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Lidar Scanning of Induction Zone Wind Fields over Sloping Terrain

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Abstract. Scanning lidar instrumentation in the form of two synchronized ground-based WindScanners and a nacelle-mounted SpinnerLidar were deployed to measure wind fields in a vertical plane in the induction zone from 0.2 to 3 rotor diameters (D) in front of a Vestas V52 test turbine (D = 52 m) situated at DTU Risø Campus. First, the two ground-based WindScanners accurately reproduced the vertical profiles of horizontal mean wind speed when compared to measurements from a reference met-mast installed 2.2D upwind in the prevailing wind direction. The vertical plane scanned wind field measurements within in the induction zone were also compared with the vertical wind profiles measured at 1D by a nacelle-mounted scanning DTU SpinnerLidar. The vertical plane wind field as measured by the two ground-based WindScanners shows that the wind field in the induction zone is influenced by the turbine as well as by the slope of the terrain.

1. Introduction

We report measurements of heterogeneous wind fields measured in the induction zone in front of a Vestas V52 test turbine operating near a coastline on sloping terrain. These measurements leverage the wind remote sensing technology developments during the past decade where scanning nacelle lidars and synchronized scanning wind lidars have been developed for detailed and accurate remote sensing of wind and turbulence velocity fields, e.g. WindScanner.eu. Today, scanning lidars have revolutionized our ability to measure many detailed wind and turbulence structures within the atmospheric boundary layer, including scanning of wind components in front and behind today’s huge wind turbines.

 Three separate units of synchronized and trajectory-coordinated scanning wind lidars are needed for instantaneous measurements of the three wind components of the velocity vector in the boundary layer. To date, however, DTU Wind Energy and ForWind have jointly, as partners within the European Research Infrastructure WindScanner.eu, designed, developed and so far only built two synchronized and trajectory-coordinated short-range continuous-wave (CW) scanning lidars equipped with 6-inch diameter telescopes. With their 6-inch telescopes, these new short-range WindScanners can measure at
focus distances up to 300 m, i.e., doubled range compared to the previously developed 3-inch based short-range WindScanners.

However, with only two WindScanners available, they have to be placed inside the measurement plane of interest, which was aligned with the mean wind direction, in order to avoid contamination from the velocity component perpendicular to the plane. The two WindScanners deployed in this study are referred to as 6-inch short-range WindScanners, as their beam-focussing apertures are built from high-quality diffraction-limited 6-inch optical lenses. The new 6-inch apertures reduce the continuous-wave (CW) WindScanners effective probe volume by a factor of four relative to the 3-inch based short-range WindScanners. In common terms of Full Width Half Maximum (FWHM), their effective probe length along the laser beams line-of-sight direction is close to 0.25 m only at a measurement range of 25 m and 4 m at a range of 100 m.

The two 6-inch short-range WindScanners are dynamically able to adjust their measurement range by focussing the laser beams within the range from 10 m (0.04 m FWHM) to 300 m (36 m FWHM) with a millisecond short response time and they are also able to scan wind and turbulence fields synchronously at a predefined set of points using a dual-prism scanner to steer the beam. This enables the scanners to generate high-spatial resolution and time-resolved (322.6 measurements per second) sampling of wind vectors within the scanned wind field.

2. The turbine inflow field experiment

During westerly winds, a V52 test turbine at DTU Risø Campus installed 9 m above Mean Sea Level (MSL) is exposed to slightly inhomogeneous inflow. The inflow fetch from this wind direction comes through the reference met-mast installed at 2.2D upwind where the terrain height is 7 m above MSL. Further upwind, a relative steep escarpment of approximately 6 m height leads down towards the coastline of Roskilde Fjord at approximately 225 m upwind. This escarpment and the sloping (about 2.3° on average) terrain influences the flow field in the induction zone.

