Author Response to Reviewer Comments

Manuscript: wes-2025-137
Title: Wake-resolving acoustic tomography: advances through numerical covariance methods
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We thank both reviewers for their careful reading of the manuscript and for their constructive feedback. We address each comment below with corresponding revisions where appropriate. Reviewer comments are shown in *italics*, and our responses follow.

Response to Reviewer 1 (RC1)

We appreciate Reviewer 1's careful assessment of our work and their recognition that this type of research is "highly useful" for emerging measurement and remote sensing techniques. The reviewer's comments have helped strengthen the clarity and reproducibility of our work.

Comment #1: Virtual ATT array description

The article is lacking a clear description of the virtual ATT array deployed in the experiment... In order for follow-up studies to duplicate the results herein, these details need to be included clearly in Chapter 2.

Response: The reviewer is correct that several important details about the virtual AT array configuration were scattered throughout the manuscript or omitted entirely. We have added detailed content in Section 3 ("Problem setup") including:

- **Array layout figure and description:** Added Figure 1 showing the virtual AT array layout with eight emission/reception points, path length matrix, and path length histogram. The accompanying text describes the 80 m × 80 m square array boundary and 100 m × 100 m retrieval domain.
- **Array coordinates table:** Added Table 3 listing the (x, y) coordinates of all eight array nodes.
- **Idealized assumptions:** The Discussion section (Section 5) now explicitly states that travel times are computed analytically from the forward model assuming perfect time-of-flight retrieval with no timing errors, no instrumental noise, multipath propagation, atmospheric absorption, or signal interference, and omnidirectional transducers with perfect colocation.
  We have also added Table 1 at the end of Section 2 summarizing the three covariance model approaches (analytical Gaussian "Model", precursor-based homogeneous "Precursor", and LES-informed heterogeneous "Data") with their descriptions, key assumptions, and computational costs.

Comment #2: Temperature fluctuation normalization

All of the normalized results for temperature fluctuation retrievals in neutral conditions are essentially meaningless... it would be better to show simply RMSE for T' instead of NRMSE, for both the convective and neutral cases.

Response: The reviewer raises a valid point. When temperature fluctuations are on the order of 10^{-4} K (as in the neutral case), the normalization by standard deviation produces NRMSE values exceeding 300, which obscures meaningful comparison. To address this concern in the new manuscript, we have:

1. **Replaced NRMSE with RMSE for temperature:** Added clarification after Eq. 3 stating: "For temperature fluctuations, we report the simple root-mean-square error (RMSE) rather than NRMSE because the normalization by standard deviation obscures meaningful comparison when temperature variability is small, particularly in the neutral ABL where σ_T ≈ 10^{-4} K."

2. **Updated figure captions:** Updated Figures 6, 7, and 14 to show NRMSE for velocity components and RMSE for Temperature fluctuations. Captions state "NRMSE is shown for velocity components; RMSE (K) is shown for temperature."
3. **Revised discussion:** Updated text to discuss temperature in terms of RMSE and absolute error magnitudes (0.25 K for neutral ABL, explaining this is at the practical resolution limit of ~0.1 K). Changed text from "median NRMSE" to "median error metrics" and "median RMSE" when discussing temperature results.

This change allows direct comparison of temperature retrieval accuracy across stability conditions without the confounding normalization effect.

Minor Technical Comment

In Figure 5, the N_r legend interferes with the data in the two leftmost graphs.
Response:
The legends have been repositioned in Figure 6 to avoid obscuring the data.

The three approaches for the covariance model choices should be listed in a table.
Response:
Added Table 1 at the end of Section 2 summarizing the three covariance approaches:

- **Model:** Analytical Gaussian correlations (Eq. 8) with fitted parameters; assumes homogeneous, isotropic, stationary conditions; low computational cost
- **Precursor:** Numerically derived from turbine-free ABL simulations (Eq. 12); assumes homogeneous and stationary; moderate computational cost
- **Data:** Numerically derived from full turbine wake simulations (Eq. 13); assumes stationary only (allows spatial heterogeneity); high computational cost

The table includes columns for approach name, description, key assumptions, and computational cost.

Response to Reviewer 2 (RC2)

We appreciate the reviewer's acknowledgment that "the simulations, the inversion, the figures and the discussion are all well performed and prepared." However, we respectfully disagree with the recommendation for rejection. We address the reviewer's concerns below.

Concern 1: Relevance to wind energy

While I do not dispute the quality of the research, I cannot see the relevance and perspectives for wind energy.

