

Characterization of wind velocities in the wake of a full scale wind turbine using three ground-based synchronized WindScanners

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Abstract. The wind energy community is in need of detailed full-field measurements in the wake of wind turbines. Here, three dimensional(3D) wind vector field measurements obtained in the near-wake region behind a full-scale test turbine are presented. Specifically, the wake of a NEG Nordtank turbine, installed at Risoe test field, has been measured from 0 to 2 diameters downstream. For this, three ground-based synchronised short-range WindScanners and a spinner lidar have been used. The 3D wind velocity field has been reconstructed in horizontal and vertical planes crossing the hub. The 10-min mean values of the three wind components reveal detailed information regarding the wake properties while propagating downwind over flat terrain. Furthermore, the wake centre is tracked from the measurements and its meander is investigated as function of yaw misalignment of the turbine. The centre-line wake deficit is calculated both in a Nacelle and Moving Frame of Reference. The results can be used in quantitative validation of numerical wake models.

1. Introduction

The need for more accurate wake models and the investigation of new techniques to assess wake effects poses a need for more reliable wake measurements. Latest developments in remote sensing techniques can provide very detailed wind field data.

Previous full-field studies of the wind turbine wake from nacelle lidars have been performed in the far-wake of the wind turbine [4, 5]. In the study of Trujillo et al. [5], the wake dynamics have been captured using a single nacelle mounted short-range 2D pulsed lidar developed by Stuttgart Wind Energy and installed on the aft balcony of a smaller (95kW) Tellus turbine formerly located also at the Risø campus of the Danish Technical University (DTU). The quantification of the wake has been compared by the Dynamic Wake Meandering (DWM) model [8]. The tracing of the wake center has been done by the least square curve fitting optimization technique, using the Levenberg–Marquardt algorithm (LMA) [9]. These methods have been evaluated by comparing the wake centre predictions in stable atmospheric boundary-layer stratification using the nacelle frame of reference (NFoR) and meandering frame of reference (MFoR) meandering wake coordinate reference systems.

Machefaux et al. [6] report also 2D lidar based wake measurements obtained with a number of unsynchronized lidars and present wake meandering measurements compared to CFD – LES simulations, based on the Actuator Line Technique (ACT) solved by the EllipSys3D flow solver. A

¹ Cf. WindScanners.eu and WindScanners.dk



similar wake center tracking procedure is presented in [5] and is here applied to the 10-min averaged time series and compared with the Dynamic Wake Meandering (DWM) Model. Previous results have shown a good agreement between measurements and DWM beside a phase lag [5].

Recently, the effect of the yaw misalignment on the wake propagation has been analysed by Trujillo et al [7] using commercial short-range pulsed lidar of type Windcube WLS-7 version 1.0 manufactured by, designed by Stuttgart Wind Energy and installed on a 5MW offshore wind turbine. They concentrated in the analysis of the path followed by the wake in the region between $0.6D$ to $1.4D$. The range limitation of this study has been discussed in the paper. Moreover, one of the conclusive remarks of that study was the need of further detailed measurements in the area very near to the rotor.

The experience so far has been done mainly with one-dimensional systems. However, the complexity of the wake flow, especially in the near wake, justifies the usage of more complex systems. Here we concentrate in the analysis of detailed three-dimensional measurements in the near wake from $0D$ to $2D$. This is performed with a The short-range WindScanners [2] are light detection and ranging (lidar) instruments, which operate synchronized and capable of scanning 3D wind velocity vector fields following flexible measurement trajectories.

The data set offers the possibility of a thorough study of the wake characteristics as a continuation to the previous full-field studies of the wind turbine wake from nacelle lidars [4, 5]. Due to the fast character of these measurements, the wind field can be studied in a steady and also in a quasi-instantaneous mode. This enables us to observe the large scale dynamic behaviour of the wake with techniques which have been applied in the past to less detailed measurements.

Besides the evaluation of the wind field and its dynamics, the type of measurements applied in this research reveals also the behaviour of the wake with respect to the yaw and thrust characteristics of the rotor.

The present study combines similar wake centre tracing method from previous conducted full scale measurements[4][5][6][7] over quasi-instantaneous wind fields for single and multiple wake characterization. However, spatial resolution of the present dataset differs from all others, since it is 3D near wake measurements that reveal all three wind components from horizontal and vertical scan planes. Since all these previous studies are conducted using nacelle mounted lidars, they are limited by the scanning range of closest distance to the rotor.

In the present study, very near wake three dimensional wind velocities are measured and characterised for different yaw error conditions. Wake centre tracing algorithm is applied to measured axial velocity deficits for these conditions. This gives an insight on wake centre behaviour for respective yaw error on near wake region in terms of deficit and spatial position. Our full scale measurements are conducted to scan fixed plane using ground based lidars. Thus, scanning limitation of previous measurement setups[4][5][6][7] are overcame for capturing very near wake characteristics in three spatial dimensions.

As it is stated in the previous studies, the wake centre meandering as well as the wake momentum deficit, entrainment and development downwind are of interest. In the present study the wake speeds are also analysed in the two frames of references, NFoR and MFoR.

