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THE INFLUENCE OF INHOMOGENEOUS WIND DISTRIBUTION ON DATA QUALITY FOR WIND PROFILING RADAR

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Abstract: Horizontal wind measured by wind profiling radar (WPR) is based on uniform wind assumption in volume of lateral beam. However, this assumption cannot completely meet in the real atmosphere. The subject of this work is to analyze the influence of atmospheric inhomogeneities for wind measurement. Five-beam WPR can measure two groups of horizontal wind components U and V independently, using the difference of horizontal wind components U and V can evaluate the influence of the inhomogeneity of the atmospheric motion on wind measurement. The influences can be divided into both inhomogeneous distribution of horizontal motion and vertical motion. Based on wind measurements and meteorological background information, a new means of coordinate rotation the two kinds of inhomogeneous factor was separated, and the impact in different weather background was discussed. From analysis of the wind measured by type of PB-II WPR (445MHz) during 2012 at Yanqing of Beijing, it is shown that the inhomogeneity of horizontal motion is nearly the same in U and V direction. Both the inhomogeneities of horizontal motion and vertical motion have influence on wind measurement, and the degrees of both influences are associated with changes of wind speed. In clear air, inhomogeneity of horizontal motion is the main influence on wind measurement because of small vertical velocity. In precipitation, the two influences are larger than that in clear air.

Key words: atmospheric sensing and sounding; wind measurement accuracy; wind profiling radar; atmospheric homogeneities; space representation

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1 INTRODUCTION

Over the past three decades the wind profiling radars (WPR) have been proven a powerful tool for wind measurement. The special detecting ability of WPR is broadly used in climate research, meteorological operation application, aviation security and many other areas (Larsen et al.[1]; Rogers et al.[2]; Jun-ichi et al.[3]; Jacoby et al.[4]; Hogg et al.[5]). Data quality control and accuracy of WPR for application of comprehensive developing meteorological operation has the vital significance (Ralph et al.[6]; Angevine[7] ; Weber et al.[8]; Lambert et al.[9]; Schafer et al.[10]).

Numerous studies for WPR measurements were compared with the wind data obtained with other instruments. The accuracy of horizontal winds measured by WPR has been estimated in comparison with radiosondes (Weber et al.[11]), aircraft (Cohn et al.[12]), lidar and towers (Adachi et al.[13]). Recently, Deng used four groups of three-beam detected pattern to evaluate effective detected height and accuracy of wind measurement in different months[14]. Strauch showed that the five beam-pointing positions of WPR can provide measurements of horizontal winds independently, and so could be compared to determine relative accuracy and precision[15]. As is demonstrated, relative accuracy of horizontal wind components was limited by atmospheric inhomogeneity. On the basis of Strauch's study, Wuertz found that vertical motion has a significant influence on wind measurement of the horizontal components in precipitation[16].

The precision and accuracy of WPR wind measurement are affected by the following factors: 1) the assumption of horizontal homogeneity, 2) the time representation, and 3) the systematic errors in the radial velocity measurement. Most importantly, 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 WPR cannot provide meaningful measurements.

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Based on the study of Strauch and Wuertz [15-16], this work give a further algorithm derivation to remove the inhomogeneous influence of wind distribution on data quality. Five-beam WPR can independently measure two groups of horizontal wind components U_e, U_w, V_n, and V_s. Using their motion difference can evaluate the influence of the inhomogeneity of the atmospheric motion on wind measurement. The influence can be divided into the inhomogeneous distribution of horizontal motion and vertical motion. Coordinate rotation is used to make the two kinds of inhomogeneous factor separated, then their impact on different weather background can be discussed. Wind measurements are used with UHF (445 MHz) WPR during 2012 at Yanqing, Beijing (40.45°N, 115.96°E; 487.9m).

2 INSTRUMENTATION AND DATA PROCESSING

The UHF (445MHz) WPR is operated with 120m (the low mode) and 240m (the high mode) pulse lengths. Each of the five beams samples a different volume of atmosphere. Four beams direct 14 degrees off the vertical toward north, east, south and west. Continuous processes were used to remove some missing measurements for the whole year of 2012. The fifth straight-up points measure the vertical velocity.

