TEMPERATURE DEPENDENT DIELECTRIC MODEL AT 1.4 GHZ FOR A TUNDRA ORGANIC-RICH SOIL THAWED AND FROZEN

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ABSTRACT

A mono-frequency dielectric model for a tundra organic-rich soil both thawed and frozen has been developed. The model is based on the soil dielectric measurements carried out in the ranges of volumetric moisture from 0.007 to 0.573 cm^3/cm^3, dry soil density from 0.564 to 0.666 g/cm^3, and temperature from 25 to -30 °C (cooling run), at the frequency of 1.4 GHz used by the SMOS instrument. To fit the results of measurements of the soil complex refractive index (CRI) as a function of soil moisture, the refractive mixing model was applied. As a result, the parameters of the refractive mixing model linked to soil solids, as well as the bound, transient, and free soil water components were derived as a function of temperature. The error of the proposed dielectric model was shown to be in the order of the dielectric measurement error itself[1].

Index Terms— Organic soil, moisture, temperature, dielectric model, thawed and frozen soil, remote sensing

1. INTRODUCTION

The dielectric models of moist soils are the essential part of the SMOS soil moisture retrieval algorithm employed to monitor soil moisture over land surfaces [1]. So far, this algorithm has been applied to the soils containing predominantly mineral solids. At the same time, such territories like boreal forest and arctic tundra are the nearest targets for the SMOS applications. The dielectric model for an organic-rich arctic soil collected on Alaska [2] is available only in [3]. The model of [3] provides the complex relative permittivity (CRP) predictions in the temperature ranges -6 °C to 25 °C (thawed soil) and -30 °C to -7 °C (frozen soil) and over the frequency range 1.0 to 16 GHz. Though it allows to estimate the soil CRPs at a frequency of 1.4 GHz used by the SMOS instrument, it is unnecessarily complex. The matter is that its spectroscopic nature demands to introduce a number of both the spectroscopic and thermodynamics parameters. In this paper, the refractive mixing dielectric model (RMDM), as formulated in [3], was used to design the temperature dependent single frequency dielectric model. In addition, a special mode of freezing was applied to ensure soil samples to get frozen. Therefore, the temperature intervals for the thawed and frozen samples measured appeared to be of 0 °C to 25 °C and -30 °C to -1 °C, respectively. The dielectric model suggested can be applied in the SMOS algorithm to retrieve soil moisture and temperature in a topsoil layer over the Arctic regions, as was suggested, for instance, in [4].

2. THE EXPERIMENTAL DATA AND REFRACTIVE MIXING DIELECTRIC MODEL

To develop the dielectric model we used the samples of an arctic soil collected from shrub tundra in Alaska during fieldwork in 2004 [2]. The percentage of organic matter in the soil was 80-90%. The CRP of the soil was measured in the frequency range from 1 to 16 GHz, gravimetric moisture was varied from 0.05 to 1 g/g, and the temperature was set in the interval from -30 °C to +25 °C. The details of the measurement technique are available in [5]. In addition to the soil dielectric data previously used in [3], by applying the specific mode of soil freezing, a set of dielectric data were obtained for frozen samples in the range of temperatures from -30 °C to -1 °C, to extend the temperature domain of applicability in the case of frozen soil, as compared to the model of [3]. As in [3], we will analyze the CRP, ε, in terms of the reduced complex refractive index (CRI):

$$(n^*-1)/\rho_d = (\sqrt{\varepsilon}-1)/\rho_d = (n-1)/\rho_d + i\kappa/\rho_d \qquad (1)$$

where $n=\mathrm{Re}\sqrt{\varepsilon}$ and $\kappa=\mathrm{Im}\sqrt{\varepsilon}$ are the real and imaginary parts of CRI, respectively. ρ_d is the density of dry soil. In the frame of the RMDM as formulated in [3], the reduced CRI does is invariant regarding dry soil density. At that, the gravimetric moisture of soil samples, m_g, appears to be the only model variable, used in fitting the reduced CRIs of soil samples measured at a fixed temperature, but with varying moisture and dry densities. The latter varies when the soil substance, having different amounts of water, was being packed into measuring cell. Due to this factor, the density of

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a soil sample in a dried condition, varied from 0.564 to 0.666 g/cm^3.

