Evaluation of DBS Wind Measurement Technique in Different Beam Configurations for a VHF Wind Profiler

I. SRINIVASA RAO AND V. K. ANANDAN

National Atmospheric Research Laboratory, Tirupati, Andhra Pradesh, India

P. NARASIMHA REDDY

Department of Physics, Sri Venkateswara University, Tirupati, Andhra Pradesh, India

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ABSTRACT

Atmospheric winds in the troposphere have been observed routinely for many years with wind profiling (VHF and UHF) radars using the Doppler beam swinging (DBS) technique. Accuracy of wind estimates using wind profiling radars with different beam configurations has its limitations due to both the system of observation and atmospheric conditions. This paper presents a quantitative analysis and evaluation of horizontal wind estimation in different beam configurations up to an altitude of 18 km using the mesosphere–stratosphere–troposphere (MST) radar located in Gadanki, India. Horizontal wind velocities are derived in three different ways using two-, three-, and four-beam configurations. To know the performance of each configuration, radar-derived winds have been compared with the winds obtained by simultaneous GPS sonde balloon measurements, which are considered to be a standard reference by default. Results show that horizontal winds measured using three different beam configurations are comparable in general but discrepancy varies from one beam configuration to the other. It is observed that horizontal winds measured using four-beam configuration (east, west, north, and south) have better estimates than the other two-beam configurations. The standard deviation was found to be varying from 1.4 to 2.5 m s^{-1} and percentage error is about 9.68%–12.73% in four-beam configuration, whereas in other beam configurations the standard deviation is about 1.65–3.9 m s^{-1} and the percentage error is about 11.29%–15.16% with reference to GPS sonde balloon–measured winds.

1. Introduction

Over the past three decades wind profiling radars have proven to be a powerful tool for atmospheric research. Remote sensing of winds and the turbulence in the middle atmosphere (over a height range of 3–100 km) by the Doppler beam swinging (DBS) technique is widely incorporated by wind profilers (Balsley and Gage 1980; Gage and Balsley 1984; Rottger 1984). By performing different experiments at different locations with different operating frequencies of radar, it has been clearly established that the Doppler shift obtained from radar is an accurate method of measuring wind velocity along the line of sight of the radar beam (Gage and Balsley 1978; Farely et al. 1979). Taking advantage of this, wind profilers have been used to monitor the atmospheric wind field (Larsen and Rottger 1982; Hocking 1986); these are only two of many possible examples. Several other instruments like radiosondes, aircraft (Angevine and Macpherson 1995; Cohn et al. 2001), and rocket sondes were used for the comparison and validation of wind measurements of VHF and UHF radars. For example, Strauch (1981), Fukao et al. (1982), Lawrence et al. (1986), Weber and Wuertz (1990), Astin and Thomas (1991), May (1993), Steinhagen et al. (1994), and Kishore et al. (2000) have made numerous comparisons with radiosondes. Comparison with radiosondes is very useful since they are by his-

Corresponding author address: V. K. Anandan, Radar Development Area, ISTRAC, Indian Space Research Organisation (ISRO), A 1-6, Peenya Industrial Estate, 1st Cross, Bangalore 560058, India.
E-mail: anandanvk@hotmail.com

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torical precedent the current standard (by default). In this paper the subject of the study is not the comparison of radar observed winds with radiosonde measurements but the evaluation of the best beam configuration to be used to estimate the horizontal winds.

In general the wind profiling radar design was optimized for the measurements of winds in clear air that are uniform over a horizontal distance of few kilometers. Five-beam radar can detect conditions of horizontal homogeneity by virtue of its ability to make independent measurements of winds from horizontally separated scattering volumes (Wuertz et al. 1988). In this paper a detailed study has been made using an Indian mesosphere–stratosphere–troposphere (MST) radar to evaluate the performance of wind measurement methods. This is the first time a quantitative analysis is being carried out on wind estimation in three different beam configurations using MST radar, and the results are compared with GPS sonde–measured winds as a reference. Here horizontal wind velocities are estimated using two-, three-, and four-beam configurations. In general, small differences are expected between radar and GPS sonde wind measurements because of temporal and spatial separation between two instruments and inherent biases and inaccuracies in the respective observational systems. So it is very important to note that any systematic bias introduced by the two systems and the general differences due to spatial separation will have similar effects on three different beam configurations in wind estimation, since the same dataset is being used in deriving wind velocities. In spite of measurement differences and inherent limitations of two measurement techniques, we are trying to distinguish the differences among different beam configurations in measuring winds in a quantitative way by showing several statistical parameters. Therefore, this type of statistical analysis is helpful to identify the accuracy of wind measurement in different beam configurations, so that estimation error can be reduced as much as possible.

