

A Variation Method for Retrieval of Three-Dimensional Wind Field by Bistatic Doppler Weather Radar Network

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Abstract. A variational method for the retrieval of 3D wind field by bistatic Doppler radar network is developed, and its performance is evaluated. This bistatic Doppler weather radar network consists of one X-band Doppler radar and one passive low-gain bistatic receiver. To allow for measurement error, this method uses the two radial velocities as weak constraints and uses the continuity equation as a strong constraint in a cost function. Improvements are brought to the classical upward integration of the continuity equation, using a weighted combination of upward and downward integrations and its adjoint. The wind field retrieval experiments are carried out by the actual observation data, and compared with the wind field retrieved by the two Doppler radars. The results show that the wind field is very close, and the synchronous observation technology of the bistatic Doppler radar network is reasonable, which has the potential application in real-time detection of 3D wind field, especially for detecting near surface wind field.

1. Introduction

Doppler weather radar has long been a valuable observational tool in the observing and forecasting of meteorological weather system. It has the ability of observing, at high and temporal resolution, the internal structure of storm systems. However, the direct measurements of it are limited to reflectivity, the radial velocity and spectrum width [1]. In order to gain the complete understanding of the severe weather, the three-dimensional (3D) wind field are needed to know. For this reason, radar meteorologists have developed a variety of methods for retrieval of wind field using single Doppler radar data, such as the VAD technique [2, 3] and velocity volume processing (VVP) method [4, 5]. Recently, the idea of combining physical constraints and Doppler radar observations with a constraining model has been explored to retrieve 2D or 3D wind field from single-Doppler radar data [6, 7]. A large number of experiments have been carried out, and some success has been achieved in some cases. However, most of these methods are based on strong assumptions for wind field retrieval, and the results are highly correlated with the type of radial velocity distribution. Therefore, in order to obtain more accurate wind field structure and evolution rules, it is necessary to obtain radial velocity in different directions simultaneously.

A bistatic Doppler weather radar consists of one transmitting Doppler radar (transmitter) and one or more remote bistatic receivers which having a non-scanning, low-gain and passive antenna [8]. The



bistatic Doppler radar can measure two or three-dimension wind field by using the dual-Doppler technique, which is a synthesis of two or three radial velocities. The bistatic radar has the advantages of easy and low cost installation, the radial velocities can be simultaneously measured from atmospheric volumes, and only one transmitting frequency is needed. Techniques have been developed since 1990s, may experiments have been done around the world [9, 10]. Although, the passive receiving antenna has low-gain and small detection range, which is easily affected by the side scattering echo of the active radar side lobe, this technique is still very useful in 3D wind field retrieval.

2. Description of methodology

2.1. Quality control and preprocessing of radar data

The radar data processing includes data filling, nine median filtering, and radial velocity dealiasing, after that, the data should be check whether the radar data points meet the requirements of wind field retrieval.

2.2. The pairing of the data received from the transmitter and the bistatic receiver

The procedure for paired data is as follows:

1) Correct the message header of the bistatic receiver according to the azimuth, elevation and GPS information.

2) Match the data received from the transmitter and the bistatic receiver according to the time of each radial.

3) Match the data of the each distance-bin according to the storage mode of the radar data and the bistatic geometry (the location of the transmitter and receiver).

After the above three steps, the data of the transmitter and the bistatic receiver are paired together, which used for the wind field retrieval.

2.3. A variational method for 3D wind field retrieval

Considering the error of radial velocity in radar observation, we use a variational method for the retrieval of 3D wind field by bistatic Doppler radar network which consists of one X-band dual-polarization Doppler radar and one passive low-gain bistatic receiver. Before the wind field retrieval, the Cressman method is used to interpolate the matched radar base data in 3D space, and interpolate to the Cartesian coordinates with a horizontal lattice distance of 500 m and a vertical lattice distance of 250 m.

