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EVALUATION OF 3-BEAM AND 4-BEAM PROFILER WIND MEASUREMENT TECHNIQUES

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1. INTRODUCTION

Most contemporary wind profilers estimate wind profiles from three- or five-beam measurements using the Doppler Beam Swinging (DBS) method. In the traditional 3-beam technique, the horizontal components of wind are derived from two orthogonal oblique beams and the vertical beam. However, vertical beam measurements are easily contaminated by ground clutter. On the other hand, the 5-beam profiler does not need to rely on the vertical antenna beam, and the horizontal components derived from the four oblique beams can be expected to have a better accuracy than the horizontal components derived from only three beams. One of the disadvantages of the 4-beam method is that it 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 accuracy in measuring horizontal components of wind has not been systematically documented.

In this study, we report a detailed evaluation of the two methods by comparing data collected by a 5-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.

2. INSTRUMENTATION AND DATA ANALYSIS

The meteorological tower at the MRI is 213 m in height and is equipped with meteorological instruments at several levels. The comparison was made using the wind measured with a propeller-driven anemometer 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 thirty minutes to minimize the spatial difference between the tower and the profiler. The wind profiler was located about 300 m north of the tower (Fig. 1).

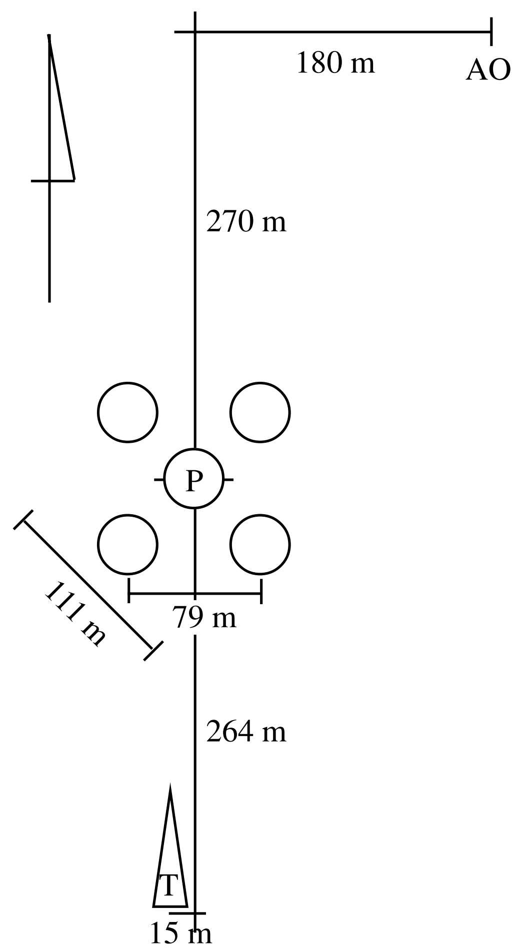

Fig. 1. Schematic layout of the relative locations of the meteorological tower (T), the 1.3-GHz profiler (P), and Aerological Observatory (AO). The footprint of the 10° vertical profiler beam at 200 m is shown to scale as a circle around the P; circular approximations of the footprint and location of the oblique beams at 200 m are indicated by circles to the NE, SE, SW, and NW of the vertical beam.

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The MRI wind profiler, a four-panel Vaisala LAP-3000, is the type originally developed at the NOAA Aeronomy Laboratory (Ecklund et al. 1988; Carter et al. 1995). The profiler was operated with 60-m (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. 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. Profiler On-line Program (POP; Carter et al. 1995) 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 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 minutes 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 for the "pseudo" three-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 vertical beam to minimize the spatial separation between the wind profiler and tower observations (Fig. 1).

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 (positive away from the radar) measured on the east and north antenna beams with the elevation angle θ 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 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 (Ecklund et al. 1988). Note that we have ignored the radar measurement errors in equations (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 simultaneous observations for the intercomparison were made for 31 days, 1 to 31 August 1997. The radar measurements are classified as taking place in clear-air (= no rain) and in precipitation by use of vertical velocity and signal-to-noise ratio thresholds (Gage et al. 1999; Williams et al. 2000). This classification is necessary 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 determined from the vertical antenna beam observations by comparing with the rain gauge measurements recorded at the Aerological Observatory (Fig. 1). 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).

