Flow analysis with nacelle-mounted LiDAR

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September 2016
ECN-E--16-041

Acknowledgement

The work reported here is carried out in the TKI LAWINE project which is partially funded by the Dutch government in the framework of TKI Wind op Zee.

Executive summary

In the LAWINE project, several LiDAR systems are evaluated, among which Wind Iris from Avent Lidar Technology. This LiDAR is installed on the nacelle of a 2.5MW research wind turbine at the ECN test site EWTW. Two measurement campaigns have been organised with this LiDAR system: one as a forward looking LiDAR system to measure the horizontal wind speed and direction ahead of the turbine, and one as a backward looking LiDAR system to measure the wake of the turbine. This report presents results from the analysis of the Wind Iris in forward and backward looking orientation. In forward looking orientation, the objective of this study is to identify possible disturbing factors when measuring the incoming wind speed in front of the rotor. In backward looking orientation, the objective is to quantify the accuracy of wake measurements with a single beam LiDAR system.

The results in forward looking orientation have shown that the blockage effect of the turbine is noticeable up to a distance of 3.5*D* in front of the rotor. Blockage effects of other wind turbines disturb the measurements in a much wider sector than expected from plots of measured turbulence intensities. When one of the lines of sight passes the rotor of another turbine within a distance of 2.5*D* from the rotor centre, the measurement of the Wind Iris is disturbed by the flow around that turbine. For accurate measurement of the undisturbed wind speed, it is therefore recommended to measure the wind speed at a distance of 3.5*D* from the rotor, while the lines of sight at this distance are at least 2.5*D* separated from the rotor axis of nearby turbines.

In backward looking orientation, measurements of the velocities at the wake centreline agree very well with FarmFlow calculations with differences of approximately 2% for single wake conditions. Also for double wake conditions the agreements are quite good. However, wake effects behind the third turbine seem to be underestimated by the Wind Iris, probably due to measurement uncertainties of the wind direction and yaw angle. To reduce these uncertainties in the future, it is necessary to measure along different lines of sight, for example with a scanning LiDAR, so that it will be possible to determine the real position of the wake centreline.

Contents

1 Introduction

With the application of a nacelle mounted LiDAR, the Wind Iris from Avent Lidar Technology, two measurement campaigns were organized on the ECN Wind turbine Test site Wieringermeer (EWTW): one with forward looking LiDAR to measure the undisturbed horizontal wind speed, and one with backward looking LiDAR to measure the wake of a wind turbine. The instrumentation setup of both campaigns is extensively described in [7]. As a forward looking system, the LiDAR may be used for power performance measurements as an alternative for a meteorological mast, and can be used to minimize yaw misalignment angles by recalibration of the wind direction sensor. As a backward looking system, the LiDAR might be used as a research instrument to measure the development, recovery and meandering of wind turbine wakes. Understanding wake behaviour helps finding ways to improve the performance of large offshore wind farms.

In this report results from the two measurement campaigns with the Wind Iris mounted on a 2.5MW research wind turbine are presented and discussed. In forward looking orientation, presented in chapter 2, the objective of this study is to identify possible disturbing factors when measuring the incoming wind speed in front of the rotor. In backward looking orientation, presented in chapter 3, the objective is to quantify the accuracy of wake measurements with a single beam LiDAR system. Conclusions are drawn in chapter 4.

2

Forward looking LiDAR

2.1 Scope

A forward looking LiDAR can be used for accurate measurement of the free wind speed at hub height upstream the wind turbine rotor. At small distances to the rotor plane, the incoming wind is disturbed by the blockage effect of the rotor. A previous analysis of the data showed unresolved differences in the blockage ratio's between two undisturbed sectors [1]. The scope of this study is to investigate possible disturbing factors that could have caused the different blocking ratio's in the two undisturbed sectors.

2.2 Experimental setup

The Wind Iris from Avent Lidar Technology is a pulsed system with two lines of sight (LOS) which are separated by a horizontal angle of 30°. It can measure the wind speed at 10 distances simultaneously in a range of 400m. The Wind Iris was mounted upon the nacelle of test turbine N6, see Figure 1. This is a 2.5MW pitch controlled wind turbine with a 3-bladed rotor with a hub height and diameter of 80 m. The position of the optical head of the Wind iris was approximately 9 m behind the rotor and 3 m above hub height. The measurement range was set to distances of 80m to 440m (1*D* to 5.5*D*) with a step size of 40m (0.5*D*), see Table 1. A downward tilt angle has been applied in order to measure at hub height at a distance of 2.5*D* ahead of the rotor. A comparison [8] between the Wind Iris inclinometer and the nacelle inclinometer (installed at the roof just under the Wind Iris) has shown that the Wind Iris inclinometer gives more trustful information. The nacelle inclinometer produces more scatter and shows a strange offset of 1° between two time periods.

Table 1: Range gate configuration of the Wind Iris in forward looking orientation.

Number	1	2	3	4	5	6	7	8	9	10
Distance [m]	80	120	160	200	240	280	320	360	400	400

Figure 1: Wind Iris mounted on the back of the nacelle of test turbine N6.

Figure 2 shows the ECN test site EWTW. For test turbine N6, two sectors are undisturbed for measurements with a meteorological mast according to IEC 61400-12-1 [2]: a wide north sector and a smaller southwest sector. In the previous study, the limits of these two sectors were defined as follows:

- Southwest: 213.1 – 244.6°
- North: 305.1 – 32.7°

The following additional selection criteria have been applied:

- Darwind and Alstom wind turbines not operating for the southwest sector
- Status Wind Iris > 0.5
- Operational mode turbine N6 10.8 – 12.2 and generator speed 700 – 1150 rpm.
- Wind speeds between 3.5 and 12.5 m/s at 80 m height measured with meteorological mast MM3.

Figure 2: Bird-eye view of the test site EWTW.

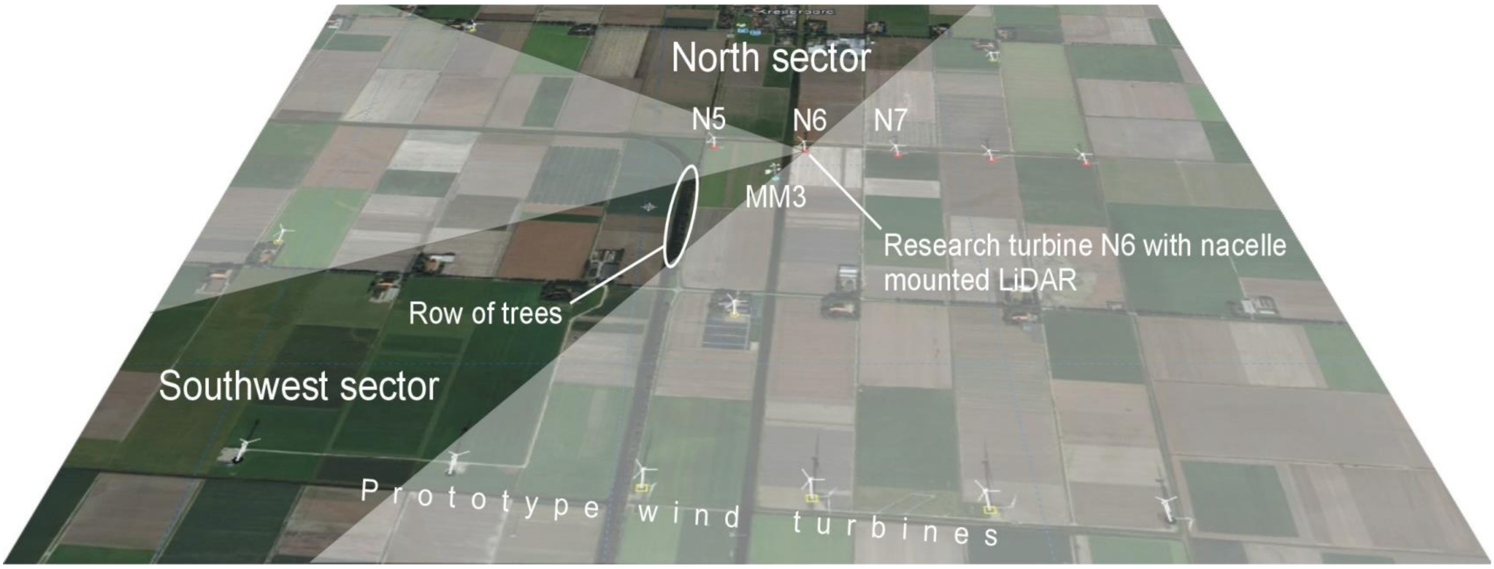
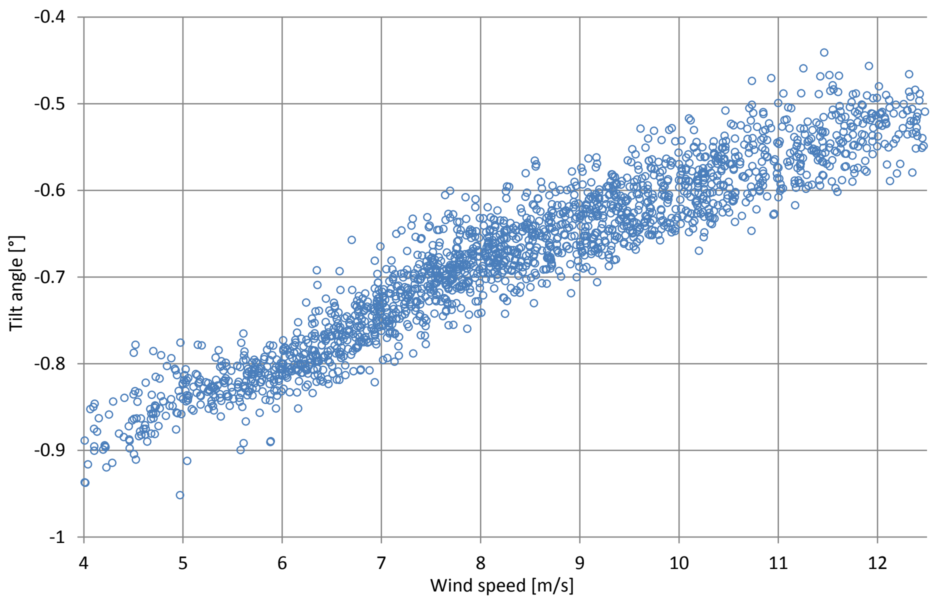


Figure 3 shows the tilt angle of the Wind Iris during the measurements as a function of the wind speed. Due to tower bending, the downward tilt angle decreases with increasing wind speed. The average of the tilt angle is -0.68°. This means that at the farthest distance (440 m), the LOS reach approximately 2.4 m below hub height, which is 0.4 m outside the required region of ±2.5% of hub height, according to the IEC 61400-12-1 standard [2].

