RELATION BETWEEN RADIO-ECHO FLUCTUATIONS AND THE MICROSTRUCTURE OF PRECIPITATION

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Abstract

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Existing radar methods for investigating the microstructure of precipitation are based on measuring the mean value of the radar reflectivity of a meteorological object. However, much more information is contained in the spectrum of fluctuations of the reflected signal, which is rigidly connected with the relative velocities of the scattering particles.

In the gravitational fall of precipitation particles, their sizes and velocities are uniquely related to one another. In this case the fluctuation spectrum of the magnitude of the reflected signal at the output of a square-law detector has the form

$$P(\Delta F) = \frac{\bar{A}^2}{\pi} \int_0^\infty p_i^*(v)\, p\left(v + \frac{\lambda}{2}\Delta F\right) dv,$$

$$p(v) = \frac{[\varphi(v)]^6}{|\varphi(v)|^6}\, w(v), \qquad \Delta F = \frac{2\Delta v}{\lambda}, \tag{1}$$

where $\bar{A}$ is the mean power reflected from the aggregate of scatterers; v is the projection of the velocities of the scatterers onto the direction of the radar beam; $w(v)$ is the distribution of the projections of the gravitational velocities; $\varphi(v) = r$ is the fall law of the scattering particle; λ is the station wavelength; Δv is the difference of the velocity projections.

If the fall law of drops and their size distribution are known, then, by computing the radio-echo fluctuation spectrum (1) and determining the root-mean-square deviation of the scatterer velocity, one can pass to their mean size.

Of greatest interest is the determination of the fluctuation spectrum of the signal from an aggregate of falling raindrops of radius 700—4000 μ, whose size distribution has been measured repeatedly ([1]):

$$f(r)\, dr \sim e^{-\beta_1 r}\, dr, \qquad \beta_1 = \frac{n}{\bar{r}}, \tag{2}$$

Fig. 1

Figure 1: Fig. 1

where $\bar{r}$ is the mean drop radius.

On the basis of ([2]) it is not difficult to show that the velocities and sizes of the particles are related by

$$r = \varphi(v) = \frac{v^2}{\alpha_1^2},$$

where α_1 is a numerical coefficient. Then the fluctuation spectrum is written in the form

$$P(\Delta F) \simeq \int_0^\infty v^{13} e^{-kv^2} \left(v + \frac{\lambda}{2}\Delta F\right)^{13} e^{-k\left(v+\frac{\lambda}{2}\Delta F\right)^2}\, dv,$$

where $k = \beta_1/\alpha_1^2$.

Figure 1 presents a parametric family of curves $P(\Delta F)$ for two values of the parameter k_2, and Fig. 2—the curve $k_2(\Delta F)$ for determining the coefficient k from the width of the fluctuation spectrum ΔF. Thus, from the experimentally measured value of the spectrum ΔF, one can determine β_1 and obtain the mean drop size $\overline{r}_c$.

A similar treatment can be carried out for precipitation of low intensity, including drops of the order of several hundred microns. For such particles there is as yet no information on their size distribution. If it is assumed that the distribution has the form

$$f(r)\, dr \sim r^2 e^{-\beta_2 r}\, dr, \tag{3}$$

where β_2 is a certain constant coefficient, and if one takes into account that the law of fall of particles of this size has the form (2)

$$r = \varphi(v) = \frac{v}{\alpha_2},$$

then the fluctuation spectrum of the radio echo is written as

$$P(\Delta F) \cong \int_0^\infty v^8 e^{-kv} \left(v + \frac{\lambda}{2}\Delta F\right)^8 e^{-k\left(v+\frac{\lambda}{2}\Delta F\right)}\, dv,$$

where $k = \beta_2/\alpha_2$.

Fig. 2

Figure 2: Fig. 2

Fig. 1. Family of curves $P(\Delta F)$. Solid lines—for $v = \alpha_2 r$; dashed lines—for $v = \alpha_1 r$.
1—$k_1 = 6.66 \cdot 10^{-2}$; 2—$k_1 = 2.22 \cdot 10^{-2}$; 3—$k_2 = 3.6 \cdot 10^{-5}$; 4—$k_2 = 1.54 \cdot 10^{-5}$.

