Retrieving Temperature Gradient in Frozen Active Layer of Arctic Tundra Soils From Radiothermal Observations in L-Band—Theoretical Modeling

Valery L. Mironov, *Member, IEEE*, Konstantin V. Muzalevskiy, and Igor V. Savin

***Abstract*—Possibility of remote sensing of both the surface temperature and the temperature gradient in the permafrost active layer from L-band brightness temperature observations is theoretically investigated at a SMOS frequency of 1.4 GHz. Bare soil emission is simulated based on the semi-empirical L-MEB model. The brightness temperature is simulated using the soil density, surface roughness, temperature, and moisture profiles measured *in situ* at the Biosphere Station Franklin Bluffs, Alaska, USA (69°39'N, 148°43'W) from September 2, 1999, to August 23, 2001. The soil permittivity is calculated using the temperature-dependent generalized refractive mixing dielectric model for the organic rich soil sample collected in North Slope, Alaska (68°38'N, 149°35'W). This model predicts the complex dielectric constant of moist soil both thawed and frozen at temperatures from $-30\ ^\circ$C to $+25\ ^\circ$C and moistures from 0 to 0.94 g/g. The brightness temperatures simulated for field-of-view angles from 0 to 60° are inverted into the temperature profiles, and their deviations from the temperature profiles measured *in situ* are estimated. The error in reconstructing temperature profiles is found to be no greater than 1.8 °C to depths of 0.15 m.**

***Index Terms*—Active layer, Arctic tundra soil, freezing, microwave remote sensing, radiometry, soil moisture and ocean salinity (SMOS), soil temperature, temperature profile, thawing.**

I. Introduction

The most comprehensive results on remote sensing of the soil temperature of the Arctic tundra using an AMSR-E microwave radiometer have been discussed in [1]. To retrieve the soil temperature, the empirical linear relationship [2] between the H- and V-polarization emissivities was applied. In this case, the remotely sensed soil temperature was identified with the effective soil temperature in the approximation of a semi-infinite isothermal soil layer. This approach allowed the effective soil temperature to be measured with a root-mean-square error of 3.9 K in summer under conditions of thawing and with a larger error up to 10.5 K in winter [1]. The authors of [1] attributed a larger error in the winter period to dramatic fluctuations of the permittivity profiles in the topsoil layer sensed during freeze-thaw transitions. Consequently, when retrieving the temperature in the topsoil, a realistic model of dielectric properties should be taking into account. Such an approach was used in this paper in development of the algorithm for retrieving the temperature of the Arctic tundra soil from SMOS modeled data. It is expected that the situation will even worsen in the case of processing the brightness temperatures measures with a SMOS radiometer MIRAS in the L-band, since in this case the variations of the differences in temperatures at the soil surface and at the depths of 20 cm should be much larger those concerning the 5-cm layer measured by an AMSR-E radiometer in the C-band. It also should be noted that the SMOS radiometers measures the radiobrightness temperatures for a whole range of field-of-view angles from 0 to 60° [3]. This additional data may decrease error of temperature retrievals and even allow to retrieve the temperature profiles in the topsoil. However, this problem has not yet been addressed.

The present work is aimed at the development of an algorithm for retrieving the surface temperature and the temperature gradient in the topsoil layer of the Arctic tundra based on the SMOS modeled data. As a first phase of these studies, we consider the bare soil with poor vegetation and snow cover. As demonstrated in [4] and [5], the effects of dry snow volume scattering and attenuation are insignificant, so that the radio-brightness temperatures are practically unaffected by the dry snow cover.

In Section II, the method of simulating the brightness temperature of the active layer of the Arctic tundra soil with allowance for the temperature profiles is described. In Section III, we describe the temperature-dependent generalized refractive mixing dielectric model (TD GRMDM) of the organic rich soil characteristic to Alaska North Slope (68°38'N, 149°35'W). In Section IV, the Arctic tundra brightness temperature is calculated. In Section V, we present a method of retrieving both the surface temperature of the active layer of an Arctic tundra soils and the temperature gradient from radio-brightness temperature observations. General analysis of the proposed retrieval algorithm is given in Section VI.

