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An evaluation of the WindEye wind lidar

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Photo by M. Sjöholm of the tested WindEye at the Risø campus, DTU, Denmark.

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Summary

Prevision of the wind field by remote sensing wind lidars has the potential to improve the performance of wind turbines. The functionality of a WindEye lidar developed by Windar Photonics A/S (Denmark) for the wind energy market was tested in a two months long field experiment. The WindEye sensor measures the wind speed along two beams to determine the wind direction of the incoming wind field. The field experiment utilized two sonic anemometers, which were located in the two centers of the measurement volumes of the WindEye, as reference instruments. The wind vectors measured by the sonic anemometers were projected onto the line-of-sight directions of the WindEye and the wind direction was calculated based on the WindEye algorithm. It was found that the WindEye measured the wind direction with a high accuracy during the whole campaign. The standard deviation between the WindEye two minute average wind direction and wind direction obtained from the two sonic anemometers was 1.3° , corresponding to $R^2 = 0.99$. The corresponding line-of-sight wind speed comparison showed a similarly high correlation on each beam, but a few percent underestimation for high wind speeds. This underestimation can be explained by the changing terrain causing a lack of homogeneity in the wind field, which in combination with the difference in the measurement volumes of the lidar and sonic anemometers, make a perfect agreement impossible.

Background and aim of study

In December 2013, DTU Wind Energy received a new version of the two-beam WindEye lidar for an evaluation of its performance against in-situ reference instruments. The primary aim of the evaluation campaign was to check that the instrument was fully functional and measured wind speed and wind direction correctly for a longer period of time and for more variable meteorological conditions, than the 36 h long evaluation documented for a prototype instrument in Rodrigo and Pedersen (2012). Another improvement relative to the comparison in Rodrigo and Pedersen (2012) concerns the experimental setup, which was optimized to fit the WindEye instrument.

The WindEye lidar was developed to improve the wind direction alignment of already operational wind turbines. The alignment of a wind turbine to the mean wind direction is achieved through the wind turbine yaw control, which typically leads to an adjustment every 0.5-5 minutes. Hence, the

current study is focused on the comparison of the minute-scale wind speeds.

Description of lidar and reference instrument

The WindEye lidar is a continuous-wave, infrared, coherent Doppler lidar. The measurement rate is 1 Hz, where the instrument alternates between measurement on the right and left eye for 0.5 s by use of an optical switch. As mentioned above, the lidar is developed to be mounted on wind turbines, which are generally difficult to access. Therefore, the lidar is light-weight and compact. The WindEye lidar contains two parts: the optical head (dimensions $443 \times 250 \times 190$ mm, weight 15 kg) and a control box (dimensions $430 \times 250 \times 120$ mm, weight 9 kg) separated by a 10m long cable. The laser is an inexpensive all-semiconductor laser, with a wavelength of 1550 nm. To withstand the vibrations of wind turbines, the WindEye lidar contains no moving parts and hence the focus distances are fixed. A more complete description of the instrument can be found at http://www.windarphotonics.com/f/f1/wp_profile_single_screen.pdf.

The prototype instrument used in Rodrigo and Pedersen (2012) has undergone significant development leading to the new instrument including an improved telescope (optical transceiver) and software enhancements (e.g. better rejection/flagging of spurious spectra).

The focus distances and probe length weighting functions of the tested instrument were investigated using a hard target rotating belt. The setup for the investigation is described in Hu et al. (2013). The focus distance of the tested instrument was measured to 93 m with a full-width half-maximum probe length of 29 m for the right eye. The corresponding results for the left eye beam were 84 m and 23 m for the focus distance and full-width half-maximum probe length, respectively (Qi Hu and Peter John Rodrigo, personal communication). The difference in measured probe lengths correspond well with the expected quadratic dependence on focus distance (Angelou et al., 2012).

