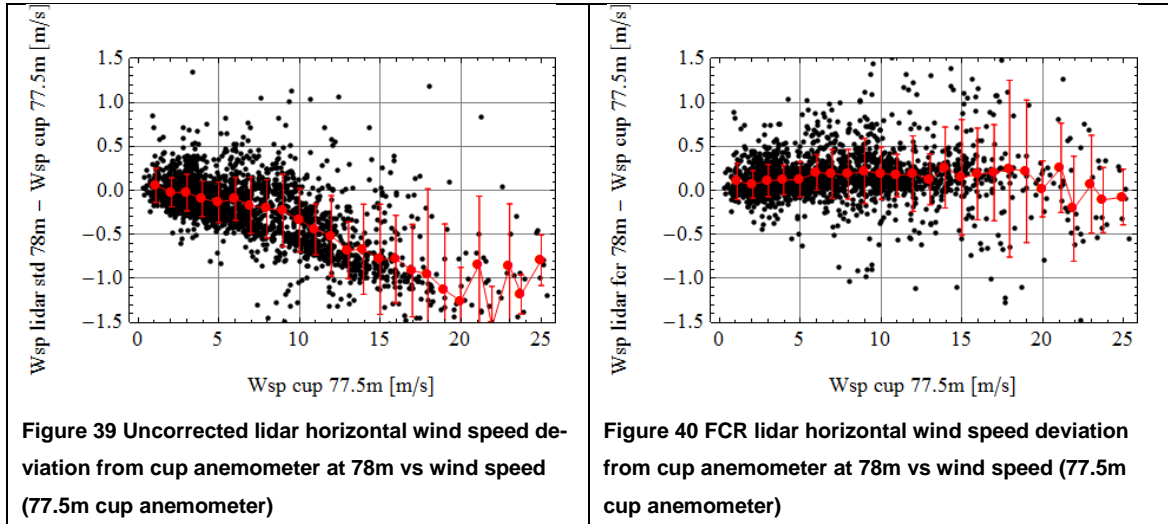
Figure 36 shows the deviation between the uncorrected lidar wind speed and the cup anemometer as a function of the wind direction, whereas Figure 37 shows the deviation between the FCR corrected wind speed and the cup anemometer. The clear negative deviation observed for uncorrected lidar wind speed in the sectors 130°-190° and 330°-30° do not appear for the FCR corrected wind speed. The FCR corrected wind speeds do not show any dependence on the wind direction; however the scatter is rather large between 100° and 200°. The deviation is slightly positive for all wind directions.

Figure 38 shows the difference between the uncorrected wind speed and the FCR corrected wind speed. As expected corrections were applied to data around the wind directions perpendicular to the local hill on which the lidar was installed (160°-340°) with larger correction around 160, the wind sector for which the largest deviations were observed. On the contrary, almost no correction was applied for the data with wind directions along the hill (70°-250°).



## Sensitivity to wind speed

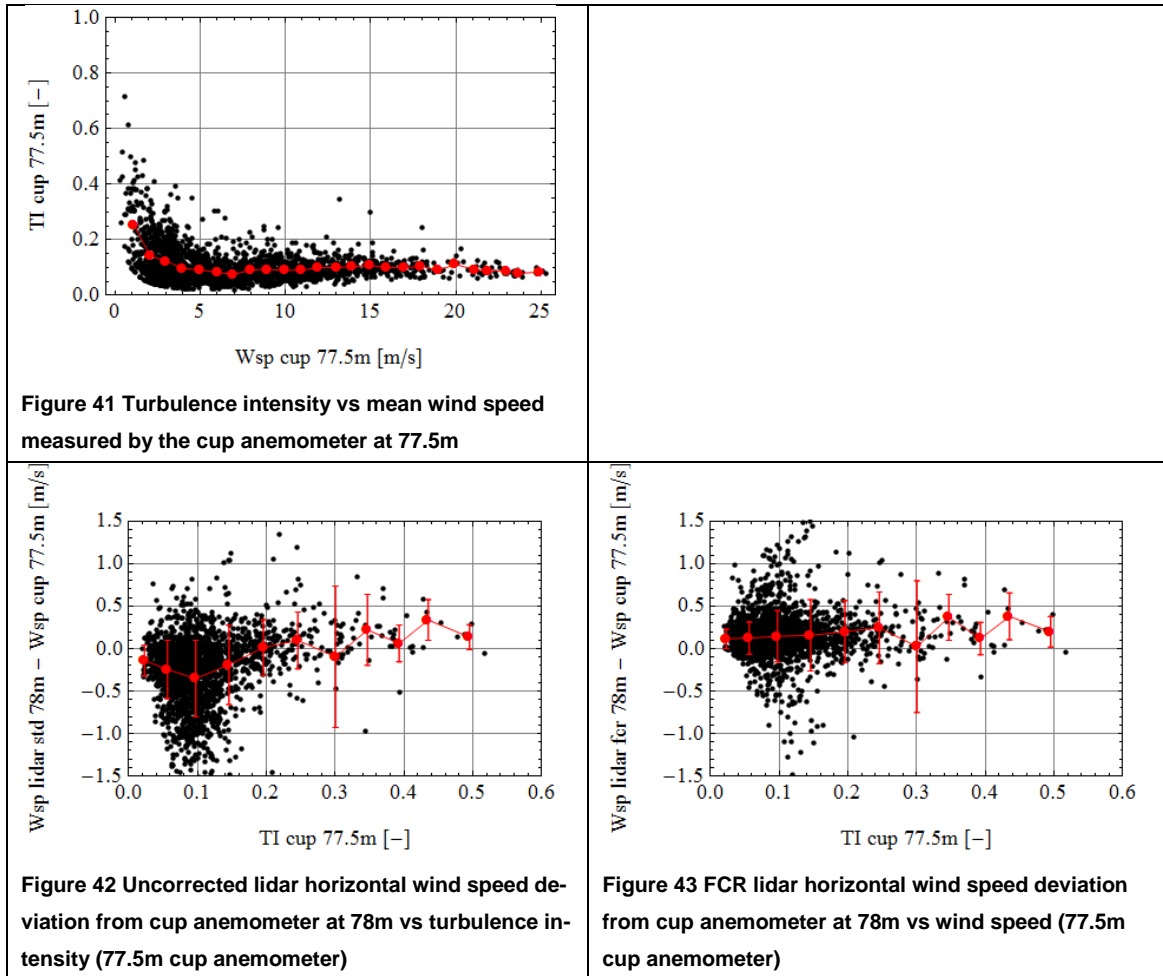
Figure 39 (resp. Figure 40) shows the deviation between the uncorrected lidar wind speed (resp. the FCR corrected wind speed) and the cup anemometer as a function of the wind speed. The deviation of the uncorrected lidar wind speed is negative for most of the wind speed range and the amplitude of the deviation increases with the wind speed. The deviation of the FCR corrected wind speed is slightly positive for most of the wind speed bins and tends to slightly increase with the wind speed.