To allow for measurement error, this method uses the two radial Doppler velocities as weak constraints and uses the continuity equation as a strong constraint in a cost function. The horizontal wind field components are calculated by minimizing the cost function J , and then the horizontal wind field component u and v is calculated, then the mass continuous equation is used as a strong constraint to calculate the vertical velocity w , and then the process is iterated in a cycle to retrieve the 3D wind field. In this proposed method, we define the cost function J as follows:

$$J = \sum_i [V_{r1,i}^{obs} - V'_{r1,i}(x)]^2 W_{1,i} + \sum_i [V_{r2,i}^{obs} - V'_{r2,i}(x)]^2 W_{2,i} \quad (1)$$

$$V_{r1} = \sin \alpha_1 \cos e_1 u + \cos \alpha_1 \cos e_1 v + \sin e_1 w \quad (2)$$

$$V_{r2} = \frac{\sin \alpha_1 \cos e_1 + \sin \alpha_2 \cos e_2}{2 \cos(\beta_2/2)} u + \frac{\cos \alpha_1 \cos e_1 + \cos \alpha_2 \cos e_2}{2 \cos(\beta_2/2)} v + \frac{\sin e_1 + \sin e_2}{2 \cos(\beta_2/2)} w \quad (3)$$

where, $x = (u_i, v_i, w_i)$ represent the 3D wind field to be retrieved; $W_{1,i}$ and $W_{2,i}$ are weights that depend on the strength of the constraint; V_{r1}^{obs} and V_{r2}^{obs} are radar observation radial Doppler velocities

of the transmitter and bistatic receiver, respectively; α_1 and e_1 represent the azimuth and elevation of transmitter; α_2 and e_2 represent the azimuth and elevation of grid location relative to the bistatic receiver; β_2 is the angle between the scatter and line between the transmitter and bistatic receiver (base line). The horizontal component of the horizontal wind field u and v treat as “control variables”, the vertical velocity w on each lattice is treated here as a fixed value, and then calculated by the following continuity equation (4) and equation (5) again. In this paper, using both upward and downward integrations and their adjoints [10].

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = -\frac{\partial(\ln \rho)}{\partial z} w \quad (4)$$

$$w = \left(1 - \frac{z_h}{z_{h_top}}\right) w_{\uparrow} + \left(\frac{z_h}{z_{h_top}}\right) w_{\downarrow} \quad (5)$$

Where (u, v, w) the three wind components in are Cartesian coordinates; ρ is the air density; w_{\uparrow} and w_{\downarrow} represent the vertical velocities of upward and downward integrations, respectively; z_h is the height of the grid and z_{h_top} is the height of downward integrations (where $w = 0$, here we use the height of the radar echo top).

3. Observation system composition and the field experiments

This Observation system consists of one X-band dual-polarization Doppler weather radar (transmitter), one passive low-gain bistatic receiver, and S-band Doppler radar. As shown in Figure 1, the bistatic receiver located 20.38 km southeast of the transmitter, and S-band Doppler radar of Beijing Meteorological Bureau, located 20.27 km southeast of the transmitter and roughly northeast of the bistatic receiver. The transmitter is a fully coherent X-band dual polarized pulse Doppler weather radar, and the bistatic receiver uses a horizontal polarization and a vertically polarized waveguide slot antenna to form a receiving antenna array. The system uses the global positioning system (GPS) to achieve the synchronization of space location, time and phase. The communication between the transmitter and the bistatic receiver realizes real-time data exchange by network.

The main purpose of the field experiments are to test the performance of bistatic Doppler radar system, use the actual observation data collected by this system to carry out the 3D wind field retrieval experiment, and then compare the retrieval results with the wind field retrieved by the two Doppler radars composed of the transmitter and the S-band Doppler radar. The ability of the system to detect the musicale structure of three-dimensional wind field is demonstrated.