As a first step in dielectric data analysis, we used the results of measurements conducted in [3] at the wave frequency of 1.4 GHz for the thawed and frozen soil samples, with the temperature, T, varying in the ranges 0°C≤T≤25°C and -30°C≤T≤-7°C, respectively. Some of those results in terms of the reduced CRI are shown in Fig.1, alongside with the fits obtained with the use of the refractive mixing dielectric model, as given in [3]:

$$\frac{n_s^*-1}{\rho_d(m_g)}=\begin{cases}\frac{n_m^*-1}{\rho_m}+\frac{n_b^*-1}{\rho_b}m_g & m_g\le m_{g1}\\ \frac{n_m^*-1}{\rho_m}+\frac{n_b^*-1}{\rho_b}m_{g1}+\frac{n_t^*-1}{\rho_t}(m_g-m_{g1}) & m_{g1}\le m_g\le m_{g2}\\ \frac{n_m^*-1}{\rho_m}+\frac{n_b^*-1}{\rho_b}m_{g1}+\frac{n_t^*-1}{\rho_t}(m_g-m_{g1})+\frac{n_{l,i}^*-1}{\rho_{l,i}} & m_g\ge m_{g2}\end{cases}\qquad(2)$$

The subscripts *s, d, m, b, t, l,* and *i,* relating to n, κ, and ρ, refer to the moist soil, dry soil, solid component of the soil, bound water, transient water, free-liquid water, and moist ice (ice crystals with adjacent unfrozen water molecules), respectively. The parameter m_{g1} separates the range of bound water from that of transient water. While m_{g2} separates the range of transient water from that of free water which exists in a form of free-liquid water and moist ice in the cases of thawed and frozen soil, respectively. As seen from Fig. 1, the fits determined with the use of (2) perfectly correspond to the measured data.

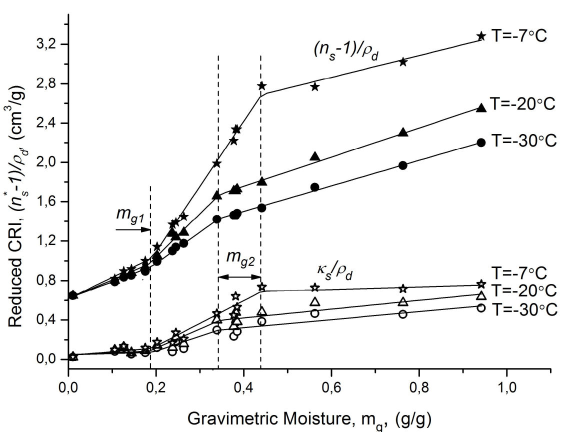

Fig. 1. A reduced complex refractive index of soil as a function of gravimetric moisture at the frequency of 1.4 GHz for frozen soil. The measured temperatures are given by inscriptions. The measured CRI values are shown by symbols. The piecewise linear fits are presented by solid lines.

These dependencies have the form of piecewise linear functions, with each specific segment of the polyline corresponding to a particular component of water. As a result, we can determine the parameters $(n_q\text{-}1)/\rho_q$ and κ_q/ρ_q concerning the solid components of the soil ($q = m$) and all the specific components of soil water ($q = b, t, l, i$) as well as the maximum fractions m_{g1} and m_{g2}. All of these parameters being a function of temperature. In the formulas (2) the dry soil density, $\rho_d(m_g)$, was assumed to be independent on temperature.

3. TEMPERATURE DEPENDENT DIELECTRIC MODEL

Based on the dielectric data like those shown in Fig. 1, we obtained the temperature dependences for all the parameters in formulas (2) representing the RMDM of moist soil. Namely, the parameters m_{g1}, m_{g2}, $(n_m\text{-}1)/\rho_m$, $(n_b\text{-}1)/\rho_b$, $(n_t\text{-}1)/\rho_t$, $(n_{l,i}\text{-}1)/\rho_{l,i}$, κ_m/ρ_m, κ_b/ρ_b κ_t/ρ_t, and $\kappa_{l,i}/\rho_{l,i}$ were derived by jointly fitting the formula (2) to both the values $(n_s\text{-}1)/\rho_d$ and κ_s/ρ_d measured at the temperatures 0, 5, 10, 15, 20, 25 °C, and -30, -25, -20 - 15, -10, -7 °C in the cases of thawed and frozen soil samples, respectively. After that, the data thus obtained for these parameters, consisting of six data points in the every temperature domain, were fitted separately in the cases of thawed and frozen soil samples, using most suitable functions, which are shown below:

Thawed soil (0ºC ≤ T ≤ +25 ºC) (3)

m_{g1}=0.185	m_{g2}=0.43+0.004exp(T/6)
$(n_m\text{-}1)/\rho_m$=0.62-0.002T	κ_m/ρ_m=0.04
$(n_b\text{-}1)/\rho_b$=2.36+0.032T	κ_b/ρ_b=0.463+0.0022T
$(n_t\text{-}1)/\rho_t$=7.37+0.032T	κ_t/ρ_t=2.23-0.03T
$(n_l\text{-}1)/\rho_l$=8.8-0.019T	κ_l/ρ_l=1.36-0.093exp(T/11)

Frozen soil (-30ºC≤T≤-7ºC) (4)

m_{g1}=0.185	m_{g2}=0.335+0.095exp(T/11)
$(n_m\text{-}1)/\rho_m$=0.62	κ_m/ρ_m=0.04-3.75•10-4T
$(n_b\text{-}1)/\rho_b$=2.31+0.02T	κ_b/ρ_b=0.43+0.0115T
$(n_t\text{-}1)/\rho_t$=7.71+0.16T	κ_t/ρ_t=2.84+0.046T
$(n_i\text{-}1)/\rho_i$=1.34-0.0026T	κ_i/ρ_i=0.45-0.15exp(T/13).

