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Weather Radar Range Resolution Improvement based on Steepest Descent MVDR Algorithm

[1,2]Xuehua Li, [1,2]Jianxin He, [1]Fugui Zhang and [1,2]Zhao Shi
[1]Department of Electronic Engineering,
[2]CMA Key Laboratory of Atmospheric Sounding, Chengdu University of Information Technology, 610225, Chengdu, China

Abstract: Range resolution enhancement of weather radar will improve the capability in observation of fine structure and motion of the atmosphere. Based on range oversampling echo signals, the range resolution of weather radar can be enhanced by using the MVDR algorithm. However, the MVDR algorithm is computationally intensive due to the inversion of autocorrelation matrix of echo signals and moreover, this inversion is not feasible as the autocorrelation matrix of oversampling echo signals of real weather radar is singular. To solve this problem, an improved MVDR algorithm based on steepest descent method is proposed in this study which obtains the optimal weighted coefficient by recursion and iteration and it can avoid the inversion of autocorrelation matrix. Simulation results show that the proposed method can realize enhancement of the range resolution of weather radar and its performance is greatly improved in comparison with the previous MVDR algorithm.

Key words: Weather radar, range resolution, steepest descent, MVDR

INTRODUCTION

Range resolution of weather radar depends on pulse width and receiver bandwidth. With higher range resolution, weather radar can observe finer structure and motion of atmosphere which will contribute to prediction and forecast of disastrous weather processes more effectively. To enhance its range resolution, the direct method is to reduce the transmitted pulse width. However, after reduction of the transmitted pulse width, the average transmitting power of radar will decrease, further reducing the detection range and detectability of radar and these consequences are actually not be expected. Another method is to adopt pulse compression to enhance range resolution by expansion of time width and bandwidth of the transmitted signal (Doviak and Zrnic, 1993),which has advantages of compact size and long service life. But based on the hardware system of the existing Doppler weather radar, it will involve major changes in transmitter, receiver and signal processor, therefore, it is unfeasible in fact.

In order to enhance the resolution of weather radar, Palmer *et al*. (1999)develop a method of range imaging, then Yu and Palmer (2001) applied range imaging in wind profiler radar and obtained a three-dimensional vertical wind field of higher resolution. Zhang *et al*. (1998) built a higher resolution reflectivity model based on radar meteorology equation between nonuniform reflectivity field within radar beam and radar measurements and adopted the least square method for inverse convolution calculation to obtain reflectivity data of higher azimuth resolution. Yu *et al*. (2006)proposed range oversampling technique to obtain more observation data, under the condition that the range weighted function is known, the MVDR algorithm is used for inverse convolution calculation along range direction to obtain higher resolution within unit pulse width. Range oversampling technique of weather radar is regarded as a relatively meaningful method not only for resolution enhancement, but also a more useful method for improvement of the accuracy of spectral moment estimation of weather radar (Torres and Curtis, 2012) However, during computation with the MVDR algorithm, it is needed to conduct inversion of the autocorrelation matrix of oversampling echo signals which is computationally intensive and direct inversion is not feasible as the autocorrelation matrix of oversampling echo signals of weather radar is singular in reality. Therefore, an improved MVDR algorithm is proposed in this study to enhance the range resolution of weather radar and solve the problem of inversion of the autocorrelation matrix through recursion and iteration, thus matrix inversion is avoided.

Corresponding Author: Xuehua Li, Department of Electronic Engineering, Chengdu University of Information Technology, 610225, Chengdu, China

RANGE OVERSAPLING SIGNAL MODEL

Assumed that the backscatters within the area irradiated by the transmitted pulses can be modeled to be distributed with multiple separate "scatters" which are uniformly along the range direction and the distance between adjacent scattering centers is bigger than the wavelength of radar and smaller than the range length determined by pulse width of radar. In the model, each scattering center represents the sum of contributions made by all scattering particles in the standard range cell whose thickness is $\Delta r = \Delta\tau_s c/2$, where c is the velocity of light and $\Delta\tau_s$ is smaller than the range width τ determined by the radar transmitted pulse width. If consideration is given to one resolution volume, it can also be understood that the target echo in unit volume can be replaced with a scattering center. Since, this study only concerns enhancement of range resolution rather than azimuth resolution, the target characteristics along azimuth direction are deemed as consistent. Here, it is assumed that the echo signals of weather radar are demodulated baseband and discrete I/Q signals, the output rate of I/Q data of the digital IF module is T_r^{-1} (sampling frequency along range direction).Hereafter, the I/Q data is taken as the time domain data that needs to be processed by radar subsequently.