Two USA-1 sonic anemometers (Metek GmbH, Germany) with a standard sensor head were used as reference instruments. The length of the USA-1 sonic anemometer measurement volume (transducer distance) is 17.5 cm. The instruments were sampled at 32 Hz and the data were calibrated for systematic flow distortion effects, which is a major source for inaccuracy in sonic anemometry, as in Bechmann et al. (2009).

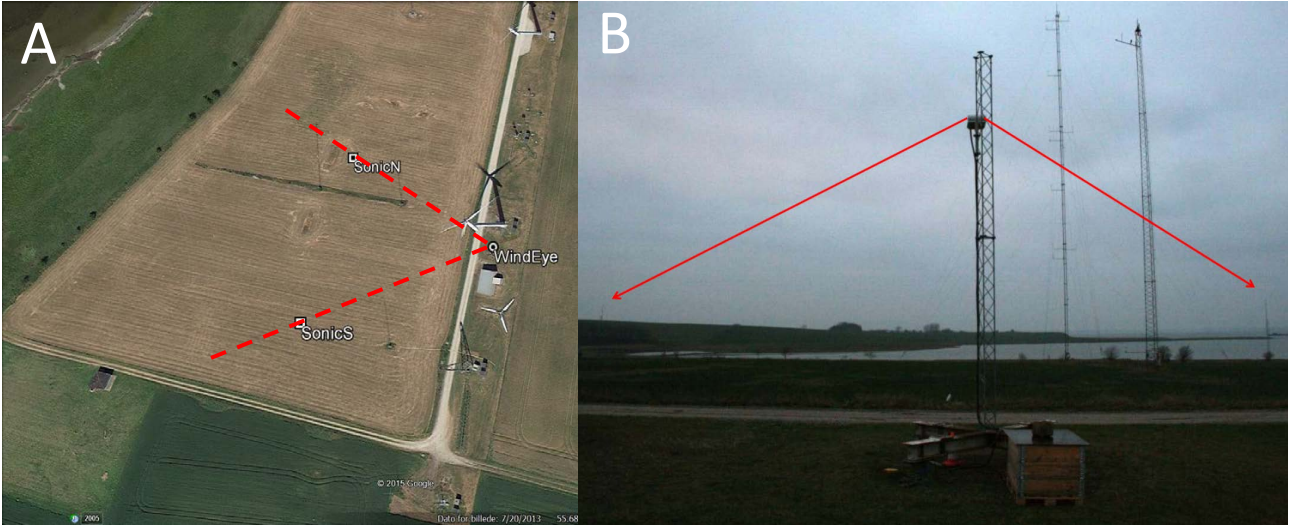


Figure 1: *Setup of the experiment: A. Positions of sonic anemometer masts and WindEye at Risø campus, DTU, B. Photo of experiment.*

Experiment

The experiment took place at the Risø campus of DTU, Denmark, between January 9th and March 23rd, 2014. Both because of financial and practical constraints, a relatively low measurement height was chosen. The WindEye sensor was mounted on a mast at 5.60 m height to measure only the horizontal wind component. The setup is illustrated in Figure 1. The tilt angle of the instrument was measured to 0.0-0.5° by an eLevel-Module inclinometer (J-MEX Inc.) with a 0.1° resolution.

The measured focus distances of the WindEye sensor were used to place two 6 m tall masts at the center of the measurement volumes of the WindEye. The sonic anemometers were top-mounted on a rod to match the vertical level of the lidar beam (8.33 m for the right eye beam and 7.21 m for the left eye beam, respectively). The differences in measurement heights were compensating for the mild variability of the terrain, which decreases towards the fjord. The location of the lidar beams were checked with a card, which is sensitive to infra-red light (Figure 2), and vertical distance between the sonic measurement volume and the lidar beam was less than 0.3 m. The careful placement of the masts and the extra check of the beam location ensured that the center of the WindEye's measurement volumes should coincide with the location of the in-situ sensors. The downside of such a low measurement height is that the flow is rarely homogeneous, in which case the large difference between



Figure 2: *The location of the laser beams relative to the reference instruments was checked with a board and a card sensitive to infra-red light.*

the WindEye and the sonic anemometer measurement volumes will cause a systematic bias in the velocity measurements.

