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Abstract

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ON THE POSSIBILITY OF DETERMINING THE CHARACTERISTICS OF THE SURFACE LAYER OF SOIL FROM ITS THERMAL RADIO EMISSION

Apparently, the most promising method for remote determination of the characteristics of the surface layers of soil, ice cover, or water basins consists in using, for this purpose, measurements of the microwave radiation of the corresponding media. Below we consider such a method, suitable for determining soil characteristics.

In the microwave range, the expression for the radio-brightness temperature of the thermal radiation of a homogeneous semi-infinite medium in the normal direction has the form

$$T' = \int_0^\infty \alpha(z)\, T(z) \exp\left[-\int_0^z \alpha(z')\, dz'\right] dz,$$

where α is the absorption coefficient; $T(z)$ is the distribution of temperature in the soil as a function of depth z, measured in the direction of radiation propagation.

The radio-brightness temperature measured at the level of the earth' s surface is related to the radiation temperature of the medium T' by the following relation (if the contribution of radiation reflected by the atmosphere, insignificant in the spectral range under consideration, is neglected):

$$T = T'(1 - R^2),$$

where R is the Fresnel reflection coefficient of the earth' s surface, equal, for normal incidence, to

$$R = (\sqrt{\varepsilon} - 1)/(\sqrt{\varepsilon} + 1)$$

(ε is the dielectric permittivity of the soil).

The dielectric permittivity of soil in the centimeter- and decimeter-wave range varies only slightly with wavelength and increases linearly with increasing moisture content ([1,4]). Therefore the dependence of R on wavelength may be disregarded in measurements at several close wavelengths in the microwave range. The absorption coefficient of soil increases with increasing moisture content approximately linearly and increases with increasing frequency, in the first approximation according to an exponential law ([2]). The strong dependence of the absorption coefficient on moisture content determines the dependence of the radio-brightness temperature of soil radiation on meteorological conditions.

Let us now write the formula for the radio-brightness temperature in the form

$$T = [1 - R(w)^2] \int_0^\infty \alpha(z, w)\, T(z) \exp\left[-\int_0^z \alpha(z', w)\, dz'\right] dz, \tag{1}$$

where w is the soil moisture content (generally speaking, dependent on depth).

Analysis of the data on the temperature regime of soil, presented in [3], showed that the temperature profiles are well approximated by the relation

$$T(z) = \{[T'(0) + \gamma(T_0 - T_2)]z + T_0 - T_2\}e^{-\gamma z} + T_2, \tag{2}$$

where T_0 is the temperature at $z = 0$; $T'(0)$ is the temperature gradient at the surface; T_2 is the asymptotic value of the temperature as $z \to \infty$; γ is an empirical parameter. According to the data of [3], in summer at any time of day $T = T_2$ already at a depth of about 40 cm.

Generally speaking, approximation of the temperature profile by expression (2) is possible for any profile characterized by a monotonic transition to T_2, or having one maximum or minimum.

As a first approximation, let us consider the case $\alpha = \text{const}$. This case is realized in the range of wavelengths for which the absorption coefficient is sufficiently large that, over the distance of the effective depth of penetration of radiation into the soil ($0 < z < 1/\alpha$), the moisture content, and together with it the absorption coefficient, do not have time to change appreciably (the case of deserts and arid steppes is an example of conditions when allowance for the influence of moisture may in general be insignificant).

Carrying out the integration in (1), taking (2) into account, we obtain

$$T = \left[\frac{T'(0)}{\alpha(1 + \gamma/\alpha)^2} + \frac{\gamma}{\alpha}\frac{T_0 - T_2}{(1 + \gamma/\alpha)^2} + \frac{T_0 - T_2}{1 + \gamma/\alpha} + T_2\right](1 - R^2). \tag{3}$$

We shall now show how, by measuring the brightness temperature at several wavelengths, it is possible to determine the moisture content and the parameters of the temperature profile.

Let us consider the range of wavelengths for which $\gamma/\alpha \ll 1$. In this case equation (3) takes the form

$$T = (1 - R^2)\left[\frac{T'(0)}{\alpha}\left(1 - 2\frac{\gamma}{\alpha}\right) + T_0\right]. \tag{4}$$

Thus, in the range of wavelengths under consideration, the brightness temperature is determined by the values of the temperature and its gradient at the surface, but does not depend on the asymptotic value of the temperature.

Since the reflection coefficient R is a complicated function of moisture content, in order to determine it, and also to find the three other unknown quantities w, γ, and $T'(0)$ (T_0 may be regarded as given), it is necessary to have data from measurements of the brightness temperature at four close wavelengths whose absorption coefficients satisfy the inequality $\gamma/\alpha \ll 1$. Let us consider the system of four equations:

$$T_i = [1 - R^2(w)]\left[\left(1 - 2\frac{\gamma}{\alpha_i(w)}\right)\frac{T'(0)}{\alpha_i(w)} + T_0\right], \quad i = 1, 2, 3, 4. \tag{5}$$

One of the possible methods for solving this system of equations, which is non-linear with respect to the sought quantities, is as follows.

