NOTES AND CORRESPONDENCE

Radar Wind Profiler Radial Velocity: A Comparison with Doppler Lidar

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ABSTRACT

The accuracy of the radial wind velocity measured with a radar wind profiler will depend on turbulent variability and instrumental noise. Radial velocity estimates of a boundary layer wind profiler are compared with those estimated by a Doppler lidar over 2.3 h. The lidar resolution volume was much narrower than the profiler volume, but the samples were well matched in range and time. The wind profiler radial velocity was computed using two common algorithms [profiler online program (POP) and National Center for Atmospheric Research improved moments algorithm (NIMA)]. The squared correlation between radial velocities measured with the two instruments was $R^2 = 0.99$, and the standard deviation of the difference was about $\sigma_r = 0.20$–0.23 m s^{-1} for radial velocities of greater than 1 m s^{-1} and $\sigma_r = 0.16$–0.35 m s^{-1} for radial velocities of less than 1 m s^{-1}. Small radial velocities may be treated differently in radar wind profiler processing because of ground-clutter mitigation strategies. A standard deviation of $\sigma_r = 0.23$ m s^{-1} implies an error in horizontal winds from turbulence and noise of less than 1 m s^{-1} for a single cycle through the profiler beam directions and of less than 0.11–0.27 m s^{-1} for a 30-min average measurement, depending on the beam pointing sequence. The accuracy of a wind profiler horizontal wind measurement will also depend on assumptions of spatial and temporal inhomogeneity of the atmosphere, which are not considered in this comparison. The wind profiler radial velocities from the POP and NIMA are in good agreement. However, the analysis does show the need for improvements in wind profiler processing when radial velocity is close to zero.

1. Introduction

Winds measured with radar wind profilers have been compared with measurements by rawinsondes, aircraft, tall towers, and other radar wind profilers. Good agreement is usually reported, and when large disagreements are found a likely explanation is proposed. Such explanations include separation in time or space of the measurements, contamination of the radar wind profiler Doppler spectra by ground clutter or birds, inhomogeneous or intermittent rain, and mechanical failure or malfunction of the radar or other instrument. In comparisons with rawinsondes, both Martner et al. (1993) and Fukao et al. (1982) found the standard deviation between radar-derived winds and nearby rawinsonde measurements to range between 3 and 5 m s^{-1}. Slightly larger standard deviations are reported by Larsen (1983). In tropical conditions with strong signal-to-noise ratio (SNR) in the radar returns, Riddle et al. (1996) report standard deviations of 1.0–1.5 m s^{-1} in a similar comparison with rawinsondes. Other comparisons of radar-derived winds with rawinsondes by Gage and Balsley (1978), Warnock et al. (1978), and Ecklund et al. (1979) show qualitative agreement. In comparisons with tower measurements, Cohn et al. (2001a) found a standard deviation of 1.5 m s^{-1} using a spaced antenna technique, and Angevine et al. (1998a) found a standard deviation of 1 m s^{-1}. Weber et al. (1990) compared wind measurements from two closely situated radar wind profilers and found a standard deviation of about 2.2 m s^{-1} for hourly wind measurements. Cohn et al. (2001b) present a comparison of radar wind profiler and aircraft winds with a squared correlation of $R^2 = 0.86$. Further examination shows the standard deviation of these data to be 1.6 m s^{-1}. In another comparison with aircraft, Angevine and MacPherson (1995) found a standard deviation of 3 m s^{-1}. In all of these comparisons,

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there are concerns about the temporal or spatial coincidence of the data, effects of ground clutter on the radar wind profiler measurements, or the limited precision of the other sensors (e.g., Fukao et al. 1982).

