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Using backward nacelle LiDARs in wake characterization for wind farm optimization

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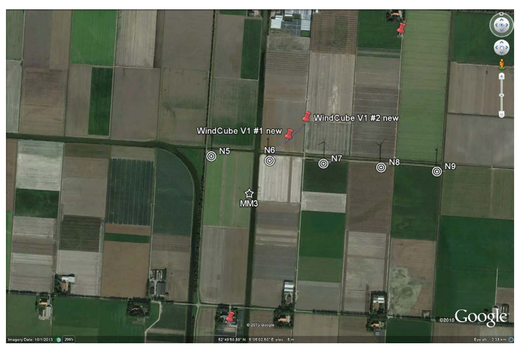
1. Introduction

In large offshore wind farms wakes play a very important role in terms of reduced yield and increased fatigue loading. Nacelle LiDARs, being relatively easy to install, offer wind farm operators the opportunity of better insight in the operation of their wind farms and to provide a pathway for performance improvements. Therefore, in this work two nacelle LiDARs are placed on a full scale wind turbine in a backward mode with the aim to quantify wakes and wake evolution. In order to do so the LiDARs are validated against an IEC compliant meteorological mast.

A Wind Iris two beam nacelle LiDAR and a Zephir 300 prototype nacelle LiDAR are placed in a backward mode on a 2.5 MW ECN research turbine on flat terrain. Here, the Wind Iris is oriented such that one beam is aligned with the nacelle. A fully instrumented IEC compliant meteorological mast is nearby and for some time two WindCube V1 ground based LiDARs were present.

2. Experimental set-up



Layout of the test site with turbines, mast and LiDARs indicated.

ECN Test Site
- Flat terrain
- 5 research turbines
- West to East
- 2nd from West

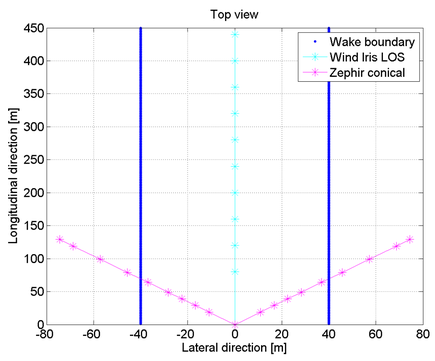
IEC mast (MM3):
- Cups, vanes and sonics at 80m
- 2.5D from turbine
- South-West

Turbine (N6):
- Nordex
- 2.5MW
- H=D=80m

Wind Iris:
- Single beam
- Along nacelle
- 1D to 5.5D, 10 steps

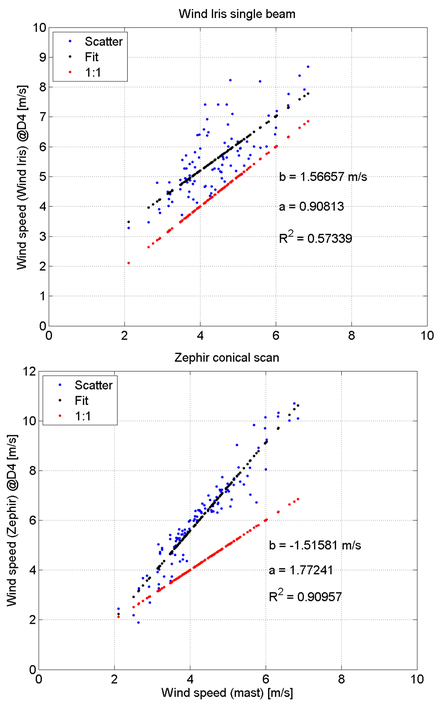
WindCube V1's:
- 1.8D & 3.5D from turbine
- North-East

Zephir:
- Conical scan
- 0.24D to 1.6D, 9 steps
- Inside and outside wake



Schematic overview of wake and scan patterns

3. Validation



The nacelle LiDAR wind speed measurements are validated against the mast for strictly North-East winds. The Wind Iris measurement distance of 200m is used and for the Zephir the distance of 49m. The latter is the largest distance still inside the wake.

Results Wind Iris
- Overestimation in considered range
- Linear fit parameter reasonable (a=0.91)
- Poor fit (R^2=0.57)

➢ LiDAR settings okay?
➢ Wake dynamics
➢ Qualitative use

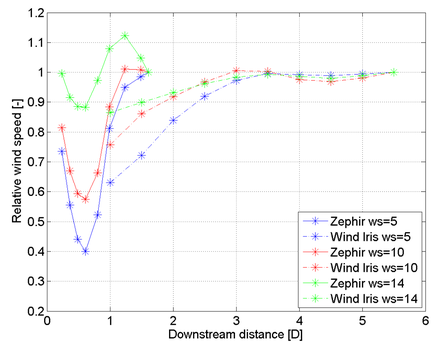
Results Zephir
- Overestimation in considered range
- Linear fit parameter poor (a=1.77)
- Reasonable fit (R^2=0.91)

➢ LiDAR prototype
➢ Measurement distance
➢ Wake dynamics
➢ Qualitative use

4. Wake Characterization

Data are selected for winds from the South-West to measure in a single wake. The Zephir measures the near wake (0.24D to 0.8D) and the Wind Iris the further wake (1D to 5.5D). The remaining Zephir measurements are at the border of or outside the wake. The mast measurements determine the inflow conditions.

