# Evaluation of Three-Beam and Four-Beam Profiler Wind Measurement Techniques Using a Five-Beam Wind Profiler and Collocated Meteorological Tower

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ABSTRACT

In this paper a five-beam wind profiler and a collocated meteorological tower are used to estimate the accuracy of four-beam and three-beam wind profiler techniques in measuring horizontal components of the wind. In the traditional three-beam technique, the horizontal components of wind are derived from two orthogonal oblique beams and the vertical beam. In the less used four-beam method, the horizontal winds are found from the radial velocities measured with two orthogonal sets of opposing coplanar beams. In this paper the observations derived from the two wind profiler techniques are compared with the tower measurements using data averaged over 30 min. Results show that, while the winds measured using both methods are in overall agreement with the tower measurements, some of the horizontal components of the three-beam-derived winds are clearly spurious when compared with the tower-measured winds or the winds derived from the four oblique beams. These outliers are partially responsible for a larger 30-min, three-beam standard deviation of the profiler/tower wind speed differences (2.2 m $s^{-1}$), as opposed to that from the four-beam method (1.2 m $s^{-1}$). It was also found that many of these outliers were associated with periods of transition between clear air and rain, suggesting that the three-beam technique is more sensitive to small-scale variability in the vertical Doppler velocity because of its reliance on the point measurement from the vertical beam, while the four-beam method is surprisingly robust. Even after the removal of the rain data, the standard deviation of the wind speed error from the three-beam method (1.5 m $s^{-1}$) is still much larger than that from the four-beam method. Taken together, these results suggest that the spatial variability of the vertical airflow in nonrainy periods or hydrometeor fall velocities in rainy periods makes the vertical beam velocities significantly less representative over the area across the three beams, and decreases the precision of the three-beam method. It is concluded that profilers utilizing the four-beam wind profiler technique have better reliability than wind profilers that rely on the three-beam wind profiler technique.

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## 1. Introduction

Doppler radar profilers are in widespread use around the world to observe vertical profiles of wind. The development of modern wind profiling over the past several decades is described in some detail by Hardy and Gage (1990) and Van Zandt (2000). Wind profilers are now commercially produced and are commonly used for meteorological and air quality campaigns, as well as for operational purposes in many countries. Most contemporary wind profilers utilize the Doppler beam swinging (DBS) method to estimate wind from three- or five-beam systems. Basically, the DBS wind profiler sequentially generates multiple beams from the antenna; one looks vertically, and the remaining two (four) are tilted typically 15.5° from the zenith in two (four) orthogonal directions. The orientation of these beams enables the horizontal and vertical components of the wind (or, alternatively, wind speed and direction) to be determined (Skolnik 2001).

Determination of the accuracy of wind profilers requires the comparison with a standard reference wind measurement. The accuracy of wind profilers in measuring horizontal components of the wind has been estimated in comparison with rawinsondes (e.g., Weber and Wuertz 1990; Martner et al. 1993; Riddle et al. 1996; Belu et al. 2001), towers (e.g., Ye et al. 1993; Baltink 1997; Angevine et al. 1998), lidar (Cohn 2002), and aircraft (e.g., Angevine and Macpherson 1995; Cohn et al. 2001). Strauch et al. (1987) and Weber et al. (1992) showed that the vertical component has a significant influence for wind profilers on the measurement of the horizontal components of the wind. However, the magnitude of vertical velocities is usually much less than the magnitude of horizontal velocities in the free atmosphere, except in convective situations (Gage 1990). Consequently, vertical velocities are easily masked by ground clutter that appears around zero velocity (Cornman et al. 1998). Indeed, Cohn (2002) showed that the estimation of the radial component from the vertical beam was difficult because of the ground clutter, even for an advanced method. Furthermore, vertical components that are measured on the vertical antenna beam are not always representative over the area across the beams, because vertical airflow has spatial variability resulting from convection (Gage et al. 1991).

For five-beam profilers, horizontal components of the wind can be derived not only from three beams (two adjacent oblique and one vertical), but also from four oblique beams, in which the radial wind produces a Doppler shift that is more easily distinguished from ground clutter than in the vertical antenna beam. Because the five-beam profiler does not need to rely on the vertical antenna beam, the horizontal components that are derived from the four oblique beams can be expected to have a better accuracy than the horizontal components derived from only three beams. It should be kept in mind, however, that the four-beam method needs greater stationarity and homogeneity in the horizontal wind field. The four-beam method has been used since the early stages of the UHF wind profiler (Ecklund et al. 1988), along with the three-beam method (Balsley and Gage 1982), but the difference of the two methods in their accuracy in measuring horizontal components of wind has not been systematically documented.

Here, we report a detailed evaluation of the two methods by comparing data collected by a five-beam profiler and processed in two different ways, with winds collected by the collocated meteorological tower at the Meteorological Research Institute (MRI) field site in Tsukuba, Japan. The data for the comparison were taken in summer when strong convection is expected, in order to maximize possible differences resulting from horizontal inhomogeneities. Instrumentation and data analysis techniques are presented in section 2. Results are presented in section 3 and are discussed in section 4. Our conclusions are given in section 5.

## 2. Instrumentation and data analysis techniques

The meteorological tower at the MRI is 213 m in height and is equipped with meteorological instruments at several levels (Fig. 1). The comparison was made using the wind measured with a propeller-driven anemometer (Koshin Electronics MV-110) mounted at the top of the tower. This anemometer was calibrated in a wind tunnel at MRI after the comparison. The tower data were recorded every minute and averaged over 30 min to minimize the spatial difference between the tower and the profiler. A more detailed description of the tower and its instruments can be found in Hanafusa et al. (1979). The wind profiler was located about 300 m north of the tower (Figs. 1 and 2).

The MRI wind profiler, a four-panel Vaisala LAP-3000, is the type originally developed at the National Oceanic and Atmospheric Administration (NOAA) Aeronomy Laboratory (Ecklund et al. 1988; Carter et al. 1995). The profiler was operated with 60- (low mode) and 210-m (high mode) pulse lengths. We use only the low-mode data in this study. The minimum range gate was 150 m from the antenna for the low mode, but the second-range-gate (=210 m) data were used for the comparison because the first gate might be too close to the antenna to obtain reliable winds


FIG. 1. Picture of the MRI and Aerological Observatory, looking north-northwest. The MRI site is covered with vegetation. A white oval at the upper left of the photo surrounds the city center.