## Sensitivity to turbulence intensity

The turbulence intensity was about 10.7% on average for this dataset and tends to decrease as the mean wind speed increases (Figure 41). In Figure 42, the deviation of the uncorrected lidar wind speed appears to be larger for low turbulence intensity however; this is probably related to the high wind speeds. In Figure 43, the deviation of the FCR corrected wind speed is not dependent on the turbulence intensity.



## Sensitivity to vertical shear

The vertical shear was estimated as the shear exponent assuming a power law between 55 and 75m. In Figure 44 to Figure 48, the shear exponent was derived from the two boom-mounted cup anemometers; since they are mounted on the same side of the mast, which has a constant section width, the mast effect is expected to be similar on both cup anemometers and therefore should not influence the shear exponent.

According to Figure 47, the largest deviations of the uncorrected lidar wind speed are observed for shear exponents between -0.2 and 0.3. This range of shear exponents includes all the data with high wind speeds (Figure 44); the large deviations are therefore probably related to the wind speed dependency observed in Figure 39.

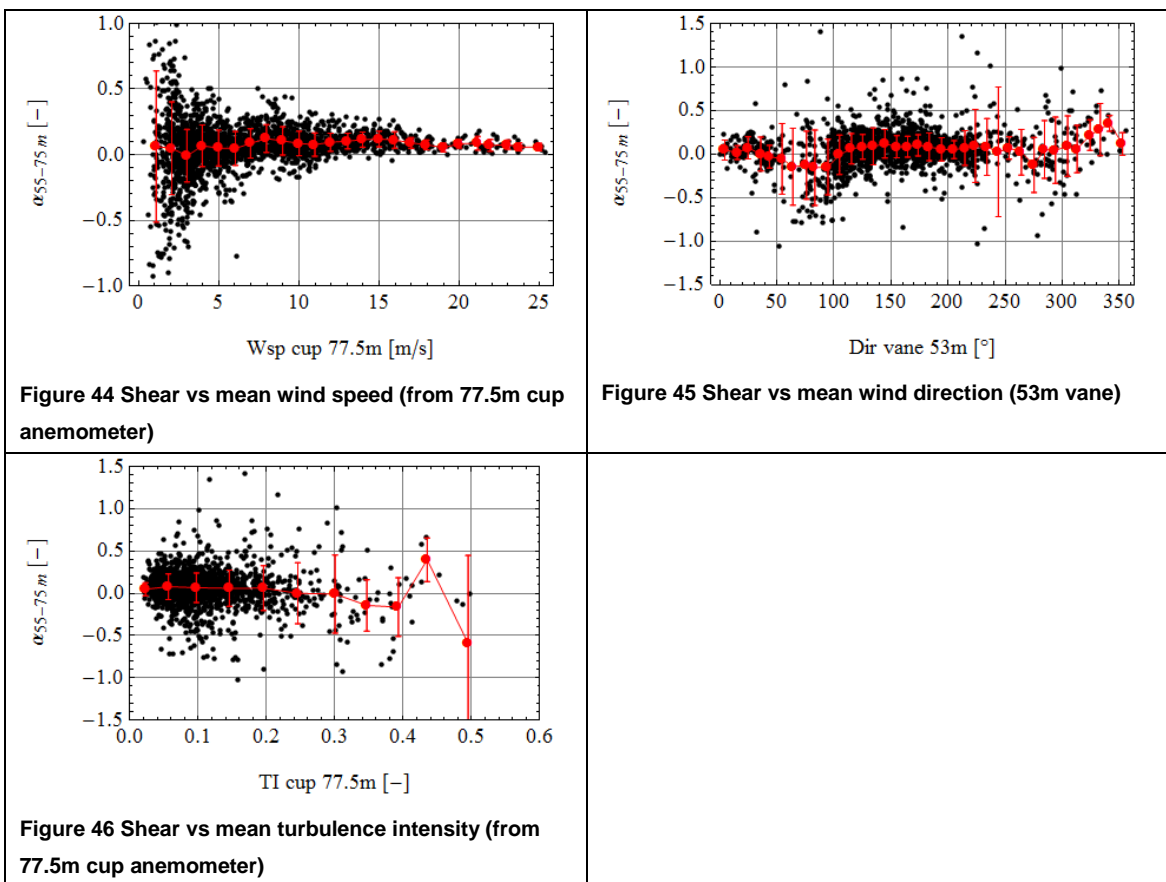
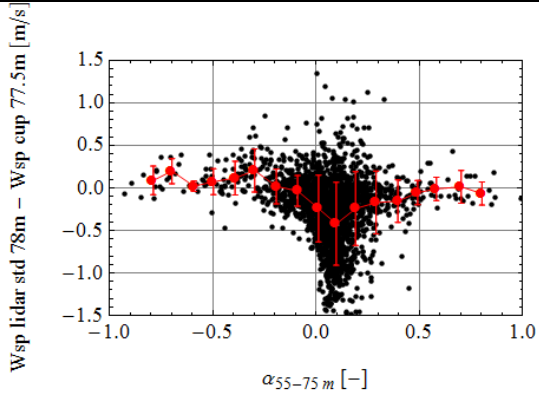


