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An Analysis on the Retrieval of Raindrop Size Distribution by Dual-Frequency Precipitation Radar

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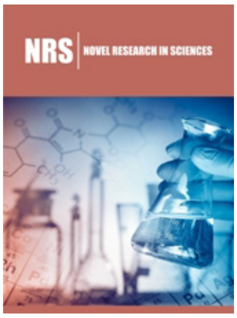

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Abstract

The retrieval of raindrop size distribution has a great significance for the study on the microphysical process of cloud and precipitation, as well as the formation and development of precipitation systems. In this paper, given raindrop size distributions, the T-matrix method is used to simulate the radar detection parameters for solid, mixed and liquid particles, with which the DPR algorithm is used to retrieve the raindrop size distribution to analyze the effect and the sensitivity of the algorithm for different phases. The results show that, for snow particles, when the normalized scale parameter N_w is fixed, the retrieved median diameter D_0 is less than the truth value, and the retrieval error increases with the increase of D_0; When D_0 is fixed, the retrieved N_w is larger than the true value and they have a notable linear relationship. With the increase of the N_w, the retrieval error decreases continuously while the retrieved value changes little. For the rain particles, the retrieval of D_0 is very good, and the retrieval of N_w is slightly worse. For the mixed particles, the retrieve D_0 is less than the true value, and the retrieve N_w is larger than the true value. The retrieval accuracy increases with the decrease of the mixing ratio.

Keywords: Drop size distribution; Dual-frequency radar; Retrieval

Abbreviations: DSD: Drop Size Distribution; PR: Precipitation Radar; GPM: Global Precipitation Measurement; DPR: Dual Frequency Precipitation Radar

Introduction

In the research field of radar meteorology, it is important to obtain the rain Drop Size Distribution (DSD) information. The retrieval of DSD is of great significance for the study on the microphysical process of cloud and precipitation, and on the formation and development of precipitation systems. It can be also used to analyze the characteristics of precipitation distribution and to improve the accuracy of radar precipitation estimation. The space borne radar has a satellite platform of a high orbit and can provide global precipitation observation. The PR (Precipitation Radar) carried by the TRMM (Tropical Rainfall Measuring Mission) is the first spaceborne precipitation radar. The Global Precipitation Measurement (GPM) is the successor to TRMM, and the Dual Frequency Precipitation Radar (DPR) onboard GPM uses dual frequency technique to detect rainfall.

Ulbrich [1] found that the three parameters of the Gamma distribution (normalized scale factor N_w, shape parameter μ, and median drop diameter D_0) were not independent of each other and had high Pearson correlation coefficients among them. Zhang et al. [2] calculated the other two parameters of Gamma distribution by the relationship between the shape parameters μ and Λ. Seto et al. [3] developed an algorithm to retrieve DSD based on spaceborne dual-frequency radar, namely the DFR (Dual-Frequency Reflectivity Ratio) method. Chandrasekar et al. [4] showed that DFR in rain area usually encountered the "double value" problem. In the current DPR algorithm, the relationship between precipitation rate R and D_m is adjusted by one or several adjustment factors to eliminate the "double value" problem when the precipitation rate is small. Liao et al. [5] evaluated the advantages of dual-frequency algorithm over single-frequency algorithm in current DPR algorithms. In this paper, the T-matrix method is used to simulate the radar detection parameters of solid, mixed and liquid particles when raindrop size distribution is given, and then the DPR algorithm is used to retrieve the DSD to analyze the effect of the algorithm for different phases.

Basic Theory

Particle model

In the study of this paper, rain particles are pure liquid particles, mixed particles are uniformly mixed particles of ice, air and water, and solid particles are uniformly mixed particles of ice and air. The particle density is calculated as in Bohren et al. [6]:

$$\rho_b = P_w \rho_w + P_i \rho_i + P_a \rho_a \quad (1)$$

Where, P_w, P_i and P_a respectively represent the percentage of water, ice and air in the whole particle ρ_w, ρ_i and ρ_a respectively represent the densities of water, ice and air, which are fixed as 1g/cm^3, 0.92g/cm^3 and 0g/cm^3. In this paper, the shape of precipitation particles is oblate ellipsoid, and the relationship between the axial ratio of the oblate ellipsoid and the equivalent diameter is modeled by Brandes et al. [7]. The specific calculation formula is:

$$r = 0.9951 + 0.02510D - 0.3644D^2 + 0.005030D^3 - 0.0002492D^4 \quad (2)$$

where r is the axial ratio of the oblate ellipsoid, and D is the equivalent diameter of the particle. In this paper, it is assumed that: 1) The dual-frequency (Ku and Ka band) radar observes stratiform precipitation; 2) The temperature of the liquid layer is 10 °C; 3) The solid particle density is 0.2g/cm^3; 4) The tilt angles of the particles θ satisfy the Gaussian distribution with a mean value of 0 and a variance of 6°; 5) The rotation angles of the particles Φ satisfies satisfy an average distribution of 0°~180°; 6) The particle diameter is 0~8mm.

