Dual-wavelength radar studies of hail clouds

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Abstract. The report deals with the study of hail clouds using the MRL-5 meteorological radar. The determination of the microphysical parameters of hail clouds is carried out using the dual-wavelength radar method for $\lambda = 3.2$ and $10$ cm.

It is known that the radar reflectivity of precipitation depends on many factors, but the results of calculations and their comparison with experimental data showed that the radar reflectivity of a population of hail particle is mainly determined by their cubic mean size ($d_3^3$) and concentration ($N$). For the case of two wavelengths, there is a system of equations that relate the radar reflectivity to the cubic mean size and the concentration of hail in the cloud (when parameterizing the remaining characteristics). In other words, for each thermodynamic regime of hail growth and melting, there will be a different set of coefficients of the system of equations. The report calculates the microstructure parameters for a real hail cloud.

1. Introduction

The progress in studying the microstructural characteristics of hail in clouds is directly related to the use of radar.

The dual-wavelength radar method allows not only to indicate hail in clouds and localize areas of hail growth and hail precipitation, but also to obtain some quantitative parameters of the microphysical characteristics of hail [1-5].

The dual wavelength hail detection method is based on the differences in the frequency dependence of the scattering of radar waves by hydrometeors of various sizes. Since the diameter of raindrops cannot exceed 0.6-0.7 cm, cumulonimbus clouds or their local volumes containing particles with a maximum diameter of more than 0.7 cm are considered hail-bearing. The optimal wavelengths for dual wavelength hail detection are $\lambda_1 = 3.2$ and $\lambda_2 = 10$ cm [1, 2, 5].

The interpreting the results of measurements of radar reflectivity at two wavelengths is associated with some difficulties. These difficulties are due, first of all, to the complexity of taking into account a large number of parameters affecting the scattering and absorbing properties of the cloud medium. Therefore, an unambiguous solution of the inverse problem of radiolocation by the two-wavelength method can be carried out only with the use of some a priori information.

2. Research methods

The rationale for using the dual-wavelength radar method to determine the parameters of the microstructure of hail precipitation was given in [1-6, 9-16] under the assumption that the scattering particles are spherical, and the scattering is single and incoherent. With this, it is assumed that the hail particles size distribution obeys the gamma distribution [8].
\[ n(r) = N \frac{b^{\mu+1}}{\Gamma(\mu+1)} \frac{d^\mu}{\bar{d}_3^{\mu+1}} e^{-\frac{d}{\bar{d}_3}}, \]  

(1)

where \( b = \sqrt{(\mu+1)(\mu+2)(\mu+3)} \); \( \mu \) – distribution curve shape parameter; \( \bar{d}_3 \) – hailstone cubic mean size.

The principles of the two-wavelength method were developed in works [1, 2, 6, 7], assuming the radio wave scattering by watered hailstones to be equivalent to the scattering by equal-sized spheres of water. However, a detailed study of the scattering properties of hail [6-7, 9-12] made it possible to deduce the calculated relationships of the two-wavelength method with a more realistic consideration of the scattering characteristics. In particular, the thickness of the surface water film on hailstones growing in the wet mode and in the melting mode, equal to a constant (0.05 cm), was considered.

Under these assumptions, the radar reflectivity \( \eta_2 \) of a system of hailstones is determined only by their size and concentration. For two wavelengths, in the general case, there is a system of two equations:

\[ \eta_{A1} = A_1 N \bar{d}_3^{a_1} \]
\[ \eta_{A2} = A_2 N \bar{d}_3^{a_2}. \]

(2)

From (2) it follows that the ratio of radar reflectivity at two wavelengths is a single-valued function of the size of scattering particles:

\[ \frac{\eta_{A1}}{\eta_{A2}} = \frac{A_1}{A_2} d_3^{a_1-a_2}. \]

(3)

For a water film with \( h = 0.05 \) cm the equation (2) can be represented as [5]:

\[ \eta_{A0} = 3.8 \cdot 10^{-8} N \cdot d_3^{5.4} \]
\[ \eta_{A3} = 6.7 \cdot 10^{-7} N \cdot d_3^{2.1}. \]

(4)

From equations (3) and (4) it is possible to obtain the cubic mean diameter:

\[ \bar{d}_3 = 2.39 \cdot \left( \frac{\eta_{A3}}{\eta_{A0}} \right)^{-0.303}. \]

(5)

A hail concentration in the spectrum can be obtained from (4) and (5):

\[ N = 2.4 \cdot 10^5 \eta_{A3}^{1.636} \eta_{A0}^{-0.636}. \]

(6)

