2013 International Siberian Conference on Control and Communications (SIBCON)

Impact of a Freezing Topsoil on Determining the Arctic Tundra Surface Deformation Using InSAR

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Abstract — **In this paper, we study the effect of the layered structure of the active topsoil of the Arctic tundra during freezing on the error of determining surface deformation. A simple Bragg scattering model was used for surface scattering modeling. The simulation was performed in the L-band for future radar missions SMAP and ALOS-2. 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°C to +25°C and moistures from 0 to 0.94 g/g. It is shown that the error of determining soil surface deformation, induced by processes of freezing of the permafrost active layer, does not exceed 1.5 cm.**

Index Terms— **SAR Interferometry (InSAR), SMAP, ALOS, permafrost, Arctic tundra soil, active layer, freezing, thawing, soil temperature.**

I. Introduction

Currently, the radar data attained by ALOS PALSAR are widely used in the differential interferometry to monitor the earth surface deformations. Within the next few years, the new spacecrafts (SMAP, ALOS-2), equipped with radars in the L-band will be launched. Feature of L-band radars as compared with other radars is its functioning in a long-wavelength range (23cm), which in most cases solves the problem of temporal decorrelation caused by changes in vegetation and snow cover. The minimum possible time interval between two consecutive radar surveys of the same part of surface is 46 days (ALOS) [1]. However, a different physical state of the soil (moisture, temperature, etc.), between the two successive radar survey, can contribute to the error in determining the deformation of the soil surface. Thus, in [2], it is shown that with using method of the radar interferometry, the error in determining of the soil surface deformation, can reach 2 cm when moisture changes from 0 to 40 %.

This work is supported by the Research Program of the Presidium of the Russian Academy of Sciencies, 2013. Project 4.6.

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The purpose of this work is to study the effect of the layered structure of the topsoil of the Arctic tundra during freezing on the error of determining surface deformation. In the literature, this issue has not been previously considered.

II. Model of a SAR Images

Complex SAR images can be represented without noise component as follow [3]:

$$\mathrm{V_{pq}} = a_{pq}\sqrt{\mathrm{K_s}}\,e^{i\varphi_{\mathrm{p,q}}}\left|S_{pq}\right|, \tag{1}$$

$a_{\mathrm{p,q}}$ – calibration constant, $\mathrm{K_s}$, $\varphi_{\mathrm{p,q}}$ - represent the gain and phase shift imposed respectively by the radar and soil surface on the backscatter, $S_{p,q}$ - scattering matrix. The value of $\varphi_{\mathrm{p,q}}$ can be calculated by the formula [3]

$$\varphi_{p,q} = \varphi_r + 2k_0R + \arg(S_{p,q}) \tag{2}$$

which is the sum of terms representing the round-trip delay between radar and object ($2k_0R$), φ_{r} - internal phase of the radar (transmitter and receiver path delay, phase errors introduced by the processor, phase noise due to system noise). A simple model of surface scattering is given by the Bragg scattering formulation derived as a low-frequency scattering approximation in the microwave band. The corresponding scattering matrix [S] is given by [4]

$$S_{\mathrm{HH}} = \frac{\cos\vartheta - \sqrt{\varepsilon_s - \sin^2\vartheta}}{\cos\vartheta + \sqrt{\varepsilon_s - \sin^2\vartheta}}, \tag{3}$$

$$S_{\mathrm{VV}} = \frac{(\varepsilon_s - 1)\left(\sin^2\vartheta - \varepsilon_s(1+\sin^2\vartheta)\right)}{\left(\varepsilon_s\cos\vartheta + \sqrt{\varepsilon_s - \sin^2\vartheta}\right)^2},$$

$$S_{\mathrm{HV}} = S_{\mathrm{VH}} = 0 \tag{4}$$

ε_{s} - the dielectric constant of the soil surface and θ is an incidence angle.