Radar-measured radial velocities contain contributions from both horizontal and vertical components of true wind. It has long been recognized that vertical correction can provide improved retrieval, if there are significant vertical motions that are uniform over the volume where the radar beams are scanned (Strauch et al. 1987; Wuertz et al. 1988; Weber et al. 1992). During nonuniform precipitation or whenever the vertical velocity has significant small-scale variability, inclusion of the vertical component leads to substantial errors in deriving horizontal winds (Wuertz et al. 1988; Weber et al. 1992; Riddle et al. 1996; Adachi et al. 2005). In convection, heavy precipitation, or in other disturbed conditions vertical velocities may vary substantially in time as well as space. This makes vertical beam velocities significantly less representative over the area across the beams and decreases the observational precision. Hence for this analysis we have considered the observations with vertical velocities less than 30 cm^{-1}, which essentially indicates clear-air conditions.

2. System description and data processing

The MST radar located at Gadanki, India (13.47°N, 79.18°E), is a monostatic coherent pulsed Doppler radar operating at 53 MHz with a peak power of 2.5 MW. The antenna system, which occupies an area of 130 m × 130 m, is a phased array of 32 × 32 three-element Yagi antenna consisting of two orthogonal sets, one for each polarization (east–west and north–south). The beam can be positioned at any look angle within ±20° off zenith in the two major planes (E–W, N–S) with 1° intervals. Details of the system description are given by Rao et al. (1995). The experiment was conducted with six beams, in which four beams were directed 10° off zenith toward the east, west, north, and south and two beams pointed zenith to provide a measurement of vertical velocity in the E–W (zenith-y), N–S (zenith-x) planes. The beam sequence was east, west, zenith-y, zenith-x, north, and south. The received echo signal is sampled at intervals of 150 m in the height range of 3.6–25.95 km. The offline data processing for parameterization of the Doppler spectrum involves the removal of dc; estimation of average noise level; removal of interference, if any; and computation of three lower-order moments. An adaptive moments estimation algorithm developed by Anandan et al. (2005) is used for the extraction of three spectral moments from the spectrum data with the expressions given by Woodman (1985). This technique has significant advantage in terms of better height coverage compared to the conventional single peak detection method. Though the experiment was designed to cover a height range of up to 25.95 km, the wind information above 18 km was not considered because of poor signal-to-noise ratio (SNR). Observations over a period of 30 days in June–August 2006 were considered for the present study. To test the accuracy of three different beam configurations in measuring horizontal winds, radar wind measurements have been compared with GPS sonde balloon measurements. GPS sondes were launched on a daily basis from the National Atmospheric Research Laboratory in Gadanki, India, at 1730 LT. The spatial separation between GPS sonde launch and MST radar is about 100 m. During the balloon launch time, the MST radar was operated continuously for 1 h (1730–1829 LT) with the specifications shown in Table 1. A quality control check has been made on radar data in which we considered data with vertical velocities less than 30 cm s^{-1} that essentially indicate clear-air conditions. Therefore, the study was limited to only 30 days of observations out of all the available data during June–August 2006. An averaging period of 1 h (1730–1829 LT) is used for MST radar data.

While deriving wind velocities it is assumed that the atmosphere is homogeneous across the radar observational volume. In the less-used two-beam configuration, two orthogonal beams (east, north) are used to measure horizontal winds; in three-beam configuration, horizontal winds are measured using two orthogonal beams (here, east and north) and a zenith beam; in four-beam configuration all four oblique beams (east, west, north, south) are used. Horizontal wind components at any given height are derived from the radial velocities (υ_R) (positive away from the radar) measured on each of the five antenna beams. If we measure radial velocities in east (υ_{RE}), west (υ_{RW}), north (υ_{RN}), south (υ_{RS}), and zenith (υ_{RV}) directions with the elevation angle θ, then

$$\upsilon_{RE} = u\cos\theta + w\sin\theta, \tag{1}$$

$$\upsilon_{RN} = \upsilon\cos\theta + w\sin\theta, \tag{2}$$

$$\upsilon_{RW} = -u\cos\theta + w\sin\theta, \tag{3}$$

$$\upsilon_{RS} = -\upsilon\cos\theta + w\sin\theta, \tag{4}$$

$$\upsilon_{RV} = w. \tag{5}$$

The corresponding zonal (u) and meridional (υ) components of wind in three different beam configurations are given by

$$u_{2B} = \frac{\upsilon_{RE}}{\cos\theta}, \tag{6}$$

$$\upsilon_{2B} = \frac{\upsilon_{RN}}{\cos\theta}, \tag{7}$$

$$u_{3B(East)} = \frac{\upsilon_{RE} - \upsilon_{RV}\sin\theta}{\cos\theta}, \tag{8}$$