The kinetic energy flux from [10]:

\[ \dot{E} = 1.53 \cdot 10^7 \eta_{A3}^{0.27} \eta_{A0}^{0.73}. \]

(7)

The cloud ice content we obtain from its determination \( W = \frac{1}{6} \pi \cdot \rho \cdot \bar{d}_3^3 \) and the equation (5):

\[ W = 5.72 \cdot \left( \frac{\eta_{A3}}{\eta_{A0}} \right)^{-0.909}. \]

(8)

The figure 1 shows graphs of changes in the reflectivities \( \eta_{A0} \) and \( \eta_{A3} \) and the attenuation coefficients \( k_{A0} \) and \( k_{A3} \) on changing the cubic mean diameter. The graphs were obtained for the hail with water film of thickness \( h=0.05 \) cm.
Figure 1. Graphs of changes in radar parameters on changing the cubic mean size of hail:

a) reflectivities \( \eta_{\text{10}} \) and \( \eta_{\text{3,2}} \); b) attenuation coefficients \( k_{\text{10}} \) and \( k_{\text{3,2}} \).

With a view to take into account the radar signal attenuation in hail, the relationship between the attenuation coefficient \( k_{\text{3,2}} \) and the reflectivity \( \eta_{\text{10}} \) is often used in the following form:

\[
k_{\text{3,2}} = A \cdot \eta_{\text{10}}^\alpha,
\]

where \( A \) and \( \alpha \) are some coefficients.

In practice, the coefficients in the relationship (9) can be obtained from experiment. So, the indicated coefficients obtained for various environments (hail, rain and rain-hail mixture) are analyzed in the work [17], with shows that \( A \) can vary within wide limits, and the coefficient \( \alpha \) varies within: 0.6-0.85 in rain, 0.5-0.7 in hail and 0.5-0.85 in a mixture of rain and hail. The most typical value of the coefficient \( \alpha \) is 0.63. The value \( \alpha = 0.65 \), obtained in the experimental work [18], is in good agreement with the data [17].

3. Research results

To study the relationship (9), we performed a numerical simulation of radar characteristics of hail using the Mie’s diffraction formulas. In this case, the calculations were carried out for hailstones, the sizes of which are described by the gamma distribution. The cubic mean diameter of hailstones varied within \( d_3 = 0.6 \pm 2.4 \text{ cm} \), the concentration \( N \) was from 0.1 to 10 \( \text{m}^{-3} \). The calculations were carried out for three different water film thicknesses on hailstones: \( h_{\text{film}} = 0.01; 0.05 \) and 0.10 \text{ cm}. Due to studies carried out, the following results were obtained: the value of the attenuation coefficient of an ensemble of watered hail particles \( k_{\text{3,2}} \) depends not only on reflectivity \( \eta_{\text{10}} \), but also on other hail parameters. In particular, it depends on the water film thickness on hailstones and the concentration of hailstones themselves. In this case, the obtained law of variation of the attenuation coefficient \( k_{\text{3,2}} \) will have the form (9) and the coefficients \( A \) and \( \alpha \) will have the values presented in the table 1.

| \( h_{\text{film}}, \text{ cm} \) | \( A \) | \( \alpha \) |
|----------------|-------|-----|
| 0,10           | \( 0.35\cdot 10^3 \cdot N^{0.61} \) | 0,39 |
| 0,05           | \( 1.06\cdot 10^3 \cdot N^{0.55} \) | 0,45 |
| 0,01           | \( 6.57\cdot 10^4 \cdot N^{0.34} \) | 0,66 |
Thus, as a result of model studies, the limits of variation of the coefficients $A$ and $\alpha$ in the formula (9) in relation to the water film thickness on hailstones were determined.

The above dual wavelength method of determination of the hail microstructure is based on the hail cloud model, in which all hailstones are covered with a water film of 0.05 cm thick. This model somewhat idealizes the reality. Firstly, it is unlikely that all hailstones in the spectrum have the same water film thickness, and secondly, it is necessary to distinguish between scattering and attenuation of radar radiation on particles growing in the cloud and particles constituting precipitation. These two hail localization areas differ significantly in the conditions for the formation of a surface film on hailstones [12].

The precipitating hailstones begin to melt in the warm part of the atmosphere and become covered with a growing film of melt water, which, under certain conditions, can detach from their surface, forming raindrops.

The common situation in the area of hail growth (area of negative temperatures) consist in that only part of the hailstones of the spectrum grow in a wet mode under a film of water, while the other part remains dry during the growth process. The relationship between the number of hailstones growing in different modes, as well as the thickness of the water film, will be determined by the temperature and water content of the cloud.