Generally, in order to estimate the spectral parameters of weather radar in arbitrary range resolution cell, it is needed to acquire L×M time sampling signals within the range volume, where L is the range oversampling ratio in the range resolution cell, M is the time average number. The L×M time series can be expressed in the form of matrix as follows (Torres and Curtis, 2013):

$$V_m = As_m \tag{1}$$

where, $V_m = [V(l_0, m),\ldots, V(l_0+L-1, m)]^T$ is the vector of oversampling echo signals whose length is L when the sampling time is m; $S_m = [S(l_0F-N_p+1, m),\ldots, S(l_0F+L-1, m)]^T$ represents the vector of equivalent back scattered echo signals of scattering centers when the sampling time is m and the length is N_p+L-1. A is the convolution matrix of pulse envelopes after change, expressed as:

$$A = \begin{bmatrix} p(N_p-1) & \cdots & \cdots & 0 \\ 0 & p(N_p-1) & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & \cdots & p(0) \end{bmatrix} \tag{2}$$

where, $A \in C^{L\times(N_p+L-1)}$ and each row of A is formed by moving the previous row rightwards by one element and filling other blanks with 0. $p_0 = [p(N_p-1),\ldots, p(0), 0,\ldots, 0]^T$ is the time inverse sequence of pulse envelops whose length is N_p+L-1.

From Eq. 1, it is obvious that that the oversampling weather echo signal V_m is the convolution sum of the parameter matrix of radar system A and the original high-resolution signal S_m. The objective of high resolution processing of the range of weather radar is to explore how to restore the original high-resolution signal S_m from the oversampling signal V_m, it is equal to deconvolution.

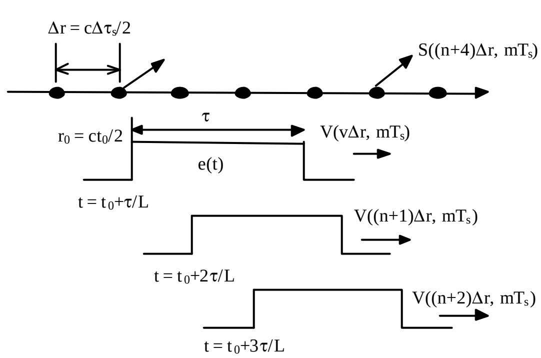

Fig. 1: Range oversampling model of weather radar

MVDR ALGORITHM

Minimum Variance Distortionless Response (MVDR) was first put forward by Capon, it is mainly used in frequency-wavenumber analysis of multi-dimensional seismic array sensor and later it was introduced into one-dimensional time series analysis by Lacoss. Being simple and stable, MVDR algorithm has been successfully applied in resolution enhancement of multiple receivers and its retrieval of three-dimensional wind field. In this study, the method is used for enhancement of the range resolution of weather radar.

Assume there is a transversal filter with M filter coefficients and the input vector and the weighted vector of oversampling echo signals, respectively defined as (He, 2009):

$$V(n) = [V(n) \quad V(n-1) \quad \cdots \quad V(n-M+1)]^T \tag{3}$$

$$w = [w_0 \;\; w_1 \ldots w_{M-1}]^T \tag{4}$$

The output of the filter can be expressed as:

$$y_i(n) = w^H_i V_m \tag{5}$$

Using MVDR algorithm, the weighting vector w^H_i in Eq. 5 can be obtained by solving the following constrained optimization:

$$\min_{w_i}(P) = \min_{w_i}(w_i^H R_V w_i) \quad \text{st.} \quad w_i^H a_i = 1 \tag{6}$$

Obviously, it is a problem concerning conditional extremum. In order to obtain the coefficient $w^H{}_i$, the Lagrange multiplier construction cost function $\Delta J(w^H{}_i)$ is used which is first to calculate the gradient and make the gradient $\Delta J(w^H{}_i) = 0$, then calculate the Lagrange multiplier according to the constrain $w^H{}_i a_i = 1$ and giving consideration to the conjugate symmetry of R^{-1}:

$$\lambda = \frac{1}{a_i^H R_V^{-1} a_i} \tag{7}$$

where, the matrix $R \epsilon C^{M\times M}$ is the $_M$-dimensional autocorrelation matrix of the vector V(n). Therefore, the optimal weight vector can be obtained by:

