The Precision and Relative Accuracy of Profiler Wind Measurements

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ABSTRACT

Two independent wind profiles were measured every hour during February 1986 with a five-beam, UHF (405 MHz) wind Profiler at Platteville, Colorado. Our analysis of the horizontal wind components over all heights for the entire month gave a standard deviation of about 1.3 m s^{-1} for the measurement errors one can expect for three-beam Profilers in clear air. This study demonstrated that it is important to include the effects of large vertical motion (caused by gravity waves or precipitation) in the horizontal wind component measurements. These vertical motions were large enough to raise the error in the horizontal wind components to 1.7 m s^{-1} in two-beam configurations where no corrections are made for the vertical motion.

1. Introduction

Doppler radars have been used by investigators for more than a decade to study atmospheric winds. Gage and Balsley (1978) and Larsen and Röttger (1982) summarized the radar concepts and reviewed the applications to atmospheric studies. Since 1983, the Wave Propagation Laboratory (WPL) has operated several VHF and UHF Doppler radars in Colorado (Strauch et al., 1984) to provide hourly averaged vertical profiles of horizontal winds. A network of 30 wind Profilers is planned for the midwestern United States toward the end of this decade (Chadwick, 1985). That network will be used both for meteorological research and to evaluate the utility and the feasibility of a national network of wind Profilers for use by the National Weather Service (NWS). The Profilers are designed to provide wind data comparable with data from the radiosondes currently being used by NWS (Hogg et al., 1980; Strauch, 1981; Strauch et al., 1982) but continuous in time. Therefore, it is relevant to ask how well these two instruments compare (Kessler et al., 1985).

A number of studies have compared radar-measured winds with winds measured by other instruments. Balsley and Farley (1976), Farley et al. (1979), Strauch (1981), Fukao et al. (1982), and Larsen (1983), for example, have made numerous comparisons with radiosondes. Lawrence et al. (1986) made comparisons with both radiosonde and lidar measurements. Comparisons with radiosondes are very useful since they are, by historical precedent, the current standard. However, the subject of this study was not the absolute accuracy of Profiler measurements. Rather, we wanted to determine the limit placed on accuracy due to measurement errors, including atmospheric inhomogeneities. To do so, we used a 405 MHz Profiler located at Platteville, Colorado. It had a phased array antenna of Yagi-Uda elements which provided five beam-pointing positions (Law, 1986). Four beams were directed 15 degrees off the vertical toward north, east, south, and west. A fifth pointed straight up to provide a measurement of the vertical velocity (see Fig. 1). The east and north beams gave one measurement of horizontal wind components while the west and south beams gave an independent measurement every hour. The zenith beam was used to correct the measured radial velocities for any vertical velocity due to vertical winds or precipitation fall speeds.

Each of the five beams sampled a different volume of atmosphere. By virtue of their 15-degree tilt from zenith, the four lateral beams interrogated volumes that were displaced about 2.7 km from the vertical beam for measurements at a height of 10 km above the ground. Hence, the total east–west and north–south displacement of the measurement volumes is more than 5 km at that height. Naturally, the separation is zero at the ground and increases with height. This beam separation from zenith exists for each individual Profiler, so a test using this configuration is a test of both the radar measurements and the assumption of horizontal homogeneity. The beam displacements for individual Profilers are small compared with the spacing between Profilers (200–400 km for the proposed Profiler network); horizontal uniformity of winds is assumed for individual Profilers over distances much less than the spacing between Profilers.

This five-beam Profiler gave two independent estimates of the horizontal wind components that were compared each hour. These comparisons cannot, of course, provide the absolute accuracy of Profiler wind measurements. However, they do test the assumption that the hourly averaged winds are uniform horizon-

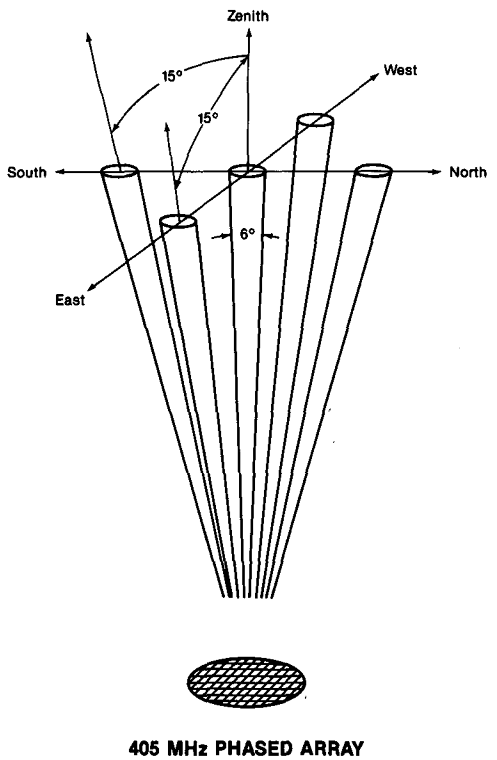

FIG. 1. Antenna beam configuration for the 5-beam UHF (405 MHz) wind Profiler at Platteville, CO.

tally over the antenna beam displacement (up to a few kilometers) of the wind Profiler. The present analysis shows that the horizontal homogeneity assumption is valid because there was close agreement between the wind measurements. These comparisons also provide a measure of the precision of Profiler wind measurements. We can compute the standard deviation (std dev) for the hourly averaged measurements of radial velocity (including vertical velocity) and horizontal wind components from the std dev of the differences between the two Profiler wind measurements. The variance of hourly averaged vertical motion of the scatterers and the impact of ignoring the effect of this motion on horizontal wind measurements were found by analyzing measurements from the four off-vertical beams.

