Response to Reviewer 1

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Main comments

The authors present an interesting statistical analysis of utility-scale turbine wakes under different and carefully characterized atmospheric conditions. The work is relevant to improving the understanding of wake physics and wind farm modeling and adds some novelty to existing literature. A few minor revisions are recommended to improve readability and rigor.

Thank you for your constructive feedback and helpful suggestions which have improved our manuscript. We particularly appreciate the thoughtful comments on lidar processing and accuracy. In the following, we address the main and specific comments and describe the corresponding modifications to the manuscript.

In Section 3.2, it may be beneficial to add a – in front of A, so that A becomes a positive-definite constant. This would avoid awkward definitions like "the amplitude A is greater than -0.1U" to indicate a shallow wake.

We agree that changing the sign of A adds to comprehension here. We have changed the sign in Eq. 5-7 and adapted the usage in the further text, i.e. for the wake detection termination criterions *"the amplitude A is greater than 0.1U"* and the definition of ΔA *"if $\mu_1 < \mu_2$, then $\Delta A = A_2 - A_1$ otherwise $\Delta A = A_1 - A_2$"*.

In Section 3.1, the lidar filtering process should be expanded and cite previous work (e.g., Beck and Kuhn, 2017).

We added some more explanation and details on the filtering steps, especially on the two-dimensional median filter, we applied. For this filtering, we mainly followed the ideas of Alcayaga, 2020. For a more complete categorisation of the filtering, we also add Beck and Kuhn (2017) to the references.

The possibility that the lidar could have an azimuth offset with respect to the turbine axis should be mentioned. Alternatively, the pointing accuracy of the lidar should be quantified. This is important to ensure that the wake deflection (which is on average 30 m at 4 D or 3.7 degrees) is real. Also, for the asymmetric wake model where the center is a weighted average between the two peak locations, the asymmetry may just induce an apparent deflection if one side of the wake is consistently deeper. This should be discussed as well.

We agree that the wake deflection estimate is susceptible for azimuth offsets of the lidar. Mechanically, the lidar is aligned to the nacelle with very little play in the screwed connection. The optics of the lidar and scanner head inaccuracies can of course lead to offsets. Vasiljevic (2014) determined the pointing accuracy for the scanning head type which is used in our lidar to approximately 0.5° without any further correction, wherein the largest part of the uncertainty is due to the leveling of the lidar. To minimize the error, we performed hard target scans, scanning towards the meteorological masts at the research park after installation of the lidar (see example hard target scan, Fig. 1). The biggest uncertainty in a determination of the pointing direction of the lidar in the wind turbine setup is the uncertainty of the yaw angle of the turbine. With the available sensors

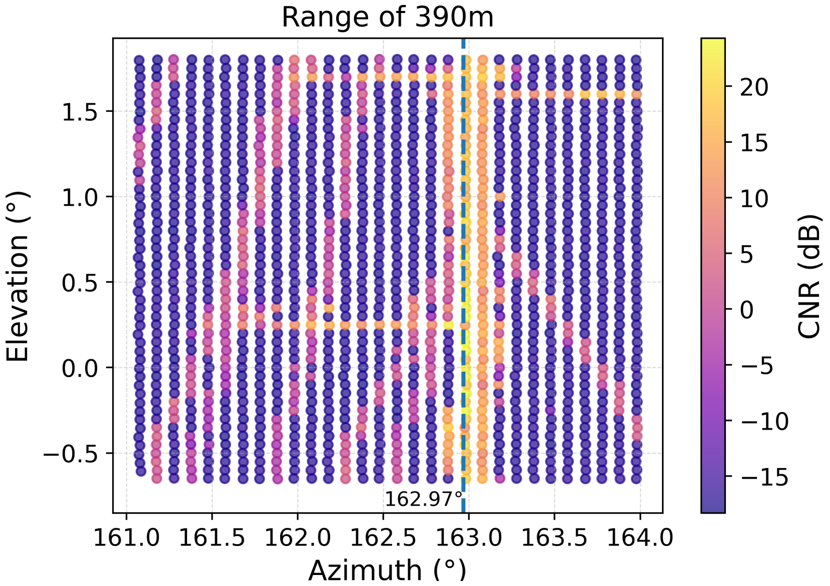

Figure 1: Hard target scan with azimuth and elevation resolution 0.1°. Based on yaw angle of the turbine calculated position of the measurement mast at 162.97° (dashed blue line). High CNR values (CNR≥10 *dB*) illustrate the mast structure itself at 163° azimuth with its booms and slightly lower CNR values (10 *dB*≥ CNR≥-5 *dB*) highlight the guy wires.

at time the dataset was taken, this could only be achieved within approximately 1°. In response to your review, we have now carefully revisited the pointing accuracy during the time frame of the presented dataset using hard target reflections of the masts during operation. This additional analysis helped to implement an average offset which was estimated to 0.3° to the dataset which should further improve the estimates of wake deflection and yaw misalignment (see Fig. 2). It also gives a good estimate of the uncertainty of the pointing direction of the order of 1° which we now mention in the revised manuscript. At $4D$ downstream, such an uncertainty yields an uncertainty of the wake deflection of 8 m, which is substantial, but much smaller than the wake deflection itself, which we thus consider a physical effect and not an artifact of the azimuth offset.