Figure 1



Situation	Filtering	Results
Nacelle LiDARs relative wind speed. Normalized at largest distance (**Figure 1**)	Inflow wind speed at mast - 3<wind speed<5. Just above cut-in - 9<wind speed<11. Optimal pitch - 13<wind speed<15. Around rated; pitching	▪ General wake profile: dip in the near wake and recovery further downstream ▪ Profile from Zephir and Wind Iris 'connect' reasonably ▪ Zephir measurements from around 0.8D on are around the wake border and outside ▪ For low wind speed the wake deficit is largest ▪ Flattened profile at 14m/s due to pitching ▪ Unclear dip at 4.5D. Influence of other wakes?
Nacelle LiDARs standard deviation wind speed (**Figure 2**)	Inflow wind speed at mast - 0.05<TI<0.07 - 0.09<TI<0.11 - 0.13<TI<0.15	▪ The standard deviation in the wake is higher for high inflow turbulence intensity ▪ The Zephir measurements at 0.8D and 1D show a clear increase in standard deviation. The measurements are just before and at the wake border ▪ Low variation standard deviation from 1D to 5.5D
Nacelle LiDARs wind speed; 8m/s inflow. Zephir data scaled such that wind speed at 1.6D is 8m/s (**Figure 3**)	7<Inflow wind speed<9 - Low inflow TI (TI<0.08) - High inflow TI (TI>0.12)	▪ Higher wind speed deficit for low inflow turbulence intensity ▪ Faster wake recovery for high inflow turbulence intensity

Figure 2

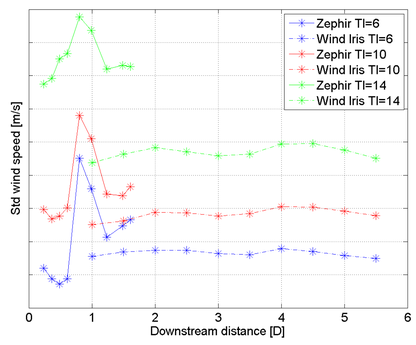
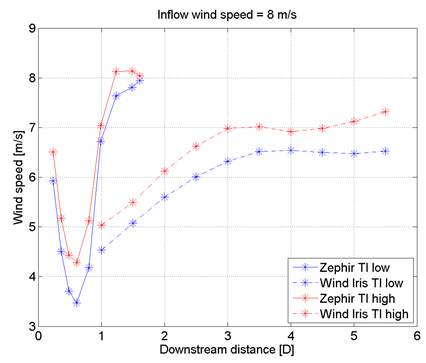
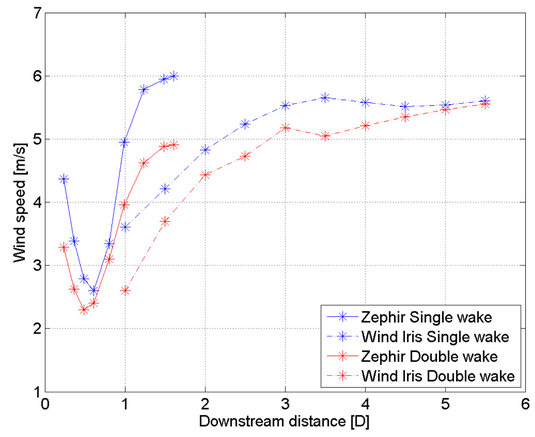


Figure 3



A **single wake** (turbine faces undisturbed wind) situation is compared to a **double wake** (turbine faces a wake) situation. In case of the single wake data are again considered from South-West. For the double wake data are strictly selected from the West with a wind direction window of 5 degrees. Both data sets have an average inflow wind speed of 6m/s and a turbulence intensity of about 10%. Both Zephir profiles are scaled in the same way such that the Zephir measurement of the single wake (blue) at 1.6D is 6m/s (mean infow).

Results
- Profiles from both LiDAR 'connect' reasonably
- Wind speed deficit higher in double wake
- Clear dip in double wake profile (red) at 3.5D. Wake faces third turbine
- Dip in double wake profile at 3.5D less deep than expected.



5. Conclusions

➢ The nacelle LiDARs do not correlate well with the mast. This is due to the operation of the LiDARs (Zephir: prototype, conical scan. Wind Iris: single beam) in combination with the highly dynamic nature of the wake. A qualitative approach works well.
➢ The nacelle LiDARs complement each other (near wake vs further wake) and the profiles 'connect' reasonably. Together they form a representative wake profile. The Zephir LiDAR clearly indicates the wake border.
➢ Different inflow conditions (wind speed, turbulence, wake) have a clear and expected influence on the wake profiles.

Acknowledgements

Work presented here was carried out in the framework of the 'Lawine' project with subsidy from the Dutch funding scheme TKI 'Wind op Zee'. The following people are acknowledged for their contributions: Gerben Bergman and Frank Kaandorp (ECN), Valerie-Marie Kumer (NORCOWE, University of Bergen).

Using backward nacelle LiDAR in wake characterization for wind farm optimization

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Summary
With the aim to quantify wakes and wake evolution a measurement campaign was organized on the ECN test site. A Wind Iris two beam nacelle LiDAR and a Zephir 300 prototype nacelle LiDAR were placed in a backward mode on a 2.5 MW ECN research turbine in flat terrain, being the second in a row of 5. Here, the Wind Iris was oriented such that one beam is aligned with the nacelle. A fully instrumented IEC compliant meteorological mast is nearby for validation and inflow measurements.

Validation of the nacelle LiDARs measurements with the mast show overestimation of the wind speed and underestimation of the standard deviation. The fits are reasonable to poor, due to the configuration of the nacelle LiDARs, the specific scan patterns in combination with the dynamics of the wake and the measurement distance.

