

# Echo Simulation of dual polarization Doppler Weather Radar based on physical Model

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## Abstract

Using the scattering characteristics of particles to simulate the radar echo can supply the test signals close to the real precipitation echo for the weather radar, and save the time and cost of the research and development and maintenance of the weather radar. In this paper, the precipitation echo of weather radar is simulated based on the theoretical basis that the raindrops in the falling process satisfy the oblate spheroidal particles in the atmosphere. The Marshal-Palmer distribution is applied to describe the raindrop spectrum distribution of precipitation particles. It is assumed that the raindrop particles of different sizes have the random distribution in the radar resolution volume, and then the spatial distribution of precipitation particles in the resolution volume is modeled. The echo signals of horizontal and vertical polarization channels of dual polarization weather radar are obtained by vector superposition of backscattering echoes of each particle. The experimental results show that this method can describe the microphysical characteristics of precipitation particles more completely and can be used to test the signal processing module of dual polarization Doppler weather radar.

**Keywords:** Scattering characteristics; Marshal-Palmer distribution; Radar resolution volume; Echo signals

## 1 Introduction

The signal receiving and processing part is one of the core parts of the Doppler weather radar system, and its indicators play an extremely significant role in the performance evaluation of the radar. In the process of production and research and development of the weather radar, the evaluation of the signal processing performance of radar receiver is an indispensable link. In this

process, it is essential to provide an effective signal source for weather radar. If we can simulate the echo sequence received by the real weather radar, it can not only optimize the design parameters of the radar system, but also help to improve the performance and advance the research and development efficiency of the weather radar. Therefore, how to quickly obtain an effective test signal source has become an important research topic.

Capsoni C et al. [1] proposed a multi-parameter radar simulator based on the physical characteristics of rainfall, but did not generate radar echo signals with polarization information. Capsoni C et al. [2] simulated the multi-parameter polarization radar by setting raindrop particle distribution units with different sizes and shapes. The contribution of each particle to the radar echo is accurately estimated, but the method is lack of real-time. Cheong B L et al. [3] avoided the shortcomings of the Capsoni C research methods, designed and implemented a real-time radar simulator, which can generate three-dimensional time series, using the Advanced Regional Prediction System(ARPS) to simulate the atmospheric field. The atmospheric field consists of many small particles, each of which corresponds to an echo signal. These echo signals are vector signals, and the radar echoes are presented by superimposing to these vector signals. But this simulation method only provides the spectral moments.

Lupidi A et al. [4] simulated the echoes of X-band polarization weather radar under rain and hail, and calculated the electromagnetic scattering field by utilizing the transmission matrix T-Matrix. Lischi S et al. [5] designed a full polarized Doppler weather radar simulator that can generate the original time series, which takes into account the scattering and propagation effects of electromagnetic waves between particles. The real weather radar observation data, combined with the power spectrum and propagation characteristics of the radar echo, were employed to present the radar echo signals. Lischi S et al [6]. combined the Weather Research and Forecasting (WRF) model and the transfer matrix coding to generate radar signals, and the 3D scenes of graupel, rain and hail are modeled. The echo signals are gained through simulating the weather radar antenna scanning mode, and the consistent result is obtained by comparing with the real radar test data. However, in this framework, the microphysical model does not output parameters such as oblateness and descent rate, there are differences between the observed results and the simulated moisture variables, especially for ice particles. Tang et al. [7] implemented the weather radar echo simulation in hardware. Taking the real radar data as the input of the simulator, a weather echo

simulation system based on power spectrum model was devised. The simulated echo map of weather radar is produced according to the generated I and Q signals, but the algorithm limits the range of input velocity. Based on the time autocorrelation between the transmitted pulses of weather radar, Zhi-Chao B U et al. [8] proposed a time-domain signal simulation algorithm of weather radar under the atmospheric stratification mode. Taking the weak precipitation echo data of C-band dual polarization weather radar as comparative data, the accuracy of the simulation algorithm was verified.

Providing weather radar echo signals with polarization information are particularly important for the development and testing on dual polarization Doppler weather radar. But the existing simulation methods require the foundation of real weather data and a great amount of computation. This paper, in the light of related research, applies the scattering characteristics of precipitation particles to simulate the echo of dual polarization Doppler weather radar. This method realizes the modeling of meteorological scene based on the theoretical basis that the shape of raindrops in the falling process basically satisfies the oblate spheroidal shape. The electromagnetic scattering by rainfall particles is calculated by T-matrix method, and the radar echo simulation of different polarization waves is achieved. In this paper, this method is applied to the simulation of dual polarization Doppler weather radar echo signals. The experimental results show that the simulation results can more completely describe the microphysical characteristics of precipitation particles and can be employed in the test of dual polarization Doppler weather radar signal processing module.