By using the weighted average for the asymmetric wakes, the wake center refers to the centroid of the distribution. Therefore, it is reflecting the asymmetry of the intensity of the wake. We thus agree that parts of the wake deflection are associated to the asymmetry effect and discuss it in the revised manuscript in Sect. 3.2 and 5.1. Further, the impact of asymmetry on wake deflection decreases with downstream distance as the wake resembles a single Gaussian. This is demonstrated in the frequency of best fits to double Gaussian with two amplitudes which is decreasing from 67% of cases at 1 D, 32% at 2 D, 19% at 3 D to 17% at 4 D.

From a more pragmatic standpoint, it should be acknowledged that the near-wake physics, in spite of its scientific interest, is less of a concern for industrial applications, where turbines are spaced significantly further along the prevailing wind directions.

We agree that most spacings between wind turbines in wind farms are further than the near wake distance. However, the industrial interest in the investigation of near wake dynamics and length is at least two-fold: on the one hand, repowering existing onshore wind farms leads to closer relative spacing. Especially in secondary wind directions this does indeed lead to spacings below the minimum defined distance for load calculations. In this case, sector-wise shutdowns have to

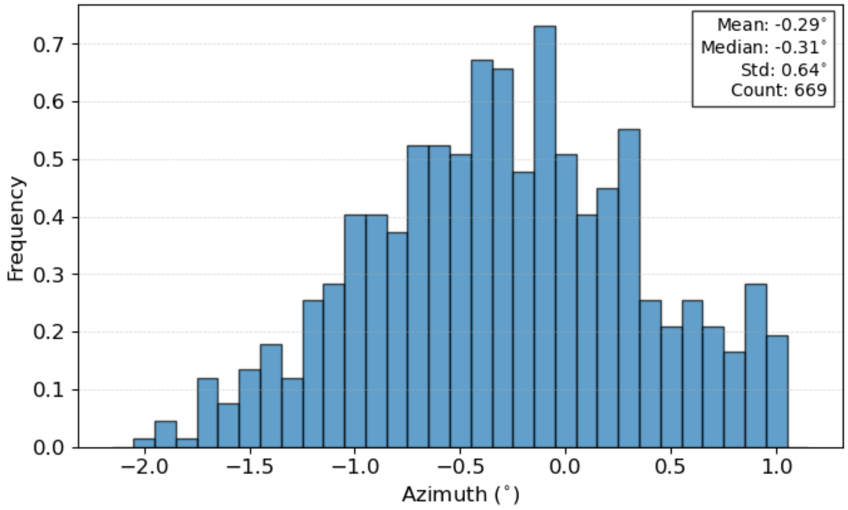

Figure 2: Relative frequency of offset in azimuth angle. The offset is given by the maximum of CNR around the position of the middle measurement mast. The data covers six hours of single lidar scans spread throughout six different time periods from Nov 2023 to June 2024.

be implemented, which has a significant impact on wind farm performance. On the other hand, it has recently been shown that engineering models for the far wake are significantly influenced by a virtual origin that is used in the models and is related to the near wake length Neunaber et al. (2024). That means that engineering models can profit directly from better estimates of near wake length. In the revised manuscript, we will explain these perspectives in the conclusions more explicitly.

Specific comments

- L 28: Please clarify that these are canonical atmospheric conditions and that there are many exceptions (for instance, during low-level jets).

  Thank you for suggesting clarification here. We edited the manuscript to now include *"ABL stability is often described using canonical regimes, although real-world ABL conditions frequently deviate from this idealized state, e.g. during low-level jets or frontal passages."*

- Eq. 3: This approach only includes the part of induction that is converted to power, which will probably cause an underestimation of thrust. Drag from tower, hub, and blade roots all contribute to thrust but not power. Electrical losses cause an underestimation of thrust. Please clarify this point and possibly cite Iungo et al., 2018.

  We appreciate this comment and have revised the manuscript to clarify the limitations of this approach. The thrust estimation solely based on power indeed neglects contributions from non aerodynamic components. We have added more explanation on these effects along Eq. 3 as follows: *"Here, the calculation of* c_T *relies on the induction factor derived from power extraction and does not account for electrical losses or drag from components not contributing to power production, such as the tower, nacelle and blade roots. Consequently,* c_T *may be lower than the turbine's actual aerodynamic loading (Iungo et al., 2018)."*

- L 113: Please explain the implications of measuring inflow quantities at 85 m which is less than hub height.