The wake profiles reveal that the Zephir measurements (0.24D -1.6D) and the Wind Iris measurements (1D-5.5D) connect reasonably. Low inflow wind speed causes the deepest wake profile due to the higher thrust coefficient of the turbine for this operational condition. High inflow turbulence causes faster wake recovery due to better mixing with the ambient wind field. The double wake profile is deeper than the single one, because more energy is extracted, and the presence of the third turbine in the row is noticed in this profile. The general profile is captured, however, the wake recovery seemingly is too fast. Here, some misalignment between wind and the turbines is one of the causes.

1. Introduction

Especially offshore wind turbines are placed in large wind farms. Therefore, in offshore wind farms wake effects play an even more important role than onshore. As is well known, wake effects can result in reduced yield and increased fatigue loading and the measuring and monitoring of these effects are of utmost importance.

Traditionally, measurements are taken by means of meteorological masts. However, especially offshore these masts are very expensive. Nacelle LiDARs potentially offer a cheaper alternative to offshore meteorological masts. They are relatively easy to install and measure in the horizontal plane at various distances. Forward looking LiDARs offer wind farm operators the opportunity of better insight in the operation of their wind farms and to provide a pathway for performance improvements. Several studies have already demonstrated the value of nacelle LiDARs for performance monitoring (see for instance [1, 2, 3, 4]) and procedures are being developed for the proper use of them [5, 6] (see also the developments in [7]).

A different approach to the same goal, and stressing the value of wakes, is to place nacelle LiDARs in the backward mode. Of course inside wind farms the wake of one turbine is the input of another, therefore backward looking nacelle LiDARs serve the goal of insight in operation. In addition, with the wake measurements of these nacelle LiDARs wind farm models can be improved serving the goal of performance improvement. Therefore, in this work two nacelle LiDARs are placed on a full scale, near shore wind turbine in a backward mode with the aim to quantify wake characteristics such as wake evolution.

Together with Avent Lidar Technology and the NORCOWE consortium, represented by CMR and University of Bergen, ECN organized a measurement campaign on its test site, where a Wind Iris two beam nacelle LiDAR and a Zephir 300 prototype nacelle LiDAR were placed in a backward mode on a 2.5 MW ECN research turbine on flat terrain. Here, the Wind Iris is oriented such that one beam is aligned

with the nacelle. A fully instrumented IEC compliant meteorological mast is nearby for validation and inflow measurements and for some time two WindCube V1 ground based LiDARs were present.

2. Experimental set-up

A measurement campaign was composed at the ECN Wind turbine Test station Wieringermeer (EWTW) [8] from the 26th of June 2014 until the 27th of November 2014. This test site is a near shore site consisting of flat, agricultural terrain with single farm houses and rows of trees. The site is located about 35km East of the ECN premises in Petten, in between the villages Kreileroord and Medemblik, along the lake IJsselmeer.

Figure 1: Layout of the test site with clearly indicated research turbine N6 with the two nacelle LiDARs. Also indicated are MM3, the ground based LiDARs and the surrounding turbines

The farm consists of a row of 5 research turbines with a rated power of 2.5MW, a hub height and a rotor diameter (D) of 80m. The spacing between the turbines is 3.8D (305m) and the orientation is 95^0 with respect to North. The turbines are numbered 5 to 9 from West to East. The prevailing wind direction is Southwest.

South of the research turbine row and in between turbines 5 and 6 a fully instrumented IEC compliant [9] meteorological mast (MM3) is located with Risø cup anemometers, Thies First class wind vanes and Gill Windmaster sonic anemometers on booms at 52m and 80m and a Gill Windmaster sonic anemometer at the top of 108m. This mast is oriented 210.5 degrees with respect to turbine 6 at a distance of 2.5D (200m).

The Wind Iris of Avent Lidar Technology [10] is installed on the cooler on the nacelle of one of the ECN research turbines, numbered 6 (2nd from West in the row). The Wind Iris is a two beam, pulsed LiDAR, where the individual beams are separated by an angle of 30^0. The Wind Iris is oriented in the horizontal plane and backward looking. It is configured such that one beam is aligned along the nacelle direction, which is done by aligning both the nacelle and the beam of the Wind Iris with respect to the mast. It is this beam that is used in the analysis. The Wind Iris measures the wind speed at distances of 80m to 440m with intervals of 40m, which coincides with 1D to 5.5D.

A prototype of a Zephir nacelle LiDAR [11] is also placed on the nacelle and behind the cooler of the same turbine. This Zephir nacelle LiDAR is a continuous wave LiDAR measuring with a conical scan where this cone is 60 degrees wide. Measurement distances are 19m, 29m, 39m, 49m, 64m, 79m, 99m, 119m and 129m, corresponding to 0.24D to 1.6D. In that sense both nacelle LiDARs complement each other. Because of the Zephir's cone angle the lateral distance between the measurement points increase with increasing longitudinal measurement distance. This is indicated in the left plot of figure 2. Given an indicative wake it shows what measurement points are expected to be inside and which points to be outside the wake. Last but not least two Leosphere WindCube V1 ground based LiDARs where placed in the field at 1.6D and 3.5D Northeast of the turbine. They are also pulsed LiDARs where the individual

beams make an angle of 28 degrees with the zenith. They are configured such that they at least measure the wind speed at 80m[1].