## 2 Methods

### 2.1 Simulation principle of Echo signal of dual polarization Weather Radar

#### 2.1.1 The shape of raindrops

The rainfall measurement of dual polarization weather radar is based on the premise that the raindrops are not spherical but have an oblate spheroidal shape, and the shape is determined by the equivalent diameter and axis ratio. The axis ratio is the ratio of the raindrop the major axis length to minor axis length ( $b/a$ ). For an oblate spheroidal raindrop, the relationship between the axis ratio  $b/a$  and the equivalent diameter  $D_e$  is given by [9]

$$D_e = 2\{(T_s / g\rho_w)[(b/a)^2 - 2(b/a)^{1/3} + 1](b/a)^{1/3}\}^{1/2} \quad (1)$$

where  $T_s$  is the surface tension of water,  $g$  is the acceleration due to gravity, and  $\rho_w$  is the water density.

### 2.1.2 Raindrop spectrum

The raindrop spectrum represents the distribution of the number of raindrops in the unit scale interval and per unit volume. The microphysical structure and evolution properties of precipitation can be got by analyzing the raindrop spectrum. The Marshall-Palmer (M-P) distribution function is widely applied to describe the raindrop spectrum, which is given by [10]

$$\begin{aligned} N(D) &= N_0 \exp(-\Lambda D) \\ \Lambda &= 4.1R^{-0.21} mm^{-1} \\ N_0 &= 8 \times 10^3 m^{-3} mm^{-1} \end{aligned} \quad (2)$$

where  $R$  is the rainfall rate in millimeters per hour,  $D$  is the diameter of different raindrops in mm.

### 2.1.3 Radar parameters

(a) *The reflectivity estimation*

Using the meteorological equation, the reflectivity can be estimated by

$$\hat{Z}_{h,v} = \hat{P}_{rec(h,v)} \cdot \frac{1024 R_{range}^2 \ln 2 \lambda^2}{P_t G_t G_r c \tau \theta_1^2 \pi^3 |K_w|^2} \quad (3)$$

where  $K_w = (\epsilon_r - 1) / (\epsilon_r + 2)$ ,  $\epsilon_r$  is the relative dielectric constant, and  $R_{range}$  is the radial distance. The  $\theta_1$  is the 3 dB beam width on the one-way power pattern,  $P_t$  is the transmit power, and  $G_t$ ,  $G_r$  are the radar transmit and receive gain, respectively. The  $\hat{P}_{rec}$  is the average power of the meteorological echo signal at the antenna, which is related to the coherent electric field echo, the radar echo electric field is given by

$$\sum E_{weight} \cdot \vec{a} = \sqrt{\frac{P_t}{(4\pi)^3}} \cdot G \lambda \sum_{n=1}^N \left( \frac{2\sqrt{\pi\sigma_n} e^{j\psi_n} \cdot e^{\left(-\frac{\theta_n^2}{\gamma^2} - \frac{\phi_n^2}{\delta^2}\right)}}{r_n^2} \right) \cdot \vec{a} \quad (4)$$

$$\gamma^2 = \frac{\theta_{3dB}^2}{4 \ln 2} \quad (5)$$

$$\delta^2 = \frac{\phi_{3dB}^2}{4 \ln 2} \quad (6)$$

Here,  $\psi_n = 2kg_{0n}$ ,  $g_{0n} = x_{0n} \sin\theta \cos\phi + y_{0n} \sin\theta \sin\phi + z_{0n} \cos\theta$ , and  $x_{0n}$ ,  $y_{0n}$  and  $z_{0n}$

are the coordinate positions of the raindrop scattering particles on the rectangular coordinate system. The  $\phi$  and  $\theta$  are the elevation of the particle position and the azimuth of the particle position, respectively. The  $G$  is the gain of radar during transmitting and receiving, that is,  $G_t = G_r = G$ , and the  $\vec{a}$  represents the direction of the electromagnetic scattering field.

