

# Atmospheric turbulence and wind turbine wakes measured with Doppler wind lidar at WiValdi

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**Abstract:** At the WiValdi research wind farm operated by DLR in Krummendeich, we have installed two Doppler wind lidars. One lidar serves as a vertical profiler in the wind farm, providing information about wind and turbulence properties throughout the atmospheric boundary layer. The other lidar is mounted on the nacelle of a wind turbine (WT), which is located upstream of a second WT in the main wind direction. This nacelle lidar has been measuring the wind field behind the rotor that is influenced by the turbine wake since WT operations started in November 2023. The measurement strategy to capture long-term wake behavior involves horizontal plan position indicator scans with three elevation angles and an opening angle of 90°. In addition, an inertial measurement unit on the nacelle aids in determining the impact of WT movement on the nacelle lidar measurements. We will describe the methods used to detect and characterize wakes from nacelle lidar measurements, including data filtering and correction for turbine motion. A particular focus will be on wake decay, which is influenced by atmospheric stability and background turbulence, and can not only be obtained from in-situ observations on measurement masts at WiValdi, but also requires lidar data.

## 1. Introduction

Wind energy has experienced rapid growth, and the efficient utilization of wind energy requires a comprehensive understanding of the atmospheric conditions that determine the operation and performance of wind turbines (WT).

Atmospheric turbulence is a fundamental challenge in the field of wind energy. Turbulence in the atmospheric boundary layer in which WTs operate can significantly affect the behavior of the WTs and lead to fluctuations in power output, increased mechanical loads and decreased turbine lifetime. Furthermore, the wakes generated by the WTs enhance turbulence of WTs downstream and thus affect the performance of the downstream turbines and the overall energy yield of the wind farms.

Traditionally, in-situ measurements aided to the understanding of atmospheric conditions in and around wind farms. Because they only deliver high-frequency data at single points, the usage of Doppler wind lidars has become popular and created opportunities to measure the wind field over large areas with high spatial and temporal resolution. Several studies have demonstrated

the effectiveness of Doppler wind lidar in quantifying turbulence intensity [1], wind shear and wake dynamics both in the horizontal and vertical [2], and for atmospheric profiling [3].

An advantage of Doppler wind lidars for wind energy research is their compactness and the possibility to install them quite flexibly at remote locations such as offshore platforms or on the nacelle of a turbine. In recent years, nacelle-mounted lidars have provided unprecedented insights into characterization of the inflow [4] and wakes of WTs [5-7]. They have the advantage of measuring directly at hub height and are automatically steered into the main wind direction due to the yaw control of the turbine.

We aim to study the effects of atmospheric stability and of background turbulence on the wake characteristics and in particular on the wake decay and wake interaction using data of a nacelle-mounted lidar in the research wind farm WiValdi. In combination with data from a ground-based lidar, a microwave radiometer and in-situ observations from meteorological masts, we aim to improve turbine wake characterization for a variety of atmospheric conditions.

## 2. Methods

The research wind farm WiValdi in North Germany features two utility-scale WTs with a total height of 150 m and a rotor diameter of 116 m. One of them is located in the wake of the other turbine in the main wind direction. This offers a unique possibility to study the impact of WT wakes and their interaction. The two WTs are accompanied by an inflow mast of 150 m height upstream of the turbines and by a set of three measurements mast, the mast array, located between the two WTs (see Figure 1). All masts are equipped with wind-measuring sensors at different heights and the inflow mast (conforming to IEC-61400) additionally with sensors to measure further atmospheric parameters, like temperature, humidity, and rain. From this data, stability and turbulence characteristics of the atmosphere can be determined. In addition, a microwave radiometer yields measurements of stability further east of the two turbines.

We operate two Doppler wind lidars of the type Leosphere Windcube 200s in the wind farm. One serves as a ground-based profiling lidar yielding statistics about wind and turbulence. The other is mounted on the nacelle of the turbine which is in the main wind direction in front of the second WT. The nacelle-mounted lidar measures the wind field behind the rotor which is affected by the WT wake. Plan position indicator (PPI) scans (Table 1) have been performed for our long-term scanning strategy since November 2023 to capture the main wake properties. Three different elevation angles of  $-7^\circ$ ,  $0^\circ$  and  $7^\circ$  are chosen to cover the vertical extent of the wake across the rotor area at 4D downstream. The azimuth angle has a total opening angle of  $90^\circ$  and a resolution of  $2^\circ$ . With this strategy the total time for one complete scan takes about 27 s.

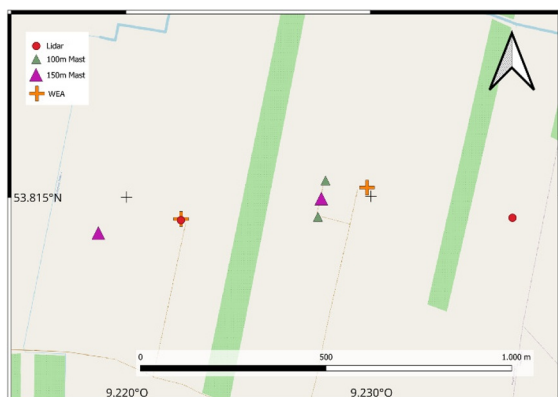


Figure 1. Map of the WiValdi research park.

