Multi-Point In-Situ Measurements of Turbulent Flow in a Wind Turbine Wake and Inflow with a Fleet of UAS

Tamino Wetz[1] and Norman Wildmann[1]

[1]Deutsches Zentrum für Luft- und Raumfahrt e.V., Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany

Correspondence: Tamino Wetz (tamino.wetz@dlr.de)

1 Review response

We want to thank the anonymous reviewer and Stefano Letizia for their valuable feedback and valid points of criticism to our manuscript.

1.1 Review Comment 1

1.1.1 RC1, General Comments

This study employs a fleet of UAS to measure the flow around a 2 MW wind turbine under various configurations and atmospheric conditions. The velocity and turbulence intensity in the wake are quantified. Exciting and convincing results characterizing the momentum fluxes in the wake and the effect of atmospheric stability on the wake shape are presented. Overall, the manuscript is well-written and provides novel contributions to the field of in-situ wind turbine wake measurements. The study is well within the scope of Wind Energy Science, and I strongly support its publication.

We thank the reviewer for their positive feedback and support as well as their constructive comments to improve the manuscript.

1.1.2 RC1, Specific Comments

1. *Table 1 could benefit from the inclusion of some additional information. In the "pattern" column, it would be helpful to know at which longitudinal distance the lateral patterns were located for each case. What was the duration of each flight? Also, adding the lapse rate for each case would provide a sense of how strongly stable or convective the boundary layer was during each measurement. Finally, the region of operation of the turbine (i.e., above or below rated power) will substantially affect the strength of the wake at any given time, so this must be included as well.*

   We include the longitudinal distance of the lateral pattern as well as the lapse rate for each case. The rated power is reached at a wind speed of $12.5\ \mathrm{m\,s^{-1}}$ so the provided inflow wind speed gives an indicator in which stage the WT is operating. For most of the present flight cases, the WT is operating below rated power, only for flights $\#\ 206$ and $\#\ 207$ the WT operated near rated power. A statement is added to the manuscript.

2. *Page 13-14: The discussion of the tip vortex measurements is not very strong. I agree that all of the factors listed will weaken the peak in the frequency spectrum. However, is the signature of the tip vortices visible in any of the time series taken at the wake edge location, even for just a short time? Is this what is meant by the line "approximately seven tip vortices could be observed between the measurement position and the WT"? Especially because tip vortex breakdown is discussed throughout the manuscript, it would be beneficial to elaborate a bit here.*

   Thank you for the comment. By seven observable tip vortices, we meant that if you take a snapshot of the wake flow, you can theoretically see, based on the revolution of the WT and the distance of the measurement, 7 tip vortices on a line between the measurement position and the WT. With this, we want to outline the travel history of the tip vortex. We clarified this statement also in the manuscript.

   The signature of the tip vortices in a time series of a single point measurement is difficult to capture, since the signature strongly depends on the position relative to the center of the vortices. However, the time series of the lateral velocity v of the relevant UAS ($\overline{y} = 0.55\ D$) measurement of flight # 606 shows in some periods the signature of the tip vortex. One segment of the time series of the lateral velocity component v where the signature is clearly visible, is shown in Fig. 1a, due to confidential reasons the labels on the y-axis have been removed. The signature of the tip vortex at hub height is characterized by a strong increase in lateral velocity followed by an abrupt change towards the opposite lateral direction and ending back in the ambient lateral wind velocity. Or, depending on the relative measurement position concerning the vortex center, the vortex can only cause a strong increase or decrease in the streamwise velocity without influencing the lateral velocity. This discussion is added to the manuscript and the figure, including additional descriptions, is added to the appendix. Additional discussions on the basis of the present dataset would be quite speculative, thus we limited the discussion on the tip vortices at this stage, and detailed experiments on this topic are necessary and planned in order to extend the discussion.

3. *Page 15: It would be nice to have a discussion of 1-2 more examples from Fig. 9a. For example, in case # 708 the velocity shows a strong increase between 1D and 2D. Do you think this is because the large value of γ is causing the centerline of the wake to be deflected away from the measurement location? Or does the large value of Ix indicate that the wake is already starting to recover?*

   A discussion of flight case # 708 is added to the manuscript. Both, the misalignment of the WT and the deviation of the pattern orientation caused the measurement to be outside the centerline, which explains the increase in wind speed in all cases. However, in this specific case and regarding the turbulence intensity of the same measurement (Fig 9b) a decrease can be observed towards x=2 D which could indicate that the wake recovery has already started, which also leads to an increase in wind speed at this longitudinal distance. This could be plausible in this case due to the high level of ambient turbulence, which supports the wake recovery.