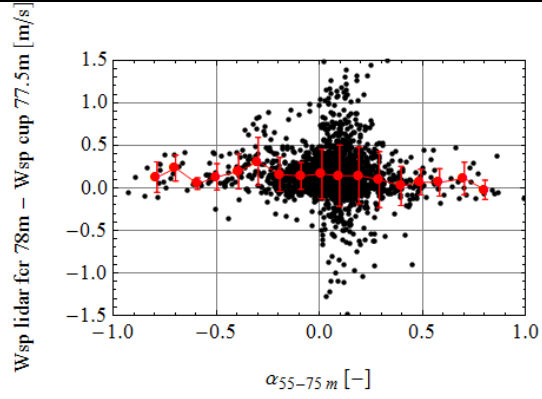
Figure 44 Shear vs mean wind speed (from 77.5m cup anemometer)

Figure 45 Shear vs mean wind direction (53m vane)

Figure 46 Shear vs mean turbulence intensity (from 77.5m cup anemometer)



**Figure 47** Uncorrected lidar horizontal wind speed deviation from cup anemometer at 78m vs shear exponent between 55m and 75m (from cup anemometers)



**Figure 48** FCR lidar horizontal wind speed deviation from cup anemometer at 78m vs shear exponent between 55m and 75m (from cup anemometers)

### 4.2.2 Comparisons at other heights

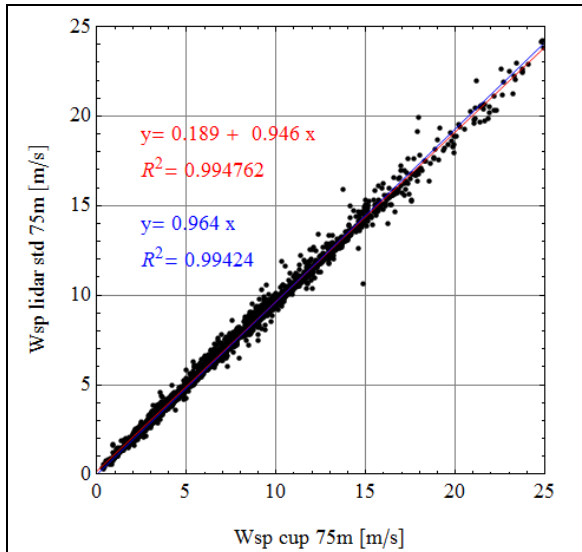
Similar comparisons between lidar wind speeds (uncorrected and FCR corrected) were done at 75m and 55m.

#### **Measurements at 75m**

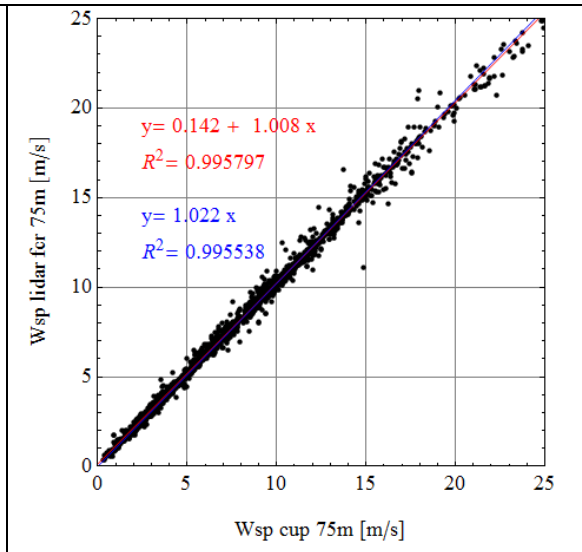
In order to compare the lidar measurements at 75m to the cup anemometer at 75m, the data for which the cup anemometer was in the wake of the mast (wind direction between 290 and 340) were excluded and the lidar data with a 10-minute availability at 75m below 80% were excluded.

The comparison results are similar to those at 77.5m:

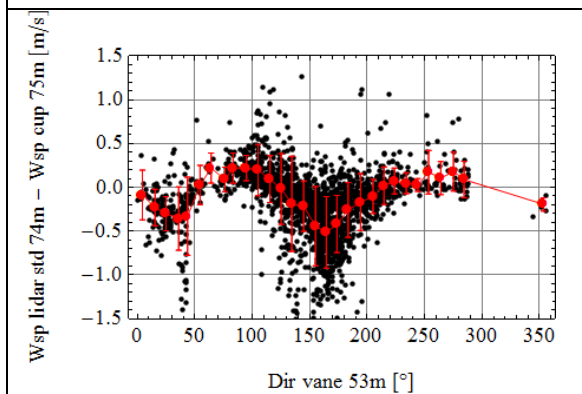
- The uncorrected lidar wind speed underestimates the cup anemometer wind speed by 3.6% on average (Figure 49) whereas the FCR corrected wind speeds overestimate the cup anemometer wind speed by 2.2% (Figure 50);
- The largest deviation of the lidar uncorrected wind speed occur for wind directions between 130 and 190 (Figure 51) whereas the deviation of the FCR data is much less dependent on the wind direction (Figure 52);
- The lidar uncorrected wind speed deviation is negative and increases in amplitude with the wind speed (Figure 53), while the FCR wind speed deviation is slightly positive and increases only slightly with the wind speed (Figure 54).



