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THE EFFECT OF FROZEN SOIL LAYER THICKNESS ON THERMAL EMISSION AT THE WAVELENGTHS 3.6–11 CM

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The results of experimental investigation of temporal dynamics of radiobrightness temperature at the wavelengths 3.6, 5, and 11 cm in the course of frost penetration and thawing are presented for the soils with different humus content. Using the method of simulating emission from a horizontally stratified medium, it is shown that radiobrightness temperature variation is related to changes in the frozen soil layer thickness. It is noted that that dielectric permittivity of the frozen layer at the temperatures around 0°C is controlled by non-frozen bound water, whose content depends on the soil type. It is also underlined that in certain cases proper interpretation of the experimental data requires inclusion of the soil moisture motion towards the cold front into consideration.

Frost penetration and thawing processes in the arctic regions of Siberia, Canada and Alaska may last from a week to a month in spring and autumn. Investigation of these processes is of practical interest for climate modeling, since it is these processes that control about a half of the heat balance in theses areas. Given the scarcity of population and difficulty to reach the northern regions, heat and moisture flows can nearly exclusively be studied by remote methods. Microwave approaches (radar and radiometric) are more advantageous over optical techniques due to their deeper probing depths. This makes it possible to monitor the process of depth variation in the frozen surface layer thickness, in particular where several wavelengths are involved in the observations.

During variation in the frozen layer thickness, the radiobrightness temperature undergoes considerable changes due to interference of the waves reflected from the upper and lower boundaries of the layer. Its oscillations are evident in the radiobrightness temperature diagrams of local surface patches [1, 2] and in satellite radiometric [3] and radar [4] images of large areas.

Dielectric permittivity (DP) of the Earth's cover at the temperatures below 0°C is largely controlled by the properties of bound water [2, 5], since free water is converted into ice whose DP ($\varepsilon' = 3.15$) is close to that of dry soil ($\varepsilon' = 2.6$–3.0). The content of bound water depends on the content of physical clay (grain size of particles less than 0.01 mm) and humus [5, 7]. Dielectric properties of bound water in different soils at 0°C, however, have been poorly studied. Some data on variation in dielectric permittivity of a soil with variations in temperature could be obtained from the measurements of brightness and thermodynamic temperatures during frost penetration, and DP of this soil could be reconstructed by solving an inverse problem of remote sensing.

In this work we investigate the dynamics of radiobrightness temperature variation for two soil surfaces differing in their humus content at the wavelengths 3.6, 5, and 11 cm for different moisture values of the surface layer. Table 1 lists the soil composition and content of humus and clay in the experimental sites. Also it tabulates the maximum content of bound water in weight units W'_t. The volumetric content is obtained from the weight relation $W_t = W'_t\rho$, where ρ is the density of a dry soil composition.

The data on moisture and density values in the layers from 0–1 to 2–3 cm as well as the maximum bound water content in volume units are summarized in Table 2. Sampling procedures for moisture and density measurements were performed after each frost penetration/thawing cycle was completed.

The measurements of radiobrightness temperature were carried out during spring frosts, when the frost penetrated a few centimeters down into the soil at night and the soil got completely thawed in the daytime. It should be noted that

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TABLE 1. Characteristics of Investigated Soil Surfaces

No. of soil surface	Content of clay, %	Content of humus, %	W'_t, g/g
2	36.1	6.6	0.17
1	43.9	0.6	0.08

TABLE 2. Moisture, Density and Maximum Bound Water Content of Soil Surfaces by Layer

No. of soil surface	Moisture by layer, cm^3/cm^3			Density by layer, g/cm^3			W_t, cm^3/cm^3		
	0–1 cm	1–2 m	2–3 cm	0–1 cm	1–2 cm	2–3 cm	0–1 cm	1–2 cm	2–3 cm
Data of 20.04.06									
1	0.52	0.41	0.33	1.4	1.1	1.0	0.24	0.18	0.17
2	0.58	0.45	0.42	1.6	1.4	1.4	0.13	0.11	0.11
Data of 01.05.06									
1	0.27	0.34	0.35	1.0	1.2	1.1	0.17	0.25	0.23
2	0.28	0.26	0.26	1.4	1.4	1.3	0.11	0.11	0.10

during the daytime the thickness of the frozen layer decreased both from the top and bottom surfaces. The experimental setup was described elsewhere [8].