2. Measurement campaign

In the context of the research project UniTTE (*Unified testing procedures for wind turbines through inflow characterisation using nacelle lidars*) [1], three short-range WindScanners¹ were installed on the ground in the prevailing upwind direction of a 550 KW and spinnerLidar[12][13] measuring upstream, 40-m rotor diameter horizontal axis NEG Nordtank test wind turbine, located in the Risø campus of the Wind Energy Department of the Technical University of Denmark (DTU).

For the setup of this measurement campaign the WindScanners could scan the 3D wind field in the induction zone during times of westerly wind [3], which is the predominant wind direction at Risø Campus. Therefore for easterly wind direction, the WindScanners were able to scan the flow in the near-wake zone up to two rotor diameters behind the wind turbine.

The three short-range WindScanners trajectory scanning coordinate system is user specified. In this study, the three lidars scan trajectories were fixed on the ground frame of reference and spinnerLidar[12][13] on nacelle frame of reference as designed in the study of Wagner et al.[1] Particularly, they were not set to automatically follow the turbine yaw orientation because the main objective of the scan setup was measurement of the inflow induction zone in front of the wind turbine.

However, one day while the wind direction turned from Westerly to Easterly, the turbine wake swept the pre-set scan area set up for Westerly inflow. This event enabled the WindScanners to scan the wake flow in the pre-set scan pattern and this provided measurements of the 3D wake structure including wind speed deficit and wake response to the wind direction turn. The measurement setup of the horizontal and vertical scan planes and the position of the three short-range WindScanners can be seen in Figure 1. The WindScanners steerable beams were scanning along the shown trajectories while continuously adjusting their focus (measurement range). The three obtained line-of-sight measurements were subsequently reconstructed into the three wind components (u , v , w) interpolated to the nearest grid represented by the red circles separated by 4 m spatial resolution.

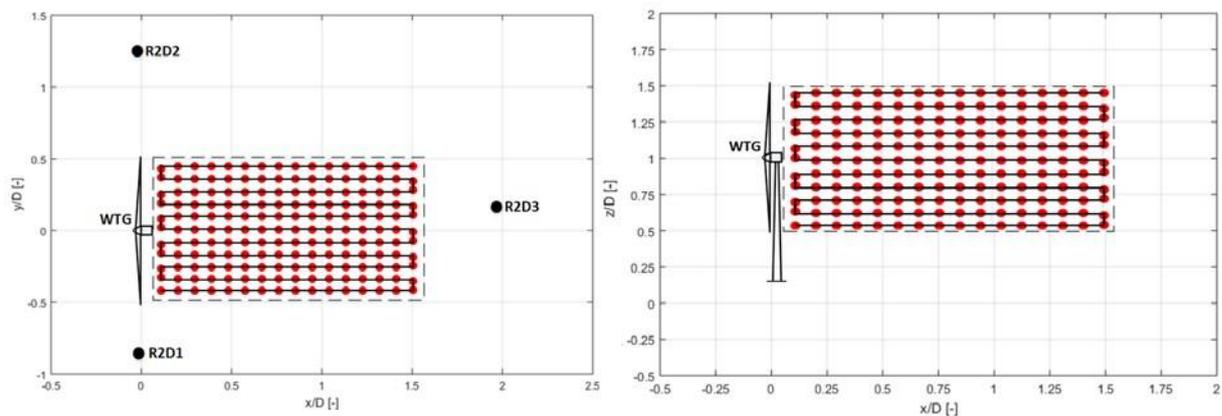


Figure 1. The layout of the horizontal (left) and vertical (right) scan trajectories followed by the three WindScanners R2D1, R2D2 and R2D3.

The measurements presented in this paper were acquired on the September 01, 2014 from 10:20 until 11:20. During this period, the mean wind speed ranged between ~ 5 and ~ 8 m/s and the yaw misalignment ranged between ~ -20 and ~ 20 Deg as can be seen on Figure 2.

2. Analysis methods

2.1. Wake Centre tracing

The wake centre tracing analysis is investigated because important wake characteristics can be revealed by it. Namely, misalignment of the wake can be compensated, or large-scale dynamic behaviour can be extracted. Several different methodologies can be used to determine the centre-of-mass coordinates, within meandering wakes. One such technique is fitting the measured velocity deficit profiles to a pre-defined deficit shapes, such as a Gaussian, at each downstream location. The downwind range from approximately $0.05D$ to $1.55D$ is called the near-wake region. Here the wake structure can be donut-shaped and it can be fitted by a double bivariate Gaussian distribution.

In the far-wake region, however, at ranges beyond say $5D$, the wake profiles are expected to become more single bivariate Gaussian distributions since the speed up effect caused by the wind-transparent nacelle in the centre of the wake here dilutes and vanishes due to wake entrainment and momentum recovery. It is known that low wind speeds can cause high turbulence due to increased wake recovery rate. The wake recovery and mixing is also highly dependent on the turbine aerodynamics and the ambient air's atmospheric stratification.

The region of the detailed wake recovery investigation in this work is selected to be in the near-region between $0.05D$ and $1D$ for the Horizontal scan, since the wake recovery in this region seems effectively inducing the double Gaussian shape in the near region into a single Gaussian after $1D$. The WindScanner measured wake profiles are next fitted to double Gaussian shaped distributions by leastsquare curve-fitting optimization techniques, using a trust region reflective algorithm [5].

Another reason for focusing on this near-wake region is the lack of prolonged trajectory scanning that could cover the wake expansion and measurements are taken from half an hour period, when large variation of the yaw-misalignment are observed. The double Gaussian shape distribution has been used for centre tracing of different yaw-misalignment conditions and this shape equation is used also in a recent study [7].

