How much flow information can a turbine-mounted lidar capture?

Anantha Padmanabhan Kidambi Sekar¹, Andreas Rott¹, Marijn Floris van Dooren¹, Martin Kühn¹

ForWind - University of Oldenburg, Institute of Physics, Küpkersweg 70, 26129, Oldenburg, Germany.
E-mail: anantha.kidambi@uni-oldenburg.de

Abstract. Turbine-integrated lidar systems are capable of scanning the wind fields upstream of the turbine, opening up an opportunity to incorporate these measurements into the turbine itself. However, lidar measurements are always subject to uncertainties which are a result of the operating principle of the lidar. In this paper, we investigate and quantify the uncertainties associated with a turbine mounted "SpinnerLidar" in a high fidelity simulation framework. A sensitivity study is performed in order to investigate the effects of the spatio-temporal resolution, probe volume averaging and directional bias and recommendations are given for different lidar applications, e.g. turbulence research, load verification and control. It is seen that the SpinnerLidar in its current state is sufficient as a control input and for load verification studies especially capturing the rotational wind spectra very well. For estimating turbulence, it is better to operate the lidar at a much faster temporal sampling rate.

1. Introduction

In recent years, remote sensing devices such as lidars have been gaining more importance in the field of wind energy. Lidars can be used for multiple purposes such as site assessment and power curve measurement. One of the most promising application of lidars, especially turbine-mounted lidars is to optimise the power production and reduce the turbine loads [1]. However, lidar measurements have sources of uncertainties which negatively impact how well the wind field can be reconstructed. For instance, a lidar device can only measure the wind speed component along the laser beam. In order to estimate a three-dimensional wind vector at a single point, at least three beams are needed. This is known as the cyclops dilemma in literature. Another limitation of accuracy for continuous-wave lidars is the probe length measurement effect. The probe length scales quadratically with the focus distance and hinders the lidars ability to capture small scale turbulent structures at large focus distances [2]. The SpinnerLidar developed by DTU Wind Energy is one of the most advanced scanning lidars available, representing a new quality of measurements with a very high spatio-temporal resolution (maximum 500 points distributed on the spherical measurement plane every second). For advanced wind turbine control and for research of wind turbulence, the lidar has to be able to capture the wind field information and the turbulence scales that are most relevant to the turbine itself. Hence, it is important to quantitatively study how well a turbine-mounted lidar can estimate the wind field, taking into account the limitations of the device. The objective of this paper is to quantify the amount of wind field information that can be measured by performing turbine-mounted SpinnerLidar [3] measurements. For this purpose, the main limitations of a SpinnerLidar i.e. line-of-sight
measurements, probe length averaging and the temporal sampling are investigated with respect to a high resolution wind field obtained from large eddy simulations.

2. Methods

2.1. Large Eddy Simulations (LES)

The LES were performed with the PArallelised Large eddy simulation Model (PALM), a commonly used LES solver for performing simulations of the atmospheric boundary layer. A turbulent unstable atmospheric boundary layer was simulated using the default settings of PALM [4]. For the effects of sub-grid scale turbulence on the resolved scale turbulence, a 1.5th order closure according to [5] is used. The domain size of the simulation was 8188 m by 4092 m by 2048 m with a equidistant grid spacing \( \delta x = \delta y = \delta z = 4 \) m with a temporal resolution of 5 Hz. For obtaining a unstably stratified wind field, a pre-run of 25 hours was performed to let the boundary layer develop and attain stationarity. For the main run, turbulent recycling as specified in [6] was applied at a distance of 3000 m from the inlet. The unstable boundary layer is generated with a roughness length \( z_0 = 0.0175 \) m, surface heat flux 0.023 kgs and a friction velocity \( u^* = 0.52 \) m/s for a total duration of 3700 s which is the total duration chosen for the analysis. The mean wind speed of the inflow at the hub height position of the turbine in the LES field is 10.1 m/s with a turbulence intensity of 11.91%. The NREL 5MW wind turbine with a diameter of 126 m is modelled inside the LES wind field with an actuator line model together in an indirect two-way coupling to generate the turbine induction zone and the wake. Figure 1 (A) shows the averaged \( u \)-component at hub height \( z = 90 \) m where the decrease in wind speed due to the induction zone of the turbine and the wake is clearly visible.