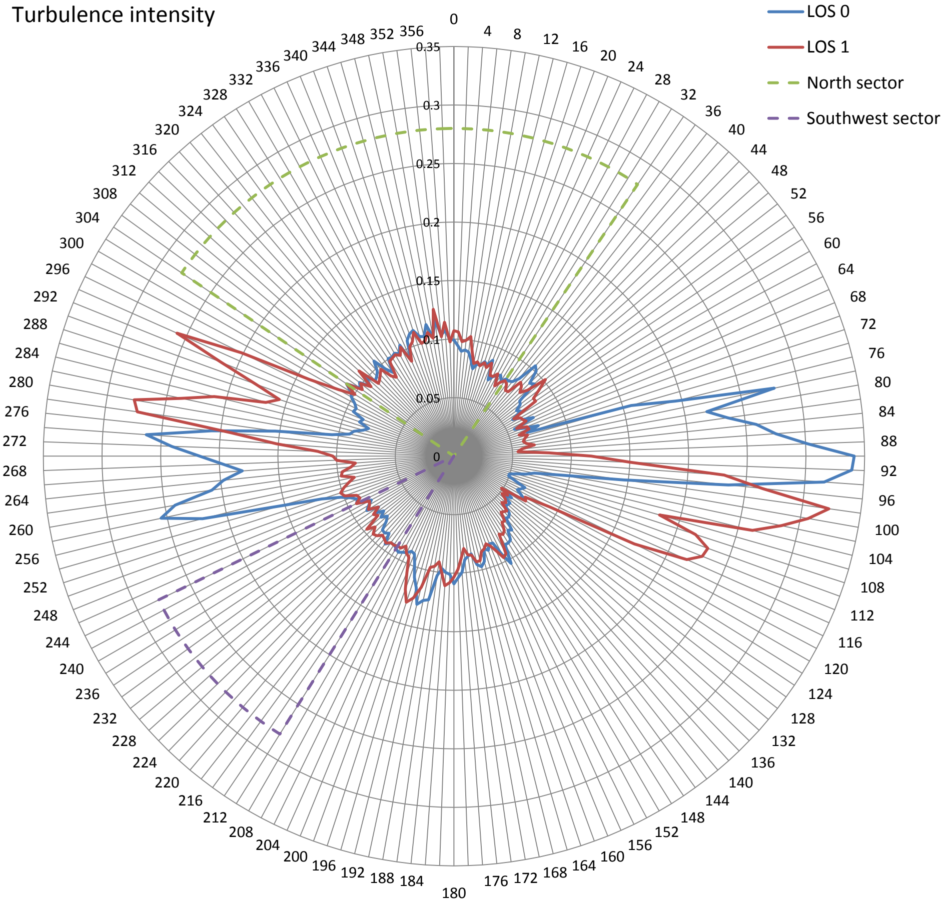
Figure 3: Tilt angle measured by the Wind Iris inclinometer as a function of the wind speed.



A plot of the measured turbulence intensities from the individual beams as a function of the yaw angle gives a very clear indication of disturbed wind sectors, see Figure 4. Disturbances from the western research turbine N5 are seen for wind directions between 250° and 300°, and from the eastern research turbine N7 between 70° and 120°. Disturbances from the prototype wind turbines south from the research turbines are seen at wind directions of 152°, 166°, 182°, and 197°. A very small disturbance can be seen around 225° from the most western prototype turbine. In the northeast sector, at 46°, a disturbance from a small wind turbine is clearly visible.

According to the measured turbulence intensities, the incoming wind for the two chosen sectors in the previous study seems not to be disturbed by objects.

Figure 4: Average turbulence intensity measured at individual LOS at a distance of 200 m (2.5*D*) as a function of the yaw angle.



2.3 Blockage effect

When measuring the incoming wind speed upwind the rotor plane with the Wind Iris, the measured wind speed will be affected by the blockage effect of the rotor.

In Figure 5 the relative mean horizontal wind speed in front of turbine N6 is plotted for the two undisturbed sectors, for wind speeds between 3.5 and 12.5 m/s and with the value measured at 5.5*D* (440m) as reference wind speed. For the north sector, the wind speed reduces with approximately 0.45% at 2.5*D* distance. In the southwest sector an up-speeding effect with a maximum of 0.75% is occurs. This up-speeding effect was already mentioned in [1], but the reason was not resolved and needed further investigation. It was mentioned that terrain effects caused by a row of trees at the west side between research turbine 5 and the westerly Siemens prototype turbine might have caused this up-speeding effect. However, as will be demonstrated with a velocity contour plot calculated with a CFD model, the up-speeding effect is mainly caused by test turbine N5, located at 305 m westward from N6.

Figure 5: Normalized horizontal wind speed in front of research turbine N6 for the north and southwest sector.

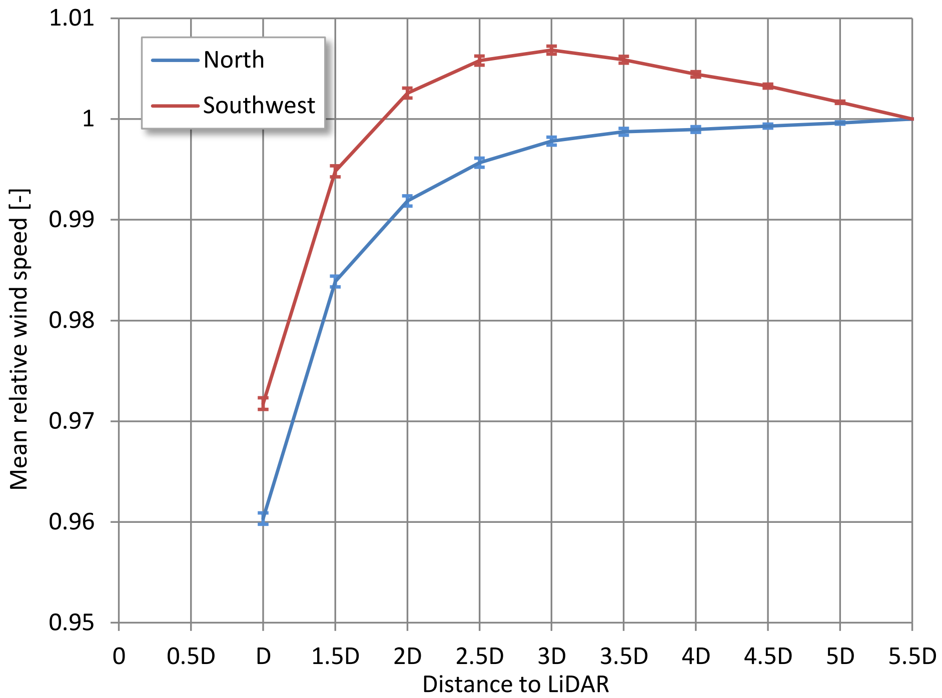
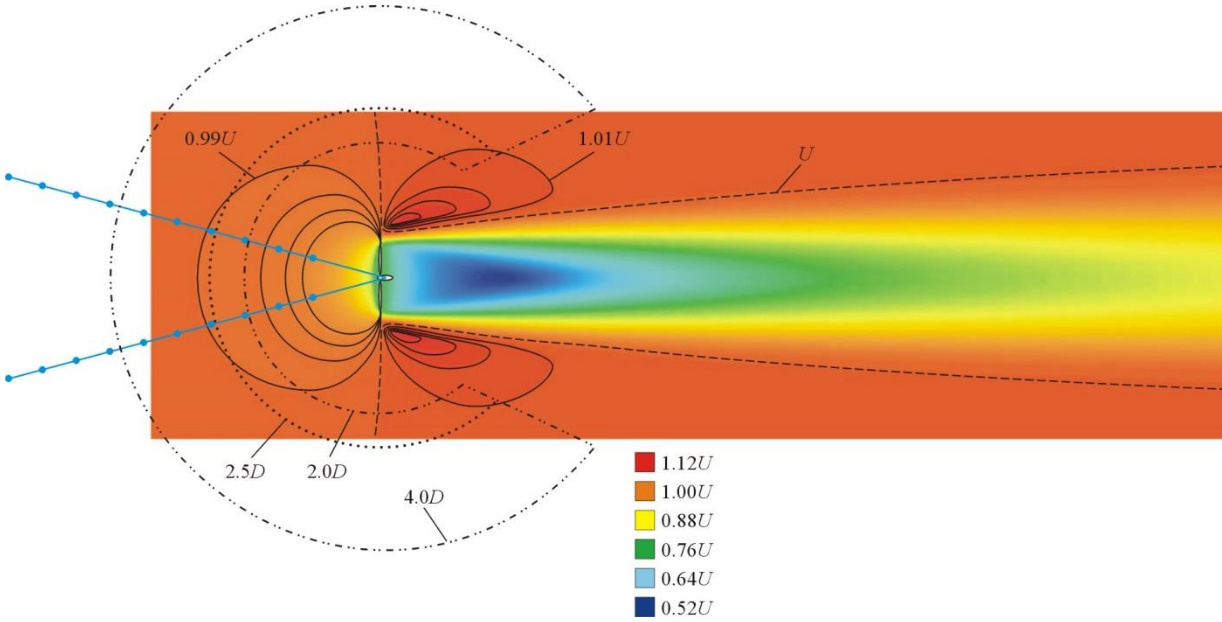


Figure 6, shows the velocity contour plot of turbine N6 based on CFD calculations for an actuator disc from [9]. According to these calculations, the blockage effect is more than 1% at the recommended distance of 2.5 rotor diameters from the rotor centre when the axial induction factor is 0.24. When a meteorological mast is used located at the recommended distance (2.5 rotor diameters from the rotor centre), the effect of the disturbance changes with wind direction, so that the blockage effect will be partly counterbalanced by the up-speeding effect in the region outside the wake. In comparison, a nacelle mounted LiDAR is always measuring ahead of the rotor. Therefore, the average disturbance on the LiDAR measurement will be larger, but also better predictable in comparison with a meteorological mast.

Figure 6: Velocity contour plot around a wind turbine calculated with an actuator disk model of the rotor with an axial induction factor of 0.24. The dashed line shows where the wind velocity is equal to the undisturbed velocity *U*. The LOS and measurement range of the Wind Iris is indicated with blue lines and bullets. The required distance (2*D*-4*D*) and recommended distance (2.5*D*) for a meteorological mast according to the IEC 61400-12-1 [2] is indicated as well.



For the wind sector 240° ± 5°, which falls for 96% inside the southwest sector (213.1° - 244.6°), LOS 0 of the Wind Iris passes the rotor centre of turbine N5 at a minimum distance between 1*D* and 1.5*D*. This is illustrated in Figure 7, where the 10 measurement ranges of the Wind Iris are sketched for the wind sector 240° ± 5°, combined with the velocity contour plot of Figure 6 applied for turbine N5. This figure clearly shows that LOS 0 is largely disturbed by turbine N5. The first 4 measurement ranges of LOS 0 are inside the region where the wind speed has increased with more than 1% due to the up-speeding effect around the wake of turbine N5. The last 5 measurement ranges of LOS 0 are inside the region where the wind speed has decreased with more than 1% due to the blockage effect of turbine N5. It is obvious that these two effects result in an up-speeding effect for the southwest sector as seen in Figure 5.

Also for the wind sector 230° ± 5°, the last three measurement ranges of LOS 0 are inside the blockage region of turbine N5, as can be seen in Figure 8. These two sectors of Figure 7 and Figure 8 cover 50° of the 'undisturbed' southwest sector.

The most undisturbed wind velocity along LOS 0 is where it crosses the dashed line, which is found between the fifth and sixth measurement range at 260m from turbine N6. This means that at a distance of 260 m (3.25*D*), the result of LOS 0 should be equal to the result of LOS 1 for true comparison of the results for both sectors. In Figure 9 this comparison is made by adjusting the reference wind speed for the southwest sector. This graph now shows how turbine N5 disturbs the results in the southwest sector, causing an up-speeding effect at distances smaller than 3.25*D*, and a blocking effect at distances larger than 3.25*D*.