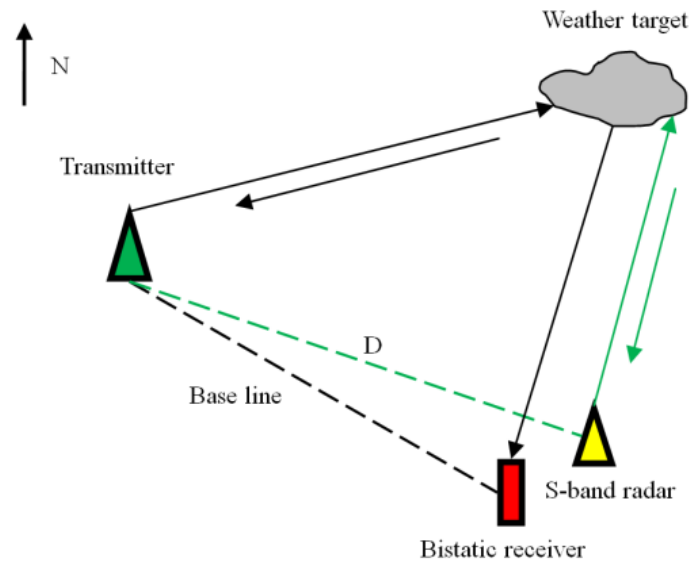


Figure 1. The location of the radar, the transmitter, one bistatic receiver, and the S-band Doppler radar (Here base line = 20.38 km and $D = 20.27$ km).

4. Preliminary results

To demonstrate the capability of our variational method, we apply it to the volume scans of data collected by this system in the case of rain in Beijing, on 1 August 2009. Figures 2a,b show the horizontal wind field of 4.5 km and 7.5 km above the ground level retrieved by the bistatic Doppler radar network at 1211 UTC.

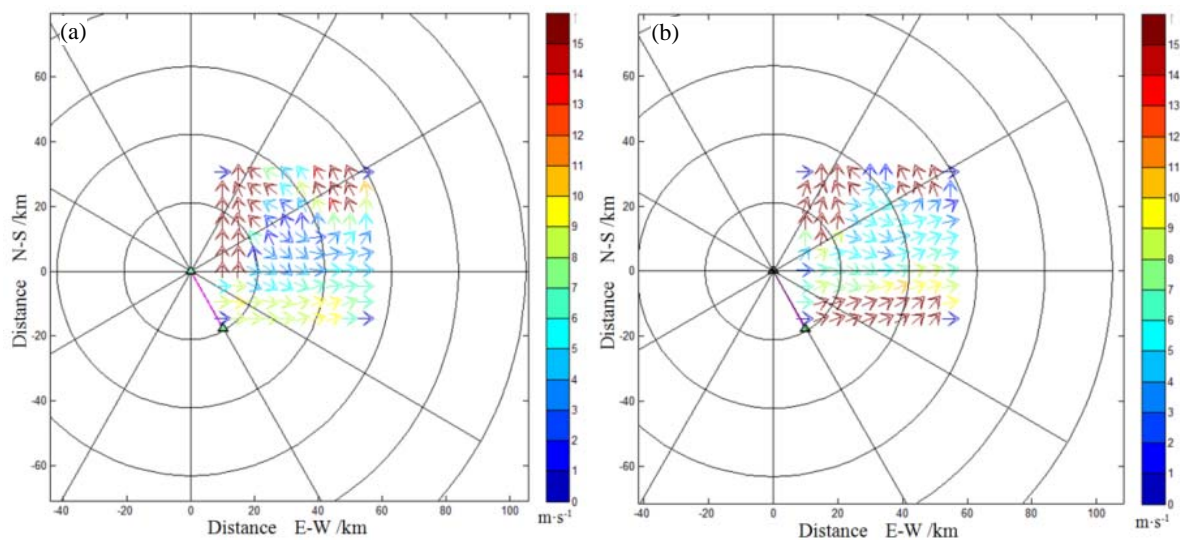


Figure 2. Horizontal wind field of (a) 4.5 km and (b) 7.5 km above the ground level retrieved by the bistatic Doppler radar network at 1211 UTC on 1 August 2009.