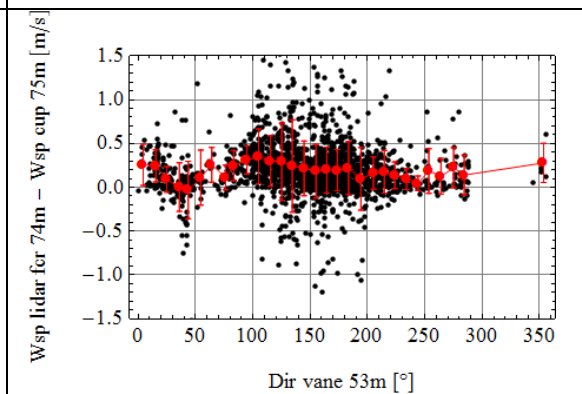
**Figure 49** Uncorrected lidar wind speed at 75m vs cup anemometer wind speed at 75m. Dataset including FCR lidar wind speed data with an availability at 75m above 80%: 2172 data (Red: two parametric linear regression; Blue: one parametric linear regression forced through 0.)



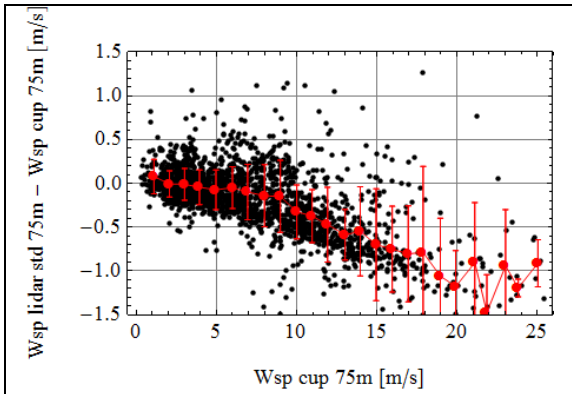
**Figure 50** FCR lidar wind speed at 75m vs cup anemometer wind speed at 75m. Dataset including FCR lidar wind speed data with an availability at 75m above 80%. (Red: two parametric linear regression; Blue: one parametric linear regression forced through 0.)



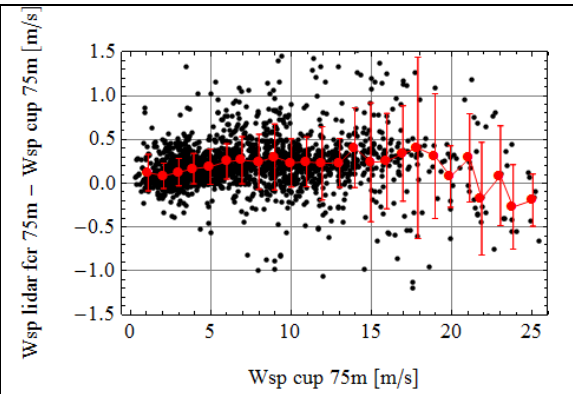
**Figure 51** Uncorrected lidar horizontal wind speed deviation from cup anemometer at 75m vs wind direction (53m vane)



**Figure 52** FCR lidar horizontal wind speed deviation from cup anemometer at 75m vs wind direction (53m vane)



**Figure 53** Uncorrected lidar horizontal wind speed deviation from cup anemometer at 75m vs wind speed (75m cup anemometer)

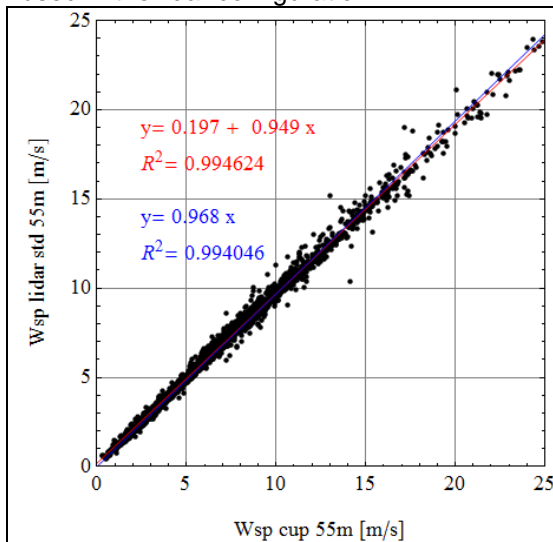


**Figure 54** FCR lidar horizontal wind speed deviation from cup anemometer at 75m vs wind speed (75m cup anemometer)

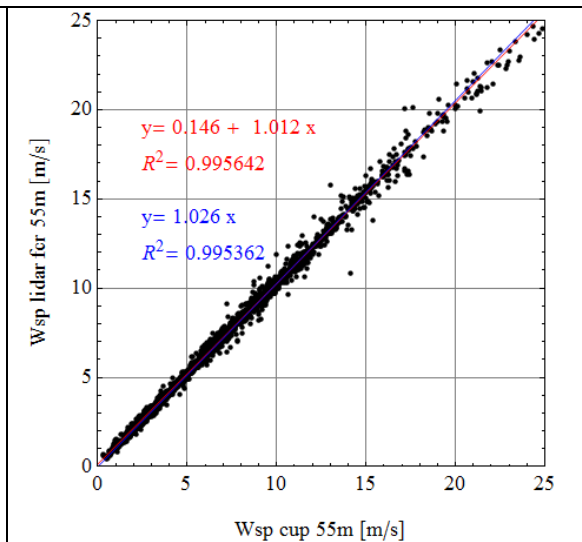
## Measurements at 55m

In order to compare the lidar measurements at 55m to the cup anemometer at 55m, the data for which the cup anemometer was in the wake of the mast (wind direction between 300° and 340°) were excluded and the lidar data with a 10-minute availability at 55m below 80% were excluded. The comparison results are similar to those at 75m (see Figure 55 to Figure 62).

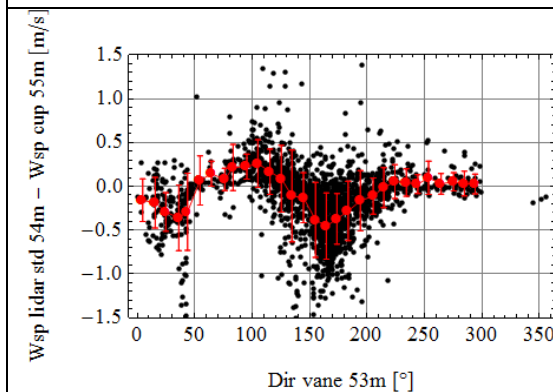
In addition the direction measured by the lidar at 55m was compared to the direction from the wind vane at 53m. The comparisons of the lidar uncorrected direction and the FCR corrected direction are not identical but very similar (see Figure 61 and Figure 62). In both cases, the linear regression results in an offset of about 11°. Part of the offset might be due to a bias in the offset used in the lidar configuration.



