Uncertainty in Wind Speed and Direction Measurements from the ARM Doppler Lidars

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Background

A key component of the on-going reconfiguration of the ARM Southern Great Plains (SGP) site involves the establishment of a network of four boundary facilities around the existing central facility that would provide continuous height-resolved measurements of temperature, humidity, and wind. The wind measurements, in particular, will be obtained using scanning coherent Doppler lidars. In this study, we focus specifically on quantifying the accuracy of horizontal wind measurements from one of the existing ARM Doppler lidars using observations from a recent off-site field campaign at the Boulder Atmospheric Observatory (BAO), i.e. eXperimental Planetary boundary-layer Instrument Assessment (XPIA) field campaign, which was funded by the DOE Office of Energy Efficiency and Renewable Energy (EERE).

In March and April of 2015 the ARM Doppler lidar that was formerly at operated at the Tropical Western Pacific site in Darwin Australia was deployed to the BAO for the XPIA field campaign. During XPIA the 300-m tower at the BAO site was instrumented with sonic anemometers at six levels. These sonic anemometers provided highly accurate reference measurements against which the lidar was compared. This provided a rare opportunity to characterize the measurement accuracy of the ARM Doppler lidar because such comparisons are difficult, if not impossible to perform using the existing 60-m tower at ARM's SGP site.

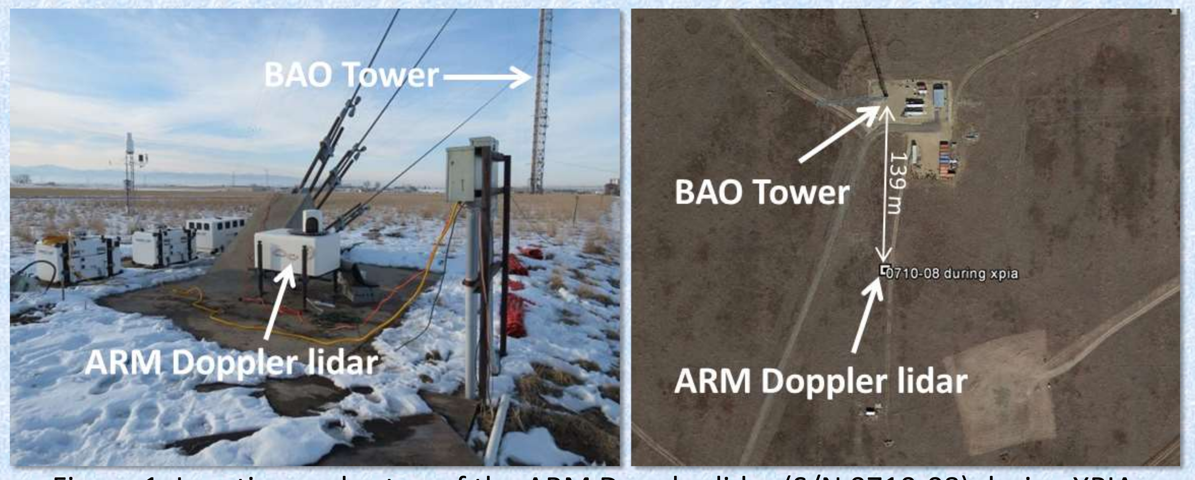

Figure 1. Location and setup of the ARM Doppler lidar (S/N 0710-08) during XPIA.

Doppler Lidar Configuration

During XPIA the Doppler lidar was operated using a fixed scan schedule. Plan-position-indicator (PPI) scans were performed once every 12 minutes using the following parameters:

- Elevation angle = 60°
- Eight evenly-spaced azimuth angles at 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°.
- Pulse integration time = 2 s,
- Time to complete a scan ~ 40 seconds.

BAO Tower Sonic Anemometers

The BAO tower was instrumented at six additional levels (50, 100, 150, 200, 250, and 300m) with fast response (20Hz) 3-D sonic anemometers (Campbell CSAT3). Each of these levels had two sonic anemometers, one mounted on a southeast boom (at a heading angle of 154°) and one mounted on a northwest boom (at a heading angle of 334°).