In this paper, the radial velocity (first moment of the Doppler spectrum) from a radar wind profiler is directly compared with radial velocity measured with a Doppler lidar. The comparison minimizes differences from separation in time or location because the measurements are coincident in time and the lidar beam volume lies within the radar wind profiler beam volume. The radar wind profiler has a 9° beamwidth (full width between the half-power points) and has a 60-m range resolution; the lidar used in the study has a 0.2-m-diameter beam with very little divergence and has a range resolution of 30 m. The lidar provides a wind measurement that is completely independent from the wind profiler, with even the source of backscatter (aerosol vs refractive index gradients) being different. Both sensors were scanned in a repeating sequence of directions, including vertical and several oblique directions. The comparison includes profiler radial velocity calculated using the National Center for Atmospheric Research (NCAR) improved moments algorithm (NIMA; Morse et al. 2002; Cornman et al. 1998) and the profiler online program (POP) real-time algorithm (Carter et al. 1995). Only high-quality data with weak or absent ground clutter, no other interference, and good SNR are used. For a comparison of NIMA and POP under a wider range of conditions see Cohn et al. (2001b) and Morse et al. (2002).

This evaluation also examines the performance of these algorithms for small radial velocities for which ground clutter, or features of the processing to avoid ground clutter, can bias the wind profiler measurements. Cohn et al. (2001b) compared NIMA-derived moments with ‘‘human-expert’’ moments. The current analysis extends this work by comparing NIMA radial velocity with independent lidar measurements and by considering vertical beam measurement data, which typically have small radial velocity.

2. Choice of dataset and quality control

During the Lidars in Flat Terrain (LIFT)/Flatland96 experiment (Cohn et al. 1998; Angevine et al. 1998b), about 2.3 h of data were collected with a Doppler lidar scanning mirror ‘‘slaved’’ to the beam pointing sequence of a boundary layer radar wind profiler. The lidar was located about 25 m from the profiler, and so the data collected were nearly coincident in both space and time. Small differences in time are present between the two sets of observations, caused by delays when rotating the lidar mirror relative to the electronic steering of the profiler beam pointing. Although the lidar volume is located entirely within the field of view of the profiler, the 0.2-m lidar beamwidth is much smaller than the wind profiler beamwidth, which ranges from about 75 m at the 0.5-km range to as much as 400 m at the 2.5-km range. So, the lidar volume is instantaneously many orders of magnitude smaller than the wind profiler volume, but as the atmosphere advects through these volumes for the 25-s integration time, the atmosphere sampled by the lidar is about 3 orders of magnitude smaller than that seen by the radar wind profiler.

The data were collected from 1322 to 1542 UTC 22 August 1996 near Monticello, Illinois. This period was during early-morning growth of a convective boundary layer with clear skies and warm temperatures. The wind profiler was a 915-MHz boundary layer radar (Ecklund et al. 1990; Carter et al. 1995). Data were collected using a repeating beam sequence of vertical, east, north, vertical, west, and south in which the oblique beams were tilted 21° from zenith. Dwell times were about 25 s for each beam direction.

Lidar radial velocity measurements were made with the National Oceanic and Atmospheric Administration (NOAA) high-resolution Doppler lidar (HRDL) described by Grund et al. (2001). To coordinate the measurements, the lidar scanning platform was modified to accept a signal from the wind profiler, indicating the azimuth and elevation angles. The lidar scanner took up to 5 s to move to a new position, whereas the profiler beam steering took about 1 s. Lidar data were collected with 1-s resolution and were later averaged to match the 25-s profiler resolution. This average included only those times when the lidar beam was within 1° of the profiler pointing direction. To ensure comparison of good-quality data, only POP measurements with SNR greater than −11 dB, NIMA measurements with NIMA first-moment confidence greater than 0.7, and HRDL radial velocities with signal intensity greater than an empirically determined threshold of 315 (unscaled units) are included. A NIMA confidence of 0.7 was used because the study of Cohn et al. (2001b) showed that for data above this threshold there is good agreement between human-expert-determined moments and NIMA moments. The SNR threshold of −11 dB was selected based on previous experience with POP measurements. Data above this threshold agree well with human-determined moments in the absence of other signal contaminants such as ground clutter and radio frequency interference. The HRDL intensity threshold removes velocities computed from weak lidar signals and noise and was the most restrictive filter. HRDL measurements were generally available from a first range of about 400 m to the top of the boundary layer. Note that POP is intended as an efficient, rudimentary real-time algorithm for radar wind profilers, but it has proven to be robust, with good-quality spectra.