$$w_i^H = \frac{R_V^{-1} a_i}{a_i^H R_V^{-1} a_i} \tag{8}$$

The restored high-resolution echo signals can be obtained by substituting Eq. 8 into 5 as follows:

$$y_i(n) = \frac{R_V^{-1} a_i}{a_i^H R_V^{-1} a_i} V_m \tag{9}$$

STEEPEST DESCENT MVDR ALGORITHM

The standard MVDR algorithm is intensive since it requires matrix inversion and moreover, direct inversion is not feasible as the autocorrelation matrix of echo signals is singular in reality. The improved MVDR algorithm based on steepest descent method (SD-MVDR) enables the weight vector to descend in the direction where the curved surface slope is the steepest and the gradient is the biggest, thus to quickly get the optimal weight; this method features quick convergence and low computational complexity and can also avoid matrix inversion.

In order to minimize the equation with weight vector $w^H{}_i$, the steepest descent method does not directly calculate the gradient or make the gradient $\Delta J(w^H{}_i) = 0$ but searches weight vectors along the gradient direction; its recursive expression can be written as (Deng, 2007; Yang and Zhao, 2012):

$$w_{i,n+1}^H = w_{i,n}^H - \mu_w \nabla J \tag{10}$$

where, μ_w is the step parameter; take the derivative of w_i with the gradient $\Delta J(w^H{}_i)$ and put the derivative into the above equation which gives:

$$w_{i,n+1}^H = w_{i,n}^H - \mu_w (2Rw_{i,n}^H - 2\lambda_n a_i) \tag{11}$$

where, λ_n needs to be updated during each iteration and each iteration should satisfy the condition $w^H{}_{i,n} a_i = 1$; thus, λ_n can be calculated by:

$$\lambda_n = \frac{1}{2\mu_w}\left(a_i^H a_i\right)(a_i^H w_{i,n}^H - 2\mu_w a_i^H R w_{i,n} - 1) \tag{12}$$

Since, R cannot be obtained accurately, there is a big error between the actual value and the estimated value obtained through echo signal sampling $R = XX^H$. Therefore, the superposition method is adopted to reduce the error of R estimation; the expression is written as (Yang and Zhao, 2012):

$$\hat{R}_{n+1} = (1 - 1/n)\hat{R}_n + 1/n\left(XX^H\right) \tag{13}$$

Detailed steps of the SD-MVDR algorithm:

Step 1: Estimate $\hat{R}$ based on the range oversampling signal X; make n = 0, initialize $w^H{}_{i,0}$ and take the step length μ_w

Step 2: Calculate the Lagrange constant λ_n

Step 3: Calculate the weight vector $w^H{}_{i,n+1}$.

Step 4: Update the matrix estimated value R_{n+1}

Step 5: Make n = n+1 and go back to step 2; update λ_n and calculate the new weight vector $w^H{}_{i,n+1}$; conduct stepwise iteration to finally obtain the optimal weighted vector of the converged $w^H{}_{i,n+1}$

The SD-MVDR algorithm avoids inversion of the correlation matrix and can reduce an order of magnitude in computation. When the correlation matrix of oversampling echo signals of weather radar is singular in reality, this method evades the computation problem when matrix inversion is absent.

SIMULATION

In order to verify the effect of the proposed method, the process of algorithm simulation involves processing with three methods, namely, processing of high-frequency signals of model (MODEL), processing of existing signals of weather radar (CSP) and resolution enhancement based on range oversampling (MVDR and SD-MVDR). The range resolutions of the final output echo signals of these three processes are 50, 250 and 50 m.

The simulation experiment is performed with point targets and distributed meteorological targets. Different target characteristics are mainly set up by the average power P and the radial velocity v. In the process of simulation, the noise power is -40 dB; to set one target at a certain position, the power at this position should be higher than the noise power. Experimental parameters include pulse repetition period which is 1ms, wavelength which is 0.1 m and pulse accumulation number which is 64. The lower the SNR of echo signals is, the bigger the estimation error of the radial velocity will be. Therefore, in order to avoid excessively big estimation error which may affect comparison of results, the power threshold for estimation of radial velocity is set to -34 dB; velocity estimation can be carried out only when the average power is above -34 dB; when the power is lower than this threshold, the velocity is set to 0.