According to rain count on surface, all data are divided into two categories: Clear air and precipitation. A total of 93,860 wind profiles of clear air and 7,582 profiles of precipitation are statically analyzed, respectively.

Through quality control, contaminated data before wind measurement were removed. The statistical filter technique (Strauch et al. [17]) was applied here and the hourly-averaged of the winds were output. For routine processing, at least 4 of the 12 values must form a consensus on each of the five beams and they must lie within a window that is 1/8 of the Nyquist velocity. Spurious outliers in the data can be recognized and removed based on this consensus.

3 ANALYSIS

Horizontal wind measurement by WPR is based on homogeneity assumption that the hourly averaged wind field is uniform across all antenna beams at a given height. Statistical tests are used to check these assumptions, and when this assumption fails, the WPR cannot provide meaningful measurements. A five-beam antenna was used just as in an earlier study (Strauch et al. [15]) which assessed the precision of wind profiler measurements in clear air. In addition, how the precision and accuracy of those measurements are affected by inhomogeneity in horizontal motion and vertical motion of different weather background are discussed in this paper.

Each of the five beams samples a different volume of the atmosphere. By virtue of elevation angle, the four lateral beams interrogated volumes that are displaced about 2.7 km from the vertical beam for measurements at a height of 10km above the ground. Hence, the total east-west and north-south displacement of the measurement volumes is more than 5km 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 the test of both the radar measurements and the assumption of horizontal homogeneity.

3.1 *Data analysis techniques*

Horizontal wind components at any given height are derived from the radial velocities (V_r) (here positive direction is away from the radar) measured on each of the five antenna beams. The radical velocities are for the east (V_{re}) , west (V_{rw}), north (V_{rn}), south (V_{rs}), and zenith (V_{rz}) directions with the elevation angle being θ. The horizontal wind components are computed from radial velocity as follows:

$$\begin{aligned} V_n &= +V_{rn}\sec\theta - V_{rz}\tan\theta = \nu + \delta V_n \\ U_e &= +V_{re}\sec\theta - V_{rz}\tan\theta = u + \delta U_e \\ V_s &= -V_{rs}\sec\theta + V_{rz}\tan\theta = \nu + \delta V_s \\ U_w &= -V_{rw}\sec\theta + V_{rz}\tan\theta = u + \delta U_w \end{aligned} \tag{1}$$

V_n, U_e, V_s and U_w are the horizontal wind components from the north, east, south and west antenna beams respectively, and the errors in these measurements are δV_n , δU_e , δV_s , and δU_w. The error term δV_r contains errors under the influence of inhomogeneous atmospheric motion on wind measurements including inhomogeneity in horizontal motion of Δu and Δv and vertical motion Δw, which are given by

$$\begin{aligned} \delta V_n &= -\Delta w + \Delta v \\ \delta U_e &= -\Delta w + \Delta u \\ \delta V_s &= +\Delta w - \Delta v \\ \delta U_w &= +\Delta w - \Delta u \end{aligned} \tag{2}$$

A useful way to compare these independent measurements is by computing their differences

$$\begin{aligned} D_U &= U_w - U_e = \delta U_w - \delta U_e = 2\Delta w + 2\Delta u \\ D_V &= V_s - V_n = \delta V_s - \delta V_n = 2\Delta w + 2\Delta v \end{aligned} \tag{3}$$

These points are emphasized by the following combinations of the velocity differences (3), referring to a study by Strauch [15]:

$$\begin{aligned} D_C &= (D_U + D_V)/2^{1/2} = 2^{1/2}\Delta w + 2^{1/2}(\Delta u + \Delta v) \\ D_S &= (D_U - D_V)/2^{1/2} = 2^{1/2}(\Delta u - \Delta v) \end{aligned} \tag{4}$$

By taking D_U to be the x-axis and D_V to be the y-axis of a right-hand Cartesian coordinate system, D_C

and D_S are the x- and y-axes of another system that is rotated 45° counterclockwise from the first system. The Δw error appears only along the D_C-axis, whereas the Δu and Δv errors appear on both axes.

