Wind turbine wake study by the NOAA High-Resolution Doppler Lidar

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1. Introduction

The assessment of the velocity deficit and turbulence associated with operational turbines is a major issue for wind farm design and optimization of the spacing between turbines. The significant velocity deficit and turbulence generated by upstream turbines (Barthelmie et al., 2007) can reduce the power production and produce harmful vibrations in downstream turbines, which can lead to excess maintenance costs. The complexity of wake effects depends on many factors both hardware (turbine size, rotor speed, and blade geometry, etc.) and meteorological (prevalent wind direction at the site, wind velocity, wind gradients, Boundary Layer stability, turbulence characteristics, etc.).

A critical issue in addressing these problems is a lack of high-quality measurements, quantitatively characterizing the structure and intensity of turbine-generated wakes and the velocity deficits accompanying them.

Remote sensing instruments, such as lidars (LIght Detection And Ranging), which can provide high-quality measurements of wind profiles up to several hundred meters above the ground, have a great potential for filling these gaps. Scanning lidars can capture the needed spatial-temporal characteristics of the turbine inflow conditions and of turbine wakes (Harris and Hand, 2006). Lidar studies of wake development behind a wind turbine have been conducted in Europe by using ground-based lidar (Käsler et al, 2010; Clive et al, 2010), some using different technological approaches: by mounting lidar at the nacelle of a test turbine (2006, Mann et al., 2006), or several lidars as in the “three Musketeers” experiment (Mikkelsen, 2008).

In this study we use the High Resolution Doppler lidar (HRDL), designed and developed at the Earth System Research Laboratory (ESRL) of the National Oceanic and Atmospheric Administration (NOAA). Over the last decade, HRDL has been used to study flows associated with wind energy, and has a documented capability to observe wakes of obstacles on land, such as trees and buildings (Grund et al., 2001), and in water, such as oil platforms and moving ships (Pichugina et al, 2010).

This paper will demonstrate HRDL’s capability to perform turbine wake measurements. It will present results on wind flow conditions at the experimental site and wind-turbine wake characteristics, such as velocity deficits and downstream extent of wakes.

2. Test site and instruments

To obtain data on wind flow conditions and wake characteristics of a 2.3 MW Siemens wind turbine, HRDL was deployed to the National Wind Technology Center (NWTC) test site south of Boulder. The NWTC is the premier wind energy research and development facility of the National Renewable Energy Laboratory (NREL), located east of the Rocky Mountains and characterized by a semiarid climate and complex terrain.

Supplementary data were obtained by a profiling Doppler sodar, a Windcube lidar, and an 80-m-tall meteorological tower, instrumented by sonic anemometers. The wind turbine has an 80 m hub-height, 50-m-long blades. It was also instrumented to measure structural loads and operational parameters. The turbine was operating most of the time during the experiment with several short shut-down periods for turbine maintenance.

In the following we focus on the HRDL scanning strategy and show examples on wind flow and wake characteristics obtained during the pilot study, collaboration among NOAA, the Cooperative Institute for Research in the Environmental Sciences, the University of Colorado and NREL. This short-time experiment was followed by a larger, DOE sponsored experiment – the Turbine Wake and Inflow

Characterization Study (TWICS).

2.1 HRDL measurements

HRDL transmits a pulse of 2-µm infrared radiation at a pulse repetition frequency of 200 Hz, velocity precision about 10 cm s^{-1}, and range-gate resolution of 30 m. From its location it is able to measure simultaneously the background inflow and the magnitude and structure of the velocity deficits downstream. These measurements extend from near the surface up to several hundred meters aloft. Such above-surface measurements have traditionally been very difficult to obtain by other means.

HRDL operations during the experiment were occasionally interrupted by heavy rain, weak wind speeds, below turbine cut-in winds, or during unfavorable wind directions. The 'favorable' wind directions to observe turbine wakes in the line-of-sight (LOS) velocity measurements are prevailing westerly winds from about 290°, frequently funneled through the Eldorado Canyon. Measurements were taken for a wide range of wind speeds and under different stability conditions of the boundary layer (BL). Survey scans were performed over 7-min every 30 min to obtain profiles of mean wind speed, direction, and turbulence.

The lidar was sited 891 m from the wind turbine. The scanner was located on the roof of the mobile platform (seatainer) at ~3 m above the ground. With this HRDL-turbine siting geometry, the lidar beam hits the turbine hub at an elevation angle of 4° and at an azimuth angle of 130.55°.

The lidar's ability to scan at a constant azimuth or elevation angle was used to provide high resolution information on wind flow both in the horizontal and vertical plane of the atmosphere. Azimuth scanning, also called conical or Plan-Position Indicator (PPI) scans, produces cones of data that at the lowest elevation angles can provide near-surface wind data. Elevation scanning, also called vertical-slice or Range-Height Indicator (RHI) scans, produce vertical slices of atmospheric flow features.