$$\upsilon_{3B(North)} = \frac{\upsilon_{RN} - \upsilon_{RV}\sin\theta}{\cos\theta}, \tag{9}$$

$$u_{4B} = \frac{\upsilon_{RE} - \upsilon_{RW}}{2\cos\theta}, \tag{10}$$

$$\upsilon_{4B} = \frac{\upsilon_{RN} - \upsilon_{RS}}{2\cos\theta}. \tag{11}$$

Note that we have not considered the radar measurement errors in the above equations. In the case of four-beam configuration, the influence of vertical velocity is not explicitly corrected while computing horizontal velocities. Instead this will get nullified when calculating the wind velocities using Eqs. (10) and (11).

TABLE 1. Radar parameters used for the experiment.

Parameter	Value
No. of beam positions	6 (10°E, 10°W, 10°N, 10°S, and 0°Zx, Zy)
Pulse length	16 μs (complementary code with 1-μs baud)
Interpulse period	1000 μs
No. of range gates	150
Range resolution	150 m
No. of coherent integrations	64
Velocity resolution	0.086 m s^{-1}
No. of incoherent integrations	1

Horizontal wind comparisons for all these measurements are carried out in a statistical sense (i.e., using mean difference, standard deviation, correlation coefficient, and percentage of error). These statistics are helpful for understanding the performance of each method in estimating horizontal wind velocities. Here, standard deviation (σ_D) is calculated for the difference in horizontal velocities between radar and GPS sonde measurements as follows:

$$\upsilon_{(D)i} = \upsilon_{(GPS)i} - \upsilon_{(P)i}, \tag{12}$$

$$\text{mean } \mu_D = \frac{1}{N}\sum_{i=1}^{N} \upsilon_{(D)i}, \tag{13}$$

$$\text{standard deviation } \sigma_D = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (\upsilon_{(D)i} - \mu_D)^2}, \tag{14}$$

where N is the total number of observations for each range bin.

Another important statistical parameter that gives the direct comparison of all the measurements is percentage error (PE). If a represents the true/reference (GPS) value, and b represents the (radar) measured value, then PE is calculated as

$$\text{percentage error } \delta = \frac{|a - b|}{|a|} \times 100\%. \tag{15}$$

3. Results and discussion

The basic difference between the three different beam configurations is that the two- and four-beam methods do not depend on vertical beam observations whereas the three-beam method does; two and three beams use one coplanar beam (east or west in zonal