In order to reconstruct dielectric permittivity of soil from the remote sensing data, modeling of radiobrightness temperature was carried out. Since thermodynamic temperatures of the thawed and frozen layers were hardly different from 0°C, the medium was considered isothermal. The radiobrightness temperature of an isothermal medium can be calculated in terms of a plane wave reflection coefficient r for this medium

$$T_{\mathrm{br}} = \left(1 - |r|^2\right) T , \tag{1}$$

where T is the thermodynamic temperature of the medium.

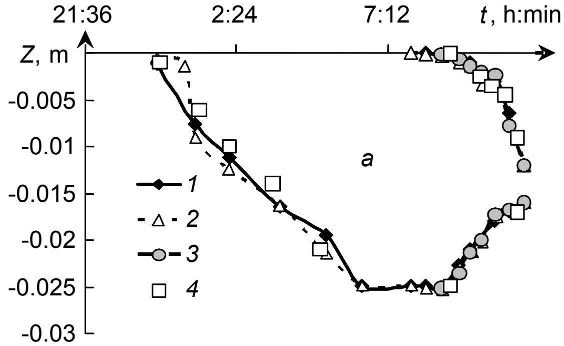
The medium in question was broken into n number of thin layers, and the reflection coefficient from this structure was then calculated by a multiple application of the relation (in terms of amplitude) for the coefficient of reflection from a two-layer medium, which for smooth boundaries has the following form:

$$r'_m = \frac{r_m + r'_{m+1} \exp(2 j k_{zn} \Delta Z_n)}{1 + r_m r'_{m+1} \exp(2 j k_{zn} \Delta Z_n)} , \tag{2}$$

where r'_m is the complex reflection coefficient from a multi-layer medium at the interface m (m = 0 between the media $n = 0$ (air) and n = 1 (first soil layer)), r_m is the complex Fresnel coefficient of reflection at this interface, r'_{m+1} is the complex reflection coefficient at the interface m + 1 from a multi-layer medium lying below n, which is found from Eq. (2) using an m + 1 index, $k_{zn} = k_0 \sqrt{\varepsilon_n - \sin\theta}$ is the projection of the medium wave number of the nth layer of the medium, θ is the probing angle, $k_0 = 2\pi/\lambda_0$ is the wave number in vacuum, and ΔZ is the thickness of the nth layer. The complex Fresnel coefficients at the interfaces between the media for the case of polar polarization are found from the formula

$$r_m = \frac{k_{zn} - k_{z(n-1)}}{k_{zn} + k_{z(n-1)}} ,$$

where $m = n$.



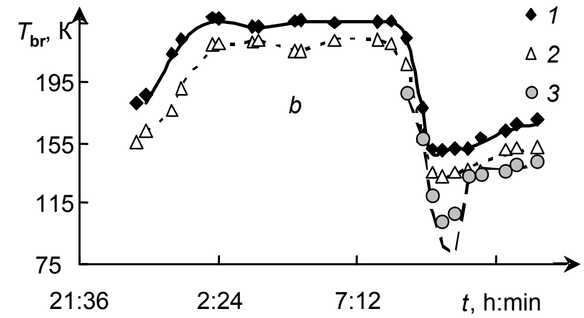


Fig. 1. Experimental results of 19.04.06–20.04.06 (soil surface 1). Variations in coordinates of the upper and lower boundaries of the frozen layer with time: simulations at the wavelengths 3.6, 5 and 11 cm (*1*, *2*, and *3*, respectively), direct measurements (*4*) (*a*) and radiobrightness temperature variations with time: experimental data (*1*, *2*, and *3* at 3.6, 5, and 11 cm, respectively) (signs) and simulations (lines) (*b*).

Shown in Fig. 1*a* are the measured depths of the frozen soil (coordinates of the lower boundary of the frozen layer) in the soil surface site 1 and thicknesses of the thawed layer (coordinates of the lower frozen layer boundary), which was observed on the soil surface in the morning hours in the experiment performed at night and in the daytime on April 20, 2006, and Fig. 1*b* shows the respective dynamics of the radiobrightness temperature at the wavelengths 3.6, 5, and 11 cm. In the final stage of the experiment a radiometer was initiated, it was tuned to the wavelength 11 cm when thawing started. Figure 1 also shows the simulated radiobrightness temperatures and coordinates of the frozen layer boundaries selected to better fit the calculated and measured data.

