Orientation correction of wind direction measurements by means of staring lidar

Michael Schmidt, Juan José Trujillo, Martin Kühn

University of Oldenburg, ForWind – Institute for Wind Energy Research, Küpkersweg 70, 26409 Oldenburg, Germany

E-mail: michael.schmidt@uni-oldenburg.de

Abstract. In spite of the efforts made at the time of installation of wind vanes or ultrasonic anemometers (Sonic), there is always a remaining uncertainty of several degrees in the absolute north of such sensors. In this research a method is presented to reduce the azimuthal orientation error of wind direction sensors by means of Doppler Lidar measurements. The method is based on the comparison between the conventional sensor and a distant long range lidar pointing to it in staring mode. By comparing their line-of-sight wind speeds any misalignment between both systems can be estimated more accurately. This method was applied in an measurement campaign in the offshore wind farm alpha ventus next to the meteorological mast FINO 1. The maximum alignment error of a Sonic was reduced to below $\pm 1^{\circ}$. This accurate alignment has asserted, that no bias exists between Lidar and Sonic wind speed measurements.

1. Introduction

At present the wind energy community is experiencing a need for more accurate orientation of wind direction sensors. For instance for testing new wind farm control techniques with active wake control as proposed by [1, 2] . Lately, Trujillo et al. have evidenced for instance the need of higher wind direction accuracy to study the effects of yaw misalignment on wake deviation [3]. Furthermore, Lidar measurements need accurate wind direction information, as they only measure the projection of the wind speed onto the Lidar's line of sight: the "line-of-sight speed" V_{los}. This speed has to be transferred to wind speed V using the wind direction α. The last is usually measured by wind vanes or ultrasonic anemometers (hereinafter referred to as "Sonic"). For some time, also "Velocity-Azimuth-Display-" (VAD-) Lidar's provide – next to the vertical wind profile – wind direction information.

Typically, wind direction data are subject to biases of several degrees. Nevertheless, this is often overlooked or in the most cases accepted as a practical limitation consequence of lack of very accurate means at installation time. Unfavourable mast structures as well as other local (e.g. weather) conditions often impede the orientation of devices exactly to North. Particularly difficult is the installation of measurement devices in offshore conditions, where no object is given to serve as reference point.

It seems, that little attention has been paid so far on the negative impact that poor wind direction sensor alignments have not only, but also on the quality of Lidar data. It is almost impossible to find reports on efforts to align direction data in literature. An exception is the use of remote sensing techniques to assess alignment errors. For instance A. Westerhellweg et al. [4], have used ground-based Lidars to estimate the wind direction using the VAD technique. This relies on a sort of average on a circle around the sensor in study, which in typical setups has a diameter equal to the height at which the sensor is installed. Due to their volumetric character, VAD measurements depend on high uniformity of the flow in that area and any non-uniformity – especially occurring onshore – will generate some bias. A direction data bias occurs as well, of course, if the VAD Lidar itself is misaligned.

In order to circumvent such alignment issues, we propose – in contrast to the VAD technique and other sensor alignment attempts – a long-range Lidar. Operated in staring mode, this Lidar is pointing from a far distance to the sensor to be aligned making quasi one-point-measurements at the location of the sensor.
With this the accuracy of both, the orientation of direction sensors, and the estimation of the staring mode Lidar wind speed bias can be improved substantially.

At first, we show the method, then we apply it to real data and finally we demonstrate it's performance in terms of wind speed biases between Sonic and Lidar data.

2. Method

2.1. Staring velocity azimuth display

We propose a method based on the analysis of the magnitude of the velocity measured in the beam direction of a staring lidar compared to the wind direction. This resembles the classical velocity azimuth display (VAD) technique, therefore we call the method staring velocity azimuth display (SVAD). In the following we explain the VAD technique to illustrate our approach.