In the scope of this study, wake velocities are evaluated as quasi-instantaneous wind fields by averaging scanned points over the time. Since large scale meandering movements characterize the wind turbine wakes [5][8][10], definition of proper frame of reference is needed. Nacelle Frame of Reference (NFoR) and Moving Frame of Reference (MFoR) are defined in order to observe wake characteristics without influence of small scale turbulence.[5][10]. Thus, deficit of the wake centre line velocities and that are in the double Gaussian part of the wake is compared.

2.1.1. Deficits as seen from Nacelle Frame of Reference (NFoR)

The sight of an observer in this frame of reference can feel the orientation of wake with respect to the NFoR, as the reference orientation follows the nacelle even though the reference frame rotates with the yaw system.

If the measurement setup would cover a larger area, the orientation of wake would be resolved in a fixed frame of reference (FFoR) as well. Wake propagation might move towards negative or positive sides of the y and z axis due to yaw error and flow dynamics. Even in the case of no yaw

misalignment, large turbulent eddies in the atmosphere are expected to affect the orientation of the wake and its meandering.

2.1.2. Deficits on Moving Frame of Reference (MFoR)

Exploration of the wake from the MFoR allows us to estimate wake characteristics without large scale atmospheric influence.[5] Thus, dynamics effects of the wake meandering can be analysed by studying the wake centre deviation with respect to time on this frame of reference. After finding the wake centre of each downstream position over time, the wake deficit of each instantaneous snapshot is averaged. (e.g. $u_{\text{meandering}} = (u(x, y_1, t) + u(x, y_2, t+1))/2$ where y_1 and y_2 are the wake centres at t and $(t+1)$ in specific downstream positions of x).

3. Results

3.1. Inflow and wind turbine yaw conditions

In Figure 2, measured mean wind speed by spinner anemometer that is mounted on the nacelle and yaw error detected by nacelle vane are shown. It is seen that, mean yaw error is around zero for entire period. Also, mean wind speed varies between 8 and 4 [m/s].

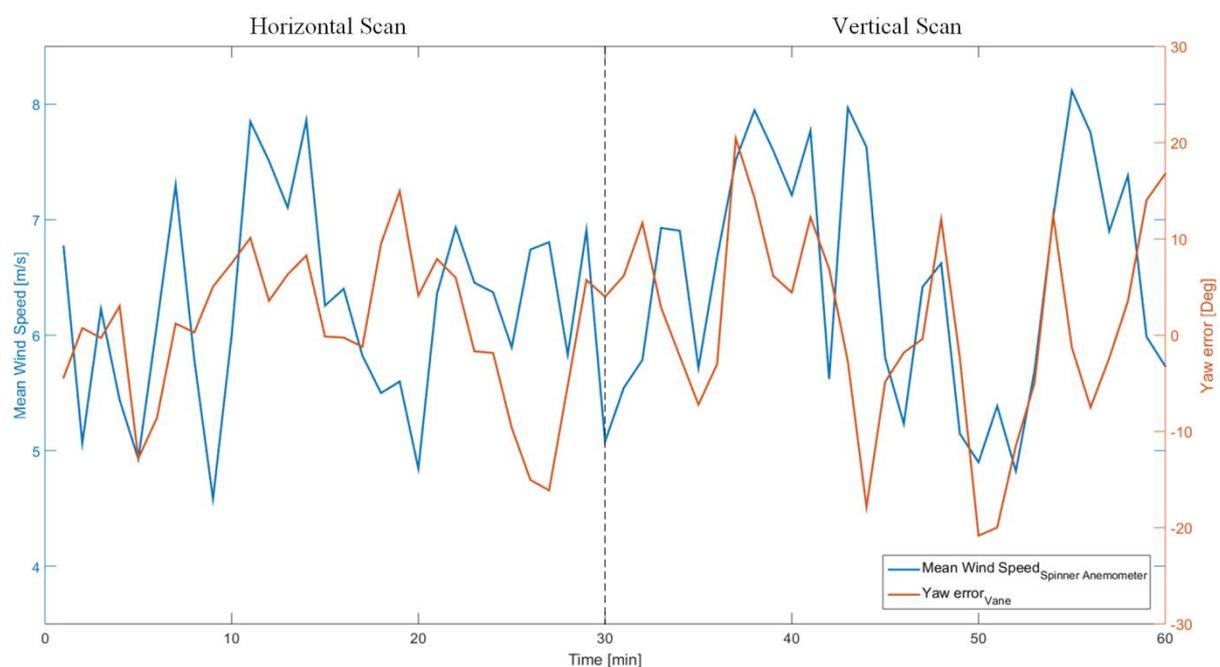


Figure 2. Blue line indicates the measured ambient conditions of the mean wind speed by a SpinnerLidar[12][13] anemometer, installed on the NKT Nordtank turbine nacelle. Red line shows the measured yaw error by the turbines own nacelle wind vane.

3.1. Averaged wind speed on horizontal plane

The horizontal scan plane consisted of 11 lines, which extended from the turbine tower down to 1.5D from the wind turbine. The lines were equally displaced by 4 m, forming this way a horizontal plane at the hub height, which was covering the full rotor span. The time duration of one scan was approximately 15 seconds, resulting in 40 scan repetitions per 10-min sampling period. In Figure 3 the

wind field measurements of the 10-min mean values of three successive periods are presented. The data have been grouped in grid cells of 4 m x 4 m dimensions resulting to 176 point measurements per plot.

