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# Measurement procedures for characterization of wind turbine wakes with scanning Doppler wind LiDARs

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**Abstract.** The wake flow produced from an Enercon E-70 wind turbine is investigated through three scanning Doppler wind LiDARs. One LiDAR is deployed upwind to characterize the incoming wind, while the other two LiDARs are located downstream to carry out wake measurements. The main challenge in performing measurements of wind turbine wakes is represented by the varying wind conditions, and by the consequent adjustments of the turbine yaw angle needed to maximize power production. Consequently, taking into account possible variations of the relative position between the LiDAR measurement volume and wake location, different measuring techniques were carried out in order to perform 2-D and 3-D characterizations of the mean wake velocity field. However, larger measurement volumes and higher spatial resolution require longer sampling periods; thus, to investigate wake turbulence tests were also performed by staring the LiDAR laser beam over fixed directions and with the maximum sampling frequency. The characterization of the wake recovery along the downwind direction is performed. Moreover, wake turbulence peaks are detected at turbine top-tip height, which can represent increased fatigue loads for downstream wind turbines within a wind farm.

## 1 Introduction

The evaluation of wind turbine performance, and design and optimization of wind farms are typically performed through a synergistical interaction of different tools. Indeed, results obtained from basic analytical models are compared to the ones of CFD numerical simulations of the wake flow produced from wind turbines, or to wind tunnel tests of down-scaled wind turbine models. However, all these tools need to be assessed through field measurements of wakes produced by real wind turbines. Current industry standards for field measurements in wind energy consist in tests preformed with instrumented masts, which could be insufficient for the characterization of wind turbine wakes, because of the limited number of measurement locations. Therefore, in order to investigate over larger measurement volumes, the use of remote sensing techniques is growing rapidly, in particular Doppler wind Light Detection and Ranging (LiDAR). Wind turbine wake measurements can be performed with ground-based LiDARs, as for Iungo et al. (2013) and for the present work, or through nacelle-mounted LiDARs in order to keep the instrument always aligned with the mean wind direction for varying wind conditions (Bingöl et al., 2010; Trujillo et al., 2011).

A Doppler wind LiDAR measures wind velocity through the evaluation of the Doppler shift undergone by a laser beam emitted into the atmosphere and back-scattered due to the presence of aerosol. Therefore, a Doppler wind LiDAR is only sensitive to the wind component parallel to the laser beam, the so-called radial velocity or line-of-sight velocity. LiDAR tests can be performed by staring the laser beam at a fixed direction, i.e. producing 1-D velocity profiles carried out with the maximum sampling frequency. These tests can be useful for the characterization of wake turbulence. 2-D measurements with a longer sampling period can be performed over vertical planes, denoted as Range Height Indicator (RHI) scans, or over conical surfaces, denoted as Plan Position Indicator (PPI) scans (see Käsler et al., 2010). 3-D scans can be also performed as a combination of consecutive RHI or PPI scans. Multi-component wake velocity field

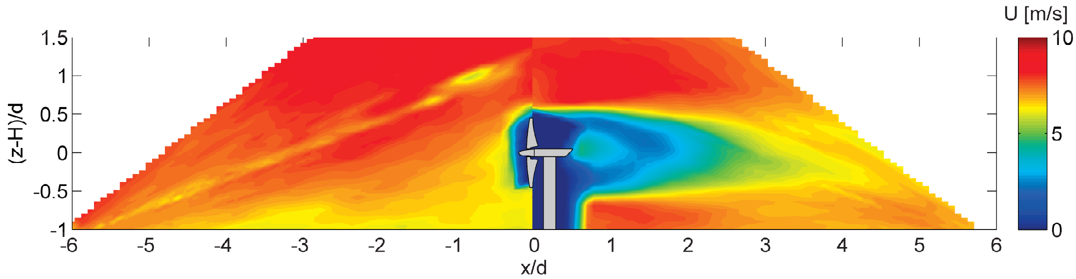


**Figure 1.** Velocity field measured over the wake vertical symmetry plane through simultaneous RHI scans with two LiDARs.

can be retrieved by simultaneously staring different LiDARs at the same measurement volume, see Mann et al. (2012) and Iungo et al. (2013). A review on remote sensing techniques for wind energy applications is reported in Emeis et al. (2007).

The paper is organized as follows: the wind turbine site and the experimental setup are described in Sect. 2, whereas the used LiDAR measurement techniques are reported in Sect. 3. Finally, conclusions are drawn in Sect. 4.