Figure 7: Location of the 10 measurement ranges along the LOS of the Wind Iris for the wind sector 240° ± 5°.

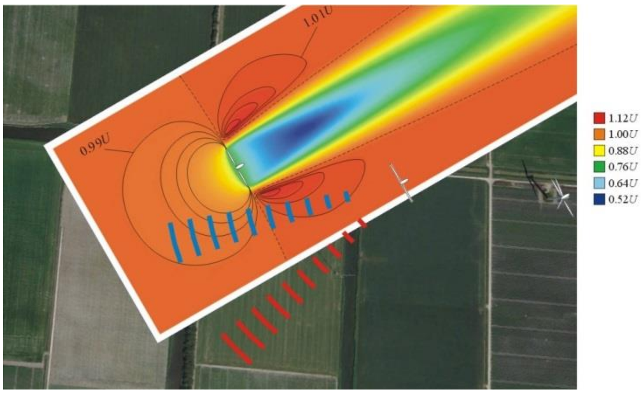


Figure 8: Location of the LOS of the 10 measurement ranges along the Wind Iris for the wind sector 230° ± 5°.

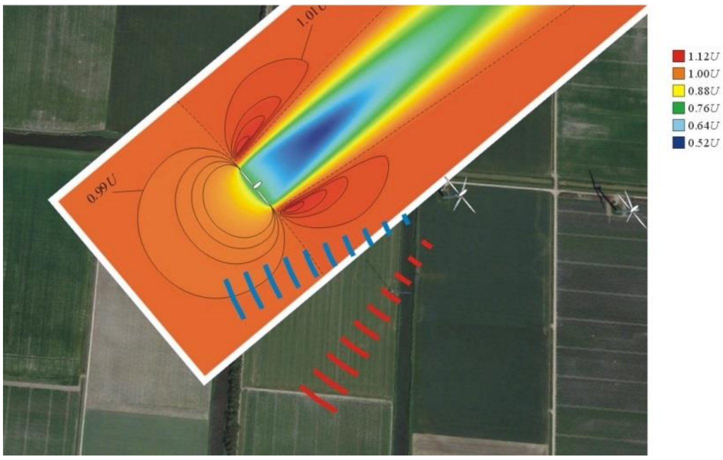
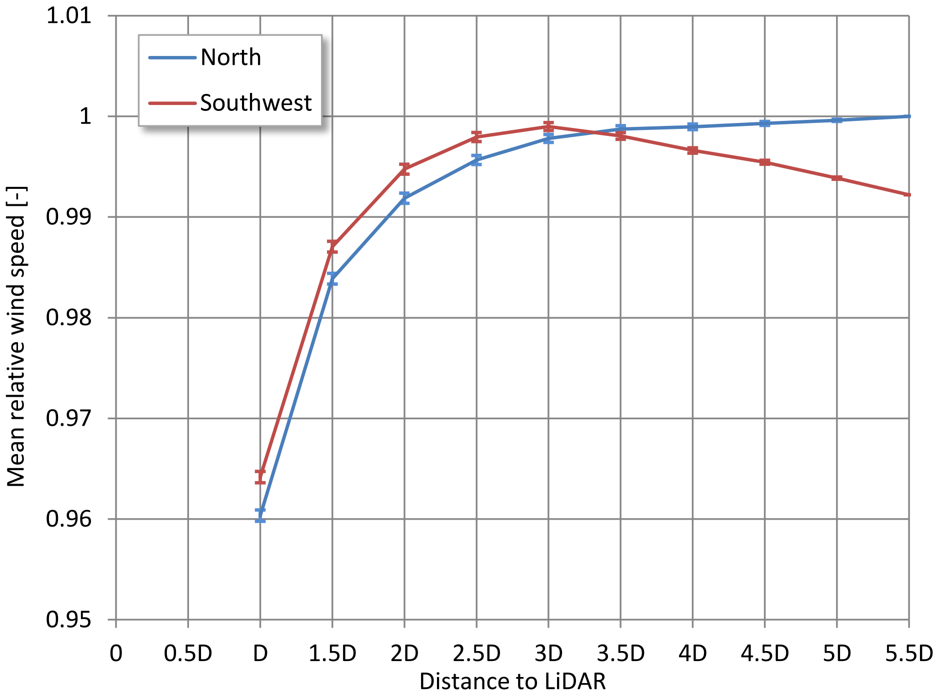


Figure 9: Normalized horizontal wind speed for the north and southwest sector. The result for the north sector is the same as in Figure 5. The reference wind speed for the southwest sector is adjusted in order that the results at a distance of 3.25*D* are identical for both sectors.



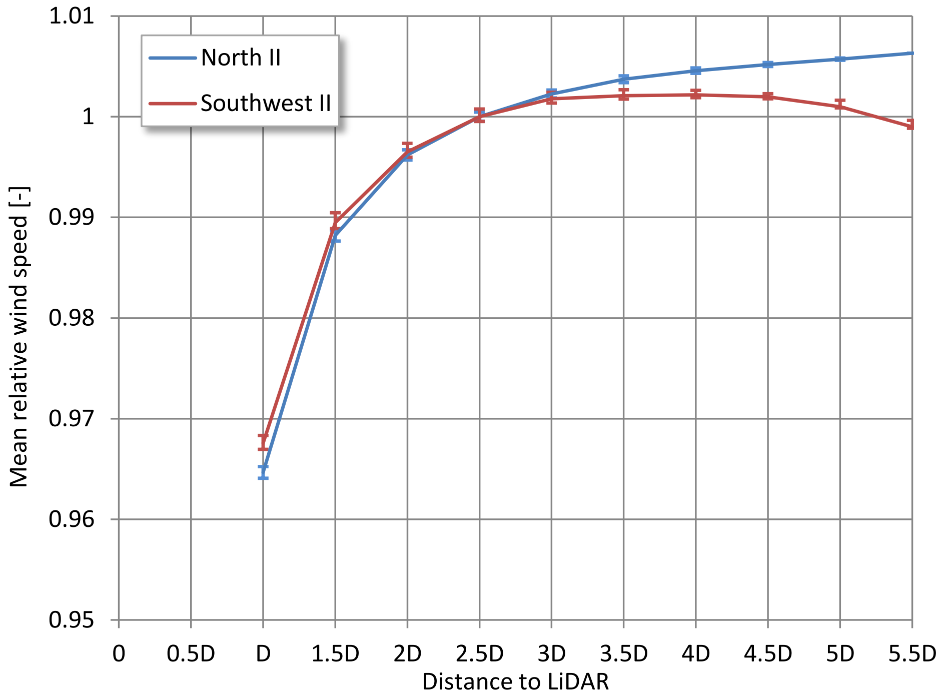
These results show that it is important to apply the minimum distance for meteorological mast also for the LOS of a LiDAR system. For the Wind Iris, this means that the undisturbed sectors must be reduced as follows:

- Southwest: 213.1 – 230.0°
- North: 320.0 – 32.7°

Note that also the North sector has reduced since for the original north sector the same blockage effect from turbine N5 occurs as for the southwest sector. However, because the undisturbed part of the north sector is more than 4 times larger than the undisturbed part of the southwest sector, the effect of the disturbance from turbine N5 on the total result of the north sector is very small

Figure 10 shows the results for the reduced sectors. No up-speeding effect is visible anymore in the southwest sector. At a distance of 3*D* and further, the blockage effect of turbine N5 is still visible, making the curve more flat, and even decreasing at a distance beyond 4.5*D*. These results are in good agreement with the observations from Figure 8. The reduced north sector is much larger and much less disturbed by turbine N5. Form this sector, it seems that the blockage effect of turbine N6 is noticeable up to a distance of at least 4*D*. From 4*D* to the end of the measurement range at 5.5*D*, the curve seems to be linearly increasing. It is not clear if this trend is still caused by the blockage of turbine N6 only, or a combined blockage effect of turbine N5, N6 and N7. Another possibility is that the wind velocity increases in the northern direction because of the position of EWTW with respect to the lake IJsselmeer, where the wind profile is characterized with much lower shear, resulting in higher wind velocities.

Figure 10: Horizontal wind speed for the reduced north and southwest sectors, normalized with the measured wind speed at 2.5*D*.



Due to the downward tilt angle, see Figure 3, the height of the measurements decreases with increasing distance, and so will the velocity due to the vertical wind profile. When the vertical shear at hub height is known, the effect of the tilt angle can be corrected to reduce the overall accuracy.

In the 9 month period before the Wind Iris was installed, a ground based LiDAR was used to measure the vertical wind profile 260 m south of the test turbine N6. A power law coefficient as a function of wind direction is determined from these measurements at 80, 100 and 108 m height. Due to wake effects from the test turbines, there is only data available between 75° and 315°, see Figure 11. In the reduced southwest sector, a very high power law coefficient of 0.21 was found. Since no data for the north sector is available, the power law coefficient must be estimated. Due to the position of EWTW with respect to the lake IJsselmeer, a much lower power law coefficient is expected for the north sector. The estimated power law coefficient used for the correction is 0.15. After applying the correction for the tilt angle, the blockage effects for the reduced north and southwest sectors become more similar, see Figure 12. For the southwest sector, a maximum velocity is measured at 5*D* distance, which is in agreement with the observations from Figure 8. For the north sector, the velocity increase is almost constant with distance from 4*D* and further. As mentioned, it is not clear if this trend is still due to the blockage of turbine N6 only, or in combination with the blockage effects from turbine N5 and N7, or that it is caused by the development of the wind profile due to increased roughness height after the wind leaves the area above the lake IJsselmeer.

Figure 11: Power law coefficient determined from measurements with a ground based 260m south of test turbine N6.