Two 6-inch WindScanners and a DTU SpinnerLidar where used to characterize the inflow towards the 850 kW Vestas V52 test turbine (D = 52 m) with a hub height of 44 m at DTU Risø Campus. The measurements with the two 6-inch WindScanners and the SpinnerLidar were acquired during periods when the mean wind direction aligned favourably with the connection line (291°) between the turbine and the reference met-mast. The analysis presented is focused on two such periods. The first period, characterised by strong winds, occurred in the morning between 6 AM and 7 AM (hereafter always local time) on October 25, 2018. During this strong wind case, the turbine was exposed to strong winds in the range of 17 m/s at hub height. The second measurement period was encountered during the afternoon on December 10, 2018. Here the average wind speed at hub height was in the range between 9 and 11 m/s. According to the 125 m tall Risø meteorological tower also on campus, the atmospheric stability was slightly unstable (the temperature difference between 118 and 44 m was -0.4 degree Celsius, whereas an exact neutral lapse rate would require a difference of -0.7 degree Celsius).

The inflow to the turbine was in both cases scanned over a cross wind plane 1D upwind using a DTU Wind Energy developed SpinnerLidar [3,4,5,6] installed on top of the V52 nacelle, see Figure 1. The dual-prism-based scanning SpinnerLidar is able to measure 400 line-of-sight radial wind speeds distributed over a complete rosette scan pattern per second. In the present setup, the incoming wind field was scanned over a crosswind rotor plane at 1D, 52 m in front of the turbine.
Figure 1. Forward scanning DTU SpinnerLidar installed on the nacelle of the V52 test turbine. Left: V52 with SpinnerLidar on top of its nacelle. Middle: The SpinnerLidar with dual prism Risley type scan head. Right: The SpinnerLidar’s rosette shaped scan pattern.

The 10-minute average line-of-sight measurements were subsequently used to generate a three-dimensional mean wind field using a three-dimensional mean wind field reconstruction algorithm based on the LINCOM [7] model. The resulting 10-min average three-dimensional mean wind field scanned upwind at 1D in the rotor plane is shown in Figure 2.

The colours in Figure 2 represent 10-minute averaged axial wind speeds in the upwind rotor plane towards the turbine. They range between 15 m/s in the lower part of the rotor plane and increase to above 17 m/s near the upper tip height of the test turbine. At hub height (44 m) the axial inflow is around 17 m/s. Black arrows inserted at every grid point also represent the two crosswind wind components. There is not much crosswind over the rotor plane in this case. However, the data show that there is a mean vertical wind speed observed in the rotor plane of the order of 1 m/s. This is due to the slope of the terrain.
During December 10, 2018, DTU Wind Energy and ForWind - University of Oldenburg operated two 6-inch short-range WindScanners [1] installed on the ground in addition to the SpinnerLidar [2]. The two ground-based WindScanners were set to measure the wind field in a vertical plane along the connection line between the turbine and its reference met mast in the induction zone. The scanning pattern as shown in Figure 3 was ranging between 0.2 and 3D upwind of the V52 test wind turbine.
A schematic drawing of the experimental setup with the sloping terrain (bottom), the two WindScanners (black squares), and the met-mast’s five measurement heights are shown with black dots in Figure 4 where the setup is depicted from North to South, with the test turbine to the left (east). In addition, a photograph is taken of the experimental setup (Figure 5). This picture is taken from South towards North, and the turbine is here seen in the outermost right part of the picture.

![Figure 4](image.jpg)

*Figure 4. The experimental setup depicted from North towards South, with turbine and nacelle installed SpinnerLidar 9 m above MSL (left); reference met mast installed at 7 m ASL, and two ground-installed WindScanners. The turbine’s reference met mast is installed on the brink of the steep slope down towards the fjord (to the far most right).*

Each of the five measurement heights are equipped with sonic anemometers and cup anemometers: 18 m (lower tip height); 31 m; 44 m (hub height); 56 m and 70 m (upper tip height). The nacelle installed SpinnerLidar is as indicated in Figure 4 scanning the incoming wind field in the rotor plane at 1D in front of the turbine.
Results

We present SpinnerLidar vertical wind profile measurements at $1D$ and compare these measurements to the two ground-based 6-inch short-range WindScanner measurements. On the December 10 campaign, the two ground-based 6-Inch WindScanners were engaged in addition to the SpinnerLidar. All three lidars therefore scanned the wind field in the same vertical plane spanning horizontally between the turbines over the met-mast and out to $3D$ while the SpinnerLidar at the same time scanned the inflow to the turbine in its crosswind rosette scan pattern upwind at $1D$.