During this period the time averaged yaw-misalignment with the scan plane axis did not exceed $\pm 5^\circ$, which indicates that the scanning pattern was well aligned with the wake propagation. The horizontal symmetry of the wake behaviour is evident in the upper row, which represents the axial wind speed component of the wake measurements. Additionally, transition of axial wind velocities from double Gaussian shape to single Gaussian shape is visible between 0.5D and 1D downstream of the rotor for the most of the cases. Furthermore, the w field reveals the rotation of the wake on the reverse direction of the turbine rotation.

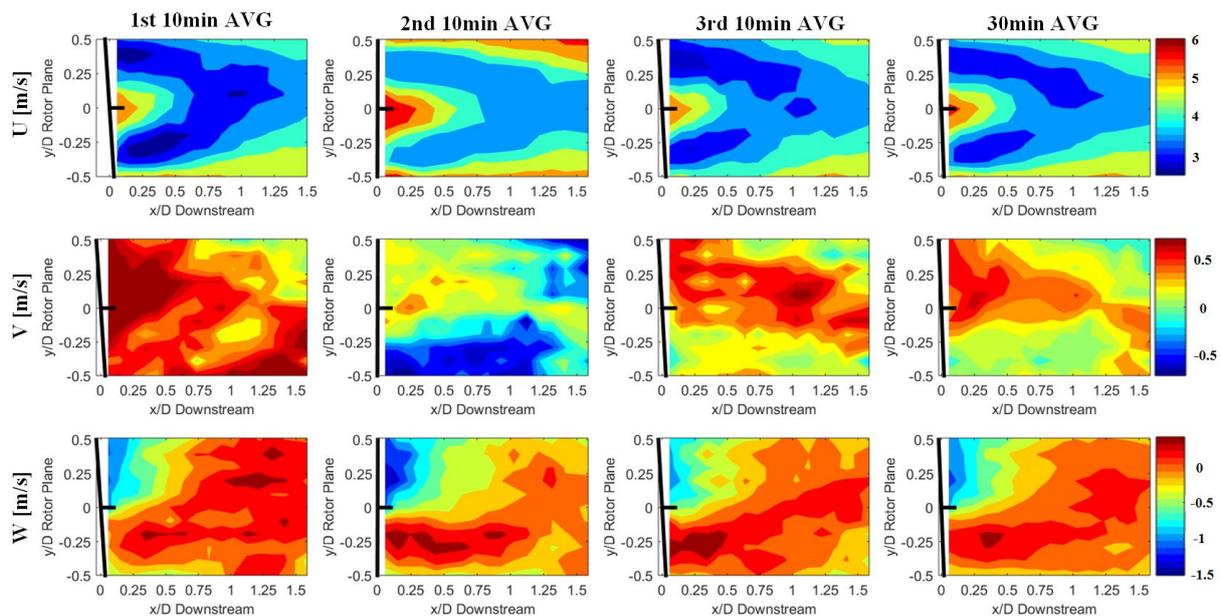


Figure. 3. The wind velocity u , v and w components of the wind field measured in a horizontal plane behind the turbine nacelle. The top, middle and bottom plots present the mean values of the three wind components in consecutive 10-min periods (first 3 columns) and in the cumulative 30-min period (last column).

3.2. Averaged wind speed on vertical plane

Similar to the case of the horizontal plane, the vertical cross section of the wake was scanned along 11 lines in a vertical plane extending from the rotor to 1.5D downwind in a vertical scan plane oriented perpendicular to the rotor and aligned centrally behind the wind turbine tower. The scanning lines and the interpolation grid had the same characteristics as used for the horizontal scan, with the only difference that the time duration of one scan was approximately 20 seconds, resulting in this case in 30 iterations per 10-min period.

The measurements of three such scans, from consecutive 10-min periods, are presented in the Figure 4. The u -field clearly reveals the wake in the axis wind component, the v -field is consistent with the clockwise rotating turbine, pushing the air in the opposite direction to the blade rotation, and the w field doesn't show any profound mean wind as anticipated in a vertical plane adjacent to the turbine tower on the turbine axis.

It is seen from Figure 5 that system is backscattering from nacelle and behind the nacelle at nearest downstream positions ($x/D = 0.05$ and $x/D = 0.15$) since length of nacelle is $\sim 8.9\text{m}$. [1] After that position, wind components behave more “Gaussian” as anticipated in the far wake region. The speed up near to blade root section is highly visible from axial wind component due to transparency of nacelle by causing double Gaussian shape and it vanished around 1D position similar to the horizontal scan results due to fast recovery in lower wind speed. Closer to edge of the rotor, axial velocity is predicted very close to the shear profile.

The average of radial (V) wind component is nearly equal to one over diameter and since the ambient condition is assumed to be zero, an offset is observed between the mean wind direction and the coordinate system used in the WindScanner.

