

Comparing measurements of the horizontal wind speed of a 2D Multi-Lidar and a cup anemometer

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Abstract. Wind measurements of a 2D Multi-Lidar and a mast mounted cup anemometer are compared in this study. Average wind speed and direction as well as the turbulence intensity of the wind speed are considered. Data analysis is mainly performed using standard regression analysis on 10 minute average data and the calculation of the power spectral density. The results show a good agreement regarding wind speed and direction and the turbulence intensity of the horizontal wind.

1. Introduction

Lidar wind profilers are more and more used for wind measurements during site assessment of wind turbines. There are big differences between the remote sensing method lidar and standard anemometry measuring “in situ”. Special features of lidars are e.g. the low spatial resolution in line of sight (LoS) direction, the measurement of the LoS component of the wind vector and the resulting need to apply special scan techniques. Despite these differences, lidar measured wind speeds averaged on 10 minute intervals agree well with standard anemometry. This is at least the case for measurements with cup or sonic anemometers mounted on a meteorological mast in flat terrain (among others [1, 2]). The measurement of turbulence with lidars however shows a poor agreement with cup or sonic anemometers (e.g. [1, 3]). One of the main reasons for inconsistent turbulence results is assumed to lay in the scan technique called velocity azimuth display (VAD). This is applied by most lidar wind profilers to measure the vertical profile of the horizontal wind above the device. For a VAD scan wind speeds are calculated from measurements in different places at different times.

An approach to overcome the limitations of the VAD scan and to obtain wind speed and turbulence with more accuracy is to resolve the two horizontal components or the full 3D wind vector by measuring two or three independent LoS wind speeds in the same volume. This can be achieved by using several synchronized lidar systems operated in different locations. Just few experiments using synchronized lidars have been reported so far. Previously measurements with two Doppler lidars simultaneously with a range resolution > 100 m have been made by [4] comparing the results to a numerical model. Comparisons of a 3D short range multi lidar with a 3D sonic anemometer were first made by [5]. Recently measurements with two synchronized long range Doppler lidars have been reported in [6].

In this study, two scanning pulsed long range Doppler lidars were located in different places, each about 800 m away from a meteorological mast, staring in the direction of a cup anemometer



on top.

This paper describes the measurement setup, presents the results of the data analysis and discusses and concludes on the results.

2. Methods

2.1. 2D Multi-Lidar

A 2D Multi-Lidar system¹ consisting of two scanning pulsed long range Doppler lidars Windcube200S (WLS200S) manufactured by the French company Leosphere was used in this study. The two lidars were connected via WiFi allowing for synchronization and remote control. For synchronizing the lidar's internal clocks, just the standard simple network time protocol (snTP) client of the MS Windows7® operating system was available. The clocks were synchronized at least hourly on a time server in the local network, so the synchronization error between the lidars was up to 2 s the maximum. The 2D scanners are able to steer the laser beams of the systems into the desired direction in integer angle steps. The range of each lidar in LoS direction in the used configuration is up to three kilometers, depending on the atmospheric conditions. The length of the laser pulses was 200 ns leading to a spatial resolution in the line of sight direction of approx. 40 m. Such a measurement volume in a specific range is called range gate. In the following, the center of the considered range gate is called the measuring point.

The data used in this study was collected during the first test setup of the 2D Multi-Lidar.

Fundamentals about lidar measurements can be found e.g. in [7] or in an article written by the manufacturer of the used systems [8].

2.2. Site and meteorological mast

The 100 m high meteorological mast is located in flat terrain with very few trees in the north of Germany. The cup anemometer (Thies, last calibration less than one year before measurements) was mounted on top of the mast, so no mast effects are to be considered while the influence of a thin lightning rod topping the sensor is neglected.

Wind directions were measured with two wind vanes (Thies, last calibration less than one year before measurements) located on the western and eastern side of the mast (282° and 103°) on 2.5 m long booms in 95.7 m and 95.9 m height. For the sector of wind directions from 13° to 193° data from the eastern vane was used, for all other directions the western vane. All data from the met mast was sampled with 20 Hz.