  Thank you for commenting on this. In the revised manuscript we now give more details on deviations resulting from using 85 m instead of hub height values in Section 2.1. *"Although the height difference of 7 m between the sonic at 85 m and hub height introduces minor discrepancies, the observed wind shear values (mean: 0.029* s^{-1}*, max: 0.086 /s) suggest that the differences in wind speed are small, on the order of 0.203* ms^{-1} *on average and up to 0.602* ms^{-1} *at maximum shear. Similar considerations apply to wind direction, where the mean difference is 0.371° and the maximum difference is 3.465° based on observed veer between 33 m and 149 m."*

- L 146: "The scan ends" is ambiguous, you can say that "the beam are blocked by the ground at 700 m".

  Thank you for pointing that out. We have revised the manuscript to clearly state that the scan range is limited to 700m due to blockage of the beam by the ground.

- L 149: Please specify the duration of the 6,099 periods (27 s? 10 minutes?).

  We thank for asking for clarification here. We refer to the periods here as 10-minute periods in the whole paragraph and adapted this in the text.

- L 152: How are "free-stream atmospheric conditions" defined?

  Thank you for this question. We have changed the terminology to use *"inflow measurements at 2 D upstream"* instead.

- L 170: Please give more details on the data filtering, namely the way the "neighborhood" is defined and the "threshold" for the median deviation.

  As stated in the General comments, we have added more details about the filtering procedure including the description of the "neighborhood", i.e. in total 11 range gates and 5 azimuth angles. The thresholds are set to two standard deviations for CNR and three standard deviations for radial velocities. We have adapted the text as follows: *"For filtering lidar data to improve data quality, several methods have been proposed, e.g. by Krishnamurthy et al. (2012), Beck and Kühn (2017) or Alcayaga (2020). To reduce noisy and erroneous measurements, the nacelle lidar data is filtered to retain only data with carrier-to-noise ratio (CNR) values between -25 and 5 dB. For enhanced robustness, a median filter, similar to Alcayaga (2020) who used a median-like filter on radial velocities, is applied to each individual scan to first CNR values and second radial velocities. Instead of using two one-dimensional moving windows like Alcayaga (2020), we apply two-dimensional windows considering radial and azimuth direction at once. This filter evaluates each data point by computing the median of CNR or radial-velocity values within its local two-dimensional window, which encompasses 11 points in radial direction and 5 points in azimuth direction. Measurements that deviate beyond a predefined threshold from the local median are excluded as outliers. Specifically, for the CNR median filter, the threshold is set to two standard deviations of the CNR values of the scan, while for the radial velocities, the threshold is three standard deviations of the radial velocities of the scan. These thresholds were determined through manual optimization on using a test set of scans, effectively removing hard targets and artifacts while preserving the wind field structures, including wind turbine wakes."*

- L 205: Please provide a reference for the F-test.

We have added a reference to Aitken et al. (2014) to support the application of the F-test.

- L 237: Can this be said more concisely as "when the difference between the centerline and maximum velocity deficit is less than 5%"?

  We agree that the phrasing was unnecessary complicated. We changed the description in the updated manuscript to make it more concise and clear to state: *"Therefore, we introduce an additional criterion for determining the near wake length: the transition occurs where the difference between the wake center and the minimum velocity ratio is less than 5%."*

- Fig. 7: The μ symbol should be introduced earlier. Also, please expand on the effect of the second wake past 4D and how it is smoothed out in these statistics by the quite large wind sector.

  Thank you for this helpful suggestion. The parameter μ has now been introduced earlier, when describing the Gaussian functions and how it is calculated for the different Gaussian forms in Sect. 3.2. Additionally, we have expanded the discussion on Fig. 7 to clarify the smoothing of the OPUS2 wake impact as we are using a wide wind direction sector as follows: *"At this distance, the wakes of the two turbines start to overlap. Though, OPUS2 is not located in the wake of OPUS1 in all cases due to the width of the chosen wind direction sector, i.e. the wakes of the two turbines will not always overlap. Consequently, the effect of OPUS2 wakes on the wake characteristics seen from OPUS1, e.g. on the velocity deficit, is smoothed out. Further downstream of OPUS2 the velocity deficit weakens again."*

- L 273: "The induction zone of the second turbine impacts the wake dynamics of the first turbine additionally" should be removed. There is no wake dynamics provided in this section but only mean quantities. Furthermore, the induction zone is probably too thin for the present lidar and grid resolution to isolate its effect.

  We appreciate this feedback. We removed the statement about the impact of the induction zone of OPUS2. We agree that the lidar resolution may not be fine enough to separate the induction effects, thus we did not discuss it further in the revised version.

- L 302: Please add discussion also of the wake width.