One additional processing step was taken. A noticeable bias was found when comparing wind profiler and lidar radial velocities. This bias was beam dependent, with the NIMA and POP radial velocities being systematically about 0.96 of the lidar radial velocity for two oblique beam directions and nearly 1.00 for the other oblique directions. The NIMA and POP radial velocities did not have a bias relative to each other. The most likely explanation for this bias is a slight offset of elevation angle for these beam directions. Given an assumption of a constant wind field, a pointing error of about 1° in elevation (e.g., the lidar pointing at 22° from zenith rather than 21°) could more than account for this bias. The effect of the pointing error on the slope would be

$$m = \sin(21°)/\sin(22°) = 0.957.$$

In the case of a constant wind field with no noise, the two radial velocity fields would be linearly related, with m as the slope of the regression line. Before further comparison, each beam direction of the lidar radial velocities was adjusted for this bias. The vertical beam data cannot be tested for a pointing bias because, for small velocities, it would be much smaller than random differences in the data.

3. Wind profiler performance

a. Oblique-beam velocity comparison

The radial velocities from the profiler and lidar are compared in Figs. 1a,b. These comparisons show an excellent correlation ($R^2 = 0.99$) over a moderate interval of velocities. The NIMA and POP results also have a high correlation, as seen in Fig. 1c. The standard deviation between profiler and lidar radial velocity measurements is 0.25 m s^{-1} for NIMA processing and is 0.23 m s^{-1} for POP processing, with an average absolute error of 0.18 m s^{-1} for NIMA processing and 0.17 m s^{-1} for POP processing. These standard deviations have contributions from noise in both measurement systems and from the turbulent motion field sampled differently in the wind profiler volume and the lidar subset of this volume. The lidar statistical precision is estimated to be approximately 0.05 m s^{-1} for the 25-s averages (V. Wulfmeyer 2000, personal communication). The error of 0.25 m s^{-1} compares favorably to a value of about 0.33 m s^{-1} found in the comparison of NIMA with human-expert-determined moments by Cohn et al. (2001b). It is unusual that a comparison between two instruments yields closer agreement than two analyses of the same dataset. However, the Cohn et al. (2001b) dataset was chosen to be particularly challenging, with clutter, radio frequency interference, and low signal strength. For the highest-quality data (data with NIMA