The two lidars were located in the south-west and south-east of the met mast. Two large multi megawatt wind turbines were located near by the mast making it necessary to distinguish between sectors with free flow and wake sectors. Wind directions from a sector of 40° , with the line from the mast to the turbine being the center line, were marked as wake. Figure 1 shows the measurement site from a top view.

2.3. Measurement setup

Measurements were taken out in staring mode. In this configuration the lidar's scanners do not move while measuring. The data rate was 2 Hz averaging over 10,000 laser pulses for each data point. The lidar's scanners were pointed in the direction of the top cup anemometer on the met mast with an error in the azimuth and elevation of maximum 0.5° due to the full integer steps in the angle settings of the lidars. The LoS distances from lidar 1 and 2 to the cup anemometer were 752 m and 800 m respectively. The lidars were aligned to the north direction using the system's internal compass (compass error 2°). An analysis of all alignment errors of the lidar's

¹ Several names have been used in the past for similar setups. Comparable names would be e.g. "Dual lidar" or "2D Windscanner".

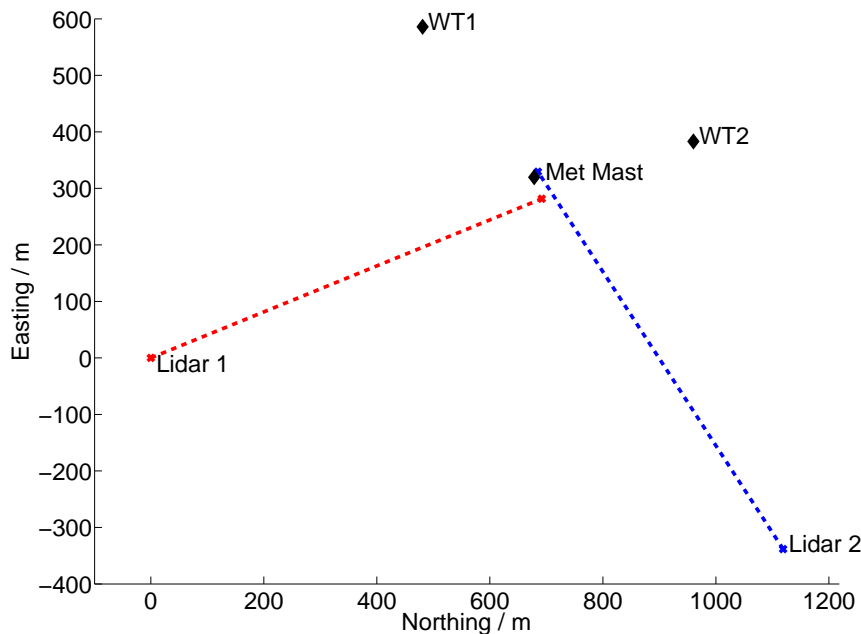


Figure 1. Sketch of the measurement site from a top view. The positions of the two lidars, the meteorological mast and the two multi megawatt wind turbines are marked. The azimuth directions and the measurement points of the lidars are shown by dashed lines and crosses. The measurement point of lidar 1 (red) lies 7.5 m below and the measurement point of lidar 2 (blue) 15.5 m below the height of the cup anemometer.

laser beams revealed high deviations from lidar 1 and lidar 2 measurement points and the cup anemometer (horizontal deviation up to 40 m, vertical deviation lidar 1: -7.5 m, lidar 2: -15.5 m with respect to the cup anemometer height). Deviations in the horizontal position are not seen very critical since the azimuth directions the scanners looked at are known and could be corrected for and the wind field can be assumed to be constant in the same altitude. The deviations in the vertical direction are seen much more critical due to wind shear with altitude. Nevertheless, no corrections to transform the measured speeds to the height of the cup anemometer were applied due to the lack of knowledge about the atmospheric stratification.

The two lidars as well as the measurement system of the met mast were synchronized about hourly via ntp on the same time server on the internet. The synchronization error between the 2D Multi-Lidar and the met mast is less than one second.