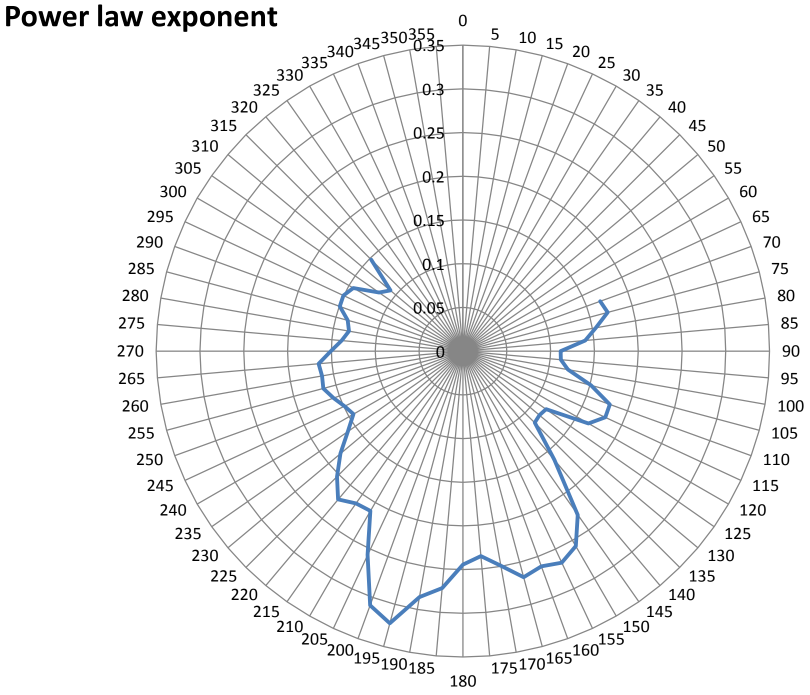
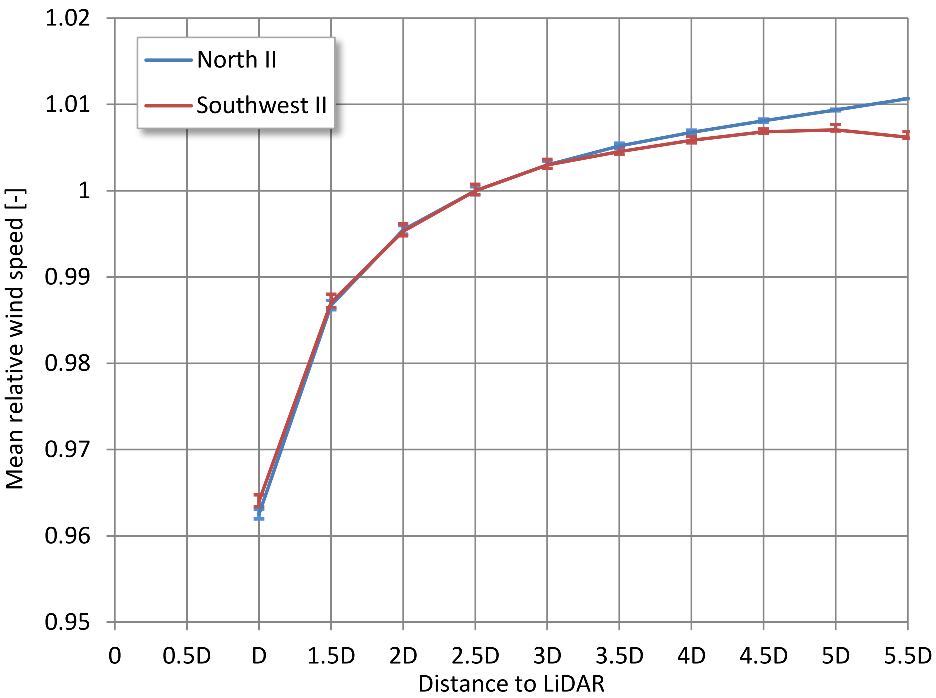


Figure 12: Horizontal wind speed for the reduced north and southwest sectors, normalized with the measured wind speed at 2.5*D*, after correction for tilt angle.



In order to investigate other disturbing factors like a row of trees on the west side of turbine N5, a comparison of measured wind speeds is made for 4 different wind directions with a deviation of 35° from the line of turbines. In Figure 13 the normalized wind speeds are plotted for the two eastern wind sectors that deviate 35° from the line of turbines (i.e. 240° and 310°). The wind velocity measured at 3.25*D* is used as reference wind speed for the normalization. The two curves are very much alike, with only higher velocities for the 60° sector at distances larger than 3.5*D*. This higher velocity with respect to 130° is most probably caused by the rotation of the wake of turbine N8. For eastern wind directions, the wake rotation causes downward flow at the north side of the wake, which transports air with higher velocity from above hub height to lower levels. The same effect causes upward flow at the south side of the wake, which transports air with lower velocity from below hub height to higher levels. A similar effect has been seen before from measurements with meteorological mast MM3 [3].

The maximum up-speeding effect occurs at a distance of 3*D*. From distances of 4*D* and further, a second blockage effect is visible, which most probably consists of two separate effects: a decreasing blockage effect from turbine N7 and an up-speeding effect caused by turbine N8.

Figure 13: Normalized wind speeds measured in eastern wind sectors when one of the laser beams of the Wind Iris passes the rotor plane of research turbine N7 at a distance of 1.0*D* from the rotor centre. The radial distances where the laser beams pass the rotor planes of turbines N7 (3.3*D*) and N8 (6.6*D*) are sketched in the figure.

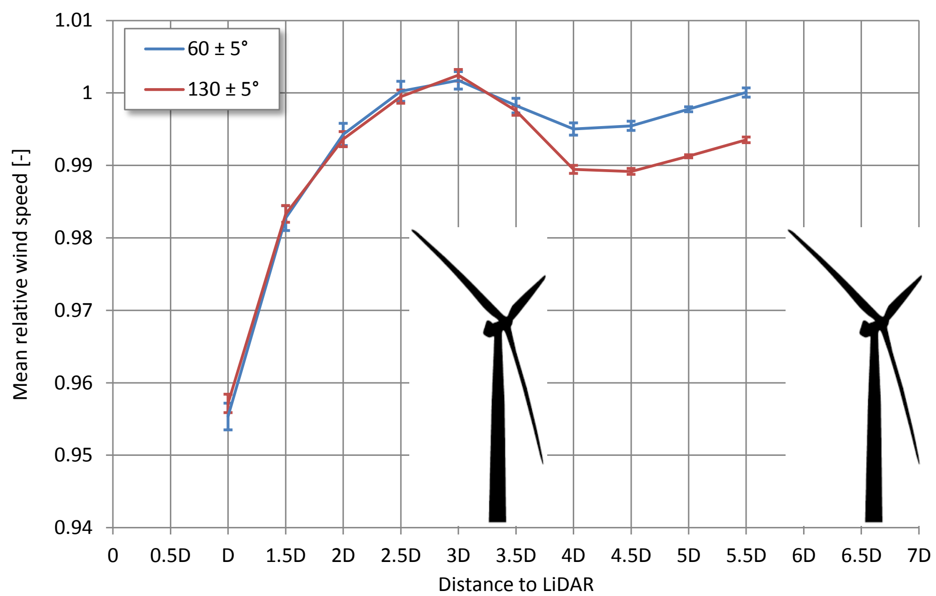
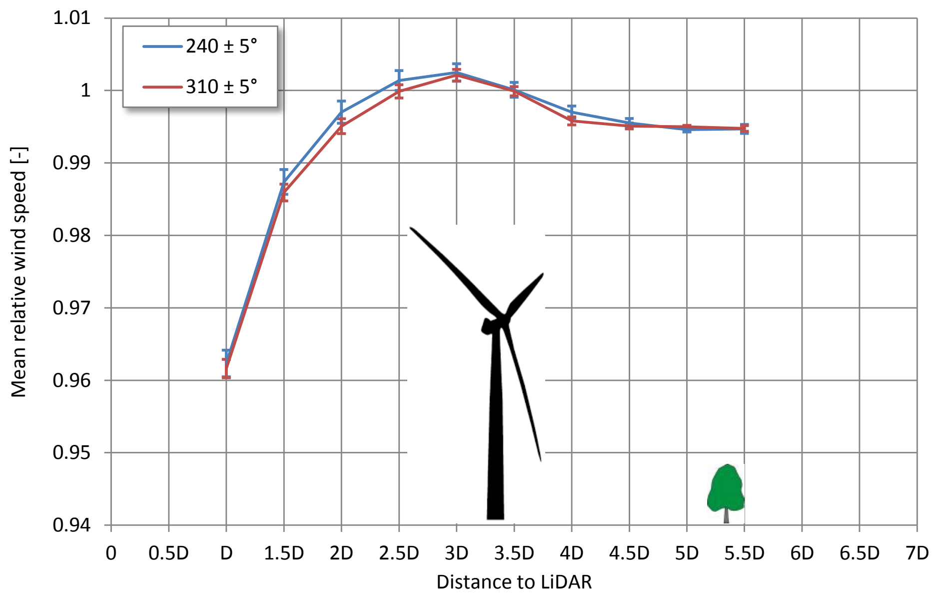


Figure 14 shows the normalized wind speeds for the two western wind sectors that deviate 35° from the line of turbines (i.e. 240° and 310°). Again, the wind velocity measured at 3.25*D* is used as reference wind speed for the normalization. The two curves are almost identical. A small increase of the velocity between 5.5*D* and 4*D* is observed that is caused by the reduced blockage effect of turbine N5, as can be seen in Figure 7. In the southwest angle (240°) the trees are larger than at the northwest angle

(310°). According to the observations from Figure 7, a small increase of the velocity is expected between 4.5*D* and 5*D*. Since this trend is not seen in Figure 14, it is possible that this effect is counterbalanced by a small up-speeding effect caused by the row of trees.

Figure 14: Normalized wind speeds measured in western wind sectors when one of the laser beams of the Wind Iris passes the rotor plane of research turbine N5 at a distance of 1.0*D* from the rotor centre. The radial distances where the laser beams pass the rotor plane of turbine N5 (3.3*D*) and a row of trees (5.3*D*) are sketched in the figure.



Appendix A contains plots of the relative velocity along the LOS for several wind directions.

2.4 Conclusions and recommendations

Measurements with the Wind Iris on the nacelle of research turbine N6 at the test site EWTW have been analysed in order to identify disturbing factors when measuring the incoming wind speed in front of the rotor. It has been found that the differences between both sectors are related to flow disturbances caused by test turbine N5.

A wide region of disturbed flow exists around a wind turbine rotor. Apart from the wake region behind the rotor, the flow already decelerates more than 3 rotor diameters upstream, while the flow accelerates around the near wake region. A meteorological mast will experience both positive and negative effects on the wind velocity, depending on the wind direction, while a nacelle mounted LiDAR only experiences the negative blockage effect. At the recommended distance of 2.5 rotor diameters, the velocity is reduced by more than 0.5% due to the blockage effect. When other turbines are around, it is advised to apply the recommended distance of 2.5 rotor diameters also for the distance between the LOS and the wake centreline of these turbines. When one of the LOS reaches within a distance of 2.5*D* from the wake centreline of a nearby turbine, a large up-speeding effect will disturb the measurements.

3

Backward looking LiDAR

3.1 Experimental setup

For the measurements with backward looking LiDAR, the Wind Iris was modified by Avent to measure negative (downstream) velocities with a single beam. The beam has been aligned with the nacelle of research turbine N6 and the measurement range was set to 10 distances between 80 and 580 m, see Table 2.

Table 2: Range gate configuration of the Wind Iris in backward looking orientation.

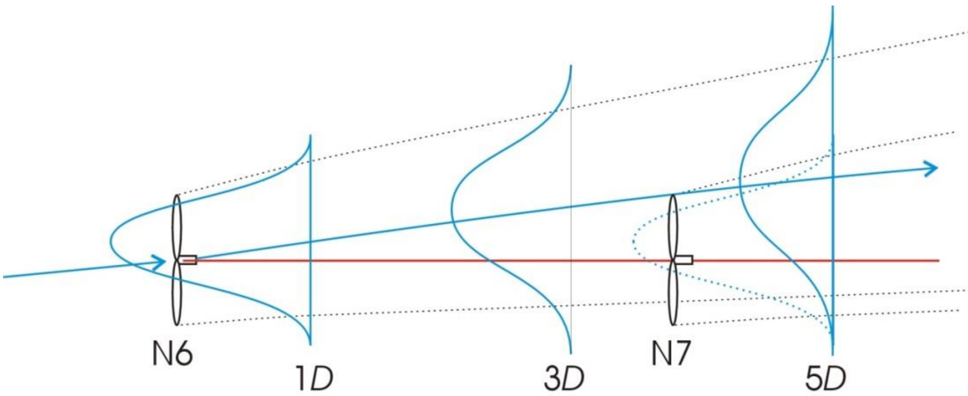
Number	1	2	3	4	5	6	7	8	9	10
Distance [m]	80	140	200	260	320	380	440	500	540	580

The distances in Table 2 are oriented along the centre line between the two lines of sight which are separated by a horizontal angle of 30°. Because now only one LOS is used, the real distances of the measurements are a factor 1/cos(15°) = 1.0353 larger than values in Table 2.