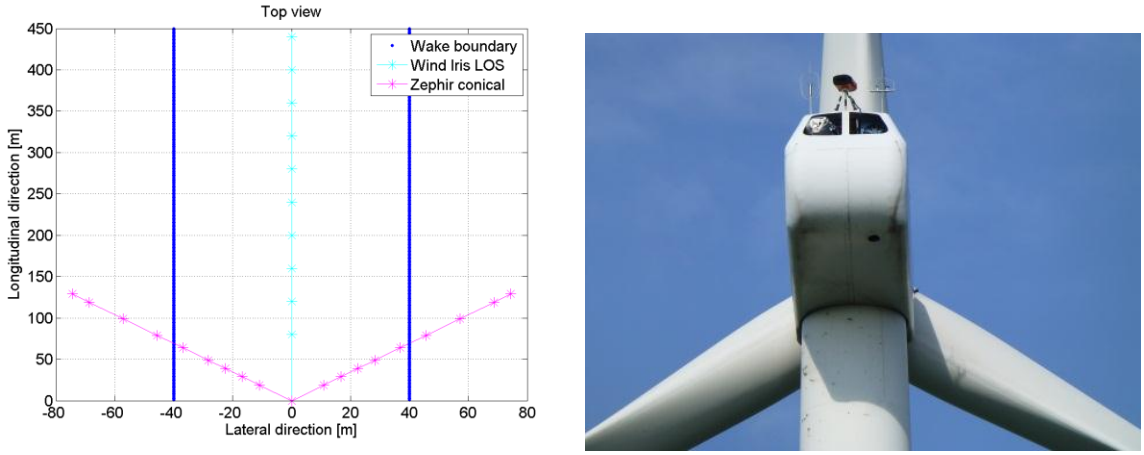

Figure 2: Left: Schematic overview of the scan patterns of the LiDARs and the wake boundary. Right: Photograph of turbine with the nacelle LiDARs

All data are gathered at the measurement pavilion also present at the test site, time synchronized and transferred to the Petten location on a daily basis and stored in a dedicated database [12]. Here, data validation takes place and statistics are created. The data analyses presented in the remainder of this paper are based on 10 minute statistics.

3. Results

3.1. Validation

The wake wind speed and turbulence measurements of the two nacelle LiDARs have been validated against meteorological mast measurements for wind directions when the mast strictly is in the center of the wake of the turbine. Here, wind vane and cup anemometer measurements are combined such that mast disturbances are minimized [8]. In order to do the validation a proper dataset was created. As indicated the mast is at 210.5 degrees from the turbine, therefore only yaw angles have been selected for 30.5 degrees with a window of 5 degrees. Furthermore data have been selected for proper turbine operation and proper LiDAR operation. Regarding the proper Zephir operation a special status signal was created using the Zephir output signals npts (number of readings used to derive the wind speed) and npackets (number of packets used to create the current average). The product of the two signals are considered to be a good representative of the Zephir status, where the threshold of the normalized product is set to 75%. For the Wind Iris an availability of 50% is found to be a good threshold. This yields a dataset of about 100 data points for both validations, the results are presented in figure 3. For the Wind Iris the 4th measurement distance, i.e. a measurement distance of 200m is chosen and for the Zephir also the 4th measurement distance is chosen. The latter corresponds to a distance of 49m, which is the largest distance from the turbine still inside the wake (see left plot of figure 2).

From the plots in figure 3 it is clearly seen that both nacelle LiDARs overestimate the wake wind speed in the considered range. The single beam of the Wind Iris shows a reasonable linear fit parameter (a = 0.90813), but the fit is poor (R^2 = 0.57339). On the other hand, the Zephir LiDAR shows a poor linear fit parameter (a = 1.77241), but the fit is reasonable (R^2 = 0.90957). Possible reasons for these results are sought in the facts that the Wind Iris was especially configured for the purpose, i.e. measuring with one beam, including adaption of the data processing. Also the Zephir LiDAR is a prototype nacelle LiDAR. Therefore, both may not have optimally been configured. Next to that, the LiDARs are measuring with their specific scan patterns the dynamics of the wake; LiDAR validation campaigns are usually done in wake free environments [13]. In this respect it is also noted that previous research has shown that LiDAR line of sight measurements are in general well capable of measuring the wind speed along that line of

[1] Although these LiDARs provide very valuable information, they are not further regarded in the remainder of this paper due to their limited added value within the current scope.

sight (see for instance [6]). Last but not least there is a measurement distance difference: for the Zephir measurements a distance of 49m is chosen whereas the mast is at 200m.

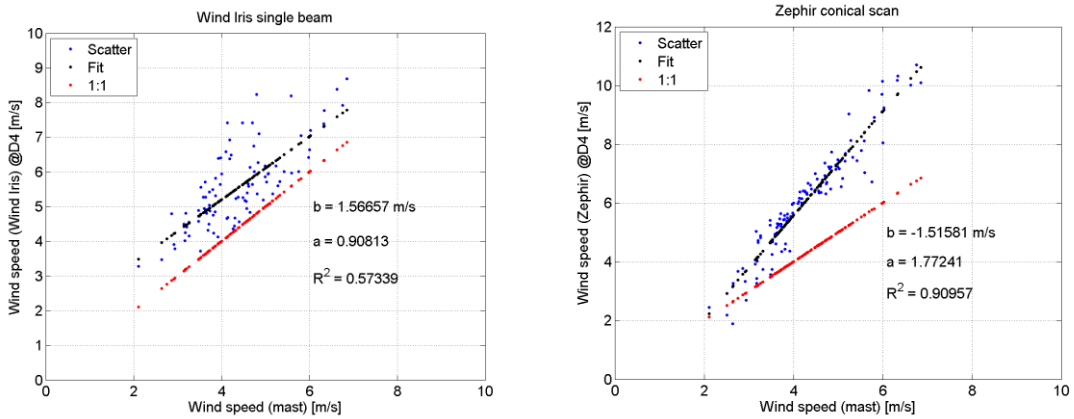

Figure 3: Left: Wind Iris wind speed against mast wind speed for 10 minute averages (blue). Right: Zephir wind speed against mast wind speed for 10 minute averages (blue). In both cases the black dots represent the two parameter linear fit and the red dots the 1:1 line.