(b) *The horizontal and vertical reflectivity factor*

For an oblate spheroidal drop, when the electromagnetic waves irradiating on all particles propagate horizontally and the apparent inclination angle is 0, the backscattering cross sections  $\sigma_{h,v}$  of horizontal  $h$  and vertical  $v$  polarization can be expressed by [11]

$$\sigma_{h,v} = \frac{\pi^5 D_e^6}{9\lambda^4} \left| \frac{m^2 - 1}{1 + (m^2 + 1)A_{h,v}} \right|^2 \quad (7)$$

$$A_v = 1/e^2(1 - ((1 - e^2)/e^2)^{(1/2)} \operatorname{asin}(e)) = 1 - 2A_h \quad (8)$$

where  $\lambda$  is the wavelength of electromagnetic wave emitted by radar,  $m$  is the refractive index of water, and  $e$  is eccentricity of the ellipsoid,

$$e = \{1 - (a/b)^2\}^{1/2} \quad (9)$$

Some polarization parameters can be gained directly from the inversion of raindrop spectrum. When the rotation axis of raindrop particles is vertically oriented, the horizontal and vertical reflectivity factors are defined as:

$$Z_{h,v} = \frac{\eta_{h,v} \lambda^4 |K_w|^2}{\pi^5} \quad (10)$$

$$\eta_{h,v} = \int \sigma_{h,v}(D_e) N(D_e) dD_e \quad (11)$$

where  $N(D_e)$  is the number of raindrop particles.

(c) *The differential reflectivity factor*

The differential reflectivity factor  $Z_{DR}$  is the logarithm of the ratio of horizontal reflectivity factor  $Z_h$  to the vertical reflectivity factor  $Z_v$ , which reflects the intensity difference between the two polarization directions, and can be obtained by using the horizontal and vertical reflectivity factors.

$$Z_{DR} = 10 \log\left(\frac{Z_h}{Z_v}\right) \quad (12)$$

The unit of  $Z_{DR}$  is  $dB$ , which has nothing to do with the number distribution of precipitation particles in the radar resolution volume, but is related to the shape distribution of precipitation particles, which reflects the spatial orientation of precipitation particles deviating from the sphere and particle swarm.

(d) *The specific differential phase*

Raindrop particles will cause phase shift of electromagnetic waves. Due to the resistance of air, and the long axis of oblate spheroidal raindrops is horizontal, the phase shift of horizontal electric field is relatively larger. The difference between the phase change of horizontal and vertical wave propagation is represented by the specific differential phase ( $K_{DP}$ ), which is not affected by beam blocking or ground clutter and little affected by attenuation, so the application of  $K_{DP}$  in quantitative precipitation measurement can improve the precision. The  $K_{DP}$  is usually related to the shape, dielectric constant, and numerical density of moisture variables, it can be expressed as

$$K_{DP} = \frac{180\lambda}{\pi} \operatorname{Re} \left\{ \int_0^{D_m} [f_h(D_e) - f_v(D_e)] N(D_e) dD_e \right\} \quad (13)$$

where  $f_h$ ,  $f_v$  are horizontal and vertical scattering coefficients, respectively.

(e) *The average radial velocity*

The average radial velocity can be expressed as

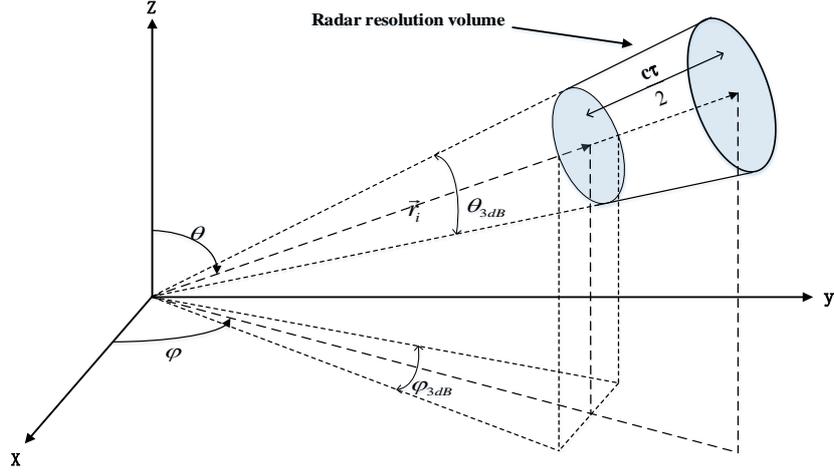
$$\hat{v} = \frac{1}{N-1} \frac{\lambda f_d}{4\pi} \sum_{n=1}^{N-1} \arg\{V_{n+1} V_n^*\} \quad (14)$$

where  $V_n$  is radial velocity,  $f_d$  is Doppler shift, and  $N$  is the number of pulses.

## 2.2 Simulation Model of polarization Radar Echo signal

### 2.2.1 Radar resolution volume

The pulse signal beam emitted by radar can be regarded as conical, and the radar resolution volume is a segment of the volume of the cone, which is drawn in Fig 1.



