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ACCURACY OF WIND FIELDS IN CONVECTIVE AND STRATIFORM ECHOES OBSERVED BY A BISTATIC DOPPLER RADAR NETWORK

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1. INTRODUCTION

A bistatic Doppler radar network consists of one transmitting Doppler radar and one or more remote bistatic receivers with a non-scanning, low-gain, passive antenna. The bistatic network has the advantages of easy and inexpensive installation, all Doppler velocities measured from individual volume simultaneously, and the requirement of only one frequency. On the other hand, it has the limitations of less sensitivity to weak echoes, and more sensitivity to sidelobe contamination owing to the broad beam bistatic antenna. Although several studies about bistatic network have been reported (Wurman 1993, 1994, Protat 1999, Satoh 1999, Hagen 1999, de Elía 2000), it is not enough to understand clearly the accuracy of wind fields observed from a bistatic network. Both theoretical and practical studies are expected to solve the problems. In this study, the accuracy of wind fields is investigated based on a mathematical examination, and is evaluated using actual observation data in convective and stratiform echoes.

2. ACCURACY OF SYNTHESIZED VECTOR WINDS

In a bistatic network, the horizontal wind components (u and v) are calculated by

$$\left.\begin{aligned}
u &= \frac{1}{\sin(a_1 - a_2)}\left[\left(\frac{\cos(a_1)}{\cos(e_2)} + \frac{\cos(a_2)}{\cos(e_1)}\right)V_1 - \left(\frac{2\cos(\beta/2)\cos(a_1)}{\cos(e_2)}\right)\left(\frac{V_2}{\cos(\beta/2)}\right)\right] \\
&\quad + \frac{1}{\sin(a_1 - a_2)}\left[\left(\frac{\cos(a_1)\sin(e_1)}{\cos(e_2)} + \frac{\cos(a_1)\sin(e_2)}{\cos(e_2)}\right) - \left(\frac{\cos(a_1)\sin(e_1)}{\cos(e_2)} + \frac{\cos(a_2)\sin(e_1)}{\cos(e_1)}\right)\right] w_p \\
v &= \frac{1}{\sin(a_1 - a_2)}\left[\left(\frac{2\cos(\beta/2)\sin(a_1)}{\cos(e_2)}\right)\left(\frac{V_2}{\cos(\beta/2)}\right) - \left(\frac{\sin(a_1)}{\cos(e_2)} + \frac{\sin(a_2)}{\cos(e_1)}\right)V_1\right] \\
&\quad + \frac{1}{\sin(a_1 - a_2)}\left[\left(\frac{\sin(a_1)\sin(e_1)}{\cos(e_2)} + \frac{\sin(a_2)\sin(e_1)}{\cos(e_1)}\right) - \left(\frac{\sin(a_1)\sin(e_1)}{\cos(e_2)} + \frac{\sin(a_1)\sin(e_2)}{\cos(e_2)}\right)\right] w_p
\end{aligned}\right\}$$

where V_1 is Doppler velocity measured by transmitting radar. Although the V_2 is actual detected Doppler velocity (apparent velocity) by a bistatic receiver, the real bistatic Doppler velocity vector at the angle of $\beta/2$, which is perpendicular to ellipsoid surfaces, is the $V_2/\cos(\beta/2)$. β is a bistatic scatter angle, which is between the transmitter-target and receiver-target directions. a and e are azimuth and elevation angles, and subscript number 1 and 2 indicate transmitting radar and bistatic receiver, respectively. w_p is the sum of vertical air motion and terminal falling velocity.