To test the performance of the variational method, we compare the results with wind field retrieved by the two Doppler radars composed of the transmitter and the S-band Doppler radar, with emphasis on efficiency, and accuracy, and robustness in this case. Figures 3a, b show the horizontal wind field of 4.5 km and 7.5 km above the ground level retrieved by the two Doppler radars.

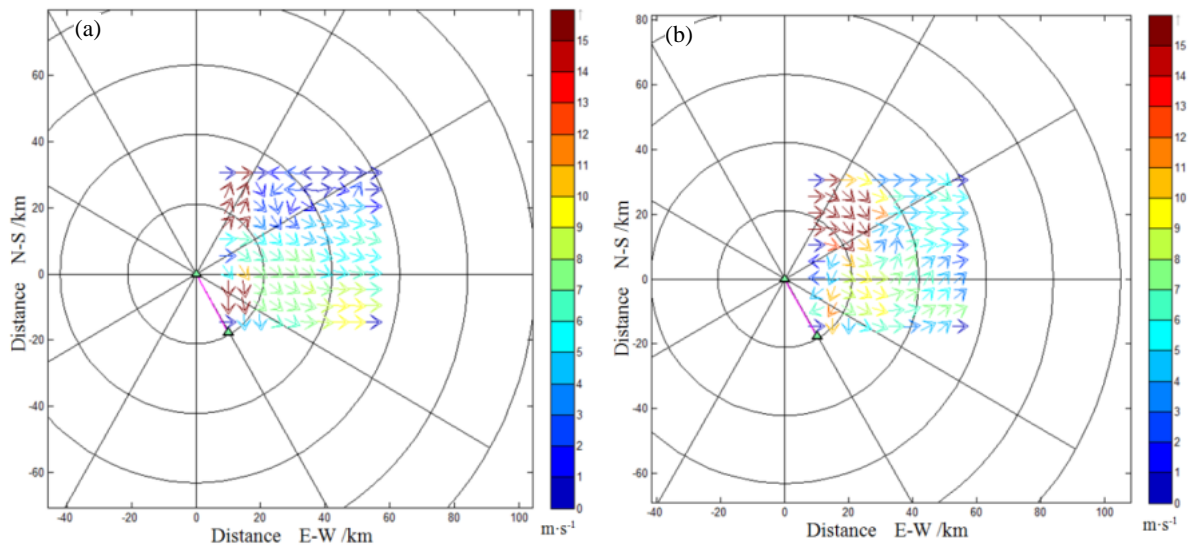


Figure 3. Horizontal wind field of (a) 4.5 km and (b) 7.5 km above the ground level retrieved by the two Doppler radars at 1211 UTC on 1 August 2009.

Figures 4a,b show the vertical velocity field retrieved from the bistatic Doppler radar network along X-Z Direction when $Y=10$ km and $Y=20$ km respectively, at 1211 UTC on 1 August 2009. Figures 5a, b, as in Figure. 4, but retrieved by the two Doppler radars.