**Fig. 1** Radar resolution volume

The volume size of radar resolution is calculated as

$$V_{res} = \frac{\pi}{4} \cdot (r_i \theta_{3dB}) (r_i \phi_{3dB}) \left(\frac{c\tau}{2}\right) \quad (15)$$

The initial parameters of the distribution position of raindrop particles are set within the resolution volume. Because of the motion of raindrop particles, it is necessary to set the boundary range of the resolution volume to determine whether the moving raindrop particles are still within the resolution volume. For the convenience of calculation, the position of raindrops is defined by polar coordinates.

### 2.2.2 The matrix of Raindrop particle size distribution

The T-matrix can be constructed by raindrop parameters, and the Table 1 is a list of raindrop parameters.

**Table 1** The raindrop particle parameters

Parameter	Value
Minimum particle diameter	0.01 mm
Boundary diameter of small and medium particles	0.5 mm
Boundary diameter of large and medium particles	3 mm
Maximum particle diameter	6 mm
Low size particle resolution	0.03 mm
Medium size particle resolution	0.1 mm

High size particle resolution

0.3 mm

wind velocity vector

[-5,0,0] m/s

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Using Eq. (2) and (7), we can calculate the required data and write them into a matrix, that is, the T-matrix mentioned above is given by

$$\mathit{matrix\_T\_round} = \begin{bmatrix} D_{e1} & \dots & D_{eN} \\ \sigma_{Iv} & \dots & \sigma_{Nv} \\ \sigma_{Ih} & \dots & \sigma_{Nh} \\ N(D_1) & \dots & N(D_N) \end{bmatrix} \quad (16)$$

### 2.2.3 The matrix Raindrop position

The position of each raindrop particle in the resolution volume is randomly distributed. The position information is described in a spherical coordinate system and stored in a raindrop position matrix, which can be written as

$$\mathit{matrixpos} = \begin{bmatrix} r_1 & \dots & r_N \\ \phi_1 & \dots & \phi_N \\ \theta_1 & \dots & \theta_N \\ \mathit{angle}_1 & \dots & \mathit{angle}_N \end{bmatrix} \quad (17)$$

where  $r$  represents the radial distance from the radar station,  $\phi$  is the elevation of the particle position, and  $\theta$  is the azimuth of the particle position. The  $\mathit{angle}$  is the angle between the particle and the centerline of the beam, which is used to determine which raindrop particles are inside the beam.

For each raindrop of diameter size, the raindrop within the resolution volume is selected according to the Eq. (17). The position of the raindrop is updated by applying the wind velocity vector and the terminal speed, which can be expressed as

$$v(D) \approx 386.6 D_{cm}^{0.67} \quad (\text{m/s}) \quad (18)$$

Using the pulse interval time, we can determine the raindrop particles, and the raindrop particle position corresponding to each pulse time is saved in the position matrix.

### 2.2.4 Polarization radar echo simulator

According to the particle scattering model and the detection principle of dual-polarization weather radar, a dual-polarization weather radar echo simulator is constructed. The input parameters of the

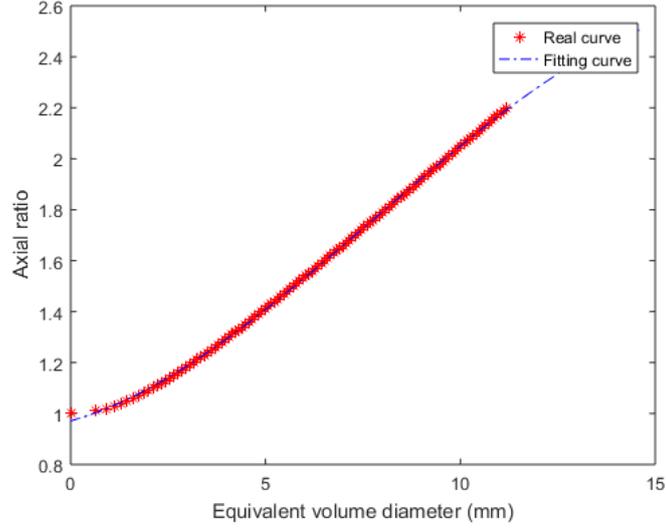
simulator mainly include two parts, namely, radar parameters and weather parameters, as shown in Table 2. The output of the simulator is the radar echo signal of vertical polarization and horizontal polarization.

**Table 2** Model input parameters

Radar parameters	Raindrop parameters
Transmitted signal power	Raindrop spectrum parameters
Transmit and receive antenna gain	Raindrop resolution size
Distance of resolution volume	Average velocity and direction of Raindrop
Beam width	Raindrop position
Pulse width	Raindrop velocity spectrum width
Signal frequency	
Pulse interval	
Elevation and azimuth	

The simulator uses different size resolutions to determine the equivalent diameter of particles in different size ranges according to the size range of raindrops. In the experiment, the axis ratio  $b/a$  needs to be obtained from the size of the equivalent diameter, but it is difficult to solve Eq. (1) directly. Hence the least square algorithm is introduced to find the best match of the data by calculating the square of the minimized error. The distribution curves of axis ratio and equivalent diameter are fitted by the least square algorithm, and the resolution of the equivalent diameter of the original data points is 0.01 cm, which can ensure that the corresponding axis ratio can be obtained by setting different precision and range of equivalent diameter (Table 1).