Simulation of point targets: This simulation mainly involves evaluation of the range oversampling technique and discrimination of independent targets with the MVDR algorithm. During simulation, three independent targets are set within the range of 500 m between the positions of 6.5 and 7.0 km; the distances between adjacent targets are 100 and 120 m, respectively; the radial velocities v are set to 10, 15 and 5 m sec^{-1}, respectively. Figure 2 shows the discrimination of the three point targets by different algorithms under large SNR. In this figure, the echo signal powers are set to -20, -10 and -15 dB, respectively and the corresponding SNRs are 20, 30 and 25 dB, respectively; the sampling multiple L is 10.

From analysis of Fig. 2, it can be known that with the traditional processing method CSP, the three targets cannot be discriminated from each other according to average power and radial velocity because the range resolution is 250 m; the strength distribution and the velocity distribution are both inconsistent with the actual changes of the three targets. However, after processing by the MVDR algorithm and the SD-MVDR algorithm, the three targets can be easily discriminated along range direction and the estimated values of average power and radial velocity are close to the set values of MODEL. For the MVDR algorithm, as the resolution is enhanced, the noise power also increases and large noise points with period L will appear which will cause false phenomena to small-SNR echo signals. When the improved MVDR algorithm is adopted, noise power points are obviously reduced which will significantly reduce false interference caused thereby.

Simulation of meteorological targets: During simulation verification of meteorological targets, a tornado target which is a typical small-scale target, is first simulated. Figure 4 shows the simulation effect of average power and radial velocity distribution of the tornado. This tornado target is 7.3 km away from the weather radar; its diameter is 200 m and maximum velocity 20 m sec^{-1}. The intensity of this tornado target is 0 dB at the center and gradually increases from the center to both ends; it increases to +20 dB at the positions 100 m away from both ends and then gradually decreases to about -25 dB. The radial velocity of the tornado in the simulation reaches the maximum value at the center which is 20 m sec^{-1} and then gradually reduces to 5 m sec^{-1} from the center to both ends.

Analysis of Fig. 4 shows that the existing processing method (CSP) of weather radar cannot distinguish the gradient change of average power at the tornado center and the average power shows relatively uniform

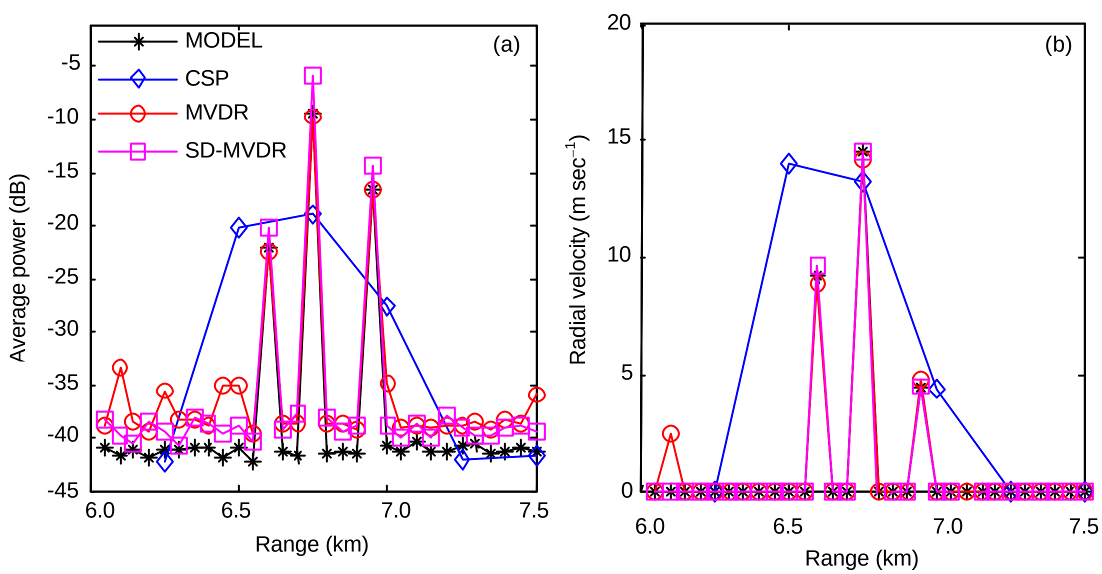

Fig. 2(a-b): Range resolution enhancement of point targets under larger SNR (a) Average power and (b) Radial velocity

