

Defining wake characteristics from scanning and vertical full-scale lidar measurements

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Abstract. This paper describes the use of lidar to capture full-scale wake characteristics. Measuring wake characteristics such as velocity deficit, wake width and asymmetry as well as wake meander with scanning Doppler lidar requires an efficient scan geometry in which wake volumes are comprehensively scanned while ‘empty’ volumes are excluded and also requires optimization for maximum spatial and temporal coverage. Some examples are given from a field experiment in Prince Edward Island in 2015 that show wake characterization from both scanning and vertical lidar.

1. Introduction and motivation

There is a need for detailed measurements of wake characteristics for use in model validation and verification exercises and for improved wind farm design and operation to optimize power output and minimize fatigue loading. Key features of wind turbine wakes necessary for characterization are the velocity deficit in the cross-stream (x) and vertical (z) directions at different downwind distances (y-plane) from which the degree of axial-asymmetry of the wake, the wake center location and the wake expansion due to meander versus diffusion can be obtained [1, 2].

Over the past ten years the use of lidar (both vertical pointing and scanning) has replaced the standard meteorological mast for measuring wind turbine wake characteristics [3]. However, use of lidars for wake characterization remains extremely challenging because of factors such as:

1. The inherent inhomogeneity of flow conditions within wakes. Depending on the type of lidar, it may not be possible to resolve wind speeds in the sampled volume in the very heterogeneous near-wake (see examples given below).
2. The uncertainty in lidar resolved flow characteristics. The uncertainty in wind speeds (and higher moments of the flow) as derived from lidar line-of-sight Doppler frequency shifts are a function of factors such as the scan geometry and the directional offset between the lidar line of sight and the wind direction and the repetition rate for sampling of a given point in the scanned domain [4].
3. The directional variability of wakes and the problems of obtaining accurate wind direction forecasts for the a priori design of scan patterns. To increase temporal resolution of lidar scans, limiting spatial extent can be necessary but this may also result in the scanned area containing limited or no wake data.
4. The need to design a priori scan geometries to capture wind turbine wakes and to probe them with sufficient detail to permit calculation of wake properties in highly varying flow conditions (see



example in Figure 1) while being cognizant of the considerations raised by point 2. The initial challenge is to devise a scan geometry that can encompass the likely area of the wake at sufficient temporal and spatial resolution without scanning too far downstream or too large an area [5] where either the wake is no longer differentiable relative to stochastic variability in the atmosphere (e.g. for downstream distances of ~ 10 rotor diameters, unless conditions are stably stratified) or where the signal-to-noise ratio of the lidar returns prohibits accurate estimation of the Doppler shift. If the elevation angle is too high, then errors associated with the assumption of a mean zero vertical velocity also becomes unacceptably large. The selection of elevation angle(s) for the scan is critical to determining the downwind distances at which a wind turbine wake would be sampled. An example is shown in Figure 1 under the assumption that the scanning lidar is located at the base of the wind turbine that has a hub-height of 80 m and a rotor diameter (D) of 93 m. In the left panel of Figure 1, the height of the center of the lidar probed volume (expressed in rotor diameter, D) is shown for a range of elevation angles at a range of discrete downwind distances (also expressed as D). In the right-hand panel, a simple wake expansion model with a range of wake decay coefficients (k) [6] is used to describe the tip height and width of a wake for the same turbine as described above. As shown, an elevation angle of 6° will scan through the rotor plane at $z = \text{hub-height} \pm 0.5D$ for about $5\text{--}14 D$ but will miss the near-wake ($< 4D$). A lower elevation angle will sample the bottom of the rotor plane, and a higher elevation angle is needed for the near-wake but will scan above the tip height for most values of D .

Given that the scan direction and wind direction that steer wakes will likely not be aligned, creating and/or selecting an efficient yet effective scan geometry to capture wake characteristics at a range of relevant distances can be challenging.

