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

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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: The authors present an analysis of errors in estimation of radial velocity variance. This is no doubt an important area of study to enable turbulence measure-

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Discussion paper

ments using Doppler lidars. The effect of sampling intervals as discussed in section 3 is especially important given the current turbulence measurement strategies being employed. In addition, this manuscript presents a very nice discussion of the implications of the various lidar measurement parameters and non-stationarity of the atmosphere. Therefore, this manuscript deserves publication. I have the following issues with the manuscript in its current form which I believe are important to be addressed. I recommend major revisions.

General comments: This manuscript is missing some important literature review in terms of work already performed in this area such as (Lenschow et al. 2000; Frehlich 2001; Frehlich and Cornman 2002; Frehlich 2004 and more). These works have tackled the question of estimating the random error variance in the radial velocity variance estimate and their applications in various measurement scenarios and atmospheric conditions.

Response 1: The works suggested by the referee, while undoubtedly very important for Doppler lidar error quantification, they mainly focus on the measurement errors associated with the uncertainty of Doppler frequency estimators. This paper focuses on the sampling error in radial velocity variance estimates (similar to the sampling error analyzed for the sonic data in (Lenschow et al. 1994). To differentiate the difference between these errors, the following review of errors in lidar turbulence measurements has been added to the introduction section of the paper (**from Page 1, Line 14 to Page 2, Line 20**):

“Using the second method mentioned above, 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).

Measurement error can be estimated and potentially removed using either the auto-covariance or spectrum of the measured radial velocities (Frehlich, 2001; Lenschow et al., 2000). Alternatively, the signal-to-noise ratio (SNR) can also be used to approximate the measurement error (Pearson and Collier, 1999). Correction for the attenuation error requires knowledge of three dimensional spatial statistics (Mann et al., 2010; Frehlich, 1997), and the accuracy of this correction depends on the suitability of the selected turbulence spectrum model and its parametrization (Sathe and Mann, 2013; Mann et al., 2010). The sampling error is well understood for turbulence statistics estimated from sonic anemometer measurements (Lenschow et al., 1994), but has not yet studied for the radial velocity variance estimated from lidar measurements. Mann et al. (2010) call for a thorough sampling error analysis in order to understand the difference between radial velocity variance and momentum fluxes derived from lidars and sonic anemometers. The size of sampling error is a function of the sampling interval and duration (Lenschow et al., 1994), both of which are determined by lidar scan geometries which can, in turn, be optimized to minimize the uncertainty in the estimated turbulence statistics (Sathe et al., 2015) ”

Another important missing element is the influence of SNR on the random errors and biases produced in the radial velocity estimates discussed in the above references).

Response 2: The effect of SNR on measurement error is discussed in Sect. 3 (**Page 5, Line 5 to 28**). The following is an excerpt from the newly added discussion:

“The random measurement error in $\hat{v}_\mathrm{R}$ is modeled by an independent Gaussian random variable with zero mean and variance σ_R^2 which is inversely proportional to the SNR (Pearson and Collier, 1999; Frehlich and Yadlowsky, 1994). Note that σ_R^2 in Eq. (10) is independent of T and can be estimated and removed using the SNR data as dicussed above.”

Specific comments:

Page 2, Line 13: “For a pulsed lidar. . . ” This statement appears to generalize that all lidars use step and stare measurement technique and 1s accumulation. However, most lidars employ continuous scanning. Therefore, please make clear that you are referring to the operation of the Galion lidar operated in step-stare mode.

Response 3:The statement has been replaced with the following sentence to specifically refer to the Galion lidar (**Page 3, Line 11**):

“The Galion lidar used here is a pulsed lidar that in this application measures radial velocity with the step-stare technique.”

Eq. (4): I am not sure I understand why the integral is over –inf to inf. Shouldn’t the integral be over the range-gate length i.e. –L/2 to L/2, where L is the length of the gate? In your case, s-L/2 to s+L/s?

Response 4: The definition of Eq. (4) is based on Eqs (21) and (22) in Frenlich (1997). The radial velocity corresponding to the return signal at one specific range (or time) is defined as

$$v_{r,pulse}(s) = \int_{-\infty}^{+\infty} v_r(s')I_n(s-s')\mathrm{d}s' \quad (1)$$

where $I_n(s)$ is the range weighting function due to the spatial extent of the laser pulse and it is often approximated by the Gaussian function. The radial velocity measured by a pulsed lidar over a range gate is best approximated as

$$v_R(s) = \frac{1}{L}\int_{s+L/2}^{s-L/2} v_{r,pulse}(s')\mathrm{d}s' \quad (2)$$

Combining the two equations above gives the definition of the lidar- derived radial velocity in Eq.(4). The integration is taken over the range gate from -L/2 to L/2, but the integrand is $v_{r,pulse}$ that has the spatial extent from -inf to +inf, mathematically and from 0 to +inf physically. Therefore, the integration is over -inf and +inf.

Page 4, Line 20 and Eq (15): How does this random error compare with the random error variance estimated using technique outlined in Lenschow et al (2000)? In addition, this seems to neglect the influence of SNR on the radial velocity error. For example, as SNR degrades, we expect the Crammer-Rao Lower Bound variance to increase resulting in greater uncertainty in the radial velocity estimate (or even biases due to improper peak estimation). How does the present formulation account for this? Also see (Frehlich 1997; Frehlich et al. 1998) for a discussion of this.

Response 5: The technique outlined in Lenschow et al (2000) is an important tool to estimate and remove the bias in radial velocity variance estimates caused by measurement error. However, this paper focuses on the sampling error in the estimated radial velocity variance. A review is provided in the introduction section to differentiate these two types of errors (**from Page 1, Line 14 to Page 2, Line 20**). Also please refer to the **Response 1** here. The measurement error in the observational data has been removed using the SNR data when estimating radial velocity variance in Sect. 4.1 (**from Page 1, Line 7 to 8**):

"Measurement errors were corrected in lidar radial velocity variance estimates usng the SNR data according to Eq. (5) in Pearson and Collier (1999). Radial velocity variance derivded from the sonic data is estimated using the method from Lenschow et al. (2000)."

Page 6, Line 18-23: Here the lidar data is used to estimate stationarity. Isn't it better to use the sonic measurements to do this as it is at a much higher data rate and captures a larger range of scales?

Response 6: The reason to use the lidar data for the stationarity test is that lidars are typically used as stand-alone instruments when no sonic data will be available. In this case, the stationarity test can only be done with the lidar data. IAs pointed out above, it is likely that better results will be obtained usinge the sonic data for the stationarity test. Therefore, the same method is applied to both the sonic data and lidar data for the stationarity test in the revised manuscript and the hours when both datasets passed the test were selected. Please see the modification **from Page 8, Line 14 to 19**:

"Thus, the hourly time series of radial velocity from both the lidar and sonic anemometers are evaluated for stationarity using the approach of Foken and Wichura (1996). Each hourly time series is evenly divided into 12 subsets. If the mean of the variance of the subsets deviates by less than 30% from the variance of the hourly time series, the time series is considered to be stationary. Among all the hourly time series obtained at the three heights, 34 concurrent pairs of lidar and sonic data pass the stationarity test (Fig. 5); therefore, they are used to derive the empirical estimates of errors."