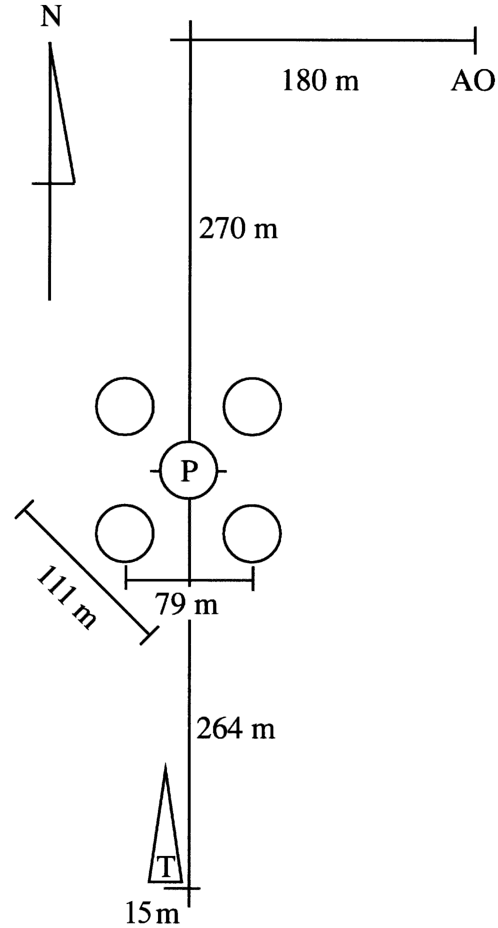


FIG. 2. Schematic layout of the relative locations of the meteorological tower (T), the 1.3-GHz profiler (P), and the Aerological Observatory (AO). The footprint of the 10° vertical profiler beam at 200 m is shown to scale as a circle around P; circular approximations of the footprint and location of the oblique beams at 200 m are indicated by circles to the NE, SE, SW, and NW of the vertical beam.

(Johnston et al. 2002). The height of the second gate for the oblique beams was 202 m AGL {=210[sin(74.5°)]}. The difference between the heights of the second gates in the oblique and the vertical beams (8 m) was neglected, as is done in the Profiler On-line Program (POP; Carter et al. 1995) because the difference was much smaller than the gate spacing (60 m). The configuration and operating parameters are summarized in Table 1. Six beams—four oblique beams in two coplanar pairs and two vertical beams of orthogonal polarizations—were used for the low mode. The beam sequence was V*y*, southwest (SW), southeast (SE), northeast (NE), northwest (NW), V*x*, V*yh*, SW*h*, and SE*h*, where *h* indicates the high mode and *x* and *y* denote antenna polarization. The dwell time for each beam was about 27 s. POP was used to retrieve moment data, including radial velocities at each range gate, from Doppler spectra observed with the wind profiler. The moment data were first processed by POP, which used consensus averaging (Fischler and Bolles 1981) on radial velocities and then constructed horizontal wind vectors. The data were further processed by using a continuity algorithm (Weber and Wuertz 1991) to reduce the effects of clutter and other noise. The consensus-averaging period of 30 min was chosen to match the tower observation interval for the comparison. To simulate three- and four-beam wind profilers from the six-beam observations, we used two orthogonal oblique beams and one vertical beam for the "pseudo" three-

TABLE 1. Parameters of the wind profiler.

| | |
|---|---|
| Frequency | 1.3575 GHz |
| Peak power | 500 W |
| Beamwidth | 10° |
| Beam elevation | 90° and 74.5° |
| Pulse width | 400 ns |
| First range gate | 150 m |
| Gate spacing | 60 m |
| Interpulse period | 20 μs |

beam system and the four oblique beams for the pseudo-four-beam system. The SW and SE beams were selected for the three-beam system along with V*y* to minimize the spatial separation between the wind profiler and tower observations (Fig. 2).

For a three-beam system with oblique beams pointed east (E) and north (N), the east component $u$ and the north component $v$ of the wind at any given height are derived from the radial velocity $V_R$ (positive away from the radar) that is measured on the east and north antenna beams with the elevation angle $\theta$ by

$$u = \frac{V_{RE} - w \sin\theta}{\cos\theta}, \quad (1)$$

$$v = \frac{V_{RN} - w \sin\theta}{\cos\theta}, \quad (2)$$

where subscripts E and N distinguish between the east and north radial velocities, and $w$ denotes the velocity measured on the vertical antenna beam (Strauch et al. 1987). A simple rotation is applied to adjust these equations for systems whose beams do not point in the cardinal directions, such as the MRI profiler. Note that the vertical beam measurement is essential for the three-beam system. In contrast, a four-beam system does not rely on the vertical antenna beam. The $u$ and $v$ components for a four-beam system, with oblique beams pointed in the cardinal directions at any given height, are derived from the four oblique antenna beams by

$$u = \frac{V_{RE} - V_{RW}}{2 \cos\theta}, \quad (3)$$

$$v = \frac{V_{RN} - V_{RS}}{2 \cos\theta}, \quad (4)$$

where the subscripts W and S denote the west and south antenna beams, respectively (Ecklund et al. 1988). Note that we have ignored the radar measurement errors in Eqs. (1)–(4). Also, in the derivation of the above equations, all three components of velocity ($u$, $v$, and $w$) are assumed to be uniform horizontally across all antenna beams. If this assumption is not consistent with the meteorological conditions, then the profiler cannot be expected to measure the winds accurately (Wuertz et al. 1988). The maximum separation between the beams at 202 m with the elevation angle of 74.5° is about 79 m for the three-beam system, and 111 m for the four-beam system (Fig. 2).

We have used a variety of statistics to explore the relationship between the time series of 30-min-averaged point measurements from the tower $Ti$, and volume-averaged measurements from the wind profiler $Wi$. All means and standard deviations are scalar, not vector, statistics, because we believe that those quantities and their differences are of most interest to users. From the wind speed time series, we computed means $\mu_T$ (for the tower) and $\mu_W$ (for the wind profiler), standard deviations $\sigma_T$ and $\sigma_W$, and medians. From the wind direction time series, we computed mean directions by summing the corresponding unit vectors and finding the direction of that resultant vector, as is appropriate for circular data (Fisher 1993; Jammalamadaka and SenGupta 2001). Similarly, we calculated the circular standard deviation [Fisher 1993, his Eq. (2.12)].