Figure 1 gives the scatter diagram of D_U versus D_V during 2012 for Yanqing, Beijing. The data without quality control and the result after quality control are shown in Fig.1a and Fig.1b respectively. Fig.1c shows the distribution density for the same data as in Fig.1b. They are conveniently displayed in a scatter diagram for which the D_U -axis is horizontal and the D_V-axis is vertical. Then, the D_C- and D_S-axes run diagonally from the lower left to the upper right and from the lower right to the upper left, respectively. There is a very distinct elliptical pattern aligned along the D_C-axis. This pattern can be explained by considering the errors in (3) and (4). Assume that Δu and Δv are uncorrelated, and their variances are the same under the large data sample. These variances of the errors are:

$$\begin{aligned} \mathrm{VAR}(D_U) &= 4\mathrm{VAR}(\Delta w) + 4\mathrm{VAR}(\Delta u) \\ \mathrm{VAR}(D_V) &= 4\mathrm{VAR}(\Delta w) + 4\mathrm{VAR}(\Delta v) \\ \mathrm{VAR}(D_C) &= 8\mathrm{VAR}(\Delta w) + 2\mathrm{VAR}(\Delta u + \Delta v) \\ \mathrm{VAR}(D_S) &= 2\mathrm{VAR}(\Delta u + \Delta v) \end{aligned} \quad (5)$$

where VAR denotes the variance computed over the year and over all height. The variances of errors Δu and Δv are assumed the same, and they are uncorrelated with each other. Expression (5) shows that the influence of the inhomogeneous distribution on wind measurements, including horizontal motion and vertical motion, can be divided. The relationship between the variance and standard deviation is as follows:

$$\begin{aligned} \sigma_{//}^2 &= \mathrm{VAR}(\Delta u) = \mathrm{VAR}(\Delta v) \\ \sigma_{\perp}^2 &= \mathrm{VAR}(\Delta u) \\ \sigma^2 &= \sigma_{//}^2 + \sigma_{\perp}^2 \end{aligned} \quad (6)$$