Besides validating on wind speed measurements it is interesting to see to what extent the nacelle LiDARs are capable of measuring the turbulence in the wake. Hereto, the standard deviations of the nacelle LiDAR wind speed measurements are compared to the standard deviations of the wind speed measurements from the sonic anemometer on the northern boom of meteorological mast 3. The sonic anemometer is chosen for the special purpose of turbulence measurements. For these comparisons the same datasets are considered with the only difference that now the sonic anemometer is considered including an additional status filter for this sensor. The latter filters do not appear to limit the data set any further. The results of the standard deviation comparison are shown in figure 4.

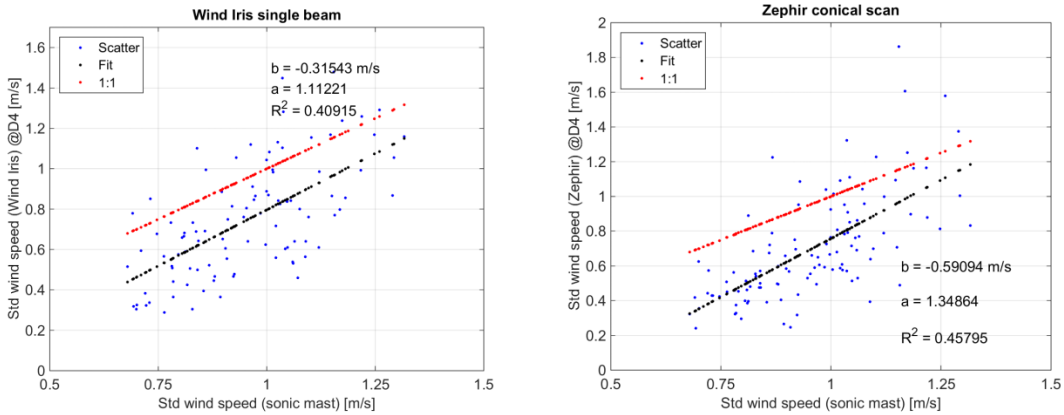

Figure 4: Left: Wind Iris 10 minute wind speed standard deviation against mast wind speed standard deviation (blue). Right: Zephir 10 minute wind speed standard deviation against mast wind speed standard deviation (blue). In both cases the black dots represent the two parameter linear fit and the red dots the 1:1 line.

From the plots in figure 4 it is clearly seen that both nacelle LiDARs underestimate the wake wind speed standard deviation in the considered range. The R^2 values for both fits are about the same: $R^2 = 0.40915$ in case of the Wind Iris and $R^2 = 0.45795$ in case of the Zephir, whereas the linear regression parameter in case of the Wind Iris is slightly closer to 1: a = 1.11221 (Wind Iris) vs a = 1.34864 (Zephir).

In the remainder of this paper the focus of the wake measurements with the nacelle LiDARs is of qualitative nature.

3.2 Wake Characterization; Inflow wind speed

Besides the validation it is examined whether the nacelle LiDARs can be used to characterize the wake of the turbine and to what extent both nacelle LiDARs complement each other. Hereto, the single wake of the turbine is considered for different inflow conditions, i.e. different inflow wind speeds and different inflow turbulence intensities. Also the single wake is compared to a multiple wake.

However, as said first the single wake for different inflow wind speeds is considered. The inflow conditions are determined from the meteorological mast, where the wind direction data are selected from the Southwest, i.e. wind directions at 80m from 210 degrees to 230 degrees. Again, it is assured that the turbine and both nacelle LiDARs operate properly yielding a total data set of almost 600 data points. From these data wake wind speed profiles are constructed in the right plot of figure 5. This plot contains the mean relative wind speeds for both nacelle LiDARs, where the Zephir measurements are in the range 0.24D to 1.6D and the Wind Iris measurements from 1D to 5.5D, indicated with solid lines and dashed-dotted lines, respectively. Here, the relative wind speed means that all wind speed measurements at the various distances are divided by the measurement at the largest distance (distance 9 in case of the Zephir and distance 10 in case of the Wind Iris). Afterwards the average is taken per distance. This can be observed by the fact that all (Zephir related) solid lines are 1 at 1.6D and all (Wind Iris related) dashed-dotted lines are 1 at 5.5D.

As indicated in the right plot figure 5 wake wind speed profiles are created for various inflow wind speed conditions as measured with the meteorological mast at 80m. Three different dataset are created with the following inflow wind speed ranges: 4m/s to 6m/s (indicated with 5m/s), 9m/s to 11m/s (indicated with 10m/s) and 13m/s to 15m/s (indicated with 14m/s). These various ranges are indicated in the turbine's power curve in the left plot of figure 5. It is seen that they represent start-up, optimal pitch and around rated (therefore including pitch behavior). This subdivision yields respective datasets of 288, 34 and 14[2] data points.