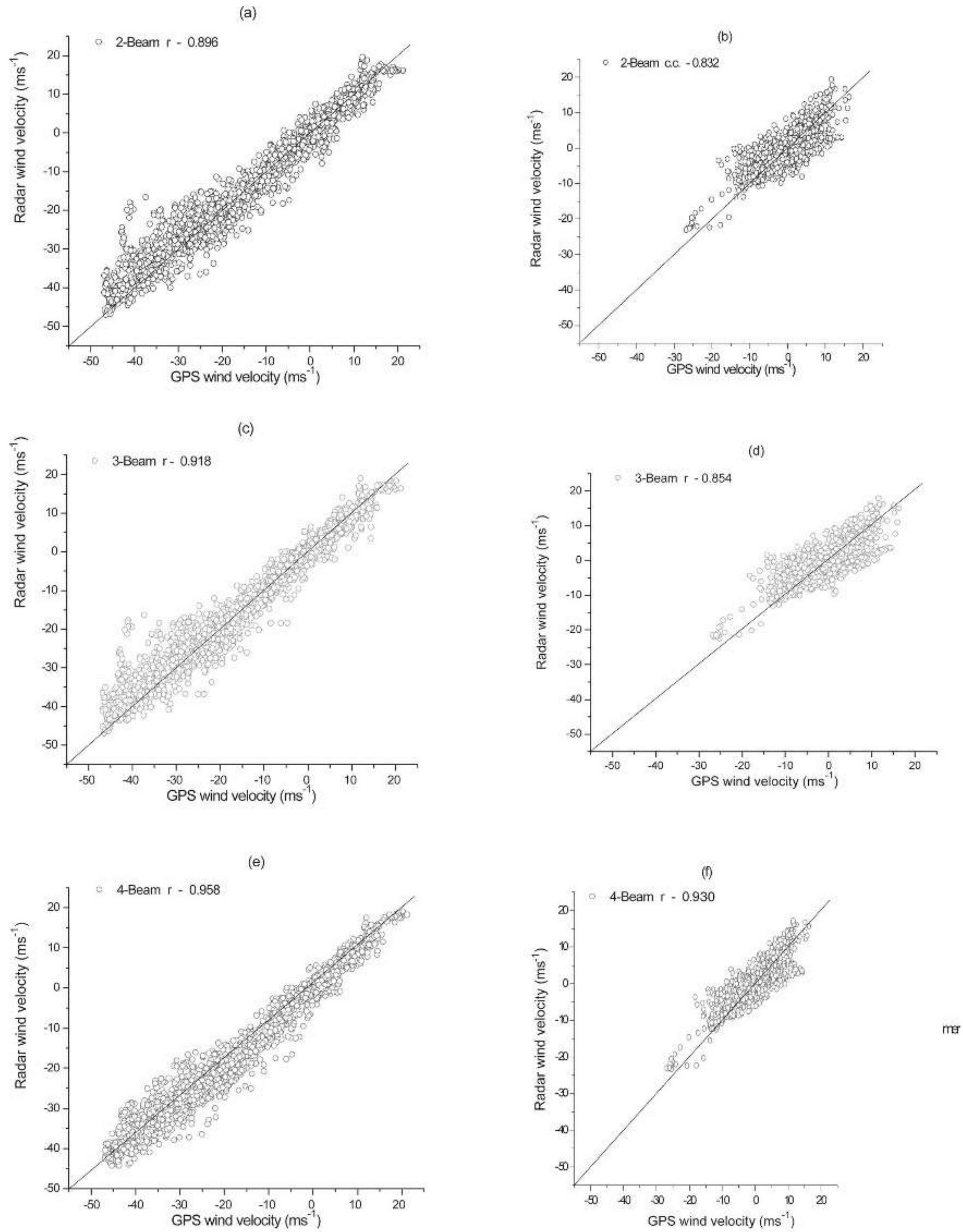


FIG. 1. Scatterplots of the GPS sonde vs radar horizontal wind velocities for different beam configurations from a height range of 3.6–18 km: (a), (c), (e) zonal and (b), (d), (f) meridional component.

direction and north or south in meridional direction) whereas four beams use two opposing coplanar (east–west and north–south) beams. Figure 1 illustrates scatterplots of GPS and radar wind measurements for different beam configurations. Figures 1a,c,e show the zonal component and Figs. 1b,d,f show the meridional component of winds. A total of 2910 points were shown in the plot from a height range of 3.6–18 km. Each point

TABLE 2. Correlation coefficients of (a) zonal and (b) meridional velocities for different beam configurations.

(a) Zonal			
	Correlation coefficients		
Height (km)	Two beams	Three beams	Four beams
3.6–6	0.89	0.92	0.96
6–9	0.90	0.93	0.97
9–12	0.92	0.96	0.98
12–15	0.90	0.91	0.96
15–18	0.86	0.87	0.92

(b) Meridional			
	Correlation coefficients		
Height (km)	Two beams	Three beams	Four beams
3.6–6	0.83	0.92	0.92
6–9	0.85	0.86	0.94
9–12	0.84	0.89	0.95
12–15	0.83	0.86	0.93
15–18	0.81	0.82	0.90

in the plot corresponds to a pair of measurements that were obtained by the two instruments with a height resolution of 150 m. A regression analysis of the radar- and balloon-measured wind components shows that GPS versus four-beam configuration is correlated well when compared with other beam configurations. The correlation coefficients of GPS versus two beams, GPS versus three beams, and GPS versus four beams are 0.896, 0.918, and 0.958 for zonal winds and 0.832, 0.854, and 0.93 for meridional winds, respectively. The variation of correlation coefficients with respect to height is given in Table 2.

From the scatterplots it is difficult to quantify the differences, as they look similar; thus, to have more clarity on the spread of the data points in each beam configuration we have calculated the difference in horizontal wind velocities between GPS and radar. These differences are binned in intervals of 1 m s^{-1} and are shown in Fig. 2. It is observed from Fig. 2a that the number of points that lie within ± 1 m s^{-1} for two, three, and four beams are 1033 (35.4%), 1078 (37%), and 1175 (40.3%), respectively. In the case of meridional winds it is observed that the number of points that lie within ± 1 m s^{-1} for two, three, and four beams are 1033 (35.4%), 1087 (37.3%), and 1193 (40.9%), respectively, as shown in Fig. 2b. This shows that 3% more data points fall inside ± 1 m s^{-1} for four-beam configuration compared to other beam configurations for both zonal and meridional winds. Our analysis shows that these differences vary from height to height and therefore we made separate comparisons over a range of heights. These ranges are separated as 3.6–6, 6–9, 9–12, 12–15, and 15–18 km. To know the velocity difference over various heights, statistics were made over a range of heights and are shown in Table 3. These statistics reveal that four-beam configuration had less velocity difference in all the heights (value varied from 1.03 to 3.23 m s^{-1} in zonal wind component and 1.13 to 2.80 m s^{-1} in meridional wind component).