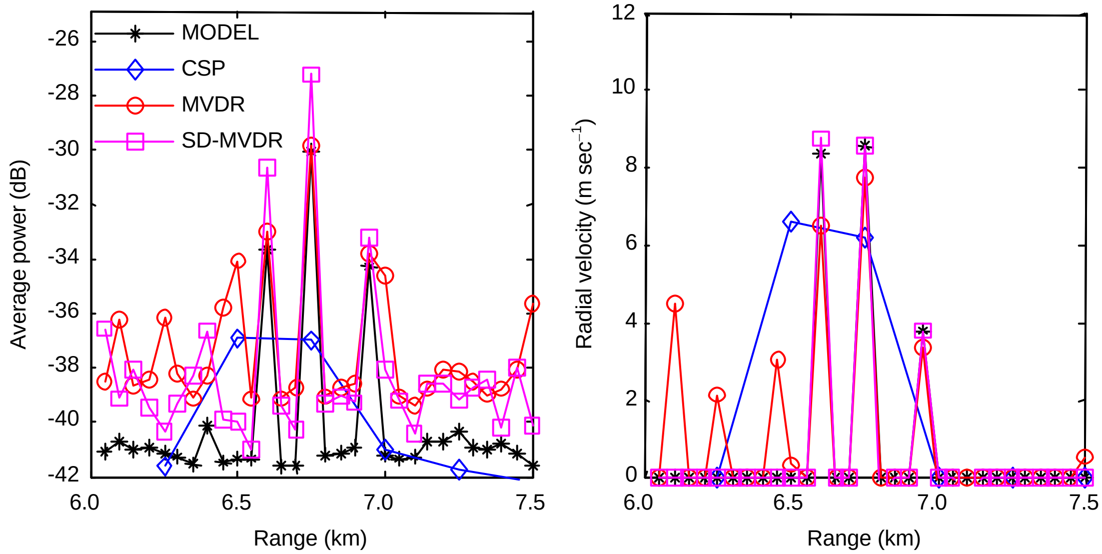

Fig. 3(a-b): Range resolution enhancement of point targets under lower SNR (a) Average power and (b) Radial velocity

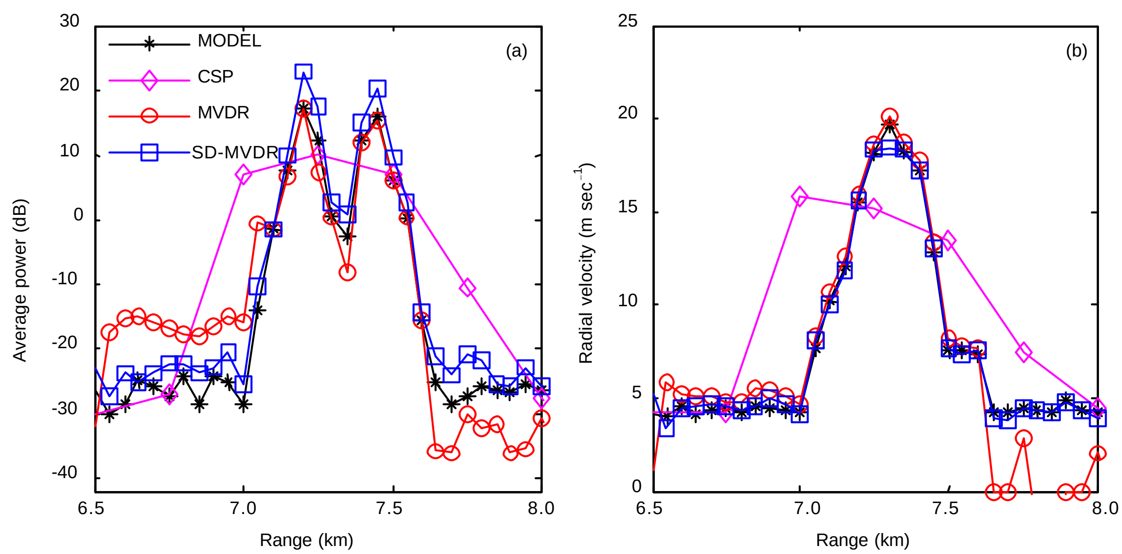

Fig 4(a-b): Range resolution enhancement of meteorological targets under larger SNR (a) Average power and (b) Radial velocity

distribution which is the result of smoothing by the range weighted function. Under CSP, the radial velocity is also relatively low, approaching 5m/s which is unfavorable for identification and analysis of the vortex characteristics of the tornado. After processing by the MVDR and SD-MVDR algorithms, the gradient change of average power at the tornado center can be well reconstructed and the values of average power and radial velocity well coincide with the reference values. Nevertheless, it can also been seen that when the gradient change of average power at both ends of the tornado is not obvious, the average power has a big fluctuation and error after reconstruction by these two algorithms. For radial velocity, similar problem exists, for example, at the position of 6.5~7.0 km in Fig. 4. Comparatively speaking, however, the fluctuation and error of average power and radial velocity obtained based on the SD-MVDR algorithm are greatly reduced and the error is relatively small; for example, such improvement can be observed at the position of 7.5~8.0 km in Fig. 4b.