Measurement data processing and quality control

As stated above, the WindEye alternates between right eye and left eye measurements at 1 Hz, whereas the sonic anemometers were sampled at 32 Hz. First, the sonic anemometer data were resampled to 1 Hz and the relative time lag between the two measurement setups was determined by optimizing the correlation between the two signals. At the start of the campaign, the time lag was found to be highly variable, which turned out to be caused by a problem in the data acquisition system of the sonic anemometers. The problem was solved at the end of January and from this time, the time lag between the two systems were adjusted on a daily basis. Once the two datasets were temporally matched, both the sonic anemometer and WindEye data were averaged into 2 minute mean values.

According to the WindEye data format, ϕ denotes the wind direction deviation from the center line (Figure 3), V_{los1} and V_{los2} denote the wind speed in the southern (left) and northern (right) beam direction, respectively, W denotes the wind speed in the center line direction, V is the length of

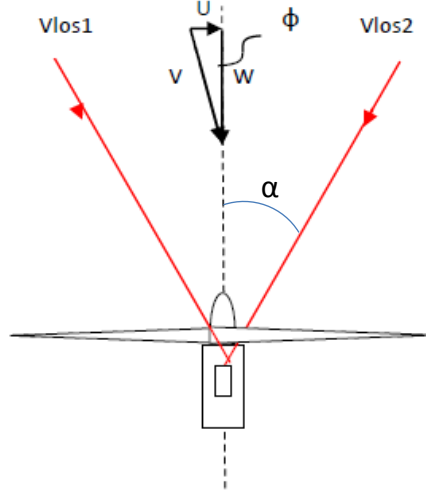


Figure 3: *Illustration of the WindEye wind notation.*

the wind vector and U is the wind component in the direction perpendicular to the center line. The relation between $V_{los1,2}$ and U , V , W and ϕ is expressed as

$$U = \frac{V_{los1} - V_{los2}}{2 \sin \alpha} \quad (1)$$

$$W = \frac{V_{los1} + V_{los2}}{2 \cos \alpha} \quad (2)$$

$$V = \sqrt{U^2 + W^2} \quad (3)$$

$$\phi = \arctan \left(\frac{U}{W} \right), \quad (4)$$

where $\alpha = 30^\circ$ is the opening angle of the WindEye. In addition to the variables in these equations, the WindEye standard output includes a quality flag, where the value 1 indicates that the measured wind was of high quality on both lidar beams.

To compare the wind speed and direction measured by the WindEye and sonic anemometers, the orientation of the sonic anemometer coordinate systems in relation to the lidar beams needed to be determined. The orientation of the sonic anemometers were estimated by skilled technicians and their relative direction kept fixed. The horizontal wind vector from both sonics were projected onto the beam directions. The final orientation of the sonic anemometers was determined by allowing the sonic anemometer orientation to vary slightly and selecting the minimum between the projected horizontal wind vector and V_{los1} and V_{los2} . For this optimization, a smaller dataset taken in the interval