A ground-based VAD-lidar interrogates the wind by describing a vertical cone with vertex at the lidar system. At a defined height the measurement domain is given by discrete points on a circle. These are covered sequentially in some period of time, ranging from some seconds to some minutes. The mean wind vector on that circle is estimated with the VAD technique, where two variables are plotted against each other: on the horizontal axis the magnitude of the horizontal projection of the measured line-of-sight wind speed at each point, and on the vertical axis the azimuthal position of the laser beam. In an uniform flow this plot reveals a sinusoidal shape from which the magnitude and direction of the wind can be derived. In effect, these are obtained from the amplitude and the phase shift of a fitted cosine function, respectively. See an example of the conical scan and the resulting sinusoidal function as presented by C. Werner [5] in Fig. 1.

If we let the lidar pointing fixed into one azimuthal direction, then it is not possible to estimate neither the wind speed, nor the wind direction. However, if at least a wind direction signal is given we can reconstruct the instantaneous wind vector. The relation of these two signals can be analysed also in long time periods. Then, the behaviour of the line-of-sight wind speed can be observed with respect to all wind directions. If then data are selected for a constant magnitude of the wind vector, then the plot of these two signals shows also a sinusoidal shape:

$$V_{los}(\alpha) = V \cdot cos(\alpha) \tag{1}$$

A comparison of two measurement techniques, that measure the wind at the same point, but having different orientations, would show a phase shift γ between their V_{los}-sinusoidals (Fig. 2). The angle Φ is necessary and sufficient to transfer the cosine function from the ("mathematical") Cartesian to the ("meteorological", wind-direction providing) compass system (0° means "North"). The origin of both systems is the measurement point (here the centre of

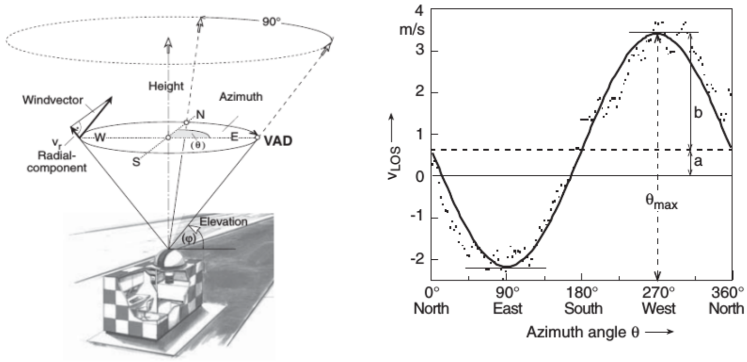

Figure 1. Left: sketch of the VAD-Lidar scan technique. Right: the measured line-of-sight speeds are arranged on a sinusoidal curve [5].

the Sonic device, equal to the centre of that Lidar beam range gate, that is the closest one to the Sonic). To the same time, Φ is used here to shift the V_{los}-maximum to the given line-of-sight-direction. It is easily seen, that one angle is sufficicient for both intentions: a cosine function can only be shifted to the left ($\Phi > 0$) or to the right ($\Phi < 0$), according to: the direction sensor is turned to the left (North-west), or right (North-east).

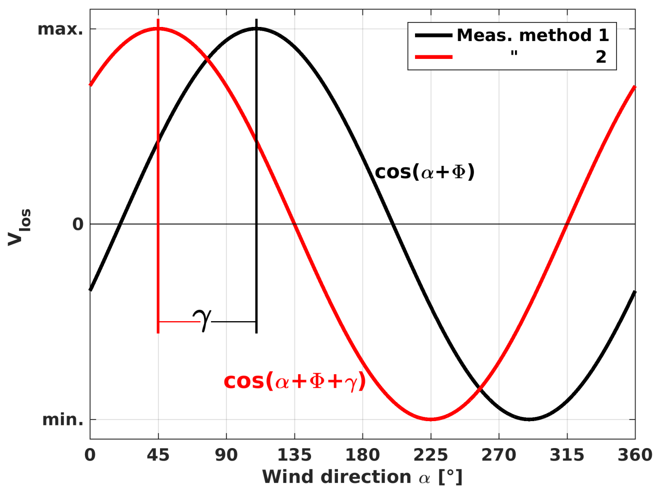

Figure 2. The V_{los} of two measurement devices, orientated to different direction, are shifted by the angle γ. The angle Φ is explained in the text.

