A procedure is proposed for ground-based passive-radar measurement of the integral humidity of a cloudy atmosphere and of the integral water content and temperature of the drop phase of the clouds. By measuring the brightness temperature of the atmosphere at two wavelengths \( \lambda_1 \) and \( \lambda_2 \) (\( \lambda_1 \) being chosen such that the brightness temperature of the atmosphere at this wavelength is independent of the height profile of the humidity; it is equal to either 1.44 or 1.26 cm), at which the absorption coefficient \( \kappa \) of the drop phase of the clouds can be regarded as inversely proportional to the square of the wavelength (for the existing cloud temperature, estimated to within \( \pm 10^\circ \) on the basis of the surface temperature of the atmosphere), the integral humidity of the cloudy atmosphere is determined. Then at wavelength \( \lambda_{\text{opt}} \), at which \( \kappa \) is virtually independent of the cloud temperature (to within \( \pm 10^\circ \)), allowing for the resultant value of the integral humidity, the integral water content is determined, and then the temperature of the drop phase on the basis of the optical thickness of the clouds measured earlier at \( \lambda_1 \) and \( \lambda_2 \). Wavelengths \( \lambda_2 \) and \( \lambda_{\text{opt}} \) are specified and the measurement accuracies are evaluated for the integral humidity of the atmosphere, the integral water content, temperature, and height of water clouds for "summer" and "winter" conditions. The possibilities offered by measurements at two wavelengths (either 1.44 cm or 1.26 cm and \( \lambda_{\text{opt}} \)), rather than three, are discussed.

1. Since the coefficient of absorption of ice in the millimeter and centimeter range is \( 10^3 \times 10^4 \) times smaller than that for water (see, e.g., Figs. 2 and 3 in [1]), while the water content of the solid phase of clouds is generally less than that of the liquid phase (see, e.g., Table 1.3.3 of monograph [2]), in the case of clouds of mixed structure passive-radar methods can yield only the integral water content, temperature, and height of the water phase of clouds. The water phase can exist down to temperatures of \(-41^\circ \)C [3].

Determination of the integral water vapor content of the atmosphere and of the integral water content of clouds (i.e., the total mass of the drop phase contained in a vertical column of the atmosphere with a base of 1 m\(^2\)) on the basis of concurrent measurements of the brightness temperature of the cloudy atmosphere at two wavelengths \( \lambda \approx 1.35 \) cm and \( \lambda = 0.8 \) cm (the latter being chosen on the basis of the fact that the contribution of water vapor and molecular oxygen to the brightness temperature at this wavelength is minimal as compared to the cloud contribution) runs into the difficulty that the absorption coefficient of water drops at 0.8 cm is strongly dependent on the temperature.

Paper [4] proposes a procedure for concurrent measurement of three quantities, viz., the integral humidity of the atmosphere, the integral water content of the clouds, and the cloud temperature, on the basis of the brightness temperatures of the cloudy atmosphere at three frequencies: \( \nu_1 = 21.5-23 \) GHz (\( \lambda_1 = 1.40-1.30 \) cm), \( \nu_2 = 32-45 \) GHz (\( \lambda_2 = 0.94-0.67 \) cm), and \( \nu_3 = 75-110 \) GHz (\( \lambda_3 = 0.40-0.27 \) cm).

In this study we will draw heavily on the fact that, for a cloud temperature lying in an "indeterminacy interval" of \( \pm 10^\circ \), there exists a wavelength \( \lambda_{\text{opt}} \) for which the absorption coefficient \( \kappa \) of the cloud is virtually independent of temperature within this \( \pm 10^\circ \) interval. The \( \pm 10^\circ \) indeterminacy interval of the cloud temperature can be established from the surface temperature of the atmosphere and, roughly speaking, corresponds to summer and winter conditions for the Central European Zone.

Unlike [4], in this paper we propose to determine the integral humidity of the summer cloudy atmosphere on the basis of measurements of the brightness temperature at two wavelengths \( \lambda = 1.44 \) cm (or \( \lambda = 1.26 \) cm) and...
\( \lambda \approx 0.8 \text{ cm} \), after which the integral water content of the clouds can be determined from measurement of the brightness temperature at a third wavelength, \( \lambda_{\text{opt}} = 0.27-0.37 \text{ cm} \) (the optimum wavelength in this range is selected on the basis of the indeterminacy interval of the cloud temperature, as specified by the surface temperature of the atmosphere; note that the 0.25- and 0.5-cm absorption lines of oxygen are not any major hindrance to measurements in this range). Using the resultant value of the integral water content of the clouds, it turns out to be possible to determine the cloud temperature from the brightness temperatures measured at 1.44 and 0.8 cm.

If the surface temperature of the atmosphere is, say, \(-25^\circ \text{C} \), and correspondingly the indeterminacy interval of the cloud temperature is taken to be \(-20 \text{ to } -40^\circ \text{C} \) (winter conditions), the integral humidity of the atmosphere can be determined by concurrent measurements at the two wavelengths, 1.44 and 1.26 cm, after which the integral water content of the clouds can be determined from measurements of the brightness temperature at one of the wavelengths \( \lambda_{\text{opt}} = 0.4 \text{ cm} \), \( \lambda_{\text{opt}} = 0.6-0.8 \text{ cm} \) (the interval \( \lambda = 0.4-0.6 \text{ cm} \) is eliminated because of strong absorption by molecular oxygen). Using the resultant value of the integral water content of the cloud, we can determine the cloud temperature from the brightness temperature of the atmosphere at 1.44 cm.