II. Model of the Arctic Tundra Soil Brightness Temperature

The brightness temperature $T_{\mathrm{br,p}}(\theta_0)$ of the bare soil can be calculated using the L-MEB model [6] in the following form:

$$T_{\mathrm{br,p}}(\theta_0) = \{1 - \Gamma_{\mathrm{p}}(\theta_0, \varepsilon_{\mathrm{s}}(T(z), W(z), f))\} \cdot T_{\mathrm{eff}}(\theta_0) \quad (1)$$

where θ_0 is the observation angle, $\Gamma_{\mathrm{p}}(\theta_0, \varepsilon_{\mathrm{s}}(T(z), W(z), f))$ is the reflectivity regarding the soil and the air interface, and the subscript p indicates the vertical ($p = V$) or horizontal ($p = H$) polarization, respectively. The reflectivity is a functional

Manuscript received September 30, 2012; revised February 22, 2013 and April 24, 2013; accepted April 28, 2013. Date of publication May 24, 2013; date of current version June 17, 2013. This work was supported by the Siberian Branch of the Russian Academy of Sciences (SB RAS) under the basic program II.10.1: "The radiophysical methods of an environment diagnostics."

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Digital Object Identifier 10.1109/JSTARS.2013.2262108

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of the relative complex permittivity profile, $\varepsilon_s(T(z), W(z), f)$, which depends on the physical temperature, $T(z)$, and moisture, $W(z)$, profiles, z is the vertical coordinate, and f is the wave frequency. The effective temperature of the emitting soil layer, $T_{\rm eff}(\theta_0)$, can be expressed by the following formula [7]:

$$T_{\rm eff}(\theta_0) = \int_0^\infty T(\mathrm{z}) \frac{\kappa_s(\mathrm{z})}{\cos(\theta_0)} \exp\left[-\int_0^z \frac{\kappa_s(\mathrm{z}')}{\cos(\theta_0)} dz'\right] dz \quad (2)$$

where $\kappa_s(z) = \mathrm{Im}\sqrt{\varepsilon_s(T(\mathrm{z}), W(z), f)}$ is the normalized attenuation coefficient at depth z. As demonstrated in [6], the reflectivity regarding rough soil surface can be expressed in the following form:

$$\begin{aligned}\Gamma_p(\theta_0, \varepsilon(T(\mathrm{z}), W(z), f)) &= |R_p(\theta_0, \varepsilon_s(T(\mathrm{z}), W(z), f))|^2 \\ &\cdot \exp\left(-\left[0.9437 \cdot \frac{S_d}{2.2913} + 0.8865 \cdot S_d\right]^6\right)\end{aligned} \quad (3)$$

where $R_p(\theta_0, \varepsilon_s(T(\mathrm{z}), W, f))$ is the Fresnel reflection coefficient regarding the smooth surface of the soil calculated by the iteration method [8], S_d is the standard deviation of soil roughness heights. Formula (3) can be used for standard deviations in the range $4.57 \leq S_d \leq 59.37$ mm. At that, the Pearson coefficient is 0.96 and the standard deviation is 0.02, when adjusting the calculated emissivity, $(1 - \Gamma_p)$, with the measured values [6]. In Section III, we consider the dielectric model of the Arctic soil.

III. Dielectric Model of the Arctic Tundra Soil

In [9]–[11], the brightness temperature of a bare soil surface was modeled. At that, the soils with predominant inorganic contents were considered in both the thawed and frozen states. In these studies, the semi-empirical model [12] for the soil complex dielectric constant was employed, with the dielectric constants of ice and liquid unfrozen water being estimated as in [13]. At the same time, this model can not be applied in the case of Arctic soils having predominant organic contents. Recently, for such a soil, the temperature-dependent generalized refractive mixing dielectric model (TD GRMDM) was introduced in [14]. The soil sample collected in North Slope, Alaska (68°38'N, 149°35'W) comprises 87% organic matter, 8% quartz, and 5% calcite. The model [14] can be used to calculate the complex relative permittivity of both the thawed and frozen soils as functions of the dry density, gravimetric moisture, temperature (from -30 °C to 25 °C), and frequency (from 0.5 to 15 GHz). It should also be noted that the model [14] was constructed based on measurements of soil samples in the process of freezing. The dielectric model of the Arctic tundra soil [14] was constructed based on the temperature-dependent dielectric model for moist soils [15] currently included into the basic algorithm of the SMOS spacecraft used to retrieve the soil moisture [16]. As an example, Fig. 1 shows the refractive index, $\mathrm{n_s} = \mathrm{Re}\sqrt{\varepsilon_s(T, W, f)}$, and the normalized attenuation coefficient calculated for typical values of density and moisture content of the topsoil layer at the Franklin Bluffs biophysical monitoring site (69°39'N, 148°43'W) Alaska, USA.