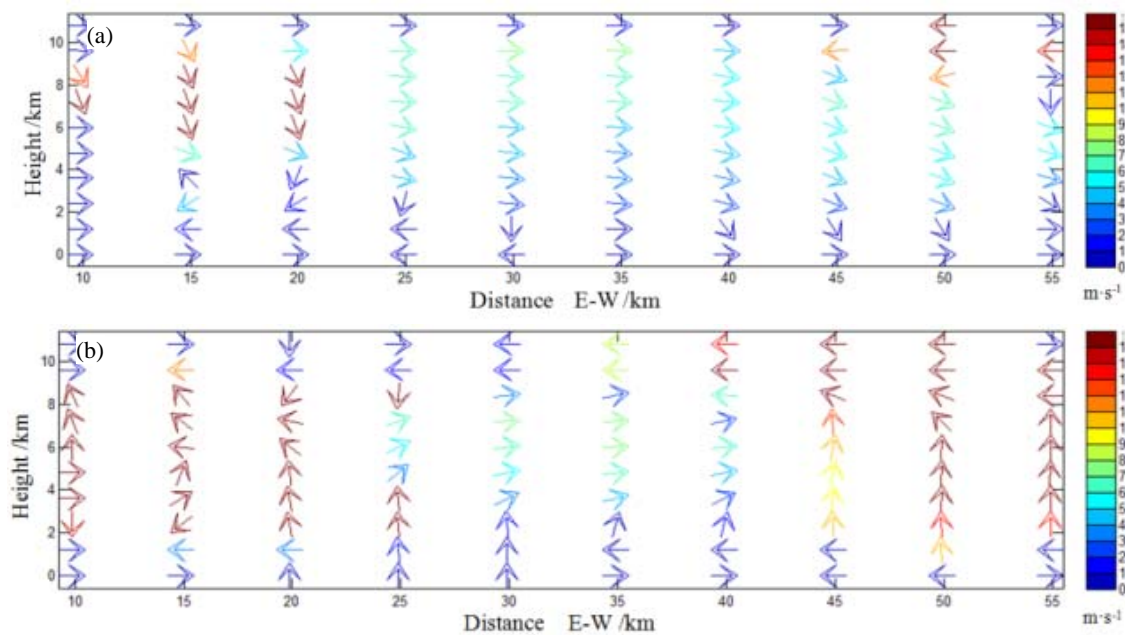


Figure 4. Vertical velocity field retrieved from the bistatic Doppler radar network along X-Z Direction when (a) $Y=10$ km and (b) $Y=20$ km.

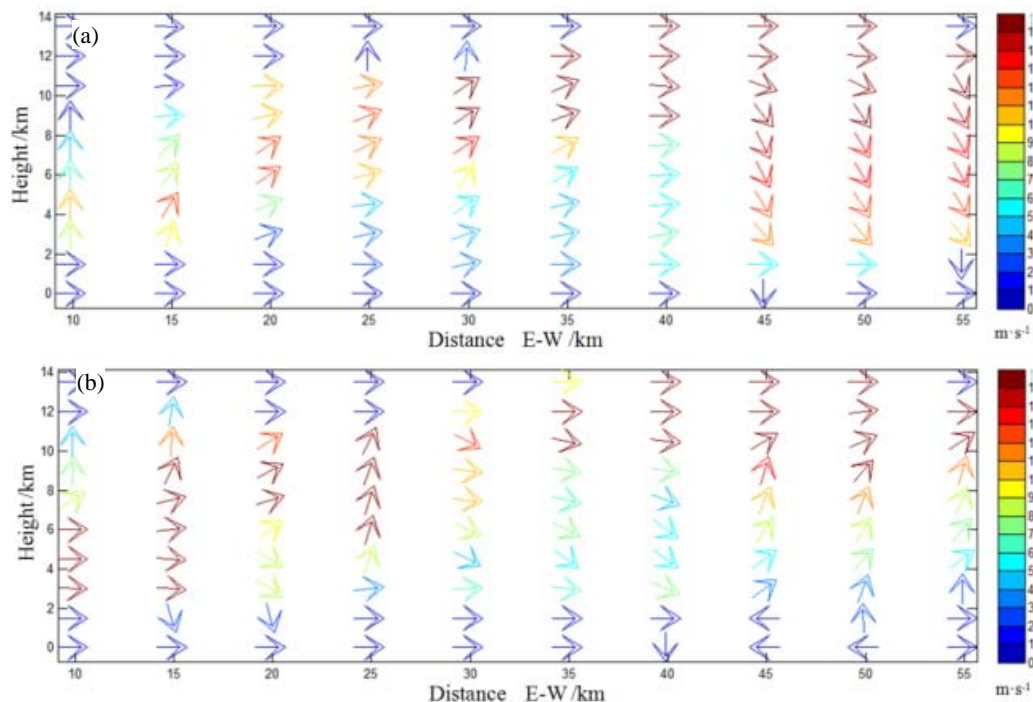


Figure 5. Vertical velocity field retrieved from the two Doppler radars along X-Z Direction when (a) Y=10 km and (b) Y=20 km.