In the interferometric SAR, surface height difference, Δh, can be retrieved using the phase difference, $\Delta\varphi$, between two SAR images of the same scene. When two or more coherent SAR images of the same scene are formed from (slightly) different look directions, the complex correlation between pairs of images can be evaluated and the system is said to operate as a SAR interferometer (InSAR). Soil surface deformation (height differences), Δh, can be calculated from a phase difference as follows [3]

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$$\Delta h = \Delta\varphi \frac{k_0 R \sin\vartheta}{2B_s \cos(\vartheta - \alpha)}, \quad (5)$$

B_s – baseline is a distance between the fight lines of the two SAR systems, α is a roll angle on the vector representing the baseline separation, ϑ - incident angle, R - is the range between the master SAR and the target on the ground. Based on formulas (3) and (5), we will investigate the impact of a freezing topsoil on determining the Arctic tundra surface deformation using InSAR technique.

In the next session, we introduced the complex dielectric model of the Arctic tundra soil, which was used in scattering model (3).

III. Model of the Complex Dielectric Constant of the Arctic Tundra Soil

Recently, for an organic rich soil, the temperature-dependent generalized refractive mixing dielectric model (TD GRMDM) was introduced in [5]. 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 [5] 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 to 25°C), and frequency (from 0.5 to 15 GHz). It should also be noted, that the model [5] was constructed based on measurements of soil samples in the process of freezing. The dielectric model of the Arctic tundra soil [5] 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 [6]. As an example, Figure 1 shows the refractive index, $n_s = \mathrm{Re}\sqrt{\varepsilon_s(T, m_g, f)}$, and the normalized attenuation coefficient $\kappa_s = \mathrm{Im}\sqrt{\varepsilon_s(T, m_g, f)}$ 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, the U.S. [7].

The profile of the complex dielectric constant of the active topsoil of Arctic tundra can be represent in the form of a symmetric transition layer by the formula [8]:

$$\varepsilon(z) = 2\varepsilon_0 - \varepsilon_\infty + \frac{\varepsilon_\infty - \varepsilon_0}{1 + e^{-m(z - z_0 + d/2)}} + \frac{\varepsilon_\infty - \varepsilon_0}{1 + e^{-m(z - z_0 - d/2)}}, \quad (6)$$

where ε_0, and ε_∞ - dielectric constant at the surface and deep inside into a soil, respectively, m=4.4/b, b is a distance of the leading/falling front rise of the transition layer, z_0 – center of the transition layer, d – thickness of the transition layer. In the following simulation, the parameters in (6) were set equal to: z_0=0.25m, b=0.05cm, $\varepsilon_0=\varepsilon_s(T_{frozen}, m_g, f)$, $\varepsilon_\infty=\varepsilon_s(T_{thawed}, m_g, f)$, T_{frozen}=-30°C, T_{thawed}=25°C, m_g=0.4g/g, r_d=0.3g/cm^3, f=1.26GHz. The profile of the complex dielectric constant in the case d=0.22 m is shown in Fig. 2. As seen from Fig.2, in the ranges of z_0-d/2-b/2<z<0, z_0-d/2-b/2<z<z_0+d/2+b/2 and z_0-d/2<z< z_0+d/2 the soil is frozen and thawed, respectively.

