Responses to Reviewers' Comments for Manuscript

Rotary-wing drone-induced flow – comparison of simulations with lidar measurements.

Addressed Comments for Publication to

Atmospheric Measurement Techniques

by

Liqin Jin, Mauro Ghirardelli, Jakob Mann, Mikael Sjöholm, Stephan T. Kral, and Joachim Reuder

Dear Reviewers,

Please find enclosed the revised version of our manuscript entitled "Rotary-wing drone-induced flow – comparison of simulations with lidar measurements". We would like to express our gratitude to you both for providing valuable comments that have greatly contributed to the improvement of our work. In this revision, we have carefully considered and addressed the comments raised, aiming to enhance the quality and clarity of the manuscript.

Below, we provide a summary of the main modifications made and a detailed point-by-point response to your comments. We sincerely appreciate your time and effort in reviewing our manuscript, and we are grateful for the opportunity to address your concerns.

Sincerely,

Liqin Jin, Mauro Ghirardelli, Jakob Mann, Mikael Sjöholm, Stephan T. Kral, and Joachim Reuder

Authors' Response to Reviewer I

General Comments. The manuscript discusses the use of ultrasonic anemometers mounted on rotary-wing drones as a potentially cost-effective alternative to traditional meteorological mast-mounted anemometers for wind energy applications. However, concerns are raised about the accuracy of wind velocity measurements due to propeller-induced flow disturbances. The study presents an experiment using three short-range continuous-wave Doppler lidars (DTU WindScanners) to measure the complex and turbulent three-dimensional wind field around a hovering drone at low ambient wind speeds. The results from lidar measurements are compared to computational fluid dynamics (CFD) simulations to validate the accuracy of drone-mounted wind sensors. While the data and measurements are promising, the manuscript has several weaknesses.

Response:

Dear Reviewer, we are glad that you find our research valuable and the results are promising. After reading through your comments, we implemented changes to our manuscript including your suggestions. We will now address, one by one, your comments and suggestions.

Comment 1

- Clarify the novelty of this research in comparison to existing studies using drones with anemometers.
- Specify whether the proposed method complements or extends current techniques in wind field measurements.
- Enhance the logical relationships between references, discussing the limitations of previous research and their relevance to the current study.
- Clearly state the contributions of this study regarding the development of advantages for rotary-wing drones in wind field measurements.

Response:

Thank you for pointing these out. We revised our paper to address this concern. We decided to combine these four points because we found a common theme: the start of the study was unclear. For this reason, we have critically revised the introduction to explain how our research advances the current state of knowledge in the use of drones with anemometers for atmospheric turbulence characterization, and also in the wind measurement field.

Our study is distinct in several key ways:

- Comprehensive approach: Our research aims at the study of full-size sonic anemometers mounted on rotary-wing UAVs, while previous studies have often focused on using lightweight anemometers or have primarily measured mean horizontal wind or vertical ABL wind profiles. This can potentially lead to more accurate measurements of three-dimensional turbulent wind velocity, which is crucial for a detailed understanding of atmospheric dynamics.
- Experimental validation: we provide experimental validation of the CFD simulation model proposed by Ghirardelli et al. [2023]. This CFD model can be further used to optimize drone-mounted sensor placement to minimize the influence of propeller-induced flow (PIF). The validation approach presented in this manuscript

helps bridge the gap between theory and real-world application, offering robust data and insights into the characteristics of PIF around large multi-copter drones.

- Innovative Application and Mounting Strategy for Standard Sonic Anemometers: While our study utilizes commercially standard sonic anemometers, we introduce a novel application by configuring these sensors in an upwind-facing, boom-mounted arrangement beneath the drone's fuselage. This configuration is unique in the context of drone-based atmospheric measurements.
- Use of CW Doppler lidars: Beyond simulations, we employ high-resolution continuous-wave (CW) Doppler lidar to investigate PIF experimentally. CW lidars can provide accurate, three-dimensional flow observations, to validate CFD simulations that will be further used to refine sensor placement for optimal data collection by drone-mounted sensors. To the best of our knowledge, this is the first study utilizing three synchronized CW Doppler lidars to investigate the turbulent three-dimensional flow around a rotary-wing drone and compare with CFD simulations.

We believe these elements collectively represent a substantial advancement in the field of atmospheric measurements using UAVs and offer valuable insights and methodologies for future research. We hope this clarification underscores the innovative aspects of our work and its contribution to the broader scientific community.

Comment 2

Address the variations in flow disturbances and spatial flow fields induced by different types of rotary-wing drones.

Response:

Thank you for your valuable feedback and for highlighting the importance of addressing variations in flow disturbances and spatial flow fields induced by different types of rotary-wing drones. We appreciate the opportunity to discuss this further. We fully acknowledge the significance of understanding these variations to provide a comprehensive overview of the propeller-induced flow (PIF) dynamics. However, we believe there is a notable lack of standardized methods and sufficient data for comparative analysis across various drone models and this is still in progress. Our approach, focusing on a single case (eight rotors in a contra-rotating set-up), was chosen to provide an in-depth understanding of propeller-induced flow for this specific drone type that is suited for lifting heavy payloads. We believe that establishing a detailed baseline for one drone can serve as a valuable reference point for future comparative studies. We therefore aim to contribute a foundational piece to the broader puzzle on which future research can be built.