![Figure 1](image)

**Figure 1.** A) The averaged \( u \)-component at hub height extracted from the LES wind field. The black vertical line indicates the position of the turbine. The low velocity regions show the wind turbine wake. (B) Example snapshot of a 1 s SpinnerLidar measurement at an upstream distance of 126 m obtained from the Lidar Simulator (LiXiM).

2.2. The SpinnerLidar and the Lidar Simulator (LiXiM)

The SpinnerLidar [3] is based on the ZephIR 300 continuous-wave Doppler lidar modified with a 2-D scanhead developed by the Technical University of Denmark. The scan head with its two rotating prisms allows the laser beam to be moved in space and measure the line-of-sight velocities on a 2-D spherical surface with a cone apex angle of 30° and a very high spatial and temporal resolution up to 500 points on the spherical surface with a rosette trajectory with a 1 s update time. The lidar simulator LiXiM [7, 8] is capable of simulating the kinematics of the SpinnerLidar and uses a model for describing the physics behind the lidar measurement principle including the volume average and the line-of-sight projection. Figure 1 (B) shows a typical snapshot of the simulated measurements with LiXiM. During the simulations its assumed...
that the turbine is aligned with the inflow, the lidar simulator performs snapshot measurements and interpolates between the grid points and that it has no pointing measurement uncertainties. The simulator allows the user to have complete control over the lidar device and its scanning properties making it possible to run multiple scanning scenarios. Datasets with varying upstream focus distances, opening angles and sampling rates, which are simulated for this study, are enumerated in the next section. For this study, the SpinnerLidar is set to measure 312 points every rosette scan. Figure 2 (A) shows a scatter plot of the LES longitudinal component at a distance of 126 m in front of the turbine on the rotor axis against the \( v_{\text{los}} \) measurement of the SpinnerLidar at the same point sampled at 5 Hz. An \( R^2 \) coefficient of 0.98 and an offset of 0.03 m/s, attributed to the probe averaging effect and the LiXiM interpolating between the LES grid points, indicates that the LES and the LiXiM simulations are correctly coupled to each other.

\[
\begin{align*}
\text{LES U (m/s)} & \quad \text{LiXiM v}_{\text{los}} \quad (\text{m/s}) \vphantom{10^0} \\
& \quad R^2=0.98 \quad N = 18498
\end{align*}
\]

(B)

Figure 2. A) Scatter plot between the LES \( u \)-component at a distance of 126 m in front of the turbine on the rotor axis against the \( v_{\text{los}} \) measurement of the SpinnerLidar at the same point. B) Visualization of the different scanning scenarios used for the study. The dotted lines indicate the area covered by the rotor, the black vertical lines show the different focus distances and the colored lines illustrate the different prism angles of the SpinnerLidar respectively.

2.3. Datasets
To study the sensitivity of the SpinnerLidar with respect to the line-of-sight velocities, volume averaging and spatio-temporal limitations, the lidar simulator is used to generate datasets with different lidar properties. These cases include changes in the upstream focus distance \( f \), sampling rate \( F_s \) and scan opening angle to quantitatively calculate the differences between the reference LES simulations and the SpinnerLidar simulations. The lidar simulations were performed at upstream distances of 30 m, 60 m, 90 m, 126 m, 150 m corresponding to 0.23, 0.48, 0.7, 1.0 and 1.2 turbine diameters. In order to quantify the effect of the opening angle, simulations are carried out by varying the opening angle of the SpinnerLidar at the above mentioned focus distances. The performance of the SpinnerLidar is investigated for prism angles of 5\(^\circ\), 10\(^\circ\), 15\(^\circ\), 20\(^\circ\), 22.5\(^\circ\). The maximum laser beam deflection that can be obtained by the SpinnerLidar is \( \pm 2 \theta_{\text{prism}} \) which means that a SpinnerLidar operating with a 5\(^\circ\) prism angle will have a maximum beam deflection of \( \pm 10^\circ \). The measurements performed with an opening angle of 15\(^\circ\) and a temporal sampling rate of 1 Hz correspond to the fixed operation of the existing SpinnerLidar system, which cannot be modified during normal operation. The total measurement set-up is summarised in Table 1 and illustrated in Figure 2 (B).
Table 1. Settings of the simulated SpinnerLidar measurements. The last row contains the operational parameters of the normal SpinnerLidar.