In this way it is possible to "separate the variables," so to speak. This separate use of two and one wavelengths makes it possible to enhance the measurement accuracy as compared with the procedure used in [4]. In particular, the results of this study can readily yield the optimum wavelength \( \lambda_{\text{opt}} \) in the ranges 0.28-0.40 cm, 0.6-0.8 cm, given by the indeterminacy interval of the cloud temperature (established from the surface value). We also feel that the allowance for possible errors in determining the integral water content, temperature, and height of the clouds is more careful in this study.

2. In accordance with [5], the complex absorption coefficient \( \tilde{m} \) for water drops for the case in which the wavelength \( \lambda \) is much greater than the drop radius \( r \), \( 2\pi r / \lambda \ll 1 \) (this condition is observed over the entire range of wavelengths \( \lambda \geq 0.3 \text{ cm} \) of interest to us, since the drop size usually does not exceed 30 \( \mu \); see, e.g., \([2]\)) is

\[
\tilde{m} = 1 - i S(0) \frac{2\pi N k^{-3}}{\lambda},
\]

where \( N \) is the number of drops per cubic centimeter, \( k = 2\pi / \lambda \text{ cm}^{-1} \), \( S(0) = \frac{1}{\lambda} k^3 \alpha \), \( \alpha = \frac{(\varepsilon_{\text{C}} - 1) / (\varepsilon_{\text{C}} + 2)}{r^3} \) is the polarizability coefficient of a water drop with complex permittivity \( \varepsilon_{\text{C}} \).

The imaginary part of \( \tilde{m} \), equal to \( n_2 = 2\pi N k^{-3} \text{ Re} S(0) \), determines the absorption coefficient \( \kappa \) of the medium:

\[
\kappa = \frac{2\pi}{\lambda} n_2 = \frac{4\pi}{\lambda} 2\pi N k \text{ Re} S(0) = \frac{6\pi}{\lambda} \text{Im} \left[ \frac{(\varepsilon_{\text{C}} - 1)}{(\varepsilon_{\text{C}} + 2)} \right] w \frac{\text{Neper}}{\text{cm}}, \tag{1}
\]

where the water content of the clouds \( w = (4\pi / 3) r^3 N \) is expressed in grams per cubic centimeter; \( \text{Im} \left[ (\varepsilon_{\text{C}} - 1) / (\varepsilon_{\text{C}} + 2) \right] \) is the imaginary part of \( (\varepsilon_{\text{C}} - 1) / (\varepsilon_{\text{C}} + 2) \).

Using the Debye expression for the permittivity of water,

\[
\varepsilon_{\text{r}} = \varepsilon_{\text{e}} - i \varepsilon_{\text{i}} = \frac{\varepsilon_0 - \varepsilon_{\text{w}}}{{1 + (\Delta \lambda/\lambda)} + \varepsilon_{\text{w}},} \tag{2}
\]

where \( \varepsilon_0 \) is the static value of \( \varepsilon_{\text{C}} \) at \( \omega = 0 \), \( \varepsilon_{\text{w}} \) is the optical value of \( \varepsilon_{\text{C}} \), \( \Delta \lambda = 2\pi[\varepsilon_0 / (\varepsilon_0 + 2) + (\varepsilon_\infty / (\varepsilon_\infty + 2))] \) (\( \tau_\Gamma \) is the Debye relaxation time), we readily obtain from (1) and (2) that

\[
\kappa = \frac{6\pi \Delta \lambda}{\lambda^2} \left[ \frac{\varepsilon_0 + 2\varepsilon_{\text{w}}}{(\varepsilon_0 + 2\varepsilon_{\text{w}})^2} + (\Delta \lambda/\lambda)^2 \right] \frac{\text{Neper}}{\text{cm}}. \tag{3}
\]

Figures 1 and 2 show \( \kappa / w \) [Neper/(g/m² km)], computed from (3), as a function of \( \lambda \) (cm) and the droplet temperature \( t \) (°C). In accordance with [6, 7], we took \( \varepsilon_0 = 88.2 - 0.44^\circ \), \( \varepsilon_\infty = 5.5 \), \( \tau_\Gamma = \exp[7.6(273 / T - 0.95)] \cdot 10^{-12} \text{ sec} \) (in a later study \([13]\), the authors give the multiplier 10 instead of 7.6). Calculations employing Eqs. (4.23) and (4.24) of monograph \([8]\) were also made; they yielded virtually indistinguishable results. The water parameters obtained in \([6]\) for the centimeter range and the applicability of the Debye formula remain valid all the way to \( \lambda = 0.1 \text{ cm} \), as became evident from subsequent studies (see the summary in \([9]\) and also \([1]\)).

It can be seen from Fig. 1 that, e.g., for a cloud temperature \( t_{\text{cl}} > -20^\circ \text{C} \) at a wavelength 0.8 cm, at \( \pm 10^\circ \text{ indeterminacy in cloud temperature lead to a } \pm 25\% \text{ indeterminacy in } \kappa \text{ values, and, correspondingly, to a } \pm 25\% \text{ accuracy in determining the integral water content of the clouds on the basis of the brightness temperature of the atmosphere. The use of additional wavelengths in the } \lambda > 0.7 \text{ cm range does not yield any additional information, since in this range Eq. (3) for } t_{\text{cl}} > -20^\circ \text{C assumes the form } \kappa / w = (\Delta \lambda/\lambda) C = f(T) / \lambda^2 C, \]

787