Comment 3

Consider using more conventional symbols to represent horizontal wind speed components to improve readability and understanding.

Response:

Thank you very much for pointing this out. We agree with this comment and have used the conventional symbols U_h to represent horizontal wind speed components. This is added in **L220** in the revised manuscript as For a clearer illustration, we normalized the horizontal wind velocity $U_h = \sqrt{U^2 + V^2}$ by subtracting the free-stream wind speed U_0.

Comment 4

Provide clearer explanations for critical aspects such as sampling frequency, sampling time, and numerical simulation parameters.

Response:

Thank you very much for this point. We have explained more clearly about sampling frequency, and sampling time in **L145**. The new sentence is After a block averaging of 726 spectra to reduce noise fluctuations, the final spectrum is sampled at a frequency of 322 Hz = (120 MHz)/(512 · 726) with the corresponding sample time of 3.1 milliseconds for each spectrum. For numerical simulation parameters, we used default setups, which is indicated in **L124** as Following the initial mesh setup and selection of the turbulence model, we used standard settings from Ansys Fluent to ensure consistency and reliability.

Comment 5

Address the potential reliability issues of averaging radar wind measurements in terms of error analysis and experimental design.

Response:

Thank you very much for this point. We agree and have addressed this comment in **L133**, which is The use of CW Doppler lidars is beneficial for a variety of wind energy applications. In spite of this, CW Doppler lidars are susceptible to moving objects away from the intended focus point, such as flying birds. Besides, their spatial resolution decreases as the focus distance increases, which may deteriorate the accuracy of wind velocity and turbulence measurements by CW lidars [Jin et al., 2022]. Therefore, we placed the three lidars as close to the intended scanning positions as possible to compact the measurement volume [Angelou et al., 2012] and minimize potential biases resulting from volume-averaging [Clive, 2008, Sjöholm et al., 2009, Forsting et al., 2017]. To improve the accuracy of flow velocity retrieval, we discard spectra containing Doppler shifts caused by hard targets and out-of-focus moving objects during the post-processing.

Comment 6

Explain the rationale behind choosing three radar wind devices and their arrangement, considering potential sources of error.

Response:

Thank you very much for this comment. We have explained the reason why we used three lidars and their arrangement in **L130** that A single CW Doppler lidar can only measure the one-dimensional projection v_{LOS} of wind velocity vector along its line-of-sight beam direction. Therefore, by combining the independent and simultaneous measurements of v_{LOS} from three Doppler lidars, a full three-dimensional wind vector can be retrieved. In **L133** we explained the potential sources of error by using CW lidars as The use of CW Doppler lidars is beneficial for a variety of wind energy applications. In spite of this, CW Doppler lidars are susceptible to moving objects away from the intended focus point, such as flying birds. Besides, their spatial resolution decreases as the focus distance increases, which may deteriorate the accuracy of wind velocity and turbulence measurements by CW lidars [Jin et al., 2022]. Therefore, we placed the three lidars as close to the intended scanning positions as possible to compact the measurement volume [Angelou et al., 2012] and minimize potential biases resulting from volume-averaging [Clive, 2008, Sjöholm et al., 2009, Forsting et al., 2017]. To improve the accuracy of flow velocity retrieval, we discard spectra containing Doppler shifts caused by hard targets and out-of-focus moving objects during the post-processing.

Comment 7

Discuss the impact of drone-mounted wind sensors on the measurement of turbulence characteristics, in addition to average wind speed.

Response:

Thank you for your valuable comment. We acknowledge the importance of understanding the impact of drone-mounted wind sensors on turbulence characteristics research.

Our research is structured into three distinct phases. The first involves CFD simulations on the PIF (Ghirardelli et al. [2023]). The second phase, which was conducted in December 2022, focused on validating these CFD simulations by comparing the wind velocities obtained with those measured by lidar. The results of this phase are the subject of the current paper. The third and final phase entailed a field measurement campaign where we combined a full-size sonic anemometer with the drone to compare both wind velocity and turbulence against data from mast-mounted sonic sensors. This phase was completed in late December 2023, and a draft detailing its findings is now in preparation.

In the revised manuscript, we calculated the velocity uncertainty based on 3-min lidar data, which is demonstrated by the error bars in Figure 11 and 12. Furthermore, we found that the flow is less turbulent as it approaches the drone since the error bars become shorter, which indicates that drone-mounted sonic sensors may impact the measurement of turbulence characteristics. However, this needs further investigations and is beyond the scope of the present study. We have implemented this comment in **L254** that The flow appears to be less turbulent as it approaches the drone, which is indicated by the shorter error bars in Fig. 11 and Fig. 12. This suggests that drone-mounted sonic sensors may impact the measurement of turbulence characteristics. However, this needs further investigations and is beyond the scope of the present study. as well as in **L290** that It will be necessary to study various wind conditions as well as the impacts of drone-mounted wind sensors on turbulence measurements.

Comment 8

Improve English language expression, particularly regarding sentence structure and readability.

Response:

Thank you very much to point this out. We agree with this comment and have carefully checked the whole manuscript to improve English language expression. Hope this time it can be accepted by you.

References

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