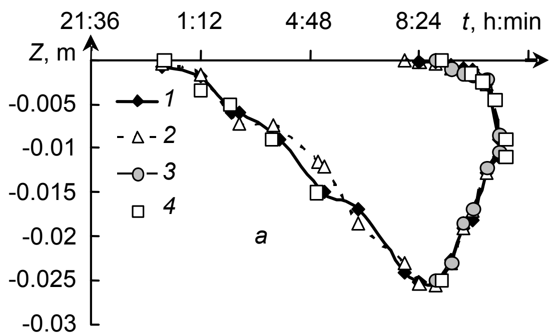
In this case, soil in the first stage of the experiment was treated as a homogeneous medium, since at high moisture the probing depth even at the wavelength 11 cm is as low as 1 cm. When a frozen layer was developed, the medium was considered to be two-layered, and finally with a layer of thawed soil on the surface it was treated as a three-layer medium. Dielectric permittivities of moist soil necessary for simulations were taken from [6]. It was found out that before frost penetration DP of the soil was $\varepsilon = 16 - i6.8$ at the wavelength 3.6 cm and $\varepsilon = 19 - i6$ at 5 cm. As the frozen layer thickness increased the radiobrightness temperature increased until the thickness exceeded the probing depth. In this case, the medium under study can be treated to be homogeneous, which provides a straightforward way to determine DP of the frozen soil layer. Using the above procedure, we obtained the following DPs: $\varepsilon = 4.2 - i1.1$ and $\varepsilon = 6 - i0.9$ at the wavelengths 3.6 and 5 cm, respectively, which were then used to simulate emission from a three-layer medium. It should be noted at this point that one measurement experiment cannot provide you with separate values of either real ε' or imaginary ε'' parts of DP, especially as the imaginary part hardly affects the reflection coefficient. Therefore, to find a relation between ε' and ε'' we used the dependences of the real and imaginary parts of DP on moisture content, which were known from dielectric measurements, assuming that dependence on moisture unambiguously gives the relationship between ε' and ε''.

It is seen from Fig. 1*b* that after completion of the frost penetration/thawing cycle at the wavelengths 3.6 and 5 cm the radiobrightness temperature is lower than in the beginning of the experiment, which is indicative of increased moisture content in the surface layer accessible for probing. A possible reason for this phenomenon could be non-isothermal moisture transfer from deeper soil layers towards freezing cold front. Assuming the completely thawed soil to be a homogeneous medium, we obtain the values of DP $\varepsilon = 20 - i7.5$, $26 - i8$, and $35.4 - i8.5$ at the wavelengths 3.6, 5, and 11 cm, respectively. The same values were ascribed to the thin thawed layer when the medium consisted of three layers. The resulting values of DP are fairly consistent with the values of moisture content measured after thawing, which are given in Table 2.

In order to obtain a better fit between the experimental and calculated data, it is suffice to more precisely select the upper and lower boundaries of the frozen layer. Considering that the absolute radiometer calibration error is 2–3 K and the fact that the frozen layer thickness was measured outside the emitting surface, we may take the agreement between the experimental and calculated data to be satisfactory.

TABLE 3. Dielectric Permittivities of Soil Layers at the Wavelengths 3.6 and 11 cm Obtained from Simulations of Radiobrightness Temperature in the Experiment on 01.05.06.

Soil	Surface site 1		Surface site 2	
	λ, cm		λ, cm	
	3.6	11	3.6	11
Non-frozen	$12 - i4.5$ $8.3 - i2.7$	$12 - i3.5$ $9 - i2.3$	$11 - i3.6$ $13.5 - i4$	$13 - i2.5$ $16 - i3.2$
Frozen	$4.1 - i0.95$ $5.8 - i1.5$	$4.2 - i0.4$ $6.1 - i0.9$	$5 - i1.4$	$5.5 - i0.8$
Thawed	$10 - i3.2$	$11 - i2.7$	$10.2 - i3.4$	$12.5 - i2.4$