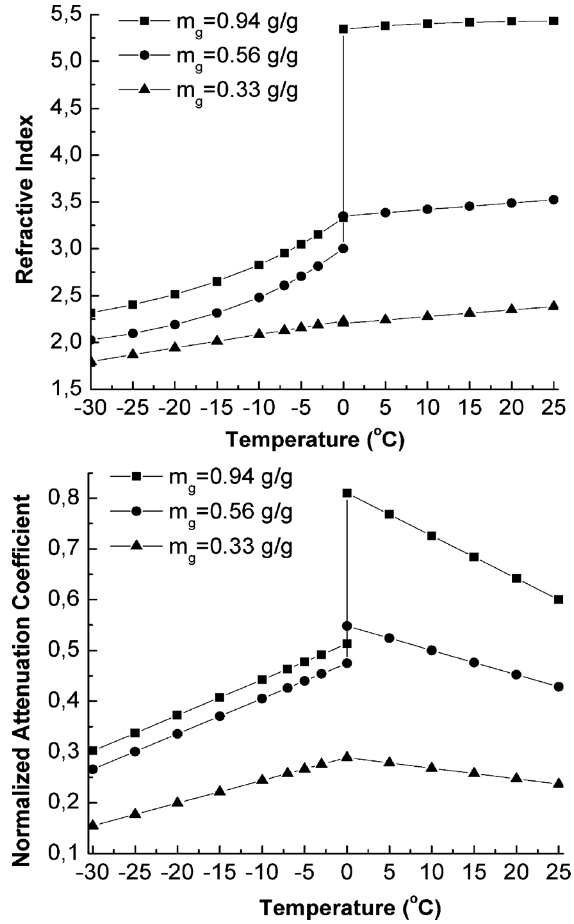

Fig. 1. Temperature dependence of the refractive index and normalized attenuation coefficient for the Arctic tundra soil calculated for the frequency f = 1.4 GHz, soil gravimetric moisture $\mathrm{m_g}$ ranging from 0.33 g/g to 0.94 g/g, and soil density of 0.6 g/cm^3.

As can be seen from Fig. 1, noticeable variations in the refractive index and normalized attenuation coefficient of the Arctic tundra soil are observed depending on the soil temperature and moisture in the process of freezing ($T < 0$ °C). This effect can be used to measure the temperature of the Arctic tundra soil using the brightness temperature data. In the next section, we simulate the Arctic tundra soil brightness temperature based on radiometric (1) presented in Section II and the dielectric model described in Section IV.

IV. Simulation of the Arctic Tundra Soil Brightness Temperature

The brightness temperature was simulated using (1)–(3) for density of 0.6 g/cm^3 and gravimetric moisture of 0.94 g/g in the topsoil. These values were considered independent of the depth z. The daily averaged temperature profiles measured to the depth of 1 m at the Biosphere Station Franklin Bluffs, AK (69°39'N, 148°43'W) from September 2, 1999, to August 23, 2001 [17] were also used. Soil sample was collected approximately 100 km apart from Biosphere Station Franklin Bluffs. As follows from [18] soils at these test sites are of the same types, namely, Typic Aquiturbels. Therefore, we assumed the dielectric model worked out for the soil sample collected at the

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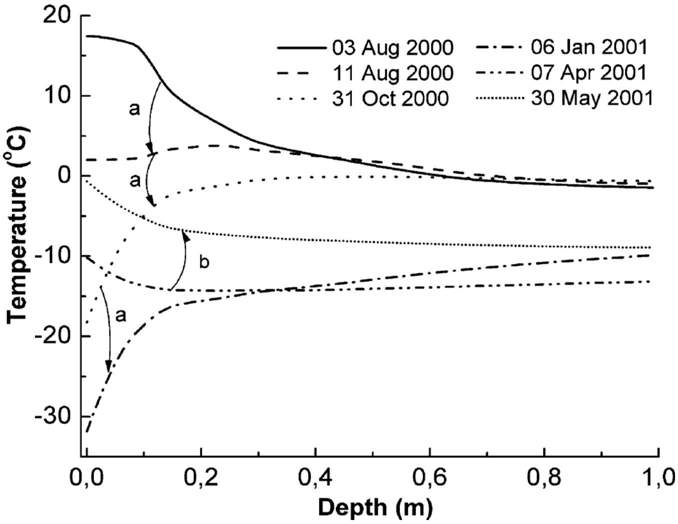

Fig. 2. Typical temperature profiles measured at the Franklin Bluffs test site in 2000–2001. (a) Freezing. (b) Thawing.