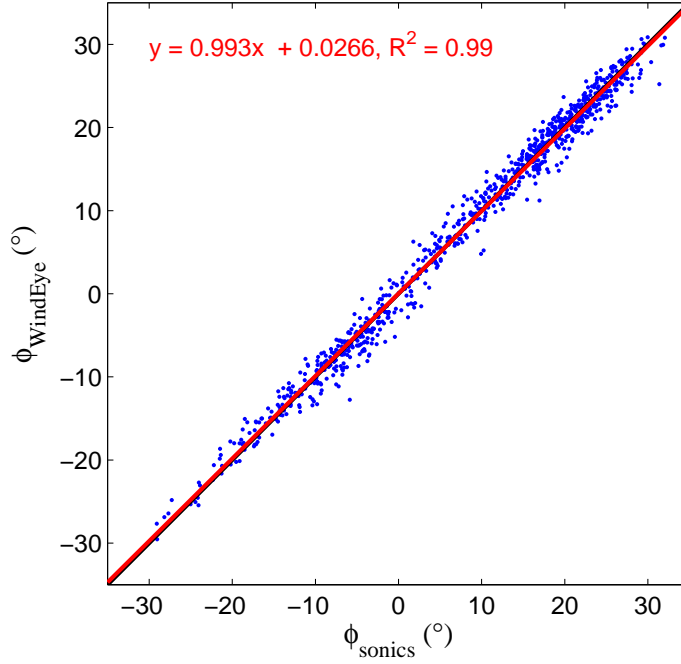


Figure 4: Comparison of the wind direction measured by the WindEye and the two sonic anemometers.

between $\phi = -30^{\circ}$ and $\phi = 30^{\circ}$ was used.

The horizontal wind speed measured by the two sonic anemometers was projected onto the north and south beams to allow for a direct wind speed comparison. Then a wind direction deviation from the WindEye center line was estimated by calculating a ϕ_{sonics} according to equations Eq. 1 - 4.

Results

The comparison between the wind direction estimated by the WindEye (ϕ) and that by the sonic anemometers (ϕ_{sonics}) in Figure 4 show a close correlation with $R^2 = 0.99$. The red line shows the least square fit to the two datasets. The red line hides a black line, which indicates $y = x$. The data in the plot were selected by requiring that each two minute block of lidar data contained at least 100 out of 120 1 Hz measurements of high quality data for both V_{los1} and V_{los2} . Further it was required that $V_{los} > 1 \text{ ms}^{-1}$ on both paths in order to have a well-defined wind field and that the wind direction was within the interval $\phi = -30^{\circ}$ and $\phi = 30^{\circ}$. The root mean square deviation between ϕ and ϕ_{sonics} was

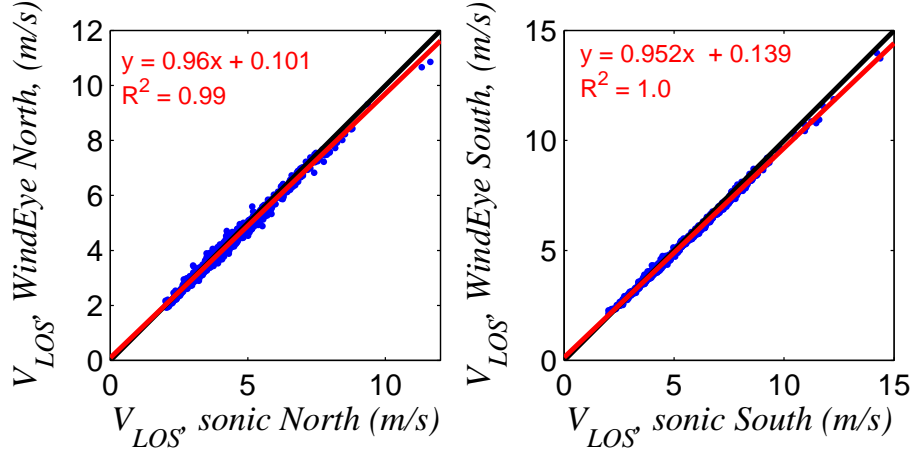


Figure 5: Comparison of line-of-sight wind speeds for the North (left) and South (right) lidar beam.

calculated to 1.3° . The selected data were taken both at the start and at the end of the measurement campaign, and there was no sign of deterioration during the measurement period.

In Figures 5 the comparison between the lidar and sonic wind speeds projected on the line-of-sight directions is shown. Again, a high correlation was found with $R^2 = 0.99$ and 1.0 , respectively. For the higher wind speeds, the lidar wind speeds were approximately 4% lower than those measured by the sonic anemometers. Possible reasons for this mismatch are discussed below.