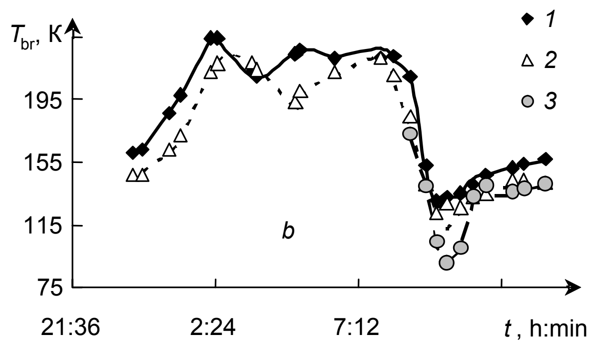


Fig. 2. Experimental results of 19.04.06–20.04.06 (soil surface 2). Variations in coordinates of the upper and lower boundaries of the frozen layer with time: simulations at the wavelengths 3.6, 5 and 11 cm (*1*, *2*, and *3*, respectively), direct measurements (*4*) (*a*) and radiobrightness temperature variations with time: experimental data (signs *1*, *2*, and *3* at 3.6, 5, and 11 cm, respectively) and simulations (lines) (*b*).

Shown in Fig. 2 are similar results obtained for the soils from surface site 2. Using simulations, DP of soil before frost penetration was found to be $\varepsilon = 21 - i7$ and $\varepsilon = 26 - i6.5$ at the wavelengths 3.6 and 5 cm, respectively. The values of DP obtained for the frozen layer were $\varepsilon = 4.8 - i1.3$ and $\varepsilon = 6.1 - i1.0$ at the wavelengths 3.6 and 5 cm, respectively. These are much higher than the respective values for the soil from surface site 1. The values of DP obtained for the completely thawed soil were as follows: $\varepsilon = 24 - i8$, $31.1 - i8$, and $35 - i6$ at the wavelengths 3.6, 5, and 11 cm, respectively.

In the experiment performed on 20.04.06, moisture content in the soil was much higher than the maximum amount of bound water, and moisture content variation with depth of the frozen layer din not, therefore, affect its dielectric permittivity, since all water was in frozen state. In the experiment performed on 01.05.06, moisture content in the upper layer on surface site 1 before frost penetration was lower than the maximum content of bound water, since motion of moisture towards cold front immediately before frost penetration affected DPs of the layer above the frozen one as well as DPs of the eventually frozen layer.

It is for this reason that simulation of the soil of surface site 1 by a 3-layer medium did not result in any agreement with the experiment. Only separation of each of the layers into two having different DPs did yield the results consistent with the experiment. Dielectric permittivities of the layers are presented in Table 3 and the radiobrightness temperature values are given in Fig. 3. A considerable difference between the calculated and experimental data is seen only in the points of maximum radiobrightness temperature in surface site 1 at the wavelength 3.6 cm. These maxima correspond to the onset of frost penetration and thawing processes. While there are maxima in the calculated curves as well, their values are approximately 10 K lower than those of the experiment.

Since the soil in surface site 2 contained a significant amount of free water, its variation due to non-isothermal transfer did not affect dielectric permittivity of the frozen layer that could be treated as homogeneous. Table 3, therefore,

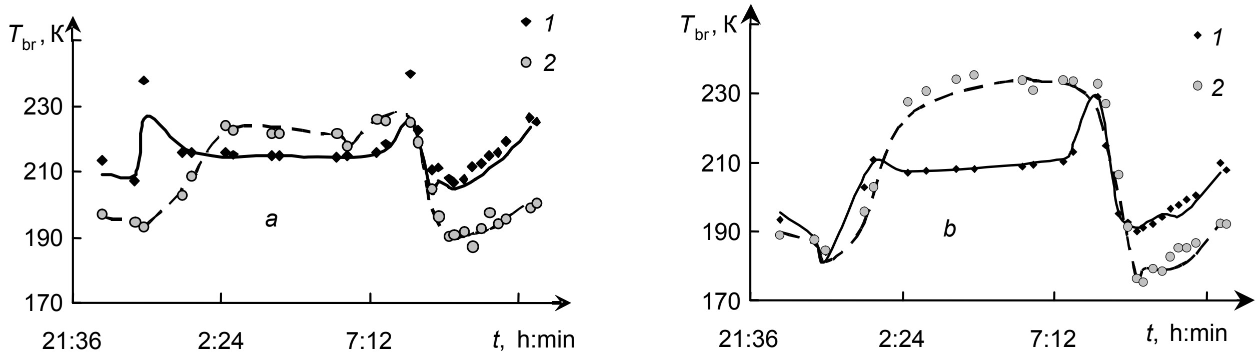


Fig. 3. Radiobrightness temperature variation on surface sites 1 (*a*) and 2 (*b*) in the period 30.04.06–1.05.06: experimental data (signs *1*, *2*) at the wavelengths 3.6 and 11 cm, respectively and simulation results (lines).

lists only one value of DP from this layer. For non-frozen and frozen soils from surface site 1 two DP values are given for the upper and lower layer, respectively.