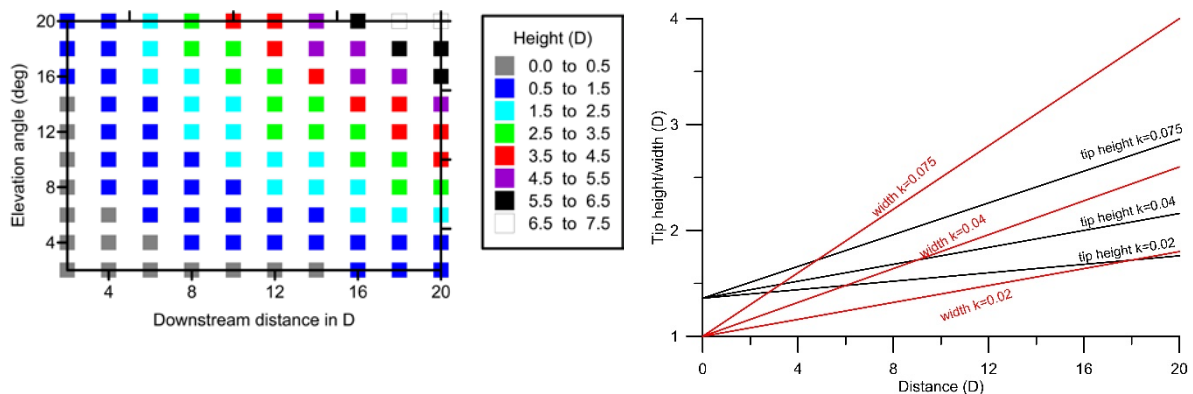


Figure 1. (left) Height of the center of the lidar probed volume as a function of elevation angle vs distance from the lidar (expressed in rotor diameters D , where the turbine rotor diameter D_0 is 93 m). (right) Approximate expansion of the wake with distance downstream (in rotor diameters, D). In this example we use a simple linear expansion of the wake wherein; $D_y = D_0 + 2 k Y$. Where; Y = distance downstream (expressed as multiples of D), D_0 = rotor diameter and k = wake decay coefficient with values ~ 0.02 for stable/offshore conditions, ~ 0.04 for offshore/neutral conditions and ~ 0.075 for land.

Below we describe the methodology we have developed for application to data from scanning lidars for retrieval of wake characteristics, and show examples of application of this method to data from the Prince Edward Island Wind Energy Experiment (PEIWE) [7].

2. Overview of the Prince Edward Island Wind Energy Experiment (PEIWE)

The field experiment was conducted at the Wind Energy Institute of Canada (WEICan) wind farm in moderately complex coastal terrain on the northwest tip of Prince Edward Island in May 2015 [7]. The primary focus of the experiment was on quantifying wakes from five DeWind 2 MW wind turbines with 93 m rotor diameter (D) and 80 m hub-height located just over 100 m inland from a 16-m high escarpment (Figure 2). However, on May 19, wind speeds were too low for wind turbine wakes so a