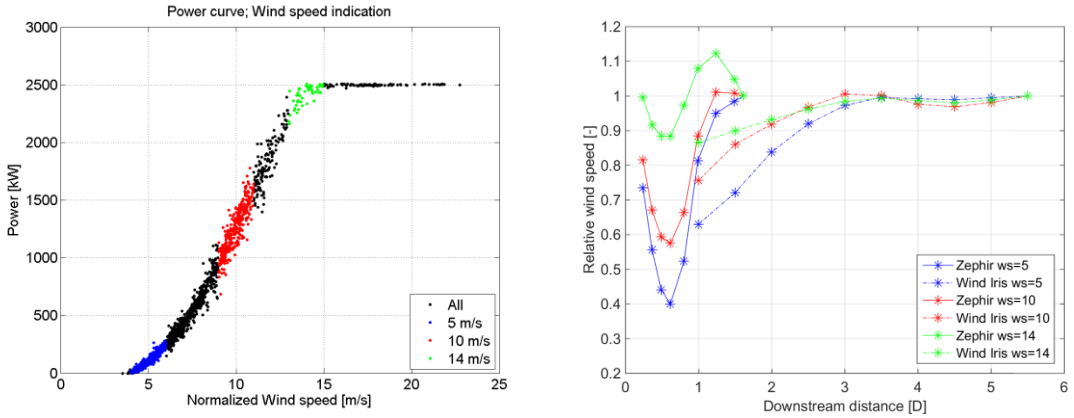

Figure 5: Left: Power curve of the relevant turbine (black). Indicated in the power curve are the wind speed ranges 4-6m/s (blue), 9-11m/s (red) and 13-15m/s (green). Right: Relative wind speed as function of distance for the Zephir measurements (solid) and Wind Iris measurements (dash-dotted) for various inflow wind speed ranges: 4-6m/s (blue), 9-11m/s (red) and 13-15m/s (green).

Concentrating on the Zephir measurements from 0.24D to 1.6D it seems that the wake recovers very quickly. However, in this respect reference is made to the left plot of figure 2, namely that the first few measurement distances up to around 0.8D are within the wake and from 0.8D on at the border and outside the wake. The largest measurement distances therefore indicate the ambient wind speed, again. Taking this into account one might say that both profiles 'connect' reasonably, i.e. complement each other from around 0.8D onwards. It is furthermore noticed that the general shape of the wake wind speed deficit is captured. First, there is a clear decrease in relative wind speed until the minimum of the profile is

[2] The power curve in the left plot of figure 5 is from a different dataset, therefore the various wind speed ranges cover a different amount of data points than indicated in the text.

reached and afterwards the wind speed increases again due to wake recovery. However, it is noticed that this recovery is faster than expected [14] and that the profile is rather flat from 3D to 5.5D or even contains a dip, where a further profile increase is expected. The reasons for these observations are unknown and may be sought in the measurement system configuration or the specific wake wind field nature. One of the reasons for the seemingly fast wake recovery may be that the wind and the nacelle are not always perfectly aligned (differences of a few degrees may easily occur) having the result that not all measurements presented in the right plot of figure 5 are performed in the center of the wake. Therefore, higher wind speeds may be included resulting in a seemingly faster recovery.

Concentrating on the different inflow wind speeds it is noticed that the lowest inflow wind speed causes the deepest wake profile. This coincides with what may be expected because at low wind speed the thrust coefficient of the turbine is highest (among others this was also seen in [15]). From the profile with a mean inflow wind speed of 14m/s it is seen that it is flattened. This is due to the pitch behavior of the turbine at rated conditions, leading to a low thrust coefficient.

3.3 Wake Characterization; Inflow turbulence

Next to the inflow wind speed also the effect of inflow turbulence on the wake profile is examined. This is done in two ways. First, the effect of the inflow turbulence intensity on the wake wind speed standard deviation is considered. This is done by considering the same data set as above in terms of wind direction, proper wind turbine operation and proper LiDAR operations. In addition, the inflow turbulence intensity is determined from the mast measurements at 80m as $TI = \sigma_U / U$. Here, U is the 10 minute average wind speed and σ_U is the 10 minute standard deviation of the wind speed, where this wind speed is the earlier indicated mast influence minimized wind speed. The inflow is characterized for three TI classes, namely TI values between 0.05 and 0.07 (TI is 6%), TI values between 0.09 and 0.11 (TI is 10%) and TI values between 0.13 and 0.15 (TI is 14%), resulting in data sets of 130, 32 and 27 data points, respectively. No additional wind speed filter is applied, here (the reader is referred to the next sections).For these three classes the mean wind speed standard deviations as measured by the nacelle LiDARs are indicated in figure 6 for different measurement ranges. Because the standard deviation values themselves do not make a lot of sense and because the focus of the figure is on the qualitative nature, no values are given on the y-axis.

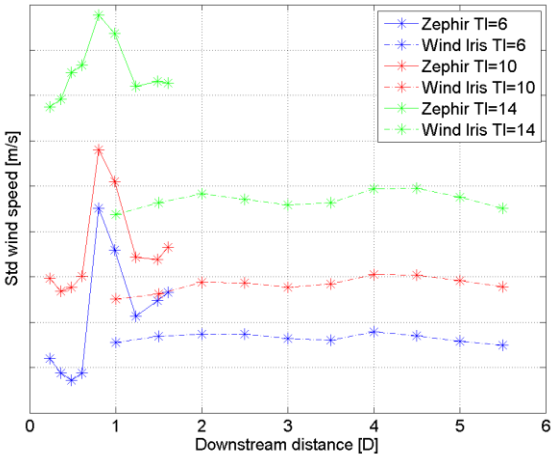

Figure 6: Wind speed standard deviation as function of downstream distance as measured with the Zephir (solid) and with the Wind Iris (dash-dotted) for various inflow turbulence intensity ranges: 5%-7% (blue), 9%-11% (red) and 13%-15% (green).