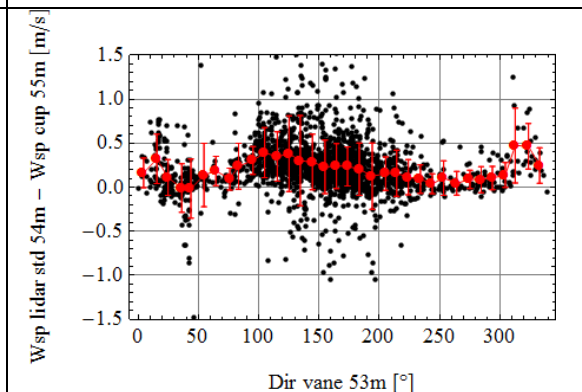
**Figure 55** Uncorrected lidar wind speed at 55m vs cup anemometer wind speed at 55m. Dataset including FCR lidar wind speed data with an availability at 55m above 80%: 2209 data (Red: two parametric linear regression; Blue: one parametric linear regression forced through 0.)



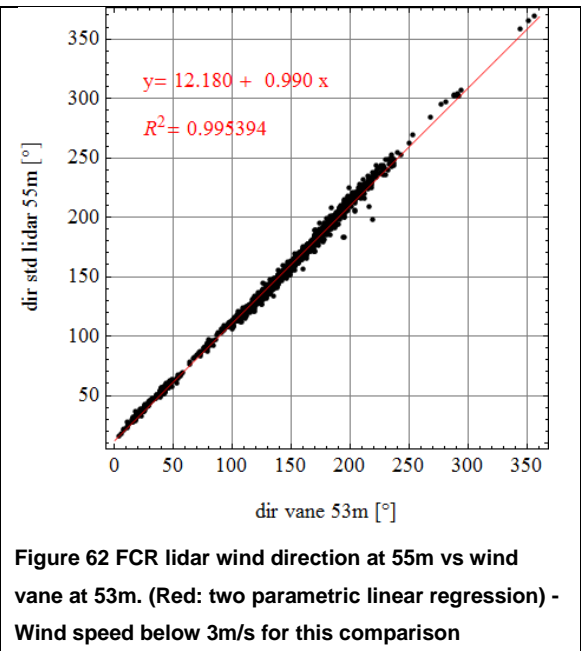
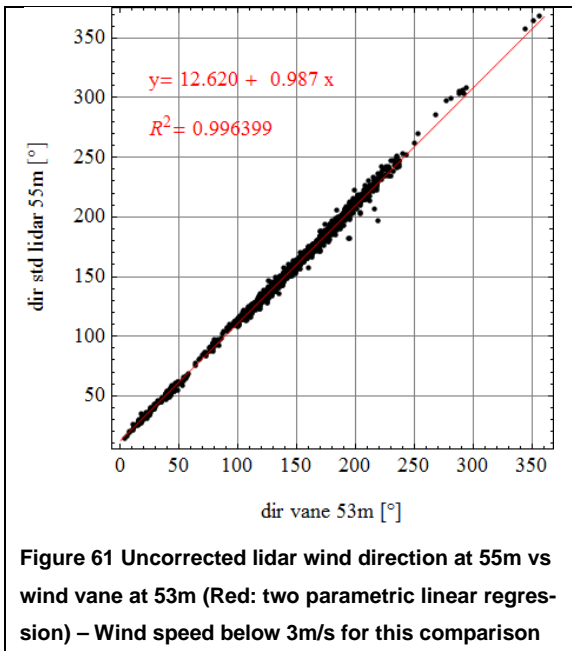
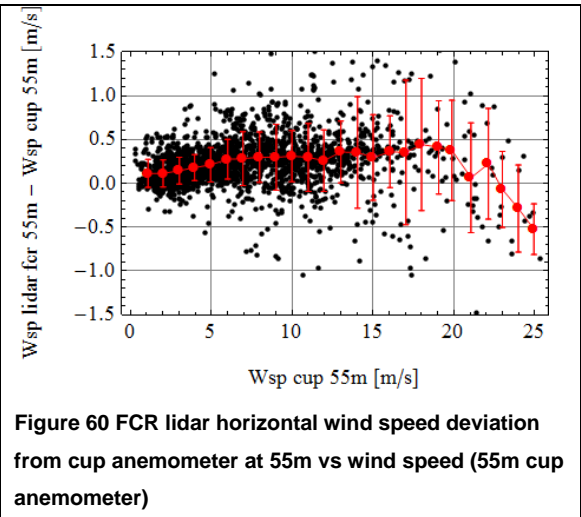
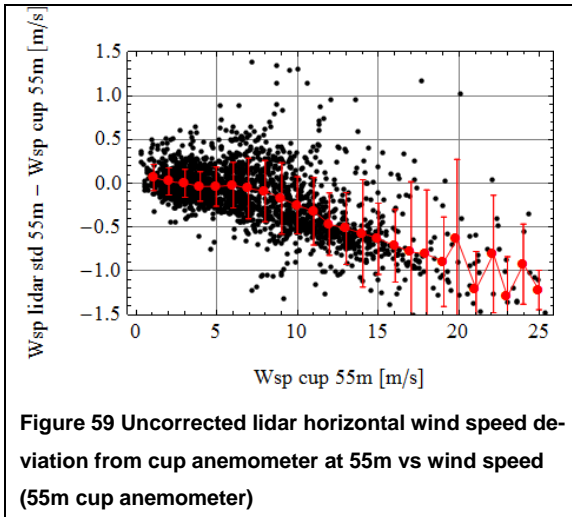
**Figure 56** FCR lidar wind speed at 55m vs cup anemometer wind speed at 55m. Dataset including FCR lidar wind speed data with an availability at 55m above 80%. (Red: two parametric linear regression; Blue: one parametric linear regression forced through 0.)