Wind Retrieval and Uncertainty Estimation

The wind retrieval algorithm uses PPI scan data to estimate wind speed and direction at a given height by minimizing the following chi-squared function with respect to the components of the mean velocity vector, $\mathbf{u}_o = (u_o, v_o, w_o)$:

$$\psi^2 = \sum_{i=1}^{N} \frac{\left(\mathbf{u}_o \mathbf{r}_i^T - u_{ri}\right)^2}{\sigma_{ri}^2} \qquad (1)$$

u_{ri} = Radial velocity

σ_{ri} = Radial velocity uncertainty

$\mathbf{r}_i$ = Unit vector from the lidar to the i^{th} observation point = $(\sin\phi_i \cos\theta, \cos\phi_i \cos\theta, \sin\theta)$

This results in a system of three equations and three unknowns, whose solution is given by

$$\mathbf{u}_o = \mathbf{C}\mathbf{b} \qquad (2)$$

C = Covariance matrix $= \left(\sum_{i=1}^{N} \mathbf{r}_i^T \mathbf{r}_i / \sigma_{ri}^2\right)^{-1}$

$\mathbf{b} = \sum_{i=1}^{N} \frac{u_{ri}}{\sigma_{ri}^2} \tilde{\mathbf{r}}_i^T$

When the individual **measurement uncertainties are known** the uncertainties in the retrieved velocity components can be obtained from the diagonal elements of the weighted covariance matrix

$$\sigma_u = \sqrt{C_{11}} \quad \text{and} \quad \sigma_v = \sqrt{C_{22}} \qquad (3)$$

When the **measurement uncertainties are NOT known**, the uncertainties in *u* and *v* can be estimated by setting $\sigma_{ri} = 1$ in equation (1) and scaling the unweighted covariance matrix with in the following manner

$$\sigma_u = \sqrt{\frac{\psi^2}{(N-N_f)} C_{11}} \quad \text{and} \quad \sigma_u = \sqrt{\frac{\psi^2}{(N-N_f)} C_{11}} \qquad (4)$$

Uncertainty Estimation Trials

Three trials were conducted using different methods for estimating the uncertainty in the derived wind components. The results of these trials were then compared to the sonic anemometer measurements on the BAO tower

Trial 1	• Set σ_{ri} = 1 in equation (1) • Equation (4) is used to estimate uncertainty in u and v
Trial 2	• σ_{ri} is estimated from a sequence of three consecutive PPI scans and two neighboring range gates. • Equation (3) is used to estimate uncertainty in u and v
Trial 3	• Set σ_{ri} equal to the radial velocity precision (see Fig 2) • Equation (3) is used to estimate uncertainty in u and v

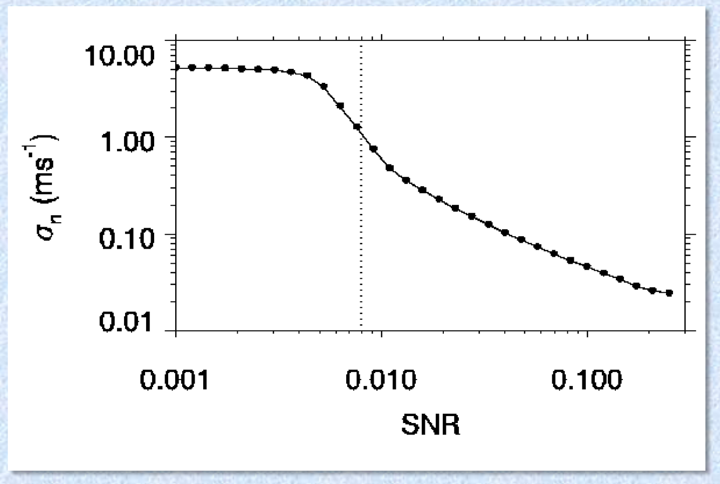

Figure 2. Radial velocity precision as a function of SNR. The radial velocity precision is used to estimate measurement uncertainty for trial 3.

Results

Figure 3 shows representative lidar wind retrieval results for 9 March 2015. The results using Trials 1, 2 and 3 are shown in panels (a), (b) and (c), respectively. The wind speed and direction retrievals (top) for all three trials look qualitatively similar, but the uncertainty estimates (bottom) are substantially different, particularly between Trial 3 and either Trial 1 or 2. The uncertainties for Trials 1 and 2 are similar in structure, although the values for Trial 2 are slightly larger and exhibit more smoothing. The uncertainties for Trial 3 are generally smaller and do not show the same diurnal dependence as either Trials 1 or 2. Trials 1 and 2 show larger uncertainties during the daytime period. By contrast, the uncertainty for Trial 3 tends to follow the SNR and therefore does not show the same strong diurnal dependence.