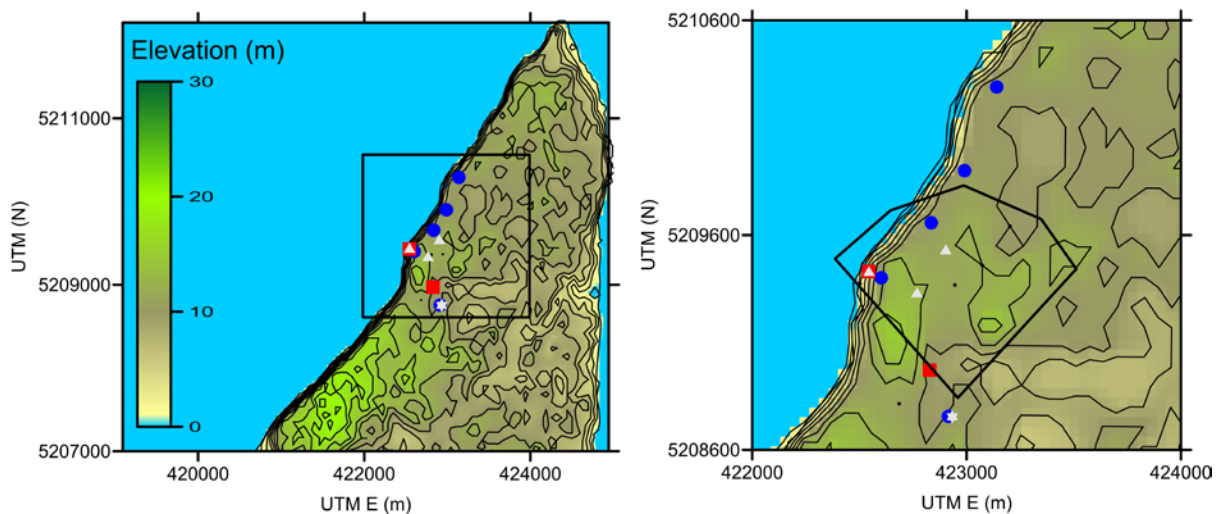


Figure 2. Locations of instruments on the northeast tip of Prince Edward Island. The left panel shows the topography of the island and the instrument locations. Blue circle are the five 2 MW wind turbines, white triangles are ZephIRs, the white star is the scanning lidar and red squares show the meteorological mast locations on which sonic anemometers were installed. The right panel shows the enlargement of the 2 km x 2 km square used in WAsP CFD simulations [7] with the approximate scanning arc of the scanning lidar (see Figure 3 for details).

series of stare scans were undertaken for analysis of turbulence characteristics from the scanning lidar relative to data from sonic anemometers [8].

The instrumentation from which measurements are presented here are:

- 3 vertical pointing continuous wave lidars (from Natural Power). Two are of the 300 series generation (Z423 and Z447, which measure at 10 preselected heights at 50 Hz for a 1 second averaging period) and one is a 150 series unit (Z125, that records at 1 Hz at 5 pre-selected heights). Z447 was located at the coast next to the short meteorological mast, Z423 was located just south of a wind turbine and Z125 was the southernmost vertical lidar.
- 1 scanning pulse lidar (Galion from Sgurr Energy) deployed with a scan geometry that included Plan Position Indicator (PPI) and Velocity Azimuth Display (VAD) (see summary in Figure 3). The range-gate length (distance between two radial measurements) is 30 m.

Figure 3 shows a time series of hub-height wind speeds and directions from the vertical lidar (Z447) indicating measured wind speeds were mainly above the wind turbines cut-in wind speed (4 ms^{-1}).

3. Methodology for deriving quantitative estimates of wake characteristics using scanning lidar

The methodology employed to derive quantitative information about wind turbine wakes from the scanning lidar is as follows:

1. The Doppler shift is used to derive line of sight estimates of wind speed from the scanning lidar (derived under the assumption that the mean vertical velocity is 0) that are used to derive wind speed and direction estimates following [4],[9].
2. The resulting data are averaged to 10-minute mean values.
3. A 3-dimensional mesh of horizontal wind speeds is then derived using a kriging interpolation.
4. The 3-dimensional mesh of horizontal wind speeds is sampled to produce horizontal slices parallel to the ground and/or rotated according to the wind direction and sampled to produce vertical slices at fixed downwind distances from a turbine.