2. Analysis

No attempt was made to determine the absolute accuracy of the wind Profiler measurements by making comparisons with standard measurements. Rather, independent Profiler measurements of the horizontal wind components were compared with one another. A similar approach had already been used (Hoehne, 1980; Kessler et al., 1985) to assess the "functional precision" of identical rawinsondes closely spaced in location and time. Hourly averaged wind components were measured on six antenna beams using the Platteville UHF (405 MHz) Profiler. Actually, only five beam directions were used since two independent measurements (separated slightly in time) were made on the beam that pointed vertically. The radar was cycled through the five beam directions 12 times every hour so that all six beam measurements were interleaved during the hour. Any vertical velocities associated with vertical winds or precipitation contributed to the Doppler velocities on the four beams directed off-vertical. Measurements on the zenith beam were used in order to identify and remove this contribution. The 12 radial measurements taken each hour were averaged using a consensus algorithm (Strauch et al., 1984). Thus, there were two independent measurements made every hour for each of the two horizontal wind components; they were separated in space by virtue of the different antenna beam-pointing directions. The comparisons of these independent measurements show how the precision and accuracy of those measurements are affected by 1) the assumption of horizontal homogeneity, 2) the removal of vertical motion, and 3) the random errors in the radial velocity measurement. The horizontal homogeneity assumption is that the hourly averaged wind field is uniform across all antenna beams at a given height. If this assumption fails, the Profiler cannot provide meaningful measurements. Also, vertical motion is present in the measurements by virtue of the 15° tilt from zenith of the lateral antenna beams. Sometimes it is necessary to remove this vertical motion because the vertical velocity can be large in the presence of precipitation or in the presence of gravity waves in clear air. Finally, the random errors in the radar measurement of radial velocity limit the precision of the estimates of horizontal wind when the wind field is horizontally homogeneous and after vertical motion has been removed.

The radial velocity (positive away from the radar) measured on each of the five antenna beams at a given height is given by

$$
\begin{aligned}
V_{rn} &= +v\cos\theta + W\sin\theta + \delta V_{rn}\\
V_{re} &= +u\cos\theta + W\sin\theta + \delta V_{re}\\
V_{rs} &= -v\cos\theta + W\sin\theta + \delta V_{rs}\\
V_{rw} &= -u\cos\theta + W\sin\theta + \delta V_{rw}\\
V_{rz} &= +W + \delta V_{rz} \qquad (1)
\end{aligned}
$$

where the subscripts n, e, s, w and z denote the north, east, south, west, and zenith antenna beams. At that height, the east-component u, the north-component v, and the vertical velocity W are uniform horizontally across all antenna beams. The vertical velocity W includes the vertical wind w along with the vertical motion due to precipitation; it is positive upward. The elevation angle θ is 75° for all four off-zenith antenna beams. The error terms δV_r contain errors in the radar measurement of radial velocity including both instrument errors and any variations of atmospheric motion from one antenna beam to another.

This analysis makes no distinction between uniform winds during the hour and uniformity of hourly averaged winds. If the winds are not uniform during the hour, hourly averaged estimates of radial velocity will have increased standard deviation, and our analysis attributes this to degraded precision of measured radial velocity. It should also be noted that the hourly averaged wind components do not always include 12 independent measurements spaced uniformly over the hour, particularly at higher altitudes where the signal-to-noise ratio is low. We required a consensus of at least 4 of the 12 estimates when calculating the hourly average for each radial direction. When as few as 4 of 12 estimates are used, there may be significant differences between the times within the hour that different radial velocities were measured for the various beam pointing directions.

The horizontal wind components were estimated from the equations (1) using three different techniques. (i) In the first technique, we estimated the horizontal wind components without correcting for vertical motion, just as would be done in a two-beam wind Profiler. The north/east antenna pair was treated as one two-beam system and the south/west antenna pair was treated as an independent two-beam system. (ii) In the second technique, we estimated the horizontal wind components while making the correction for vertical motion, as would be done in a three-beam system. But, the same zenith measurement was used to make that correction on both the north/east and the south/west antenna pairs. Hence, the results are not completely independent. (iii) The third technique was identical to the second except that independent zenith measurements were used on the north/east and south/west antenna pairs. As a result, we have two completely independent three-beam wind Profiler measurements in this case.

a. Two-beam systems with no vertical correction

When no correction is made for vertical motion, the horizontal wind components are computed from (1) as follows.