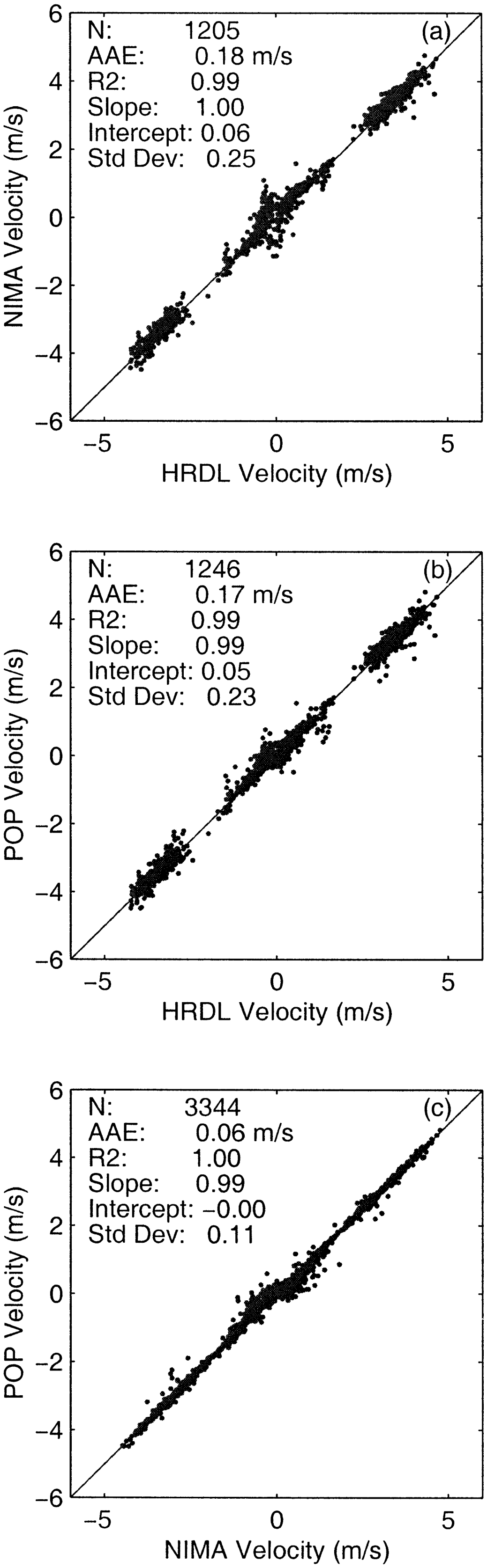

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FIG. 1. Scatterplot of radial velocity measurements for oblique beams for 22 Aug 1996: (a) profiler velocity using NIMA vs the HRDL velocity, (b) profiler velocity using the POP real-time algorithm vs the HRDL velocity, and (c) profiler velocity using NIMA vs the POP real-time algorithm. The plotted line has a slope of 1 and an intercept of 0. In the legend, N is the number of points included, AAE is the average absolute error, R2 is the squared correlation coefficient, the slope and intercept are of a least squares fit line, and std dev is the standard deviation of the data.

confidence above 0.9) in the Cohn et al. (2001b) study, a standard deviation of 0.23 $\mathrm{m\ s^{-1}}$ was observed. Like in the Cohn et al. (2001b) study, as well as in the simulations of Morse et al. (2002), POP and NIMA are in excellent agreement for high-quality data (Fig. 1c).

An interesting feature in Fig. 1 is the region within about 1 $\mathrm{m\ s^{-1}}$ of zero velocity, where the correlations are weaker. Ground clutter centered at zero velocity is a known contaminant of radar wind profiler data at lower altitudes. This contamination has known effects on both POP and NIMA processing. The lidar, with a narrow beam, should not be affected by ground clutter. For the comparison dataset, there is very little ground clutter present in the profiler data because HRDL measurements become available only above 400 m. The NIMA velocities tend to be larger than HRDL velocities; the POP velocities tend to be smaller than HRDL velocities. Relative to POP, NIMA velocities tend to be larger. Velocity differences caused by clutter will depend on the power and spectral width of both the atmospheric and clutter signals. This dependence is discussed further in the next section, in which vertical beam measurements are examined. When statistics are computed for the oblique-beam dataset, excluding radial velocities less than 1 $\mathrm{m\ s^{-1}}$ (accounting for approximately one-half of the values), standard deviations of 0.20, 0.23, and 0.07 $\mathrm{m\ s^{-1}}$ are found for NIMA–HRDL, POP–HRDL, and POP–NIMA comparisons, with corresponding average absolute errors of 0.16, 0.17, and 0.04 $\mathrm{m\ s^{-1}}$, respectively.

b. Vertical-beam velocity comparisons

A comparison of radial velocities for data collected with vertically pointed beams is shown in Fig. 2. Vertical motions are mostly less than 1 $\mathrm{m\ s^{-1}}$, as would be expected in an early-morning boundary layer. The correlations of these data are relatively poor ($R^2 = 0.4$), resulting from a small range of values, but the standard deviations are comparable to that seen with the oblique beams. The standard deviation of the radial velocity measurements in Figs. 2a,b, without correction for any bias, is $\sigma_r = 0.30\ \mathrm{m\ s^{-1}}$ for the NIMA measurements and $\sigma_r = 0.15\ \mathrm{m\ s^{-1}}$ for the POP measurements.