Figure 3 shows the mean zonal velocity plots estimated using Eq. (13) and horizontal bars on the plots represent standard deviation σ_D estimated using Eq. (14) for different beam configurations. The variation of σ_D is shown in Fig. 4 for zonal and meridional winds using different beam configurations. It is observed that

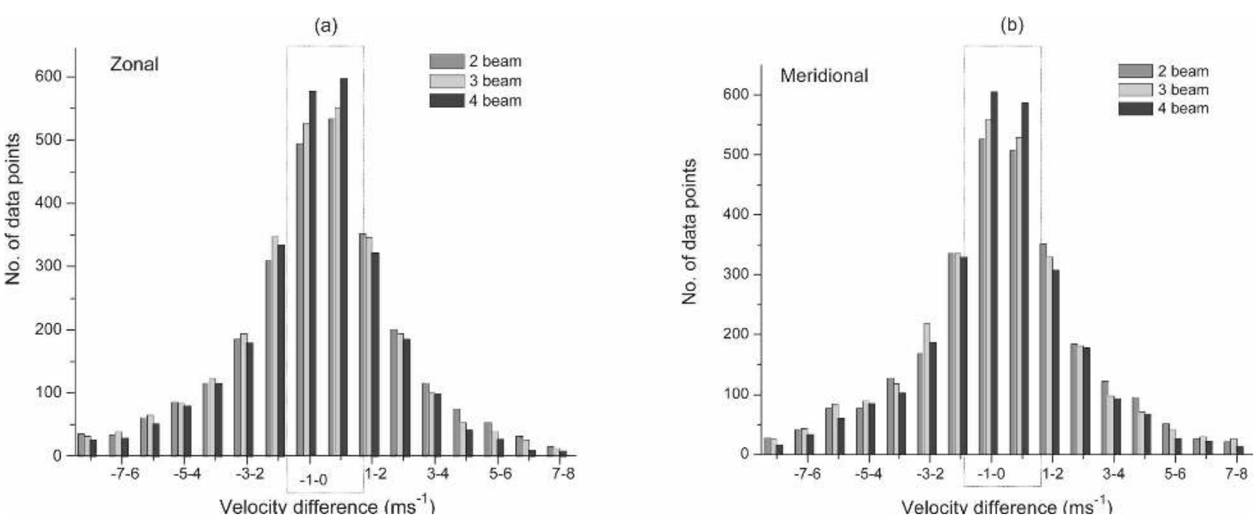
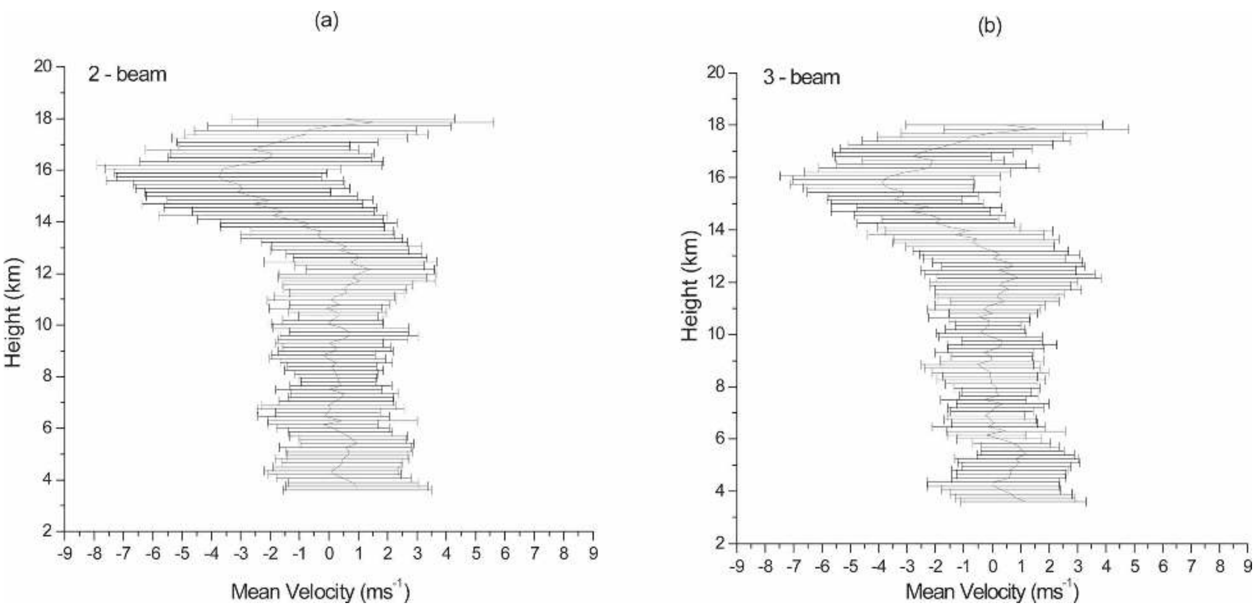


FIG. 2. Difference in horizontal wind velocities for (a) zonal and (b) meridional components between GPS sonde and radar with an interval of 1 m s^{-1}.