DSD model

Ulbrich proposed the Gamma distribution to describe the characteristics of DSD [1]. The Gamma distribution includes the concentration parameter N_0 (m^{-3}mm^{-1}), the shape factor μ (dimensionless) and the scale parameter Λ (mm^{-1}):

$$N(D) = N_0 D^{\mu} \exp(-\Lambda D) \quad (3)$$

where D is the equivalent volume diameter (mm). In the Gamma distribution, since the unit of N_0 is not consistent with the DSD concentration N(D) and has no clear physical meaning, it is not conducive to the retrieval of concentration parameters. Willis proposed a "normalized" Gamma distribution as shown in (4) [8], which introduces the volume median diameter D_0 (mm) and normalized scale factor N_w (m^{-3}mm^{-1}):

$$N(D) = N_w f(\mu)\left(\frac{D}{D_0}\right)^{\mu} \exp\left[-(3.67+\mu)\frac{D}{D_0}\right] \quad (4)$$

$$N_w = \frac{N_0}{f(\mu)} D_0^{\mu} \quad (5)$$

$$f(\mu) = \frac{6}{3.67^4}\frac{(3.67+\mu)^{\mu+4}}{\Gamma(\mu+4)} \quad (6)$$

In this paper, according to the DPR algorithm, μ is set to 0 in the ice and melting ice regions and set to 3 in the rain region.

The retrieval algorithm of DSD

The current DPR algorithm adds R-D_m relations to constrain the retrieval of DSD. If the Gamma distribution has a fixed shape factor μ or a mass-weighted diameter D_m function, it will have only one parameter D_m.

$$R = \varepsilon^r p D_m^q \quad (7)$$

When the DSD satisfies the Gamma distribution, and μ≥-2, there is a relationship between D_m and D_0: $(3.67+\mu)D_m=(4+\mu)D_0$. According to the analysis of observations by Kozu et al. [9] the values of r,p,q in the current algorithm are 0.401, 6.131 and 4.649 in stratiform precipitation, and 1.370, 5.420 and 4.258 in convective precipitation, respectively [9]. ε ranges from 0.2 to 5, and its optimal value is determined by the minimization of the difference between the simulated and the measured radar reflectivity, and between the calculated and the estimated PIA (the integral attenuation caused by precipitation particles from the surface to the radar). Z_{Ku} and D_m are related in a one-to-one pattern when ε is given so that D_m can be uniquely derived from Z_{Ku}, and then N_w can be obtained from D_m and Z_{Ku}. It can be seen from (Figure 1) that for the same Z_{Ku}, D_m (for rain particles)>D_m (formelting particles)>D_m (for snow particles), and D_m decreases as ε increases.

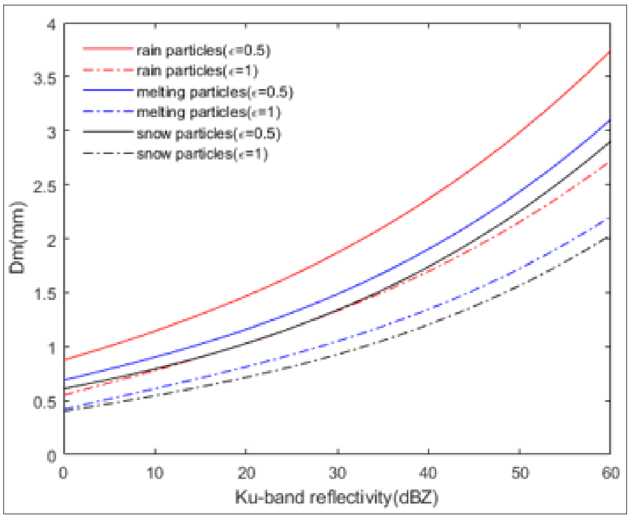

Figure 1: D_m-Z_{Ku} relations for ε value of 0.5 (solid lines) and 1 (dashed lines) for rain particles(red), melting particles (blue), snow particles (black) in the case of stratiform precipitation.