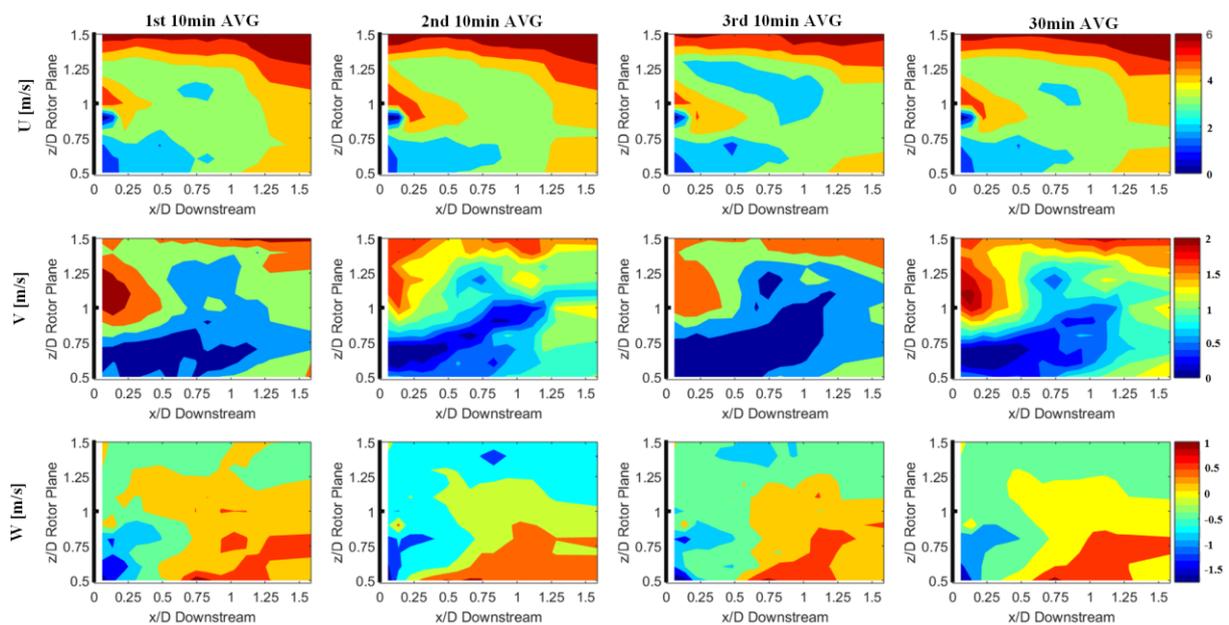


Figure 4. The wind velocity u , v and w components of the wind field measured in a vertical plane behind the turbine nacelle. The top, middle and bottom plots present the mean values of the three wind components in consecutive 10-min periods (first 3 columns) and in the cumulative 30-min period (last column).

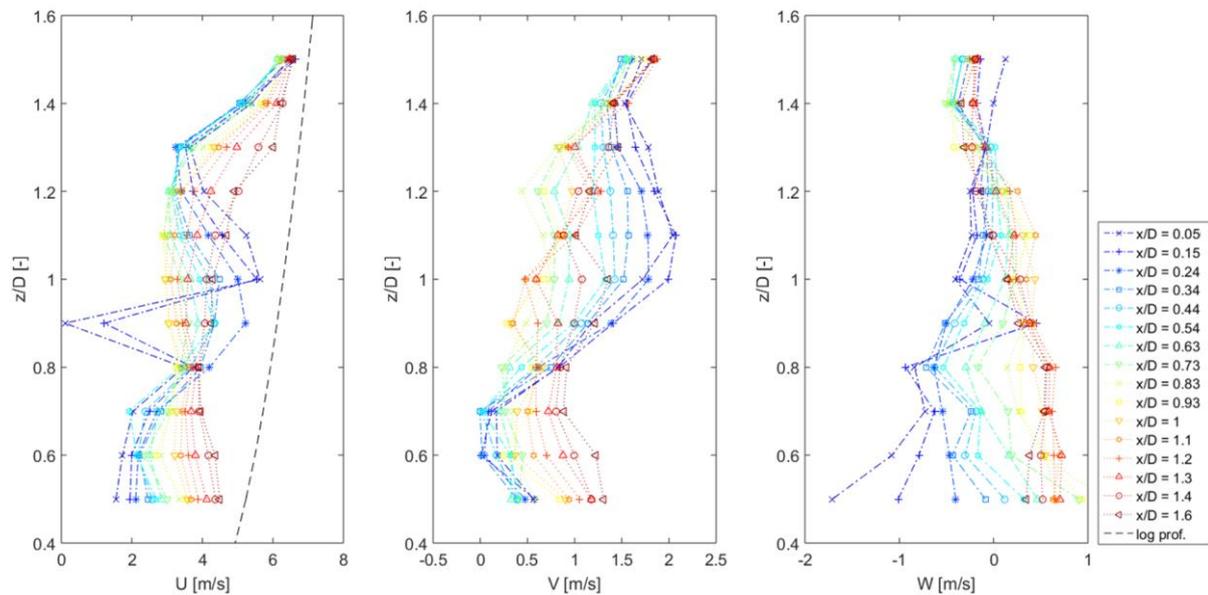


Figure 5. The 30 minutes averaged wind components of each measured downstream position. (Log profile is generated for U component by shear coefficient of $\alpha = 0.26$ which is measured at 1D upstream by nacelle oriented SpinnerLidar[12][13].)