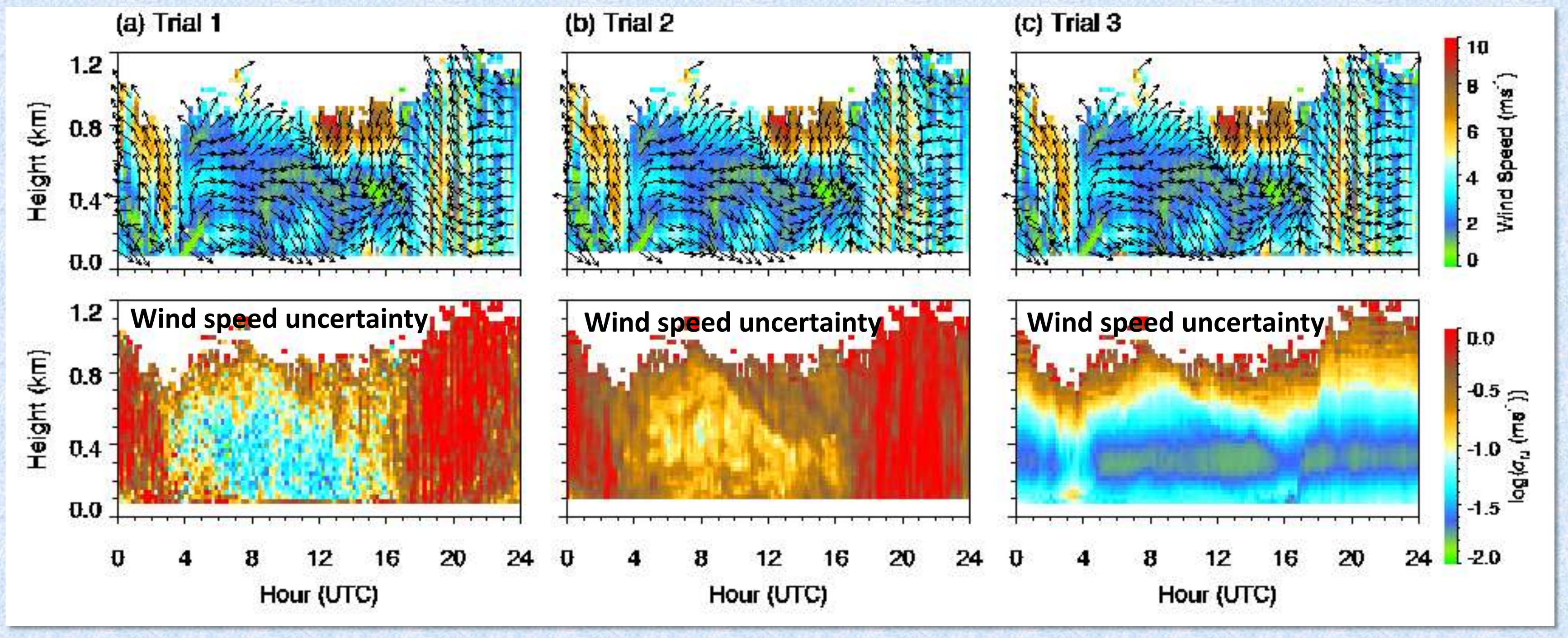

Figure 3. Time-height cross sections for 9 March 2015 showing retrieved winds (top) and estimated wind speed uncertainties (bottom) for a) Trial 1, b) Trial 2, and c) Trial 3.

Tower Comparison

Table 1 summarizes the results of the comparison between the lidar and BAO tower winds for Trials 1, 2 and 3. These results represent averages taken over 4 height levels (142.9, 194.9, 246.8 and 298.8 m) and over the entire deployment period from 6 March through 16 April, 2015.

The results shown in Table 1 are divided into two data quality control categories. The first category uses no data rejection. In this category all of the measurements are used in the computation of the statistics, and no attempt is made to remove poor quality measurements. The second group (i.e. last three columns of Table 1) shows the results with 50% data rejection, i.e. rejection of data with uncertainties in the upper 50th percentile. In this way, the effectiveness of the estimated uncertainty as an indicator of data quality can be assessed.