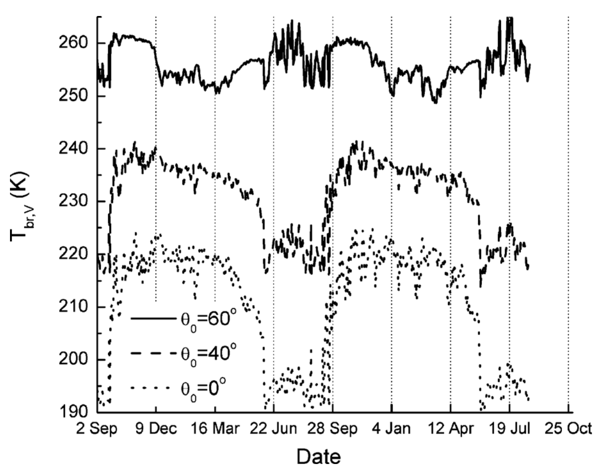

Fig. 3. Seasonal variations of the brightness temperature for the V-polarization at field-of-view angles of 0, 40, and 60°.

North Slope, Alaska (68°38'N, 149°35'W) test site to be appropriate for modeling the radio brightness temperatures with the use of the temperature profiles measured at the Franklin Bluffs test site. The typical temperature profiles of the active soil layer at the Franklin Bluffs test site observed from August 3, 2000, to May 30, 2001 are shown in Fig. 2.

The roughness standard deviation, central wave frequency, and field-of-view angles were set equal to 6 cm, 1.4 GHz, and 0–60°, respectively. The results of simulation for the brightness temperature are shown in Fig. 3 for the indicated field-of-view angles as functions of time. They are complemented with series of the soil temperature measured at some depth which are shown on a Fig. 4. As can be seen from Figs. 3 and 4, the time variations of the brightness temperature are correlated with those of the temperature at different depths in the soil. This correlation provides the basis for retrieving the soil surface temperature and the temperature gradient in the soil from brightness temperature observations. The method of retrieving these values is considered in Section V.

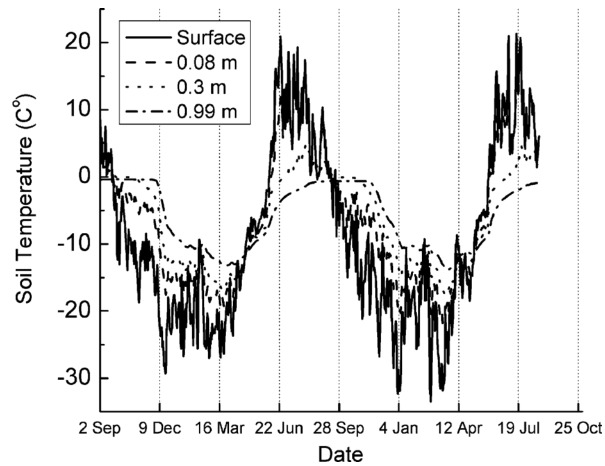

Fig. 4. Seasonal variations of the physical temperature at depths of 0.08, 0.3, and 0.99 m.

V. METHOD OF RETRIEVING THE TEMPERATURE AND TEMPERATURE GRADIENT

First, we investigated the decreasing sensitivity of the brightness temperature to the soil temperature with increasing depth. For this purpose, the brightness temperature was calculated for the measured temperature profiles truncated at the depth z_L and set equal to $T(z_L)$ at depths $z_L < z < 1$ m. These calculations demonstrated that the brightness temperatures determined in this way deviated from the brightness temperatures simulated using the temperature profiles measured at $0 \geq \mathrm{z} \geq 1$ m by less than 1% provided the truncation depth z_L was set equal to or greater than 8 cm. With this fact in mind, we approximated the temperature profile in the topsoil of the Arctic tundra by the piecewise linear function

$$T_{\mathrm{pw}}(z) = \begin{cases} T_{\mathrm{s}} + Gz, & z \leq z_L \\ T_{\mathrm{s}} + Gz_L, & z \geq z_L \end{cases} \tag{4}$$