From the figure it is clearly seen that the highest inflow turbulence intensity gives the highest wind speed standard deviation in the wake. This is seen for both nacelle LiDAR measurements, i.e. in the near wake and in the further wake. It is even more clear that a peak occurs around 0.8D. Looking at the left plot of figure 2 it is believed that this increase in standard deviation is because the measurement points are around the wake border. In the range 1D to 5.5D the Wind Iris measurements show low variation.

Inflow turbulence intensity also has its effect on the wake wind speed profile. In order to detail this with the measurements the above indicated dataset is filtered on an inflow wind speed at 80m of 8m/s, i.e. wind speeds as measured with the meteorological mast between 7m/s and 9m/s. This, in order to exclude the effect of inflow wind speed on the wake (see right plot of figure 5). The data set is further split up

according to the inflow turbulence intensity at 80m yielding a data set for low inflow turbulence (TI<0.08) and high turbulence (TI>0.12) with 32 and 27, data points respectively. With these two data sets the wake wind speed is indicated for the various measurement ranges and for both nacelle LiDARs in figure 7. Here, the Zephir data are scaled such that the wind speed measurements at 1.6D, i.e. outside the wake and therefore ambient wind speed, is 8m/s.

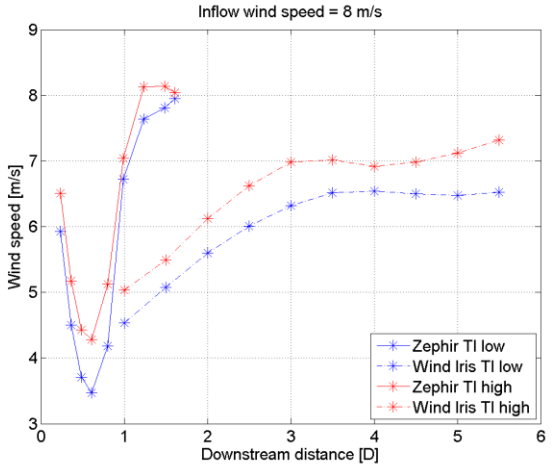

Figure 7: Wake wind speed as function of downstream distance as measured with the Zephir (solid) and with the Wind Iris (dash-dotted) at a mean inflow wind speed of 8m/s and for low (blue) and high (red) inflow turbulence intensity.

Figure 7 shows that the profile for high inflow turbulence is less deep and recovers faster, say in the range 1D to 3D, as compared to low inflow turbulence. This fast recovery of the wake for high inflow turbulence is less obvious in the region 3D to 5.5D; on the other hand it contradicts neither. That the wake recover faster for higher inflow turbulence is because the wake mixes better with the ambient wind field in this situation, therefore more energy flows inside the wake and the wind speed is higher.

3.4 Single wake vs Double wake

Last part of the analysis is the comparison between the single wake and the double wake. Here, single wake means that the turbine N6 faces free stream wind conditions, i.e. winds from the Southwest as before, and double wake means that the turbine N6 faces the single wake of an upfront turbine, i.e. winds from the West. In both cases the meteorological mast measures the free stream conditions. The strategy has been to construct a dataset for the double wake case including wind directions sector from 275 degrees and with the aim to keep this sector as small as possible, i.e. a wind direction window of 5 degrees. From this dataset the mean wind speed and mean turbulence intensity is obtained from the mast measurements. Afterwards a dataset is created with wind directions between 210 degrees and 230 degrees, as before, and with additional wind speed and turbulence filters such that the same inflow conditions are met as in the double wake case. In case of the double wake situation the dataset has 13 data points, a mean wind speed of 6.0m/s and a mean turbulence intensity of 9.6%. In case of the single wake situation the constructed dataset has 81 data points, a mean wind speed of 6.1m/s and a mean turbulence intensity of 10.4%. For these two cases the mean wind speed wake profiles are constructed and shown in figure 8, similar to the ones in figure 7. Here, the single wake Zephir data are scaled such that the wind speed measurements at 1.6D, i.e. outside the wake and therefore ambient wind speed, is 6m/s. The same scaling factor is used for the double wake Zephir data.

Because the single wake wind speed profile has already been dealt with in the right plot of figure 7 the focus here is on the double wake wind speed profile compared to that. It is in both Zephir data and Wind Iris data seen that the double wake wind speed profile is deeper than the single wake profile, i.e. more deficit. This is what may be expected from a double wake as more energy is extracted. It is also noted that the operating point of the turbine may be different due to lower inflow wind speed.

It has already been argued that the 1.6D Zephir measurements in the single wake situation are outside this wake and measure therefore the ambient wind. From figure 8 it is seen that this mean wind speed of the Zephir measurements at 1.6D is in the double wake situation lower as compared to the single wake situation. This most probably means that this measurement point may be outside the double wake, but still is inside the single wake of the preceding turbine.