If the position of the V_{los}-curve of one of the techniques is accepted as to be true (because the line-of-sight is accurately known), this curve serves as a reference. Then, a shift γ denotes the misalignment of the other instrument. We mention, that the described method would also work, if wind speed data from one or both measurements are biased. Not the maximum V_{los}, but only their phases are of interest here.

In our configuration a long-range Lidar serves as reference, as the line-of-sight direction can be estimated very accurately. It points to a second instrument with an unknown azimuthal bias, which is a Sonic in our case. For other configurations the second direction measurement method could also be a combined cup anemometer and wind vane, or even a ground-based VAD-Lidar.

2.2. Determination of the phase shift
As already mentioned in section 2.1, the V_{los}-data of both instruments (in our example staring mode Lidar and Sonic) have to be categorized ("binned") by wind speed magnitude to reveal their direction-depending sinusoidal character. In other words: there is one sinusoidal for each bin.

To have satisfying numbers of V_{los}-data in each wind speed bin, we choose the binning $0.5 - 1.5m/s, 1.5 - 2.5m/s, ..., 30.5 - 31.5m/s$ (number of bins is n=30). Then, for each bin, the sinusoidal function

$$V_{los} = \overline{V} \cdot cos(\alpha + \Phi + \gamma) \tag{2}$$

has to be fitted to the V_{los}-data of method 2.

In equation 2, $\overline{V}$ denotes the centres of the wind speed bins, Φ is fixed (was introduced to shift the expected maximum V_{los} to the line of sight in compass system), and γ is the fit parameter. Non-zero-γ's indicate, that sinusoidals (and maxima) of method 2 are not at the expected position, but shifted with respect to the reference method's sinusoidals. The reference method's V_{los}-data don't have to be fitted, as it's sinusoidal is fixed for all bins: maximum is at line-of-sight, so γ of the reference method is 0 always.

We get slightly different γ's for the wind speed bins, because the V_{los} data must not exactly lie on the sinusoidals, as each wind speed bin has a finite width (e.g. bin width $1m/s$ allows distances of V_{los}-data to their sinusoidals of $< \pm 0.5m/s$). In this way, the finite width of wind speed bins introduces a statistical uncertainty to the method. We propose to calculate the weighted average of the γ's using

$$\overline{\gamma} = \frac{\sum_{i=1}^{n} w_i \cdot \gamma_i}{\sum_{i=1}^{n} w_i}. \tag{3}$$

As weights w_i we propose the number of V_{los}-data in the n wind speed bins. The weight-averaged $\overline{\gamma}$ is stated as misalignment of sensor 2 with respect to sensor 1 (reference, precisely aligned by the well-known line-of-sight, here: direction of the long-range Lidar pointing to the Sonic).

2.3. Re-calculating Sonic and Lidar data
Now that the size of sensor 2's misalignment is found, $\overline{\gamma}$ is used to correct the data. To align Sonic data, a rotation matrix (fixed coordinate system, vector (u,v) rotates counter-clockwise, if $\gamma > 0$) is used:

$$\begin{pmatrix} u \\ v \end{pmatrix}_{\substack{Sonic, \\ aligned}} = \begin{bmatrix} cos(\overline{\gamma}) & -sin(\overline{\gamma}) \\ sin(\overline{\gamma}) & cos(\overline{\gamma}) \end{bmatrix} \begin{pmatrix} u \\ v \end{pmatrix}_{\substack{Sonic, \\ not\,aligned}} \tag{4}$$

Of course, the wind speed ($\sqrt{(u^2 + v^2)}$) is unchanged, but the wind direction α has to be re-calculated. Knowing α precisely, we are able to compute the right V_{los} of the Sonic as well as the right Lidar wind speed V. Equation 1 is applicable for both operations.