$$
\begin{aligned}
V_n &= +V_{rn}\sec\theta = v + \delta V_n \\
U_e &= +V_{re}\sec\theta = u + \delta U_e \\
V_s &= -V_{rs}\sec\theta = v + \delta V_s \\
U_w &= -V_{rw}\sec\theta = u + \delta U_w
\end{aligned}
\tag{2a}
$$

where V_n, U_e, V_s and U_w are the radar-measured horizontal wind components from the north, east, south, and west antenna beams, respectively. The errors in these measurements are

$$
\begin{aligned}
\delta V_n &= +W\tan\theta + \delta V_{rn}\sec\theta \\
\delta U_e &= +W\tan\theta + \delta V_{re}\sec\theta \\
\delta V_s &= -W\tan\theta - \delta V_{rs}\sec\theta \\
\delta U_w &= -W\tan\theta - \delta V_{rw}\sec\theta.
\end{aligned}
\tag{2b}
$$

There are two independent measurements of the east- and north-components of wind. They will be identical only if the errors (2b) vanish; that is, (i) if the winds are horizontally homogeneous, (ii) if the vertical velocity W is zero, and (iii) if there are no radar measurement errors. A useful way to compare these independent measurements is by computing their differences,

$$
\begin{aligned}
DU &= U_e - U_w = \delta U_e - \delta U_w \\
&= 2W\tan\theta + (\delta V_{re} + \delta V_{rw})\sec\theta \\
DV &= V_n - V_s = \delta V_n - \delta V_s \\
&= 2W\tan\theta + (\delta V_{rn} + \delta V_{rs})\sec\theta.
\end{aligned}
\tag{3a}
$$

It is clear that uniform vertical motion contributes the same amount $2W\tan\theta$ to both velocity differences. Random radar measurement errors, on the other hand, produce uncorrelated differences in the velocities. These points are emphasized by the following combinations of the velocity differences (3a).

$$
\begin{aligned}
DC &= (DV + DU)/2^{1/2} = 2^{3/2}W\tan\theta \\
&\quad + (\delta V_{rn} + \delta V_{re} + \delta V_{rs} + \delta V_{rw})\sec\theta/2^{1/2} \\
DS &= (DV - DU)/2^{1/2} \\
&= (\delta V_{rn} - \delta V_{re} + \delta V_{rs} - \delta V_{rw})\sec\theta/2^{1/2}.
\end{aligned}
\tag{3b}
$$

By taking DU to be the x-axis and DV to be the y-axis of a righthand Cartesian coordinate system, we see that DC and DS are the x- and y-axes of another system that is rotated 45° counterclockwise from the first system. The uniform vertical velocity W appears only along the DC-axis, whereas random measurement errors appear on both axes.

Data are conveniently displayed in a scatter diagram for which the DU-axis is horizontal and the DV-axis is vertical. Then, the DC- and DS-axes run diagonally from lower left to upper right and from lower right to upper left, respectively. Figure 2 shows data with no vertical velocity correction during a winter month, when we expect relatively strong vertical velocities in the lee of the Continental Divide, even when averaged for one hour. There is a very distinct elliptical pattern aligned along the DC-axis. This pattern can be explained by considering the errors (3a) and (3b). We assume that the errors δV_r are random with zero mean, that they are uncorrelated with the uniform vertical velocity W, and that they are uncorrelated on all four off-zenith antenna beams. Then, these variances of the errors are

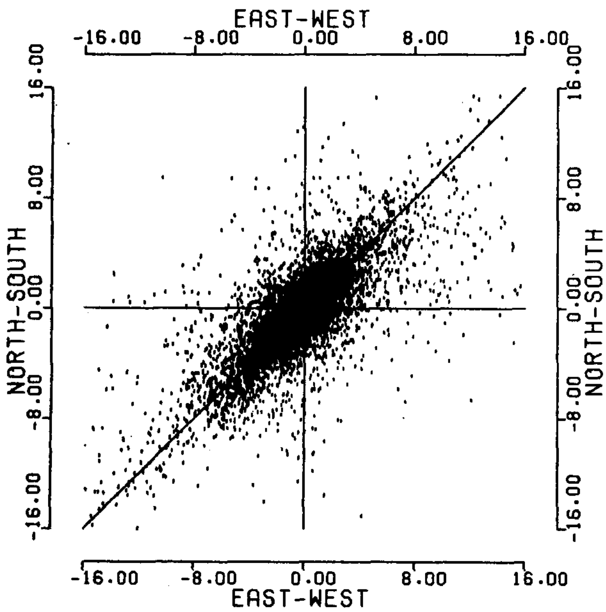

FIG. 2. Scatter diagram of $(V_n - V_s)$ vs $(U_e - U_w)$ during February 1986 for Platteville, CO, UHF (405 MHz) Profiler; two two-beam radar systems (no vertical velocity correction). Data with a consensus of 4 or more estimates out of 12 possible each hour were used.