The double wake wind speed profile also shows a drop in wind speed at around 3D to 3.5D. This is most probably due to the presence of the third turbine in the row (turbine N7 at 3.8D) blocking the wind and therefore causing this wind speed reduction. However, because this turbine also extracts energy from the wind field a further decrease in wind speed is expected in the double (actual now triple) wake situation at around 4D and beyond. This is not seen. Again, a seemingly faster recovery than expected is noticed for which some causes have been touched upon. It is stressed that also here the wind and the turbines are not always perfectly aligned, meaning that the measurements are not always taken in the center of the wakes.

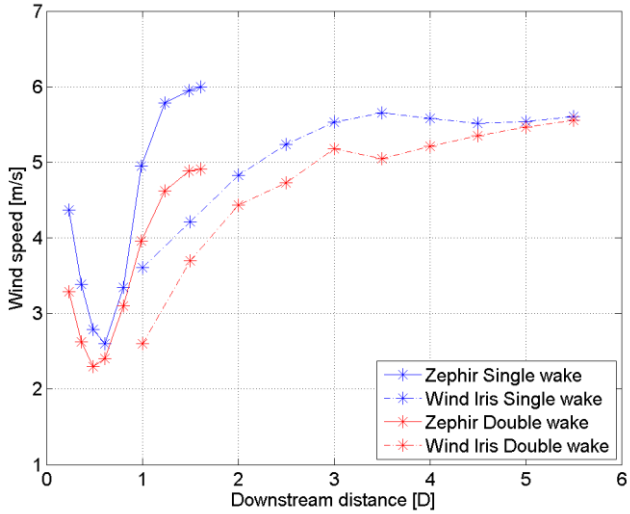

Figure 8: Wake wind speed as function of downstream distance as measured with the Zephir (solid) and with the Wind Iris (dash-dotted) for the single (blue) and double (red) wake situation.

4. Discussion

The Wind Iris single beam wake measurements at 200m and the Zephir conical scan measurements at 49m have been validated against the IEC compliant mast at 200m. Both comparisons show an overestimation of the wind speed and underestimation of the standard deviation. Regarding the wind speed the Wind Iris measurements show a reasonable linear fit parameter (a = 0.908), but the fit is poor (R^2 = 0.573). On the other hand, the Zephir LiDAR measurements show a poor linear fit parameter (a = 1.77), but the fit is reasonable (R^2 = 0.910). Regarding the wind speed standard deviation the R^2 values for both fits are about the same: R^2 = 0.409 in case of the Wind Iris and R^2 = 0.458 in case of the Zephir, whereas the linear regression parameter in case of the Wind Iris is slightly closer to 1: a = 1.11 (Wind Iris) vs a = 1.35 (Zephir). Possible reasons for these results are sought in the configuration of the nacelle LiDARs and the specific scan patterns (single beam Wind Iris and prototype Zephir conical scan) in combination with the dynamics of the wake and the measurement distance. For the Zephir measurements a distance of 49m is chosen whereas the mast is at 200m. Therefore the focus of the wake measurements are qualitative of nature.

The wake profiles reveal that the Zephir measurements (0.24D to 1.6D) and the Wind Iris measurements (1D to 5.5D) connect reasonably and that they complement each other. Here, it needs to be taken into account that the Zephir measurements from 0.8D onwards at the border and outside the wake. Therefore the outer measurement points measure ambient wind speeds. In the double wake situation this wind speed measurement is lower as compared to the single wake situation, therefore most probably this measurement point may be outside the double wake, but still is inside the single wake of the preceding turbine.

The general shape of the wake wind speed deficit is captured. First, there is a clear decrease in relative wind speed until the minimum of the profile is reached and afterwards the profile increases again due to the wake recovery. However, it is noticed that this recovery is faster than expected and that the profile is rather flat from 3D to 5.5D or even contains a dip, where a further profile increase is expected. The reasons for these observations are unknown and may be sought in the measurement system

configuration or the specific wake wind field nature. One of the reasons for the seemingly fast wake recovery may be that the wind and the nacelle are not always perfectly aligned (differences of a few degrees may easily occur) having the result that not all measurements presented in the right plot of figure 5 are done in the center of the wake. Therefore, higher wind speeds may be included resulting in a seemingly faster recovery.

Low inflow wind speed causes the deepest wind speed wake profile due to the higher thrust coefficient of the turbine and from the wake profile with a mean inflow wind speed of 14m/s it is seen that it is flattened. Most probably this is due to the pitch behavior of the turbine at rated. High inflow turbulence causes faster recovery of the wake due to better mixing with the ambient wind field and in addition the highest inflow turbulence intensity gives the highest wind speed standard deviation in the wake. The Zephir measurements at 0.8D are at the border of the wake, which is also shown in the increase in the wind speed standard deviation.

The double wake wind speed profile also shows a drop in wind speed at around 3D to 3.5D indicating the presence of the third turbine in the row (turbine N7) blocking the wind and therefore causing this wind speed reduction. However, because this turbine also extracts energy from the wind field a further decrease in wind speed is expected in the double (triple) wake situation at around 4D and beyond. This is not seen. Again, a seemingly faster recovery than expected is noticed.

5. Conclusions

This work shows that care must be taken when using the considered nacelle LiDARs for absolute wake measurements and the interpretation of wake recovery. Here, special attention is to be paid to the LiDAR configuration including its measuring strategy and the alignment of inflow wind direction and nacelle orientation. This in combination with the dynamics of the wake.

In qualitative sense this work shows that the considered nacelle LiDARs are capable of capturing the general wake profile, roughly, and that they complement each other. Various inflow conditions as wind speed, turbulence and wake wind fields have the expected effects on these wake profiles.

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