  Thank you for mentioning this. We expanded the discussion to include the correlation of wake width with turbine operating conditions as well which states: *"The wake width exhibits similar correlation patterns as the velocity deficit. σ_w is highest correlated with wind speed and turbine conditions c_T, c_P and λ at 1 D with these correlations diminishing further downstream. The negative correlation between σ_w and U can be explained by the significant reduction in wake width above rated wind speed. Therefore, the positive correlations with c_T, c_P and λ are predominantly caused by the fact that these parameters, like σ_w, decrease above rated power."*

- Fig. 11: Please explain better the legend either in the caption or the section.

  We agree that the figure description lacked some details about the legend. We have now added more explanation in the figure caption (*"Histogram of detected near wake lengths in (a) with stacked bars which colors indicate the choice of the criterion for near wake length determination"*) and referred to the colors of the bars in the text as well for clarification.

- L 415: "wake tilt" may be mistaken for vertical deflection, while it sounds here we are talking about the skewness or stretching of the velocity deficit in the cross-stream plane. Please clarify.

Thank you for this suggestion. We agree that the term “wake tilt” could be ambiguous. Therefore, we have revised the manuscript to describe it as *“skewness in the cross-stream plane”*.

- L 424: Please add a reference to a simple wake model that uses turbulence to predict wake deflection.

  We appreciate the reviewer’s comment and we acknowledge a mistake in our earlier statement. We claimed that there are simple wake models taking turbulence into account to estimate wake deflection. While turbulence is often considered for modeling wake expansion, we haven’t found a simple model that uses turbulence for estimating wake deflection. We have corrected the sentence to solely mention yaw misalignment and removed turbulence from this statement.

- L 520: The link between (tip?) vortex dynamics and wake asymmetry is unclear. Earlier it was claimed that the asymmetry arises from a combination of wake rotation and shear, with stability enhancing its persistence. Please resolve this ambiguity.

  Thank you for this valuable comment that actually touches on an interesting question that our findings raise. We see that there is an asymmetry in the mean values of the wake parameters, as well as in the occurrence, circulation and core radius of tip vortices (Wildmann and Kistner, 2025). At this point, we cannot clearly disentangle the causality between the dynamics in the near wake. Parameter studies in LES suggest that the asymmetry is clearly related to the inflow shear and veer in combination with the turbine rotational direction, but if tip vortex stability is enhancing this effect, or vortex breakdown is more effectively forced by stronger shear on one side of the wake remains to be shown in future studies. We will thus change the statement about tip vortices in the manuscript, simply stating that the *“interaction between tip vortices and the asymmetric mean flow requires further studies to fully understand the near wake dynamics.”*

References

Aitken, M. L., Banta, R. M., Pichugina, Y. L., and Lundquist, J. K.: Quantifying Wind Turbine Wake Characteristics from Scanning Remote Sensor Data, Journal of Atmospheric and Oceanic Technology, 31, 765–787, https://doi.org/10.1175/jtech-d-13-00104.1, 2014.

Alcayaga, L.: Filtering of pulsed lidar data using spatial information and a clustering algorithm, Atmospheric Measurement Techniques, 13, 6237–6254, https://doi.org/10.5194/amt-13-6237-2020, 2020.

Beck, H. and Kühn, M.: Dynamic Data Filtering of Long-Range Doppler LiDAR Wind Speed Measurements, Remote Sensing, 9, 561, https://doi.org/10.3390/rs9060561, 2017.

Iungo, G. V., Letizia, S., and Zhan, L.: Quantification of the axial induction exerted by utility-scale wind turbines by coupling LiDAR measurements and RANS simulations, Journal of Physics: Conference Series, 1037, 072 023, https://doi.org/10.1088/1742-6596/1037/7/072023, 2018.

Krishnamurthy, R., Choukulkar, A., Calhoun, R., Fine, J., Oliver, A., and Barr, K.: Coherent Doppler lidar for wind farm characterization, Wind Energy, 16, 189–206, https://doi.org/10.1002/we.539, 2012.

Neunaber, I., Hölling, M., and Obligado, M.: Leading effect for wind turbine wake models, Renewable Energy, 223, 119 935, https://doi.org/10.1016/j.renene.2023.119935, 2024.

Vasiljevic, N.: A time-space synchronization of coherent Doppler scanning lidars for 3Dmeasurements of wind fields, Ph.D. thesis, DTU Wind Energy, `https://backend.orbit.dtu.dk/ws/portalfiles/portal/102963702/NVasiljevic_Thesis.pdf`, 2014.

Wildmann, N. and Kistner, J.: In situ measurements of near wake dynamics with a fleet of multicopter drones, Journal of Physics: Conference Series, 3016, 012 011, https://doi.org/10.1088/1742-6596/3016/1/012011, 2025.