3. Results
The temporal sampling, $v_{los}$ measurements and probe length averaging limitations of the SpinnerLidar are investigated based on their relevance for turbine control and turbulence estimation and are compared with the reference wind field. For consistency, we define the results of the SpinnerLidar simulations with the volume averaging effect as a probe measurement and the simulations without it as a point measurement henceforth.

3.1. Effect of sampling rate: First order moments of the time series

To analyse the influence of the sampling rate on the one point statistics of the measurements, Figure 3 shows the first four standardized statistical moments of the time series calculated from a point located on the rotor axis at different upstream distances. The effect of the induction
zone is visible in the plot of the mean wind speed, marked by a decrease in speed towards the
turbine located at focus distance $f = 0$ m. There is no influence on the mean value neither
due to the sampling rate nor the probe effect. The difference between the LES 5 Hz curve and
the SpinnerLidar can be attributed to the interpolation carried out by the LiXiM simulator. 
The Euclidean distance between the LES grid point and the closest lidar point chosen for the
analysis is 2 m. Hence, this interpolation can be attributed as an artefact of the lidar simulator.
The influence of the low-pass filtering caused by the probe length effect is clear on the variance
plot, with the SpinnerLidar measuring a lower variance at higher focus distances in comparison
to the point measurements, which follow the trend of the LES results from the same location.
The effect of sampling rate on the skewness hints that for lower sampling rates, the velocity
distribution becomes more left-leaning compared to the reference measurements with this trend
increasing towards higher focus distances. Due to the small scale fluctuations being filtered, the
distribution is pushed more to the right. The shape of the distribution (defined by the kurtosis)
is highly dependant on the sampling rate with an increasing trend towards larger focus distances
with the kurtosis being over-predicted for a lower sampling rate. It is very interesting to note
that for the kurtosis, the sampling rate of the SpinnerLidar has a higher influence than the probe
averaging effect as shown by the point lidar measurements.

3.2. Kinetic energy loss due to probe length averaging

Due to the low-pass filtering effect, the SpinnerLidar is unable to capture all of the turbulent
kinetic energy present in the wind. In order to quantify this effect, we isolate the probe averaging
effect of the SpinnerLidar by taking a point at the center of the Rosette trajectory ([9]) and
comparing the time series at this location with its corresponding ideal point measurement at
different focus distances (Figure 4, (A)). At shorter focus distances (until $f \approx 60$ m), the effect
of probe averaging is absent due to the probe volume being smaller than the grid size $\delta x$.
With larger focus distances, the low-pass filtering effect of the SpinnerLidar can be clearly observed
in the time series of the probe measurements becoming smoother than the point measurements.
To quantify the total kinetic energy that is captured by a SpinnerLidar as function of focus
distance, the ratio of total signal kinetic energy between the probe and the corresponding point

![Figure 4](image-url)
measurement obtained by integrating the area under the turbulent spectrum for the total 3700 s duration is shown in Figure 4 (B). The blue region indicates the unresolved measurements due to the grid spacing of 4 m being smaller than the probe volume. The total kinetic energy that is not detectable due to the probe length effect is inversely proportional to the focus distance (and hence the probe volume) with a Pearson coefficient of $\rho(\text{KE}, 2\Gamma) = -0.997$. At $f = 126$ m, which is equivalent to scanning one turbine diameter ahead, approximately 5% of the kinetic energy is lost.