$$\mathrm{VAR}(DU) = \mathrm{VAR}(DV) = 4\ \mathrm{VAR}(W)\tan^2\theta + 2\ \mathrm{VAR}(\delta V_r)\sec^2\theta$$
$$\mathrm{VAR}(DC) = 8\ \mathrm{VAR}(W)\tan^2\theta + 2\ \mathrm{VAR}(\delta V_r)\sec^2\theta$$
$$\mathrm{VAR}(DS) = 2\ \mathrm{VAR}(\delta V_r)\sec^2\theta \quad (4)$$

where VAR denotes the variance computed over the month and over all heights, and where we assumed the variances of the errors for the radial velocities (1) are the same for all four off-zenith antenna beams. The expressions (4) show that the effect of uniform vertical velocity W can be separated from the effect of measurement error δV_r. By taking the variances of the errors (2b) for the wind component estimates (2a), we find that

$$\mathrm{VAR}(\delta V_n) = \mathrm{VAR}(\delta U_e) = \mathrm{VAR}(\delta V_s) = \mathrm{VAR}(\delta U_w) = \mathrm{VAR}(W)\tan^2\theta + \mathrm{VAR}(\delta V_r)\sec^2\theta \quad (5)$$

which is a combination of vertical motion and measurement error. Therefore, we can use (4) to determine how much of the error in horizontal wind estimates is due to vertical motion and how much is due to measurement error.

There are 8864 data points in Fig. 2; their statistics are listed under antenna system A in Tables 1a and 1b. Note that the mean values along all axes are small, being just a few cm s^{-1}. The monthly average of vertical velocity can be estimated from (3a) if the radial velocity errors δV_r are ignored. The mean W given by the mean of $(DU + DV)/4\tan\theta$ is about -0.01 m s^{-1}. Thus, the data for this experiment were collected mostly in clear air. Vertical winds in convection and precipitation fall speeds would produce large errors (several m s^{-1} or more) in a two-beam system. It is encouraging that the mean of DS is smaller than the other mean values. This implies that the monthly average of measurement errors δV_r [from (2b)] is only an insignificant few cm s^{-1}. The std dev along the DS-axis is also the smallest. By using the expression in (4) for the variance along the DS-axis, we compute a std dev of 0.29 m s^{-1} (Table 2a) for the error δV_r in the hourly averaged radial velocity measurement. Since an average of nine measurements are used in the hourly averages, the std dev of individual radial velocity estimates (obtained in about 60 s) is about three times the std dev of the hourly estimate or 0.9 m s^{-1}. Then by using the expressions in (4) for the variances along the DC-, DU-, and DV-axes, we compute the std dev of hourly-averaged vertical velocity W to be 0.34 m s^{-1} (Table 2b).

By using the std dev of the vertical velocity W (0.34 m s^{-1}) and the std dev of the radial velocity measurement error δV_r (0.29 m s^{-1}) in the expression (5), we compute the std dev of the error for the horizontal wind components to be 1.7 m s^{-1} for a two-beam system. The radial velocity measurement errors alone would have given a std dev of 1.1 m s^{-1} (Table 2d). This is the std dev of the error in the horizontal wind components for a two-beam system when there is no

TABLE 1a. The mean difference and std dev of two independent wind component measurements with and without vertical correction.

Antenna system*	*DU* Mean (m s^{-1})	*DU* Std dev (m s^{-1})	*DV* Mean (m s^{-1})	*DV* Std dev (m s^{-1})	Number of pairs	Consensus out of 12
A	−0.0757	3.0675	−0.1120	2.9415	8864	4
B-1	+0.3336	2.2163	+0.2925	2.0426	8449	4
B-2	+0.3577	2.1655	+0.3065	2.0130	8433	4
C	+0.3507	1.9793	+0.3148	1.8249	8217	4
C	+0.3626	1.5617	+0.3531	1.5034	6883	8
C	+0.5676	1.2110	+0.5828	1.2935	1622	12

* Antenna system A is two-beam with no vertical correction; antenna systems B-1 and B-2 are three-beam each with a different common vertical correction; and C is three-beam with different vertical correction on the north/east and south/west pairs.

TABLE 1b. The mean difference and std dev of two independent wind component measurements referenced to axes rotated 45° counterclockwise from those in Table 1a.

	DC		*DS*			
Antenna system*	Mean (m s^{-1})	Std dev (m s^{-1})	Mean (m s^{-1})	Std dev (m s^{-1})	Number of pairs	Consensus out of 12
A	−0.1327	3.9515	−0.0257	1.5643	8864	4
B-1	+0.4427	2.6162	−0.0291	1.4966	8449	4
B-2	+0.4696	2.5406	−0.0362	1.5122	8433	4
C	+0.4706	2.2677	−0.0254	1.4510	8217	4
C	+0.5061	1.9251	−0.0067	0.9965	6883	8
C	+0.8135	1.6558	+0.0107	0.6310	1622	12

* See footnote to Table 1a.

vertical motion. However, the vertical motion alone would have given a std dev of 1.3 m s^{-1} (Table 2d). We conclude that it is important to include vertical motion when that motion is large compared with the radial velocity measurement error, such as with precipitation or gravity waves.