At 0% data rejection all three trials produce very similar results. However, we see significant improvements in wind speed and direction standard deviations, correlation coefficients and linear regressions for Trials 1 and 2 when 50% of the largest uncertainty estimates are removed. By contrast, the results for Trial 3 are largely unaffected by this filtering operation, indicating that the uncertainty estimates for Trial 3 are poor indicators of data quality.

Data Rejection	0%			50%		
Trial	1	2	3	1	2	3
Mean wind speed difference (lidar-tower) (ms^{-1})	0.02	0.02	0.02	-0.02	-0.01	0.07
Wind Speed Difference Standard Deviation (ms^{-1})	0.73	0.70	0.72	0.43	0.52	0.75
Regression offset (ms^{-1})	0.063	0.052	0.041	0.012	-0.003	-0.153
Regression Slope	0.982	0.986	0.988	1.001	1.001	1.012
Correlation Coefficient	0.975	0.977	0.975	0.992	0.988	0.974
Mean Wind Direction Difference (lidar-tower) (deg)	-0.87	-0.93	-0.85	-1.09	-1.01	-0.48
Wind Direction Difference Standard Deviation (deg)	20.99	20.60	20.76	6.16	6.06	12.55

Table 1. Results of the comparison between the lidar-derived winds and the BAO measurements.

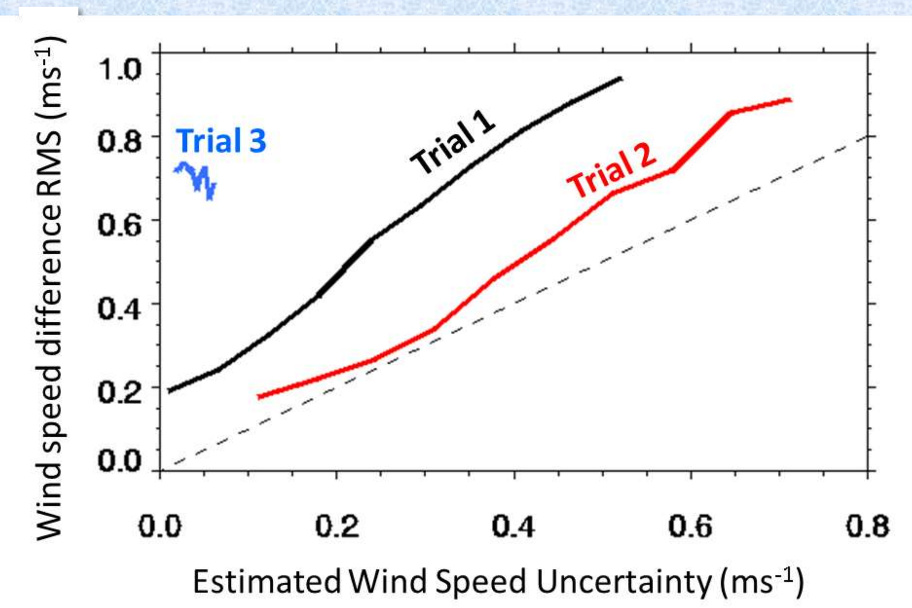

Figure 4. Root-mean-squared difference in wind speed between the lidar and tower wind speed as a function of the estimated lidar wind speed uncertainty. The black, red and blue curves show the results for Trials 1, 2 and 3 respectively.

Figure 4 shows the relationship between the root-mean-squared wind speed difference (lidar – tower) and the estimated lidar wind speed uncertainty. All three Trials tend to underestimate the actual observed differences, as represented by the RMS of the lidar-tower differences. Trial 2 produces error estimates that are closest to the observed differences; whereas Trial 3 produces estimates that are far smaller than the observed differences.

For trial 3 the effects of turbulence are completely neglected such that the radial velocity measurement uncertainty is due solely to instrumental noise. As a result, Trial 3 grossly underestimates the "true" uncertainty.

Trial 1 represents the method that is currently employed by the Doppler lidar wind VAP (dlprofwind4news). Although this method produces better results than the method used in Trial 3, there is still room for improvement by going with the technique used in Trial 2. Operational implementation of the Trial 2 method would require that the lidar execute a sequence PPI scans in quick succession. Radial velocity standard deviations would then be computed along each look direction and used as estimates of the measurement uncertainty

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