2.4. Data analysis

The measurement campaign started in the middle of March 2012 and lasted until the end of June 2012. Due to technical availability and other tasks performed with the system, appropriate data for this study was collected on 17 days in this period. 1591 ten minute intervals were analyzed regarding averaged wind speeds and directions, 842 of them from free sectors. The power spectral density (PSD) was calculated using 624 ten minute intervals from free sectors.

The steps to process the LoS velocities v_{LoS} being measured by the two lidars to obtain the direction and the magnitude of the horizontal wind as measured by a cup anemometer and a wind vane were the following: first the LoS velocities were filtered on the carrier to noise ratio (CNR) of the measurement using a very conservative threshold of -22 dB and on very few outliers (non-physical high peaks in the time series). Since the lidar's clocks were synchronized but not the starting times of the measurements, the time stamps of the data were rounded to half seconds (0.5 s) to obtain synchronous data points. The error in the time stamps resulting is less than a quarter of a second (≤ 0.25 s).

To estimate the horizontal wind speed the horizontal components $v_h = v_{LoS} / \cos(\beta)$ of each lidar's LoS velocity was calculated using the elevation angle β of the scanner. For this the assumption of no vertical wind speed ($w = 0$) was made. For the long term this is certainly right

in flat terrain. But vertical fluctuations caused by convection will contaminate the measurement of the horizontal wind for the single measurement. The vertical component w contributes to the LoS velocity with the sine of the elevation angle. So for elevation angles of the lidars of less than 10° the vertical fluctuations cause low fluctuations in the LoS and so in the calculated horizontal component. VAD Lidars using typically elevation angles of 60° to 75° suffer much more from this effect [9].

Next the horizontal wind components u and v were calculated (u points in the x or north direction, v in the y or east direction) from the horizontally projected radial speeds of both lidars using the solution of the linear system

$$\begin{bmatrix} v_{h1} \\ v_{h2} \end{bmatrix} = \begin{bmatrix} \sin(\gamma_1) & \cos(\gamma_1) \\ \sin(\gamma_2) & \cos(\gamma_2) \end{bmatrix} \cdot \begin{bmatrix} u \\ v \end{bmatrix} \quad (1)$$

reading

$$u = \frac{v_{h1} \cos(\gamma_2) - v_{h2} \cos(\gamma_1)}{\sin(\gamma_1 - \gamma_2)} \quad \text{and} \quad v = \frac{v_{h2} \sin(\gamma_1) - v_{h1} \sin(\gamma_2)}{\sin(\gamma_1 - \gamma_2)} \quad (2)$$

using the azimuth angles γ_1 and γ_2 of Lidars 1 and 2 respectively. From u and v the wind direction ϕ and horizontal wind speed u_{hor} were calculated.

Each day with valid data was divided into 10 minute intervals. Just intervals with at least 50% valid measurement points were used for the regression analysis. This low value was chosen due to the limited amount of 10 minute data sets. The PSD was calculated from the 10 minute time series with at least 90% valid data points available. On each selected interval the mean wind speed \bar{u}_{hor} , the turbulence intensity Ti and the mean wind direction $\bar{\phi}$ were derived from the data of the cup anemometer/ wind vane and the 2D Multi-Lidar. Before calculating the PSD all invalid or missing points in the 10 min time series were replaced by interpolated values.

Scatter plots of lidar data over cup anemometer data were made for mean wind speeds, the turbulence intensities and the mean directions, separating free sectors and wake sectors. Linear regression fits with and without offsets ($y = a + bx$ and $y = mx$) were calculated using the data from the free sectors, from the wake sectors and all data together. The coefficient of determination R^2 was given for each fit.

The power spectral density was calculated on ten minute intervals without applying a window function.

3. Results and discussion

All results have to be seen with the background regarding the deviations of the desired LoS directions and the limited amount of data collected.

3.1. Wind speed

Figure 2 shows a scatter plot of the 2D Multi-Lidar's ten minute average horizontal wind speeds vs. the cup anemometer's and the regression analysis. The regression reveals an agreement in the free sectors between cup anemometer and 2D Multi-Lidar almost as good as achieved before by standard profilers in flat terrain [1, 2]. Regarding the alignment errors this is a good result. As expected the agreement in the wake sectors is worse than in the free sectors due wake turbulence and shear affecting both measurement systems.