b. Three-beam systems with common vertical correction

Next, consider two three-beam systems using a common zenith beam to correct for the vertical velocity on all four off-zenith beams. Then the horizontal wind components are computed from (1) by

$$\begin{aligned} V_n &= +V_{rn}\sec\theta - V_{rz}\tan\theta = v + \delta V_n \\ U_e &= +V_{re}\sec\theta - V_{rz}\tan\theta = u + \delta U_e \\ V_s &= -V_{rs}\sec\theta + V_{rz}\tan\theta = v + \delta V_s \\ U_w &= -V_{rw}\sec\theta + V_{rz}\tan\theta = u + \delta U_w \end{aligned} \qquad (6a)$$

in which V_{rz} is the same measurement in all four expressions. These expressions are to be contrasted with those (2a) for the two-beam systems, whose errors (2b) are replaced with

$$\begin{aligned} \delta V_n &= -\delta V_{rz}\tan\theta + \delta V_{rn}\sec\theta \\ \delta U_e &= -\delta V_{rz}\tan\theta + \delta V_{re}\sec\theta \\ \delta V_s &= +\delta V_{rz}\tan\theta - \delta V_{rs}\sec\theta \\ \delta U_w &= +\delta V_{rz}\tan\theta - \delta V_{rw}\sec\theta. \end{aligned} \qquad (6b)$$

Notice that the same error δV_{rz} in the measurement of vertical velocity enters all four equations just like the vertical velocity itself enters all four equations in (2b). As a result, errors in the vertical velocity measurement will have the same effect upon this three-beam comparison as the vertical velocity has upon a two-beam system. That is, they both shift the data in a scatter diagram along the *DC*-axis. Of course, we expect the magnitude of the shift to be smaller in a three-beam system when the error δV_{rz} is smaller than the vertical velocity W. This may not always be the case in clear air, in which case the errors in a two-beam system would be smaller than those in a three-beam system.

The velocity differences for this three-beam system are given by

$$\begin{aligned} DU &= -2\delta V_{rz}\tan\theta + (\delta V_{re} + \delta V_{rw})\sec\theta \\ DV &= -2\delta V_{rz}\tan\theta + (\delta V_{rn} + \delta V_{rs})\sec\theta \\ DC &= -2^{3/2}\delta V_{rz}\tan\theta \\ &\quad + (\delta V_{rn} + \delta V_{re} + \delta V_{rs} + \delta V_{rw})\sec\theta/2^{1/2} \\ DS &= (\delta V_{rn} - \delta V_{re} + \delta V_{rs} - \delta V_{rw})\sec\theta/2^{1/2} \end{aligned} \qquad (7)$$

which are to be contrasted with (3a) and (3b). If the errors δV_{rz} are smaller than the vertical velocity W, then we expect the scatter diagram for a three-beam system to have less scatter than the scatter diagram for a two-beam system. Figure 3 confirms this prediction. The scatter diagram in Fig. 3 was made with data on all four off-zenith beams corrected with the same zenith

TABLE 2a. Standard deviation of off-zenith radial velocity measurements, computed along the *DS* axis in the scatter diagrams for two- and three-beam systems.

Antenna system*	Std dev V_r (m s^{-1})	Consensus out of 12
A	0.2863	4
B-1	0.2739	4
B-2	0.2768	4
C	0.2656	4
C	0.1824	8
C	0.1155	12

* See footnote to Table 1a.

TABLE 2b. Standard deviation of the vertical velocity, inferred from two-beam Profiler wind measurements.

Std dev W (m s^{-1})	Consensus out of 12
0.3436	4

TABLE 2c. Standard deviation of vertical velocity measurements, computed for three-beam systems.

Antenna system*	Std dev V_{rz} (m s^{-1})	Consensus out of 12
B-1	0.2028	4
B-2	0.1930	4
C	0.2328	4
C	0.2206	8
C	0.2049	12

* See footnote to Table 1a. The std dev V_{rz} did not change with consensus number because this was the consensus number for the off-zenith beams. The consensus number was kept at 6 on the zenith beam throughout.

measurement. Another scatter diagram, made with the same data on all four off-zenith beams but corrected with the other independent zenith measurement, shows the same pattern and gives nearly identical results.

Assuming that the errors on all five antenna beams are uncorrelated, the variances in (4) and (5) for the two-beam system are replaced here for the three-beam system by

$$\mathrm{VAR}(DU) = \mathrm{VAR}(DV) = 4\,\mathrm{VAR}(\delta V_{rz})\tan^2\theta + 2\,\mathrm{VAR}(\delta V_r)\sec^2\theta$$

$$\mathrm{VAR}(DC) = 8\,\mathrm{VAR}(\delta V_{rz})\tan^2\theta + 2\,\mathrm{VAR}(\delta V_r)\sec^2\theta$$

$$\mathrm{VAR}(DS) = 2\,\mathrm{VAR}(\delta V_r)\sec^2\theta$$

$$\mathrm{VAR}(\delta V_n) = \mathrm{VAR}(\delta U_e) = \mathrm{VAR}(\delta V_s) = \mathrm{VAR}(\delta U_w) = \mathrm{VAR}(\delta V_{rz})\tan^2\theta + \mathrm{VAR}(\delta V_r)\sec^2\theta. \quad (8)$$

In all of the above expressions, the error in the vertical velocity measurement appears for the three-beam system in the place of the vertical velocity for the two-beam system.