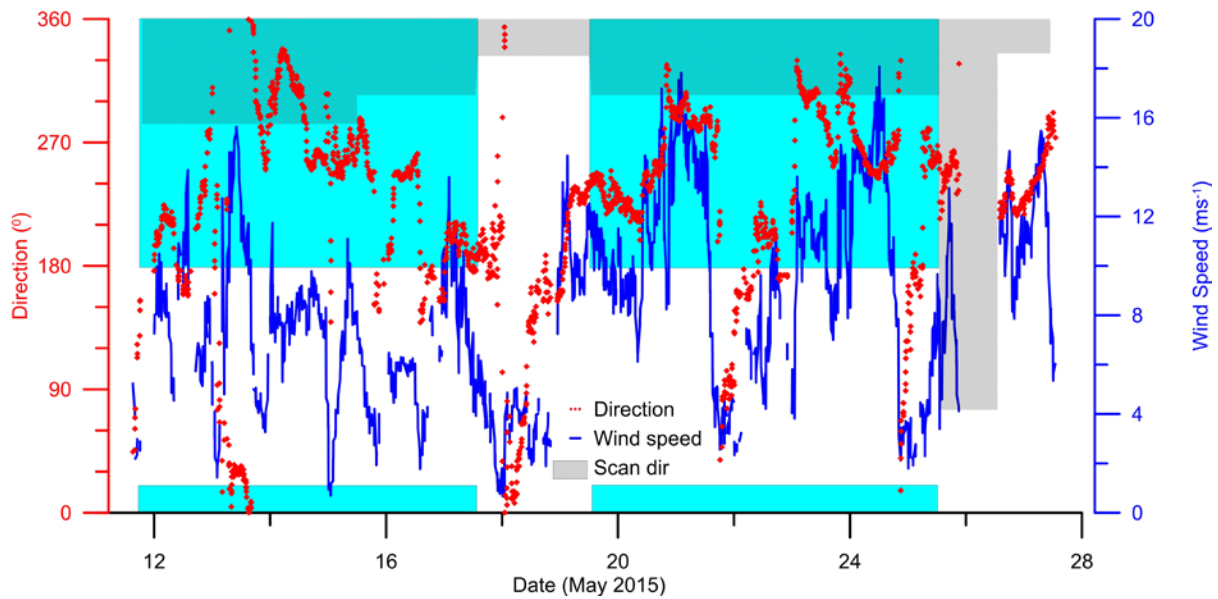


Figure 3. Overview of the scanning geometry used for the Galion, and wind speed and direction time series for a height of 80 m at Z447. All times are given in UTC. The cyan shading depicts directions for which it is feasible that wakes may be scanned, the gray shading (Scan dir) indicates the actual scanning directions employed.

4. Examples of wake characteristics derived using data from PEIWEE

In this section, we present example results of wake analyses drawn from measurements during the period May 12-15 2015 when the wind direction was predominantly northerly and wind speeds were consistently above cut-in, but exhibited significant variability (Figure 3). During this period arc scans were performed with azimuth angles of 304.5° to 34.5° over north at 2° intervals and six elevations angles (2-12°). This scan geometry (that also included a VAD scan) took approximately 10-minutes to complete (hence the temporal discretization used in the data homogenization procedure).

An example of the dynamic nature of the wind turbine wakes is shown in Figure 4 for a period during May 13 during which the wind direction remained between 320 and 340° (allowing a full scan of wakes from wind turbines WT2, WT3 and WT4), but the freestream wind speed at 80 m height dropped from just over 11.4 m s⁻¹ at the start of the hour (16:00 UTC) to less than 7.0 m s⁻¹ at 16:50 UTC. The individual wind turbine wakes are evident as is the temporal variability (at 10-minute intervals) of both the freestream wind speed and wakes. Figure 5 (first panel) shows wind speeds from all heights and the locations of vertical slices at 2D upstream of WT3 and 2D, 4D and 6D downstream for a single 10-minute period. The initial freestream wind speed at 80 m height, v_f , is 6.7 m s⁻¹, which is reduced to a minimum of 2.8 m s⁻¹ at the center of the wake immediately downstream of the wind turbine v_w (thus the wake wind speed deficit is 3.9 m s⁻¹ and the velocity deficit v_d where $v_d = (v_f - v_w)/v_f$ is 0.58). Interestingly at this location 1D downstream the velocity minimum is evident at a height of 124 m (i.e. considerably above the hub-height). This is in qualitative agreement with data from the ZephIR lidars, sonic anemometers and modeling with WASP-CFD that showed streamlines with a positive flow inclination angle at this inland distance from the escarpment [7], but implies a steeper flow inclination angle (of ~20°) than is manifest in the observations (Figure 6). At this time of day, the sonic anemometers on the meteorological mast indicate the atmosphere was very unstable ($z/L = -0.33$ at 60 m height where L is the Monin-Obukhov length and z is height). Hence, a potential reason for the discrepancy between the mean flow inclination angle and the implied lifting of the wake may be lofting of the wake by convective eddies. However, this case study also illustrates the challenges in conducting such an analysis. The combination of scan geometry and temporal averaging mean the data field presented to the kriging algorithm is highly heterogeneous. At this time stamp, no low elevation scans are included in the time average and thus the interpolation between data points located at about 127 m

and 190 m heights makes defining the top of the wake difficult. Nonetheless, the lowest wind speeds of 2.63 and 2.76 ms^{-1} are observed at heights of 123 m and 127 m (i.e. very close to the top of the rotor), respectively indicating that this is the wake center.