Fig. 1 depicts a parametric family $P(\Delta F)$ for two values of the parameter k_1, and Fig. 2 gives the curve $k_1(\Delta F)$ for determining the coefficient k from the width of the fluctuation spectrum. As is seen from Fig. 2, one and the same spectrum width corresponds to two values of the parameter k; therefore, in determining the mean drop size, the radar reflectivity of the precipitation should be measured simultaneously with the spectrum.

Fig. 2. Dependence of the parameter k on the spectrum width.
1—for the case $v = \alpha_2 r$;
2—for the case $v = \alpha_1$.

Let us show how the radar reflectivity Z is related to the mean size of the scattering drop. Since the sizes of the drops are much smaller than the wavelength, the quantity Z, characterizing the radar reflectivity of rain,

$$Z \cong \int_0^\infty r^6 f(r)\, dr = \frac{\Gamma(9) N_0}{\Gamma(3)\beta^6},$$

if $f(r)dr \sim r^2 e^{-\beta r} dr$ and N_0 is the number of drops per unit volume. The power of the radar signal is directly proportional to the quantity Z. Therefore, for known station parameters it is not difficult to determine the value of Z, and consequently also the mean drop size $\bar{r}_p$, since $\beta = n/\bar{r}_p$.

If the particles are indeed distributed according to law (3), then the mean particle sizes determined from the width of the fluctuation spectrum and from the value of the radar reflectivity Z should coincide.

Such a comparison is apparently the only way of objectively assessing the correctness of the theoretical assumptions underlying the measurement method.

The principle of determining the spectrum of scatterer velocities by the radar method is as follows: the received radio-echo signal is picked up by the antenna, amplified by the receiver and detected, and then fed to an additional selector unit, which converts it into a form convenient for spectral analysis. The selector passes to the analyzer a signal arriving only from a specified range interval. The selector output signal, supplied for spectral analysis, is a sequence of pulses of equal duration, following one another with the repetition frequency of the radar transmissions. The enveloping sequence of pulses is determined by the relative motion of the particles in the object under study. The analyzer automatically performs a spectral analysis of the received signal.

Fig. 3. Block diagram of the installation

Figure 3: Fig. 3. Block diagram of the installation

Fig. 4. Comparison of r_c and r_p

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Fig. 3. Block diagram of the installation

Simultaneously with the fluctuation spectrum, the value of the radar reflectivity is measured.

Fig. 4 gives experimental results obtained from measurements in 12 rainfalls during the summer of 1960. $\bar{r}_p$ is the radar value, equal to 8/3 of the mean radius calculated from the value of the radar reflectivity Z; $\bar{r}_c$ is the spectral value, equal to 8/3 of the mean radius calculated from the fluctuation spectrum of the radio echo. It is seen from the graph that the data agree satisfactorily up to values $\bar{r}_p = 600\,\mu$. In determining $\bar{r}_p$, the mean number of drops per unit volume N_0 is specified, which does not remain constant for rains of different intensity. According to our data, the variations of N_0 should amount to 480 ± 300, so that all experimental points would fall on the straight line $\bar{r}_c = \bar{r}_p$. Such a scatter ΔN does not exceed the experimentally measured deviations of N in rains of different intensity.

Fig. 4. Comparison of $\bar{r}_c$ and $\bar{r}_p$

At large values of $\bar{r}_p$, which correspond to precipitation of high intensity, a substantial divergence is sometimes observed between the data obtained by the two methods. This is probably due to the fact that there is a significant deviation of the actual form of the drop-size distribution from that assumed in (2), and the radio-echo signal is formed by a small number of the largest drops.

The formulas by which $\bar{r}_c$ and $\bar{r}_p$ are determined were obtained for the case when the drop-size distribution has the form (3). Direct calculations show that, when the exponent of r is varied from 1 to 6, the errors in determining $\bar{r}_c$ do not exceed 15%, and for $\bar{r}_p$, 50%.

The work carried out has shown that only a combined study of the magnitude and the spectrum of fluctuations can provide complete information on the microstructure of precipitation.

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Note: Figure translations are in progress. See original paper for figures.