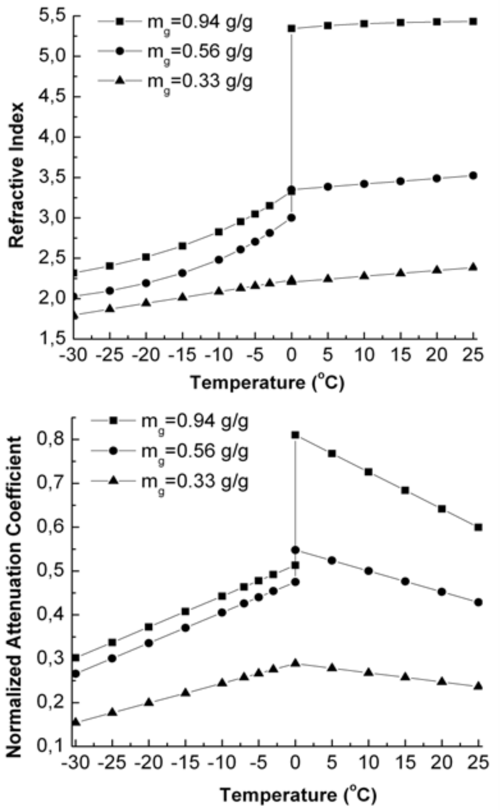

Fig. 1. Temperature dependence of the refractive index and normalized attenuation coefficient for the Arctic tundra soil calculated for the frequency f = 1.3 GHz, soil gravimetric moisture m_g ranging from 0.33 g/g to 0.94 g/g, and soil density of 0.6 g/cm^3.

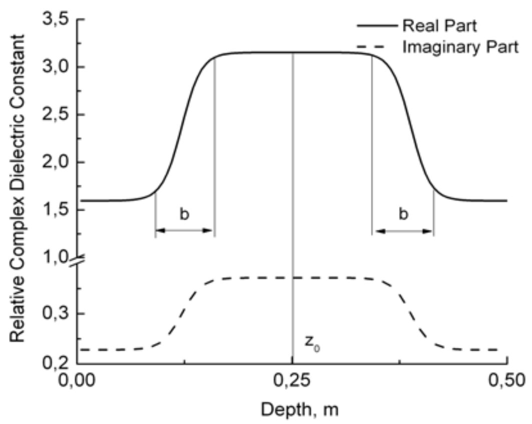

Fig. 2. Modeled profile of the complex dielectric constant of the active layer.

IV. Numerical Modeling of the Arctic Tundra Surface Deformation

For simplicity, let us consider the two-dimensional problem with the flat relief. A pair of radar images will be constructed as follows. The first SAR image will be calculated for thawed topsoil, with thickness of the transition layer being of 0.6m (see formula (6)). The second SAR image will be calculated for freezing topsoil, when a thickness of the transition layer (see formula (6)) can be calculated by the formula:

$$d(x) = 0.6\sin\left|\frac{2\pi}{416}x\right|, \quad (7)$$

where x is a coordinate on the plane of the relief, was set in the range of 0<x<100m, with pixel size of 5m. Using formula (5), we can calculate an apparent relief from two phases, which were determined from two SAR images (see Fig. 3).

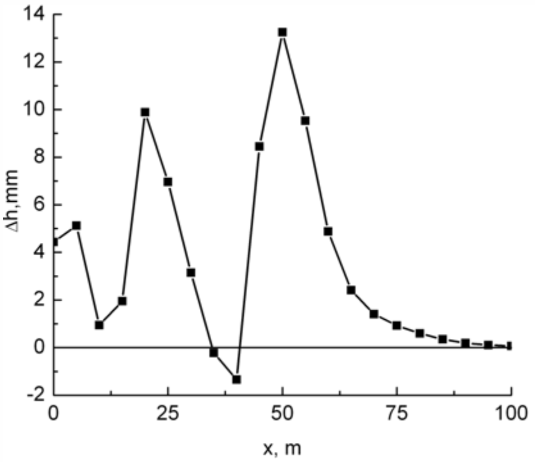

Fig. 3. Soil surface deformation depends on the transition layer thickness. Master satellite height 100 km, baseline 10mm, roll angle is a 20°.

As can be seen from the result, shown in Fig. 3, when the soil is completely thawed, a soil surface displacement is zero (see Fig.3 at x=100m). In the case, when the layer is completely frozen (see Fig. 3 at x=0m) apparent soil relief rise up about 5mm. The oscillation of the retrieved apparent soil relief (see Fig.3) is caused by increasing the thickness of the freezing topsoil and does not exceed 1.5 cm.

V. CONCLUSION

The study shows, that the error in determining the soil surface deformation on the basis of differential interferometry in the case of the surveys taken by the radars SMAP or ALOS-2, first. for completely thawed and, second, for completely frozen soil can reach abpit 0.5cm. However, in the case when the single radar surveys are taken during the process of freezing of the active topsoil, the error of determining soil relief may increase up to 1.5 cm.

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