The presented dual wavelength method of determination of the hail microstructure with accurate calibration of both channels and attenuation correction at $\lambda = 3.2$ cm ensures an increase in the accuracy of measuring the hail microstructure in comparison with the single-wavelength method.

The dual wavelength method can be easily implemented in automated radar measurements of the microstructure of hail. It was used in the Antigrad automated radar system and in the MeteoX system to determine the microstructure of hail along the radar beam.

With that, the horizontal and vertical cuts of the field of microstructure parameters are usually displayed on the computer screen. The figure 2 shows the algorithm of the automated dual wavelength method for determining the parameters of the hail microstructure obtained along the observation beam.

Let us give an example of the analysis of the microstructure of hailstones in the severe hailstorm developed over the central part of the North Caucasus on 7 June 2012 [19].

**Figure 2.** Algorithm for automated radar measurements of the hail microstructure along the beam.
Continuous and long hours radar studies of the hailstorm on 7 June 2012 were carried out at the field research site «Kyzburun-1» using a dual-wavelength ($\lambda_1 = 3.2$ cm, $\lambda_2 = 10$ cm) meteorological radar MRL-5, equipped with an automated computer system «MeteoX» for collecting, processing and analyzing radar information. The figure 3 shows the radio echo of hail cells giving hail on 7 June 2012 at 16:44.

![Radio echo of hail cells located to the northwest of Nalchik.](image)

The main microphysical characteristics of hail in the cloud, calculated by the dual wavelength radar method, are presented in the table 2. As can be seen from the table, the maximum cloud parameters were observed at 16:44. At that time, the cell was located to the west of Nalchik. It was there that the largest hailstones fell and the maximum damage was recorded.

The hailstones that fell approximately from 16:40 to 17:00 are shown in figure 4. Only hailstones of the maximum size were included in the sample. As can be seen from the figure, the maximum size of hailstones corresponds to 4.5 – 5 cm, in good agreement with the dates of table 2 at 16:44. The radar echo position of the cell at this moment also corresponds to the place of finding the collected hailstones.

| Hour | Maximum size of hail, cm | Concentration, m$^3$ | Kinetic energy flux, J/(m$^2$s) | Ice content, g/m$^3$ | Attenuation coefficient, dB/km | Hail core volume, km$^3$ |
|------|--------------------------|----------------------|-------------------------------|---------------------|-------------------------------|------------------------|
| 15$^{54}$ | 1.6 | 2.50 | 0.79 | 0.45 | 0.61 | 6 |
| 16$^{08}$ | 2.7 | 0.35 | 1.17 | 0.30 | 0.30 | 70 |
| 16$^{36}$ | 3 | 0.33 | 1.77 | 0.39 | 0.37 | 359 |
| 16$^{44}$ | 5.3 | 0.10 | 6.94 | 0.65 | 0.44 | 884 |
| 17$^{00}$ | 2.5 | 0.65 | 1.53 | 0.44 | 0.47 | 703 |
| 17$^{20}$ | 3.5 | 0.25 | 2.68 | 0.47 | 0.41 | 421 |
| 17$^{45}$ | 2.1 | 1.53 | 1.65 | 0.62 | 0.72 | 224 |
| 18$^{15}$ | 1.8 | 2.17 | 1.17 | 0.55 | 0.70 | 66 |
| 18$^{36}$ | 1.5 | 3.09 | 0.73 | 0.45 | 0.64 | 8 |

*Figure 3. Radio echo of hail cells located to the northwest of Nalchik.*

*Table 2. Microphysical characteristics of hail in the cloud (hail core) for the cell 2.*
Figure 4. Hailstones of the maximum size that fell to the southwest of Nalchik from 16:40 to 17:00.

The comparison of radar and ground data shows a good agreement.

4. Conclusions

The principles of using the two-wavelength radar method for measuring the microstructure of hail growing in a cloud are considered. The method is based on the hail cloud model, in which all hailstones are covered with the same film of water of 0.05 cm thick. Despite its drawbacks, the dual wavelength method of determination of the hail microstructure with accurate calibration of both channels and inputting the attenuation correction at \( \lambda = 3.2 \text{ cm} \) ensures an increase in the accuracy of measuring the hail microstructure in comparison with the single-wavelength method.

Using the automated radar measurements of the hail microstructure, the dual-wavelength method can be easily implemented to determine the hail microstructure along the radar beam. It was used in the Antigrad automated radar system and in the MeteoX research system incorporated into the radar MRL-5, placed in the field research site of the High-Mountain Geophysical Institute.

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