"Evaluating the Impact of Motion Compensation on Turbulence Intensity Measurements from Continuous-Wave and Pulsed Floating Lidars"

Revision 1

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Authors response to Anonymous Referee #1 comment RC1 (2025-04-10 https://doi.org/10.5194/wes-2025-45-RC1)

We would like to sincerely thank Anonymous Referee #1 for their detailed, constructive, and thoughtful review of our manuscript. We greatly appreciate the time and effort you invested in evaluating our work. Your comments and suggestions helped us to significantly improve the clarity, structure, and scientific depth of the paper. We have carefully addressed all points raised, revising the manuscript accordingly and providing clarifications where necessary.

Below, we respond to each comment in a point-by-point manner. Reviewer comments are shown in bold, followed by our response and a description of the changes made to the manuscript. Further, the results from the raw Windcube V2.1 pulsed lidar data changed slightly, as the system had been partially applying vector averaging. To ensure consistency, the data was reprocessed using scalar averaging.

Major Comments

- **Redundancy in Structure: The manuscript could benefit from reducing repetitive explanations, particularly in the outline sections (e.g., Lines 117–128).**

We have reviewed the manuscript and revised the introductory paragraphs of all major subsections to remove structural repetition. These have been rephrased to focus on the scientific content rather than reiterating the document outline.

- **Methodology Motivation: The paper lacks a clear motivation and novelty statement regarding the proposed motion compensation method. It is not evident how this approach differs from or improves upon existing techniques.**

We appreciate this comment and have clarified the motivation and contribution of our work in the revised manuscript, particularly in the introduction (lines 111 – 126), a reworked Section 2.2 and an expanded Discussion (lines 571 -576).
The novelty of our work lies not in the invention of a new motion compensation algorithm, but in the controlled and transparent application of an established deterministic, geometric method to systematically assess its performance across two different lidar types. Previous studies have typically evaluated motion compensation on single lidar platforms, often under varying environmental conditions and using proprietary or only partially disclosed algorithms. In contrast, our study isolates the impact of lidar type on turbulence intensity measurements by holding both the platform motion and the compensation algorithm constant.
The applied algorithm, originally developed by one of the authors and described in Wolken-Möhlmann et al. 2014, has been further refined and is fully disclosed in this study. By deploying a cw and a pulsed lidar on floating platforms of the same type and compensating both with the same algorithm under similar offshore conditions, we create a unique experimental configuration. This setup enables a direct comparison of the systems' responses to motion and its compensation, an aspect that has not been

previously documented in the literature.
The multi-metric approach allows for a comprehensive and differentiated evaluation, capturing both systematic and random errors, and enabling meaningful comparison with existing studies and best-practice criteria in the field.

- **Description of Lidar Retrieval Methods: The VAD (Velocity Azimuth Display) and DBS (Doppler Beam Swinging) methods should be more thoroughly described. Consider including detailed explanations in an appendix if necessary.**

Both lidar retrieval methods were mentioned in the context of their respective systems (Section 2.2.2), we agree with the reviewer that providing a dedicated explanation improves clarity. We have therefore added Appendix A, which briefly summarizes the principles, assumptions, and references for both methods. The main text in Section 2.2 (lines 176 – 177) now includes a reference to this appendix.

- **Motion compensation method definition: The manuscript should thoroughly define/formulate the motion compensation method used.**

We appreciate this comment and agree that a clearer and more thorough formulation was needed. We have comprehensively revised Section 2.2, which now includes a step-by-step mathematical formulation of the deterministic motion compensation method used.

- **Comparison with Existing Literature: The results should be compared to existing studies in the field, such as those by Kelberlau et al. (2020, 2023) and Gutiérrez-Antuñano et al. (2018), which report statistical indicators with similar magnitudes. Such comparisons are essential to contextualize the study's contributions.**

We sincerely thank the reviewer for this valuable suggestion. We fully agree that situating our findings in the context of existing literature is essential to highlight the study's contributions and relevance. Accordingly, we have expanded the discussion section (lines 619 – 661) to include detailed comparisons with relevant recent studies, including Kelberlau et al. (2023), Rapisardi et al. (2024), and Uchiyama et al. (2024). These works employ a variety of motion compensation approaches (deterministic, machine-learning-based), and multi-platform comparisons and report statistical indicators that align well with those used in our analysis (e.g., MBE, RMSE, Representative TI, regression slope, and R^2). This allowed us to benchmark our results and identify common trends as well as key differences.
We also relate these comparisons back to the three core factors identified in our study (lidar type, platform motion, and compensation method), and reflect on how differing sea states, motion characteristics, and reference instrumentation may account for variations in performance across studies.