In addition, we computed several statistics based on the differences between the two platforms, $D_i = W_i - Ti$. For speeds, we use the definitions, but not the notation, of Hoehne (1971) and Ye et al. (1993). The bias (systematic error) of the speed differences is

$$\mu_D = \frac{1}{N} \sum_{i=1}^{N} (Wi - Ti) = \frac{1}{N} \sum_{i=1}^{N} Di, \quad (5)$$

while the standard deviation (precision) of the speed differences is

$$\sigma_D = \left[ \frac{1}{N} \sum_{i=1}^{N} (Di - \mu_D)^2 \right]^{1/2}, \quad (6)$$

where $N$ is the number of observations. We also calculated the median speed differences and the root-mean-square of the speed differences,

$$\text{rms} = \left[ \frac{1}{N} \sum_{i=1}^{N} Di^2 \right]^{1/2}. \quad (7)$$

For direction, we calculated the circular mean and standard deviation of the differences. In addition, we calculated Spearman's rank correlation (Wilks 1995), or the circular rank correlation (Jammalamadaka and SenGupta 2001), for all of the paired time series and all of the paired difference time series. We also study the difference between the four-beam and the three-beam technique to gain insight into the difference between point measurements (tower) and volume-averaged measurements (wind profiler).

The simultaneous observations for the intercomparison were made for 31 days, from 1 to 31 August 1997. The radar measurements are classified as taking place in clear air (= no rain) and precipitation by use of vertical velocities and signal-to-noise ratios, as utilized in other studies (e.g., Ralph 1995; Angevine 1997; Gage et al. 1999; Williams et al. 2000), because the scattering mechanism is quite different for the two conditions; the wind profiler operating at 1.3 GHz senses Bragg scattering in clear air, but senses Rayleigh scattering from raindrops in precipitation. We confirmed rain periods

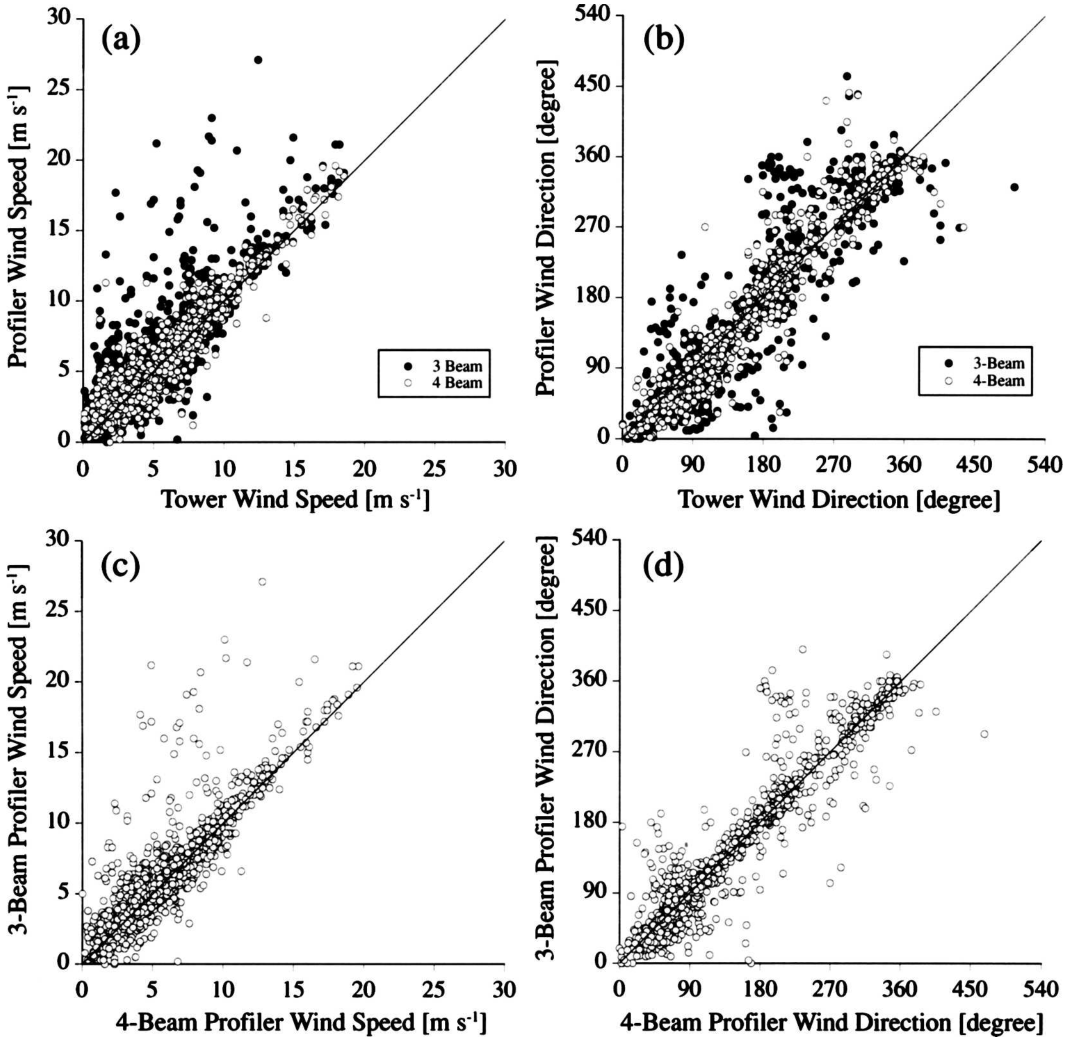


FIG. 3. Scatterplots of the (a), (c) speed and (b), (d) direction of the wind profiler vs the tower measurements, and of the three-beam system vs the four-beam system, respectively, measured at about 200 m for clear air. The data with the low tower wind speed (less than 0.5 m $s^{-1}$) were excluded in the wind direction plots. The data derived from the three-beam (four beam) system are plotted as closed (open) circles in (a) and (b). The data were averaged over 30 min. The thick lines are 1:1.

that are determined from the vertical antenna beam observations by comparison with the rain gauge measurements recorded at the Aerological Observatory (Figs. 1 and 2).