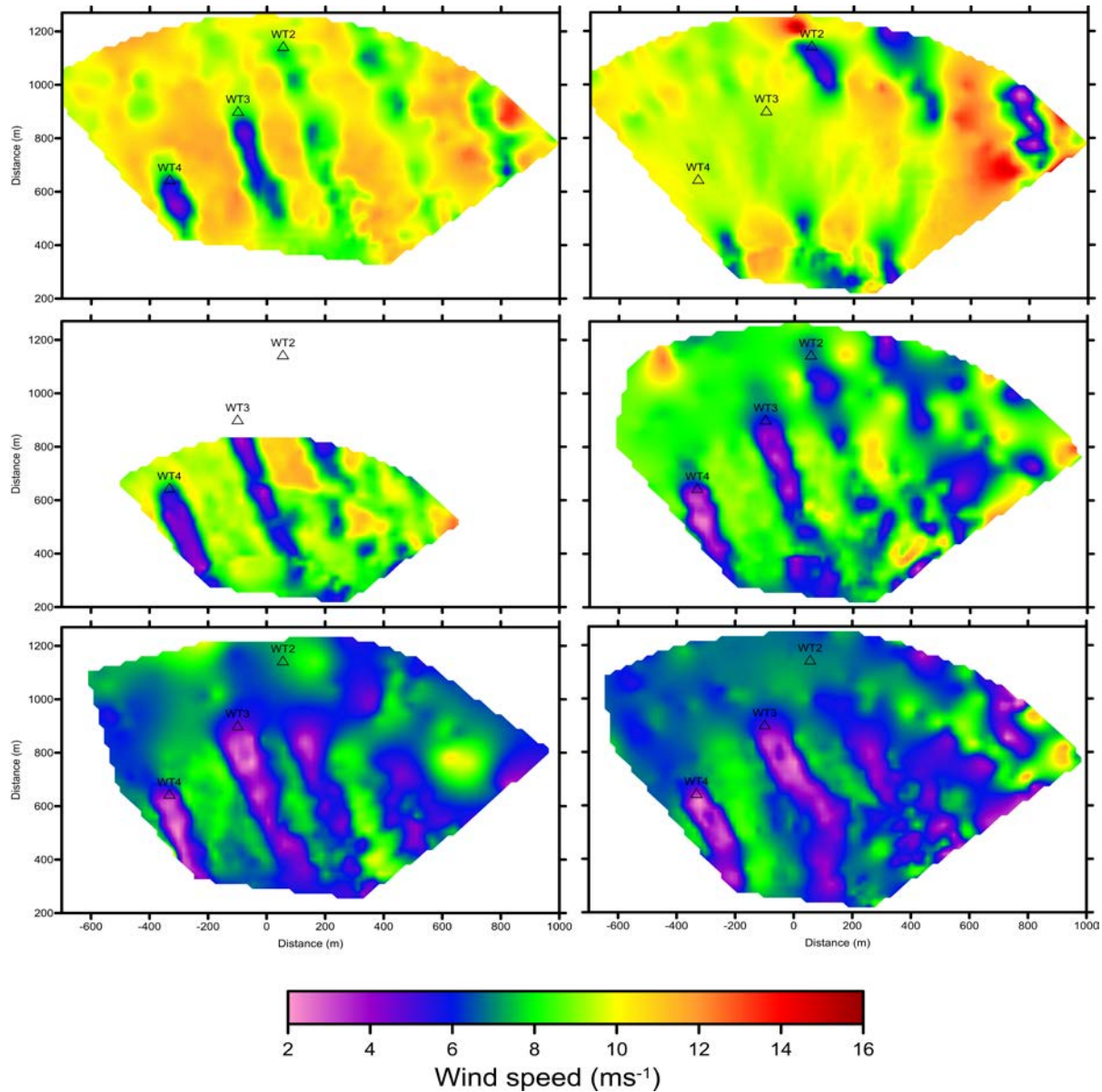


Figure 4. Ten-minute mean wind speeds (ms^{-1}) projected onto a horizontal surface centered at 80 ± 10 m during 16.00-17:00 UTC on 13 May. The top left panel shows data from 16.00-16.10 UTC, top right from 16.10 to 16:20 UTC and so on. The coordinate system is such that the scanning lidar was deployed at a nominal location of 0,0 and the coordinates are not rotated (i.e. the y-axis is geographic north). The locations of the three wind turbines within the scanned volume are shown by the black triangles labeled by the letters; WT4, WT3 and WT2.