If we represent frozen soil as a mixture of dry soil and bound water, then, according to the refraction model from [9] in order to obtain the real DP part of the mixture equal to 4.5, DP of the bound water should be equal to 10 for its maximum content in the soil of 0.17 cm^3/cm^3 and the soil density equal to 1.0 g/cm^3.

The maximum depth of frost penetration into the soil in this experiment was 2 cm, which is deeper than that obtained by probing at the wavelength 3.6 cm, therefore, at the temporal radiobrightness temperature diagrams there are sections where the radiobrightness temperature varies in time but slightly. Note that this temperature in surface site 1 slowly decreases while in surface site 2 it slowly increases. The decrease in radiobrightness temperature in surface site 1 occurred due to a decrease in thermodynamic temperature of the soil proportionally to this temperature completely in accordance with Eq. (1). The increase in radiobrightness temperature in surface site 2 could be accounted for by a decrease in DP of the soil. Since the frozen layer temperature in this experiment did not decrease below –1°C, a decrease in DP of soil could be caused by both a decrease in DP of freezing free water that was present in the soil in this surface site (see Table 2) and a decrease in DP of bound water. An unambiguous conclusion cannot be drawn from the data of this experiment, especially because no such phenomenon was observed in the experiment of 20.04.06.

To sum up, we can make the following conclusions. Natural processes of frost penetration and thawing allow us to investigate the behavior of dielectric permittivity in the vicinity of the phase transition temperature. From the results of such experiments one can, using a refraction model, determine dielectric permittivity of bound water at the temperatures much lower than 0°C. Variation in radiobrightness temperature of soils during frost penetration and thawing is unambiguously determined by the variation in the frozen layer thickness. When calculating dielectric permittivity of a soil, the latter can be viewed as a mixture of dry soil, ice, and bound water. If before freezing the content of water in soil is higher than the maximum content of bound water, then the frozen layer could be treated as a homogeneous layer whose dielectric permittivity is controlled by the content of bound water in this soil. Measuring of the temporal series of radiobrightness temperatures allows one to obtain information on dielectric permittivity of bound water at its maximum content in the soil, since representation of the soil by three homogeneous layers in this case is quite adequate.

When, however, the moisture content in the soil is such that there is no free water or its content is little, then it would be the radiobrightness temperature dynamics during freezing that would affect the inflow of moisture towards cold front from deeper layers. Note that even the frozen layer turns out to be inhomogeneous in terms of DP, and it should be modeled by at least two layers.

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REFERENCES

1. M. Schwank, M. Stahli, H. Wydler, *et al*., IEEE Trans. Geosci. Rem. Sens., **42**, No. 6, 1252–1260 (2004).
2. V. L. Mironov, P. P. Bobrov, P. V. Zhirov, *et al*., Radiobrightness Dynamics of Freezing/Thawing Processes for Different Soils, in: Proc. IGARSS'2006, Denver, Colorado, USA, **6**, 3015–3018 (2006).
3. V. V. Melentiev, O. M. Iohanensen, and O. G. Donchenko, in: Proc. Int. Sci. Conf. Remote Sensing of the Earth's Covers and Atmosphere using Aerospace Techniques", 20–22 June, Murom (2001).
4. V. Wismann, IEEE Trans. Geosci. Rem. Sens., **38**, No. 4, 1804–1809 (2000).
5. S. A. Komarov and V. L. Mironov, Microwave Sensing of Soils [in Russian], Nauka, Novosibirsk (2000).
6. T. A. Belyaeva, A. P. Bobrov, P. P. Bobrov, *et al*., Earth Research from Space [in Russian], No. 5, 28–34 (2003).
7. V. L. Mironov and P. P. Bobrov, in: Proc. IGARSS'03 V. II, Toulouse, France (2003).
8. P. P. Bobrov, O. A. Ivchenko, and S. V. Krivaltsevich, Earth Research from Space [in Russian], No. 2, 82–88 (2005).
9. V. L. Mironov, M. C. Dobson, V. H. Kaupp, *et al*., IEEE Trans. Geosci. Rem. Sens., **42**, 773–785 (2004).