TABLE 3. Mean velocity difference of zonal velocities for different beam configurations.

Height (km)	Velocity difference ($m\ s^{-1}$)		
	Two beams	Three beams	Four beams
3.6–6	1.64	1.43	1.15
6–9	1.45	1.29	1.03
9–12	1.72	1.56	1.30
12–15	3.20	2.95	2.51
15–18	4.05	3.85	3.23

the four-beam configuration has less σ_D in wind estimation compared to the estimation from other two-beam configurations. As shown in Fig. 4a, for zonal winds the σ_D of four-beam configuration varies from 1.48 to 2.58 $m\ s^{-1}$, whereas in the case of two- and three-beam configurations, σ_D varies between 1.85 and 3.95 $m\ s^{-1}$ and between 1.65 and 3.37 $m\ s^{-1}$, respectively. This is also true for meridional winds as shown in Fig. 4b. Figure 5 shows the percentage of data points that fall in different σ_D ranges in steps of 0.5 $m\ s^{-1}$. It is observed that in zonal winds, 54% of the points were below 2 $m\ s^{-1}$ for four-beam configuration, whereas in the case of two- and three-beam configurations, it is about 29% and 42%, respectively. In the case of meridional winds the σ_D values for two-, three-, and 4-beam configurations are 26%, 38%, and 56%, respectively. It is observed from the previous studies that for three-beam systems, Weber and Wuertz (1990) found a



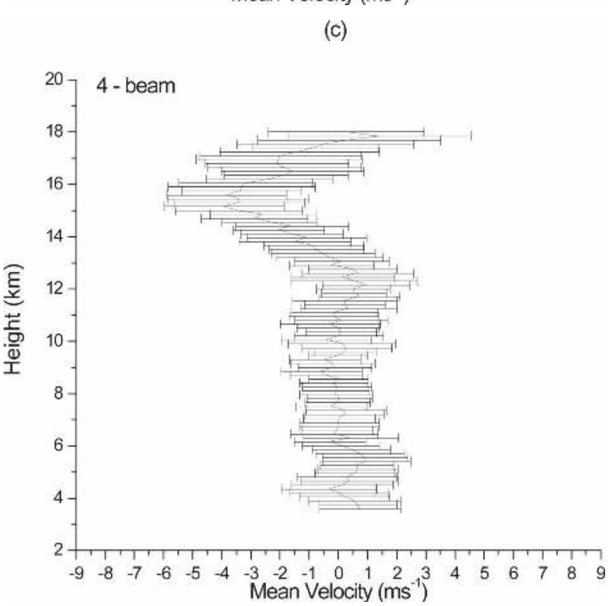


FIG. 3. Mean zonal velocity plot for (a) two-, (b) three-, and (c) four-beam configurations. Error bars on the plot represent std dev.