4. *Page 17, lines 361-362: If future researchers are to use this UAS method to measure wind turbine wake flows, it would be helpful to have some elaboration on the difficulties. What do you think are the sources of uncertainty in the lateral velocity measurements and how could they be addressed in future studies? Do you think there could be vertical wake*

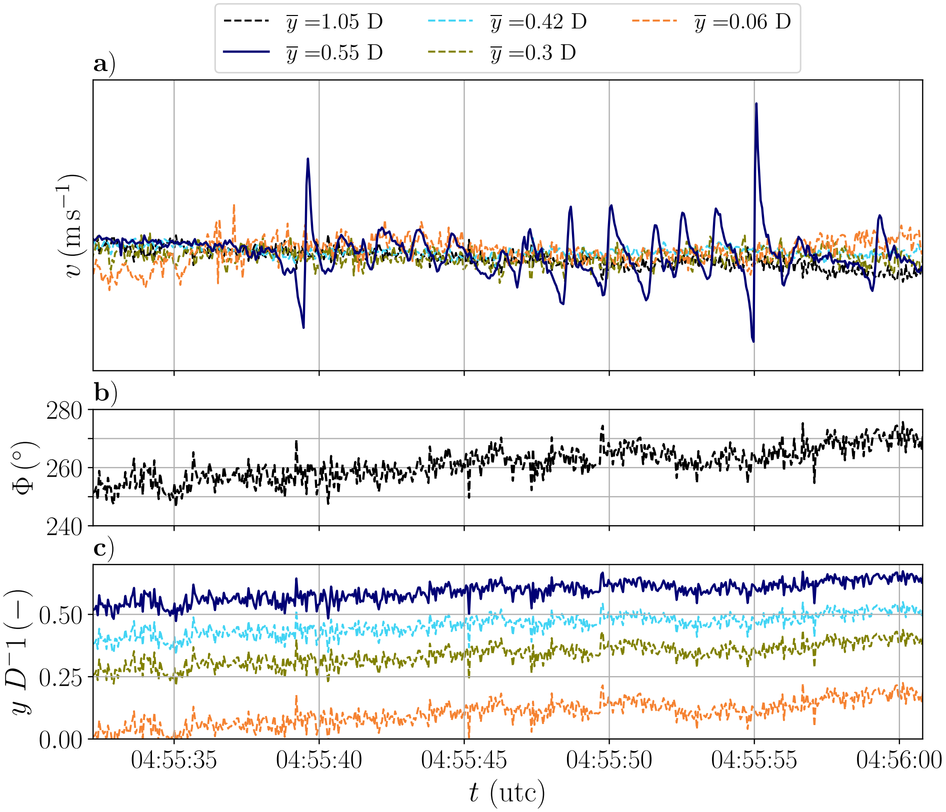

Figure 1. Time-series of the lateral velocity component a), wind direction in b) and lateral position c) of a lateral flight pattern in stable conditions (fl. # 606). The lateral positions are calculated using the wind direction of reference UAS measurement, which is shown in the middle figure. The black bar in c) indicates the lateral position of the WT.

deflection caused by the terrain? Or is this due to some uncertainty in the lateral velocity measurements themselves or the positioning of the UAS? This information could help future researchers decide whether this method is appropriate for their investigations. This elaboration could also be added to the conclusion section of the manuscript.

In the conclusion, we already included sources of uncertainty for the measurements. However, we extend the statement about the difficulty of far-wake measurements at this point and include it also in the conclusion. The complex terrain on one hand can cause additional variability in the inflow wind direction, which leads to large lateral deflections of the wake and makes the positioning of single point measurements in the wake challenging. On the other hand, the present complex terrain could also cause vertical deflection due to the significant slope to the west of the WT, which could also affect the vertical position of the WT wake. Strong terrain effects were for example shown in the Perdigao experiment with dual-Doppler lidar measurements (Wildmann et al., 2018). However, in that case, the WT was directly on a mountain ridge with slopes starting only few tens of meters up and downstream of the WT, in our case, there is no steep change in terrain downstream and the escarpment upstream is more than two rotor diameters away. A similar sight has been investigated at the Swabian Alp, which shows that flow inclination quickly recovers after the escarpment (Wildmann et al., 2017). Since the lateral velocity components are comparably small, the uncertainty for the velocity measurements are more crucial for this component.