**Figure 57** Uncorrected lidar horizontal wind speed deviation from cup anemometer at 55m vs wind direction (53m vane)



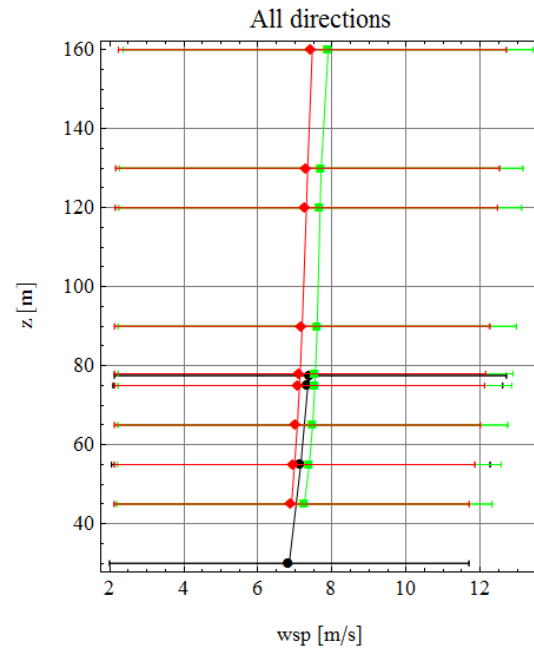
**Figure 58** FCR lidar horizontal wind speed deviation from cup anemometer at 55m vs wind direction (53m vane)



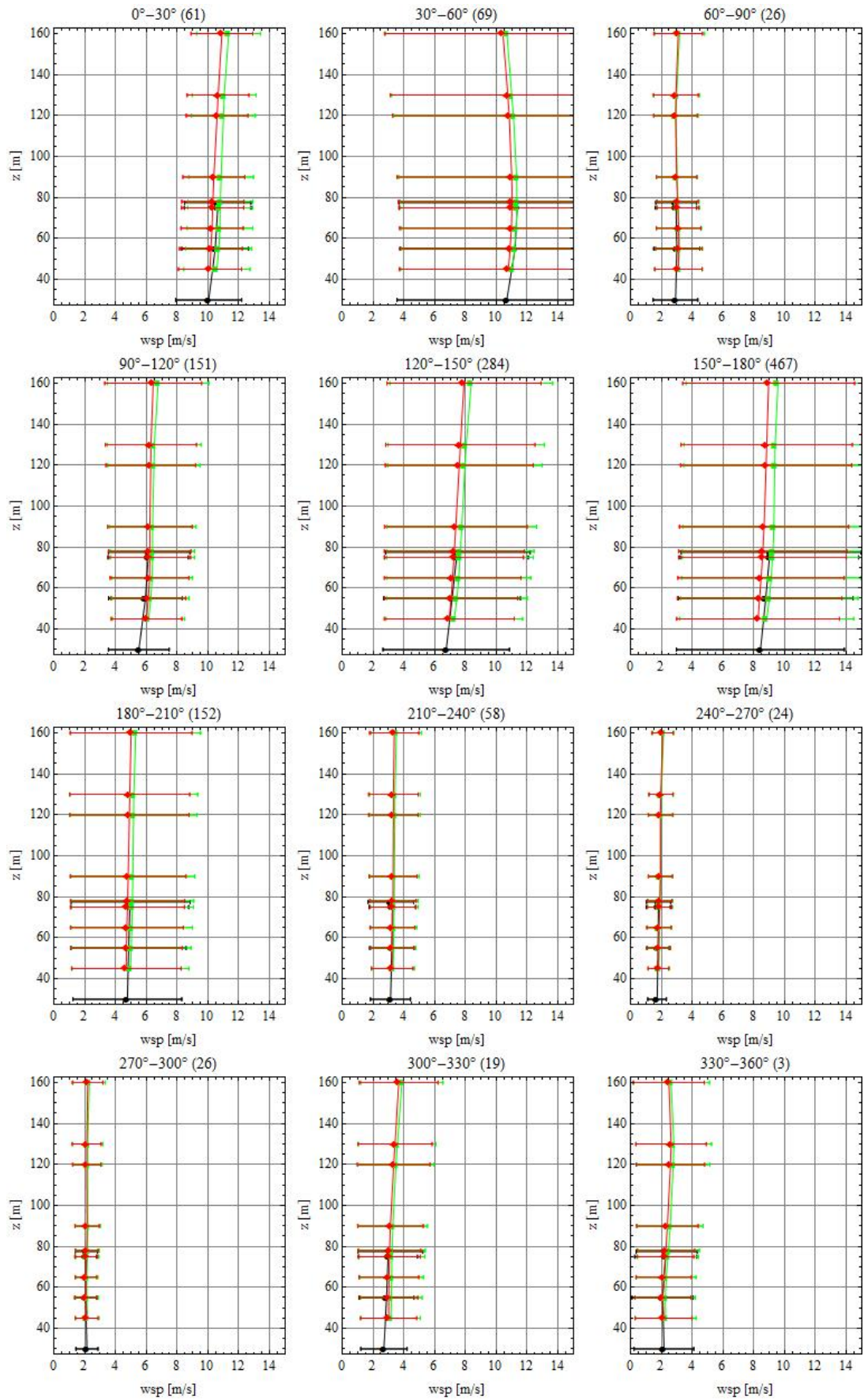


### 4.2.3 Wind profile and shear

The average wind speed profiles per wind sector measured with the mast between 30 and 77.5m and with the lidar between 45 and 160m are displayed in Figure 64.

