THE RADIOBRIGHTNESS AND DEPTH OF FROZEN SOIL DURING CYCLES OF FREEZING AND THAWING

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1. INTRODUCTION

The Northern circumpolar region encompassing vast portions of Siberia, northern Canada, and the North Slope of Alaska are experiencing significant changes due to global climate change. It is known that processes of thawing and freezing define more than half of thermal balance; therefore, studies of this processes in the circumpolar region are of significant scientific interest. Because of distant location, remote sensing technology is perhaps the only realistic means of monitoring this important region. Microwave remote sensing using radiometers and radars, is capable of providing information on land surface processes, such as soil moisture and heat fluxes, with the impact of soil freezing and thawing being taken into account. Nevertheless, only a few papers are available in the literature regarding the problem of radio thermal radiation of the freezing/thawing soil. For instance, in [1], there were identified the areas of topsoil freezing by the radio thermal technique. While in [2], a model of heat and moisture transfer through frozen soil was developed and the respective radiobrightnesses calculated at the frequencies of 19.35, 37.0, and 85.5 GHz. However, remote sensing of the depth of freezing layer based on the radiobrightness measured as a function of time, remained still a challenging problem, which is considered in this paper.[1]

2. EXPERIMENTAL RESULTS

The measurements of radiobrightness were carried out at the test site “Pogorelsky Bor” of the Institute of Forest SB RAS located near the city of Krasnoyarsk (Russia). The soil radio emission was measured at the look angle of 45º relative to nadir. The bandwidths of the radiometers at 1.4 and 6.9 GHz were equal to 60 MHz and 200 MHz, respectively. The fluctuation sensitivity of radiometers was estimated to be about 0.3 K. A metal sheet reflecting the sky radiation and smooth water surface were used as standards to calibrate radiometers.

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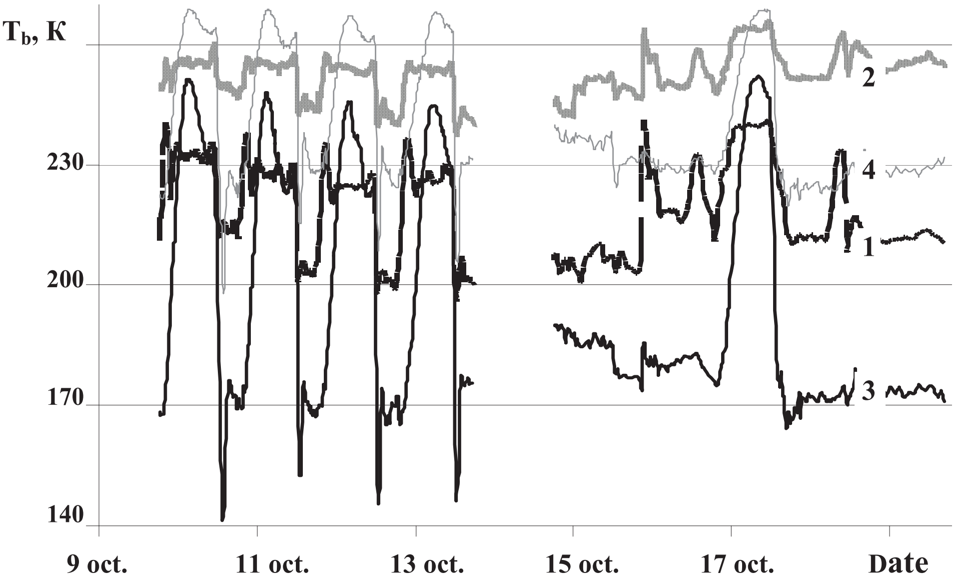

Fig.1. Diurnal cycles of radiobrightness, T_b, for the topsoil soil freezing and thawing conditions in the period from October 9, 2007 to October 24, 2007. 1 – frequency of 6.9 GHz, horizontal polarization, 2 – frequency of 6.9 GHz, vertical polarization, 3 – frequency of 1.4 GHz, horizontal polarization, 4 – frequencies of 1.4 GHz, vertical polarization.

The radiobrightness diurnal cycles measured for freezing/thawing topsoil are shown in Fig. 1. Sharp fluctuations in the period from October 9, 2007 to October 20, 2007 are caused by variations of a frozen topsoil layer thickness.

We carried out numerical simulation for the radiobrightness diurnal cycles observed. Since the relative bandwidth of the radiometers didn't exceed 4%, the simulation was performed only at a central frequency of each radiometer using the formula

$$T_b = (1 - R\ )T \tag{1}$$

where $R = |r|^2$ is the reflection coefficient by power, r is the reflection coefficient by amplitude, T is the effective absolute temperature of the topsoil layer. In general, the models of radiation from the layered medium must take into account the temperature profile inside medium [3, 4]. We used the method not taking into account the temperature profiles across the topsoil layers. Because the temperature of frozen and unfrozen soil within the sensed layer differed no more than 4ºC, we applied the approximate formula (1). The reflection coefficient for a multilayer medium was calculated using the following expression [5]:

$$r = \frac{r_0 + r_1^{/} \exp(-2jk_1\Delta X)}{1 + r_0 r_1^{/} \exp(-2jk_1\Delta X)}, \tag{2}$$

where r_0 is the Fresnel coefficient at the upper boundary, r'_1 is the reflection coefficient at the lower boundary of the topsoil, $k_{z1} = k_0\sqrt{\varepsilon_1 - \sin^2\theta}$ is a normal projection of the wave number vector pertaining to the topsoil layer medium, $k_0=2\pi/\lambda_0$ is a wave number in the vacuum, ε_1, ΔX are the complex dielectric constant and thickness of the topsoil layer, respectively.