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The variance of synthesized horizontal winds (u and v) at w_p =0 are expressed by

$$\sigma_u^2 + \sigma_v^2 = \frac{4\cos^2(\beta/2)\sigma_1^2 + 4\sigma_2^2}{\sin^2\beta}$$

Assuming $\sigma_1=\sigma_2$, the ratio of the synthesized velocity variance to the measured Doppler velocity variance is

$$\frac{\sigma_u^2 + \sigma_v^2}{\sigma_1^2 + \sigma_2^2} = \frac{2\left\{\cos^2(\beta/2)+1\right\}}{\sin^2\beta}$$

Figure 1 shows the ratio of the standard deviation as a function of β and the result of traditional monostatic dual-Doppler case (Lhermitte and Miller, 1970). The ratio of standard deviation indicates accuracy of dual-Doppler observation. If the ratio of standard deviation less than 3 is effective to calculate accurate vector winds, the bistatic dual-Doppler observation range is expressed by 40< β < 150 degree. The minimum variance, which means the best accuracy, appears when β is about 100 degree. While, the minimum variance of monostatic dual-Doppler winds appears when β=90 degree. The ratio of 3 in bistatic case is an empirical value. Although the ratio of 2 has been often used in a monostatic dual-Doppler network, the bistatic network has an advantage of simultaneous measurement of two Doppler velocities. Since the variance of measured velocity includes some observation error, the bistatic simultaneous measurement will reduce the error. It is difficult to avoid the difference in strict observation time in case of monostatic dual-Doppler using volume antenna scans.

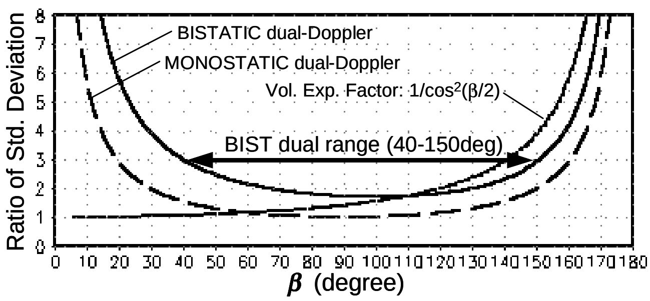

Fig. 1. The relationship between the standard deviation ratio of synchronized wind velocity to observed Doppler velocity and the scatter angle Beta. The solid and hashed lines show the ratio for bistatic and monostatic dual-Doppler, respectively. The dotted line shows the expansion rate of the bistatic resolution volume.

3. BISTATIC RESOLUTION VOLUME

Bistatic resolution volume is determined by a region enclosed with the transmitting radar beam-width and two ellipsoid surfaces as shown in Fig. 2. The ellipsoid surface, which has foci at transmitter and receiver, means constant arrival time of transmitting pulse to bistatic receiver. The interval is determined by transmitting pulse width $C\tau$ and scatter angle β. The bistatic resolution volume, which has a cutting column shape at a slant, becomes a large flat shape with large β, while it becomes almost the same size as monostatic resolution volume with small β as shown in Fig. 1. The bistatic resolution volume is calculated using Gaussian shape for the transmitting beam pattern as follows

$$V = \frac{\pi R1^2 \theta \phi C \tau}{16 \ln(2) \cos^2(\beta/2)}$$

Using this resolution volume, a bistatic radar equation is expressed by

$$P_r = \frac{P_t G_1 G_2(\theta_B) \lambda^2 \theta \phi C \tau}{1024 \ln(2) \pi^2 R2^2 \cos^2(\beta/2)} \sum_{vol} \sigma_i, \quad \sigma_i = \sigma_0 \sin^2 \chi$$

where G_1 is the transmitting antenna gain, $G_2(\theta_B)$ is bistatic antenna gain as a function of the azimuth direction from receiver to target. That is, the bistatic broad beam is regard as a linear approximation within a resolution volume. λ is the wavelength, θ and ϕ are horizontal and vertical beam widths of transmitting antenna, $R2$ is the distance between target and receiver. σ_i, which is the oblique-scattering cross-section area, is a function of the angle χ between the incident E vector in vertical polarization and the propagation vector at the target. Remark that the bistatic range-correction term is $20\log[R2\cos(\beta/2)]$, instead of $20\log R1$ in a well-known monostatic radar equation.

