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Atmospheric Measurement Techniques Discussions

Interactive comment on "Errors in radial velocity variance from Doppler wind lidar" *by* Hui Wang et al.

Hui Wang et al.

hw524@cornell.edu

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Dear referee,

Thank you for spending your time reviewing this manuscript and providing insightful comments. Your comments have been addressed and the manuscript has been revised accordingly. A point-by-point response to your comments are given in the following. Your comments are italicized and followed by our responses starting with the word **Response**. Please refer to the manuscript for papers cited here.

Summary:

This manuscript discusses methods for quantifying random and systematic errors of variance from Doppler lidars. Factors such as sampling volume size, dwell time, and sampling period are taken into account and the effects of these factors on the auto-correlation and covariance of the radial wind speed are demonstrated using models. The random and systematic errors of variance between sonic anemometers and lidar measurements are compared using data from a field campaign.

Overall, the paper is well-written, although information in the paper should be expanded to make it more applicable to a general audience. A section on error quantification (e.g., difference between random and systematic errors, definition of expected values, etc.) should be added toward the beginning of the paper to assist readers who are unfamiliar with error quantification.

Response 1: The following content has been added to introduce the necessary definitions for error quantification (**from p. 1 Line 20 to p.1 Line 24**):

"Estimates from both methods have errors relative to the true or expected values defined as the ensemble means over all possible realizations and these errors are commonly quantified in terms of the systematic and random components. Systematic errors are consistent deviations from the true values in all estimates and they are also referred to as biases. Random errors are varying deviations from the true values arising from unknown reasons and commonly modeled as random variables following Gaussian distributions."

In addition, the motivation and wider application of the error quantification presented in the paper should be discussed in greater detail.

Response 2: A review of lidar turbulence measurements and associated errors has been included in the introduction part of this paper to provide the background for error quantification and emphasize the motivation of this paper (**from p. 14 Line 9 to p. 2**

Line 23). The following is an excerpt for from the newly added review that addresses the comment here:

" errors in the estimated variances and momentum fluxes are accumulations of the following three types of errors in the estimated radial velocity variance:

- Measurement error caused by radial velocity estimator uncertainty and atmospheric turbulence (Frehlich, 1997).
- Attenuation error due to the volumetric averaging effect of lidar measurement (Sathe and Mann, 2013; Mann et al., 2010).
- Sampling error as a result of estimating the ensemble mean by the time average (Mann et al., 2010; Lenschow et al., 1994)."

It is currently somewhat unclear how this error quantification method would be applied in the real world to select appropriate lidar scanning strategies and dwell times. A section after the discussion would be useful for describing general applications or perhaps a use case for the error quantification method.

Response 3: A paragraph has been added at the end of the discussion section (Sect. 5) to describe how the errors in the estimated radial velocity variance propagate through to the final estimates of turbulence statistics. The related mathematics expressions are given in the Appendix A. The role of the scanning geometry in the error propagation is clear in the newly added text. A case study is presented. The case study applied the observed errors of radial velocity variance from the experimental data to the six-beam method and calculated the uncertainties in the estimated streamwise velocity variance and the vertical momentum flux. Please see **the last paragraph in Sect. 5 and Appendix A** for detail.

Specific comments on different sections are listed below. Because of the work needed to improve the wider applicability of the paper, I recommend that the paper be accepted with major revisions.

Specific comments

p. 1 (Section 1: Motivation and approach) – Existing methods for quantifying lidar turbulence error should be discussed (e.g., Lenschow et al. 2000, Mann et al. 2010, Sathe et al. 2011)

Response 4: A discussion about errors in lidar turbulence measurements has been added to the introduction part (**from p. 14 Line 9 to p. 2 Line 23**) in correspondence to this review. Please refer to the excerpt in **Response 2** above for the revised content.

p. 1, Line 15: Not all techniques for deriving second-order moments directly involve radial velocity variance. The u, v, and w components derived from the radial velocities can also be used to estimate variance. However, understanding error characteristics from the radial velocity is important, since all derived parameters will be dependent on the accuracy of the radial velocity estimates. Please rewrite this sentence for clarification.

Response 5: The manuscript has been revised to include the two methods for turbulence measurements and point out the reason to use the radial velocity variance for turbulence estimate (**from p. 1 Line 14 to p. 2 Line 2**). The following is the newly added discussion in correspondence to this comment:

"Two methods are commonly used to derive the second order moments (i.e., velocity variances and momentum fluxes) of turbulent flow from lidar data (Sathe and Mann, 2013). The first method initially estimates the three orthogonal wind components from radial velocities acquired through a scan geometry (e.g., the conical scan) and then

uses the eddy covariance method to derive the turbulence statistics. The second method involves three steps: (1) obtaining radial velocity variance from the time series at different locations through a scan geometry, (2) estimating radial velocity variance from the time series obtained in (1), and (3) deriving the second order moments based on their relationships with the radial velocity variance.