Firstly, the distribution of the original data points is drawn, and then the least square algorithm is used to fit the original discrete data points according to the distribution. The fitting effect is shown as Fig. 2, it can be seen clearly that the fitting results of the least square algorithm are basically consistent with the theoretical data.



**Fig. 2** Fitting effect of the least square method

Thus the effective scattering area of each raindrop particle can be calculated according to Eq. (7).

When the rainfall intensity and particle size are determined, the numerical concentration  $N(D)$  corresponding to particles of different sizes can be gained by raindrop spectrum distribution function Eq. (2).

By superimposing the scattering echo vector of each raindrop particle to obtain the radar effective scattering cross section, which is given by

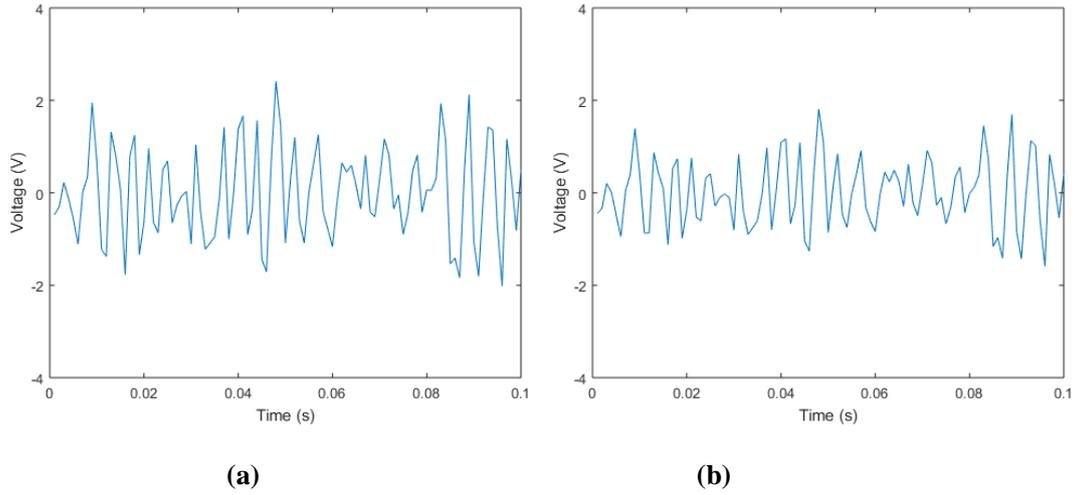
$$E_{total}(t_k) = \sum_s \sum_{i=1}^{N_s} \sqrt{\sigma_{D_s}} \cdot e^{i2k\vec{r}_i(t_k)} \quad (19)$$

where  $t_k$  is the sampling time,  $s$  is the diameter of raindrop particles.

The echo simulator finally outputs the weighted electric field echo, which can be applied to calculate the precipitation parameters such as echo power, reflectivity, differential reflectivity, velocity and so on.

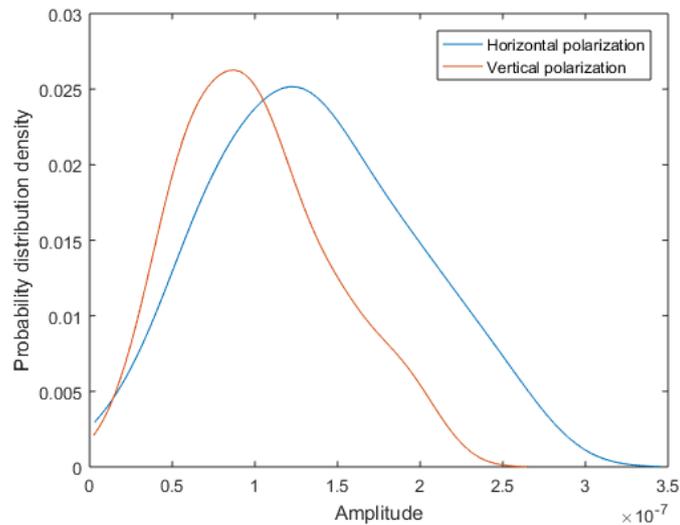
### 3 Results and Discussions

In order to prove the accuracy of the simulation signal, the time-frequency characteristics of the signal are analyzed, and the results are as follows. The form of echo voltage is shown in Fig. 3. It is obviously that the variation rules of horizontal and vertical echo voltage are basically coincident.