2.4. SVAD procedure
The accurate alignment of a sensor's wind direction data by means of a staring mode Lidar requires the following steps:

(i) Pre-process all data as usual to ensure high quality data,
(ii) Apply a filter method to the Lidar data to remove periods of low signal-to-noise ratio,
(iii) Average all data to 10-min means,
(iv) Project the sensor's data to the Lidar's line-of-sight to get $V_{los,sensor}$,
(v) Classify all data into direction and wind speed bins,
(vi) Fit cosine-functions (Eq.2) to the Lidar data to find the misalignment γ for each wind speed bin. Here data have to be rejected for wind directions with non-free flow conditions such as mast and wind turbine wakes, etc. Moreover, data in directions near the perpendicular to the Lidar line-of-sight $\pm 10°$ should be rejected.
(vii) Average the γ's to get the weight-averaged misalignment angle $\overline{\gamma}$'s: this is the estimated angle to align the sensor's direction data,
(viii) Use the matrix equation given in section 2.3 for aligning, and finally re-calculate the sensor's wind direction data α as basis for the correction of all V_{los}- and wind speed data.

2.5. Theoretical estimation of Lidar wind speed errors
The usefulness of corrected, i.e. aligned direction data is illustrated here by an estimation of the – systematic – wind speed error $\Delta V(\alpha)$, that arises with a misalignment $\Delta\alpha$ (identical with a misalignment γ). The wind speed is simply calculated by:

$$V(\alpha) = \frac{V_{los}}{cos(\alpha)}. \tag{5}$$

For the error estimation the first derivative of equation 5 is used as customary:

$$\Delta V(\alpha) \sim \frac{\partial V(\alpha)}{\partial \alpha} \Delta\alpha \tag{6}$$

To derive the secant function $1/cos(\alpha)$ the quotient rule is used to get

$$\frac{\partial(1/cos(\alpha))}{\partial \alpha} = \frac{sin(\alpha)}{cos^2(\alpha)}. \tag{7}$$

By combining equations 6 and 7 we obtain finally:

$$\Delta V(\alpha) \sim \frac{sin(\alpha)}{cos^2(\alpha)} \Delta\alpha. \tag{8}$$

The factor $sin(\alpha)/cos^2(\alpha)$ is mathematically fixed, it's behaviour is shown in Fig. 3. At directions 90° and 270°, identified as to be perpendicular to the Lidar's laser beam (where $V_{los} = 0$), the wind speed error is inevitable infinite. For directions close to 0° and 180° (parallel and anti-parallel to the Lidar beam, resp.) errors are small.

In the end, the fast growth of the secant functions derivative ($\sim 1/cos^2(\alpha)$) urges us to minimize the misalignment $\Delta\alpha$ to keep the wind speed error ΔV as small as possible.

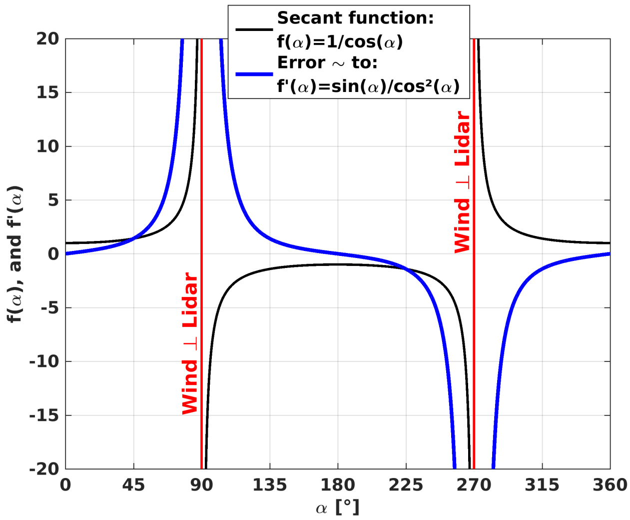

Figure 3. Closer to angles $\alpha = 90°$ and 270° (wind direction is perpendicular to Lidar beam), the derivative of the secant function is growing faster than the secant function itself.