3.2 Yaw misalignment

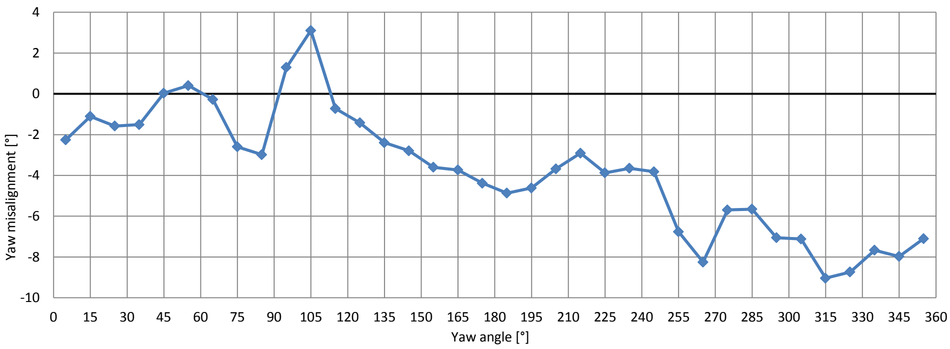
Due to the use of a single beam, the accuracy of the wake measurements with the nacelle mounted LiDAR is strongly affected by yaw misalignment. In several measurements [3, 4, 5] it has been shown that the angle between the wake of a turbine and the rotor axis is approximately a factor 1.24 times larger that the yaw misalignment angle (the angle between the wind direction and the rotor axis). Figure 15 shows how a yaw misalignment angle of only 5° results in a large underestimation of the maximum wake effect at a distance of 3*D* and further.

Figure 15: Sketch of the LOS of the Wind Iris looking backward on research turbine N6 with a yaw misalignment of 5°, which results in a large underestimation of the wake effects.



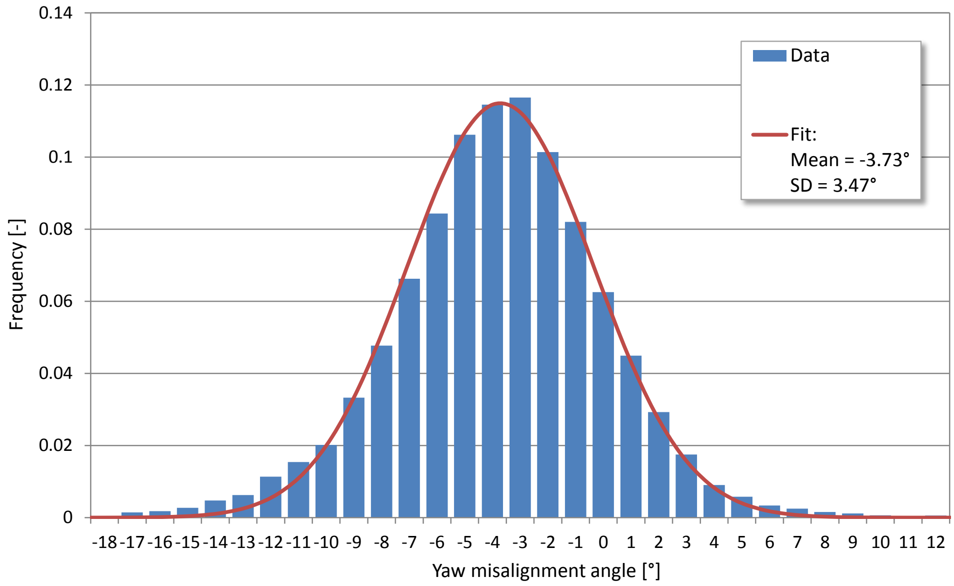
In Figure 16, the average yaw misalignment angle of research turbine N6 is plotted against the yaw angle. Measurements have been averaged in wind direction bins of 10°, starting at 5° so that full wake situations from test turbines N7 at 95° and N5 at 275° both fall in a single bin. In order to have enough measurements in each wind direction bin, the results are averaged for all wind speeds between 5.5 and 10.5 m/s. The yaw misalignment angle (i.e. the difference between the yaw angle and the wind directions measured with the meteorological mast MM3) has an average value of -3.6° and depends strongly on the wind direction. In the range 75° - 115° and 255° - 295° a sine function with an amplitude of 3° is clearly visible. This behaviour of the yaw misalignment has been found before [3], when measurements at EWTW over a period of 4.5 years were analysed. This behaviour of the yaw misalignment angle is the result of asymmetric wake expansion caused by an asymmetric flow profile in partial wake flow from turbines N5 and N7. It is obvious that for multiple wake measurements with the Wind Iris, this behaviour has a negative effect on the accuracy.

Figure 16: Yaw misalignment of research turbine N6 as a function of the wind direction.



A histogram of all measured yaw misalignment angles is shown in Figure 17. The yaw misalignment angles follow a normal distribution with an average value of -3.73° and a standard deviation of 3.47°. Approximately 37% of the time the yaw misalignment angle is larger than 5°.

Figure 17: Histogram and fitted normal distribution of the measured yaw misalignment angle for all wind directions at wind speeds between 5.5 and 10.5 m/s.



Other causes of particular yaw misalignment angles are calibration errors and flow disturbance at the wind vanes of the meteorological mast. At wind directions between 60° and 180° the wind vane at the 120° beam is used, while for wind directions between 180° and 300° the wind vane at the 240° beam is used. Due to a calibration error between both vanes, a difference of approximately 4° between the right side (360°) and the left side (0°) of Figure 16 can be explained.

3.3 Wake turbulence

Measurements of the turbulence intensity have been averaged in small wind direction bins of 2°. the results are averaged for all wind speeds between 5.5 and 10.5 m/s. Turbulence intensities at different distances in the wake of research turbine N6 are plotted in Figure 18. Three distances (1.04*D*, 1.81*D* and 2.59*D*) are in the near wake region of turbine N6 and one distance (6.47*D*) is in the far wake region of N6. Multiple wakes are measured around 95° and 275° (±10°), recognizable by the high turbulence intensities of around 0.25. Single wakes are measured in all other wind directions, resulting in turbulence intensities below 0.2.

According to the measured turbulence in the near wake region, the centreline of the wakes from turbine N5 and N7 are approximately at 274° and 95° respectively. In the far wake, the centreline of these wakes are found approximately at 278° and 98°. Because the turbulence intensities are averages of multiple 10 minute samples, this change of the wake centreline with distance from the LiDAR cannot be caused by wake meandering, and must therefore be due to yaw misalignment of the LOS of the Wind Iris caused by yaw misalignment turbine N6. At a distance of 6.47*D* the measurements indicate a yaw misalignment angle of -3°, which corresponds well with the average yaw misalignment angle of -3.73° as found in Figure 17.

Figure 18: Average turbulence intensity measured with one beam at distances of 1.04*D*, 1.81*D*, 2.59*D* and 6.47*D* in the wake of research turbine N6, as a function of yaw angle.

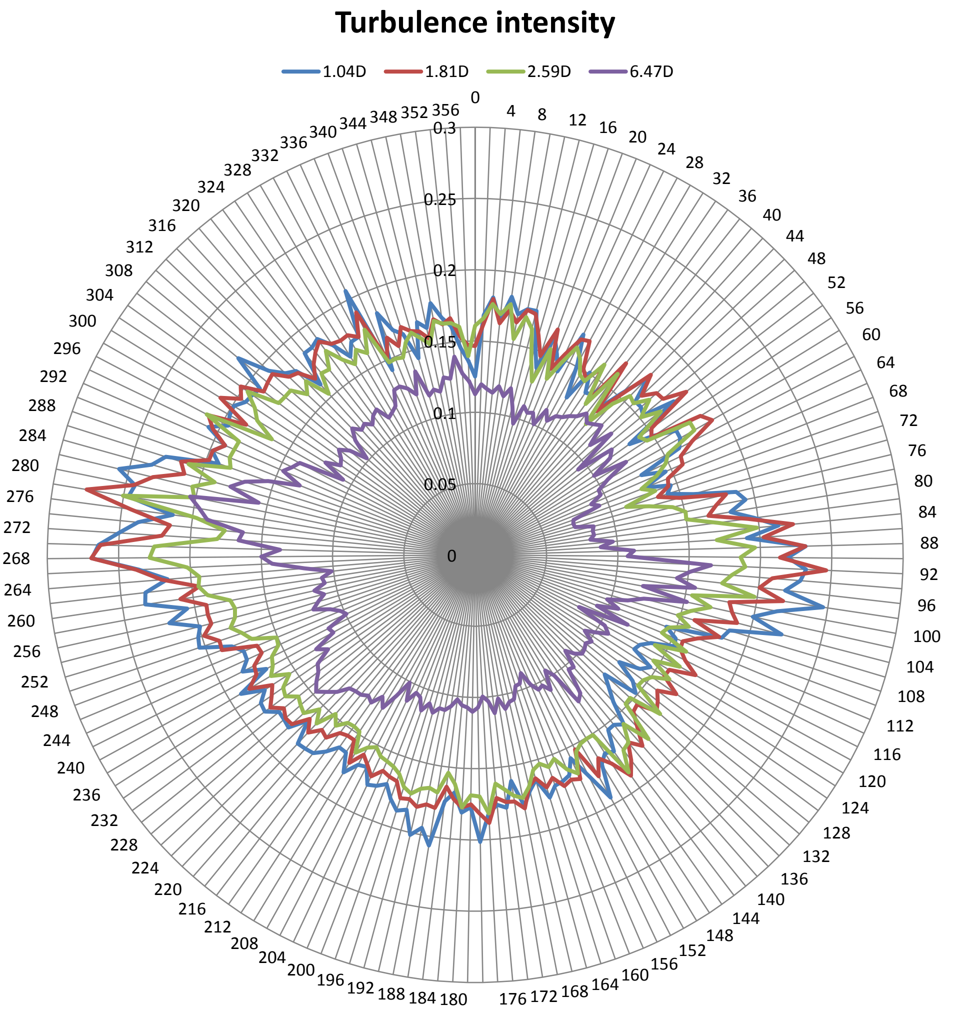
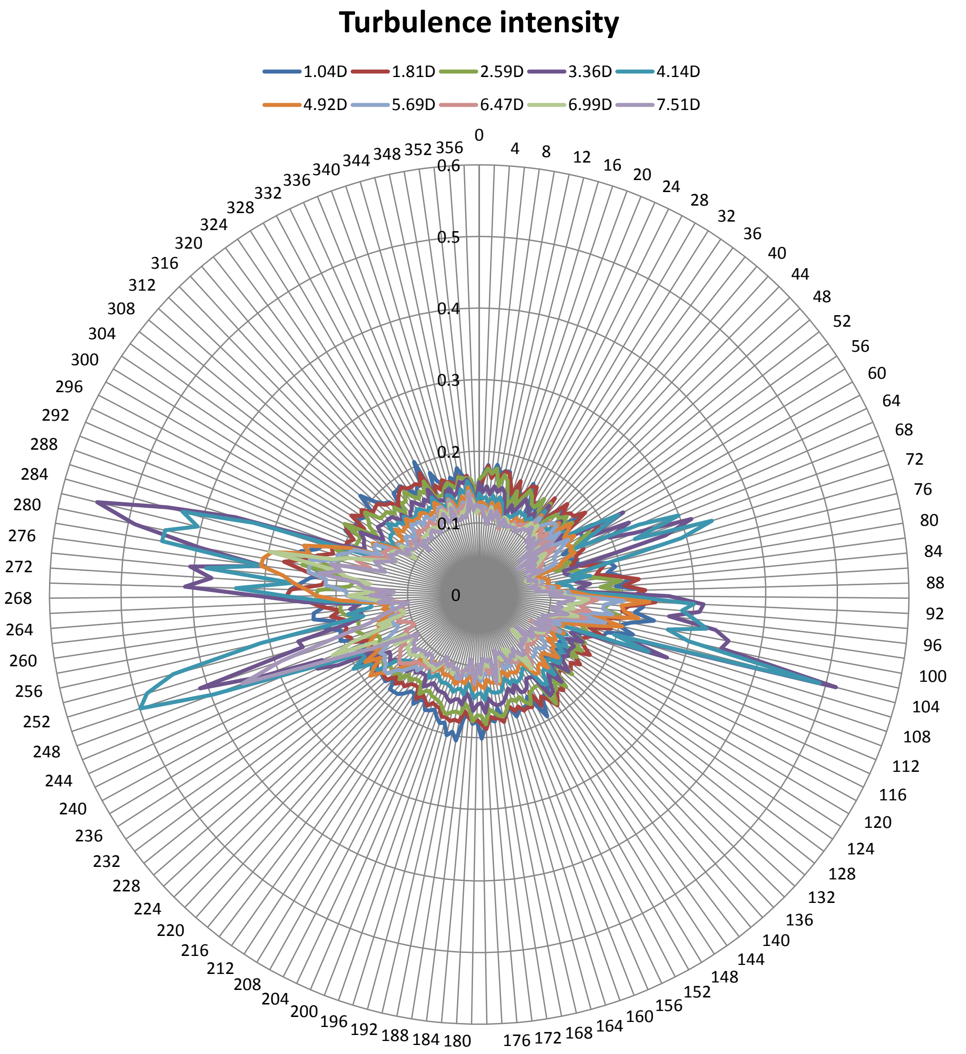