## 2 Wind turbine site and experimental setup

The presented LiDAR measurements were performed in June 2012. The tested wind turbine is a pitch-regulated 2.3 MW Enercon E-70, located in Collonges, Switzerland, in the central part of a narrow valley. The turbine rotor diameter, $d$, is 71 m, while hub height, $H$, is 98 m.

Three Streamline Doppler wind LiDARs, produced by Halo Photonics, were used for this campaign. The LiDAR laser is characterized by a wavelength of 15 µm and a pulse repetition rate of 15 kHz. The highest spatial resolution is 18 m, with the first measurement point at a distance of 40 m from the LiDAR location, and maximum range of 3 km. The maximum sampling frequency available to obtain a single velocity profile along the direction of the laser beam is 0.77 Hz.

The wind turbine location, the LiDAR locations and azimuthal displacements of the LiDAR laser beams were evaluated through a GPS system. The used reference frame has its origin at the the base of the turbine tower. The x-axis corresponds to the mean wind direction, positive in the downstream direction. The z-axis is along the vertical direction, positive from the bottom to the top, while the y-axis is along the spanwise direction. Throughout this paper the approximated streamwise velocity is always reported, which is the projection of the measured line-of-sight velocity on the $x$ direction. This calculation is performed by considering geometrical relations that take location, azimuthal and elevation angles of the LiDAR into account (Machefaux et al., 2012). More details about the site, the LiDARs and the setup can be found in Iungo et al. (2013).

## 3 LiDAR measurements

The first LiDAR measurement technique described in the present paper is the simultaneous RHI performed with two LiDARs over the vertical symmetry plane of the wind turbine wake. One LiDAR was located upwind at $x/d = -6$ and a second LiDAR at $x/d = 6$. The two LiDARs measured simultaneously by varying the elevation angle of the laser beams from 1° up to 38° with an angular step of 1°. The sampling period required for a single RHI scan was 77 s, and 30 consecutive scans were performed with roughly constant mean wind conditions.

The mean velocity field obtained as average of all the selected RHI scans is reported in Fig. 1. Velocity values reported for the locations upwind to the wind turbine position, i.e. with $x/d < 0$, are obtained from the LiDAR located upwind at $x/d = -6$. Conversely, the wake velocity measurements for $x/d > 0$ were performed by the downwind LiDAR at $x/d = 6$. A large error on the velocity measurements is observed for the locations $-0.5 < x/d < 0.5$ and $(z-H)/D < 0.5$, which is due to the back-scattering produced from the wind turbine and affecting wind measurements at those locations.

The vertical heterogeneity of the atmospheric boundary layer (ABL) flow investing the wind turbine is observed, as well as the wake flow produced from the wind turbine. The typical velocity deficit induced by the blade rotation, which is strictly connected to the power production, is clearly detected. Moving downstream the wake recovers, and the velocity deficit is reduced.

More quantitative information can be gained if the vertical profiles of the velocity field are extracted, as reported in Fig. 2. For instance, the vertical profile of the incoming wind, evaluated for the location $x/d = -2$, clearly represents an ABL flow. This velocity profile is fitted through a power law with an exponent of 1.085, which is typical for neutral stability conditions of the ABL. The LiDAR measurements performed within the wake confirm the typical velocity profiles of wind turbine wakes, which have been observed through wind tunnel tests (e.g. Chamorro and Porté-Agel, 2010) and numerical simulations (e.g. Wu and Porté-Agel, 2011). The largest velocity deficit is observed in proximity of

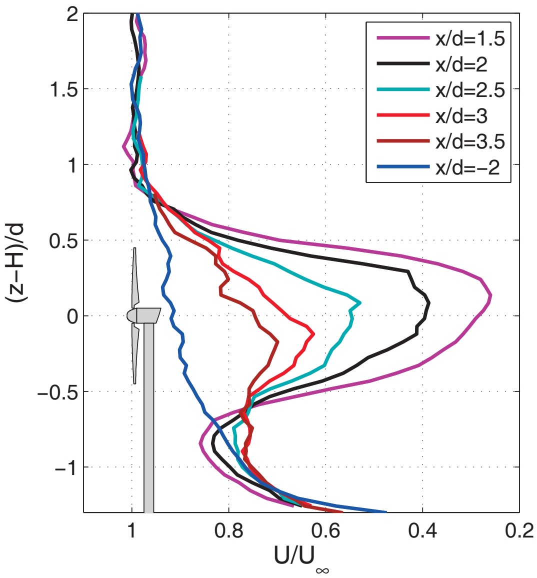


**Figure 2.** Vertical velocity profiles obtained through simultaneous RHI scans.

the hub height, then moving downstream the wake recovers approaching the vertical profile of the incoming ABL flow.