Supposedly, the error δV_{rz} is smaller than the vertical velocity W because the scatter diagram in Fig. 3 is more compact than that in Fig. 2. However, the mean values of the velocity differences DU and DV (Table 1a) are noticeably larger for the three-beam systems than for the two-beam systems. They are about +0.33 m s^{-1} compared with about −0.10 m s^{-1} for the two-beam systems. Apparently, an over-correction for vertical motion was made due to measurement errors. The mean value of the error δV_{rz} can be estimated from the mean of $(DU + DV)/4\tan\theta$ to be about −0.04 m s^{-1}. Several plausible explanations, including a small tilt (less than a degree from vertical) of the zenith beam, have been dismissed. Now it appears that this bias in the mean of δV_{rz} may be due to the way sampling is done on the antennas. During the course of an hour, the Profiler antenna is switched among the five beam-pointing directions in a sequence (north, east, south, west, and zenith). This sequence is repeated 12 times during an hour, so that each radial velocity measurement on each beam takes about one minute. Thus, the measurements on the different antenna beams are not simultaneous. Since this study was completed, we have discovered that biases in the mean values of DU and DV for a three-beam system are reduced to about the same size as those for a two-beam system when the subhourly measurements on all antenna beams are interpolated to the same time. Unfortunately, we could not test this idea with the present data because only hourly averaged measurements were available.

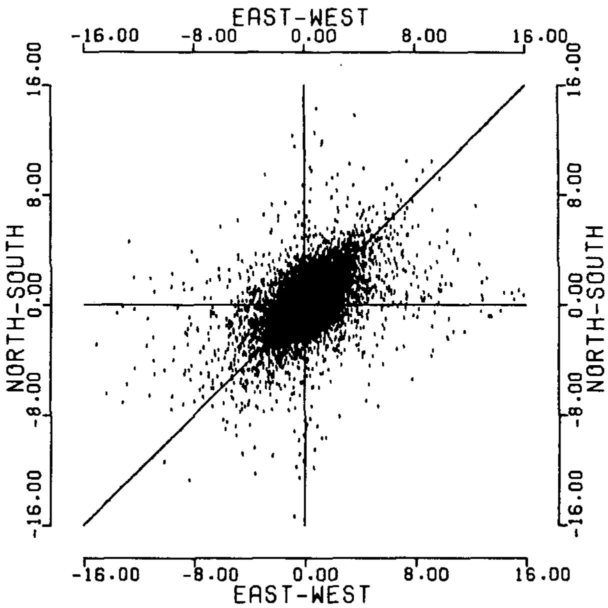

FIG. 3. Scatter diagram of $(V_n - V_s)$ vs $(U_e - U_w)$ during February 1986 for Platteville, CO, UHF (405 MHz) Profiler; two three-beam radar systems (common vertical velocity correction). Data with a consensus of 4 or more out of 12 possible estimates each hour were used.

TABLE 2d. Standard deviation of estimates of horizontal wind components for two- and three-beam systems.

Antenna system*	Consensus out of 12	Std dev horizontal wind component† (m s^{-1})
A	4	1.6937 / 1.2826 / 1.1062
B	4	1.2952 / 0.7386 / 1.0639
C	4	1.3445 / 0.8687 / 1.0262
C	8	1.0837 / 0.8233 / 0.7047
C	12	0.8855 / 0.7648 / 0.4463

* See footnote to Table 1a.
† The first value gives the std dev; the second gives the std dev due to vertical velocity (two-beam) or vertical velocity measurement error (three-beam); and the last is the std dev due to radial velocity measurement error on the off-zenith antenna beams.

The std dev along the DU-, DV-, and DC-axes are smaller for three-beams, being about ⅔ of the values for the two-beam systems. The std dev of DS, on the other hand, is nearly the same for the two- and three-beam systems. (See Tables 1a and 1b.) This is not surprising since neither vertical velocity W nor its measurement error δV_{rz} should affect data along the DS-axis. This fact is demonstrated in (4) for two-beam systems and in (8) for three-beam systems. By using the std dev of DS (8), we compute the std dev of the radial velocity measurement on the off-zenith beams to be 0.27 m s^{-1} (Table 2a), which is nearly identical to the value found with two-beam systems. Then by using (8), it is possible to compute the std dev of the vertical velocity measurement on the zenith beam to be 0.20 m s^{-1} (Table 2c). It is smaller than the value for the off-zenith beams because slightly different averaging times were used. Finally, the std dev of the error for the estimates of horizontal wind components can be computed with (8). By using the std dev of the vertical velocity measurement error δV_z (0.20 m s^{-1}) and the std dev of the radial velocity measurement error δV_r (0.27 m s^{-1}) in the expression (8), we compute the std dev of the error for the horizontal wind components to be 1.3 m s^{-1} for these three-beam systems, compared with 1.7 m s^{-1} for the two-beam system. The radial velocity measurement errors on the off-zenith antenna beams alone would have given a std dev of 1.1 m s^{-1} (Table 2d), as in a two-beam system. But the measurement errors on the zenith antenna beam contributed only a std dev of 0.7 m s^{-1}, compared with 1.3 m s^{-1} (due to vertical motion) for a two-beam system. We conclude that the accuracy of hourly averaged winds for a three-beam Profiler is limited by measurement errors, whereas the accuracy of a two-beam Profiler is limited by vertical motion of the scatterers in the atmosphere when that motion is large compared with measurement errors.