Figure 19 shows the average of the measured turbulence intensities for all distances and wind directions. At distances of 3.36*D* and 4.14*D*, large turbulence intensities (> 0.25) are found at wind direction sectors 60° - 76°, 90° - 108°, 244° - 256°, and 270° - 286°. The first and third sector match almost perfectly with the rotors of research turbines N7 and N5 (located at a distance of 3.8*D*), especially when the sectors are corrected for the measured yaw misalignment angle of -3.5°. The two other sectors match also with these two turbines, when the unused LOS is directed to them.

Figure 19: Average turbulence intensity measured with one beam at distances between 1.04*D* and 7.51*D* in the wake of research turbine N6, as a function of yaw angle.

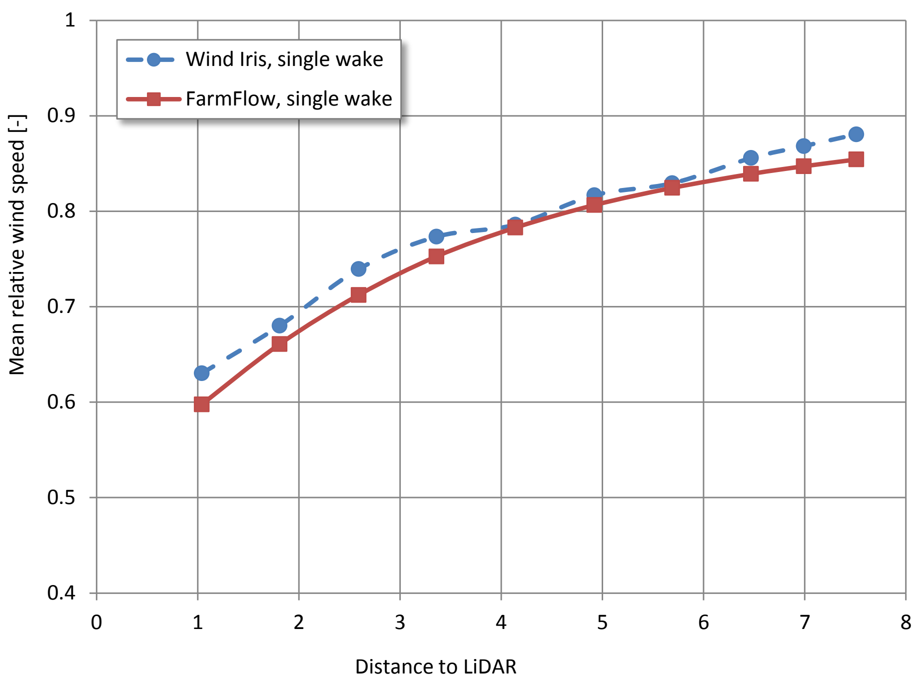


According to Avent Lidar Technology, the two LOS on this Wind Iris system are not fully isolated from each other. During the pulses emission on one LOS, a small part of the laser signal is also sent through the second LOS, while during the reception a small part of the backscattered signal along this second LOS is passing through to the LOS being measured. The contamination is very limited and the isolation is high enough when light pulses are backscattered on aerosols only, i.e. it does not appear in most use cases. However, when the leaked emission through the second LOS is reflected on a hard target, the backscattered signal is strong enough to contaminate the measurement. With newer versions of the Wind Iris this effect has been solved with an increased isolation between the LOS and additional signal processing techniques.

3.4 Wake velocities

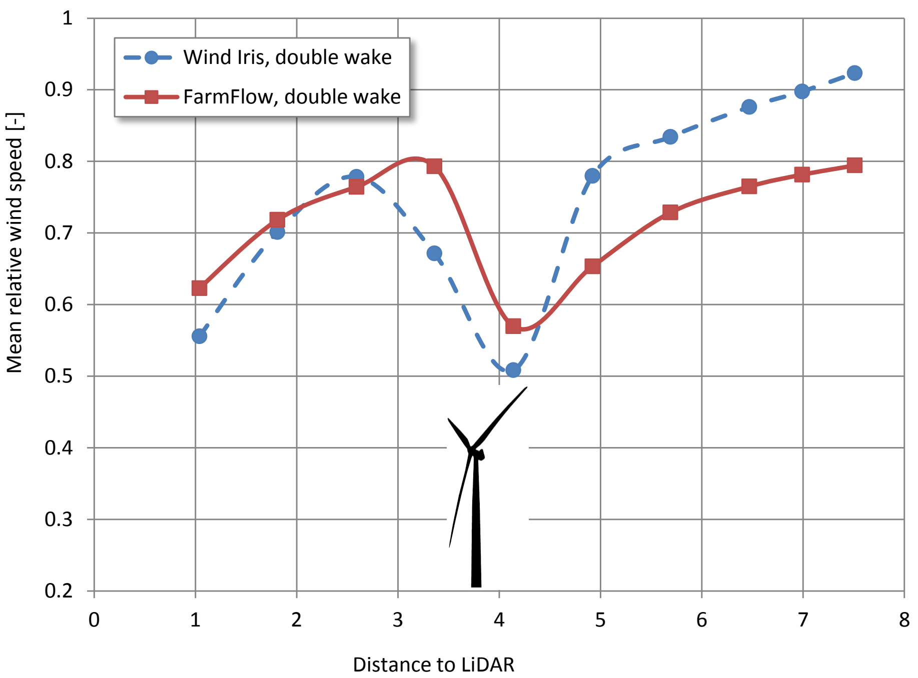
Measured wake velocities at the wake centreline as a function of the distance behind the rotor of research turbine N6 are plotted in Figure 20. The wake velocities are normalized with the free stream wind speed at hub height, which is measured with the meteorological mast MM3. The dataset was filtered for wind speeds between 3.5 and 10.5 m/s and for wind directions from the southwest sector (213.1° - 244.6°). Only data is selected when the status of the signal was larger than 0.5 and when the absolute value of the yaw misalignment angle was smaller than 8°. The average wind speed of this dataset as measured with MM3, is 7.25 m/s, and the average turbulence intensity is 0.102. For comparison, results from FarmFlow simulations [5] with the same average wind speed and turbulence intensity are also presented. The FarmFlow calculations are very consistent with the measurements, with an average absolute difference of 1.8% with the measured wind speeds, and a maximum difference of 3.3% occurring at the first range of 1.04*D* behind the LiDAR. For this comparison one has to realize that FarmFlow calculates the wake from an actuator disc concept with uniform loading. For a real wind turbine however, the centre area is actually the least uniform part of the rotor swept area due to the blade roots, tower and nacelle. Because these effects are neglected in the modelling, differences are to be expected in the near wake region.

Figure 20: Comparison of measured and calculated normalized wind velocities as a function of distance behind the rotor for free stream conditions (single wake).



In Figure 21, the measured and calculated wake velocities at the wake centreline are shown for the wind sector 270°-280°, i.e. for double and triple wake conditions. This dataset, created with the same selection criteria, consists of 5 data points for each distance, except for the fourth distance of 260 m which contains only 2 valid data points, and the fifth distance of 320 m, which contains only one valid data point. In total 7 values for the fourth and fifth data point were rejected because of too low status value of the signal. In between these two data points the laser beam passes the rotor surface of turbine N7 at a distance of 296 m. It is obvious that reflections on the blades of turbine 7 are the reason of the low status values here. The average undisturbed wind speed of this dataset is 5.72 m/s, and the average turbulence intensity is 0.098. For comparison, FarmFlow calculations are performed with the same average wind speed and turbulence intensity.

Figure 21: Comparison of measured and calculated normalized wind velocities as a function of distance behind the rotor in wake conditions (double wake between 0 and 3.8*D* and triple wake between 3.8*D* and 7.6*D*). A turbine is sketched in the figure at the position where the laser signal passes turbine N7.



The LiDAR measurements and FarmFlow calculations are reasonably consistent. At a distance of 3.36*D* behind the LiDAR, approximately 0.35*D* in front of turbine N7, the LiDAR measures a reduction of the wind velocity of 12% due to the wake effect of turbine N7. However, FarmFlow only calculates wake effects *behind* the rotor, which explains this difference. For distances larger than 4.5*D* (i.e. for triple wake conditions), the LiDAR seems to underestimate the wake effects, since the measured wake deficit behind the three turbines N5, N6 and N7 is much smaller than the measured wake deficit behind two turbines N5 and N6. This underestimation is probably caused by measurement uncertainties of the wind direction and the yaw angle of turbine N6. When the maximum yaw misalignment angle is increased from 8° to 12°, no reduction behind turbine N7 is visible anymore. With a reduction of the maximum yaw misalignment angle from 8° to 6°, a maximum of only 3 valid data points remain.

For these single beam measurements, it is expected that the wake centreline will deflect from the rotor axis due to yaw misalignment. As explained in Figure 15, deflections of the wake centreline will result in an underestimation of the wake deficit. Uncertainties of the yaw misalignment angle are in the order of 4°, while uncertainties of the wind direction are in the order of 3°. To reduce these uncertainties, it is necessary to measure along different LOS, for example with a scanning LiDAR, so that it will be possible to determine the real position of the wake centreline.