5. *Figures 9 and 10: For the longitudinal flight patterns, did the authors consider applying conditional averaging? Since the wind direction is changing, you could take the average of all velocities that are measured when the instantaneous misalignment angle β is less than a certain value (see references below).*

   From the complete dataset, we already only present flight cases with a pattern misalignment angle β of less than 20 degrees. We appreciate the idea of grouping the data depending on the misalignment angle β. However, for the remaining flight cases, the number of flight cases is too low to obtain a significant statement by grouping the flight cases. Therefore, we decide to present the flight cases separately without grouping, so that the individual flight cases are transparently visible.

6. *Page 20: A couple other field studies have observed the double Gaussian shape of the near wake. These should be included for completeness:*
   - *Abraham, A., Dasari, T., and Hong, J. (2019). Effect of turbine nacelle and tower on the near wake of a utility-scale wind turbine. Journal of Wind Engineering and Industrial Aerodynamics, 193, 103981.*
   - *Keane, A. (2021). Advancement of an analytical double-Gaussian full wind turbine wake model. Renewable Energy, 171, 687-708.*

   We appreciated the additional literature for field studies and included both in the manuscript.

1.1.3 RC1, Technical corrections

1. *Why are Δx and Δy used rather than x and y throughout the manuscript? If they are different, make sure they are clearly defined.* The manuscript is corrected towards x and y, since the origin of the coordinate system is placed at the turbine hub, so the distance to the WT equals the coordinate points.
2. *Figure 1: The numbers on the elevation contours are not clearly visible.* The position and size of the numbers on the elevation contours are adjusted.
3. *Page 7, lines 175-176: “laps” should be “lapse”.* Corrected.
4. *Figure 4 legend: There is no black bar in the figure.* Corrected.
5. *Figures 4, 8-14, and A1: Please make the symbols bigger so the different cases can be differentiated more easily.* All figures are updated accordingly in the manuscript.

6. *Figure 7: Does the dotted line represent k-5/3? Also based on the caption, the y-axis label should be Su.* Thank you for the comment. We corrected the dotted line label to $k = -5/3$ and the axis label.

7. *Page 22, line 435: I believe the authors are referring to a different case, as* $\#$ 206 *occurs under unstable atmospheric conditions per Table 1.* Corrected.

References

Wildmann, N., Bernard, S., and Bange, J.: Measuring the local wind field at an escarpment using small remotely-piloted aircraft, Renewable Energy, 103, 613 – 619, https://doi.org/https://doi.org/10.1016/j.renene.2016.10.073, 2017.

Wildmann, N., Kigle, S., and Gerz, T.: Coplanar lidar measurement of a single wind energy converter wake in distinct atmospheric stability regimes at the Perdigão 2017 experiment, J. Phys.: Conf. Ser., 1037, 052 006, https://doi.org/10.1088/1742-6596/1037/5/052006, 2018.

Relevant changes to the manuscript

We list here the relevant changes to the manuscript:

1. Introduction:
   - Text modifications in response to referee comments.
2. Experiment:
   - Text modifications in response to referee comments.
   - Fig. 3 is modified in response to referee comments.
3. Methods:
   - Text modifications in response to referee comments.
   - Table 1 is modified in response to referee comments.
4. Results:
   - Text modifications in response to referee comments.
   - Fig. 4 is modified in response to referee comments.
   - Fig. 7 is modified in response to referee comments.
   - Fig. 8 is modified in response to referee comments.
   - Fig. 9 is modified in response to referee comments.
   - Fig. 10 is modified in response to referee comments.
   - Fig. 11 is modified in response to referee comments.
   - Fig. 12 is modified in response to referee comments.
   - Fig. 13 is already included now in Fig. 12 and therefore removed in response to referee comments.
   - Fig. 14 is modified in response to referee comments.

5. Discussion:
    - Text modifications in response to referee comments.
6. Conclusion:
    - Text modifications in response to referee comments.
7. Appendix:
    - Fig. A1 is modified in response to referee comments.
    - Fig. B1 is added in response to referee comments.