On December 10 in the afternoon between 15:00 and 18:00, both the wind direction and wind speeds at the test site were favourable. The wind direction aligned nicely and constantly within a few degrees of the 291-degree direction between the reference-met mast and the test turbine. The sky was overcast indicating near-neutral atmospheric stability conditions and the 10-minute averaged mean wind speeds ranged between 9 and 11 m/s. According to the 125 m tall Risø meteorological tower also co-located on the DTU Risø campus the atmospheric stability was slightly unstable (the temperature difference between 118 m and 44 m was -0.4 degrees compared to a neutral lapse rate temperature difference of -0.7 degrees between these heights. The observed wind veer measured in the Risø campus met-tower by the wind vanes at 77 m and 125 m heights was less than one degree.

With data from this setup, the SpinnerLidar measurements of the vertical wind profile at the centre line could be compared with the WindScanner measured vertical wind profiles also at $1D$. In addition, the WindScanner measured the vertical wind profile at $2.2D$ and this could be compared with the vertical wind profiles observed in the co-located reference met-mast. The experimental setup was consequently applicable as a test and evaluation case for both the nacelle installed SpinnerLidar and of the two ground-based and trajectory coordinated and scan pattern-synchronized 6-Inch WindScanners.

First, we compared the WindScanner profile measurements with the turbine’s certified reference met-mast data at $2.2D$. Subsequently, we evaluate the SpinnerLidar vertical profile measurements at $1D$ with the WindScanner vertical profile measurements also at $1D$. 

Figure 5. The experimental setup in the test field at DTU Risø Campus on December 10, 2018. The inserted pictures show the locations where in the field the two 6-inch short-range WindScanners, R2D1 and R2D2 were installed.
In total eighteen 10-minute consecutive measurement periods with data from the SpinnerLidar and the two 6-Inch WindScanners and the reference met mast where selected. The 10-min measurement periods showed very similar results. Therefore, for simplicity, we concentrate on a single 10-min period chosen because it represented the period with the highest wind speeds. The following case study was sampled during the time interval on December 10 from 17:10 to 17:20.

![WindScanner vertical plane 10-minute mean wind field measurements](image)

*Figure 6. WindScanner vertical plane 10-minute mean wind field measurements. Horizontal wind speeds are colour coded and the in-plane measured wind vectors are represented by arrows. The positions of the calibrated cup anemometers installed in the reference met-mast are represented by black dots. At the bottom contour of the sloping terrain is shown and the position of the two WindScanners. The curved part of the black triangle to the left indicate the nacelle mounted SpinnerLidar measurement range.*

The wind speeds measured by the two WindScanners along the six horizontal lines in the scanning trajectory (see Fig. 3) are presented in Figure 6 and Figure 7. Upwind of the met-mast located at $2.2D$ (115 m) the wind speeds at all measurement heights are found to increase towards the met-mast. Such a speed-up is expected due to the inflow over sloping terrain, which is augmented by the presence of the steep escarpment between the met mast and the coastline. However, from the met mast and towards the turbine, the wind speeds are seen to systematically decrease at all heights. This decrease is due to the presence of the turbine. The decrease in wind speed at all measured heights becomes more and more evident as the flow approaches the test turbine. At 10 m/s, the turbine is operating 4 m/s below rated power. The decrease and deflection of streamlines around the rotor are a clear effect of the test turbine induced induction zone. The difference in terrain slope from the turbine to the met-mast is only 2 m, whereas the terrain immediately further upwind of the met-mast is dropping close to 6 m within the next 10-20 m. We believe that this escarpment is the cause of a kink in the horizontal profile of the wind speeds at all heights, which occurs close to the position of the reference-met mast.
Figure 7. Horizontal wind speed component in the vertical scanned measurement plane at the six trajectory heights in Figure 3 (Left). Corresponding speed profiles normalized to a common value of unity at the met-mast position (Right).

In Figures 8 the WindScanner, measured vertical profiles of the horizontal wind speed have been compared with those of the cup anemometers. The WindScanner and the met mast wind profiles are in very good agreement. The vertical profile calculated by the LINCOM model is also shown. LINCOM is a linearized Navier-Stokes flow model calculating perturbations to the mean flow under the influence of terrain effects while preserving momentum and mass [8]. As input to drive LINCOM, horizontal wind speed measured by the WindScanners at 80 m height at the location of the reference met-mast was used.