As a model for the profile of complex dielectric constant, the expression proposed in [3] was applied:

$$\varepsilon^{/}(x) = \varepsilon_t - (\varepsilon_t - \varepsilon_f)\cdot\left(1 - \left(\frac{1}{1 + \exp((x - x_{fr})/Q)}\right)\right) \tag{3}$$

where ε_t, ,and ε_f are the complex dielectric constants of the thawed and frozen soil, respectively; x is the depth coordinate, x_{fr} is an average depth of frozen topsoil; Q is a parameter to determine the thickness of partly frozen transition layer. The transition layer thickness is equal to about $10Q$. To take into account variations of moisture with depth, we considered the complex dielectric constant of both thawed and frozen soil to be polynomial functions of depth. The complex dielectric constant as a function of soil moisture was determined with the use of the refraction model [6]. A typical dielectric profile of freezing soil is shown in Fig. 2. We optimized the parameters in (3) to make the difference less then 3K between the radiobrightnesses measured and modeled with the equations (1)-(3). The measured data were fitted simultaneously at the two frequencies and both vertical and horizontal polarizations. As a result, there was determined the depth of frozen topsoil layer, which is shown in

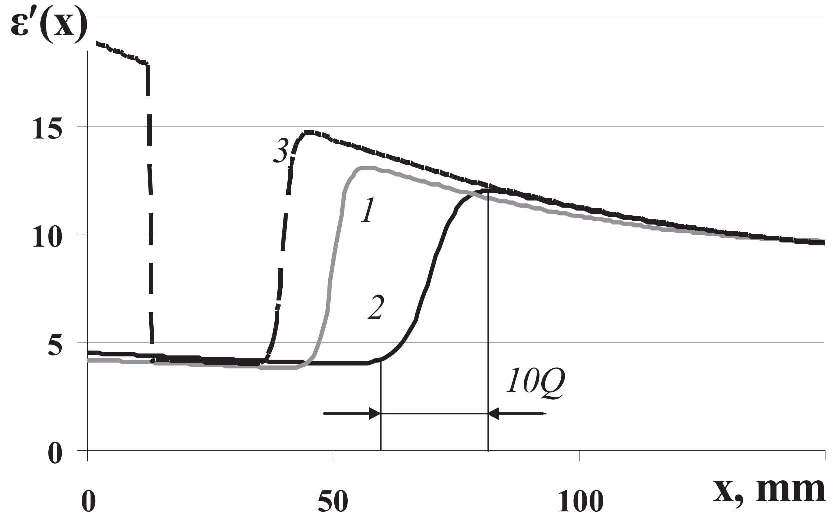

Fig. 2. The model for dependence of the dielectric constant of topsoil on depth in the processes of freezing (1,2) and thawing (3). 1 -the frozen soil depth is equal to 45 mm, 2 - the frozen soil depth is equal to 60 mm. Arrows indicate the boundaries of the transition layer for the graph 2.

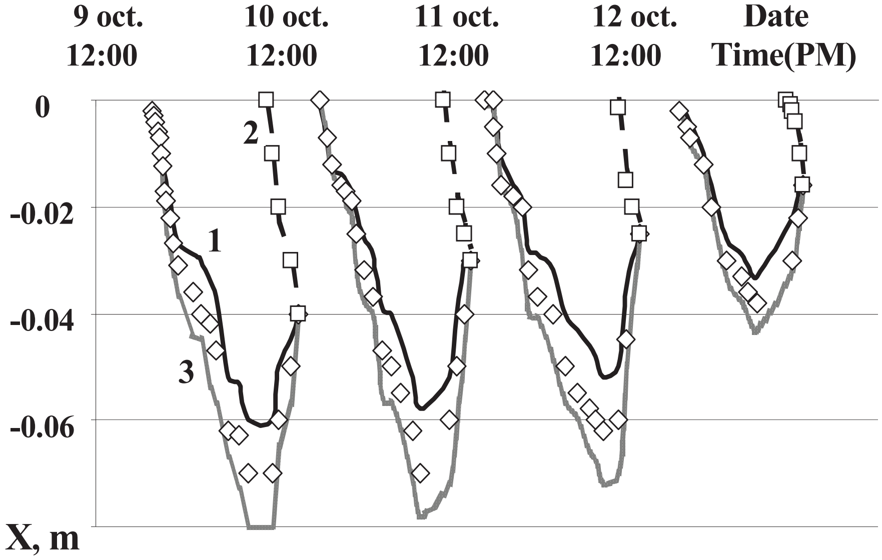

Fig. 3. Depth of frozen topsoil as a function of time. The depths of lower and upper boundaries for a frozen layer as a function of time observed in the process of freezing and thawing. 1 and 2 – simulated depths of the lower and upper boundaries, respectively. 3 – simulated depth of the lower boundary for a transition layer. The data obtained using mechanical probe are shown by symbols.

Fig.3 as a function of time, together with the values of depth measured by a mechanical probe. As seen from Fig. 3, the radio thermal detection of a frozen topsoil layer appeared to be quite feasible. At that, the worst error of sensing was found not to exceed 15 to 20%.

3. CONCLUSION

The radiothermal experimental technique was developed to sense the depth of boundaries for a frozen soil layer emerging in the topsoil in the course of freezing and thawing. The worst error of sensing was found to be less then 15 to 20%. This method can be applied to study freezing and thawing processes over the cold regions with the use of the data collected by the SMOS mission.

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