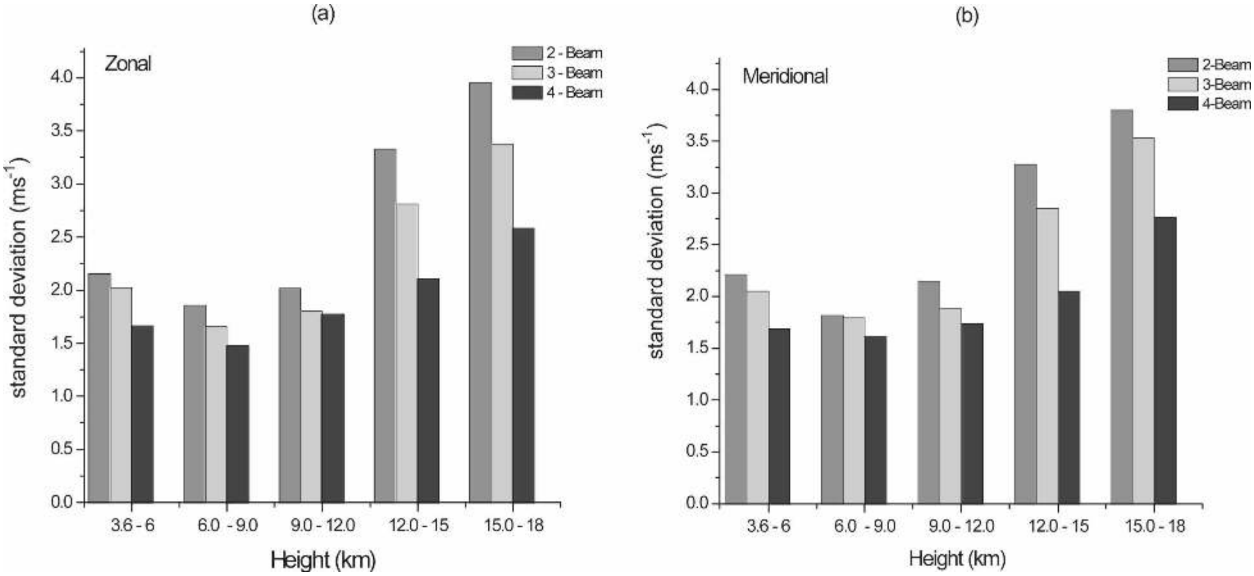


FIG. 4. Std dev of difference of GPS sonde and the radar-observed wind velocities measured using different beam configurations at various heights for (a) zonal and (b) meridional components.

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} when compared with aircraft measurements 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 in clear air. Adachi et al. (2005) reported a standard deviation of 1.2 m s^{-1} in comparison with a tower. Therefore, the value of standard deviation for this type of study mainly depends on the type of standard instrument used as reference and also on the spatial resolution of the two instruments. Figure 6 shows the PE for wind measurement in three different beam configurations for the zonal and meridional velocities. From Fig. 6, it is observed that for zonal winds the PE lies in between 9.68 and 12.73 for four-beam configuration, whereas for two and three beams the PE values are varying from 11.4 to 15.16 and from 11.3 to 13.36, respectively. Similarly, for meridional velocities

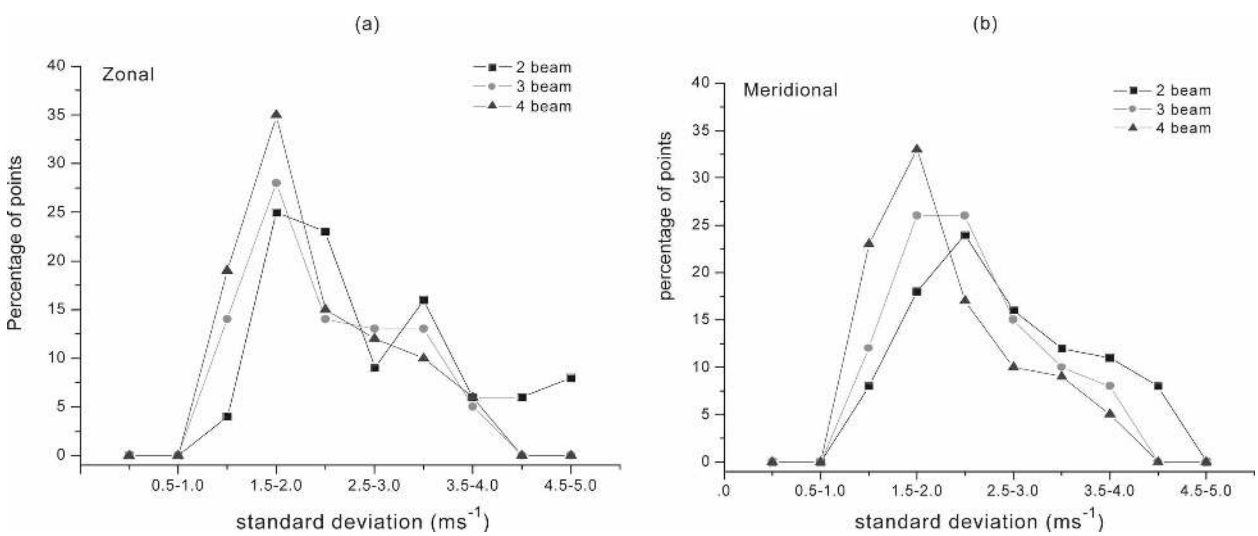


FIG. 5. Distribution of the std dev of the difference between GPS and radar winds, presented as a percentage of points per 0.5 m s^{-1} bin for (a) zonal and (b) meridional components.