3. Experimental setup

We have applied the method to align Sonic data by using staring Lidar data. Sonic and Lidar data have been recorded during a four week measurement campaign in the offshore wind farm alpha ventus next to the meteorological mast FINO 1 in the North Sea in December 2013 and January 2014, when South-Easterly to South-Westerly wind directions were predominant.

A Gill R3-50 Sonic anemometer was mounted on the North-western boom of FINO 1 at height of 41.5 m LAT (lowest astronomical tide). A Windcube 200S Lidar was located 2864 m apart from the Sonic on the substation at height of 23.5 m LAT South-west of alpha ventus.

The direction from the Sonic towards the Lidar (the line-of-sight expressed as wind direction) was estimated as 306.47° as result of a positioning of the Lidar and the meteorological mast through GPS (Fig. 3). The wind direction perpendicular to the Lidar beam, where Lidar errors are expected to be highest, is at 216.47° (of course, 90° apart from line-of-sight).

3.1. Lidar and Sonic data

The Lidar was operated in staring mode only for wind directions between 140° and 300°, the sampling rate was about 1.5 Hz. We have used the Lidar data filter of H. Beck et al. [6], basically to filter out data having a low signal-to-noise ratio. Subsequent averaging has left 1243 10-min mean $V_{los,Lidar}$-values for the comparison with the Sonic data.

The 10 Hz Sonic wind speed data were averaged to 10-min mean values as well. Mast distortion effects on the data (up to 2.7m/s in the mast shadow sector) were corrected using the mast correction function provided by the German Wind Energy Institute DEWI [7]. The "Sonic-line-of-sight wind speed" $V_{los,Sonic}$ was obtained by projecting the wind speed onto the Lidar beam direction.

The Lidar $V_{los,Lidar}$ data were classified by the magnitude of the Sonic wind speed using 1m/s-bins. For each wind speed bin, all the V_{los} data lie close to sinusoidal curves. An example is shown in Fig. 5 for the wind speed bin 12.5–13.5m/s. The maximum $V_{los,Sonic}$ appears at 306.47°.

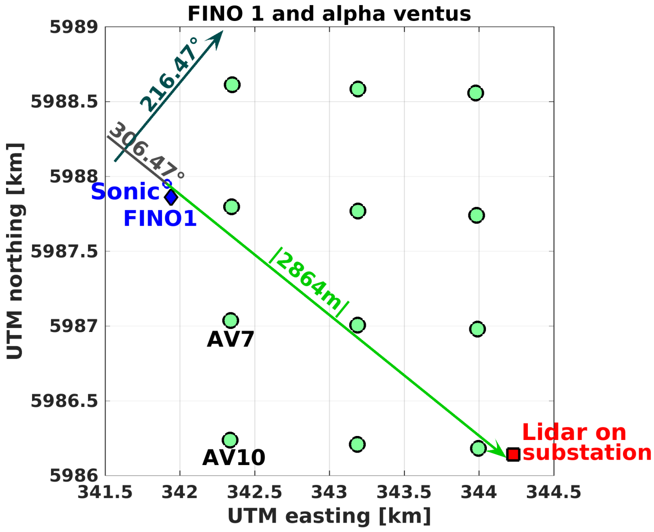

Figure 4. Measurement setting in wind farm alpha ventus, consisting of 12 5MW-turbines. We'll see, that turbine AV7 has influenced the measurements, but AV10 did not.

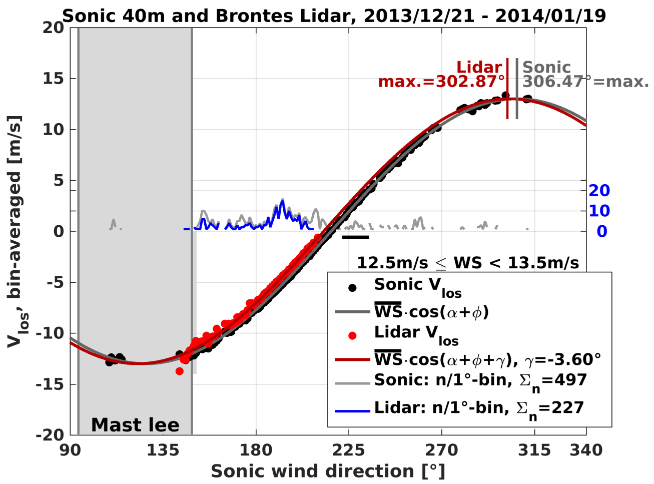

Figure 5. The shift between the sinusoidal curves for the Sonic and the Lidar in the wind speed bin 12.5–13.5m/s is $\gamma = -3.60°$. The amplitude of the sinusoidal is equal to the bin centre (13m/s).