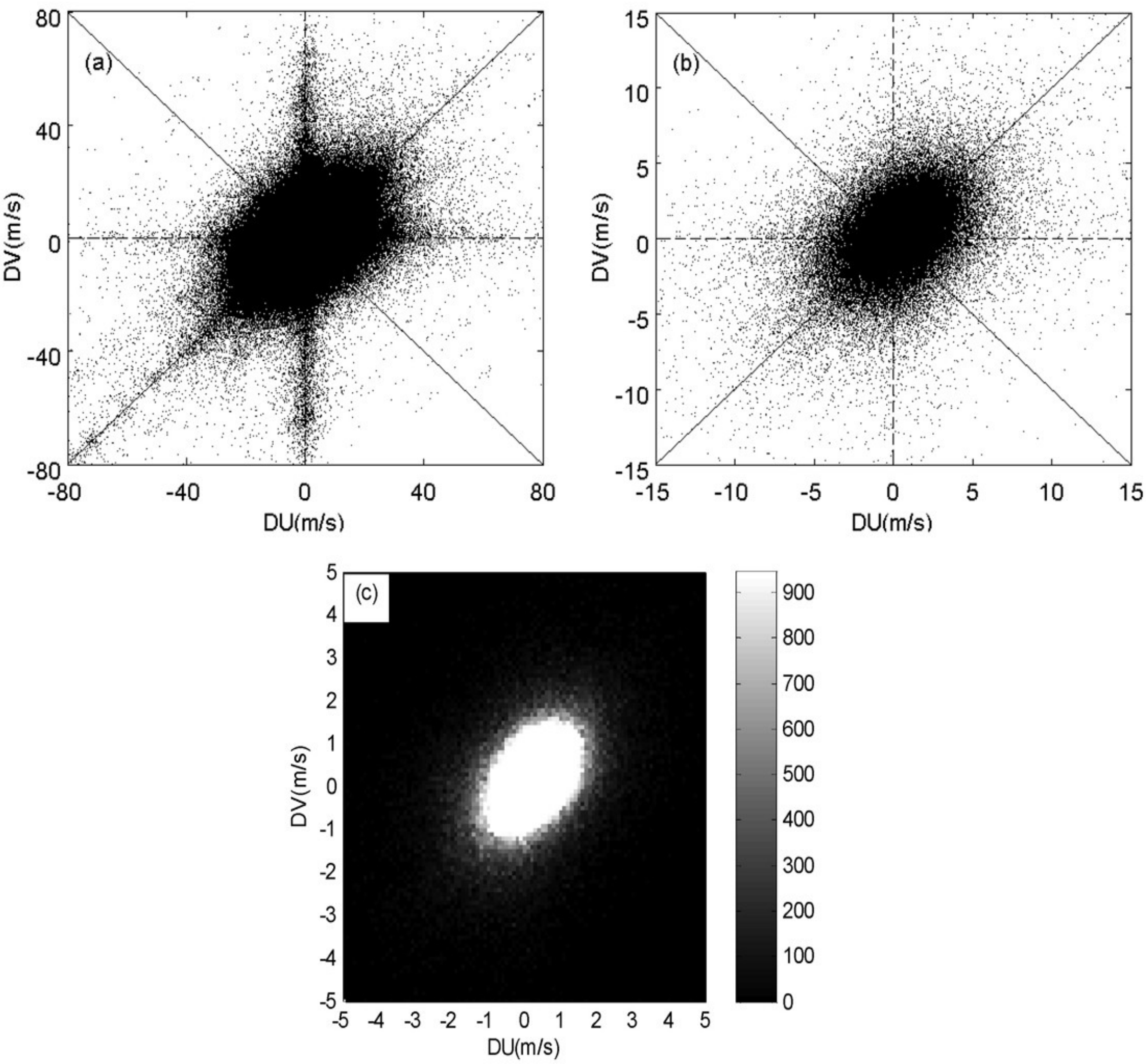

Figure 1. Scatter diagram of D_U versus D_V during 2012 for Yanqing. a: after data quality control; b: density diagram. a: before data quality control b: after data quality control c: density diagram.

Figure 2 shows the percentage of data points in Fig.1b that fall in different D_U and D_V range in steps of 1m/s. It is observed that 86.9% of D_U lie between −2m/s and 2m/s, whereas in the case of D_V, it is 86.4%, and both values are nearly the same. So the statistical data confirm the assumption of $VAR(\Delta u) = VAR(\Delta v)$.

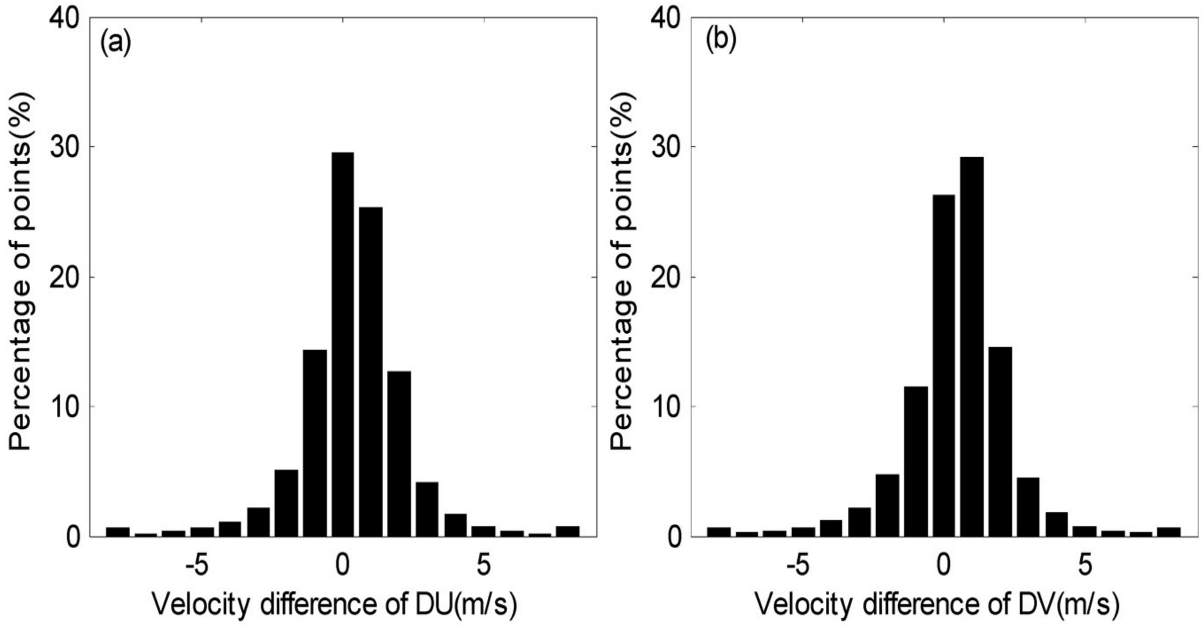

Figure 2. Frequency diagram of D_U (a) and DV (b) in 2012, Yanqing of Beijing.