Although, averages of vertical profiles of W components do not tend to zero for most of the downwind locations, W component is assumed to be zero in the ambient flow. However, this is not the case for further downstream positions. Average of axial velocities at further downstream stations is nearly zero due to domination of vertical shear as it is stated in the study of Kermani et al.[11] for influence of intermediate wake region. The reason of the negative average of closest downstream positions may be caused by the tower shadow on W component from vertical plane, since vertical plane is aligned with the tower position. Another reason for the bias might be the averaging of high and low values of yaw-error conditions in 30min bin.

3.3. Wake centre tracing results

After calculating the wake centre location in each downstream position, it is possible to derive the wake centre deficit from it. In this section, calculated wake centre locations and their corresponding deficits are shown.

3.3.1. Wake center tracing of horizontal scan

The trace algorithm works perfectly fine for downstream positions of less than 1.2D downwind. After 1D, double Gaussian wake profile starts merging to single Gaussian shape, and algorithm fails to predict it. Thus bivariate single Gaussian shape is much suitable to characterize wake region after 1.2D downstream. Also, wake flow moves out of the scan plane for high values of yaw-errors, thus both double and single Gaussian shapes cannot be visualized due to bounds of trust region reflective algorithm[5] variables as they are very close to ones from previous studies.[5][7]

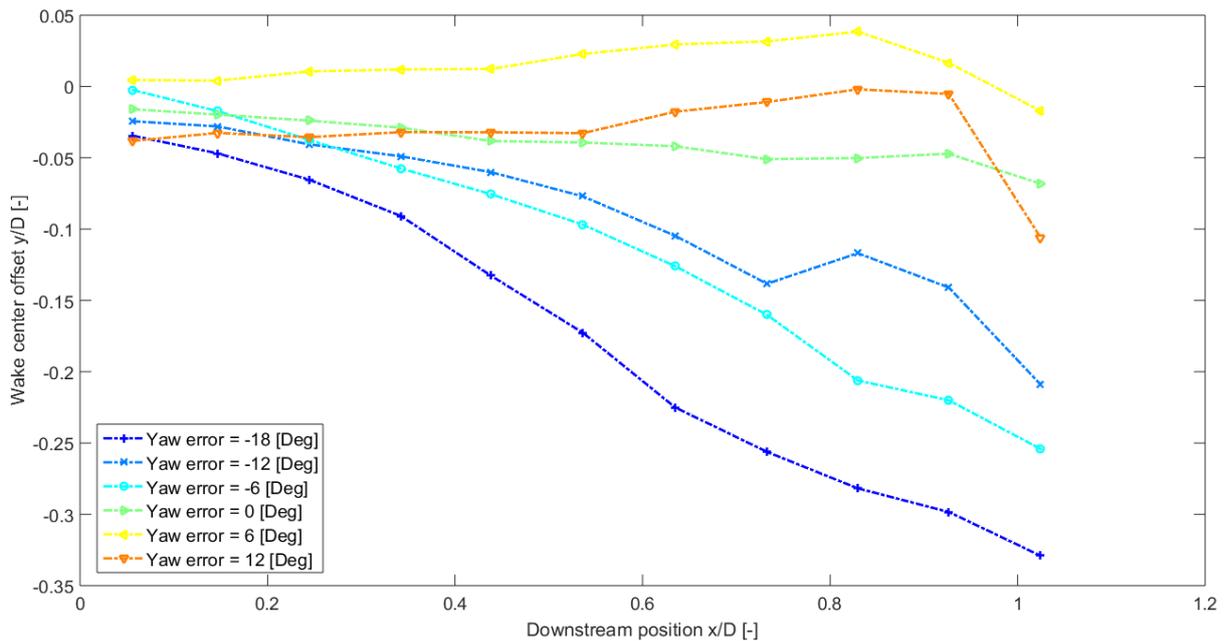


Figure 6. Wake centre deviation due to different yaw-misalignment cases on NFoR from horizontal scan with ± 3 [Deg].

The calculated wake centre positions show that systematically, wake propagates towards negative y direction. Steepness of the profile is highly affected by the yaw-misalignment condition. This is shown on Figure 6 from NFoR frame. The asymmetry of the wake centre deviation is observed. Mainly, for positive misalignment, the wake does stays somewhat centred. But in the other direction it does not. The traced wake centre allows us to explore the wake centre characteristic at specific downstream positions. Normally, the wind speed at wake centre is expected to decrease until 1D and to increase on further downstream positions (see Figure 7). The reason for such decrement is the double Gaussian shape of wake deficit due to speed up near blade root section. Measurements show that this speed up effect tends to decrease until the double Gaussian shape vanishes. Lastly, measured results meet the expected behaviour of the wind turbine wakes in terms of velocity profile.