Response: The scope of *Wind Energy Science* explicitly includes "wind and the atmosphere (atmospheric physics; wind and turbulence)" and "wakes and wind farm aerodynamics." Our work directly addresses wake turbulence characterization, which is central to scientific discovery and validation of simulation and modeling tools used in wind turbine design and wind farm optimization.

The manuscript contributes: (1) theoretical advancement extending TDSI to heterogeneous wake flows; (2) wake physics insights quantifying how rotor forcing reshapes the correlation tensor; (3) proof of concept for remote sensing retrieval methods that increase spatial and temporal resolution beyond alternative methods; and (4) foundational research for an emerging measurement technique. As Reviewer 1 noted, "for immature sensing techniques... this type of intermediate, building-block research is highly useful."

Concern 2: Dependence on prior correlation structure

In order to measure the flow one needs detailed information about the flow in advance.

Response:
While this is true, all inverse problems require regularization or prior information to approach solutions. Our results show that analytical models perform competitively in many scenarios, requiring only bulk estimates of variance and length scale obtainable from standard meteorological measurements. The analytical model even outperforms LES-informed covariances for $N_f > 4$ in several cases.

The purpose of testing LES-informed covariances is to establish upper performance bounds and identify which correlation structure aspects are most critical. This work will guide development of practical models parameterized by operational conditions, not requiring practitioners to run simulations before each campaign.

Concern 3: Economic and practical challenges

For a modern size turbine with a hub height exceeding 150 m one would have to erect (at least) seven mast of the same height.

Response:

Economic and commercialization considerations are outside the scope of fundamental research articles. While this numerical study uses a V27 turbine (31.5 m hub height), representative of research-scale facilities where AT has been deployed, we acknowledge the practical challenges of scaling to utility-scale turbines in the discussion section.

"Scaling to utility-scale turbines will require alternative array configurations such as vertical planar arrays spanning two meteorological towers or hybrid ground-aerial systems using uncrewed aerial systems. These alternative deployment strategies are explored in greater detail in a technical report (Hamilton, 2022)."

This addition acknowledges the reviewer's concern while pointing to prior work on practical deployment configurations. We also note that fundamental research is often required to advance new instrumentation toward commercial viability, as seen with sonic anemometry and Doppler lidar.

Concern 4: Rotor noise interference

Some of the acoustic beams would pass the rotor... corrupting the travel time estimations.

Response: This is a valid concern that will require serious consideration in future years.

We have added a dedicated paragraph in Section 5 (Discussion and Conclusions) addressing rotor noise challenges:

"For field deployment near utility-scale wind turbines, several practical challenges must be addressed beyond those considered in this study. Differentiating the AT acoustic signals from aeroacoustic emissions from the turbine itself in the form of rotor noise presents a significant challenge if they overlap in the frequency domain. Acoustic travel-time paths that may be corrupted by broadband aeroacoustic emissions from blade-vortex interactions and turbulent boundary layer noise. To mitigate these impacts, future systems should endeavor to design chirps in the range of 100-500 Hz, below the peak rotor noise spectrum. Other strategies include coded pulse sequences that enable robust time-of-flight estimation in noisy environments, temporal gating to avoid blade-passage events, and array geometry optimization to minimize rotor-intersecting paths."

As noted in the new paragraph, the NREL Flatirons Campus AT array already operates near turbines and has demonstrated successful signal isolation, though further development is needed for wake-resolving configurations.

Regarding the comparison to Doppler lidar

Doppler lidar provides measurement much easier, more precise, with fewer assumptions.

Response: This characterization warrants careful examination. Lidar measures only line-of-sight velocity (12-30 m maximum resolution for commercial systems); derived quantities like Cartesian velocities and Reynolds stresses require strong homogeneity assumptions and miss small-scale features. AT measures in-plane velocity components (u, v) and temperature simultaneously, with temporal/spatial resolution (~2 Hz, ~1.25 m) an order of magnitude better than commercial lidar. Critically, AT measures temperature fluctuations, which is simply not possible with lidar. AT might also offer advantages in terms of measuring velocity and temperature fields near solid bodies where wind lidar suffers from hard returns that dominate measurements.

In the manuscript, we do not claim AT will replace lidar, but that it offers complementary capabilities. The existence of mature alternatives does not and should not preclude research on emerging techniques.

Summary

This manuscript extends established theory to new domains, provides quantitative benchmarks, and offers guidance for practical covariance models—contributions aligned with *Wind Energy Science*'s mission to publish "fundamental and pioneering research." We respectfully request reconsideration of the rejection recommendation.

We thank both reviewers for their time and constructive engagement with our work.

Respectfully,
Nicholas Hamilton
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