Figure 3 shows estimated bistatic antenna pattern from the difference between main radar reflectivity and bistatic reflectivity in a long time (>8 hour) integration of stratiform rainfall echoes data. The data is observed by NCAR SPOL and a north bistatic receiver during CASES-97 described in Satoh and Wurman (1999). From the estimated bistatic antenna pattern and the bistatic radar equation, we can calculate the distribution of minimum detectable reflectivity (Fig. 4).

4. CONVECTIVE AND STRATIFORM ECHOES

In case of convective echoes with large gradients of reflectivity, it has been known that the sidelobe contamination of transmitting antenna may be dominant cause of bistatic wind retrieval error (Wurman 1994). The bistatic reflectivity is determined by both transmitter and receiver antenna patterns. Since the transmitter sidelobe pattern (out of Gaussian main beam) is ignored in the above bistatic radar equation, the

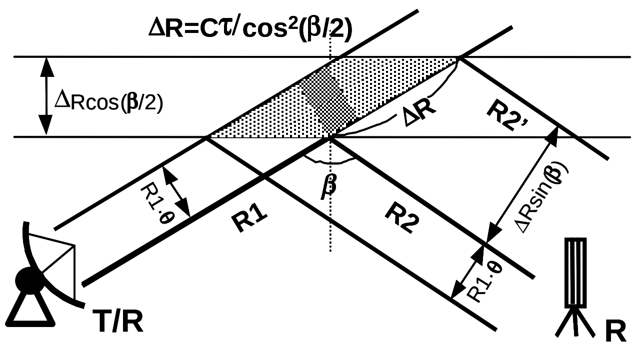

Fig. 2. Conceptual figure of bistatic resolution volume, which is enclosed with the transmitting radar beam-width and two ellipsoid surfaces. Heavy and light shade regions indicate monostatic and bistatic resolution volume, respectively.

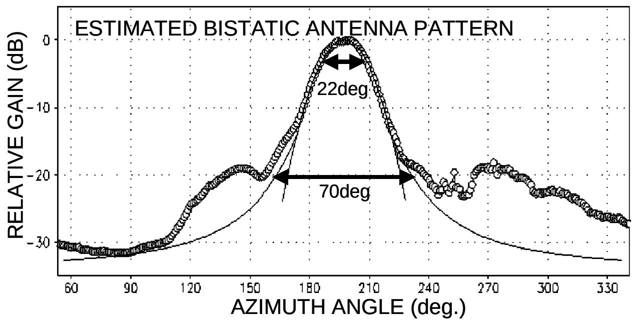

Fig. 3. Estimated bistatic antenna pattern from the difference between main radar reflectivity and bistatic reflectivity using actual observation data. The thin lines show the gauss approximation and the broad beam approximation using a function. The 3 dB beam width is about 22 degree, while effective angle range extends more than 70 degree.

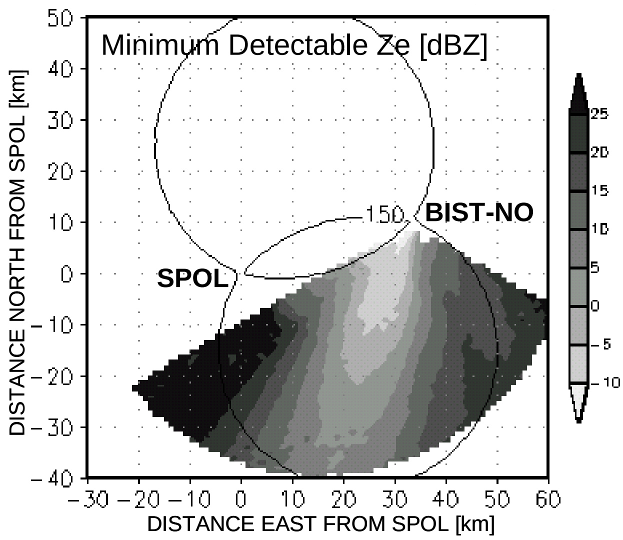

Fig. 4. Distribution of minimum detectable reflectivity calculated from the bistatic radar equation and the estimated bistatic antenna pattern shown in Fig. 3.

difference between bistatic reflectivity and transmitting radar reflectivity will indicates the sidelobe contamination in the bistatic data. This idea is similar to de ElÍa and Zawadzki (2000). Figure 5 shows an example of actual data observed in Kansas. The maximum reflectivity is over 50 dBZ, and the horizontal gradient is also large. Around such a region, the sidelobe contamination is very large, and the actual bistatic velocity data is also unreal. The blank regions along the shear line in the synthesized wind fields (Fig. 5(b)) are elimination marks owing to the sidelobe contamination.