The scanning strategy, developed for simultaneous measurements of upstream and downstream flow associated with the wind turbine operations, includes sequences of vertical-slice, conical, and low-elevation sector scans—conical scans performed over a narrow azimuth range. An example of a vertical-slice scan, performed with maximum elevation angle of 12°, shows measurements of up to 6 km from the lidar on Figure 1. The LOS velocity is scaled from 0 to 8 m s^{-1}. A velocity deficit of 4 m s^{-1} can be seen just behind the wind turbine as a green color area extending more than 5 rotor diameters downstream.

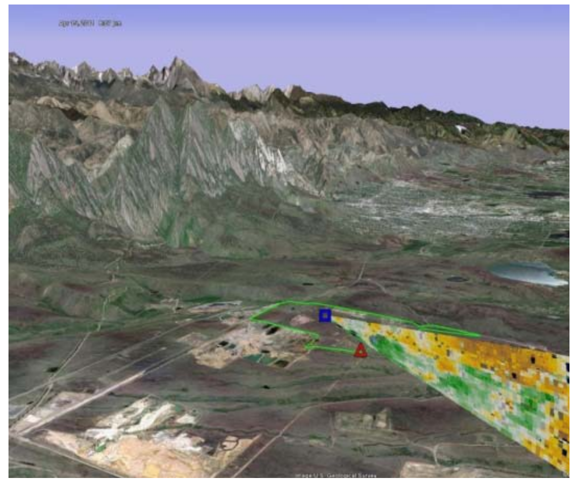

Figure 1. A vertical-slice scan, performed at 1° to the north of the azimuth to the turbine at shallow elevation angles, superimposed on a Google Earth image of the study area. The green line indicates the boundary of the experimental site. Locations of the wind turbine and the HRDL are shown by the red triangle and the blue square respectively.

Details of the velocity reduction behind the wind turbine, observed on April 15 at 0547 UTC are illustrated on Figure 2. Two vertical-slice scans were performed with the elevation of laser beam from -1° to 12° and at azimuth angles of 130° (left) and 131° (right) A velocity deficit of 6-7 m s^{-1} downstream of the wind turbine persists for more than 5 rotor diameters and expands from the top of turbine almost to the ground.

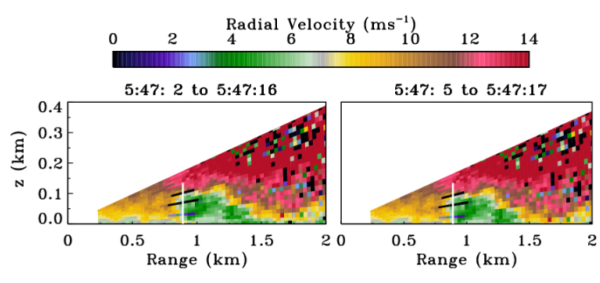

Figure 2. Vertical-slice scans, performed 0.5 degree off the HRDL/turbine direction, illustrate velocity deficit downstream of the wind turbine, as shown on the plot by white vertical line. The horizontal axis is the distance from the lidar.

Profiles from the half-hourly survey scans were combined into time-height cross sections as shown in Figure 3. Time is shown in UTC and local MDT (mountain daylight time). In April the difference between MDT and UTC is 6 hr. Sunrise was at 0625 MDT and sunset at 1937 MDT.

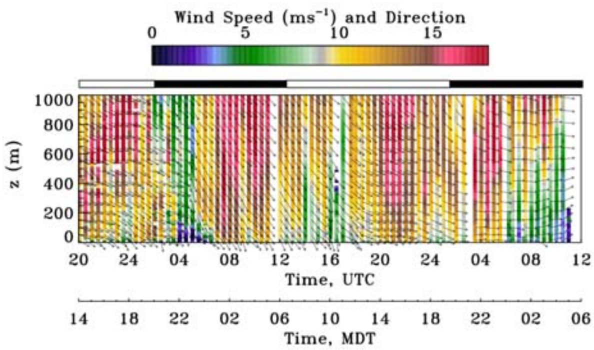

Figure 3. Time-height cross section of mean wind speed and wind direction. Horizontal axis is hour UTC and MDT. Wind speed is color coded from 0 to 18 m s^{-1}, and wind direction is shown by black arrows. The bar below the color scale shows local daytime (white) and nighttime (black) hours.

Frequent occurrences of the Low-Level Jet (LLJ) are evident during both daytime and nighttime hours, with a wind maximum at 400-600 above the ground. A broad span of wind speeds from almost 0 to 15 m s^{-1} was observed during both local nighttime and daytime hours with a predominant north-westerly wind direction most of the time changing to southwesterly by the end of the Intensive Observational Period (IOP).

A significant drop in the wind speed (ramp event) was observed around 21-22 MDT on April 14, probably due to a density-current passage. During this period the turbine was not operating due to weak hub-height winds, well below the turbine cut-in winds.

3. Preliminary results on wakes

The result of this project was a dataset consisting of images of the momentum fields and quantitative data on the strength of the upstream and downstream winds, from which magnitudes and persistence of the changes in wind speed due to the turbines was determined for a range of daytime and nighttime meteorological conditions.