The $V_{los,Lidar}$ data are located apart from the given sinusoidal function for $V_{los,Sonic}$. The fitting procedure using Eq. 2 – executed only for the direction range $170° - 210°$ to exclude mast shadow and farm wake distorted data – yields for the example in Fig. 5 the phase shift $\gamma = -3.60°$. This involves the maximum $V_{los,Lidar}$ being at 302.76°. The explanation for not finding the Lidar's maximum at the line-of-sight: the x-axis of Fig. 5 – labeled with "Sonic wind direction" – is shifted by γ: this is the Sonic's misalignment.

3.2. Error estimation
Assuming maximum geographical position errors of $\pm 5\,m$ (according to typical GPS inaccuracies) for the Sonic as well as for the Lidar, the direction error is in the range of $\pm 0.28°$ – this is simply due to the large distance. Caused by the Windcube 200S setting options for the beams azimuth and elevation angles it is not possible to target for example a Sonic at a met mast with higher accuracy than $\pm 0.1°$. From both, position and targetting errors, the maximum distance from the Sonic to the centre of the Lidar range gate at $2864\,m$ is estimated to be shorter than $8\,m$.

As explained in chapter 2.2, the $1m/s$- binning fixes the V_{los} not entirely, giving statistical uncertainty some space. For the 12 wind speed bins $10.5 - 11.5m/s, ..., 21.5 - 22.5m/s$ (we have ignored low weighted wind speed bins containing less than 30 10-min mean values), we got by fitting the γ-values $2.98°, 3.21°, 3.60°, 3.71°, 3.68°, 3.66°, 3.88°, 3.91°, 4.00°, 4.13°, 3.55°$, and $4.04°$. The weighted average according to Eq. 3 is $\overline{\gamma} = -3.69°$, the standard deviation of the γ's is $0.34°$.

The height difference of the Sonic and the Lidar results in the elevation angle $0.36°$. This allows to assume that the measurement setting was 2-dimensional, because the horizontal wind components are almost fully captured. The vertical wind component w is – except for extreme situations like in tropical cyclones or downbursts in thunderstorms – smaller than $\pm 0.1m/s$ (usually 10 to 100 times smaller than the horizontal components u and v). Furthermore, the Lidar setting here measures only the horizontal projection of w. Therefore, w is negligible in this experiment.

To estimate the overall-error of the aligning method for our data set, we sum up the location errors of Sonic and Lidar (together $0.28°$ at maximum), the Lidar's hard targeting error ($0.1°$ at maximum), and the standard deviation of the distribution of the γ's for each wind speed bin ($0.34°$) using

$$E_r = \sqrt{0.28^2 + 0.1^2 + 0.34^2}\ [°], \tag{9}$$

resulting in $E_r \approx 0.45°$. The SVAD method determines the misalignment of FINO 1's Sonic at 41.5 m LAT height to

$$\overline{\gamma} = -3.69° \pm 0.45°. \tag{10}$$

4. Evaluation of the SVAD method
The alignment of the Sonic on 41.5 m LAT at FINO 1 by applying $\gamma = -3.69°$, reduces the bias between the V_{los} of Sonic and Lidar in the sector $170° - 210°$ from $-0.95m/s$ to $+0.02m/s$ (Fig. 6).