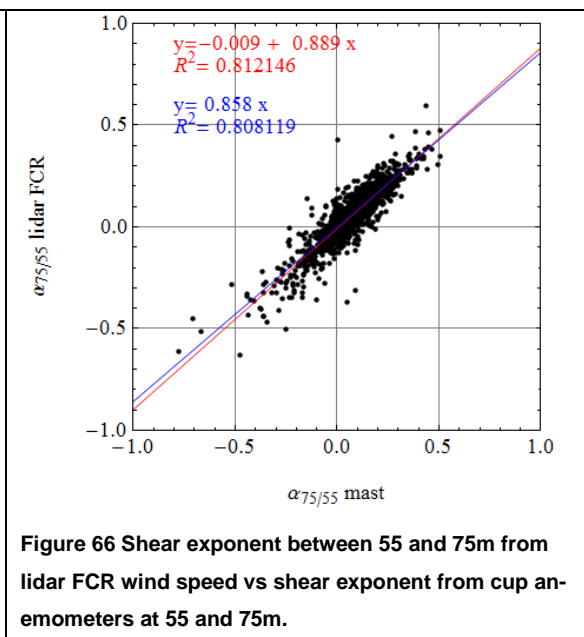
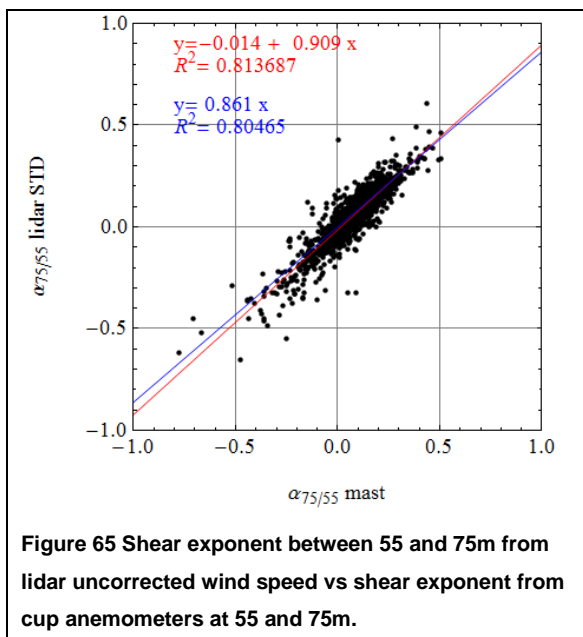


**Figure 63 Average wind speed profile. Black: met mast, Red: uncorrected lidar, Green: FCR corrected lidar. The wind sector is indicated at the top of each plot**

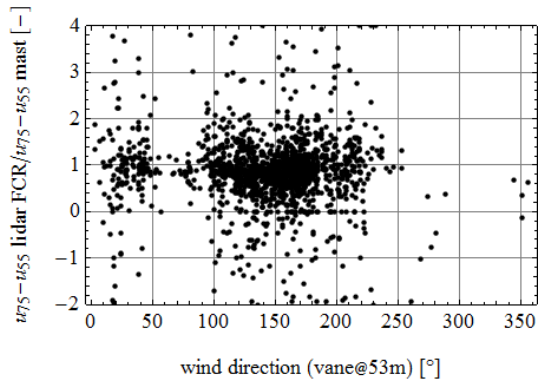
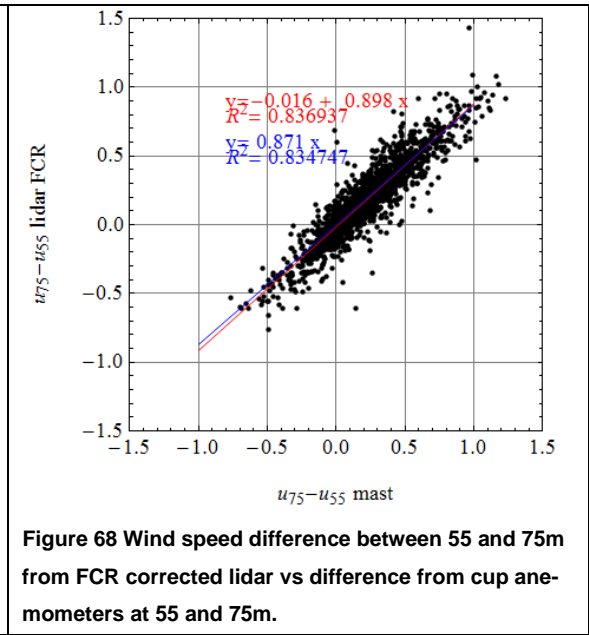
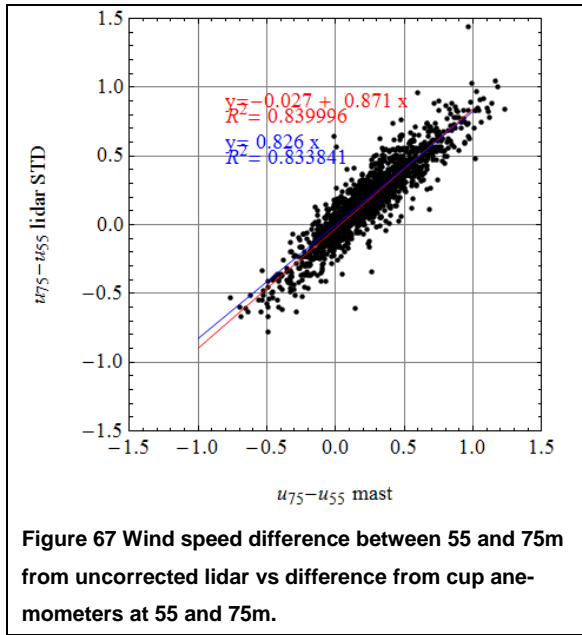


**Figure 64 Average wind speed profile per 30° wind direction bin. Black: met mast, Red: uncorrected lidar, Green: FCR corrected lidar. The wind sector is indicated at the top of each plot and with the number of data within that sector in parenthesis.**

Figure 64 shows the comparison between the shear exponent derived from the lidar uncorrected wind speed and the shear exponent derived from the cup anemometers at 55 and 75m. Figure 65 shows the same comparison for the shear exponent derived from the lidar FCR corrected wind speed. In both cases the lidar shear exponent has a clear correlation with the mast shear exponent, but there is a large scatter. However the FCR corrected data do not compare better to the mast data than the uncorrected lidar data, the linear regression even results in a slightly lower slope for the FCR corrected data than for the uncorrected data.