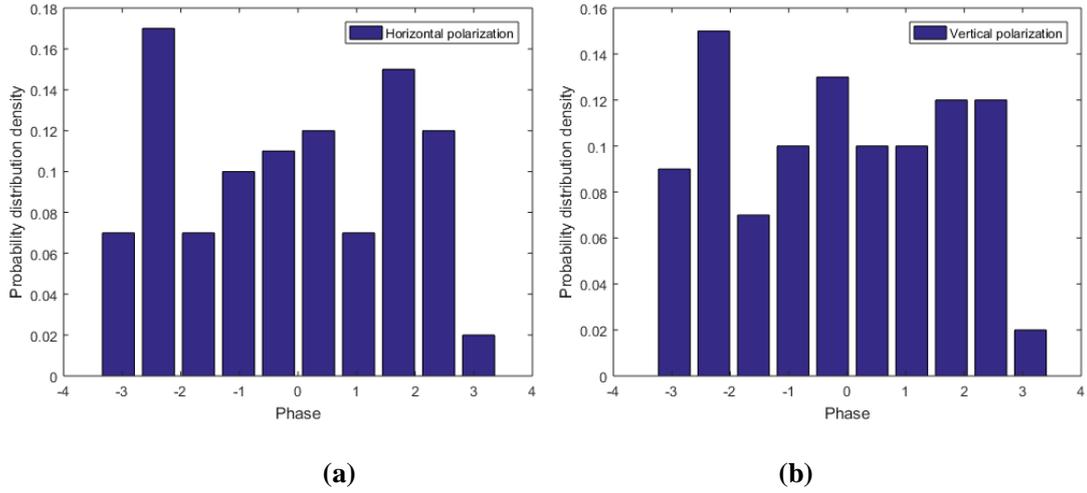


**Fig. 3** Echo voltage, **a** horizontal polarization echo voltage,  
**b** vertical polarization echo voltage

The meteorological echo is composed of a large number of discrete scattered particle echoes, the position of these scattered particles will change due to the movement of the scatterer, and the amplitude of the echo will fluctuate in that the change of the position. Therefore, the statistical characteristics of echo amplitude can reflect part of the particle variation information. Fig. 4 shows the statistical characteristics of echo amplitude in time-domain. It can be seen that the echo amplitude spectrum has the Rayleigh distribution, which is determined by the microphysical characteristics of precipitation itself. The statistical characteristics of the phase distribution are shown in Fig. 5, from where we can see that the phase has the uniform distribution, which is essentially in agreement with the statistical characteristics of precipitation echoes described in reference [12].