3.2. Wind direction

Figure 3 shows the horizontal wind direction measured by the lidars over those of the wind vanes and the regression analysis. The agreement between both measurements in the free sectors is very good (slope $m = 0.997$, offset $b = -0.13^\circ$ for free sectors). This is comparable to results of

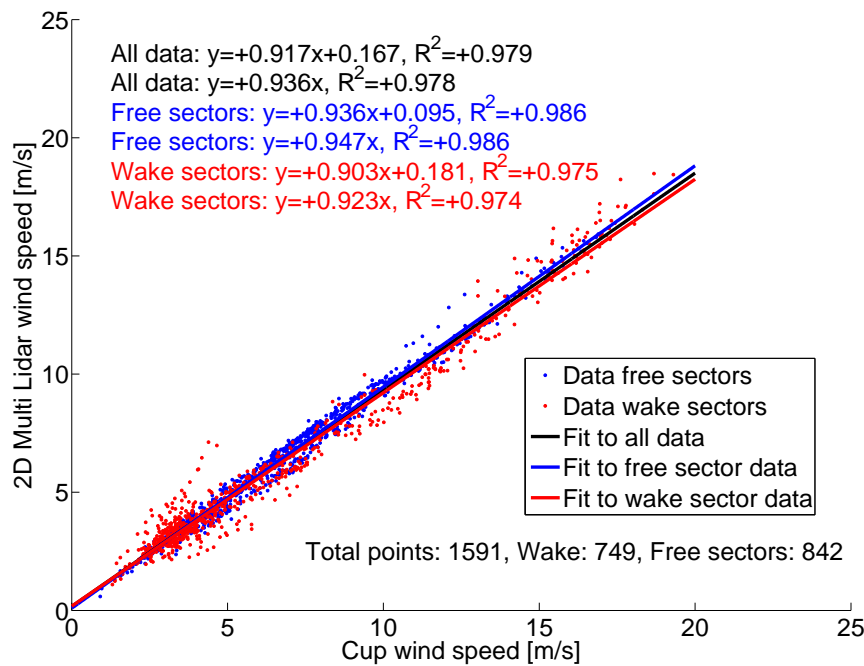


Figure 2. Scatter plot of the measured horizontal wind speeds of the 2D Multi-Lidar over the cup anemometer for 10 minute intervals.

VAD profilers. In the wake sectors especially the offset is bigger ($m = -7.66^\circ$) than in the free sectors.