On the other hand, in case of stratiform echoes, the effect of sidelobe contamination is small. The accuracy of the retrieved vector winds is dominated by β described in section 2. Although the minimum detectable reflectivity (Fig. 4) plays an important role in accurate bistatic wind retrieval, the uncertain velocity data around the noise level in the bistatic receiver can be eliminated using NCP (Normalized Coherent Power) data. The actual data had been displayed in Satoh and Wurman (1999).

5. CONCLUSIONS

In convective echoes with large gradient of reflectivity, the sidelobe contamination is the prime cause of the wind retrieval error. The sidelobe contamination can be eliminated using the difference between transmitting radar reflectivity and bistatic reflectivity. The bistatic reflectivity is calculated by the bistatic radar equation, which includes the bistatic resolution volume enclosed by a transmitting antenna beam and two ellipsoid surfaces, and the estimated bistatic antenna pattern. On the other hand, in weak stratiform echoes, the scatter angle β and the minimum detectable level dominate the wind accuracy. When the ratio of standard deviation of the synthesized horizontal wind to measured Doppler velocity is less than three, accurate vector winds will be retrieved in a range of 40 < β < 150 degree. The best accuracy appears when Beta is about 100 degree.

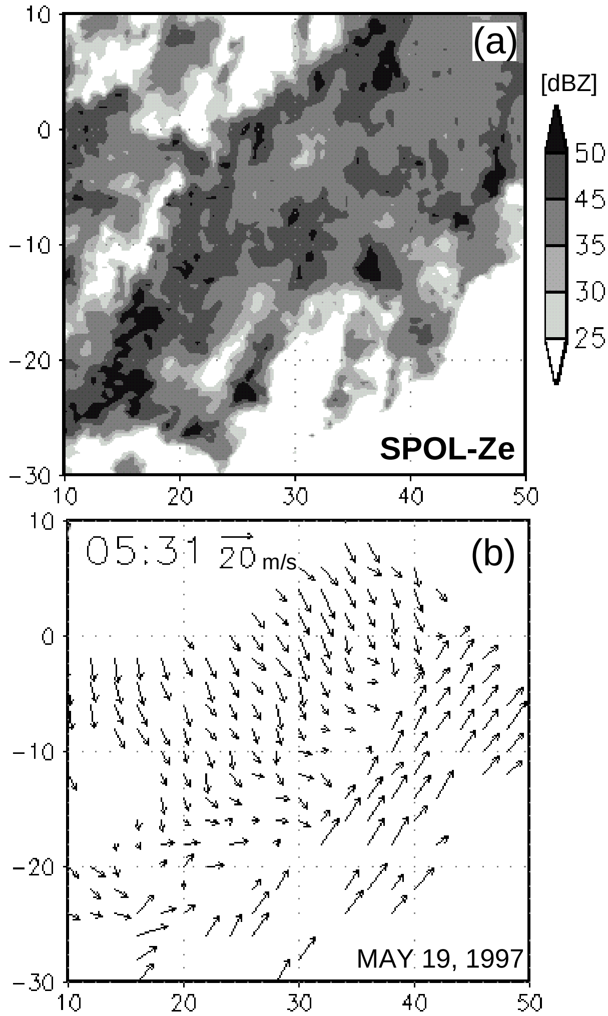

Fig. 5. Horizontal distribution of (a) transmitting radar reflectivity, and (b) synthesized vector winds in a convective echo system. The transmitting radar (NCAR SPOL) is located on x=0, y=0, and the bistatic receiver is installed on x=33 km, y=10 km (see Fig. 4.).

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