Radar reflectivity of thunderstorm clouds

L T Sozaeva, M A Sherieva
High Mountain Geophysical Institute, Nalchik, Russia

ljk_62@rambler.ru

Abstract. The contribution of various types of hydrometeors to the total radar reflectivity was estimated based on numerical modeling of thunderstorm clouds. Isolines, time course and change of reflectivity with the height at two wavelengths due to the contribution of drops and hailstones are constructed. It is shown that when solving inverse problems of the scattering theory at a wavelength of 3.0 cm, it is necessary to take into account the contribution of raindrops to reflectivity, and at a wavelength of 10 cm, it can be ignored. The contribution of cloud droplets and crystals at both wavelengths can be ignored.

1. Introduction
Currently, knowledge about the microstructure of thunderstorm clouds can be obtained both by direct measurements and remote methods. Obtaining experimental data by direct methods is associated with great difficulties due to the presence of unsafe phenomena in such clouds (lightning discharges, the presence of electric fields, high turbulence). This makes it necessary to develop remote methods for studying the microstructure of thunderstorm clouds. Particular attention is drawn to methods based on solving inverse problems of restoring the distribution function of hydrometeors based on radar reflectivity measurements. The solution of this problem is associated with a number of difficulties, one of which is the simultaneous existence in hail clouds of rain and cloud drops, crystals, hailstones, etc., which contribute to the value of radar reflectivity. Therefore, it is necessary to assess the contribution of various hydrometeors to the total radar reflectivity. Due to technical difficulties, it is impossible to obtain experimental data on their microstructure, especially in the zone of maximum reflectivity. Therefore, the contribution of various types of hydrometeors to the total radar reflectivity is estimated based on the results of numerical modeling.

This article presents the results of model studies of total radar reflectivity using a three-dimensional non-stationary model of a convective cloud [4].

2. Research methods
Radar methods for studying clouds and precipitation are based on the interpretation of the reflected signal received by the radar. The formation of the reflected signal is based on the effect of electromagnetic wave scattering on various hydrometeors (cloud and rain drops, crystals, hailstones, etc.). The value of this signal depends on the concentration, size, complex index and cross-section of the backscattering of hydrometeors.

The relationship between the size distribution function, the cross-section of the hydrometeor backscattering, and their radar reflectivity is written as a Fredholm integral equation of first kind:

$$\sum \int \sigma_n(r, \lambda, m)n_i(r)dr = \eta(\lambda),$$  

(1)
where \( n_i(r) \) – is the distribution function of hydrometeors of the \( i \)-st type by size; \( \sigma_i(r, \lambda) \) – cross-sections of backscattering of hydrometeors of the \( i \)-st type; \( \eta_i(\lambda) \) – radar reflectivity at the wavelength \( \lambda \) known from the experiment; \( \lambda \) – the wavelength of the radar; \( a, b \) – the minimum and maximum radius of hydrometeors, \( N \) – the number of varieties of hydrometeors in the cloud environment, \( r \) – the radius of hydrometeors, \( m \) – the complex refractive index of hydrometeors.

The total radar reflectivity of a unit of cloud volume containing a set of hydrometeors is equal to:

\[
\eta(\lambda) = \sum_{i=1}^{N} \eta_i(\lambda),
\]

where \( n_i(r) \) – contribution to the total reflectivity of hydrometeors of the \( i \)-st type.

The solution of the inverse problem (1) in order to restore the distribution function of hydrometeors by radar measurements meets a number of difficulties. One of them is related to the simultaneous presence of various hydrometeors (\( N \) types) in the cloud. Therefore, there is a need to simplify equation (1), which should take into account the features of the formation of various hydrometeors in the cloud and the nature of their interaction with electromagnetic radiation. Simplification of equation (1) will be associated with the assessment of the contribution of different types of hydrometeors to the right side of equation (2) and the determination of the spatial distribution of hydrometeors of different types, related to the conditions of their growth in hail clouds [2, 6].