c. Three-beam systems with independent vertical correction

Lastly, consider two three-beam systems using one zenith measurement to correct for vertical motion on the north/east antenna pair and a second independent zenith measurement to correct for vertical motion on the south/west antenna pair. The horizontal wind components are computed from (6a) and their errors are given by (6b), except that the vertical velocity measurement V_{rz} and its error δV_{rz} are different for the north/east and south/west pairs. Thus, two independent errors δV_{rz} now appear in the velocity differences DU, DV, DC and DS instead of the one in (7). This causes the variances (8) to become

$$\mathrm{VAR}(DU) = \mathrm{VAR}(DV) = 2\,\mathrm{VAR}(\delta V_{rz})\tan^2\theta + 2\,\mathrm{VAR}(\delta V_r)\sec^2\theta$$

$$\mathrm{VAR}(DC) = 4\,\mathrm{VAR}(\delta V_{rz})\tan^2\theta + 2\,\mathrm{VAR}(\delta V_r)\sec^2\theta$$

$$\mathrm{VAR}(DS) = 2\,\mathrm{VAR}(\delta V_r)\sec^2\theta$$

$$\mathrm{VAR}(\delta V_n) = \mathrm{VAR}(\delta U_e) = \mathrm{VAR}(\delta V_s) = \mathrm{VAR}(\delta U_w) = \mathrm{VAR}(\delta V_{rz})\tan^2\theta + \mathrm{VAR}(\delta V_r)\sec^2\theta. \quad (9)$$

The only changes are in the variances of DU, DV and DC. That is, the contribution to these variances due to variance in the vertical velocity measurement error is reduced by a factor of ½. This is due to the fact that two independent vertical velocities were used. Figure 4 shows the scatter diagram for this comparison. The std dev of DU, DV, DC and DS in Tables 1a and 1b are consistent with this analysis. Furthermore, the std dev of the radial velocity measurements (Tables 2a and 2c) are consistent for all two- and three-beam systems. The std dev of the horizontal wind components are consistently smaller for three-beam systems compared with two-beam systems. Table 2d shows a std dev of 1.3 m s^{-1} for all three-beam systems to within a few centimeters per second. The std dev is 1.7 m s^{-1} for the two-beam systems. This consistency and the smallness of both the mean and std dev of the velocity differences DU and DV indicates that the assumption of horizontal homogeneity was valid for this experiment.

Since the std dev and mean difference of the Wind Profiler comparisons are determined by radial velocity measurements, it would seem logical to assume that the Profiler performance could be improved by improving this measurement. All data up to this point in our discussion consist of cases for which there were 4 or more estimates out of 12 possible estimates of radial velocity during each hour. We tested this hypothesis by selecting only data with high consensus numbers[1] for three-beam data where there were 8 or more estimates averaged out of a possible 12 (Fig. 5) or 12 out of a possible 12 (Fig. 6). Clearly, the ellipse in the scatter diagram shrinks as the consensus or signal-to-noise ratio increases. Tables 1a and 1b show the decrease in std dev for the increased consensus which is characteristic of the Profiler performance at lower altitudes. Therefore, the precision of the u- and v-component measurements made with a three-beam Profiler is certainly better at lower heights than the precision cited here for all heights. However, the mean differences for these last two cases are slightly greater. The std dev of u and v estimates are given in Table 2d. For data with a consensus of 12 out of a possible 12 the std dev of u and v estimates is less than 0.9 m s^{-1}.

3. Conclusions

We have compared independent measurements of the horizontal wind components using a UHF (405 MHz) Profiler at Platteville, Colorado with a phased array of Yagi-Uda elements that had five beam-pointing positions. The comparisons were made over an entire winter month (February 1986) in essentially clear air. They demonstrated that the accuracy of Profiler estimates of horizontal wind components was limited

[1] In order for the consensus number to be high, two conditions must be met. First, the signal-to-noise ratio in the radar Doppler spectra must be large. Second, the horizontal winds and the vertical velocity must be uniform over the observation time (1 h).

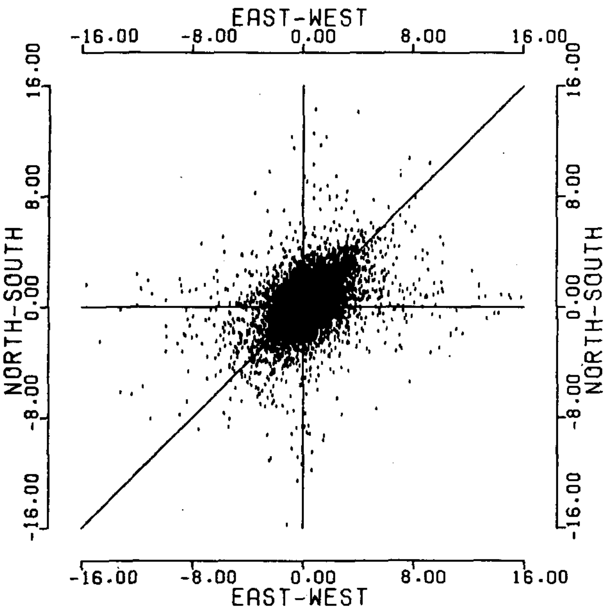

FIG. 4. Scatter diagram of $(V_n - V_s)$ vs $(U_e - U_w)$ during February 1986 for Platteville, CO, UHF (405 MHz) Profiler; two three-beam radar systems (independent vertical velocity corrections). Data with a consensus of 4 or more out of 12 possible estimates each hour were used.