3.5 Conclusions and recommendations

The Wind Iris has been used to measure the centreline velocities in the wake of turbine N6, the second turbine in a line of 5 test turbines. The results of these measurements have been analysed and compared with FarmFlow calculations for two sectors. For the southwest sector with free stream conditions for both the test turbine and the meteorological mast, the calculations and measurements agree very well with differences of approximately 2%. Also for double wake conditions, the agreements are quite good. However, for measurements behind the third turbine, the wake effects seem to be underestimated by the Wind Iris, probably due to measurement uncertainties of the wind direction and yaw angle. To reduce these uncertainties in the future, it is necessary to measure along different LOS, for example with a scanning LiDAR, so that it will be possible to determine the real position of the wake centreline.

4 Conclusions

Data from two measurement campaigns on the ECN test site EWTW with a nacelle mounted LiDAR, the Wind Iris from Avent Lidar Technology, have been analysed. In the first campaign, the Wind Iris was used to measure the undisturbed wind speed in front of the wind turbine by means of two horizontal laser beams. In the second campaign, the Wind Iris was used to measure the recovery of the wake in backward looking orientation, with only one laser beam that was aligned with the rotor axis.

A wide region of disturbed flow exists around a wind turbine rotor. Apart from the wake region behind the rotor, the flow already decelerates more than 3 rotor diameters upstream, while the flow accelerates around the near wake region. While a meteorological mast will experience both positive and negative effects on the wind velocity, a nacelle mounted LiDAR only experiences the negative blockage effect. Due to this blockage effect, the velocity is reduced by more than 0.5% at the recommended distance of 2.5 rotor diameters. When other turbines are around, it is advised to apply the recommended distance of 2.5 rotor diameters also for the distance between the LOS and the wake centreline of these turbines. When one of the LOS reaches within a distance of 2.5*D* from the wake centreline of a nearby turbine, a large up-speeding effect will disturb the measurements.

In backward looking orientation, measurements of the velocities at the wake centreline agree very well with FarmFlow calculations with differences of approximately 2% for single wake conditions. Also for double wake conditions the agreements are quite good. However, wake effects behind the third turbine (triple wake conditions) seem to be underestimated by the Wind Iris, probably due to measurement uncertainties of the wind direction and yaw angle. To reduce these uncertainties in the future, it is necessary to measure along different LOS, for example with a scanning LiDAR, so that it will be possible to determine the real position of the wake centreline.

5

References

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[6] J.W. Wagenaar, K. Boorsma, E. Bot, S. Davoust, and B. Svardal. *Using backward nacelle LiDAR in wake characterization for wind farm optimization*, EWEA 2015

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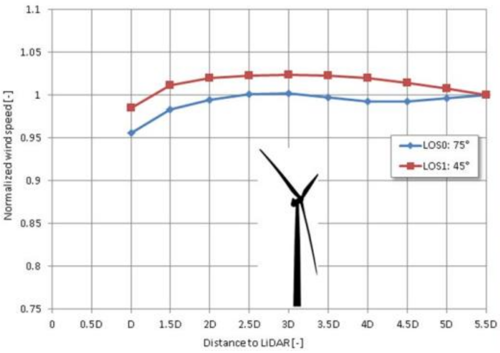
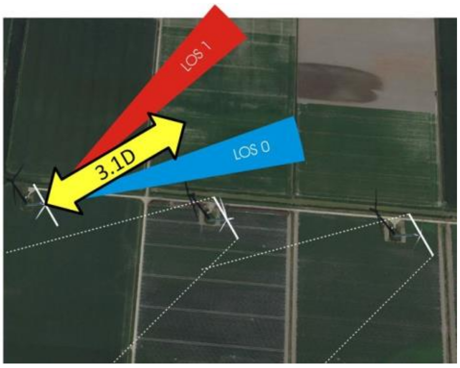
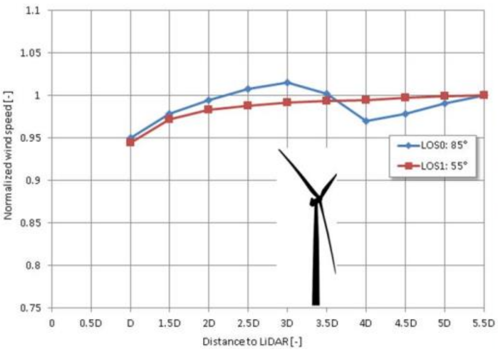
[9] C.R. Jones et al., *WindNet: Improving the impact assessment of wind power projects*, AIMS Energy, December 2014

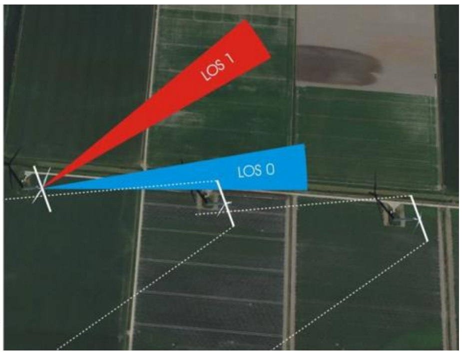
A

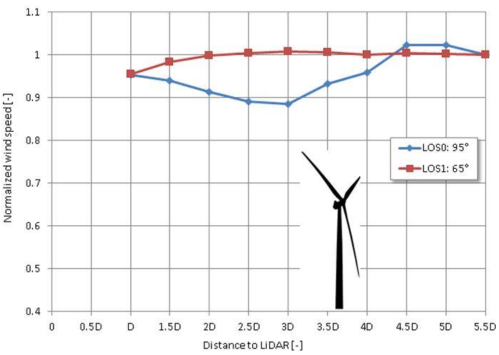
LOS velocities Wind Iris (forward looking)