3.2 *Overall statistics of wind measurements in 2012 year using standard processing*

The statistics for the wind data in different weather background are given in Table 1. The mean and standard deviation of D_U, D_V, D_C and D_S are listed. Note that the mean of D_U and D_V is less than 0.5m/s no matter what the weather is, which shows that there is no obvious systematic error of the WPR, and the atmosphere is homogeneous in the direction of v and u. But the standard deviation of D_U, D_V, D_C and D_S is obviously different in different weather background. Wind measurements in clear air are the best, and the standard deviation of D_U and D_V are 1.98m/s and 1.85m/s, respectively. In precipitation, the standard deviation of D_U and D_V increases to 4.4m/s and 4.3m/s, respectively. Besides, affected by raindrop, the standard deviation of D_U and D_V increases to 2.5m/s and 2.4m/s, respectively in the whole of 2012. The results show that the atmosphere is inhomogeneous in precipitation. On sunny days, the standard deviation of D_S is 1.58m/s, close to that of D_U and D_V. In precipitation, the standard deviation of D_S is 2.32m/s, less than that of D_U and D_V, which are 4.39m/s and 4.30m/s, respectively, because the vertical wind motion or the raindrop fall speed is the same on all antenna beams at the same height and time.

Table 1. The mean difference and standard deviation of D_U, D_V, D_C and D_S.

	D_U (m/s)		D_V (m/s)		D_C (m/s)		D_S (m/s)	
	Mean	Std*	Mean	Std	Mean	Std	Mean	Std
All	0.38	2.53	0.48	2.39	0.61	2.94	0.07	1.82
No precipitation	0.43	1.98	0.56	1.85	0.70	2.17	0.09	1.58
Precipitation	0.24	4.39	0.39	4.30	0.45	5.47	0.10	2.32

*: Standard deviation

Table 2 describes the change of $\sigma, \sigma_{/\!/}$ and $\sigma_{\perp}$ with the wind speed. Horizontal velocity changes much with height, and according to the maximum and minimum horizontal velocity within the radar detectable height, we can divide horizontal velocity V_h into $V_h \leqslant 5$m/s, 5m/s$<V_h \leqslant 10$m/s, 10m/s$<V_h \leqslant 15$m/s and $V_h>15$m/s. Referring to the experiment results made by Yang[18], we can divide vertical velocity into $|W| \leqslant 1$m/s, 1m/s$<|W| \leqslant$ 4ms/ and $|W|>4$m/s. The atmosphere is stable when the vertical velocity is $|W|<1$m/s. When the vertical velocity

$|W|$ is within 1m/s and 4m/s, it is usually in updrafts or downdrafts. When the vertical velocity $|W|$ is over 4m/s, it is raining.

Table 2 shows statistical distribution of σ, $\sigma_{//}$ and $\sigma_{\perp}$ under the condition of different horizontal velocity and vertical velocity. The percentage of horizontal velocity less than 10m/s is 61.35%, whereas in the case of $V_h \leqslant 5$m/s and 5m/s<$V_h \leqslant 10$m/s condition, the percentage is 29.40% and 31.95%, respectively, which does not differ much. The percentage of 10m/s<$V_h \leqslant$ 15m/s is 16.90% and V_h>15m/s is 18.16%. As shown in Table 2, the percentage of $|W| \leqslant 1$m/s is 90%, whereas the percentage of 1m/s<$|W|$<4m/s and $|W|$>4m/s is 4.4% and 1.55%, respectively, which shows that the atmospheric and atmospheric environment is basically stable in the whole year. With $|W|$>4m/s, σ is more than 3m/s, that is, the vertical wind or the precipitation falling speed may not be the same on all antenna beams at the same height and time. This leads to a violation of the fundamental assumption of horizontal homogeneity.

Table 2. σ, $\sigma_{//}$ and $\sigma_{\perp}$ with the change of $|W|$ and V_h.