The data presented in Fig. 2 do provide insight into POP and NIMA performance for small Doppler shifts for which ground clutter is expected. The lidar can be taken as being closer to ‘‘truth’’ than the profiler because it is not susceptible to ground clutter. The POP routine uses a simple algorithm to avoid ground clutter, but the algorithm has no effect when the clear-air radial velocity approaches zero (Carter et al. 1995). Because of this fact, POP velocities are sometimes biased toward zero radial velocity, because a ground-clutter feature is chosen rather than a weaker clear-air feature. The dataset used in this study minimizes this effect relative to more typical wind profiler datasets. NIMA alternatively has fuzzy-logic interest maps, which de-emphasize features

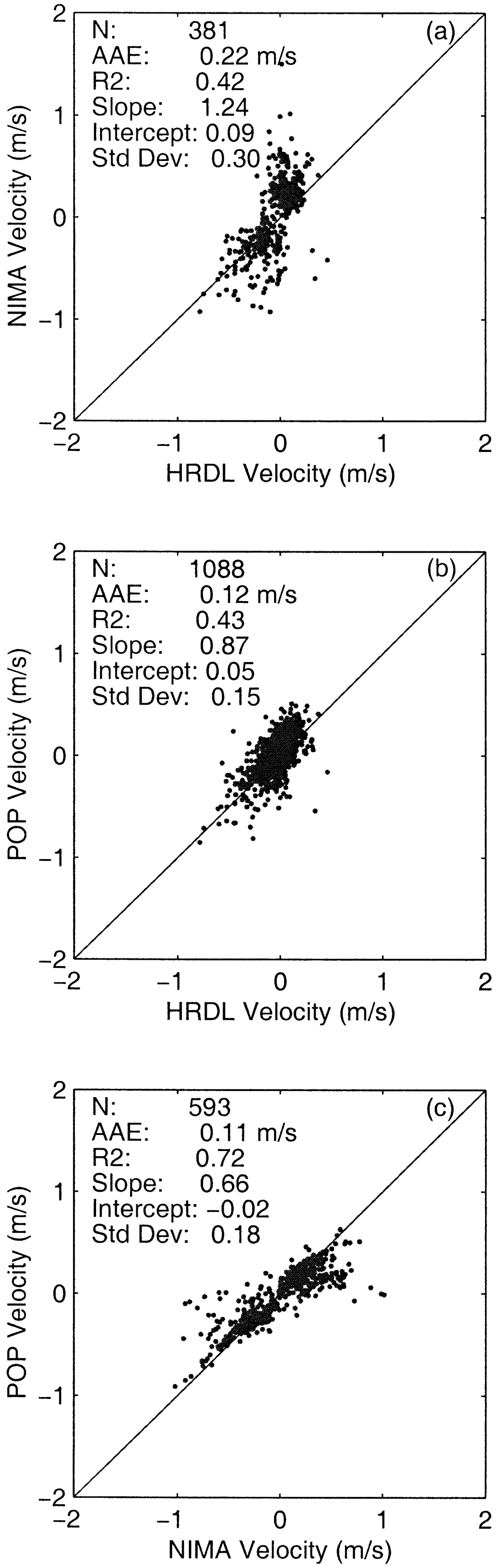

FIG. 2. Same as in Fig. 1, but of radial velocity measurements for vertical beams.

near zero velocity, and so it has a bias against zero radial velocity whether or not ground clutter is present. NIMA assigns low confidence to velocities near zero (Morse et al. 2002) so a confidence-filtered dataset will be biased away from zero velocity. These effects can be seen in Fig. 2c, in which some POP radial velocities are closer to zero than the corresponding NIMA values.