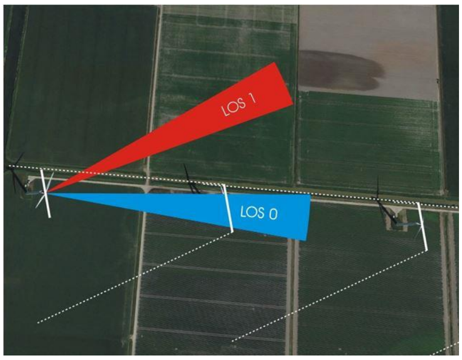


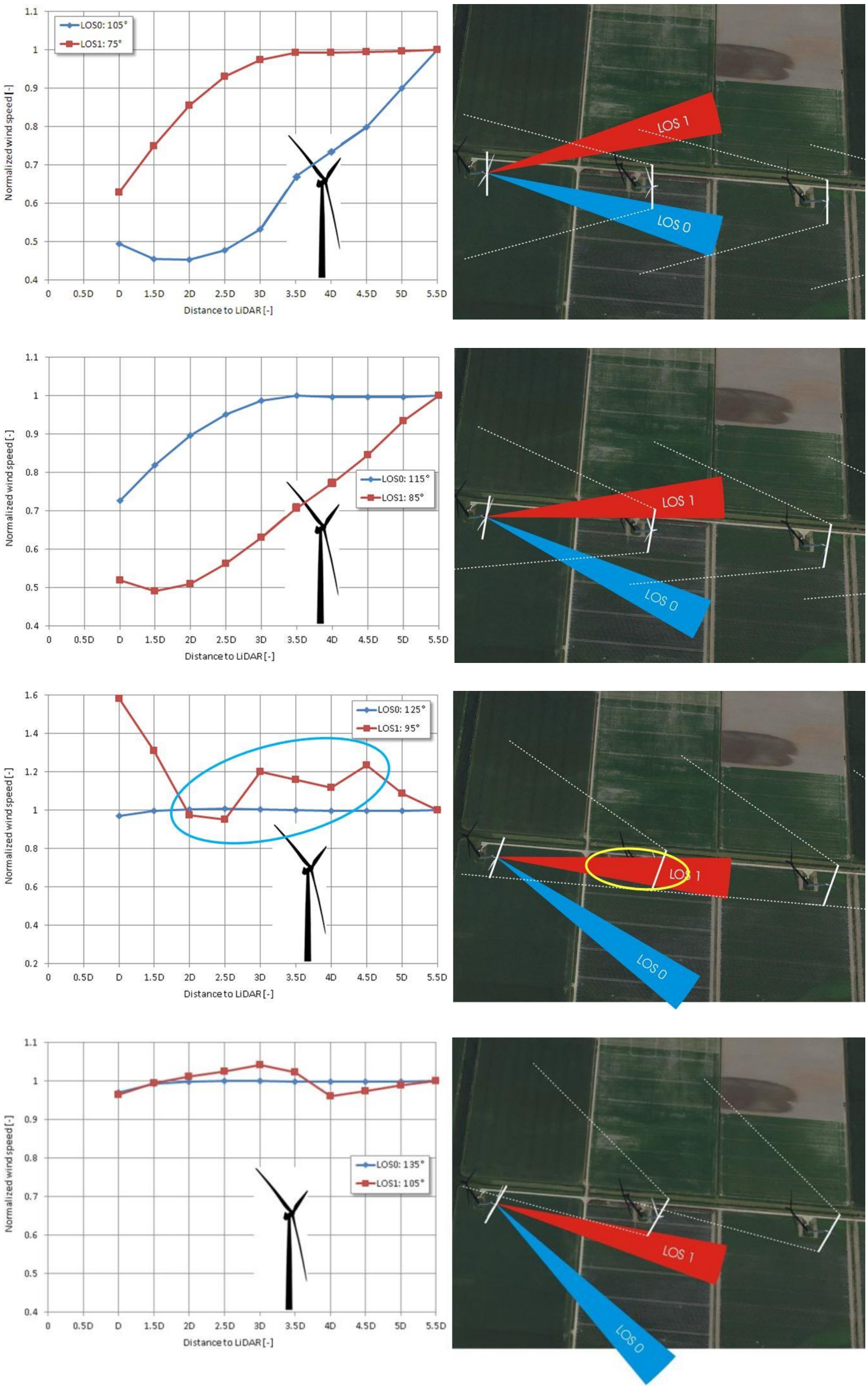




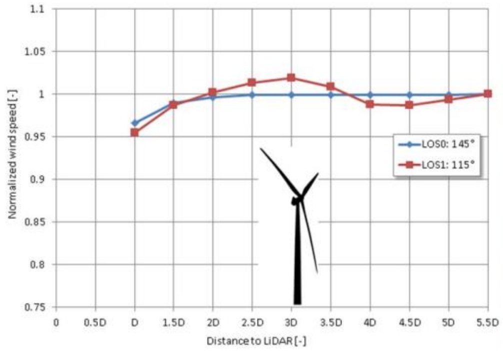








LOS0: 105°
LOS1: 75°
Normalized wind speed [-]
Distance to LiDAR [-]
0
0.5D
D
1.5D
2D
2.5D
3D
3.5D
4D
4.5D
5D
5.5D
LOS 1
LOS 0
LOS0: 115°
LOS1: 85°
LOS0: 125°
LOS1: 95°
LOS0: 135°
LOS1: 105°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Distance to LiDAR [-]
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LOS1: 115°
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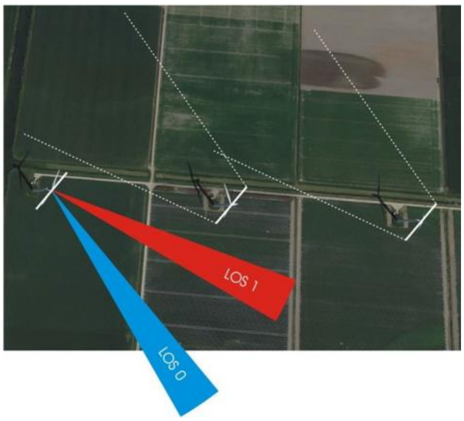
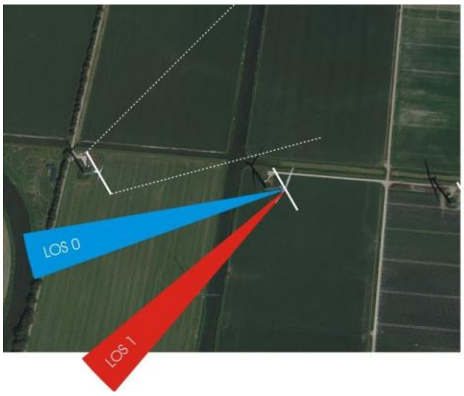
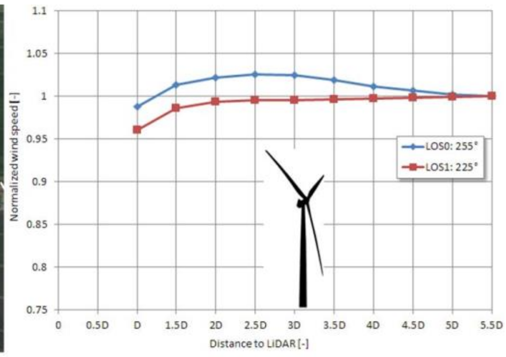
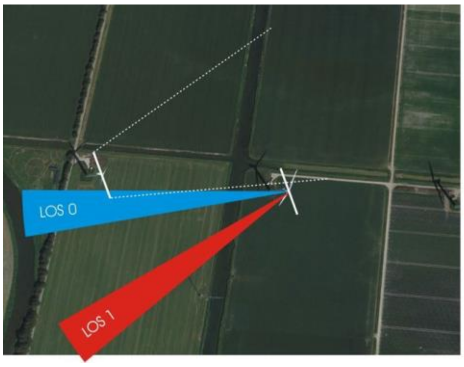
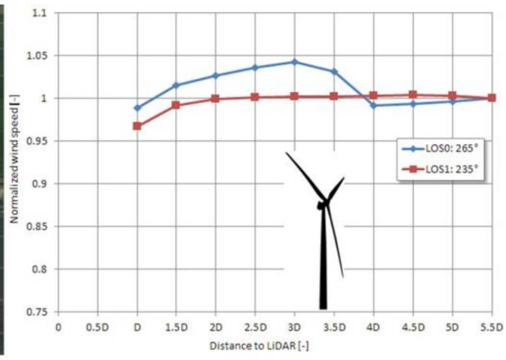
1.1 1.05 1 0.95 0.9 0.85 0.8 0.75


LOS 1
LOS 0


LOS 0
LOS 1


Normalized wind speed [-]
Distance to LiDAR [-]
LOS0: 255°
LOS1: 225°
0 0.5D D 1.5D 2D 2.5D 3D 3.5D 4D 4.5D 5D 5.5D
1.1 1.05 1 0.95 0.9 0.85 0.8 0.75


LOS 0
LOS 1


Normalized wind speed [-]
Distance to LiDAR [-]
LOS0: 265°
LOS1: 235°
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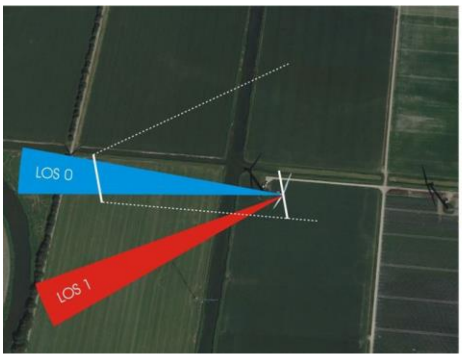
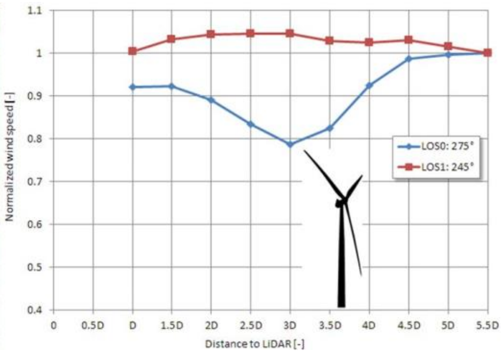
1.1 1.05 1 0.95 0.9 0.85 0.8 0.75


LOS 0
LOS 1


Normalized wind speed [-]
Distance to LiDAR [-]
LOS0: 275°
LOS1: 245°
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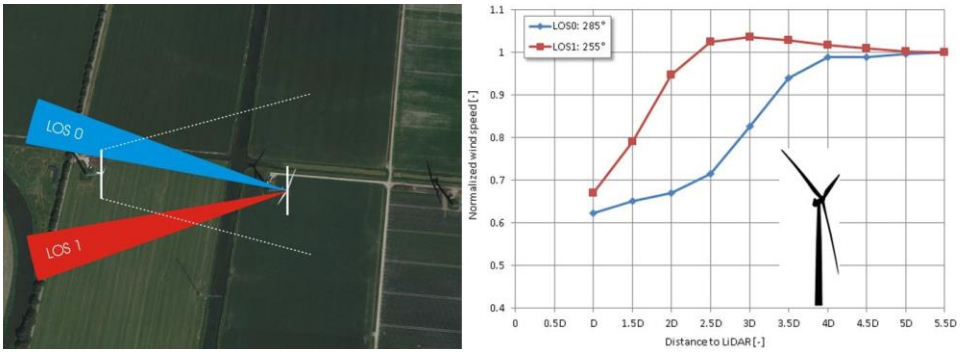
1.1 1 0.9 0.8 0.7 0.6 0.5 0.4


LOS 0
LOS 1
LOS0: 285°
LOS1: 255°
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Distance to LiDAR [-]
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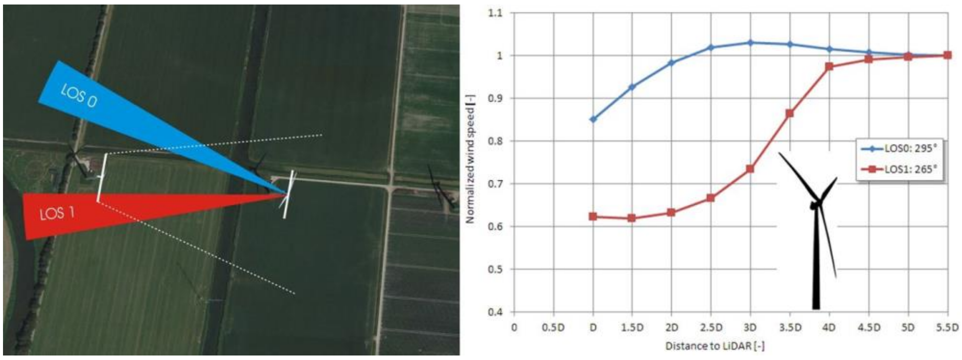
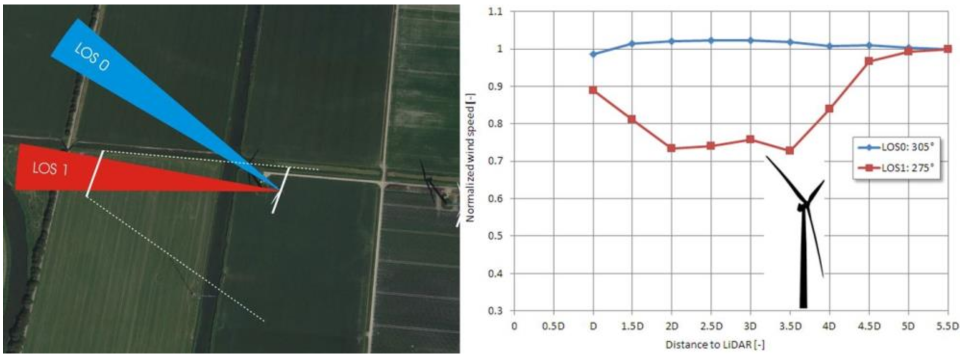

LOS 0
LOS 1
LOS0: 295°
LOS1: 265°
Normalized wind speed [-]
Distance to LiDAR [-]
0 0.5D D 1.5D 2D 2.5D 3D 3.5D 4D 4.5D 5D 5.5D


LOS 0
LOS 1
LOS0: 305°
LOS1: 275°
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Distance to LiDAR [-]
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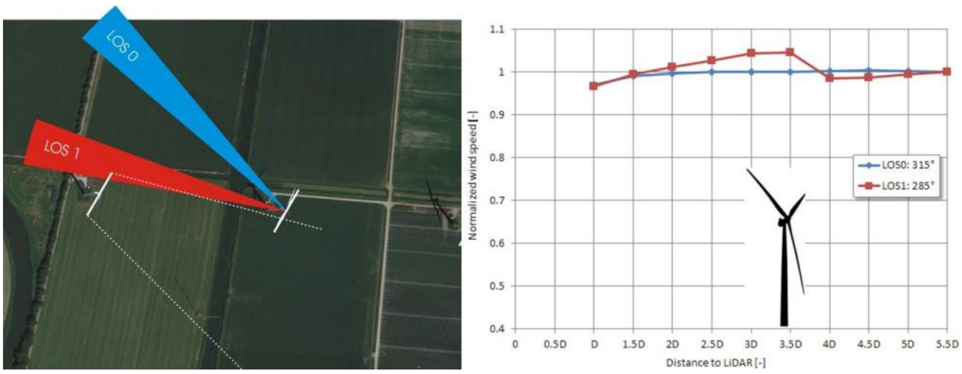
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LOS 1
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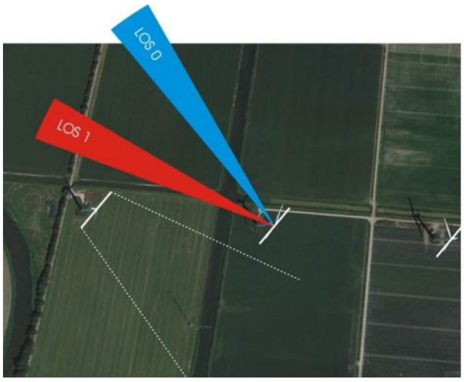
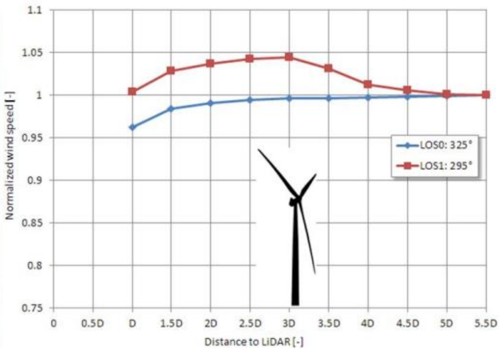

LOS 0
LOS 1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Distance to LiDAR [-]
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1.05
1
0.95
0.9
0.85
0.8
0.75
0
0.5D
D
1.5D
2D
2.5D
3D
3.5D
4D
4.5D
5D
5.5D

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