Let us form expressions for the three quantities

$$\frac{T_1 - T_k}{T_k} = \frac{T'(0)}{T_0}\left[\left(1 - 2\frac{\gamma}{\alpha_1}\right)\frac{1}{\alpha_1} - \left(1 - 2\frac{\gamma}{\alpha_k}\right)\frac{1}{\alpha_k}\right], \quad k = 2, 3, 4. \tag{6}$$

Eliminating $T'(0)$ from them, we obtain the equalities:

$$\begin{aligned} 2\gamma\left(\frac{1}{\alpha_2} - \frac{1}{\alpha_3}\right) &= 1 - \frac{(T_1 - T_2)}{(T_1 - T_3)}\frac{T_3}{T_2}\frac{(\alpha_3 - \alpha_1)\alpha_2}{(\alpha_2 - \alpha_1)\alpha_3}, \\ 2\gamma\left(\frac{1}{\alpha_2} - \frac{1}{\alpha_4}\right) &= 1 - \frac{(T_1 - T_2)}{(T_1 - T_4)}\frac{T_4}{T_2}\frac{(\alpha_4 - \alpha_1)\alpha_2}{(\alpha_2 - \alpha_1)\alpha_4}. \end{aligned} \tag{7}$$

Excluding γ, we finally find

$$\begin{aligned} &(a_2 - a_3)(a_1 - a_4)(T_2T_3 + T_1T_4) + (a_2 - a_4)(a_3 - a_1)\times \\ &\times(T_2T_4 + T_1T_3) + (a_3 - a_4)(a_1 - a_2)(T_3T_4 + T_1T_2) = 0. \end{aligned} \tag{8}$$

Substituting the known linear dependences of α_i on moisture, $\alpha_i = \alpha_i(w)$ ([1]), we arrive at a quadratic equation for determining soil moisture. Restoring the values of the absorption coefficients α_i, we compute the parameter of the temperature profile γ from either of the two relations (7). The slope of the curve $T'(0)$ can now be determined from any of the three equations (6). Finally, R is found from equations (5).

Thus, from four measured values of the radio-brightness temperature in the wavelength range for which $\gamma/\alpha \ll 1$, provided that T_0 is specified (the value T_0 can be obtained from measurements in the infrared range) and given the dependence of the absorption coefficients on moisture at these wavelengths, one can in a simple way determine the soil moisture and the temperature gradient at the surface, the surface reflection coefficient, and the exponential factor of the temperature profile. We note that the data required for solving a problem of this kind are currently available only for wavelengths of 60, 10, and 3.3 cm and for two soil types (see ([1])).

The case $\gamma/\alpha \ll 1$ considered above occurs under strong absorption. Estimates based on the data of work ([1]) show that, for moisture exceeding 6%, the inequality $\gamma/\alpha \ll 1$ is satisfied in the wavelength range of about 3 cm. At lower moisture, sounding should be carried out at shorter wavelengths.

The second limiting case, that of long wavelengths, for which $\gamma/\alpha \gg 1$, makes it possible to determine the asymptotic value of the temperature profile T_2 from the equality

$$T = (1 - R^2)\left[T_2 + 2\frac{\alpha}{\gamma}(T_0 - T_2) + \frac{\alpha^2}{\gamma^2}\frac{T'(0)}{\alpha}\right]. \tag{9}$$

This is the case of weak absorption, and, naturally, the main contribution to the radio-brightness temperature is made by layers at temperature T_2.

Under the condition $\alpha = \text{const}$, T_2 is determined from a single measurement of T. The inequality $\gamma/\alpha \gg 1$ is satisfied for wavelengths in the decimeter range. For example, for a wavelength of 60 cm, when moisture changes from 3 to 12%, γ/α changes approximately from 60 to 15.

We note that if the absorption coefficient is so small that the corrections to T_2 in formula (9) can be neglected, i.e.,

$$T = (1 - R^2)T_2, \tag{10}$$

then T does not depend on the absorption coefficient, which is due to the isothermality of the profile at great depths, and expression (10) is valid for an absorption coefficient varying with depth. Thus, in the approximation $\alpha = \text{const}$, the proposed method makes it possible, while avoiding cumbersome calculations, to determine, with the aid of a small number of measurements, the basic characteristics of the state of the surface soil layer: the moisture and the parameters of the temperature profile. Since the data of such measurements refer to wavelengths located in the regions of atmospheric transparency windows, this facilitates the practical solution of the problem of remote sounding from any altitude.

Main Geophysical Observatory
named after A. I. Voeikov
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Note: Figure translations are in progress. See original paper for figures.