It is also useful to note the fraction of points removed by each of the data-quality filters. The HRDL signal threshold removed 66% of available vertical measurements as compared with 57% of the oblique measurements. The majority of these were at high altitudes with very weak aerosol backscatter. In the radar wind profiler analysis, the POP SNR threshold of −11 dB removed 30% of the vertical measurements as compared with 6% of oblique measurements, and the NIMA confidence threshold of 0.7 removed 77% of vertical measurements and 6% of oblique measurements. This large effect reflects the tendency of NIMA to de-emphasize small velocities and to lower the confidence estimate for values that it does choose that are close to zero velocity. This suggests that the NIMA confidence can be improved, increasing confidence in values near zero velocity when appropriate.

NIMA was initially developed for a four-beam wind profiler sequence that did not include a vertically pointing beam. The algorithm has been expanded to include five-beam profiler sequences, but there has been little experience with vertical beam measurements. The developers of NIMA are aware of its limitations for small velocities and plan improvements in the future (C. Morse 2001, personal communication).

4. Implications for radar wind profiler precision

It is straightforward to estimate the effect of a given precision in radial velocity on the horizontal wind estimate. For this calculation we use a value of $\sigma_r = 0.23$ m s^{-1}. For a three-beam wind profiler configuration (for simplicity, a vertical beam and oblique beams pointed north and east at a zenith angle of ϕ), the wind is given by

$$\left(u = \frac{a_E - a_V \cos\phi}{\sin\phi},\ v = \frac{a_N - a_V \cos\phi}{\sin\phi},\ w = a_V\right), \tag{1}$$

where u, v, and w are the eastward, northward, and vertical components of the wind, respectively, and a_x is the radial measurement with the subscript x indicating the beam direction (E for east, V for vertical, etc.). Here the convention is chosen so that a_x is positive away from the profiler. If it is assumed that the measurement variance σ_r is the same for each beam direction, that there is no error in the zenith angle, and that errors in different directions are independent and have zero mean, then a propagation of error analysis yields

$$\sigma_u = \sigma_v = \frac{\sigma_r}{\sin\phi}\sqrt{1 + \cos\phi^2}; \quad \text{and} \quad \sigma_w = \sigma_r. \tag{2}$$

For our value of $\sigma_r = 0.23$ m s^{-1} and a zenith angle of $\phi = 21°$, this gives a measurement standard deviation in each horizontal wind component of $\sigma_u = \sigma_v = 0.88$ m s^{-1} and in the vertical wind of $\sigma_w = 0.23$ m s^{-1}.

A similar analysis can be done for a five-beam wind profiler, with a vertical beam and oblique beams tilted in the north, east, south, and west directions. In this case,

$$u = \frac{a_E - a_W}{2\sin\phi}, \qquad v = \frac{a_N - a_S}{2\sin\phi}, \quad \text{and} \quad w = a_V \tag{3}$$

and the random errors propagate as

$$\sigma_u = \sigma_v = \frac{\sigma_r}{\sqrt{2}\sin\phi}, \quad \text{and} \quad \sigma_w = \sigma_r. \tag{4}$$

This equation gives a measurement standard deviation in each horizontal wind component of $\sigma_u = \sigma_v = 0.45$ m s^{-1} and in the vertical wind of $\sigma_w = 0.23$ m s^{-1}.

These are the standard deviations expected in the horizontal wind retrieved from a single three-beam or five-beam measurement sequence from turbulence and instrument noise. These random errors can be reduced by averaging. For example, POP uses a consensus average (Carter et al. 1995) and NIMA uses a confidence-weighted average (Goodrich et al. 2002). If, for example, a 30-min average is done of 30-s beam dwell times, these values would be reduced by a factor of $\sqrt{20}$ (=4.5) for a three-beam system (20 cycles) or by a factor of $\sqrt{12}$ (=3.5) for a five-beam system (12 cycles). These estimates assume independence of measurement errors between cycles and do not include errors from spatial inhomogeneity between the separated volumes of different wind directions or temporal changes over the 30-min averaging period. Our analysis is specific to data collected with the profiler parameters of the 22 August 1996 dataset. However, these parameters are typical for good operation of a boundary layer profiler.