Figure 4 shows sector scans performed on April 15 at azimuth angles of 113°-142° and elevations of 3° (left) and 3.5° (right). The two scans in the top panel were performed at 0554:23 and 0555:42 UTC, when westerly winds were about 8 m s^{-1}. The two bottom panels show scans

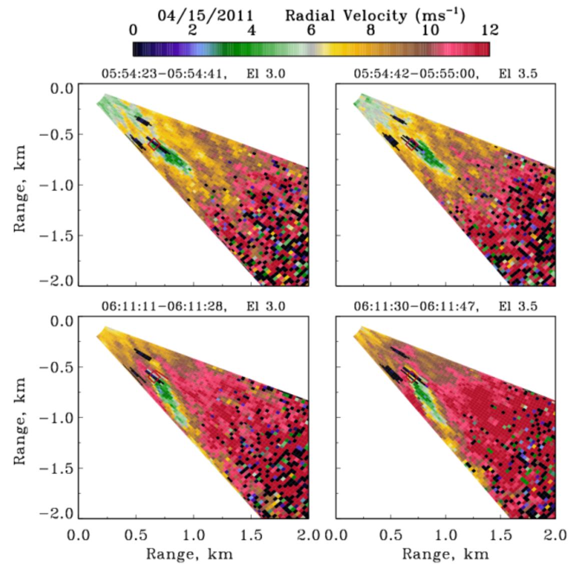

Figure 4 Sector scans performed at 3° (left) and 3.5° (right) elevation and within range of azimuth angles of 112°-145°. Horizontal and vertical axes are distance from lidar in km. Wind speed is color coded from 0 to 12 m s^{-1}.

performed 15-min later, when stronger winds shifted to a more northerly direction and mean winds increased to 10 m s^{-1}. Velocity deficits of 4-5 m s^{-1} can be seen on all plots as a green area extending up to 500-600 m downstream of the turbine (shown on all plots as a red square).

An example of an analysis of wind-flow details obtained from such scans is shown on Figures 5 and 6.

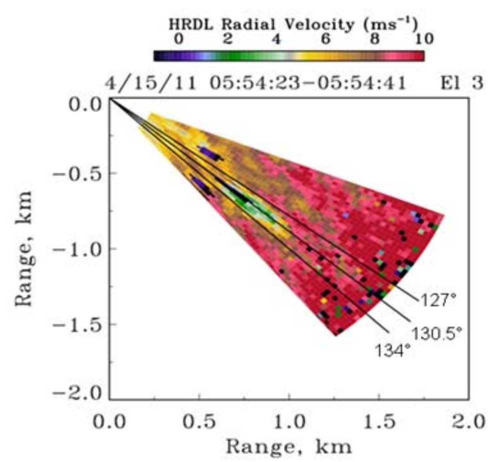

Figure 5 Enlarged and annotated sector scan of Fig. 4 (left, top). Solid lines indicate range of azimuth angles (127°-134°), and azimuth of a turbine location (130.5°).

Horizontal velocity, plotted as a function of the distance from the lidar, is shown on Figure 6 for several azimuth angles as indicated on Figure 5.

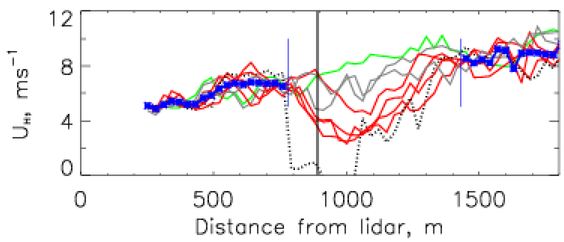

Figure 6 Propagation of the horizontal velocity, measured along several azimuth angles azimuth as indicated on Fig. 5. The horizontal axis is the distance from the lidar.The black solid line indicates the location of the wind turbine at 130.5° and 891 m from the HRDL.

Different colors on this plot indicate the horizontal velocity as a function of distance from HRDL along several azimuth angles ranging from 127° to 134°.The green line on this plot shows free-stream flow at 127° azimuth; two gray lines indicate slightly disturbed flow at 128° and 134°. Winds during wakes observed at (129°,130°, 132°, and 133°), are shown in red. Black dotted line shows velocity at 131°, when the lidar beam hits the turbine. Blue lines with asterisks are mean winds, averaged over all azimuths at each range gate before and after the wake. The eyeball estimated length of the wakes is shown by two vertical blue lines at 780 – 1400 m with velocity deficit of 2-4 m s^{-1} compared with the free stream.

Summary

Results obtained show the ability of HRDL to provide continuous information about the vertical and horizontal structure of flow features and turbulence produced by operational wind turbine. It has been shown that HRDL is a powerful tool for wind-energy research, which will help to understand wake effects as necessary to optimize distances between turbines in wind farms and to improve modeling of wind turbine wakes for single turbines, as well as for wind farms. A scanning technique for wake capturing both in the horizontal and vertical directions has been developed. We plan a detailed analysis of these measurements for different boundary-layer conditions during daytime and nighttime hours. A comparison of HRDL data with measurements obtained by other instruments during the experiment is underway. Furthermore, the integration of turbine inflow and wake observations from a 2-micron lidar into a wind energy forecasting model is planned.

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