Numerical experiments conducted using a non–stationary one–and–a–half–dimensional model of a convective cloud have shown that the ratio of the contribution of raindrops and hailstones to the total radar reflectivity of hail clouds depends on the stage of their development [5].

For numerical experiments, we used a three–dimensional non–stationary model of a convective cloud with a detailed account of microphysics, developed at the High–Mountain Geophysical Institute [3]. The microphysical block of the model contains the function of distribution of hydrometeors by size (mass) as the main equation. Microphysical processes such as condensation and coagulation of droplets, sublimation and coagulation of crystals, accretion of droplets and crystals, etc. are taken into account in detail.

In this model, hail clouds may contain liquid droplets and solid particles depending on the stage of development [4]. Drops are divided by mass into 60 intervals (from water vapor to raindrops), and crystals into 75 intervals (from small crystals to hailstones).

As a result of numerical experiments, changes in the distribution functions of hydrometeors in space and time were obtained. Further, the reflectivity isolines and their time course caused by the transformation of droplets and solid particles were calculated and constructed using the data of hydrometeor spectra.

3. Research results and discussion

Modeling of the cloud development process was performed according to the data of aerological sounding in the airport of Mineralnye Vody for 2 April 2014. On this day, the Stavropol paramilitary service recorded showers, thunderstorms and hail within the radius of the probe’s representativeness.

The cloud was initiated by setting a pulse at the earth’s surface with overheating \( \Delta T = 1.5 \) \( ^\circ \)C. The shape of the pulse was represented as a three–dimensional cylinder, with a radius 2.6 km in the horizontal plane, and 2 km – in the vertical. The dimensions of the spatial area were set: 80 km horizontally and vertically. Grid step by coordinates X and Y amount to 1000 m, by Z amount to 200 m. In the figures below, there is an auxiliary grid 2 km \( \times \) 2 km.

Based on the results of calculations of the evolution of the cloud microstructure, the reflection isolines at the wavelength \( \lambda=3.2 \) cm (figure 1) and \( \lambda=10 \) cm (figure 2) and the spatial distribution of solid particles (figure 3) at various points in the cloud development were constructed.

At the 24th minute of cloud development, a full spectrum of droplets formed, reaching sizes \( r = 4 \) mm. At this time, the contribution of crystals to the total reflectivity was 37 dBz, and drops 50 – 53 dBz (figure 1A, 2A). No hail was observed.

At the 30th minute of cloud development, as a result of deformation of the fields of thermodynamic parameters (temperature, humidity, etc.), under the influence of updrafts in the temperature range –
10…−20 °C, a zone favorable for hail growth was formed in the cloud. In it, the contribution of hailstones to the total reflectivity in the region of the maximum value was 61.1 dBz, and drops 64 dBz at the wavelength $\lambda = 3.2$ cm. At the wavelength $\lambda = 10$ cm, the contribution of hailstones to the total reflectivity was 65 dBz, and drops 61 dBz (height − 4400 m, temperature – 11.2 °C). The contributions of drops and hailstones to the total radar reflectivity became comparable (figure 1B, 2B). In the area of maximum reflectability, the hailstones have reached the size 0.75 − 1 cm (figure 3A).

At the 40th minute of cloud development at height 4000 m, the hail grew to size 1.5 ± 2 cm (figure 3B). Reflectivity in the zone of maximum values reached 69 dBz (the contribution of hailstones) and 37 dBz (contribution drops) the wavelength $\lambda = 3.2$ cm and 80 dBz (the contribution of hailstones) and 62 dBz (contribution drops) on the wavelength $\lambda = 10$ cm (figure 1B, 2B). That is, at this point in time, solid particles began to contribute more to the total reflectivity than drops.