## 3. Results of comparisons

Scatter diagrams comparing tower wind speed and direction during conditions that are classified as clear air with those from the wind profiler are shown in Figs. 3a and 3b. The statistics for the 30-min mean sample speeds and directions shown in Fig. 3 are given in Table 2, along with the corresponding statistics for the data taken in rain and all-weather conditions. Closed and open circles indicate data from the three-beam and the four-beam methods, respectively. Scatter diagrams comparing wind speed and direction measured with the four-beam method versus the three-beam method are shown in Figs. 3c and 3d. The three-beam-method data that do not have corresponding four-beam-method data at the same time were removed before the comparison; that is, the number of observations for each method is equal in the figure. Note that wind directions for the two instruments in Figs. 3b and 3d have been adjusted so that the absolute values of their difference are less than or equal to 180° by adding 360°, where necessary. Furthermore, data with a low tower wind speed (less

TABLE 2. Statistical values for the comparison of wind profiler vs tower measurement of (top) wind speed and (middle) wind direction, and (bottom) the comparison of the three- vs four-beam system. The data with low tower wind speed (less than 0.5 m s$^{-1}$) were excluded from the wind direction statistics.

| | Clear air | | Rain | | All weather | |
|---|---|---|---|---|---|---|
| Wind speed | Four beam | Three beam | Four beam | Three beam | Four beam | Three beam |
| Total points | 1314 | 1314 | 58 | 58 | 1372 | 1372 |
| Mean (tower, m s$^{-1}$) | 5.2 | 5.2 | 8.6 | 8.6 | 5.3 | 5.3 |
| Mean (profiler, m s$^{-1}$) | 5.6 | 6.0 | 8.8 | 9.5 | 5.7 | 6.2 |
| Bias (m s$^{-1}$) | 0.4 | 0.9 | 0.2 | 0.9 | 0.4 | 0.9 |
| Median difference (m s$^{-1}$) | 0.3 | 0.5 | 0.2 | 0.7 | 0.3 | 0.5 |
| Standard deviation (m s$^{-1}$) | 1.2 | 2.2 | 1.5 | 3.0 | 1.2 | 2.2 |
| Rms difference (m s$^{-1}$) | 1.3 | 2.3 | 1.5 | 3.1 | 1.3 | 2.4 |
| Spearman's rank correlation | 0.90 | 0.81 | 0.95 | 0.77 | 0.90 | 0.82 |
| | Clear air | | Rain | | All weather | |
| Wind direction | Four beam | Three beam | Four beam | Three beam | Four beam | Three beam |
| Total points | 1297 | 1297 | 58 | 58 | 1355 | 1355 |
| Mean (tower, °) | 117.4 | 117.4 | 51.4 | 51.4 | 115.8 | 115.8 |
| Mean (profiler, °) | 99.4 | 93.9 | 35.8 | 38.0 | 97.8 | 92.0 |
| Mean difference (°) | −2.2 | −1.5 | 0.3 | −1.2 | −2.1 | −1.5 |
| Standard deviation (°) | 14.7 | 22.5 | 15.4 | 17.4 | 14.8 | 22.3 |
| Circular rank correlation | 0.92 | 0.77 | 0.77 | 0.70 | 0.92 | 0.77 |
| | Clear air | | Rain | | All weather | |
| Three beam vs four beam | Speed (m s$^{-1}$) | Direction (°) | Speed (m s$^{-1}$) | Direction (°) | Speed (m s$^{-1}$) | Direction (°) |
| Total points | 1314 | 1297 | 58 | 58 | 1372 | 1355 |
| Mean (four beam) | 5.6 | 99.4 | 8.8 | 35.8 | 5.7 | 97.8 |
| Mean (three beam) | 6.0 | 93.9 | 9.5 | 38.0 | 6.2 | 92.0 |
| Bias or mean difference | 0.5 | 0.7 | 0.7 | 1.6 | 0.5 | 0.7 |
| Median difference | 0.2 | N/a | 0.7 | N/a | 0.2 | N/a |
| Standard deviation | 1.9 | 18.2 | 2.5 | 16.8 | 2.0 | 18.1 |
| Rms difference | 2.0 | N/a | 2.5 | N/a | 2.0 | N/a |
| Rank correlation | 0.88 | 0.84 | 0.87 | 0.89 | 0.88 | 0.84 |

than 0.5 m s$^{-1}$) were excluded from the wind direction scatterplots.

This figure shows that both the three-beam and four-beam methods generally agree well with the tower measurements of wind speed (Fig. 3a). Rank correlations (Table 2) are highest between the tower and the four-beam method, and are lowest between the tower and the three-beam method. The mean bias between the profiler and the tower is less than 1 m s$^{-1}$ under all conditions, and the three- and four-beam methods also agree well with each other (Figs. 3c and 3d). For all three wind speed datasets, the ratio of the standard deviation to the mean is 0.63, 0.62, and 0.60, which is well within the (0.4, 1.0) typical range put forth by Hennessey (1977). The situation is a bit more complicated for wind direction. Figure 3b indicates fair agreement between the two platforms, and the rank correlations are again highest between the tower and the four-beam method. However, histograms of these same data (not shown) indicate an important difference in the distribution of wind direction; all platforms show distributions with two primary peaks at roughly 60° and 200°, but in the tower data those peaks are of a similar magnitude, while in both profiler datasets the 60° peak is roughly twice as large as the one at 200°. These differences are reflected in the mean directions shown in Table 2; under all conditions, the three- and four-beam mean directions are closer to each other than they are to the tower mean direction, with the latter being 15°–20° greater than the profiler directions. The mean differences, which are not equal to the differences between the means because of the circular statistics used, are smaller for the tower versus the three-beam comparisons than for the tower versus the four-beam comparisons, except in rain, but the standard deviation of those same difference time series are largest for the tower versus the three-beam comparison.

The remainder of our analysis focuses on wind speed. As is typical with wind speed data, all three datasets are well represented by a Weibull distribution (Conradsen et al. 1984; Tuller and Brett 1984; Wilks 1995). The Weibull distribution is a positive and skewed distribu-