Comparing the wind speed measurements of the Lidar and the Sonic after the alignment, we have to distinguish three direction sectors (Fig. 7). Around $155°$, in the wake of wind turbine AV 7, we notice differences up to $1m/s$ (Lidar wind speed is reduced). We explain these differences with an "integrating effect" of the Lidar. It measures the reduced wind speed along a path (length is estimated to be 60 m) in line-of-sight, but the Sonic measures the wind only in a small volume. The difference between a remote sensing- and a in-situ technique is clearly seen only here. We could not find such a wake effect of turbine AV 10 in our data set. Presumably, the distance between this turbine and FINO 1 ($1626\,m$) is too far for this (the distance of AV 7 to FINO 1 is 872 m).

In the direction sector $170° - 210°$, the Lidar-to-Sonic bias is $-0.02m/s$. The bias error of the Sonic alone should be 0, if it has been calibrated properly, but we do not know. However, the small Lidar-to-Sonic bias in our experiment might be explaind by statistical uncertainty due to the restricted amount of Lidar data (around 900 10-min mean values in this sector).

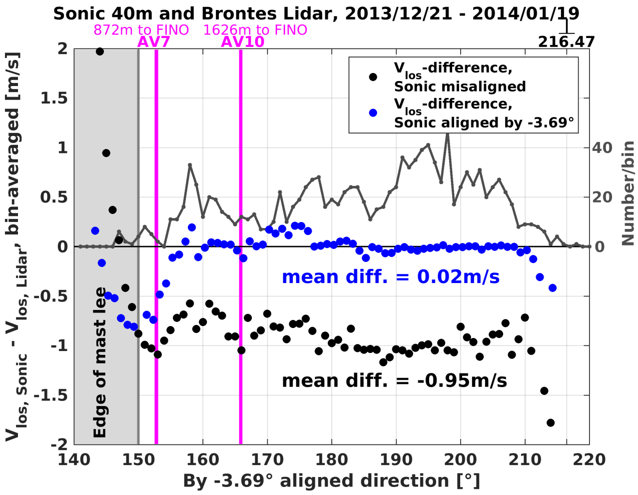

Figure 6. The aligning procedure reduces the V_{los}-difference considerably. The Sonic data suffer from the mast shadow more than the Lidar data do.

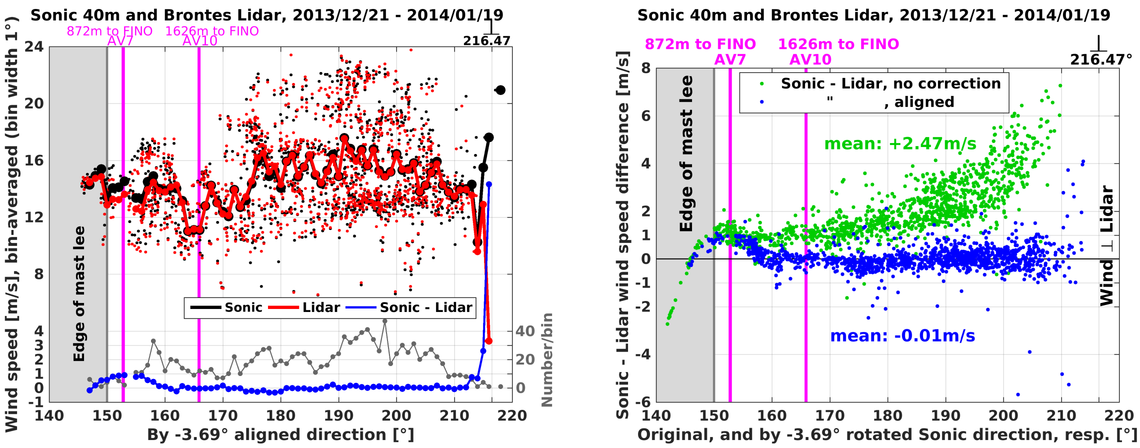

Figure 7. Left: red and black dots, small: 10-min mean values, big: these data direction-bin averaged. Blue dots: Sonic-to-Lidar differences. Left: reasons for Lidar-to-Sonic differences for three direction sectors (wake region of turbine AV 7, around 155°, wind almost perpendiclar to Lidar beam close to 216°, and the "undisturbed" sector in between) are explained in the text.