According to (1), the real, ε_s' and imaginary, ε_s'', parts of the soil CRP can be expressed via the real, n_s, and imaginary parts, κ_s, of CRI as follows:

$$\varepsilon_s' = n_s^2 - \kappa_s^2, \quad \varepsilon_s'' = 2n_s\kappa_s. \quad (5)$$

Equations (2) - (5) represent the model that predicts values of the CRP at 1.4 GHz for both the thawed and frozen soils as a function of dry soil density, soil moisture, and temperature.

4. VALIDATION OF DIELECTRIC MODEL

To conduct validation dielectric measurements for a frozen soil in the temperature range -7 °C< T≤-1 °C, an ice nucleation process in soil was started at of -7 °C and completed at the temperature of -1 °C. In the course of further cooling, there were also conducted measurements of soil CRPs at the temperatures of -3 °C and -5 °C. The dry soil densities, ρ_d, and respective soil moistures, m_g and m_v, observed in these measurements are given in Table I.

Table I. Dry soil densities (g/cm^3), ρ_d, and the respective gravimetric (g/g) and volumetric (cm^3/cm^3) soil moistures, m_g and m_v, observed in the validation measurements

m_g	0.086	0.114	0.299	0.516	0.602	0.992
ρ_d	0.633	0.611	0.538	0.541	0.570	0.531
m_v	0.054	0.070	0.161	0.278	0.343	0.536

The results of validation measurements for the soil real CRPs are displayed in Fig. 2 as a function of temperature together with the respective predictions obtained with the use of the formulas in (2)-(6).

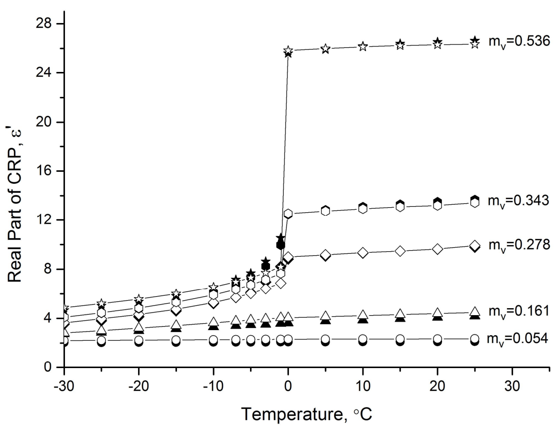

Fig. 2. The real CRP of moist soil as a function of temperature for fixed volumetric moistures m_v (given by inscriptions) at a frequency of 1.4 GHz. The values of $\rho_d(m_v)$ are given in Table I. The measured and predicted real CRP values are shown by similarly shaped black and white symbols, respectively.

As seen from Fig. 2, the predicted and measured CRP values are well correlated with each other, including the temperature range -7°C < T≤ -1°C, which confirms the extrapolation of the equations in (5) over this range. To make error estimation, we calculated the coefficient of determination for the real, $R^2_{\varepsilon'}$, and the imaginary, $R^2_{\varepsilon''}$, parts of the CRP. Their values were found to be $R^2_{\varepsilon'}$ =0.999 and $R^2_{\varepsilon''}$ = 0.993. While the estimates of the RMSE of the predicted values relative to the measured ones, yielded the following values: $RMSE_{\varepsilon'}$ = 0.27 and $RMSE_{\varepsilon''}$ = 0.18. Such errors of the CRP predictions are quite acceptable for practical use in the remote sensing algorithms.

5. CONCLUSION

The dielectric model for an arctic organic-rich soil both thawed and frozen is developed at the SMOS wave frequency of 1.4 GHz in the ranges of volumetric soil moisture and temperature from 0 to 0.6 cm^3/cm^3 and from 25 to -30 °C, respectively. The dry soil density is a variable of the model, allowing to adjust the model to the values observed in natural conditions. For the soil under study, the density of dry soil determined at the site of collection equals 0.254 g/cm^3. The model provides predictions for the real and imaginary parts of complex relative permittivity with the RMSE of 0.27 and 0.18, respectively, which is quite acceptable for practical use. The dielectric model suggested can be applied to develop remote sensing algorithms for retrieving near-surface soil moisture and temperature in both thawed and frozen topsoil layer over the Arctic tundra regions.

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