Table 1. PPI scan settings

Parameter	Value
Physical resolution	50 m
Range gate separation	20 m
Min. range gate	100 m
Max. range gate	4080 m
Azimuth opening angle	$90^\circ$
Elevation angles	$-7, 0, 7^\circ$
Angular resolution	$2^\circ$
Accumulation time	200 ms

To reduce noisy and erroneous measurements, the lidar data is filtered to use only data with CNR values between  $-25$  and  $5$  dBZ. To make the filtering even more robust, a 2D median filter is applied to the CNR values and radial velocities.

A robust algorithm for detecting and describing wakes is essential for investigating wake characteristics under different atmospheric conditions. As has been shown before [8], the horizontal structure of a wake can be described by a Gaussian function (Eqn. 1) in the far wake, where the impact of the rotor is less relevant for the shape of the wake.

$$u(x) = A e^{-\frac{(x-b)^2}{2\sigma^2}} + d \quad (1)$$

$u(x)$  is the function of horizontal wind speeds in dependency of the position  $x$ ,  $A$  the amplitude,  $b$  the maximum position,  $\sigma$  the standard deviation and  $d$  an additional offset.

Closer to the WT, in the near-wake, the rotor shape is important for the structure of the wake and it can typically be approximated by a double Gaussian shape (Eqn. 2).

$$u(x) = A \left[ e^{-\frac{(x-b_1)^2}{2\sigma^2}} + e^{-\frac{(x-b_2)^2}{2\sigma^2}} \right] + d \quad (2)$$

where  $b_1$  and  $b_2$  are the respective center positions and  $\sigma$  is the same standard deviation for both overlapping functions.

For each distance downstream starting at the minimum range gate of 100 m, both functions are fitted to the data to determine the wake center, wake width, and the wind velocity deficit. To decide which function best fits the wake structure, an extra-sum-of-squares F-test is used. For the first distance, the wake center initial guess is set to be at the WT position itself, and for the subsequent distances the wake center from the prior distance is used [9]. The

wake detection stops once the fit to Equations 1 or 2 is impossible or one of the following conditions is met:

- the detected wake center plus wake width is out of bounds of the observed region in x-direction,
- the difference of the wake position of two succeeding wake centers is greater than 3 times the grid distance in x-direction (10 m)
- the amplitude  $A$  is smaller than  $1 \text{ ms}^{-1}$
- $\sigma$  is greater than 2 rotor diameters

Additionally, the first wake detection should be valid close to the WT (200 m), otherwise the whole case is neglected.

In order to determine the effects of the movement of the WT on the lidar measurements, an inertial measurement unit (IMU) is installed on the nacelle. This provides us with measurements of the yaw, pitch and roll angles of the WT.

### 3. Results and Outlook

The collected Doppler wind lidar measurements provide a rich data set for the detailed analysis of atmospheric turbulence and WT wakes. Preliminary analyses show promising insights into the spatio-temporal dynamics of these phenomena.

Our study will involve filtering of the nacelle-mounted lidar data, applying the Gaussian wake algorithm to detect wakes and their characteristics, and retrieving atmospheric characteristics like stability and turbulence from other remote sensing and in-situ measurements at the wind farm. An example of a wake measurement downstream from the nacelle-mounted lidar is displayed in Figure 2. The WT with the lidar are located at the zero point. It shows radial wind speeds on the 13.02.2024 averaged over 30 minutes, with the detected wake center line along with the outer lines indicating the wake width. In this case, the wake could be detected about 17 rotor diameters downstream.

We will then perform an analysis of wake decay under different conditions of atmospheric stability and background turbulence to understand the complex interactions between turbulent flows and WT wakes.

In addition, the IMU measurements will be used to investigate the effects of tower movement on

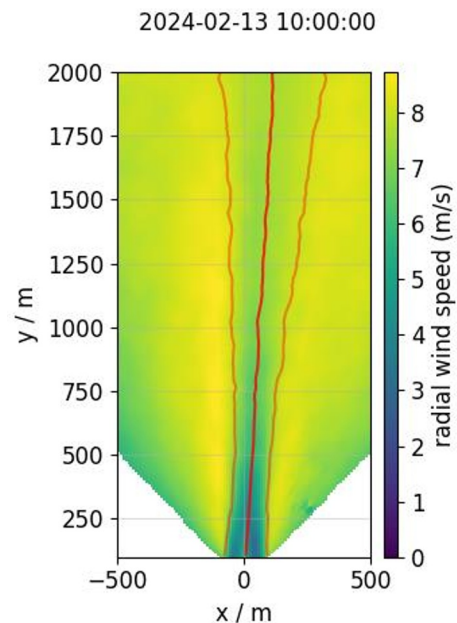


Figure 2. Time-average radial wind speed with wake center line and wake width lines.

the lidar measurements in order to assess the robustness of the measurements and identify possible sources of uncertainty.

### 4. References

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