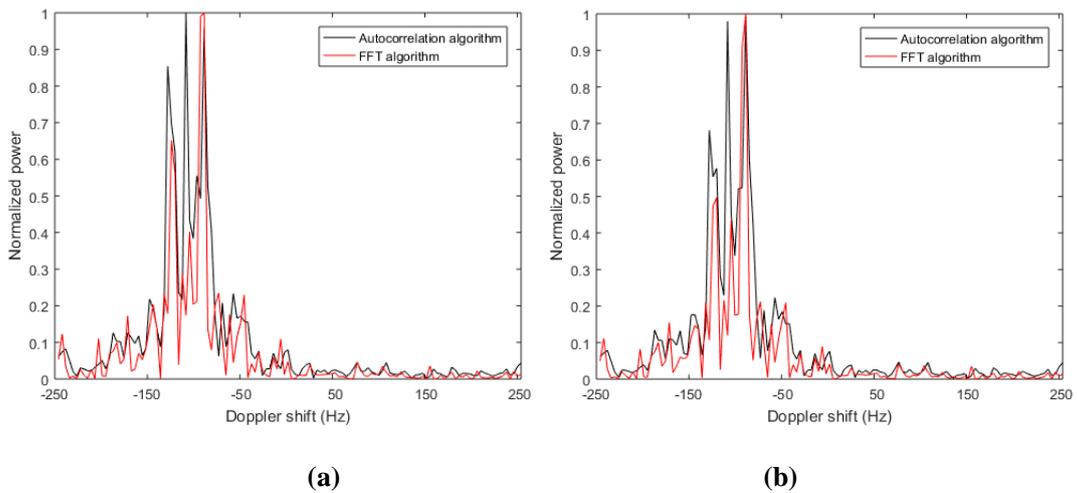


**Fig. 4** Amplitude probability distribution density



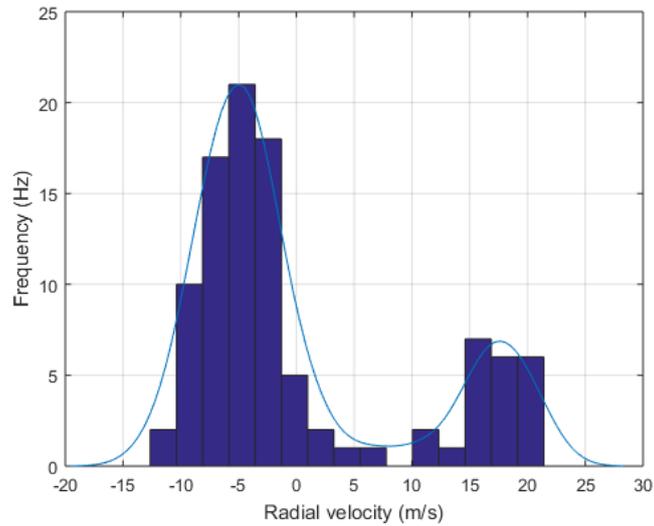
**Fig. 5** Phase probability distribution density, **a** horizontal polarization, **b** vertical polarization

The meteorological echo signal is a random fluctuation signal, and its power spectrum can be expressed by power spectral density, as shown in Fig. 6. Fig. 6 (a) shows the normalized power spectral density for echo of horizontally polarized waves, which is calculated by FFT(fast Fourier transforms) algorithm and Fourier transform of autocorrelation algorithm respectively. The corresponding power spectral density of vertically polarized waves is shown in Fig. 6 (b), from which we can conclude that the distribution of power spectral density calculated by these two methods is basically the same for both vertical polarization and horizontal polarization. And the distribution regulation is approximate to Gaussian distribution, which conforms to the conclusion of reference [13].



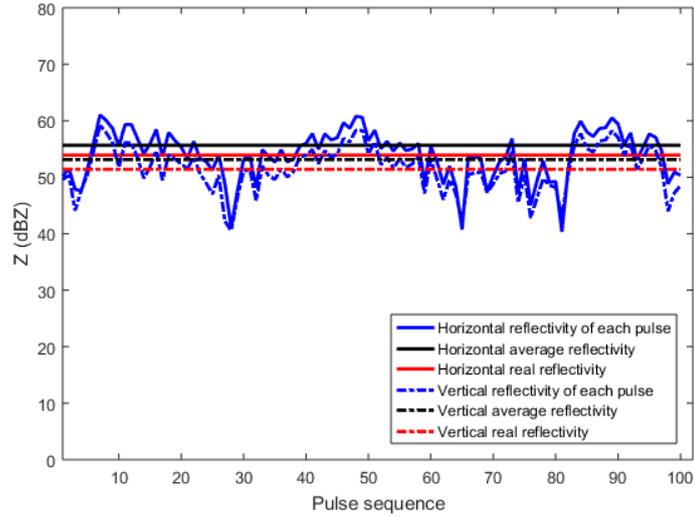
**Fig. 6** Power spectrum, **a** horizontal polarization power spectrum, **b** vertical polarization power spectrum

Fig. 7 shows the histogram of distribution of the radial velocity calculated according to each pulse pair, and the longitudinal coordinate represents the frequency of the velocity interval. The Gaussian fitting function is used for fitting the histogram. It is clearly that the transverse coordinate value corresponding to the peak value of the Gaussian function is basically consistent with the Doppler frequency shift corresponding to the peak value of the power spectrum, and is fundamentally same with the initial set velocity value.