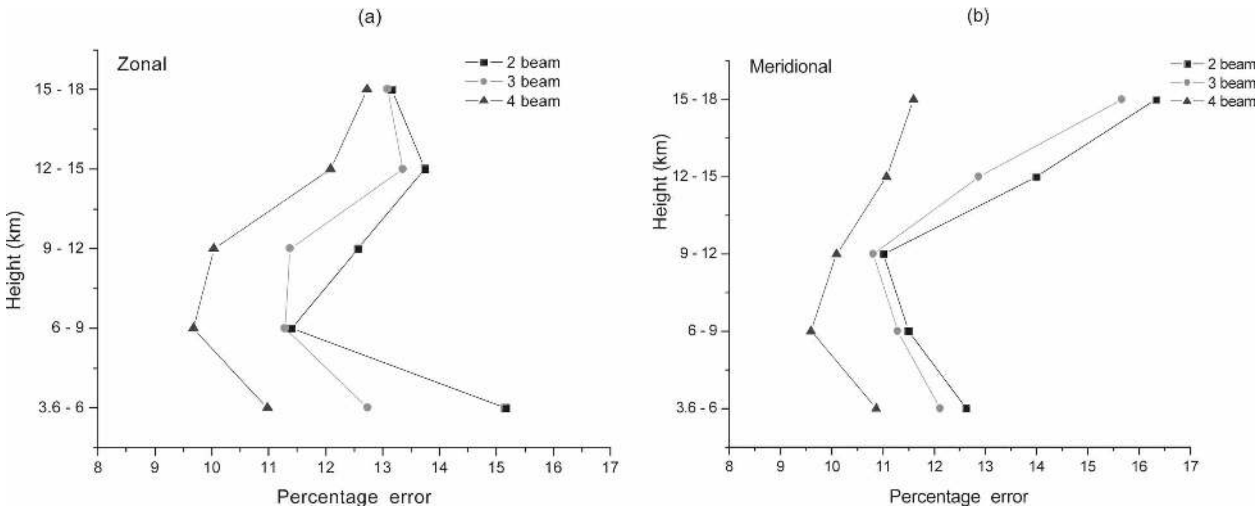


FIG. 6. Percentage error in wind components as a function of height band for (a) zonal and (b) meridional components calculated using different beam configurations.

the PE values for two-, three-, and four-beam configurations are varying from 11.5 to 15.33, 11.29 to 15.6, and 9.6 to 11.9, respectively. In the case of two- and three-beam configurations, the opposite pair of beams (west and south for two beams and west, south, vertical for three beams) have been tested and similar results observed (not shown).

It is evident from the above results and statistics that radar beam configurations influence the horizontal wind velocity estimation. The present statistical study reveals that four-beam configuration has better agreement with GPS than two- and three-beam configurations. It is also observed that in all the beam configurations the velocity difference increases above 12 km. This difference may be attributed to two reasons. One is the decrease in SNR at higher altitudes by the radar measurement and the other is due to a sonde that might have shifted far away from the radar site along with the background wind, hence measuring a slightly different wind field. Consequently, these biases and error will appear in all the beam configurations and that is why we have a minimum of 9.6% error (PE) even in the four-beam configuration, which has the best agreement when compared with other beam configurations. From the results it is observed that two-beam configuration has more standard deviation, more percentage error, and less correlation coefficient in all the heights than the other beam configurations. This is due to the fact that vertical velocity correction has not been applied for the two-beam configuration in computing horizontal wind velocities. Although the magnitude of vertical velocities seems to be less ($\leq$30 cm^{-1}), its contribution to the radial component is strong enough or large enough to produce a mean error of 1.5 m s^{-1} when it is excluded in horizontal wind estimation. It is evident from the three-beam configuration (in which vertical correction was applied) that it has an improved performance over the two-beam configuration in terms of all the statistics shown in the figures. The advantage of four beams is that they give average wind information within the radar scanning volume, whereas it is not possible with two- or three-beam configuration.

Here the study has been reported for VHF radar wind profiler observations. Since the wind extraction method used in the DBS technique is the same for UHF wind profilers that are normally used for the observation of the lower atmosphere (0.5–10 km), it is expected that the observation presented here also holds true for UHF wind profilers.

4. Conclusions

A quantitative study is presented in order to determine the performance of different beam configurations in estimating horizontal wind velocities. The analysis was carried out with an Indian MST radar in the height range of 3.6–18 km in clear-air conditions. A variety of statistics was explored in evaluating the winds measured by two-, three-, and four-beam configurations and we compared these results with simultaneous GPS sonde wind measurements. From the results it is observed that all the statistical parameters are in favor of four-beam configuration. Standard deviation and percentage error are reduced to the minimum value in all the heights when horizontal winds are estimated with a four-beam configuration, and they are highest for a two-beam configuration. This study shows that horizontal winds computed in a four-beam configuration have better agreement with a GPS sonde–measured winds over other beam configurations. This also suggests that five-beam (east, west, north, south, and zenith) wind profilers may be used over conventional three-beam profilers (east or west, north or south, and vertical) for wind estimation.

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