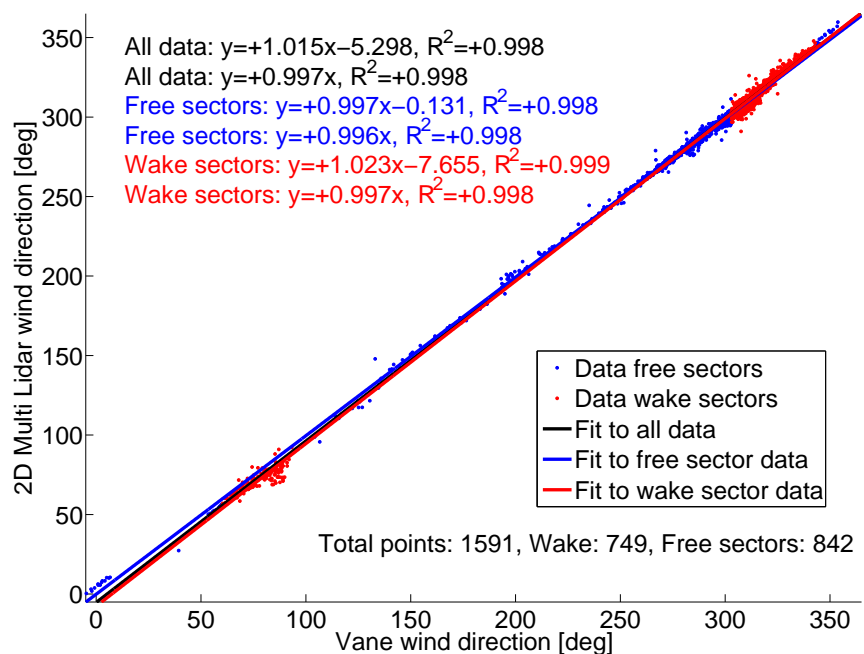


Figure 3. Scatter plot of the measured wind direction of the 2D Multi-Lidar over the wind vane for 10 minute intervals.

3.3. Turbulence

Figure 4 shows the turbulence intensity of the lidar data over the one derived from the cup data and the regression analysis. The agreement in the wake sectors is poor (slope $m = 0.769$, offset $b = 0.027$, $R^2 = 0.652$), but in the free sectors a very good agreement is found (slope $m = 0.977$, offset $b = -0.006$, $R^2 = 0.87$). The coefficient of determination R^2 is relatively low due to the

high scatter in the data. Nevertheless, these values are already better than those measured with VAD lidars. To further improve especially the turbulence measurements of the 2D Multi-Lidar a better filtering of longer time series should be done, since wake turbulence will still influence intervals marked as free sectors. In the wake sectors, the reason for the bad agreement is seen in the different measurement volumes of the two devices. The cup anemometer measures in a volume with a diameter of ≈ 0.1 m, the 2D Multi-Lidar gains information from a volume with a length scale of ≈ 40 m. While the cup anemometer just sees or not sees the wake's turbulence, there are many cases when the measurement volume of the lidar is partly intersected by wakes. This makes it harder to distinguish between wake and free sectors for both sensors at a time.

As another comparison between turbulence measurements figure 5 shows the averaged power

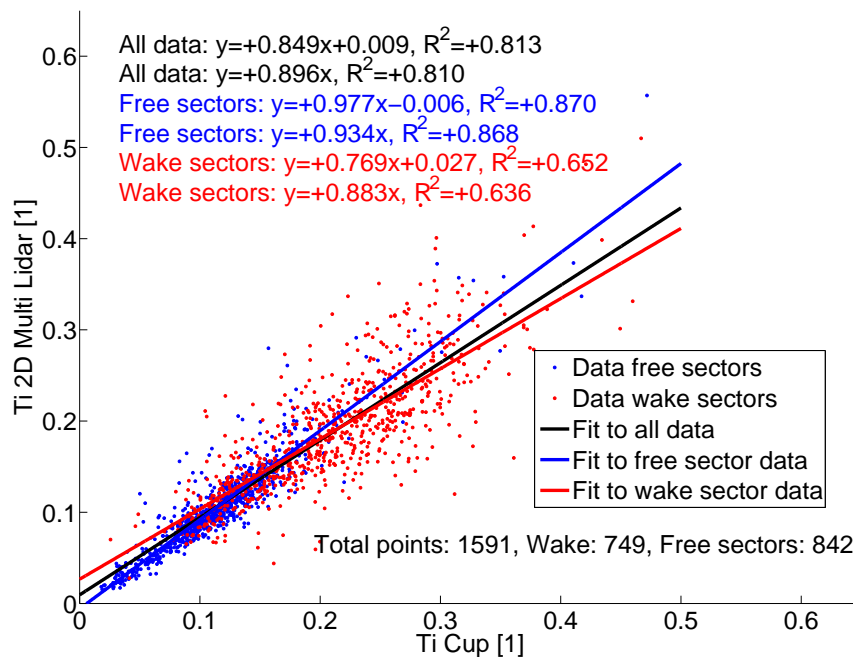


Figure 4. Scatter plot of the measured turbulence intensity Ti of the 2D Multi-Lidar over the cup anemometer for 10 minute intervals.

spectral density calculated of ten minute time series from free sectors of the lidar data and the cup data. Additionally a linear slope of $-5/3$ is plotted. Both spectra agree very well. The overestimation of the power in a wide frequency range and the minima resulting from the temporal averaging in the spectrum of VAD lidars like found in measurement data by [1] and in simulated lidar data by [9] are not observed here.