3.3. Effect of directional bias

A single lidar is only capable of measuring the wind velocity projected on its radial beam direction. Hence, a single lidar device is incapable of measuring a 3-D wind velocity at a point without making assumptions about the flow itself [10, 11]. For turbine-mounted inflow sensing lidars, the assumption that the line-of-sight speed is the longitudinal $u$-component can be valid as the magnitude of the cross-wind components are quite low, i.e. $u \gg v, w$. However, the pointing error due to the deflection of the laser beam relative to the position of the lidar and the inflow should be taken into account. To quantify the error of the directional bias, the line-of-sight velocity measured by the SpinnerLidar is given by:

$$v_{\text{los}} = \cos \chi \cos \delta u + \sin \chi \cos \delta v + \sin \chi w,$$

where $\chi$ and $\delta$ are the azimuth and elevation angle of the laser beam respectively. By aligning the laser beam into the mean wind direction ensures that the lateral and vertical components disappear ($v, w = 0$), we can write:

$$\hat{u} = \frac{v_{\text{los}}}{\cos \chi \cos \delta},$$

where $\hat{u}$ is the projection estimation of the longitudinal wind speed. Rearranging these equations by substituting Equation (2) in Equation (1), we obtain an error of the longitudinal velocity ($\epsilon_u$) as:

$$\hat{u} - u = \epsilon_u = \tan \chi v + \frac{\tan \delta}{\cos \chi} w.$$  

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**Figure 5.** (A) The variation of the longitudinal error $\epsilon_u$ as a function of the azimuth and elevation angles of the SpinnerLidar for the case $v = w = 1$ m/s in Equation (3). (B) The effect of directional bias which results as a function of the azimuth angle shown for four cases $\chi = 5^\circ$, $13^\circ$, $21^\circ$, $27^\circ$ at a focus distance $f = 126$ m in front of the turbine.
From Equation (3), for a SpinnerLidar perfectly aligned with the inflow measuring on a horizontal line parallel to the rotor axis, the elevation angle is $\delta = 0$. On this horizontal line, the error in estimation of $u$ when the azimuth angle $\chi$ is small and hence the contribution of the cross-wind components to the error is quite low. When $\chi$ increases, the error scales as a function of $\tan \chi$ which is termed as the directional dependence error or bias in the estimation of the longitudinal wind component. Figure 5 (A) illustrates the calculated analytical error $\epsilon_u$ and its gradient as a function of the elevation $\delta$ and azimuth angles $\chi$ by setting $v = w = 1$ m/s in Equation (3). The estimation error lies within $\pm 0.5$ m/s in the $\pm 30^\circ$ opening angles of the normal SpinnerLidar operation. However, this error increases following a tan function. If the instantaneous yaw misalignment $\delta_h$ and up-tilt $\theta$ of the turbine is taken into account, then this error scales with $\tan(\chi + \delta_h)$ and $\tan(\delta + \theta)$, which increase the projection error $\epsilon_u$ at higher opening angles. Figure 5 (B) illustrates the effect of directional dependence as a function of azimuth angle at an upstream distance of 126 m from the LES simulations. For smaller azimuth angles $\chi = 5^\circ$, $13^\circ$, the effect of the directional dependence is barely visible, while at larger azimuth angles $\chi = 21^\circ$, $27^\circ$, the effect of the directional bias is more significant than the probe length averaging.

![Figure 6](image-url)

**Figure 6.** Calculated effective velocities within the induction zone of the projected longitudinal component $u_{proj}$ shown in dotted lines as a function of the upstream measurement focus distance for different prism angles $\theta$. The black line is the effective wind speed calculated based on a circle of 126 m diameter equivalent to the NREL 5 MW turbine from the LES simulation.