The vertical extent of the V52 rotor is also indicated on the left ordinate in Figures 8 and 9. The rotor contour has been raised by 2 m to include the height difference of 2 m between the turbine foundation (9 m ASL) and the met-mast foundation (7 m ASL).

We investigated the vertical wind profiles measured by the SpinnerLidar at 1D. In Figure 9 an intercomparison of the vertical profiles of the horizontal wind speeds measured by the WindScanners and by the SpinnerLidar is presented. Three different data processing algorithms have been applied to generate the horizontal wind speed profiles from the SpinnerLidar measured line-of-sight radial speed measurements. 1) A cosine-projected radial wind speed measurements (Astrup), 2) the horizontal wind component derived from the three-dimensional wind field reconstructing methodology, similar to the method applied to reconstruct the wind field for the strong wind case 1 above, and 3) an alternative line-of-sight wind speed cosine projection method based on raw SpinnerLidar measurements (Peña).

As seen from the measured profiles presented in Figure 9, there are no significant differences between the results of the three different data processing methods compared to the WindScanner measured vertical profile at 1D, which we may consider as a base line instrument after evaluating its performance against the met-mast measurements at 2.2D. All three algorithms applied to processing the SpinnerLidar’s line-of-sight measurements into vertical profiles of the horizontal wind component seem accurate.

In Figure 9, we also include the vertical profile measured at the met-mast at 2.2D. Relative to the met-mast, the wind speeds at 1D are reduced by almost 2% at hub height and even more at the upper tip height. This indicates the effect of the induction zone.

The LINCOM hill model clearly over-predicts the measured wind profiles at 1D. However, this is not surprising because LINCOM is not able to include information about the presence of the turbine and hence it is not able to predict the effects of the turbine generated induction zone.
Figure 8. Vertical profiles of mean horizontal wind speeds at 2.2D at met-mast position by 1) reference met-mast class 1 certified cup anemometers, and 2) profile measured by the two ground-based WindScanners. Also shown is the model prediction of the vertical wind profile calculated by the LINCOM flow over hill perturbation model.
Figure 9. Vertical profiles of mean horizontal wind speed at 1D measured by 1) the SpinnerLidar (three different data processing algorithms) and 2) by the ground-based WindScanners. Also shown (in grey) is the corresponding profile measured by the met mast at 2.2D, and (in green) the prediction by the LINCOM flow over hill model prediction at this location.
3. Discussion

The measurement campaign with the WindScanners and SpinnerLidar conducted in 2018 have demonstrated the usefulness and capacity of the wind lidar research infrastructure instruments developed. The SpinnerLidar was useful for performing measurements within the induction zone and has shown capacity to generate data sets of radial wind field measurements suited for a three-dimensional wind field reconstruction methodology. The two new 6-inch synchronised and trajectory coordinated short-range WindScanners have proven to be powerful for scanning of wind fields in a vertical plane at a test site influenced by the combined effects of terrain-inhomogeneity and a wind turbine induced induction zone.

The vertical plane wind field scanned between the met mast and the turbine has shown significant influence by both turbine induction zone and terrain effects; caused by the escarpment, an increased wind speed extends from the ground and up to approximately 40 m height. In front of the turbine, the vertical wind components diverge due to induction around the rotor.

Stagnation in the horizontal wind speed could be observed already in the vertical profile of the met-tower at 2.2D. At 1D, the SpinnerLidar simultaneously acquired line-of-sight measurements on a 30° wide spherical surface. First, the lidar-scanned wind field was compared with the measurements from the reference met-mast equipped with certified cup anemometers at five measurement heights. Subsequently, the WindScanner measured vertical profile of the axial wind speed was used as reference measurements for assessment of the accuracy of the axial wind component derived from the SpinnerLidar measurements at 1D.

At 1D, both the cosine projected and the three-dimensional reconstructed vertical wind profiles showed clear and identical evidence of the induction zone reduced inflow to the test turbine. The WindScanner measured profiles also showed divergence in the vertical wind component as the wind field approached the rotor.

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