Minor Comments

Sect. 2.

- **Figure 1. Typically IMUs use an inertial reference system with respect to North-East-Down (or different). Please indicate those in the figure.**

We thank the reviewer for pointing this out. Figure 1 has been updated to include the North-East-Down (NED) reference system for clarity. The figure caption has also been revised to explicitly describe the orientation of the IMU in relation to the NED frame.

Sect. 3.

- **Why only use wind speed data within the range 4-16 m/s?**

The wind speed interval of 4–16 m/s was chosen to reflect the typical operational range of modern wind turbines, where turbulence intensity has the greatest impact on turbine performance, particularly up to rated wind speeds around 10 m/s. This range ensures a relevant assessment of TI under realistic operating conditions. Additionally, it aligns with common practices and recommendations in existing guidelines such as the OWA Roadmap 2018 and the IEC 61400 series, which often define or analyse performance metrics within similar wind speed intervals. That said, we note that the results remain very similar even without applying this wind speed filter.

- **A comparison between mean horizontal wind speeds measured by the FLSs and the anemometers should be provided.**

We thank the reviewer for this suggestion. In response, we have added correlation plots comparing the mean horizontal wind speeds from the non-corrected and motion-compensated FLS data with those from the reference sensors in Appendix B (lines 695 and on), and referenced this addition in the Results section of the manuscript. The comparison shows very good agreement across all evaluated systems. The raw FLS data already meets the best-practice criteria for mean wind speed accuracy as defined in the OWA Roadmap 2018. Nevertheless, the application of motion compensation further improves the agreement in respect to regression slope and R^2.

- **Lines 315-319: This is not expected. Typically, CW lidars measure lower turbulence values than anemometers due to their inherent temporal and spatial averaging. For instance, see https://wes.copernicus.org/articles/10/83/2025/wes-10-83-2025.html and https://journals.ametsoc.org/view/journals/atot/28/7/jtech-d-10-05004_1.xml . Please, comment on that.**

We thank the reviewer for this insightful observation. Indeed, it is generally expected that cw lidars report lower turbulence intensity than cup anemometers due to their inherent spatial and temporal averaging, as demonstrated in the cited studies.
We have re-checked the data and confirmed the finding. We have observed a similar behaviour in other offshore datasets involving fixed cw as well as pulsed lidars at FINO3. We believe this may be attributed to a combination of factors specific to the offshore environment and site configuration, such as atmospheric stability conditions or mast effects. Further, lidar based turbulence measurements suffer from systematic errors caused by inter- (cross contamination) and intra-beam effects which could lead to under- or overestimation (refer to https://wes.copernicus.org/preprints/wes-2024-93/). It is also worth noting that the referenced publications primarily analyse onshore measurement setups, where terrain-induced turbulence and mast wake effects may differ from those in offshore environments. While the typical expectation remains valid in general, our results emphasize the importance of site-specific evaluation when interpreting TI comparisons across different measurement technologies.

- **Lines 321-322: Please comment on how the underlying measurement principles of the instruments generate the discrepancies. Do they cause the CW lidar TI over-estimation as well?**

The measurement principle for profiling lidar is complex from a geometrical point of view. Under the assumption of temporal and spatial homogeneity of the wind field in the scales of the lidar measurement, virtual wind vectors are reconstructed. These vectors may deviate from the actual wind vector over the lidar. We only know that the 10 minute average value of the vectors are a good representation of a reference cup and wind direction measurement. Even if components of the turbulence are decreased due to the size of the measurement volume and the duration of one scanning pattern, the method of wind field reconstruction from several radial velocity measurements may result in variations in the reconstructed wind vectors. This research question remains to be investigated further.