We investigated the effect of the opening angle of the SpinnerLidar by performing simulations with a prism deflection angle varying from $5^\circ$ to $22.5^\circ$ and analysed the directional bias on the rotor averaged quantities relevant for turbine control. For this purpose, we calculate the rotor effective wind speed from the SpinnerLidar measurement as $u_{eff}(t) = \frac{1}{n} \sum_{i=1}^{n} u(x_i, t)$, where $n$ is the total number of points measured by the SpinnerLidar and the velocity of the cosine projection with the assumption of zero lateral and vertical component as derived in equation 3. The effective wind speeds, calculated for the longitudinal projected $u$-component as a function of measurement distance for different prism angles, are presented in Figure 6. The impact of directional bias is clearly visible in the effective wind speeds. For $\theta \geq 15^\circ$, the SpinnerLidar measurements at points in the outer section of the scan trajectory have a considerable cross-contamination of the $v$, $w$-component with a corresponding $\cos 2\theta$ factor change in the projection estimation of the wind speed. At large upstream distances and smaller opening angles $f = 126$ m and $\theta = 5^\circ$, $10^\circ$), the projection error is quite low and most of the fluctuations in the rotor plane are captured leading to smaller estimation errors (see figure 2 (B)).
effective velocity from the projected component has almost no error at this upstream distance as all the variations in that plane are captured. Hence, for the calculation of the rotor effective wind speed at upstream distances in the range of the rotor diameter, small opening angles are preferred. Conversely at shorter focus distances, the area scanned with a higher prism angle has a considerable cross-contamination which leads to an error in the estimation of \( u_{\text{eff}} \). As a result, at shorter focus distances, the error in \( u_{\text{eff}} \) estimation reduces with decreasing prism angle.

3.4. Spectral investigation of the probe length effect

Figure 7. (A) Comparison of 5 Hz turbulent spectra of a single point in the direction of the rotor axis between the LES and the lidar simulations at four upstream distances (\( f = 60 \) m, 90 m, 126 m, 150 m). (B) Turbulent spectra in the rotating frame of reference measured by a SpinnerLidar at 1 Hz of the line-of-sight measurements following a point located at 90% of the SpinnerLidar scan radius (wind speed = 10.1 m/s, rotor speed = 11.88 rpm, lidar focus length \( f = 30, 126 \) m).

Figure 7 (A) shows the power spectral densities (PSD) calculated for a single measurement point at upstream distances of 30 m to 126 m in the direction of the rotor axis with (dotted lines) and without (solid lines) the probe length averaging property of the lidar. For the lidar measurements without any probe length averaging effects, the spectra follow the slope of the spectrum from the LES simulations and the \(-\frac{5}{3}\) Kolmogorov slope. The effect of the probe length averaging as a function of the focus distance is clear, especially when considering the drop-off frequency where the lidar measurements start to deviate from the \(-\frac{5}{3}\) slope. As the probe length scales quadratically with the focus distance, the effects of the low-pass filter become more pronounced at larger focus distances and hence the lidar captures less energy at higher frequencies. For instance, at a focus distance of 126 m, which fits well to multi-megawatt turbines, the spectrum already begins to drop off at 0.1 Hz. It is observed that the theoretical cut-off frequency, based on Taylor's hypothesis defined as \( f_{\text{cutoff}} = 0.5 \cdot \frac{u_{\text{mean}}}{2 \Gamma} \), is not a good prediction indicator. This is due to the spatial weighting function of the SpinnerLidar described by a Lorenzian function extending beyond the definition of the probe volume hence filtering out some low frequency components as well.