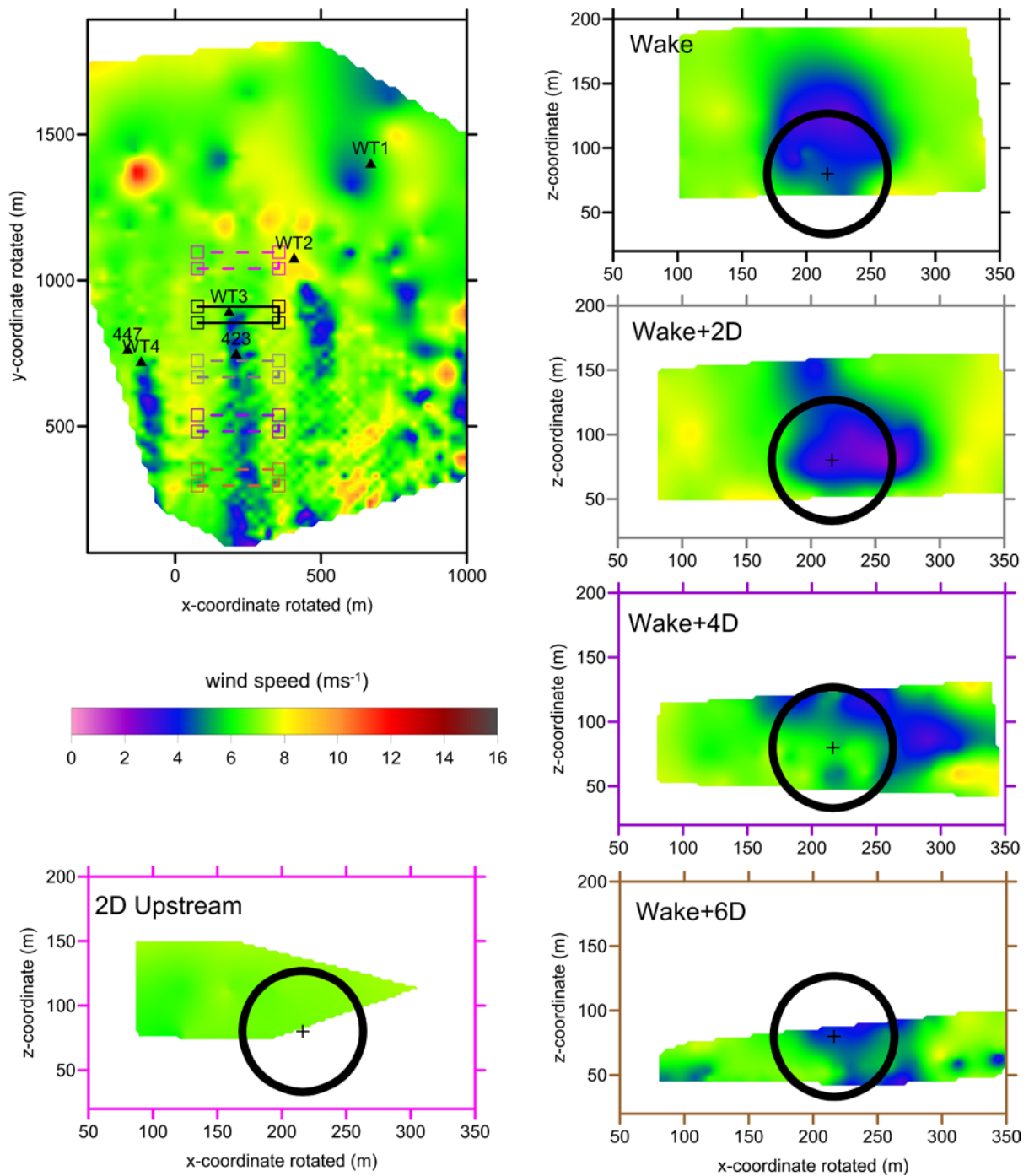


Figure 5. An example of wakes at fixed downstream distances from data collected on May 13 2015 at 16.50-17:00 UTC. The top left panel is a horizontal composite of wind speeds from all heights and shows the locations of the sampled volumes used to characterize conditions in the remaining frames. The remaining frames show vertical slices at 2D upstream of WT2, within 1D downstream of this WT and then at 2D, 4D and 6D downwind of the turbine. Each slice is generated by considering a sample volume that is centered at that downwind distance and extends $\pm 0.3 D$ in the streamwise direction and $\pm 1.5 D$ in the crosswise direction. The solid circle with central cross shows the rotor plane and nacelle center for WT3. Coordinate rotation is undertaken to align with the wake direction from WT3.