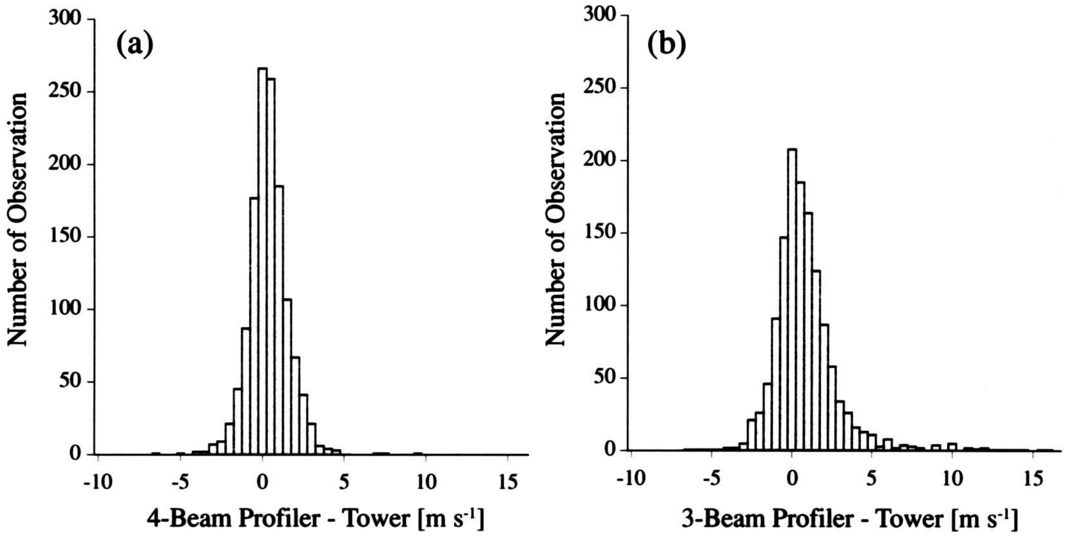


FIG. 4. Histograms of the differences in horizontal wind components in the clear air between the wind profiler and the tower with the interval of 0.5 m s$^{-1}$ for the (a) four-beam and (b) three-beam systems.

tion described by two parameters: shape and scale. If the shape parameter, which is dimensionless, is less than 1.0 the distribution peaks at 0.0; otherwise, it peaks at some positive value. The scale parameter has the same units as the variable being described, and gives an indication of the spread of the distribution. Fitting Weibull distributions to the tower and profiler data yield shape parameters ranging from 1.6 to 1.8 and scale parameters ranging from 5.7 to 6.9 m s$^{-1}$ (not shown). It is because the wind speed distribution is clearly not Gaussian that we have calculated Spearman's rank (or nonparametric) correlation coefficient, instead of Pearson's linear correlation coefficient (Wilks 1995).

In spite of the general agreement between the time series, it is also evident that there are a number of points where the three-beam-method wind speed is too high (Fig. 3a). That these outliers in the three-beam-method measurements are absent from the four-beam measurements can be seen in Fig. 3c. The difference from the tower in the profiler wind speed measurements from Fig. 3a is presented in Fig. 4 by histograms. These distributions are also non-Gaussian; they are positively skewed (asymmetrical, with a longer tail to the right of the peak) and have a very large kurtosis, or degree of peakedness. Because of this, we have again used Spearman's rank correlation to describe the time series, and rely on verbal comparisons rather than typical statistical significance testing. When plotted in 0.5 m s$^{-1}$ bins, the wind speed differences for both methods have peaks centered on 0.0 m s$^{-1}$. The median differences from the tower for the four- and three-beam methods are 0.3 and 0.5 m s$^{-1}$, respectively (Table 2). However, the wind speeds derived from the four-beam method differ from the tower wind speeds by at least 5.0 m s$^{-1}$ less often than do the wind speeds derived from the three-beam method. Indeed, 99.7% of the four-beam wind speeds are located within $\pm5$ m s$^{-1}$ from the tower-measured wind speeds. In contrast, the three-beam wind speeds are more widely and asymmetrically distributed, and 4% of these speeds are more than 5 m s$^{-1}$ greater than the tower speeds. These facts are reflected in the bias and standard deviation of the differences for the three-beam method versus the four-beam method (Table 2).

The statistics for the 30-min mean sample values shown in Figs. 3a–d are given in Table 2, along with the corresponding statistics for the data taken in rain and all-weather conditions. Note that the difference in the mean wind direction is not the same as a bias, because those values are not linear and were calculated using circular statistics.

The standard deviations in the wind speed difference for three-beam and four-beam methods are comparable to those found by other studies. For the three-beam system, Strauch et al. (1987) and Weber et al. (1992) report that standard deviations of the difference between pairs of independent wind components observed with an identical wind profiler in clear air range between 1.0 and 1.3 m s$^{-1}$. Weber and Wuertz (1990) found a standard deviation of 2.5 m s$^{-1}$ in the comparison with rawinsondes. Ye et al. (1993) report standard deviations of 1.7 m s$^{-1}$ in the comparison with a tower. For wind profilers deploying more than three beams, Angevine and Macpherson (1995) report a standard deviation of 3.0 m $s^{-1}$, and Baltink (1997) found a standard deviation of 0.9 m $s^{-1}$ using five-beam systems. Angevine et al. (1998) found a standard deviation of 1.0 m $s^{-1}$ using a six-beam system for hourly wind measurements in clear air. Cohn et al. (2001) found a standard deviation of 1.5 m $s^{-1}$ using a spaced antenna technique. The larger standard deviations in precipitation than in clear air (Table 2) agree with the result of Wuertz et al. (1988). They attributed the large standard deviations in wind speed difference to spatial inhomogeneities that occur during some periods of rain.

In summary, our statistical results show that, in general, the four-beam method has better accuracy and precision than the three-beam method in measuring horizontal components of wind. The four-beam method has smaller biases, standard deviations in wind speed, and larger correlation coefficients in both wind speed and direction in every weather condition when compared with the tower observations than does the three-beam method. The three-beam outliers occurred during transition periods between clear-air and rain conditions. This fact could explain the cause for the difference. Because the outliers for the three-beam method are clear in wind speed data, we focus on the difference in wind speed measurements and its cause in the following section.

## 4. Discussion

As reported above, we have found many instances in which the four-beam technique outperforms the three-beam technique as measured in the wind speed statistics in comparison to the tower. We focus our attention here on the result derived from the wind speed statistic and examine more thoroughly the possible causes for the reduced performance using the three-beam methodology. In this section we examine separately the effect of nonuniform vertical velocities on the retrieval of horizontal wind in precipitation and clear air, respectively. Note that we differentiate clear air from precipitation by the magnitude of the vertical Doppler velocity, as described in section 2.

In applying the three-beam methodology to horizontal wind measurement it has long been recognized that a vertical correction can provide an improved retrieval when there are substantial uniform vertical motions or precipitation over the profiler. In a case study involving lee waves Clark et al. (1985) showed the improvement that can be obtained using the vertical beam, but also cautioned that at times the vertical beam observation was not representative and could lead to substantial errors in horizontal velocities. Riddle et al. (1996) also had the best results when removing the vertical component only during precipitation. Wuertz et al. (1988) discussed the accuracy of profiler-retrieved horizontal winds in rain. They drew attention to the problems that can occur when rainfall is nonuniform (patchy) over the profiler. In both situations the presence of nonuniform or unrepresentative vertical velocities can compromise the retrieval of the horizontal wind. It is important in this context to recognize that the vertical velocities may vary substantially in time as well as space. This fact is noteworthy because most wind profilers take data in different directions sequentially, not simultaneously.