Figure 7 (B) shows the comparison of the \( v_{\text{los}} \) rotationally sampled spectra of the wind measured by the SpinnerLidar at an upstream distances of 30, 126 m for a sampling rate of 1 Hz with the one generated from the full three-dimensional LES wind field by tracing and following the point
location. The rotational spectra is of great importance for calculating the loads experienced by the blades as they move in a circular pattern through the wind field. Due to the well known rotational sampling effect, also called eddy slicing, turbulent energy is accumulated at integers of the rotor speed frequency denoted as 1P, 2P and so on [12]. In the present case 1P corresponds to 0.198 Hz, since the rotational speed is 11.85 rpm. The SpinnerLidar rotational spectrum is able to capture the turbulent energy at 1P and 2P very well. These observations are remarkable since in the non-rotating spectra shown on Figure 7 (A) the PSD captured at 126 m focus length is diminished by a factor of 10 at 1P (0.2 Hz) and a factor of 100 at 2P (0.4 Hz). It is also observed that the rotational spectra calculated at a upstream position of 30 m also captures the rotor speed harmonics as well. The higher harmonics present in the rotationally sampled LES spectra are not recorded due to the Nyquist sampling limitations. It is also observed that the rotationally sampled \( v_{los} \) spectra contains more energy at lower frequencies below 0.1 Hz compared to the rotationally sampled longitudinal component of the LES wind field. This can be attributed to the cross contamination of the line-of-sight speed by the lateral and vertical wind speed components which occur due to the beam opening angle of approximately 30\(^\circ\) with respect to the rotor axis for the SpinnerLidar in its normal operational mode.

4. Discussion

The effect of the temporal sampling limitations, probe volume averaging and directional bias effects are investigated for a turbine-mounted SpinnerLidar based on lidar simulations in an LES field. Figure 3 reveals that for the calculation of single point statistics of a time series of velocity measurements from SpinnerLidar, the sampling rate is important to reduce the uncertainty of turbulence estimates. The mean wind speed is independent of the sampling rate and the probe effect averaging while its variance is slightly influenced by the sampling rate, as the larger probe volume at further focus distances causes an under-prediction of variance. The skewness and the kurtosis are highly dependant on the sampling rate and the total amount of samples, as exemplified by the skewness \( \gamma_1 \) of the distribution becoming more left leaning for a lower sampling rate of 1 Hz. The kurtosis of the signal becomes positive-excess with a lower sampling rate, indicating that the distribution has a heavier tail with more outlier values. At larger focus distances, the kurtosis is influenced more by the sampling rate than the probe length averaging effect which is indicated by the difference between the dotted and the solid lines (see Figure 3). As revealed in Figure 4 (A), the probe length averaging effect plays the role of a low-pass filter at larger focus distances causing the high frequency components in the measurement to be reduced. The amount of kinetic energy that is not measured by the lidar as a result of the probe length averaging effect is perfectly anti-correlated to the focus distance (see Figure 4 (B)), with an energy loss of approximately 5 % at a focus distance of 126 m. As a result, the amount of signal turbulent kinetic energy that is lost due to the probe length effect of the lidar can be calculated if the properties of the laser are known. Figure 5 (A) shows the error estimation as a function of the azimuth and elevation angles of the SpinnerLidar. It is estimated that the error associated with projecting the longitudinal component will exceed more than \( \pm 0.5 \) m/s when the pointing angle exceeds 20\(^\circ\). This effect is more pronounced when the turbine is operated at a yaw misalignment or an up-tilt (see Equation (3)). From figure 5 (B), it can be concluded that even at larger focus distances, the effect of directional bias dominates over the probe averaging effect. Even though smaller opening angles typically exhibit smaller projection errors, they are unable to capture a rotor effective wind field parameter which is more relevant from a control perspective.

The spectral analysis in Figure 7 points out the dominant effect of probe volume averaging when measurements in a non-rotating frame of reference are performed with long focus lengths beyond 100 m with the captured turbulence spectrum dropping off already at frequencies above 0.1 Hz. The dynamic loading of wind turbine blades which is dominated by the accumulation of turbulent...
energy at multiples of the rotational frequency is captured quite well by the SpinnerLidar especially the 1P and 2P peaks. This impact of the turbulent wind field on the rotor at typical 1P and 2P frequencies, occurring below approx. 0.5 Hz, can be sensed with high accuracy for focus length beyond 100 m even when the SpinnerLidar is operated at a sampling frequency of 1 Hz due to the high spatial resolution which enables the lidar to capture the shear and the spatial variations in the inflow.