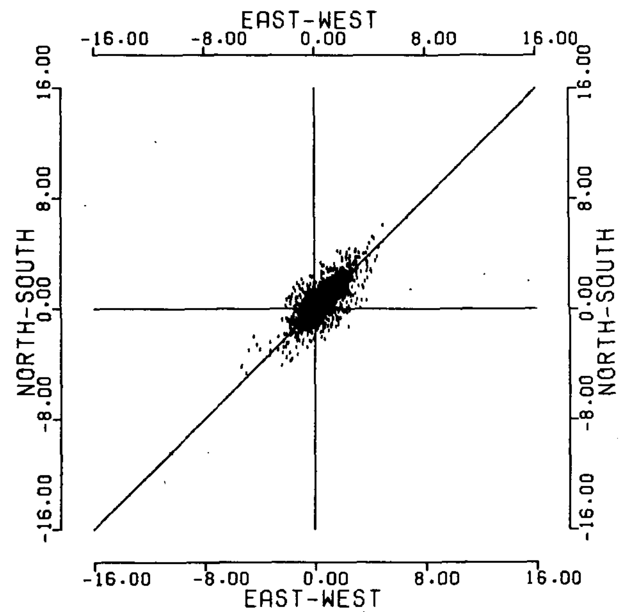

FIG. 6. Scatter diagram of $(V_n - V_s)$ vs $(U_e - U_w)$ during February 1986 for Platteville, CO, UHF (405 MHz) Profiler; two three-beam radar systems (independent vertical velocity corrections). Data with a consensus of 12 out of 12 possible estimates each hour were used.

by errors in the radial velocity measurements, including instrument errors and atmospheric inhomogeneities. This study also demonstrated the importance of making the correction for vertical motion when that motion is large. The std dev of the error in the horizontal wind components was 1.7 m s^{-1} without this correction (two-beam configuration) and 1.3 m s^{-1} with this correction (three-beam configuration). Additional proof that measurement errors were the limiting factor in a three-beam Profiler was supplied when only measurements with the highest signal-to-noise ratios were analyzed. They had a std dev of 0.9 m s^{-1}.

This study has shown that the precision of horizontal wind estimates is better for higher signal-to-noise ratios. Therefore, we may expect the planned network of thirty UHF (405 MHz) wind Profilers to perform better than the Profiler used in this experiment. The network radars will have increased sensitivity compared with the Profiler used in this study. The new Profilers will use only three beams instead of the five used here, so the operating time on each beam during the hour will nearly double. Also, the data processing will be more efficient for the new radars. All of these factors will improve the signal-to-noise ratio for the new Profiler compared with the one used here and, thus, it is reasonable to expect improvement in the precision. The results of this study do not necessarily apply to all locations and all seasons; in particular we note that the comparisons in this case study were made in conditions where lee waves would be expected to degrade Profiler performance but where precipitation was not a significant factor. At 405 MHz, precipitation usually presents a stronger radar echo than clear air. During precipitation it is very important to correct for the fall speed of the scatterers. We are presently analyzing the effects of precipitation on the performance of the UHF (405 MHz) wind Profiler.

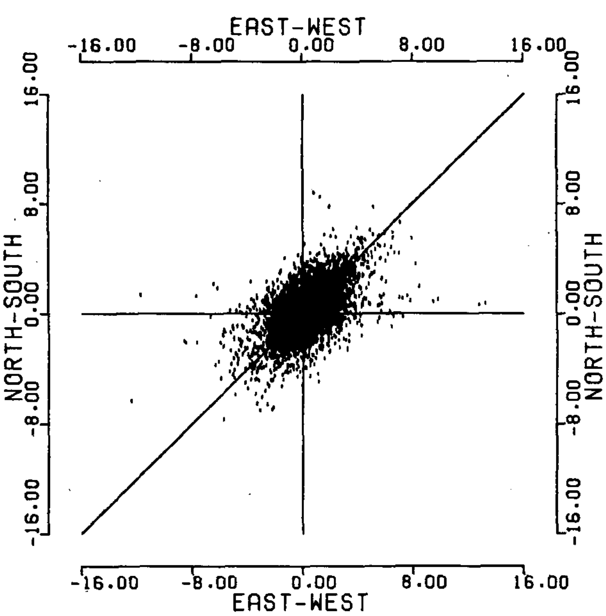

FIG. 5. Scatter diagram of $(V_n - V_s)$ vs $(U_e - U_w)$ during February 1986 for Platteville, CO, UHF (405 MHz) Profiler; two three-beam radar systems (independent vertical velocity corrections). Data with a consensus of 8 or more out of 12 possible estimates each hour were used.

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