The first method can suffer from cross contamination errors (biases) due to the correlation between the radial velocities used for wind velocity estimates (Sathe et al., 2011). Therefore, the second method is considered to be more suitable for lidar turbulence measurements (Newman et al., 2016; Sathe et al., 2015; Sathe and Mann, 2013; Mann et al., 2010)"

p. 1, Line 21: Change "that" to "the technique" or "the theory"

Response 6:The change has been made. Please see **p. 2, Line 25**.

Section 2 (Preliminaries): The discussion of the difference between vr and vR and the definition of the covariances in the x1 direction is a bit confusing. I would recommend including a schematic to show the coordinate system being used.

Response 7:A schematic of the coordinate system has been added. Please see **Fig. 1** in the manuscript.

p. 4, Line 2: Define the difference between systematic and random errors

Response 8:The following definition is made in the introduction part of this paper (**from p. 1 Line 23 to 24**) for systematic and random errors:

"Systematic errors are consistent deviations from the true values in all estimates and they are also referred to as biases. Random errors are varying deviations from the true values arising from unknown reasons and commonly modeled as random variables following Gaussian distributions."

p. 4, Line 6: Define and give a reference for the VAD technique

Response 9: Because of the revision made for the comment below, the VAD technique is not mentioned any more in the new manuscript.

p. 4, Lines 6-7: A VAD technique can also be applied to a lidar that samples at 4 or 5 locations. 6 locations is not the minimum

Response 10: The description in this part was written based on the six beam method for velocity covariance tensor estimation. Therefore, 6 locations are required. In the manuscript, a specific reference has been made to the six beam method to avoid ambiguity (**from p. 5 Line 29 to p. 6 Line 1**). The following is the revised text:

"For example, when a pulsed lidar is configured to estimate turbulence statistics with the six beam method of Sathe et al. (2015), the lidar samples six locations sequentially and therefore the sampling interval (δt) at one location is six times the sampling interval per one lidar measurement (i.e., δt > 6 sec and is at least 60 times slower than a sonic anemometer sampling at 10 Hz)."

p. 6, Line 15: State which hours in the time series in Fig. 4 were affected by the turbine wake

Response 11: The hour around which measurements were affected by the wake has been defined. The sentence has been modified (**p. 8 Line 11**):

"with the exception of periods around 20150518 23:00 UTC when the measurements were in the wake of a wind turbine"

pp. 7-8 (Sect. 4.3: Observed errors): The discussion of Figs. 6-8 here is a little thin. It would be useful to compare differences in error for the different measurement heights.

Response 12:The following discussion about the dependence of error with height has been added (**from p. 9 Line 26 to p. 10 Line 2**):

"The random errors estimated from both methods in general decrease with height except for a few cases related to the M_ρ method (Fig. 9). The systematic errors show a similar trend with height (not shown here). This is possibly the result of increasing turbulence integral length scale with height. For a pulsed lidar, increasing integral length scale can cause the amount of attenuation of radial velocity variance to decrease (Mann et al., 2010) and consequently the errors to decrease (as demonstrated in Fig. 2)."

Technical corrections

p. 1, Line 10: Delete parentheses around 2013 in reference

Response 13:The parentheses have been removed. Please see **p. 1, Line 10**.

p. 3, Line 4: Change "respectivley" to "respectively"

Response 14: The change has been made. Please see **p. 4, Line 4**.

p. 3, Line 17: Change "lenght" to "length"

Response 15:The change has been made. Please see **p. 4 Line 17**.

p. 4, Line 6: Delete parentheses around 2015 in reference

Response 16: This part of text has been removed and the correct citation format is used. Please see **p. 5, Line 29 and 30**.

p. 6, Line 5: Change "repletion" to "repetition"

Response 17: The change has been made. Please see **p. 7 Line 31**.

p. 6, Line 6: Change "wiht" to "with"

Response 18: The change has been made. Please see **p. 7 Line 32**.

p. 8, Line 10: Change "th" to "the"

Response 19: The change has been made. Please see **p. 10 Line 12**.

p. 9, Line 32: Change “icreases” to “increases”

Response 20: The change has been made. Please see **p. 12 Line 20**.

p. 16, Figure 2 caption: Change “Rr and Rr” to “Rr and RR” and “r and r” to “r and R”

Response 21: The change has been made. Please see the caption of now **Figure 3**.