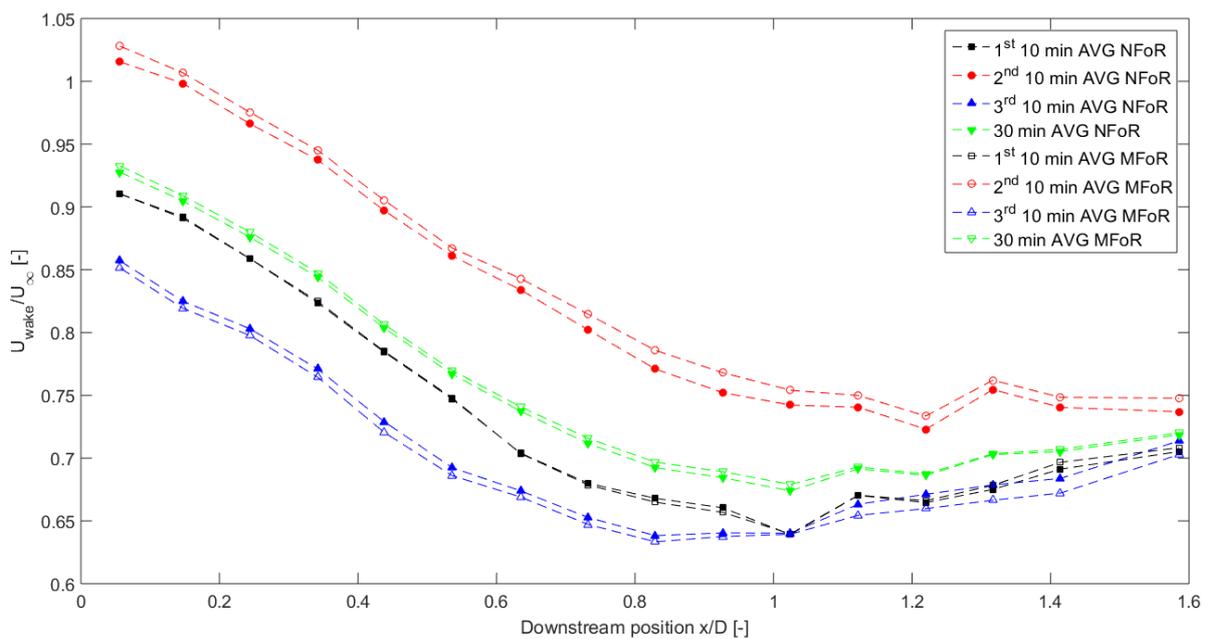


Figure 7. Wind speed at wake centre of different time averages with respect to NFoR and MFoR along the downstream positions of horizontal scan. Profiles are normalized by ambient axial wind component which is measured by SpinnerLidar[12][13] at 1D upstream position.

3.3.2. Wake centre tracing of vertical scan

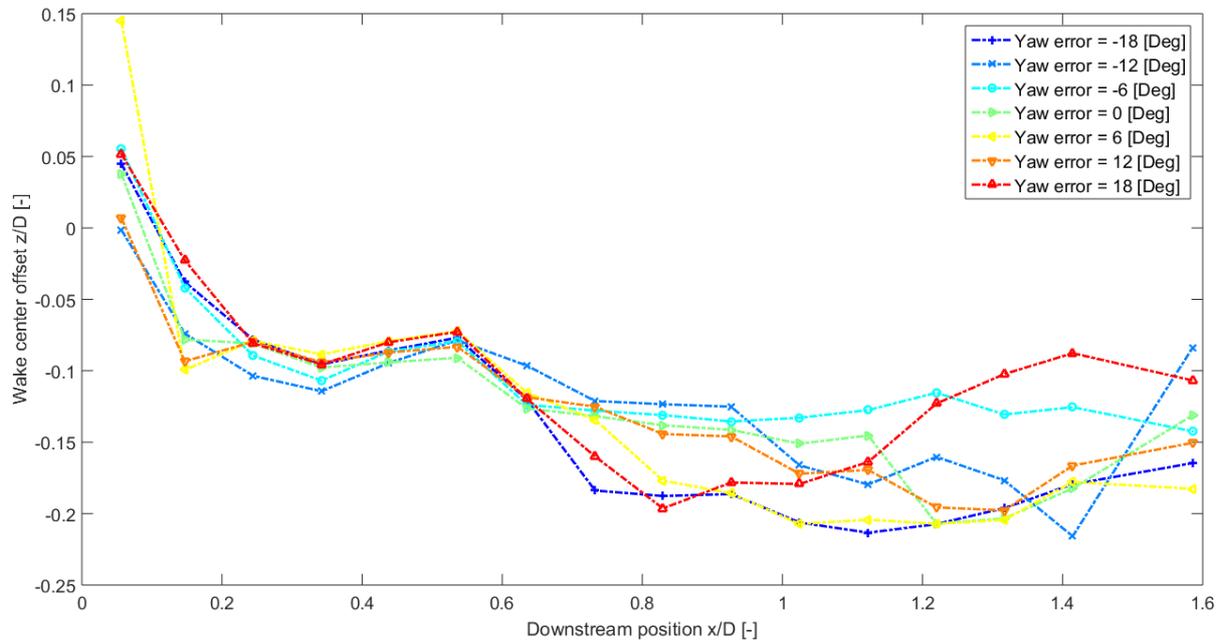


Figure 8. Wake centre deviation due to different yaw-misalignment cases on NFoR from vertical scan with ± 3 [Deg].

The wake centre deviation of vertical scan on the NFoR can be seen on Figure 8. It is observed that the wake propagates downwards due to vertical shear domination.[8], nacelle and tower blockage. However, terrain elevation difference is found to be 1.5m between tower location and 1.6D downstream (SRTM terrain library), so that vertical wake centre deviation is not dominated by the terrain elevation. Thus, higher shear would fasten the wake recovery by pushing the wake centre downwards.