3. RESULTS OF COMPARISONS

A scatter diagram comparing tower wind speed during conditions classified as "clear-air" with that from the wind profiler are shown in Fig. 2a. Closed and open circles indicate data from the three-beam and the four-beam methods, respectively. A scatter diagrams comparing wind speed measured with the four-beam method versus the three-beam method are shown in Fig. 2b. Those figures show that, while the winds measured using both methods are in overall agreement with the tower measurements, some of the horizontal components of the 3-beam derived winds are clearly spurious when compared with the tower-measured winds or the winds derived from the four oblique beams. The statistics for the 30-minute mean sample values shown in Figs. 2a are given in Table 2.

The 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 when compared with the tower observations than does the three-beam method. Further analysis shows that the three-beam outliers occurred during transition periods between clear-air and rain conditions (Adachi et al. 2005). This fact could explain the cause for the difference.

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
Inter-pulse period	20 ms

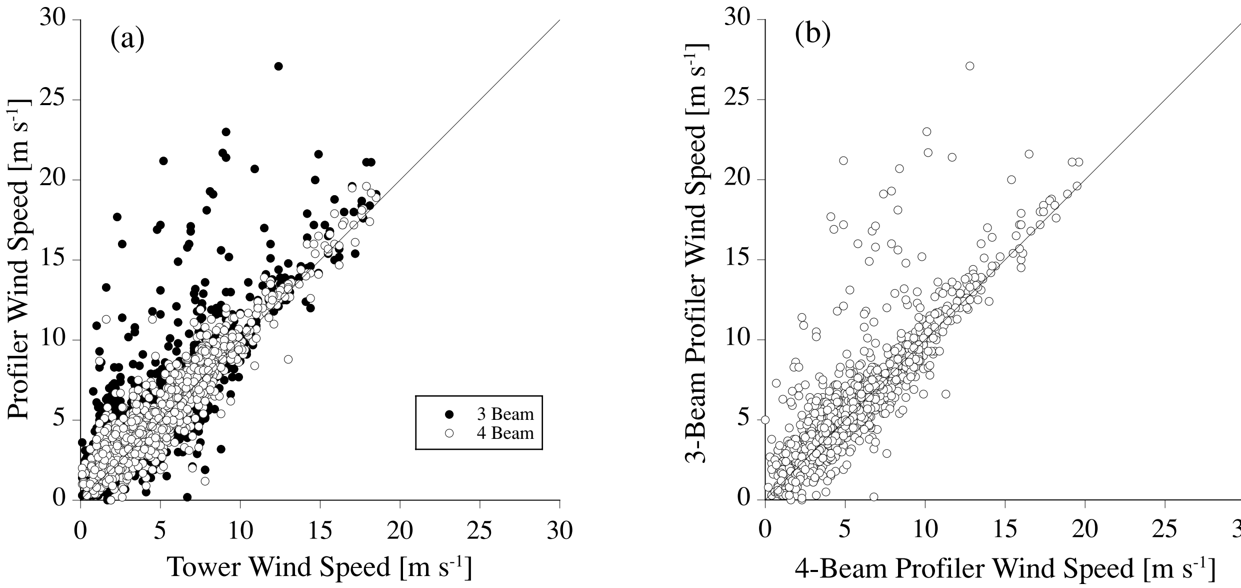

Figure 2. Scatter plots of the wind profiler versus the tower speed (a) and of the three-beam system versus the four-beam system (b) measured at about 200 m for clear-air. The data derived from the three-beam (four-beam) system is plotted as closed (open) circles in (a). The data were averaged over thirty minutes. The lines are 1:1.

4. DISCUSSION

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 most weather conditions directly over the wind profiler, it did not definitively determine whether precipitation was present in an oblique beam. Thus, in patchy rain and/or in the transition between clear air and rain substantial errors in horizontal wind measurement could occur. Even consensus averaging, as used here, did not completely eliminate this problem. 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 order to diagnose patchy precipitation more completely, we introduce the inter-beam standard deviation (σi) defined by the standard deviation of four wind speeds that are estimated from four combinations of orthogonal beams and vertical beam (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 inter-beam standard deviation is larger than the measurement error, we consider that vertical velocity and /or the horizontal winds are non-uniform horizontally across antenna beams (Wuertz et al. 1988).