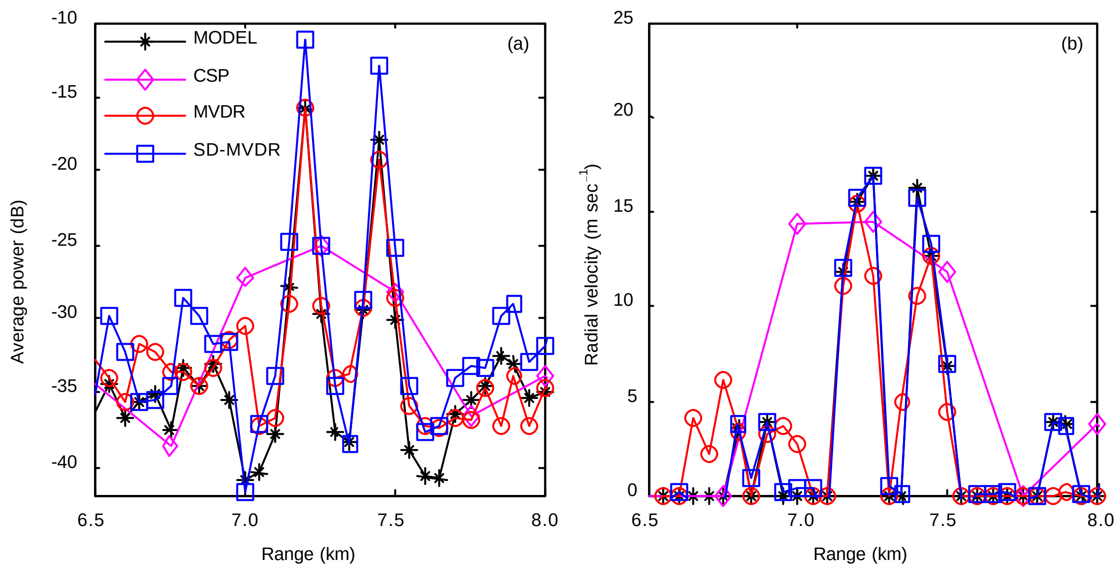

Fig 5(a-b): Range resolution enhancement of meteorological targets under low SNR (a) Average power and (b) Radial velocity

Based on the conditions for tornado simulation in Fig. 4 the intensity of the target within 200 m away from the tornado center is reduced by 45 dB; the result shows that the SNR at the tornado center is close to 5 dB. It is worth noting that the tornado target of such intensity may not exist in reality and here, it is only for the purpose of verifying the resolution enhancement of distributed meteorological targets under low SNR. Figure 5 shows the reconstruction effects of the MVDR and SD-MVDR algorithms under low SNR. Although the SNR is low, the maximum value of 15 dB is still maintained and the gradient change of average power at the tornado center can still be distinguished; however, the SNR at both ends is relatively low and the reconstructed average power has a big fluctuation which makes it relatively difficult to discriminate tornado targets. Since, the SNR at the tornado center is too low, a big error exists in estimation of radial velocity; as to the depression in the middle, it is formed as a result of the fact that the SNR is set to 0 because it is lower than the estimation threshold.

CONCLUSION

To enhance the range resolution of weather radar and solve the problem that the MVDR algorithm is computationally intensive since it requires matrix inversion, this study proposes an improved MVDR algorithm based on steepest descent method. In this study, the oversampling echo signal model of weather model is derived in detail and a reconstructed signal model of higher range resolution is established based on the derivation of this signal model. With the range weighted function, this model builds relationships between actual range oversampling echo signals of weather radar and assumed range echo signals in the high resolution cell. This study, respectively introduces the MVDR algorithm and the improved MVDR algorithm based on steepest descent method (SD-MVDR) as well as their realization processes. Simulation experiments and effect verification are performed for the range oversampling technique using the two MVDR algorithms, respectively with point targets and distributed meteorological targets. Results show that the improved MVDR algorithm can realize enhancement of the range resolution of weather radar and its performance is greatly improved in comparison with the previous MVDR algorithm.

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