Through comparison and analysis, the spatial distribution and trend of the wind field retrieval from the two methods are very close, and the wind speed in the retrieval region is basically the same. But there are still some problems, such as the wind speed is not very consistent on the retrieval area boundary, and the wind speed retrieved from bistatic Doppler radar network is generally large, the main reason may be due to the inconsistency of the two radar speed resolutions in the two Doppler radars.

5. Conclusion

In this paper, a variational method for the retrieval of 3D wind field by bistatic Doppler weather radar network is developed, and its performance is evaluated. This bistatic Doppler radar network consists of one X-band dual-polarization Doppler radar and one passive low-gain bistatic receiver. To allow for measurement error, this method uses the two radial velocities as weak constraints and uses the continuity equation as a strong constraint in a cost function. Improvements are brought to the classical upward integration of the continuity equation, using a weighted combination of upward and downward integrations and its adjoint.

The wind field retrieval test is carried out by the actual observation data, and the results are compared with the wind field retrieved by the two Doppler radars composed of the transmitter and the S-band Doppler radar, with emphasis on efficiency, and accuracy for rain event. The results show that the retrieved wind field is very close, and the synchronous observation technology of the bistatic Doppler radar network is reasonable, which has the potential application in real-time detection of 3D wind field, especially for detecting near surface wind field. Because of the low-gain, small detection range, there is a general phenomenon of side lobe pollution. In future work, we will consider use the characteristics of dual polarization of the transmitter to eliminating the side lobe pollution. We believe that the variational method of 3D wind field retrieval by bistatic Doppler weather radar network has the potential to improve capability of the short-term forecast.

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References

- [1] Gao, J. D. and Xue, M., A variational method for the analysis of three-dimensional wind fields from two Doppler radars. *Mon. wea.rev.*, 127 (1999) 2128 - 2142.
- [2] Lhermitte, R. M., and D. Atlas, Precipitation motion by pulse Doppler radar. *Proc. Ninth Weather Radar Conf.*, Kansas City, MO, Amer. Meteor. Soc., (1961) 218 - 223.
- [3] Browning, K. A., and R. Wexler, The determination of kinematic properties of a wind field using Doppler radar. *J. Appl. Meteor.*, 7 (1968) 105 - 113.
- [4] Easterbrook, C. C., Estimating horizontal wind fields from a two-dimensional curve fitting of single-Doppler radar measurements. *Preprints, 16th Radar Meteorology Conf.*, Houston, TX, Amer. Meteor. Soc., (1975) 414 - 416.
- [5] Waldteufel, P., and H. Corbin, 1979: On the analysis of single-Doppler radar data. *J. Appl. Meteor.*, 18 (1979) 532 - 542.
- [6] Xu, Q., C. J. Qiu, and J. X. Yu, Adjoint-method retrievals of low-altitude wind fields from single-Doppler wind data. *J. Atmos.Oceanic Technol.*, 11 (1994) 579 - 585.
- [7] Laroche, S., and I. Zawadzki, A variational analysis method for retrieval of three-dimensional wind field from single-Doppler radar data. *J.Atmos. Sci.*, 51 (1994) 2664 - 2682.
- [8] Satoh, S., and J. Wurman, Accuracy of wind field observed by a bistatic Doppler radar network. *J. Atmos. Oceanic Technol.*, 20 (2003) 1077 - 1091.
- [9] Satoh, S., and J. Wurman, Accuracy of composite wind fields derived from a bistatic multiple-Doppler radar network. *Proc. 29th Conf. on Radar Meteorology*, Montreal, QC, Canada, Amer.Meteor. Soc., (1999) 221 - 224.
- [10] Liu, L. P., Mo Y. Q., Sha X. S., Su T, Radar Data Processing and a Variational Algorithm for 3-Dimensional Wind Field Retrieval by C Band Bistatic Radar Network [J].*Chinese Journal of Atmospheric Sciences (in Chinese)*, 29(6) (2005) 986 - 996.