Since 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} (e.g., Strauch et al. 1987), we assume horizontal velocity measurements with an inter-beam standard deviation greater than 2 m s^{-1} may not be reliable. Figure 3 shows the data from Fig. 2a for the three-beam method, where the data with an inter-beam 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 inter-beam standard deviations than the measurement error. The statistics for the data with an inter-beam standard deviation of less than 2 m s^{-1} in Fig. 3 are given in Table 3 along with those for the four-beam method in Table 2. All the statistical results are better than those in Table 2 for the three-beam method. For instance, the standard deviation in wind speed decreased from 2.2 m s^{-1} to 1.5 m s^{-1} after removal of the data with a large inter-beam standard deviation. However, these values are still larger than those for the four-beam method even though the statistics for the four-beam method include the measurements in patchy rain.

We believe the difference in vertical motion representativeness between the three-beam method and the four-beam method accounts for the more robustly accurate four-beam results found here. Another real possibility, contamination from ground clutter, 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

Table 2. Statistical values for the comparison of wind profiler versus tower measurement in wind speed for clear-air.

	4-Beam	3-Beam
Total points	1314	1314
Mean (Tower) in m s^{-1}	5.2	5.2
Mean (Profiler) in m s^{-1}	5.6	6.0
Bias (m s^{-1})	0.4	0.9
Median difference (m s^{-1})	0.3	0.5
Standard deviation (m s^{-1})	1.2	2.2
RMS difference (m s^{-1})	1.3	2.3
Spearman rank correlation	0.90	0.81

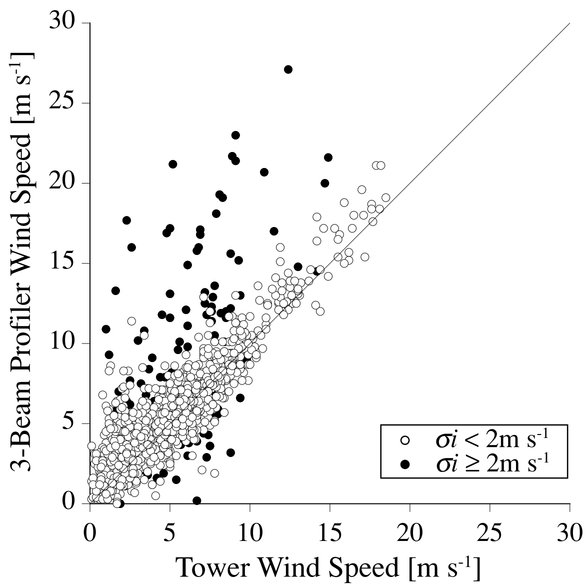

Figure 3. Scatter plots of the three-beam method profiler wind speed versus the tower wind speed measured at about 200 m, for conditions classified as clear-air using the vertical beam of the profiler. Data from half-hours with inter-beam standard deviation (σi) greater than or equal to (less than) 2 m s^{-1}, i.e. during patchy rain (no rain in any beam) are plotted as closed (open) circles. The thick line is 1:1.

control processes 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.

5. CONCLUSION

We compared wind profiler measurements with tower measurements to estimate the accuracy of the wind profiler in measuring horizontal components of the wind in clear air. The wind profiler data were processed as if from a three-beam system 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, 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 the patchy rain. 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. See Adachi et. al (2005) for details of this study.

Table 3. Statistical values for the comparison of wind profiler versus tower measurement in wind speed for clear-air. For the three-beam method, the data with an inter-beam standard deviation of less than 2 m s^{-1} are used.

	4-Beam	3-Beam
Total points	1314	1161
Mean (Tower) in m s^{-1}	5.2	5.1
Mean (Profiler) in m s^{-1}	5.6	5.7
Bias (m s^{-1})	0.4	0.6
Median difference (m s^{-1})	0.3	0.5
Standard deviation (m s^{-1})	1.2	1.5
RMS difference (m s^{-1})	1.3	1.6
Spearman rank correlation	0.90	0.85

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