### a. *Representativeness of the vertical Doppler velocity measurement using the vertical beam in patchy rain*

Using the three-beam method in precipitation, it is necessary to account for the significant vertical velocity of falling hydrometeors. As noted earlier, Doppler velocity measured on the vertical antenna beam is used to classify the observations into clear-air and precipitation conditions. Although this method worked well to determine weather conditions directly over the wind profiler, it did not determine whether precipitation was present near but not over the profiler, in an oblique beam. Thus, in patchy rain and/or in the transition between clear air and rain, substantial errors in horizontal wind measurement can occur. Even consensus averaging, as used here, did not completely eliminate this problem.

In forming a consensus, each of the (sub-half-hourly) radial velocity samples is classified into one of a variable number of consensus groups, by requiring that the samples lie within specified velocity-threshold windows. The final consensus average is the average of the group with the greatest number of samples that comes latest in the averaging period (Brewster 1989). Thus, the consensus algorithm is effective in reducing the influence of random noise, but if, say, the vertical beam forms a consensus corresponding to the clear-air part of the averaging period, and any of the oblique beams form a consensus during the precipitation part of the averaging period, or vice versa, then the wrong vertical velocity correction will be applied to the horizontal wind estimates (Wuertz et al. 1988). Indeed, we found that many outliers, seen predominantly in the three-beam method, occurred during periods of transition between clear air and precipitation. This suggests that the three-beam method is significantly more susceptible to patchy precipitation than the four-beam method. In the appendix we consider some plausible scenarios for the nonuniform and transitional precipitation that support the conclusion that the four-beam estimates of horizontal wind speed are superior to the three-beam estimates under these circumstances.

To diagnose patchy precipitation more completely, we introduce the interbeam standard deviation ($\sigma_i$), defined by the standard deviation of four wind speeds that are estimated from four combinations of the orthogonal and vertical beams ($V_{RE}$–$V_{RN}$–$V_Z$, $V_{RS}$–$V_{RE}$–$V_Z$, $V_{RW}$–$V_{RS}$–$V_Z$, and $V_{RN}$–$V_{RW}$–$V_Z$). Then, if the interbeam standard deviation is larger than the measurement error, we consider that the vertical velocity and/or the horizontal winds are nonuniform horizontally across the antenna beams (Wuertz et al. 1988).

Because the error of the three-beam wind profiler in measuring the horizontal wind velocity has been widely reported to range between 1 and 2 m s$^{-1}$, we assume that horizontal velocity measurements with an interbeam standard deviation greater than 2 m s$^{-1}$ may not be reliable. Figure 5 shows the data from Fig. 3a for the three-beam method, where the data with an interbeam standard deviation of less than (greater than or equal to) 2 m s$^{-1}$ are denoted with open (closed) circles. As we expect, most of the outliers have larger interbeam standard deviations than the measurement error. The statistics for the data with an interbeam standard deviation of less than 2 m s$^{-1}$ in Fig. 3 are given in Table 3. All of the statistical results are better than those in Table 2 for the three-beam method in clear air. For instance, the standard deviation in wind speed decreased from 2.2 to 1.5 m s$^{-1}$ after removal of the data with a large interbeam standard deviation. However, these values are still larger than those for the four-beam method in Table 2, even though the statistics for the four-beam method include the measurements in patchy rain.

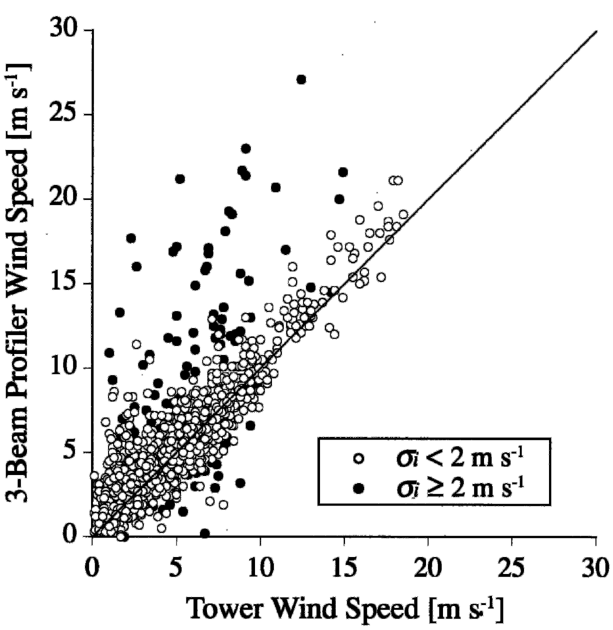


FIG. 5. Scatterplots of the three-beam method profiler wind speed vs the tower wind speed measured at about 200 m, for conditions classified as clear air using the vertical beam of the profiler. The data were averaged over 30 min, and the thick line is 1:1. Data from half-hours with interbeam standard deviation ($\sigma_i$) greater than or equal to (less than) 2 m s$^{-1}$, i.e., during patchy rain (no rain in any beam), are plotted as closed (open) circles.

TABLE 3. Statistical values for the comparison of three-beam system vs tower measurement for clear air in wind speed. The data with an interbeam standard deviation of less than 2 m s$^{-1}$ are used.

| Wind speed | Clear air |
|---|---|
| | Three beam |
| Total points | 1161 |
| Mean (tower, m s$^{-1}$) | 5.1 |
| Mean (profiler, m s$^{-1}$) | 5.7 |
| Bias (m s$^{-1}$) | 0.6 |
| Median difference (m s$^{-1}$) | 0.5 |
| Standard deviation (m s$^{-1}$) | 1.5 |
| Rms difference (m s$^{-1}$) | 1.6 |
| Spearman's rank correlation | 0.85 |

We believe that the difference in vertical motion representativeness between the three- and the four-beam method accounts for the more robustly accurate four-beam results found here. Another real possibility—contamination from ground clutter, to which vertical beam observations are especially sensitive—did not seem to be a factor in this case. The signal from the summertime clear air was nearly always strong enough to override the ground clutter effects. Moreover, both POP and additional quality control processes that are employed during the analysis rejected most of the ground clutter outliers that did occur. This conclusion, that small-scale variations in vertical velocities associated with patchy precipitation is the main source of error, is consistent with the results of Strauch et al. (1987) and Weber et al. (1992) who showed that the vertical component has a significant influence on three-beam wind profiler determinations of horizontal velocities. We consider next the extension of these ideas to conditions in the absence of any precipitation.