5. Discussion and conclusions

The standard deviations presented between radar wind profiler and lidar radial wind measurements can be attributed to turbulent variability and instrumental noise. The chosen dataset minimizes differences from temporal uncertainties, spatial uncertainties, and effects of ground clutter and other interfering signals. Although the lidar measurement volume was largely contained within the wind profiler volume, it was sampling a small subset of this larger volume and therefore was sampling a different ensemble of turbulent motions. Both turbulence and instrument noise are zero-mean, random processes, and it is beyond the scope of this study to separate quantitatively the contributions to the total observed standard deviation from each. However, one indication that turbulence is a significant factor comes from examination of the variability of the 1-s lidar measurements, which were averaged to the 25-s dwell time of the radar wind profiler. The distribution of standard deviations of each of the averages has a mean value of 0.17 m s^{-1}, and about 80% of the values lie between 0.1 and 0.3 m s^{-1}.

In this study, radial velocities measured with a boundary layer radar wind profiler and a Doppler lidar whose beam was within the profiler beam have been compared. For oblique data, excluding small velocities for which there are known limitations of wind profiler data processing, the standard deviation of the 2.3-h comparison was about $\sigma_r = 0.20$–0.23 m s^{-1}. This result confirms that, although the radar wind profiler energy scatters from refractive index gradients and the lidar energy scatters from aerosols, both instruments observe essentially the same radial velocity. Because the measurements are independent, it also provides an indication of the precision of radial velocity measured with these instruments over a 25-s integration. These radial velocity standard deviations would result in standard deviations in the horizontal wind of less than 1 m s^{-1} for a single beam cycle of measurements. However, this result is based on a small sample of data and the analysis should be repeated in similar experiments before being generalized as characteristic of boundary layer wind profiler measurements. Also, the standard deviations found for horizontal wind measurements include only random errors of turbulence and noise and do not account for variation caused by atmospheric conditions inconsistent with the assumptions of a horizontally uniform and stationary-mean wind field.

Wind profiler radial velocities found with NIMA and POP agree well with a standard deviation of 0.07 m s^{-1} when small radial velocity data are excluded and a standard deviation 0.18 m s^{-1} for the small radial velocity measurements of the dataset. Note that this result is for data that contain very little ground clutter. For these small velocities, POP values are sometimes biased toward zero velocity, whereas the NIMA values are biased away from zero velocity. In addition, the NIMA confidence may be lower for data near zero velocity, even when agreement with the lidar is very good. This result suggests that NIMA can be improved for small velocities.

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REFERENCES

Angevine, W. M., and J. I. MacPherson, 1995: Comparison of wind profiler and aircraft wind measurements at Chebogue Point, Nova Scotia. *J. Atmos. Oceanic Technol.,* **12,** 421–426.

——, P. S. Bakwin, and K. J. Davis, 1998a: Wind profiler and RASS measurements compared with measurements from a 450-m tall tower. *J. Atmos. Oceanic Technol.,* **15,** 818–825.

——, A. W. Grimsdell, J. M. Warnock, W. L. Clark, and A. C. Delany, 1998b: The Flatland boundary layer experiments. *Bull. Amer. Meteor. Soc.,* **79,** 419–431.

Carter, D. A., K. S. Gage, W. L. Ecklund, W. M. Angevine, P. E. Johnston, A. C. Riddle, and C. R. Williams, 1995: Developments in UHF lower tropospheric wind profiling at NOAA's Aeronomy Laboratory. *Radio Sci.,* **30,** 977–1001.