A limitation of the simultaneous RHI technique is that the two LiDARs must be deployed in such a way to perform scans over the wake vertical symmetry plane. Thus, by considering fixed LiDAR locations, this setup can be ensured only for a roughly constant wind direction, and with negligible adjustments of the turbine yaw angle. For the presented test the standard deviation of the wind direction was 0.7°. In case a proper setup is not ensured, RHI scans are performed over planes not parallel to the mean wind direction, thus misleading wake measurements can be carried out.

To overcome this drawback, wind turbine wake flow can be characterized through simultaneous PPI scans, which are performed with a fixed elevation angle of the LiDAR laser beams and varying the azimuthal angle. By performing PPI scans, variations of the wind direction, thus of the turbine yaw angle, are observed through changes of the wake location. For these tests one LiDAR was located upwind and one LiDAR downwind, both at a streamwise distance of 6 $d$ from the turbine location. The LiDARs measured over an azimuthal range of 16°, centered with the azimuthal location of the wind turbine, and an angular step of 0.5°. The sampling period for each PPI scan was 70 s.

The upwind LiDAR measured with an elevation angle of the laser beam of 15.4°, in order to intersect hub height at the location $x/d = -1$, which is convenient for the characterization of the incoming wind. The downwind LiDAR measured with different elevation angles in order to intersect hub-height at different downstream locations. In Fig. 3 the mean velocity field obtained by scanning the downwind LiDAR at hub-height at the location $x/d = 2$ is reported. This plot was obtained by averaging 30 consecutive PPI scans performed with roughly constant wind conditions. For this tested wind direction, the downwind LiDAR is not aligned with the mean wind direction, but located at the transversal location $y/d = 1$ for logistical reasons.

The wind turbine wake is characterized through the simultaneous PPI scans, as well as the incoming wind. Besides the possibility of performing wake measurements with varying wind direction and turbine yaw angle, the physical interpretation of the wind data obtained through simultaneous PPI scans is not straightforward as for the simultaneous RHI scans. Indeed, each transversal velocity profile, i.e. measurements with a fixed streamwise position $x/d$, corresponds to different heights. In other words, in Fig. 3 velocity variations are due to changes both in streamwise and vertical positions.

To overcome possible issues related to the variability of wind direction and turbine yaw angle, for the RHI scans, or to physical interpretation of the wind data, for the PPI scans, volumetric scans of the wind turbine wake flow field were also performed. These measurements were carried out by varying both elevation and azimuthal angles of the LiDAR laser beam, thus they can be considered as a combination of consecutive PPI or RHI scans. Measurements were performed by varying the azimuthal angle of the laser beam within a range of 20°, centered with the turbine location, and an angular step of 2°. The elevation angle was varied from 2° up to 16° with an angular step of 2°. The measurement volume was chosen big enough to include the wake and considering possible variations of the turbine yaw angle. Consequently, a limited spatial resolution was used, i.e. angular step of 2°, in order to ensure a reasonable sampling period. Each volumetric scan was performed with a sampling period of 220 s, if all the measurements were acquired with one LiDAR; otherwise the sampling period was halved if the measurements were simultaneously carried out with two LiDARs, thus the measurement volume split in two parts. A third LiDAR was used to characterize the incoming wind.

A wake velocity field measured through a volumetric scan is reported in Fig. 4. For this test the LiDAR was deployed at the downstream location $x/d = 12$. Transversal planes are reported for different downstream locations, which enable to characterize cross-sections of the wind turbine wake, in particular its shape, location and wake velocity deficit. It is evident the clarity for the physical interpretation of the wind data obtained through a volumetric scan; however, the significant sampling period required does not enable to investigate possible time variations of the wake and wake turbulence.

To this end, the maximum sampling frequency of 0.77 Hz was achieved by scanning the LiDAR at fixed directions, by setting the laser beam over four different elevation angles, and using 110 gates. Consecutive measurements were performed for a sampling time of 11 min for each tested laser direction. In Fig. 5 vertical profiles of standard deviation show peaks for different elevation angles in correspondence of the turbine top-tip height for downstream distances lower than