The better agreement in the turbulence measurement of the 2D Multi-Lidar with the cup anemometer compared to VAD lidars was expected. The 2D Multi-Lidar measures two components of the wind vector in the same volume at approximately the same time using small elevation angles ($< 10^\circ$). The fact that no scanning is applied by the 2D Multi-Lidar allows for higher data rates and though higher frequencies to be detected. No temporal averaging is performed, so no minima in the spectrum are observed. VAD lidars use quite high elevation angles of typical 60° or 75° . This leads to a high contamination of the LoS measurement with vertical fluctuations that are projected to the horizontal direction leading to the overestimation of the horizontal fluctuations and to the higher power in the spectrum. The 2D Multi-Lidar is just very little contaminated by vertical fluctuations due to the small elevation angle. This explains the good agreement of the spectra.

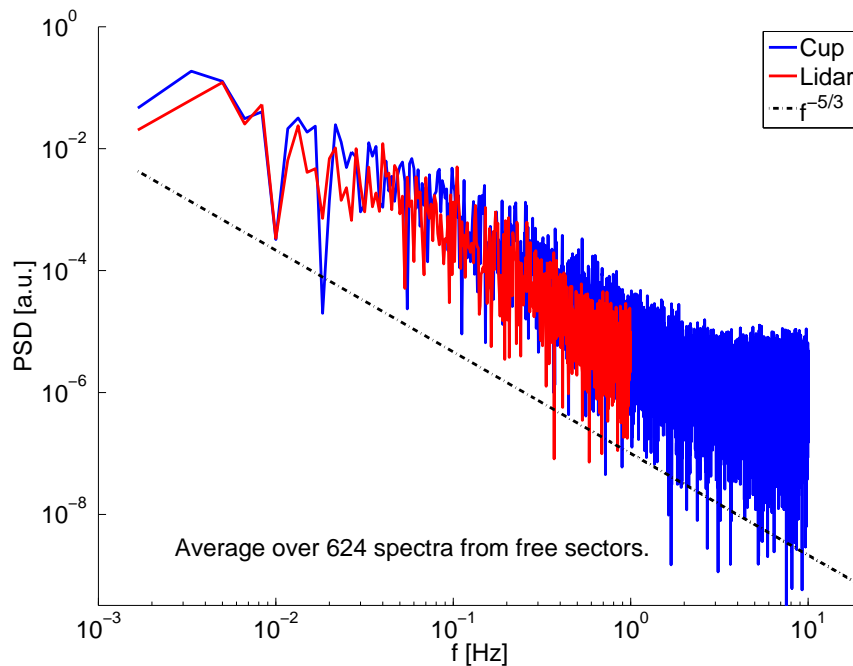


Figure 5. Double logarithmic plot of the power spectral density PSD of the horizontal wind speed measured in free sectors with the 2D Multi-Lidar and the cup anemometer computed on ten minute intervals and averaged.

4. Conclusions

A first comparison between measurements of a mast mounted cup anemometer and a 2D Multi-Lidar is presented. Despite quite large deviations in the positions of the measurement points of the lidars good agreements of the 2D Multi-Lidar and the cup anemometer are found regarding 10 minute averaged wind speeds and directions. Concerning turbulence measurements, the comparison reveals good results in the free sectors. The spectra of the 2D Multi-Lidar and the cup anemometer agree well. As expected, the overestimation of the power in the spectrum due to the VAD-Scan as found in measurement data by [1] and simulation data by [9] is not seen here. The measurement of turbulence in the wake badly agrees with the cup data due to the different size of the measurement volumes of the sensors.

Better performance of the 2D Multi-Lidar is expected from a next measurement campaign when the focus will be on accurate positioning and alignment of the lidars. Furthermore an upgrade will enable the lidars to move their scanners in steps of 0.1° . A high potential for measurements with the 2D Multi-Lidar is seen in the use in complex terrain or in complex flows like wind turbine wakes.

Acknowledgments

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