V_h(m/s)	$\|W\|$ (m/s)	$\sigma_{\perp}$(m/s)	$\sigma_{//}$ (m/s)	σ (m/s)	Ratio of data (%)
$V_h \leqslant 5$	$\|W\| \leqslant 1$	0.49	0.89	1.02	28.50
	1<$\|W\|$<4	1.27	1.43	1.91	0.46
	$\|W\| \geqslant 4$	2.75	2.23	3.54	0.42
	mean	0.63	0.94	1.13	29.40
5< V_h <10	$\|W\| \leqslant 1$	0.58	1.19	1.32	30.46
	1<$\|W\|$<4	1.73	1.72	2.44	0.85
	$\|W\| \geqslant 4$	2.39	2.34	3.34	0.64
	mean	0.73	1.24	1.44	31.95
10$\leqslant V_h$ <15	$\|W\| \leqslant 1$	0.60	1.37	1.50	16.90
	1<$\|W\|$<4	1.53	1.82	2.38	0.94
	$\|W\| \geqslant 4$	2.82	3.26	4.32	0.36
	mean	0.80	1.46	1.67	18.20
$V_h \geqslant 15$	$\|W\| \leqslant 1$	0.94	1.54	1.81	18.16
	1<$\|W\|$<4	1.44	1.71	2.24	2.16
	$\|W\| \geqslant 4$	4.98	3.06	5.84	0.13
	mean	1.10	1.57	1.92	20.45

Table 3 gives the mathematical relationship of σ, $\sigma_{//}$ and $\sigma_{\perp}$ with $|W|$ and V_h, with the fitting formula being $Y = AX + B$, and Fig.3 shows their scatters distribution. The fitting linear slope of σ, $\sigma_{//}$ and $\sigma_{\perp}$ with the change of V_h is 0.064, 0.059 and 0.028, respectively, and the fitting linear slope of σ, $\sigma_{//}$ and $\sigma_{\perp}$ with change of $|W|$, respectively is 0.61, 0.36 and 0.53, respectively. That means σ, $\sigma_{//}$ and $\sigma_{\perp}$ increase with the enhancement of horizontal velocity and vertical velocity, and are more sensitive to vertical velocity than horizontal velocity.

Based on the above analysis, the values of σ, $\sigma_{//}$ and $\sigma_{\perp}$ are related with horizontal velocity and vertical velocity. σ, $\sigma_{//}$ and $\sigma_{\perp}$ are larger with the increase of horizontal velocity and vertical velocity, and they are more sensitive to vertical velocity than horizontal velocity. When $|W|$>4m/s, σ is more than 3m/s, that is,

Table 3. Fitting parameters of σ, $\sigma_{//}$ and $\sigma_{\perp}$ with change of |W|, V_h.

Parameters	A	B
$\sigma_{\perp}$=A$\|W\|$+B	0.53	0.54
$\sigma_{\perp}$=A V_h +B	0.028	0.49
$\sigma_{//}$ =A$\|W\|$+B	0.36	1.13
$\sigma_{//}$ =A V_h +B	0.059	0.73
σ =A|W|+B	0.61	1.23
σ =A V_h +B	0.064	0.89

the vertical wind or the raindrop falling speed may not be the same on all antenna beams at the same height and time. This leads to a violation of the fundamental assumption of horizontal homogeneity.

3.3 *Comparison of wind measurements in precipitation and clear air using standard processing*

From the scatter plots it is difficult to quantify the differences in each of the heights. Thus for more clarity, the spread of the data points in different heights were calculated. The σ, $\sigma_{//}$ and $\sigma_{\perp}$ were binned for height in intervals of 1km for different weather (clear air and precipitation), and the results are shown in Fig.3.

