Microwave radiometric sensing of soils

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We outline new physical foundations of microwave radiometric method of remote study of soils, and overview the methods of determination of effective temperature, estimation of surface roughness, and treatment of atmospheric effect. The possibilities of the radiometric method for estimation of the hydrophysical soil characteristics are demonstrated.

The microwave methods of remote sensing, (active (radar) and passive (radiometric) methods) have been increasingly used for study of the properties of the underlying surface and for determination of heat and moisture fluxes between the soil surface and the atmosphere. The microwave methods are all-weather tools. In the frequency range 1–10 GHz, the atmosphere is practically transparent for electromagnetic waves; the atmospheric effect should be taken into account only at the highest frequencies of this range. The basis of the radiometric method is the dependence of radio thermal radiation itself of the underlying surface on its dielectric properties.

In the microwave range, we can use with high accuracy the long-wave approximation of Plank formula (the Rayleigh–Jeans law) for the brightness of blackbody radiation $B(f, T)$:

$$B(f,T) = \frac{2f^2}{c^2}kT,$$

where T is the thermodynamic temperature of the body; f is the frequency; k is the Boltzmann constant; and c is the speed of light in vacuum.

Brightness of non-black bodies can be represented as

$$B'(f_0,T) = eB(f_0,T) = B(f_0,T_B),$$

where e is the emissivity (less than unity for all real bodies); and T_B is the brightness temperature. Whence it follows that $T_B = eT$. If the emitting surface is non-isothermal, i.e., its temperature changes with depth, the latter formula remains valid in the following form: $T_B = eT_e$, where T_e is the effective temperature. The emissivity depends on the frequency and polarization of received radiation, as well as on the direction of the beam with respect to the normal to the surface θ (angle of sensing). In accordance with the Kirchhoff's law,

$$e_p = 1 - R_S(\theta, p),$$

where $R_S(\theta, p)$ is the (power) reflection coefficient of the plane wave; and p is the polarization index (V/H for the vertical/horizontal polarization).

The radiation of non-black bodies has, in addition to the self-radiation, the component of reflected radiation which, for the underlying surface, is determined by the sky brightness temperature $T_{B\text{sky}}$:

$$T_{Bp} = \left[1 - R_S(\theta,p)\right]T_e + R_S(\theta,p)T_{B\text{sky}}.$$

The sky brightness temperature is caused by 3 K blackbody relic radiation (CBR), radiation of galaxies, and atmospheric radiation, and is ~4–8 K in the decimeter wavelength range.

The surface properties are determined by the reflection coefficient, and for its determination through the measured brightness temperature, it is important to correctly quantify the effective temperature of the emitting medium. Determination of the effective temperature T_e is especially required in low-frequency studies, when within the emitting layer, making 0.1–0.2 of wavelength, the temperature may change substantially. Simple formula for T_e is presented in Ref. 1:

$$T_e = T_\infty + (T_S - T_\infty)\,C,$$

where T_∞ is the temperature at a depth of 50 cm; T_S is the temperature at a depth of 0–5 cm; and C is the parameter, which depends on the soil wetness and on the frequency. According to Ref. 2

$$C = (W_S/W_0)^b,$$

where W_S is the moisture content in a surface layer of 0–3 cm; W_0 and b are parameters, which depend on soil characteristics. For a frequency of 1.4 GHz, these parameters are determined by comparing the experimental results with calculations: $W_0 = 0.377$ and $b = 0.262$. In this case, the brightness temperature error is about 1.4 K.

However, in remote sensing, it is not always possible to determine the temperature in the layers 0–3 cm and at a depth of 50 cm. More often, it is only possible to determine the soil surface temperature with the help of IR radiometer. When the moisture gradients and the depth of sensing are small (i.e., at high frequencies), we can assume that $T_e = T_S$. However, in many cases this can lead to large errors. For instance, Van de Griend[3] analyzed many-year data, obtained at a frequency of 6.6 GHz with the help of Scanning Multichannel Microwave Radiometer (SMMR) installed on the Nimbus satellite, and found that in 90% of cases the daytime values of the effective temperature are 12.5 K lower than the surface temperature, while the nighttime values are correspondingly 5 K higher. This is associated with the presence of temperature gradients in the surface layer, especially notable during day.