At 2D downstream the wake width has expanded to ~ 100 m (about a 10% increase), there has been little recovery of the centerline wind speed and the wake has also meandered from its central position by about 40 m ($0.43D$) to the east. At 3D (not shown) the wake center is aligned with the wind turbine, while 4D it is displaced further east, exhibits a highly asymmetric form and the wake deficit has decreased to $\sim 2 \text{ m s}^{-1}$ ($v_d=0.7$). Despite efforts in the field to optimize the scanning geometry, Figure 5 also illustrates a challenge in assessment of wakes using scanning lidar, by 6D there are insufficient data to effectively capture the wake. It is important to note that while the processing methodology is objective and repeatable, it also includes a number of subjective decisions. For example, the range gate of the instrument is 30 m so increasing the depth of the box from $\pm 0.3 D$ will include further measurement points, but this will also decrease the resolution of the wake in space.

Figure 6 shows the same case study but illustrates the challenge in using the vertical-pointing lidars for near-wake quantification. This figure shows the vertical profile of wind speeds for the period 13 May 16:50 to 17:00 (UTC) from the two 300-series ZephIRs and the scanning lidar measurements for those locations. During this period Z423 was directly in the wake of WT3 at $\sim 2D$ downwind. This meant the ZephIR requirement for homogeneous flow across the 30 deg sampled cone was violated and thus no wind speed was retrieved. For the ZephIR outside the wake the agreement between wind speed retrieved from the scanning lidar and those from the ZephIR (Z447) is very good up to 120 m height, but exhibits a substantial offset at greater heights (Figure 6). The cause of this discrepancy is under investigation.

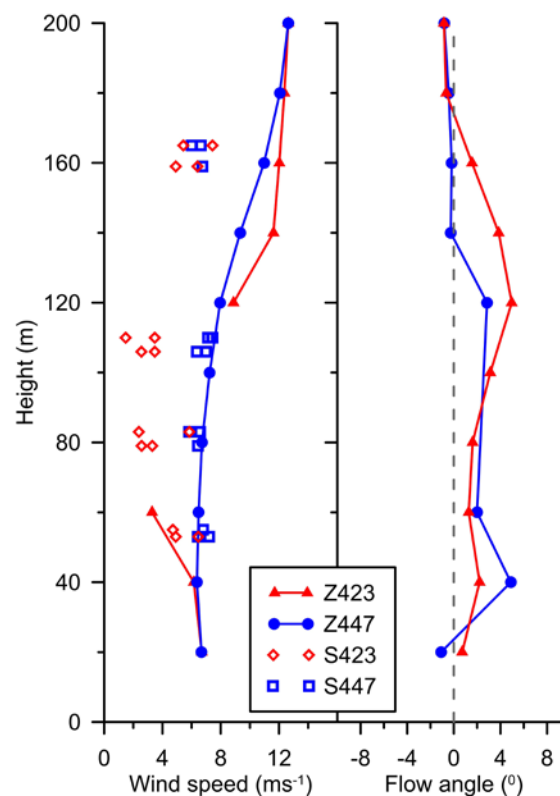


Figure 6. Vertical profiles of wind speed and flow inclination angle from the 300-series ZephIR lidars (Z447, Z423) at 16:50-17:00 UTC on 13 May. Also shown are the wind speeds retrieved from the scanning lidar for these locations (shown as S447 and S423, respectively) at this time.

5. Conclusions

Using lidar for wake measurements brings many advantages, principally that measurement heights can, with most commercially available lidars, extend to 200 m and beyond, so it is possible to routinely and conveniently measure both wind speed and turbulence to (and beyond) turbine tip-heights. In addition,

scanning lidars can provide a complete visualization of wakes and their behavior over a relatively large volume. However, as indicated in the analysis shown, the change of sampled height along the line-of-sight of a scanning lidar, combined with the expansion and meander of the wake can make it difficult to optimize the scan geometry such that there is complete and effective coverage of the wake volume at difference distances downstream, as well as making it difficult to determine the freestream velocity. The non-homogenous flow that defines wakes can also mean that assumptions of homogeneity in retrieving wind speeds from vertically pointing lidars are violated. Nonetheless, it is possible to retrieve wake characteristics and here we present the initial development of a methodology to process scanning lidar datasets that will also provide feedback to optimized scanning geometry.

6. References

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