### b. *Representativeness of the vertical velocity measurement using the vertical beam in clear conditions*

The difficulties of retrieving accurate horizontal velocities using the three-beam method during nonuniform rainfall suggest that similar difficulties may be encountered, even during clear conditions whenever the vertical velocity has substantial small-scale variability.

To further examine the effect of the often poor representativeness of the vertical beam velocities, we next compare them to the vertical motions derived in clear air using the minimizing the variances of the differences (MVD) method, introduced by Gossard et al. (1998). The MVD method determines the vertical velocity that minimizes the variance between the four horizontal velocity components calculated from four oblique radial velocities (see Adachi et al. 2004 for details). In the implementation of the MVD method, we did not use the data averaged over 30 min after the quality control processes, but used individual four-beam sequences. The MVD method yields the vertical velocities, along with the corresponding speed variances from each cycle of the four-beam sequence. Only the vertical velocities whose corresponding standard deviation was equal to or less than 0.2 m $s^{-1}$ were averaged over 30 min. This removes data for times of substantial spatial variability in the horizontal and vertical components from the time average. This process works as a quality control for vertical velocities derived from the MVD method. Because this quality control process is different from that used for the vertical beam data, the number of observations in the 30-min mean are not always the same.

Figure 6 shows the time series of the 30-min mean vertical velocity values at about 200 m AGL for both the vertical antenna beam and the MVD method. The data of Fig. 6 cover the period from 1 to 3 August, during a period of high pressure over the site when no rain was observed. Because the average and maximum temperature of these 3 days were among the highest for the year, convection likely occurred in the daytime, and, indeed, the vertical velocities derived from the vertical antenna beam and from the MVD method show distinct diurnal cycles. There are strong downward velocities in the middle of the day, but there is less departure from the expected value of zero at night. This diurnal cycle agrees well with the observations of Angevine (1997), and the daytime downward motion observations support our argument that the vertical antenna beam is free from ground clutter, because ground clutter biases the measured velocities toward zero. Angevine (1997) attributed the daytime downward bias to insects or hydrometeors that are not detectable, and, indeed, this site is largely covered by vegetation with many insects (Fig. 1). The effect of urban heat islands (Oke 1987) might also contribute to this bias (Worthington 2003), because our site is located in a rural area just outside of Tsukuba city (where the population is approximately 200 000).

Figure 7 shows the time series of the difference in the absolute value of the horizontal components of wind speed and the absolute value of the difference in the vertical velocities. The thick line shows the difference in the horizontal components of wind speed between the tower and the three-beam method, and the thin line represents the difference between the tower and the four-beam method. The dashed line indicates the absolute value of the difference between the vertical beam and MVD vertical velocities. For ease of viewing, differences in the horizontal wind speed less than 1.0 m $s^{-1}$ and differences in the vertical component less than 0.1 m $s^{-1}$ are plotted at 0.0 m $s^{-1}$ because they lie within the error of the profiler wind measurement in clear air. This figure clearly shows that even in clear air the three-beam method often has large discrepancies in horizontal wind speed from the tower. It is also obvious

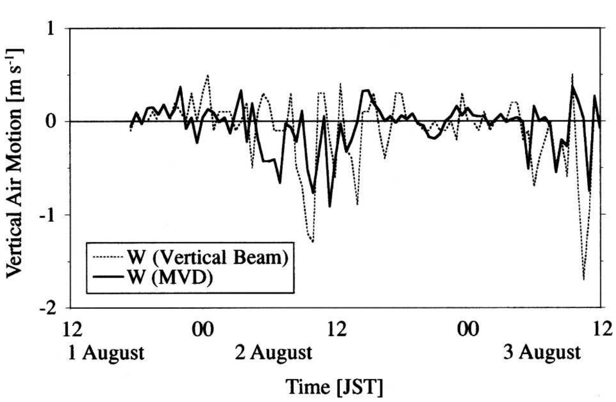


FIG. 6. Time series of vertical components at about 200 m measured by the vertical beam (dotted line) and derived from the MVD method (thick line) from 1 to 3 Aug 1997. The time is local [Japan standard time (JST) = UTC + 9 h].

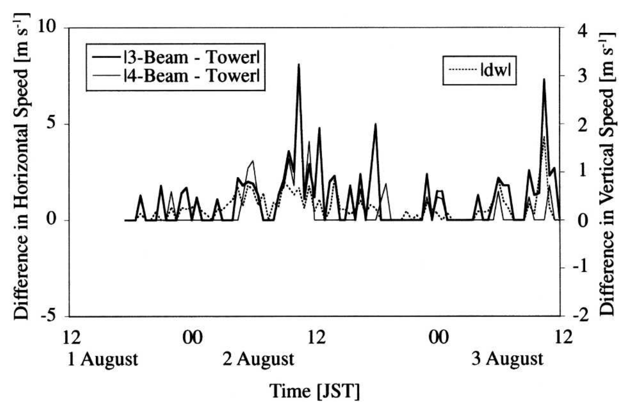


FIG. 7. Time series of the differences of horizontal wind speeds between the tower and the three-beam system (thick line), between the tower and the four-beam system (thin line), and the difference in vertical components derived from the vertical antenna beam and that from the four oblique beams (dotted line) in absolute values. The differences of horizontal wind speeds less than 1 m $s^{-1}$, and those of the vertical components less that 0.1 m $s^{-1}$, are set to 0 m $s^{-1}$ for ease of viewing.

that these discrepancies and the differences in vertical velocities have a close relationship; in general, the discrepancy of the three-beam method increases when the difference between the vertical velocities increases. This, again, implies that the unrepresentativeness of the vertical velocity that is measured by the vertical beam is a major factor contributing to the larger measurement errors for the three-beam method. In contrast, the four-beam method, with few exceptions, agrees better with the tower, and any relationship between the discrepancy of the four-beam method from the tower and the difference in vertical velocities is difficult to perceive. These facts again suggest that horizontal wind measurements using the four-beam method have consistently better accuracy and reliability than those obtained using the three-beam method.