where T_{s} and G are the surface temperature and the temperature gradient, respectively. To retrieve these values from the simulated brightness temperature values like those shown in Fig. 3, we used the Levenberg–Marquardt algorithm [19] and minimized the norm of the difference between the brightness temperatures calculated with the measured temperature profiles $\mathrm{T(z)}$, on the one hand, and with piecewise function (4), on the other hand. The norm was constructed for 11 field-of-view angles ranging from 10 to 60° with an increment of 5°. In this procedure, the standard deviation of soil roughness heights was set to be equal 6 cm, which was used in calculation of the initial values of brightness temperature. As follows from the mission objectives and scientific requirements of the SMOS, the error of radio-brightness temperature measured is about 3 K [20]. For that, in addition to the brightness temperatures calculated with the measured temperature profiles $T(\mathrm{z})$, the noise component was calculated as a random variable with a Gauss distribution having a half-width of 3 K. The measured and retrieved temperature profiles $T(z)$ and $T_{\mathrm{pw}}(z)$ are shown in Fig. 5 for the indicated dates of freezing and thawing cycles.

In addition, a correlation between temperatures measured and retrieved in the 15-cm topsoil layer is shown in Fig. 6. As seen

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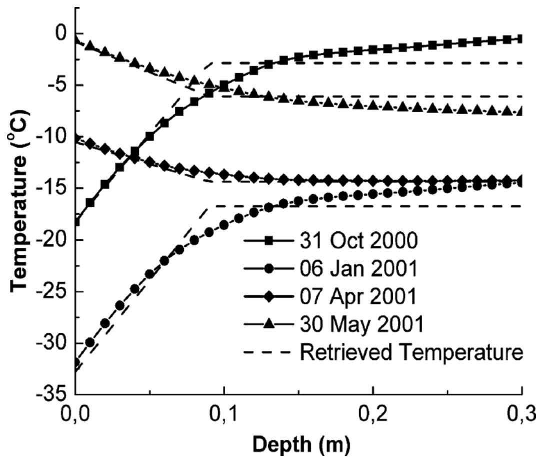

Fig. 5. Retrieved (dashed curve) and measured (symbols) temperature profiles corresponding to the data shown in Figs. 1 and 2.

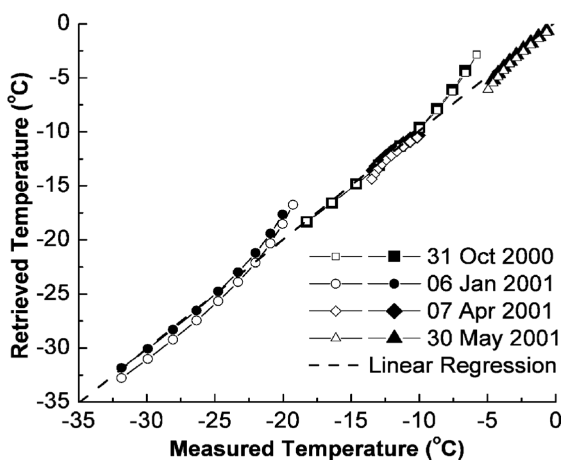

Fig. 6. Correlation between the retrieved and measured soil temperatures. The linear regression is shown by the dashed curve. Open and closed symbols correspond to the horizontal and vertical polarizations, respectively.

from Figs. 5 and 6, the retrieved and measured temperatures are strongly correlated. In this case, the estimated Pearson coefficient and the root-mean-square error were found to be 0.99 and $\pm$ 0.87 °C, respectively.

VI. Conclusion

In this paper, the possibility of measuring both the temperature gradient and the surface temperature of the active layer of the Arctic tundra soils from observations with the L-band microwave radiometer has theoretically been investigated. Theoretical analysis was carried out using the permittivity of the Arctic tundra soil calculated for the temperature-dependent generalized refractive mixing dielectric model of the organic rich soil sample collected in the North Slope area, Alaska. The dielectric model takes into account the moisture, electromagnetic field frequency, physical soil temperature, and phase transitions between different types of soil water. The brightness temperatures simulated for field-of-view angles from 0 to 60° were used to reconstruct the surface soil temperature and the surface topsoil temperature gradient. The reconstructed temperature profiles deviated from their values measured *in situ* by no greater than ± 0.87 °C for the 0.15-cm layer both for the vertical and horizontal polarizations. The proposed method was specially designed for implementation in the SMOS algorithms intended for measuring the temperature of frozen soil and mapping of permafrost degradation in the Arctic region.

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