At the 50th minute of cloud development, hail increased to 2 cm (figure 3C) and the area of hail localization increased. For clarity, figure 3 shows the distribution of hailstones at the 60th minute, which shows that the area of hail localization has increased even more. This cloud was at its maximum development stage (quasi–stationary stage), which lasted about two hours. The contribution of hailstones to the total reflectivity reached the maximum value 80 dBz, and the contribution of drops became equal 65.5 dBz at the wavelength $\lambda = 3.2$ cm (figure 1D).

At the wavelength $\lambda = 10$ cm, the reflectivity due to hailstones increased to 91 dBz, and due to drops − 62 dBz at the height 3400 m (figure 2D) in the zone of maximum reflectivity. The areas of maximum localization of drops and hailstones are separated horizontally. This is due to the fact that precipitation (rain and hail) began to fall out of the cloud at this time.

It is known that the value of radar reflectivity in hail clouds depends on the stage of development. To illustrate this phenomenon, the time components of the total reflectivity due to the contribution of drops and hailstones were constructed (figure 4).

In the initial stage of cloud development, the contribution of droplets to the total reflectivity is greater than the contribution of solid particles. Then, with the further development of the hail cloud, the reflectivity due to drops and hail converges (after 30 minutes), and further the contribution of hailstones to the total reflectivity begins to prevail over the contribution of drops. After 40 minutes, this cloud becomes quasi–stationary. At the 50th minute, the hail reaches its size $r = 2$ cm, and the contribution of hailstones to the overall reflectivity becomes greater than the contribution of raindrops.

Note that the reflectivity due to the presence of hailstones reached its maximum value at the 60th minute, while the height of the maximum reflectivity zone is highest at the 70th minute (at the same time, the minimum temperature in the cloud is observed). The speed of updrafts is maximum at the 35th minute of cloud development. This discrepancy in the time when these parameters reach their maximum values is typical for convective development clouds.

The ratio of the contribution of drops and hail to the total reflectivity varies in height. Figure 5 shows vertical radar reflectivity profiles due to the presence of drops and hailstones in the zone of increased reflectivity at the 45th minute of cloud development.

Vertical profiles of radar reflectivity in the region of the presence of hail with altitude decrease. This is due to the fact that the concentration and size of droplets and solid particles decreases with height.
Figure 1. Reflectivity isolines ($dBz$) due to the contribution of drops (solid line) and hailstones (dotted line) at various points of cloud development at the wavelength $\lambda = 3.2 \text{ cm}$: a) $t = 24 \text{ min}$, b) $t = 30 \text{ min}$, c) $t = 40 \text{ min}$, d) $t = 50 \text{ min}$. 
Figure 2. Reflectivity isolines (dBZ) due to the contribution of droplets (solid line) and hailstones (dotted line) at various points of cloud development at the wavelength \( \lambda = 10 \) cm: a) \( t = 24 \) min, b) \( t = 30 \) min, c) \( t = 40 \) min, d) \( t = 50 \) min.
Figure 3. Spatial distribution of solid particles at various points of cloud development 0.5 – (r = 0.5 ± 0.65 cm); 1 – (r = 0.7 ± 0.9 cm); 2 – (r = 1 ± 1.9 cm).

a) t = 30 min, b) t = 40 min, c) t = 50 min, d) t = 60 min.

Figure 4. The course of the maximum value of radar reflectivity due to the presence of drops (solid line) and hailstones (dotted line). a) λ=3.2 cm, b) λ=10 cm.
Figure 5. Vertical profiles of radar reflectivity due to the presence of drops (solid line) and hailstones (dotted line). a) $\lambda=3.2$ cm, b) $\lambda=10$ cm.

In the cloud under study the following calculation points were identified in the zone of high reflectivity:
1, 2 – in the upper part of the cloud;
3– zone of maximum reflectivity (on 1–1.5 km the below points 1 and 2);
4 – 200 m above point 3.
5 – 200 m below point 3;
6 and 7 – 1 km forwards and backwards from point 3;
8 and 9 – 1 km to the right and left of point 3;
10 – 400 m below point 3.