Cohn, S. A., S. D. Mayor, C. J. Grund, T. M. Weckworth, and C. Senff, 1998: The Lidars in Flat Terrain (LIFT) experiment. *Bull. Amer. Meteor. Soc.,* **79,** 1329–1343.

——, W. O. J. Brown, C. L. Martin, M. S. Susedik, G. Maclean, and D. B. Parsons, 2001a: Clear air boundary layer spaced antenna wind measurement with the Multiple Antenna Profiler (MAPR). *Ann. Geophys.,* **19,** 845–854.

——, R. K. Goodrich, C. S. Morse, E. Karplus, S. W. Mueller, L. B. Cornman, and R. A. Weekley, 2001b: Radial velocity and wind measurement with NIMA–NWCA: Comparisons with human estimation and aircraft measurements. *J. Appl. Meteor.,* **40,** 704–719.

Cornman, L. B., R. K. Goodrich, C. S. Morse, and W. L. Ecklund, 1998: A fuzzy logic method for improved moment estimation from Doppler spectra. *J. Atmos. Oceanic Technol.,* **15,** 1287–1305.

Ecklund, W. L., D. A. Carter, and B. B. Balsley, 1979: Continuous measurement of upper atmospheric winds and turbulence using a VHF Doppler radar: Preliminary results. *J. Atmos. Terr. Phys.,* **41,** 983–994.

——, ——, ——, P. E. Courier, J. L. Green, B. L. Weber, and K. S. Gage, 1990: Field tests of a lower tropospheric wind profiler. *Radio Sci.,* **25,** 899–906.

Fukao, S., T. Sato, N. Yamasaki, R. M. Harper, and S. Kato, 1982: Winds measured by a UHF Doppler radar and rawinsondes: Comparisons made on twenty-six days (August–September 1977) at Arecibo, Puerto Rico. *J. Appl. Meteor.,* **21,** 1357–1363.

Gage, K. S., and B. B. Balsley, 1978: Doppler radar probing of the clear atmosphere. *Bull. Amer. Meteor. Soc.,* **59,** 1074–1093.

Goodrich, R. K., C. S. Morse, L. B. Cornman, and S. A. Cohn, 2002: A horizontal wind and wind confidence algorithm for Doppler wind profilers. *J. Atmos. Oceanic Technol.,* **19,** 257–273.

Grund, C. J., R. M. Banta, J. L. George, J. N. Howell, M. J. Post, R. A. Richter, and A. M. Weickmann, 2001: High-resolution Doppler lidar for boundary layer and cloud research. *J. Atmos. Oceanic Technol.,* **18,** 376–393.

Larsen, M. F., 1983: Can a VHF Doppler radar provide synoptic wind data? A comparison of 30 days of radar and radiosonde data. *Mon. Wea. Rev.,* **111,** 2047–2057.

Martner, B. E., and Coauthors, 1993: An evaluation of wind profiler, RASS, and microwave radiometer performance. *Bull. Amer. Meteor. Soc.,* **74,** 599–613.

Morse, C. S., R. K. Goodrich, and L. B. Cornman, 2002: The NIMA method for improved moment estimation from Doppler spectra. *J. Atmos. Oceanic Technol.,* **19,** 274–295.

Riddle, A. C., W. M. Angevine, W. L. Ecklund, E. R. Miller, D. B. Parsons, D. A. Carter, and K. S. Gage, 1996: In situ and remotely sensed horizontal winds and temperature intercomparisons obtained using integrated sounding systems during TOGA COARE. *Contrib. Atmos. Phys.,* **69,** 49–61.

Warnock, J. M., T. E. Van Zandt, J. L. Green, and R. H. Winkler, 1978: Comparison between wind profiles measured by Doppler radar and by rawinsonde balloons. *Geophys. Res. Lett.,* **5,** 109–112.

Weber, B. L., and Coauthors, 1990: Preliminary evaluation of the first NOAA demonstration network wind profiler. *J. Atmos. Oceanic Technol.,* **7,** 909–918.