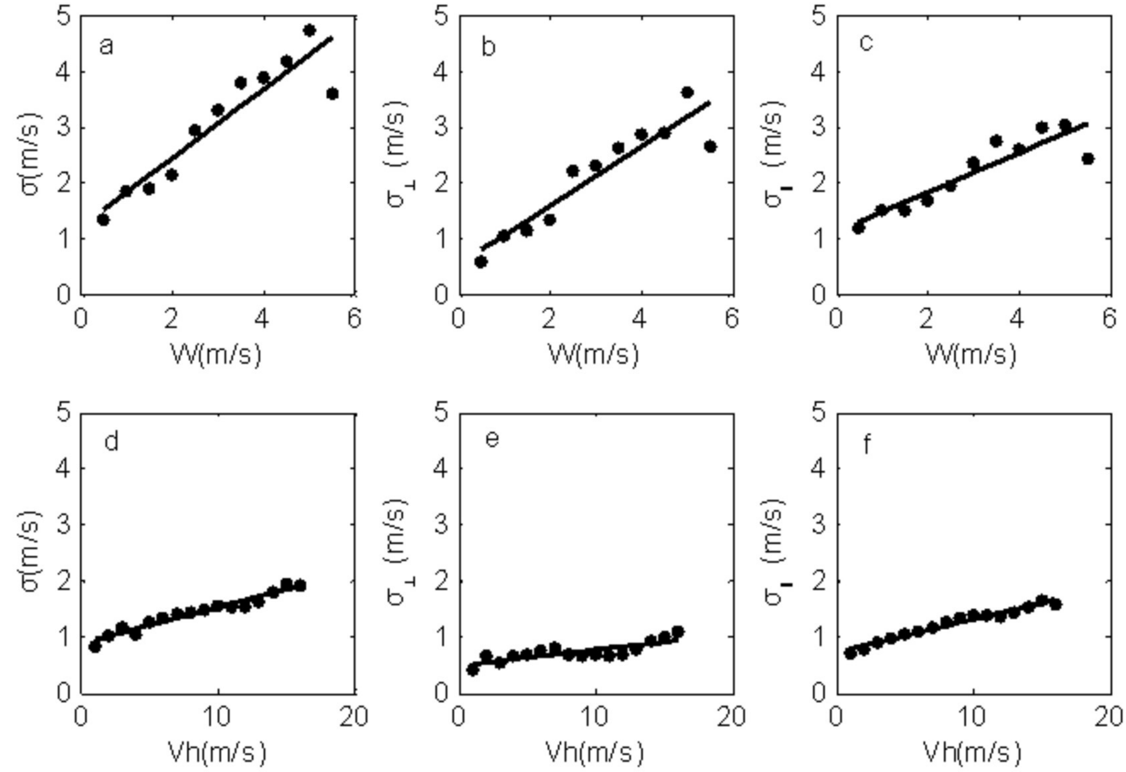

Figure 3. Variation of $\sigma, \sigma_{//}$ and $\sigma_{\perp}$ with vertical velocity (a, b, c) and horizontal velocity (d, e, f).

Figure 4 (a and b) shows the variation of σ, $\sigma_{//}$ and $\sigma_{\perp}$ with altitude in clear air and precipitation. It is observed that the σ, $\sigma_{//}$ and $\sigma_{\perp}$ in clear air configuration is below 4km, all is less than 1.5m/s, and the ratio of $\sigma_{//}$ to $\sigma_{\perp}$ is 1:2, whereas in the case of precipitation configuration, σ, $\sigma_{//}$ and $\sigma_{\perp}$ varies from 1.8 to 3.1m/s, and the ratio of $\sigma_{//}$ to $\sigma_{\perp}$ is 1:1, which has larger standard deviation compared to the estimation in clear air condition. Precipitation does not necessarily deteriorate the quality of wind measurements from WPR, rather it is the spatial and temporal non-uniformity of the atmospheric conditions across the radar coverage area that decreases the precision of the measurements when it is raining below 4km.

However σ, $\sigma_{//}$ and $\sigma_{\perp}$ increase obviously over 5km. Theoretically, the higher the altitude and the more stable atmosphere, the less influence of inhomogeneous wind distribution on the WPR measurement. So σ, $\sigma_{//}$ and $\sigma_{\perp}$ should decrease with height, and actually, with an increasing trend over 5km in clear air. The reason is that the maximum creditable height of CFL-08 WPR detection is about 6km, which varies with the season, and clear-air turbulence presents a smaller scattering target than raindrop in precipitation for radars above 5km, thus deteriorating the radar SNR.