## 5. Conclusions

We compared wind profiler measurements with tower measurements to estimate the accuracy of the wind profiler in measuring the horizontal components of the wind. The wind profiler data were processed as if from a three- and a four-beam system. Results show that the four-beam method has better accuracy and precision of wind speed than the three-beam method. For instance, in clear air, the standard deviation for the four-beam method in wind speed (1.2 m $s^{-1}$) is smaller than that for the three-beam method (2.2 m $s^{-1}$). It is also demonstrated that the three-beam method is more susceptible to patchy rain than the four-beam method. Even after removal of the data taken in patchy rain, the standard deviation for the three-beam method (1.5 m $s^{-1}$) is still much larger than that for the four-beam method with patchy rain. We also found a close relationship between the discrepancies of the three-beam method from the tower and the difference in vertical velocities between those derived from the vertical antenna beam and those estimated from the four oblique beams. We conclude that the larger error of the three-beam method arises from the fact that the vertical velocities measured by the vertical antenna beam are not representative of the airflow over the area across the beams whenever the vertical airflow has spatial variability. This finding implies that the four-beam method is less susceptible than the three-beam method not only to patchy rain, but also to the vertical airflow with spatial variability.

We have also documented interplatform differences in wind directions. Here, the wind directions from the two profiler methods are more like each other than those of the tower, both in terms of the mean statistics and distributions. We have also found that the four-beam method has a larger rank correlation with the tower than does the three-beam method in every weather condition. However, further work will be needed to more rigorously document and explain these differences.

The results of this study do not necessarily apply to all locations, altitudes, and seasons; in particular, we note that the comparisons in this case study were made in the boundary layer during summer when strong horizontal inhomogeneity would be expected. This condition is possible even in other seasons and at higher altitudes, but the frequency and/or intensity is likely to be less. However, in the other seasons, the vertical beam observation, which is essential for the three-beam wind profiler, could easily be contaminated by ground clutter because the clear-air echo becomes weak under conditions of low temperature and humidity, and the contamination could decrease the reliability of the three-beam wind profiler. Although it needs a longer duration for observation, it is demonstrated that four-beam wind profilers have better reliability than three-beam wind profilers in measuring horizontal components of the wind.

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## APPENDIX

### Effects of Nonuniform Rain on the Three-Beam and Four-Beam Measurements

Here we show, with plausible assumptions, that in nonuniform rain the error in measuring horizontal winds with the three-beam method can be expected to be greater than the error in measuring the horizontal winds with the four-beam method.

To estimate the effect of patchy precipitation on both three- and four-beam systems, let us assume that the east component of horizontal wind ($U$) is uniform in the area across all antenna beams, and that the vertical component of wind ($w$) is the same in the west and vertical antenna beams. Both the vertical and west beams are assumed to observe clear air, but the east beam is assumed to observe precipitation. The east component, measured by the three-beam system ($U_{3B}$) at a given height on the vertical and east antenna beams with the elevation angle of $\theta$, is given by Eq. (1) as

$$U_{3B} = \frac{V_{RE} - w \sin\theta}{\cos\theta}, \quad \text{(A1)}$$

where all of the notations are the same as in Eq. (1). It is clear that this estimation is incorrect because the vertical component on the east beam is not equal to that measured on the vertical beam ($w$), but is equal to the fall velocity of precipitation ($w_p$). The correct three-beam system east component of wind is given by

$$U = \frac{V_{RE} - w_p \sin\theta}{\cos\theta}. \quad \text{(A2)}$$

The measurement error for the three-beam system in measuring the horizontal wind speed ($\delta U_{3B}$) is given by

$$\delta U_{3B} = |U_{3B}| - |U|, \quad \text{(A3)}$$

where $U$ is assumed to have the same sign as $U_{3B}$. Note that we take the absolute values of the horizontal component of the wind because wind speed is always equal to or greater than 0 m s$^{-1}$.

On the other hand, the east component of the wind, measured in the west and vertical antenna beams ($U'_{3B}$), is given by

$$U'_{3B} = \frac{-V_{RW} + w \sin\theta}{\cos\theta} = U, \quad \text{(A4)}$$

where $U'_{3B}$ is equal to $U$ because the vertical component of wind is assumed to be homogeneous in the west and vertical antenna beams.

The east component of wind derived from the four-beam system ($U_{4B}$) is given from Eqs. (3), (A1), and (A4) by

$$U_{4B} = \frac{U'_{3B} + U_{3B}}{2} = \frac{U + U_{3B}}{2}. \quad \text{(A5)}$$

Therefore, the measurement error for the four-beam system in measuring the horizontal wind speed ($\delta U_{4B}$) is given by

$$\delta U_{4B} = \left|\frac{U + U_{3B}}{2}\right| - |U|. \quad \text{(A6)}$$

The difference in measuring error (DU) between the four-beam system and the three-beam system is given by

$$\mathrm{DU} = |\delta U_{3B}| - |\delta U_{4B}|. \quad \text{(A7)}$$

If the sign of DU is positive, the measurement error for the three-beam system is larger than that for the four-beam system in measuring the horizontal wind speed. To derive the sign of DU, we define DU$^2$ as

$$\mathrm{DU}^2 \overset{\text{def}}{=} (\delta U_{3B})^2 - (\delta U_{4B})^2. \quad \text{(A8)}$$

Note that the sign of DU$^2$ is equal to that of DU. By substituting Eqs. (A3) and (A6) for (A8), we derive

$$\mathrm{DU}^2 = \frac{1}{4}(U_{3B} - U)^2 + \frac{1}{2}(|U_{3B}| - |U|)^2 \geq 0. \quad \text{(A9)}$$

The minus signs in Eq. (A9) change to plus signs when $U$ is opposite in sign to $U_{3B}$.

Equation (A9) clearly shows that the measurement error for the three-beam system in measuring the horizontal wind speed is always larger than that for the four-beam system in patchy rain. It is also evident from Eqs. (A1), (A2), and (A9) that the measurement errors of the two systems are identical when the vertical components measured on each beam are homogeneous in the horizontal direction. As we show below, this conclusion can also be derived using equations for the horizontal component of wind.

Using the horizontal wind velocity, we do not need to take absolute values of the horizontal component of the wind. The measurement error for the three-beam system in measuring the horizontal component of the wind is given by (A3) as

$$\delta U_{3B} = U_{3B} - U. \quad \text{(A10)}$$

The measurement error for the four-beam system in measuring the horizontal component of the wind is given by (A6) as

$$\delta U_{4B} = \frac{U + U_{3B}}{2} - U = \frac{U_{3B} - U}{2}. \quad \text{(A11)}$$

By substituting (A10) for (A11), we derive

$$\delta U_{3B} = 2\delta U_{4B}. \quad \text{(A12)}$$

Equation (A12) clearly shows that the measurement error for the three-beam system in measuring the horizontal component of wind is always larger than that for the four-beam system in patchy rain, which is consistent with (A9).

Both Eqs. (A9) and (A12) could suggest that the four-beam system is less susceptible than the three-beam system to horizontally inhomogeneous vertical components of wind in the area across the antenna beams.

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