The Performance of the DPR Retrieval Algorithm

Because the values of N_w usually have a very large range, they are shown by the logarithmic scale in this study. For the snow particles, As shown in Figure 2, when N_w is fixed and the range of D_0 is 0.5mm~1.0mm, 1.0mm~1.5mm and 1.5mm~2.0mm, the retrieved D_0 is less than the truth value and the retrieval error increases with the increase of D_0; When D_0 is fixed and the range of N_w is $1\times10^3m^{-3}mm^{-1}\sim4\times10^3m^{-3}mm^{-1}$, $4\times10^3m^{-3}mm^{-1}\sim7\times10^3m^{-3}mm^{-1}$ and $7\times10^3m^{-3}mm^{-1}\sim1\times10^4m^{-3}mm^{-1}$, the retrieved N_w is larger than the true value and they have a notable linear relationship. With the increase of N_w the retrieval error decreases while the retrieved value changes little. For rain particles, the DSD parameters in DPR product are taken as the true value. It can be seen from (Figure 3) that the retrieval of D_0 is very good and the retrieval of N_w is slightly worse. For the mixed particles, the DSD parameters in DPR product are taken as the true value, and the mixing ratio is set to 0.25, 0.5 and 0.75, respectively. As shown in Figure 4, the retrieved D_0 is less than the true value, and the retrieved N_w is larger than the true value. The retrieval accuracy increases with the decrease of the mixing ratio.

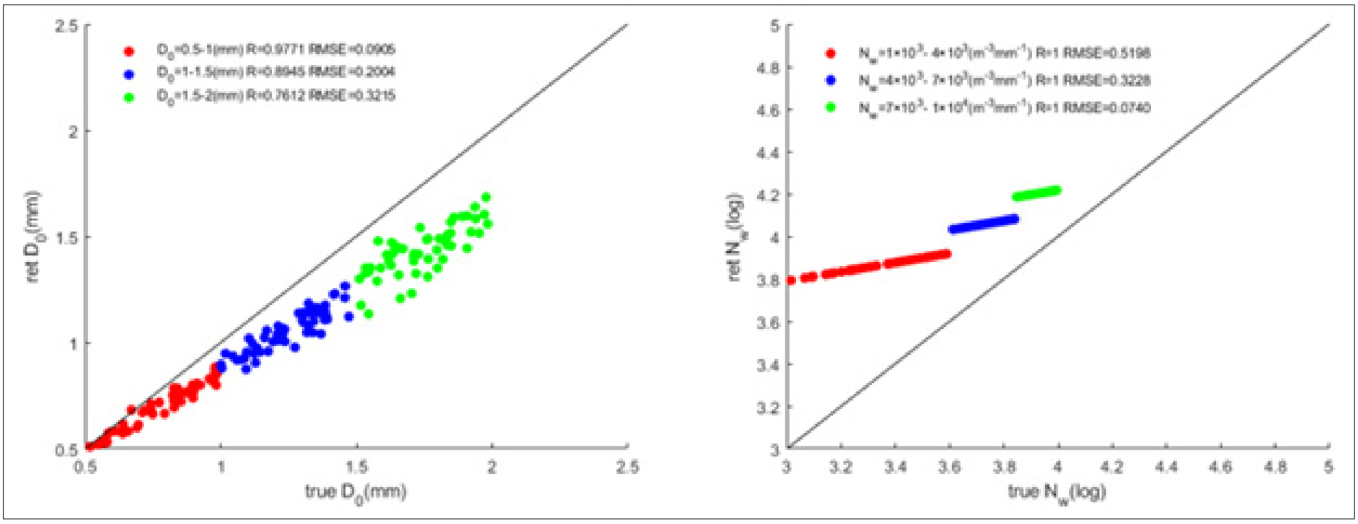

Figure 2: The true values of D_0 (left) and N_w (right and in log scale) and retrieved values by the DPR algorithm for the snow particles.