4 CONCLUSIONS

This study does not attempt to determine the absolute accuracy of the measurements of WPR, but rather concentrates upon evaluating the influence of inhomogeneous wind distribution on the measurement of the WPR. This five-beam WPR gives two independent estimates of horizontal wind components that are compared each other. These comparisons cannot, of course, provide absolute accuracy of wind measurements. However, they do test the assumption that the hourly averaged winds are uniform horizontally over the antenna beam displacement (up to a few kilometers) of the WPR. The present analysis shows that the horizontal homogeneity assumption is valid because

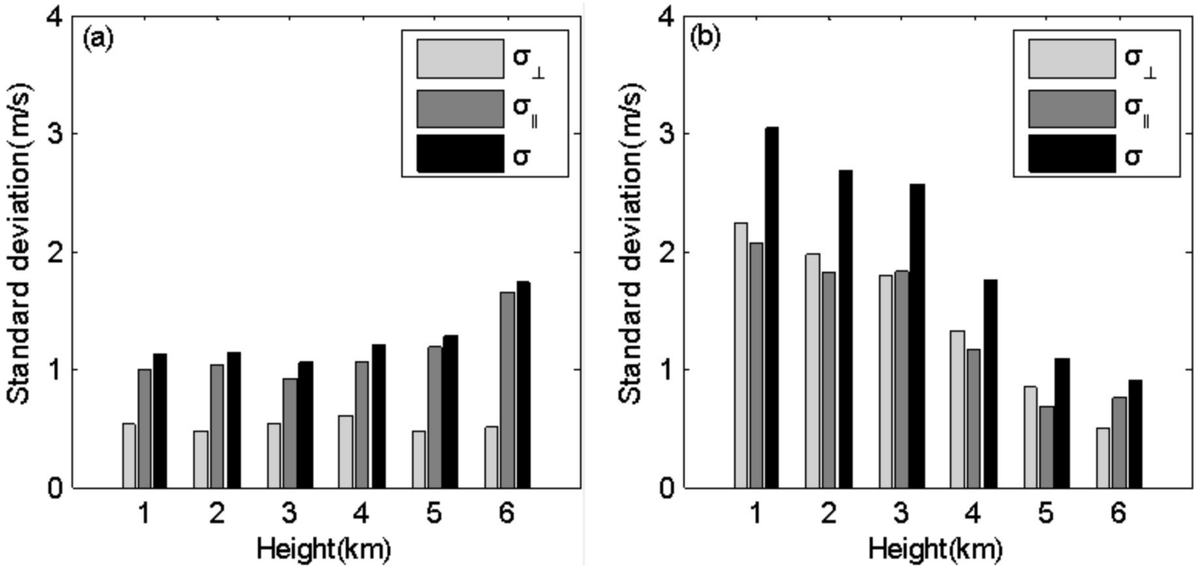

Figure 4. $\sigma, \sigma_{/\!/}$ and $\sigma_{\perp}$ in different height in clear air (a) and precipitation (b).

there was close agreement between the wind measurements. These comparisons also provide a measure of the precision of wind measurements. The standard deviation for the hourly averaged measurements of the differences between the two wind measurements can be computed to evaluate the relative accuracy and precision.

This paper demonstrates a new means of coordinate rotation feasible in the aspect of analyzing the influence of inhomogeneous distribution on wind measurement. Clear air configuration has small σ, $\sigma_{/\!/}$ and $\sigma_{\perp}$. Below 4 km, all is less than 1.5m/s, and the ratio of $\sigma_{/\!/}$ to $\sigma_{\perp}$ is 1:2, whereas in the case of precipitation configuration, σ, $\sigma_{/\!/}$ and $\sigma_{\perp}$ varies from 1.8 to 3.1 m/s, and the ratio of $\sigma_{/\!/}$ to $\sigma_{\perp}$ is 1:1, which has larger standard deviation compared to the estimation in clear air condition. The standard deviation of the error in the horizontal wind component is 1.24 m/s, whereas in the case of precipitation it is 2.4 m/s. In clear air, inhomogeneity of horizontal motion is the main influence on wind measurement because of small vertical velocity. In precipitation, the two influences on wind measurement are larger than that in clear air. Two kinds of radar measurement error are analyzed. σ, $\sigma_{/\!/}$ and $\sigma_{\perp}$ increase with the increase of horizontal velocity and vertical velocity, and they are more sensitive to vertical velocity than horizontal velocity.

This work is a pre-study for proposing reasonable algorithms to reduce the error of horizontal wind.

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