The left part of Fig. 7 shows big Lidar-to-Sonic differences only for wind directions close to 216.47° (wind perpendicular to Lidar beam). In this region, $V_{los,Lidar}$ is due to the projection of the wind speed onto the line-of-sight small (exactly 0, if wind is exactly perpendicular to the Lidar beam). This leads to big relative V_{los}-errors, and therefore (see Equation 1) to large Lidar wind speed errors. In this way, the measurement data confirm the theoretical error estimation for wind speed that we made in section 2.5 (please see Fig. 3 again). Even after a proper aligning procedure, Lidar wind speed data from the sector $\pm 5°$ around the 'perpendicular direction' still are not reliable – fortunately only in this small direction sector.

Just to emphasize the importance of having highly accurate wind direction data just once more, we look at the the Sonic-to-Lidar wind speed differences before and after the aligning procedure in Fig. 7. Without alignment, the Lidar's wind speed error starts to become bigger than $2m/s$ for wind directions 35° apart from the 'perpendicular' direction. Aligning the Sonic wind direction reduces Lidar wind speed errors in a wide direction range: the Lidar-to-Sonic bias has almost vanished.

An alternative aligning method, suggested by the left part of Fig. 7: if there is some confidence in the similarity of Lidar and Sonic wind speed data, also a minimisation method may used to detect that alignment angle, for which the cost function, given by the Lidar and Sonic wind speed differences, is minimal.

An advantage of the alternative method (not checked up to now): the wind direction binning is obsolete, so, a relatively short measurement period might produce a sufficient amount of data for wind direction alignment. Nevertheless, measurements for a wide range of wind directions will improve the alignments accuracy.

5. Conclusions

This research illustrates that even small misalignments ($<4°$) of wind direction sensors produce fatal Lidar wind speed errors. It shows that long-range Lidar's, operated in staring mode technique, can be applied to improve the estimation of the absolute orientation of wind sensors, in fact after installation of the measurement system. Moreover, it can be applied from the ground without need for access to the sensor or the meteorological mast.

We presented the application of this method for comparisons of Lidar and ultrasonic anemometer measurements. The staring velocity azimuth method (SVAD) achieves direction information with previously unknown accuracy.

Line-of-sight- and wind speed differences between the ultrasonic anemometer and the Lidar measurement techniques have revealed to be negligible after the alignment of direction data.

We expect this method to be useful also for aligning wind vane or VAD-Lidar data. Directing a long-range Lidar to met mast sensors at several heights may provide more accurate insight in the height-depending rotation of wind (veer).

6. References

[1] Jimenez A, Crespo A and Migoya E 2010 *Wind Energy* **13** 559–572 ISSN 1099-1824 URL `http://dx.doi.org/10.1002/we.380`

[2] Fleming P A, Gebraad P M, Lee S, van Wingerden J W, Johnson K, Churchfield M, Michalakes J, Spalart P and Moriarty P 2014 *Renewable Energy* **70** 211 – 218 ISSN 0960-1481 special issue on aerodynamics of offshore wind energy systems and wakes URL `http://www.sciencedirect.com/science/article/pii/S0960148114000950`

[3] Trujillo J J, Seifert J K, Wrth I, Schlipf D and Khn M 2016 *Wind Energy Science* **1** 41–53 URL `http://www.wind-energ-sci.net/1/41/2016/`

[4] Westerhellweg A, Canadillas B, Beeken A and Neumann T 2010 *10th German Wind Energy Conference – DEWEK 2010*

[5] Werner C 2005 *Doppler Wind Lidar* chap 12, pp 325–354

[6] Beck H Schmidt M K M 2016 *18th International Symposium for the Advancement of Boundary-Layer Remote Sensing (ISARS 2016)* oral presentation

[7] Westerhellweg A, Neumann T and Riedel V 2012 *DEWI Magazin* 60–66 URL `http://www.dewi.de/dewi_res/fileadmin/pdf/publications/Magazin_40/09.pdf`