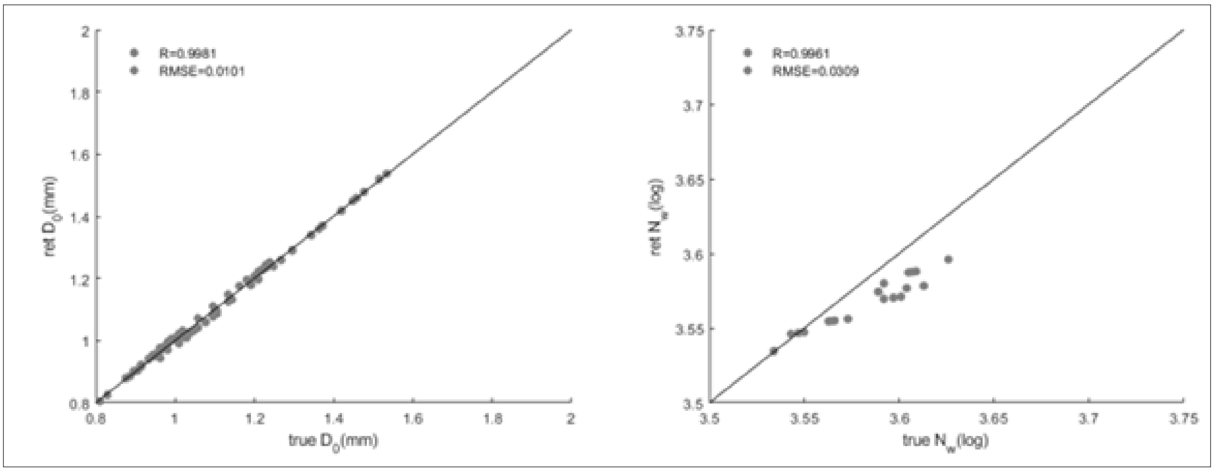

Figure 3: The true values of D_0 (left) and N_w (right and in log scale) and the retrieved values by the DPR algorithm for the rain particles.

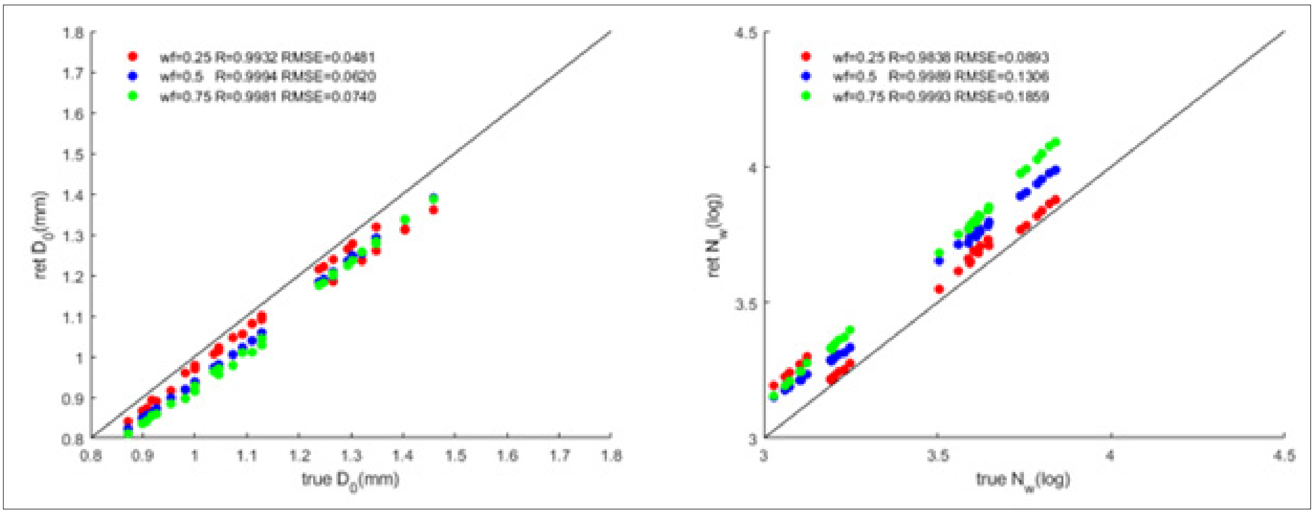

Figure 4: The true values of D_0 (left) and N_w (right and in log scale) and the retrieved values by the DPR algorithm for the melting particles with the water fraction of 0.25 (red), 0.5 (blue), 0.75 (green).

Summary and conclusion

In this paper, the T-matrix method is used to simulate the radar detection parameters of solid, mixed and liquid particles given the DSD, and then the DPR algorithm is used to retrieve the DSD based on the radar detection parameters. The retrieval results are analyzed by comparison with the true values and the conclusions are as follows:

a. For the snow particles, when N_w is fixed, the retrieved D_0 is less than the truth value, and the retrieval error increases with the increase of D_0; When D_0 is fixed, the retrieved N_w is larger than the true value, and the retrieved value and the true value have a notable linear trend. With the increase of the N_w true value range, the retrieval error decreases while the retrieved value changes little.

b. For the rain particles, the retrieval of D_0 is very good, and the retrieval of the N_w retrieve is slightly worse.

c. For the mixed particles, the retrieved D_0 is less than the true value, and the retrieve N_w is larger than the true value. The retrieval accuracy increases with the decrease of the mixing ratio.

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