5. Conclusions
A comparative sensitivity study is made where the three major causes of lidar uncertainties and limitations of the SpinnerLidar are studied in detail and quantified in comparison to high fidelity simulations. For a turbine mounted lidar, the overall purpose of the measurements, for instance either as an input to a controller or for load analysis or as a device to measure turbulence ultimately decides its operating parameters. For turbine control, the lidar can be operated at a lower spatio-temporal resolution while operating with smaller prism angles in order to avoid cross contamination from the $v$ and $w$ components. For turbulence research, it is beneficial to operate the lidar at higher sampling rates. For instance, the mean wind speed is sufficient as control input and this is already captured very well by the current SpinnerLidar temporal sampling at 1 Hz. For load verification, where the variance in the wind field plays a major role, a sampling rate of 1 Hz is sufficient. However, when resolving turbulence, it is beneficial to operate the lidar with a higher sampling rate. Investigations of spatio-temporal characteristics of turbulent wind fields in a fixed frame of reference, e.g. done with the lidar mounted on the nacelle or on a met mast, should be executed only at a shorter focus length of 30 m to 50 m. In contrast, the SpinnerLidar performs very well in the rotating frame of reference, i.e. when mounted in the rotating hub of wind turbine. For turbine control, it is beneficial to measure further away in the order of one turbine diameter and have minimal prism deflection angles to avoid cross-contamination of the measurements. The effect of wind evolution which then plays a major role in the uncertainty will be investigated in the future. Simulations using different wind conditions must be performed to test the sensitivity of the lidar to different stability, wind speed and turbulence intensity scenarios.

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References
[1] Simley E, Fürst H, Haizmann F and Schlipf D 2018 Remote Sensing 10 863
[2] Sjöholm M, Mikkelsen T, Mann J, Enevoldsen K and Courtney M 2009 Meteorologische Zeitschrift 18 281–287
[3] Mikkelsen T, Angelou N, Hansen K, Sjöholm M, Harris M, Slinger C, Hadley P, Scullion R, Ellis G and Vives G 2013 Wind Energy 16 625–643
[4] Maronga B, Gryschka M, Heinze R, Hoffmann F, Kanani-Sühring F, Keck M, Ketelsen K, Letzel M O, Sühring M and Raasch S 2015 Geoscientific Model Development 8 2515–2551
[5] Deardorff J W 1980 Boundary-Layer Meteorology 18 495–527
[6] Lund T S, Wu X and Squires K D 1998 Journal of Computational Physics 140 233 – 258 ISSN 0021-9991
[7] Beck H and Kühn M 2019 Remote Sensing 11 ISSN 2072-4292
[8] Trabucchi D 2019 Lidar measurements and engineering modelling of wind turbine wakes Ph.D. thesis Submitted to: Carl von Ossietzky Universität Oldenburg
[9] Herges T G, Maniaci D C, Naughton B, Hansen K, Sjoholm M, Angelou N and Mikkelsen T 2017 Scanning Lidar Spatial Calibration and Alignment Method for Wind Turbine Wake Characterization
[10] Kapp S and Kuhn M 2014 A five-parameter wind field estimation method based on spherical upwind lidar measurements *Journal of Physics: Conference Series* vol 555 (IOP Publishing) p 012112

[11] Kidambi Sekar A P, van Dooren M F, Mikkelsen T, Sjöholm M, Astrup P and Kühn M 2018 *Journal of Physics: Conference Series* **1037** 052008

[12] Kristensen L and Frandsen S 1982 *Journal of Wind Engineering and Industrial Aerodynamics* **10** 249 – 262 ISSN 0167-6105