The presence of clouds in the atmosphere makes the satellite IR measurements impossible. For determination of effective temperature in this case, a model of T_e calculation is proposed,[4] that uses data on the air temperature in near-surface layers (for high soil wetness) or values of the brightness temperature at the frequency 10.7 GHz (in the dry period). The error in determination of the effective temperature at the frequencies of the L- and C-bands does not exceed 5 K for smooth soil and increases up to 10 K in the case of the rough surface.

Another problem, arising in remote determination of the properties of the underlying surface, is to correctly account for the roughnesses, leading to increase of the emissivity. There are two approaches to the problem. For the given parameters of the surface roughnesses, the reflectivity can be calculated by integrating the scattering coefficient for bistatic radar sensing over the upper half-space.[4–6] When solving the inverse problems of radiometry, semiempirical models are most frequently used. In one of such models,[1,7] the reflection coefficient at polarization p is written as

$$R_S(\theta, p) = \left[(1 - Q)R_S^*(\theta, p) + QR_S^*(\theta, q)\right]\exp(-h\cos^N \theta),$$

where q is the polarization index, orthogonal with respect to the polarization p; $R_S^*(\theta,\ p \text{ or } q)$ is the Fresnel coefficient of reflection from the smooth surface. The roughness parameters Q, h, and N are selected for better coincidence with results of experiment. Physically, Q describes the energy exchange between orthogonal polarizations (V and H), caused by the surface roughnesses. In measurements at one frequency and two polarizations, it is impossible to select three parameters Q, h, and N and dielectric constant of the soil; therefore, in such measurements, the model is simplified by assuming that $Q = 0$.

Initially,[1] it was proposed to use $N = 2$; however, it was shown[8] that, for the sensing angle variations between 10 and 60° at frequencies of 1.4, 5, and 10.7 GHz, it is better to use $N = 0$.

It was shown[2] that with data in hand on soil moisture content in the near-surface layer, the best results are obtained when h is represented as

$$h = A(W_S)^B(\sigma/l)^C,$$

where σ is the root-mean-square deviation of heights of the surface roughness; and l is the correlation radius. For a frequency of 1.4 GHz, obtained the following values of the constants: $A = 0.5761$, $B = -0.3475$, and $C = 0.4230$. Accounting for the surface roughnesses when measuring with ground-based means, allows one to obtain the error between 2.9 and 6% in the soil moisture content measurement at a depth of 2 cm.

The coefficient of reflection from the smooth surface is calculated by Fresnel formulas, taking into account the dependence of dielectric constant of soils on the soil moisture content. These dependences differ for different soils and are determined primarily by the amount of bound water. The dielectric constant of soils is determined using the mixing models.[9,10] It is found that the dielectric constant of soils depends not only on the granulometric composition, but also on the humus content.[11,12]

A serious problem in the study of the earth surface from space is the low resolution of radiometric systems; however, in the future, this task can be solved both by the methods of aperture synthesizing and through the simultaneous use of radio radar and optical higher-resolution images.

Since the main soil characteristic, determined by remote radiometric method, is the moisture content, all methods of studying the hydrophysical properties of soils are based on long-time multifrequency measurements of the emissivity. By studying the temperature and moisture distribution over the depth, it is possible to determine the water–air regime of soils and, hence, to estimate soil quality from the agronomical viewpoint. The soil salinization leads to decrease of emissivity in the decimeter range, as well as to slowing down of vaporization and to reducing the rate of the emissivity decrease, which can be determined from measurements in the centimeter range.[13,14] The evaporation processes in soils with different humus content also substantially differ. Moreover, the moisture gradients, appearing in the surface layers of soils, and dynamics of emissivity at different frequencies also differ.[15–17] The differences in the hydrophysical characteristics also show themselves in the processes of freezing and melting.[18,19]

Thus, the radiometric sensing of soils makes it possible not only to determine the moisture dynamics in the near-surface layer, but also to estimate the quality of soils used in the agriculture.

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