The wake centre shows a slight downward trend in average. We conjecture three combined effects, namely, the terrain slope, vertical wind shear and the nacelle-tower wake effect. However, separation of these effects are not taken care of. Additionally, the terrain effect can be approximated to 0.04D (1.5m) between tower location and 1.6D downstream.

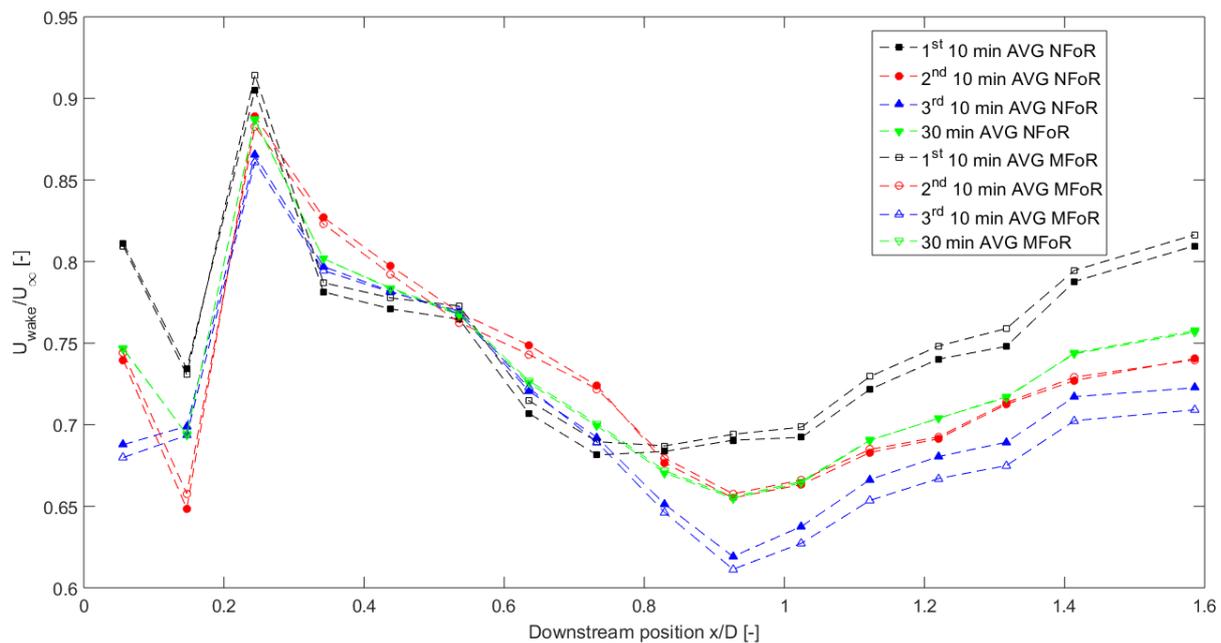


Figure 9. Normalized wind speed at wake centre of different time averages with respect to NFoR and MFOR along the downstream positions of vertical scan. Profiles are normalized with ambient axial wind component.

Similar behaviour of wake is observed in vertical scan exploration as in horizontal scan. Hence, influence of speed up effect tends to vanish before 1D and can be seen on Figure 9. Wake recovery is quite high at around 1.6D since wake centre speed reaches to value of 0.85. As expected, the calculated wake profiles are observed to be larger in the MFOR compared to the NFoR. Only in the 3rd 10min averaged values in the NFoR are higher than in the MFOR. Additionally, normalized wake velocities are highly affect by nacelle due to its sizing between $x/D = 0$ and $x/D = 0.20$ as seen on Figure 9, since origin of the scan starts from edge of the nacelle and second measured point is in complex flow conditions behind turbine nacelle. Because of measuring 1D upstream, normalized wake velocities seem to be increased. Since, ambient velocities were already induced by the induction zone along the centreline at 1D for same turbine.[1]

4. Conclusions

High-resolution full scale 3D wind velocity field measurements have been obtained in the near wake of a full scale test wind turbine located in flat terrain. Wind field velocity measurements were acquired in a horizontal and a vertical plane from three synchronised ground-based short-range WindScanners engaged via the research infrastructure WindScanner.dk. The scanned planes were both perpendicular to the wind turbine rotor and extended downwind to 1.5 D. The acquired high-resolution 3D wind field now provides valuable wake field data set for insight into the detailed 3D wake properties enabling enhanced knowledge on the near- field wake characteristics. The presented data set represents a new reference baseline for further wake structure analysis and it can contribute to the further evaluation and improvement of CFD-based modelling.

Expected wake behaviours are observed from full scale 3D Lidar measurements both from Horizontal and Vertical scans. Thus, measurements meet the expectations.

Wake centre tracing analysis showed the transition of the double Gaussian shape axial wake velocities into single Gaussian shape in the region around 1 - 1.2D downwind. This result, however, will be dependent on the thrust loading of the wind turbine, which we did not analyse here.

The propagation of the wake tends to move down from the hub height due to the vertical sheared flow which influences the wake recovery. Thus its proper modelling is quite important for capturing actual characteristics of the wake.

One of the main limitations of the here reported wake measurements is the fixed frame of scan patterns due to the constraint in the scanning strategy, this is why the wake sometimes propagates out of the scan area in high yaw misalignment cases. Wake-focused measurement scanning will, if possible, overcome this issue and will allow us to capture the entire wake structure for larger degrees of yaw misalignment.

5. Acknowledgements

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