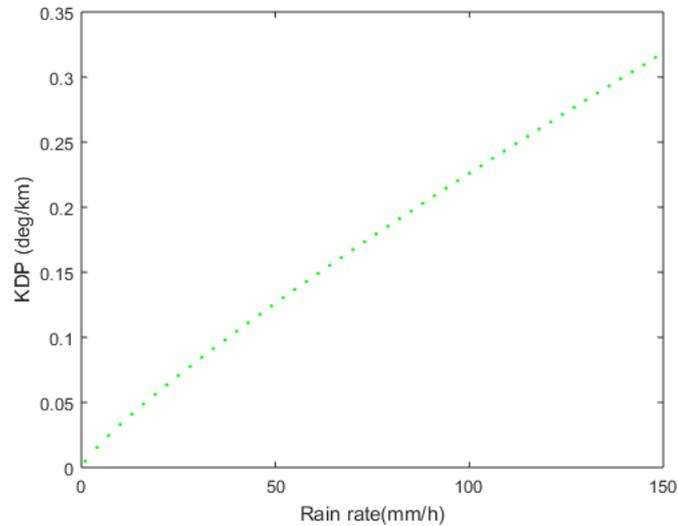
**Fig. 7** Radial velocity distribution

Fig. 8 shows the calculations of the reflectivity of each pulse when it returns. The reflectivity of each pulse is estimated by the receiving voltage, and the average value of each pulse is calculated, as shown in the average reflectivity curve in the Fig. 8, where the actual reflectivity is calculated according to the distribution function of droplet size. It can be seen that the changing trends of the two polarization directions are basically the same, and the reflectivity of horizontal polarization is about 2 *dBZ* larger than that of vertical polarization, which is identical with that described in reference [14]. And it can be concluded that the reflectivity calculated by the droplet size distribution function is slightly larger than the estimated reflectivity, which proves that the simulation results are consistent with the theoretical values.



**Fig. 8** Reflectivity estimation

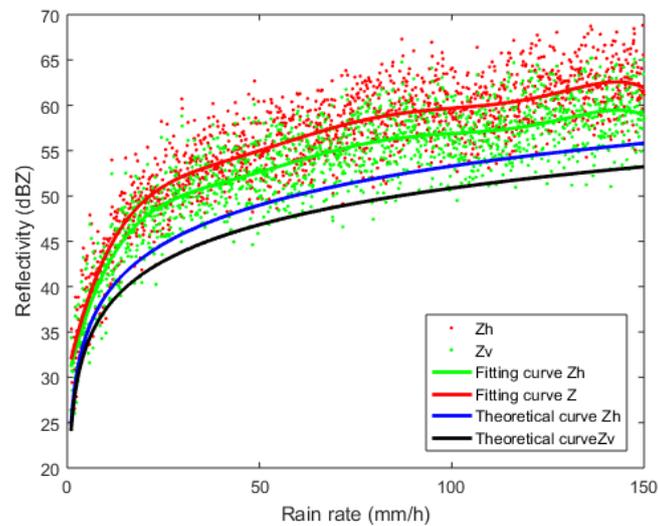
In order to verify the accuracy of the precipitation model, the value of  $K_{DP}$  is calculated by Eq. (13) in the light of the distribution of raindrop size, as shown in Fig. 9. It is clearly from Fig. 9 that the value of  $K_{DP}$  increases with the increase of rain rate, the reason is that when the rain rate is large, the raindrop distribution function assumed by the model corresponds to more heavy raindrop particles, while  $K_{DP}$  is related to raindrop size distribution [15].



**Fig. 9** Relationship between specific differential phase and rain rate

By setting different rainfall rates, the relationship with the reflectivity can be derived, as shown in Fig. 10. The red dots represent the reflectivity factor calculated by the horizontal echo data, and the green dots indicate the reflectivity factor calculated by the vertical echo data. It can be seen that the horizontal reflectivity factor is slightly larger than the vertical reflectivity factor,

and its distribution law basically conforms to the theoretical research results of Crozier et al. [14].



**Fig. 10** Relationship between rain rate and reflectivity

## 4 Conclusions

In this paper, the simulation of precipitation echo of dual polarization weather radar is realized by using the theoretical basis that the shape of raindrops in the falling process of raindrops in the atmosphere basically satisfies the oblate spheroid. The Marshall-Palmer distribution is used to describe the raindrop spectrum distribution of precipitation particles, and it is assumed that the raindrop particles satisfy random distribution in the radar resolution volume, thus the spatial distribution of precipitation particles in the radar resolution volume is modeled. The least square algorithm is applied to solve the problem that it is difficult to calculate the axis ratio of precipitation particles. The backscattering echo of each precipitation particle under horizontal and vertical polarization electromagnetic wave is calculated by simulating the dual polarization radar detection mechanism, and then the echo signals of dual polarization radar in horizontal and vertical polarization channels are obtained by vector superposition of the echoes of precipitation particles. The experimental results show that this method can describe the microphysical characteristics of precipitation particles more completely, and can be used in the test of dual polarization Doppler weather radar signal processing module. It is of great significance to the research and development of dual polarization weather radar.

## **Abbreviations**

M-P: Marshal-Palmer; ARPS: the Advanced Regional Prediction System; WRF: the Weather Research and Forecasting; FFT: the fast Fourier transforms.

## **Availability of data and materials**

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

## **Authors' contributions**

HJW proposed the study and put forward the echo simulation model. QTJL conducted the experiments and wrote the manuscript. SPH and JHZ analyzed and evaluated the experimental results. MQG drew the figures and improved the structure of the manuscript. All authors read and approved the final manuscript.

## **Competing interests**

The authors declare that they have no competing interests.

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