The contribution of drops at these points to the total radar reflectivity was evaluated. The results of calculations, starting from the 30th minute of cloud development for 2 hours in the quasi–stationary state are presented in table 1, which shows that in the zone of increased reflectivity the contribution of drops to the total reflectivity reaches 30% at $\lambda=3.2$ cm and 3% at $\lambda=10$ cm. Thus, the contribution of droplets at the wavelength cannot be ignored when solving inverse problems.

Table 1. The contribution of droplets to total radar reflectivity.

| № of points | The contribution of droplets to total radar reflectivity, % | Temperature in the cloud, °C | Height in the cloud, m |
|-------------|----------------------------------------------------------|-----------------------------|------------------------|
|             | $\lambda=3.2$ cm | $\lambda=10$ cm            |                         |
| 1           | 0.4            | 0.2                        | -13\textpm20            | 5200–5400              |
| 2           | 0.8            | 0.4                        | -13\textpm20            | 5200–5400              |
| 3           | 13.0           | 0.6                        | -6\textpm12             | 3600–4400              |
| 4           | 26.6           | 1.9                        | -7\textpm13             | 3800–4600              |
| 5           | 7.7            | 0.3                        | -5\textpm10             | 3400–4000              |
| 6           | 17.7           | 1.1                        | -6\textpm11             | 3600–4400              |
| 7           | 16.1           | 0.8                        | -7\textpm10             | 3600–4400              |
| 8           | 13.2           | 1.5                        | -6\textpm13             | 3600–4400              |
| 9           | 21.7           | 3.0                        | -6\textpm12             | 3600–4400              |
| 10          | 6.6            | 0.3                        | -5\textpm9              | 3200–4000              |
4. Conclusion
When solving inverse radar problems in the zone of high reflectivity at the wavelength $\lambda=3.2\ cm$, it is necessary to take into account the contribution of drops to the total reflectivity. At the wavelength $\lambda=10\ cm$, the contribution of raindrops can be ignored. The contribution of the small-drop fraction of rain (cloud drops) and crystals at both wavelengths can be ignored.

In the upper part of the cloud (crystalline), the contribution of droplets can be ignored at both wavelengths.

The results obtained are in agreement with the data obtained from modeling by a group of GGO researchers [5], and with data from studies of the characteristics of scattering and attenuation of radio waves in hail clouds [1].

References
[1] Abshaev M T, Kuliiev D D 1989 Proceedings of the High–Mountain Geophysical Institute. Hydrometeoizdat Scattering and attenuation of radio waves in hail clouds and precipitation with mixed microstructure 72 pp 76–81
[2] Ashabokov B A, Sosayeva L T 2010 News of higher educational institutions. North Caucasus region. Series: Natural Sciences The inverse problem of radar for single–phase clouds №3(157) pp 37–39
[3] Ashabokov B A, Fedchenko L M, Tapaskhanov V O, Shapovalov A V, Shapovalov V A, Makuashev M K, Kagermazov A H, Sosayeva L T, Tashilova A A, Kesheva L A 2013 Nalchik: Printing house Hail physics of clouds and active influences on them: the state and directions of development p 216
[4] Ashabokov B A, Fedchenko L M, Shapovalov A V, Shapovalov V A 2017 Nalchik: Printing house Physics of clouds and active influences on them p 240
[5] Veremey N E, Dovgalyuk Yu A, Savchenko I A, Sinkevich A A, Stepanenko V D 1999 Bulletin of the Russian Academy of Sciences. Division of atmospheric and ocean physics Investigation of the possibility of radar detection of clouds formed in the atmosphere during accidents at nuclear power plants № 4 Vol 35 pp 523–530
[6] Sosayeva L T, Kagermazov A H 2018 In the collection: "Actual problems of applied mathematics", Materials of the IV International scientific conference Nalchik: Editorial Board of Elbrus magazine Investigation of the possibility of applying the regularization method of A. N. Tikhonov to the restoration of microstructural characteristics of hail clouds p 326