However it was noticed in Figure 64 that the averaged profiles do not typically follow a power law. Therefore the wind speed difference between 75m and 55m was directly compared for the various types of measurements (Figure 66 and Figure 67). In this case the FCR lidar measurements correlate slightly better than the uncorrected lidar measurements. As shown in Figure 68 no dependence on wind direction can be observed. Note, for comparison, that at Høvsøre, Denmark (flat terrain), for westerly wind, the gain observed for the wind speed difference is about 1.06 and the coefficient of determination about 0.95.



## 5. Discussions

### 5.1 Operational difficulties

A measurement campaign was carried out with a Windcube v2 lidar placed next to a 77.5m met mast in complex terrain, at Hrgud, in Bosnia and Herzegovina.

The lidar was connected directly to the electrical grid via the local power line. However this power line has been hit by lightnings several times during the measurement campaign, which has destroyed the 240V to 24V convertor twice and has damaged the lidar unit first deployed on this site. Although this solution of power supply was chosen because it appeared as the most stable one (compared to batteries or diesel generated that need to be regularly replaced or refilled), these unfortunate events demonstrate the importance of protecting the power supply of the lidar from an exposed power line.

The lidar software also happened to be unstable, since several periods of data were missing although the system had power. Furthermore, very often uncorrected wind speed and direction data could be provided but not the FCR corrected data. One issue was detected to be related to daily synchronization of the lidar system; this issue was solved in November 2013.

Finally, due to the unstable network connection on-site, the data could not be transferred via the internet but had to be collected manually when Impro Impex went on site, which could not be done on a regular basis because of the remote location of the site. A more regular data monitoring may have helped to detect the failure and react faster to fix them.

For these various reasons, the lidar measurements were interrupted many times and the data collected are discontinuous. The measurement campaign had to be extended by 3 months (compared to the initial plan) to collect a representative dataset. A dataset of more than 2000 data with FCR correction were collected with wind speed and direction distributions representative of the site.

### 5.2 Applying Lidar measurements in complex terrain to reduce uncertainties on AEP

#### 5.2.1 Vertical extrapolation

The FCR improved the accuracy of the lidar measurements for this measurement campaign. At the Hrgud site the met mast was measuring very close to the hub height and therefore the vertical extrapolation uncertainty was rather limited. However, useful information was gathered about the wind shear above hub height; e.g. it reduced the concern about the occurrence of low level jets or negative shear; since none has occurred during the measurement periods with the lidar. The FCR corrected lidar profile measurements between 40 to 200m were used to validate the simulated profiles obtained with the CFD model used in the resource assessment.

Measurements taken with a Windcube with FCR at complex wind farm sites used as supplement to met masts could probably reduce the vertical extrapolation uncertainty for higher hub

heights or where lower met masts are installed; and eventually they could help reducing the uncertainties on AEP estimate. Nevertheless, complex sites can be very different and the FCR technique being proprietary of Leosphere, it is not possible to generalize the results.

### 5.2.2 Horizontal extrapolation

The horizontal extrapolation of the wind speed (i.e. variation of the wind speed from one location to another within a large site) is one of the primary sources of uncertainty in energy yield estimate with the vertical extrapolation discussed above. For instance the horizontal extrapolation and model uncertainty at the Hrgud site is approximately 5 % on AEP. Measuring at different locations on a complex site, such as the Hrgud site, for limited periods of time (e.g. 2 to 3 months) with a lidar could probably help reducing the uncertainty related to the horizontal extrapolation. The duration of the measurement at each specific location would of course depend on the specific wind conditions at the site, and on the seasonal variations.

Furthermore, complex sites are often difficult to access and require additional investments to prepare the installation site for a met mast. A lidar is relatively fast to move and install compared to a met mast.

It has been not possible to test this measurement strategy at the Hrgud test site because of lidar availability time constraints (which has been significantly reduced due to the lightning incidents).

## 6. Conclusions

The lidar uncorrected wind speed was in general lower than the wind speed measured by the cup anemometer at the same height by about 4%. This is consistent with the model predicting an underestimation of the wind speed by the lidar when the flow goes over a hill, i.e. the flow has a positive tilt angle on one side and a negative angle on the other, and the lidar is on top of the hill [1].

The lidar deviation was observed to be direction dependent; the largest deviation occurring around  $165^\circ$ . This direction more or less coincides with the direction perpendicular to the hill on which the lidar and the mast were installed; it is therefore the directions in which the local terrain is the most inhomogeneous. Based on a rough analysis of the surrounding topography, it seems that the lidar deviation is mainly affected by the topography around the lidar within a radius of 500m but the major features of the topography within a larger radius has also some influence. This would need to be further investigated with numerical tools.

The lidar uncorrected speed deviation was also observed to increase with the wind speed.

The FCR corrected wind speeds were higher than the cup anemometer wind speed by about 1.5%. This deviation was not dependent on the wind direction and slightly increasing with the wind speed. The FCR was therefore seen to (over-)compensate for the effect of the topography on the wind speed reconstruction by the lidar.

The positive deviation of the FCR corrected wind speeds compared to cup anemometer measurements have already been observed in several other measurement campaigns [6, 7]. Such analysis should be completed by estimating the expected error or uncertainty in the cup anemometer measurements due to the inflow angle or the turbulence intensity, which can in some cases make the cup anemometer underestimate the wind speed.

The lidar uncorrected wind directions compared well to the wind vane and the FCR correction had no significance influence on this comparison.

Finally the shear exponent derived from the lidar wind speeds, both without and with FCR, only compared relatively well with the shear exponent from the mast mounted cup anemometers.

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7. Operation of the Windcube V2 lidar at CRES Test Station, Test Report 546-01B, CRES, February 2011



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