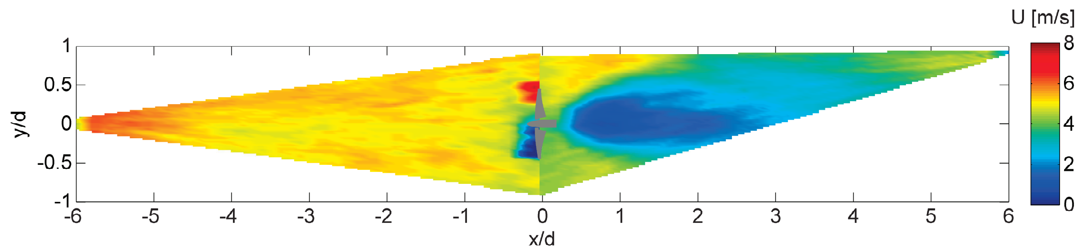


**Figure 3.** Velocity field measured through simultaneous PPI scans.

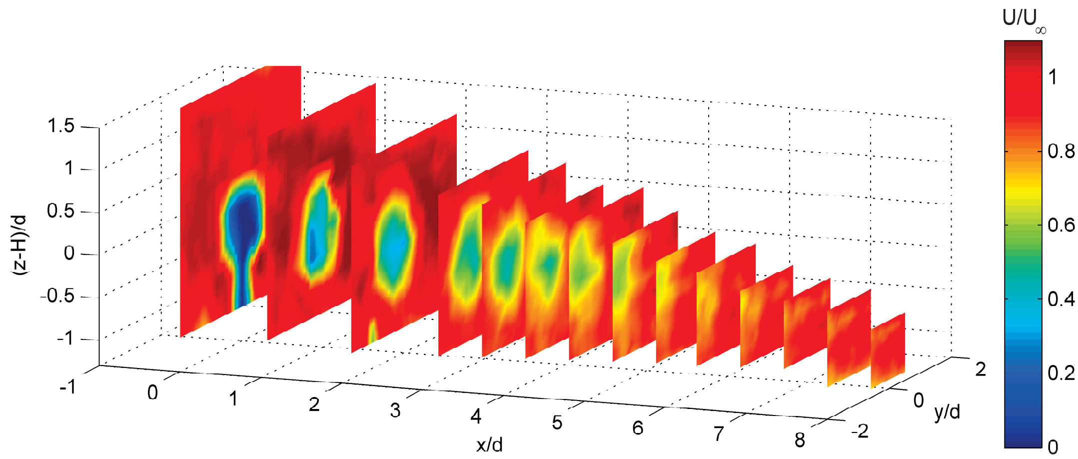


**Figure 4.** Volumetric scan of the wind turbine wake.

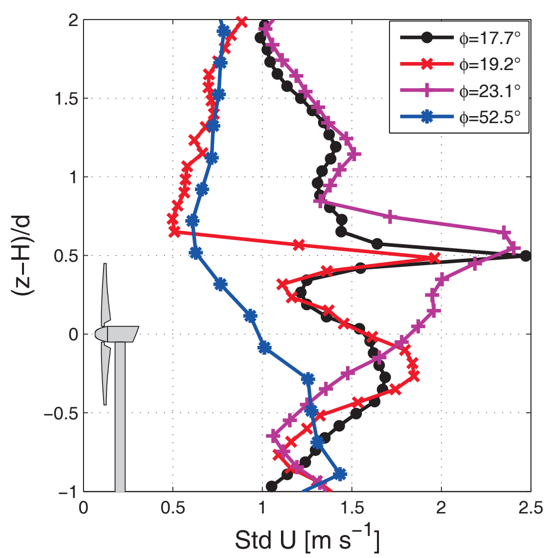


**Figure 5.** Velocity standard deviation obtained by staring a LiDAR with different elevation angles.

5 *d*. This increased turbulence could represent a wake region with an increased turbulence and a hazard for downstream turbines, because of the increased fatigue loads. This wake feature confirms previous results presented in Chamorro and Porté-Agel (2010) and Wu and Porté-Agel (2011) through wind tunnel tests and numerical simulations, respectively.

## 4 Conclusions

Several LiDAR measurement procedures have been presented for the characterization of the wake flow produced from an Enercon E-70 wind turbine. Simultaneous tests were performed with three scanning Doppler wind LiDARs in order to characterize incoming wind and wake flow. The presented measurement techniques are characterized by different size of the measurement volume, spatial resolution and sampling period, depending if they were optimized for the characterization of the mean wake flow or of the wake dynamics. 2-D scans were performed over the wake vertical symmetry plane, in order to characterize the wake recovery, or over conical surfaces to detect variations of the wake position due to changes of the wind direction and turbine yaw angle. 3-D volumetric scans were also performed for a global characterization of the wake flow; however, the significant sampling period required does not enable to investigate wake dynamics. Finally, tests with fixed directions of the LiDAR laser beam were performed with the maximum sampling frequency in order to characterize wake turbulence. Turbulence peaks have been observed in correspondence of the turbine top-tip height, which can represent dangerous fatigue loads for downstream wind turbines within a wind farm.

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