Discussion

The difference between the wind direction estimated by the WindEye (ϕ) and sonic anemometers (ϕ_{sonics}) showed no systematic difference and a root mean square error of 1.3° . For comparison, the wind direction difference between the two sonic anemometers was analysed. This comparison (Figure 6, right) showed both a small bias as well as a lower correlation coefficient than in the comparison shown in Figure 4. The root mean square error of this comparison was 3.4° , which is more than double the deviation calculated between the direction estimate from using both the anemometers and the WindEye. The lower R^2 and the higher root mean square deviation shown in Figure 6 indicates that the way the WindEye estimates the mean wind direction in a heterogeneous flow field integrates the effect of spatial heterogeneity well.

There are several possible reasons for the small mismatch of sonic and lidar wind speed shown in Figure 5. Both the lidar and sonic anemometers could be suffering from small systematic errors. We judge that the sonic anemometer wind speed is accurate to within a few percent. A further inaccuracy could be caused by a vertical misalignment in the mounting of the sonic anemometers. Based on an analysis of tilt angles from both anemometers (not shown), we however estimate that this uncertainty is negligible. A third possibility concerns the rotation to match the sonic coordinate system to that of the WindEye. The main cause for the disagreement could however be found in the different measurement volumes of the WindEye and sonic anemometers. The sonic anemometer measurement volumes is approximately 1% of the full-width half-maximum probe length volume of the lidar beams. Due to terrain and wind field heterogeneity, the instruments can therefore never be expected to coincide perfectly. The terrain heterogeneity will not only cause a single well-defined bias between the instruments, but the bias will vary due to the temperature structure of the atmosphere and the wind direction. With this limitation of the current experiment in mind, we conclude that the WindEye measures the line-of-sight wind speed well for the whole observed wind speed range.

To illustrate the flow heterogeneity at the site, the wind direction difference measured by the two sonic anemometers was analysed as a function of geographical wind direction (Figure 6 left). The blue dots denote all the two-minute data, the red circles the mean of 10° direction bins and the dashed vertical lines the direction of the lidar beams. Large deviations were observed for southerly winds, where an upwind farm as well as the Risø test wind turbines distort the mean wind field, but a small systematic deviation can also be observed for the relatively open direction interval between the two vertical lines, which correspond to the direction interval used in the analysis.

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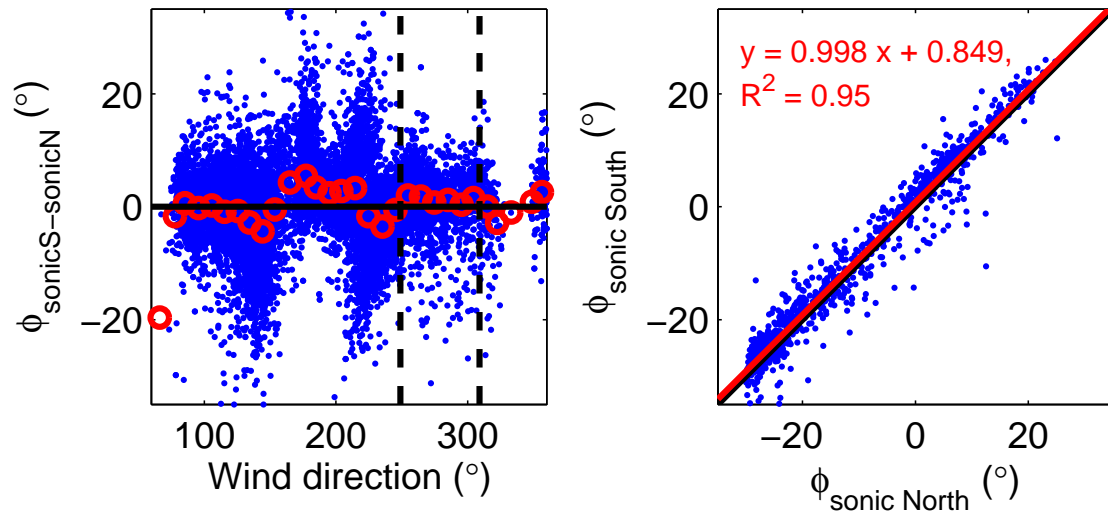


Figure 6: *Illustration of the wind direction heterogeneity at the Risø test site.*

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