TESTING SEMI-EMPIRICAL MODEL OF REFLECTION COEFFICIENT BASED ON GNSS-R MEASUREMENTS

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ABSTRACT

In this paper, with using of semi-empirical model of the reflection coefficient, which is implementing to calculate the brightness temperature of the SMOS spacecraft at 1.4GHz in [1], [2] the soil moisture was retrieved from the reflection coefficients, which were measured by GNSS-reflectometer at a test site on the Yamal Peninsula. The model of reflection coefficient with root-mean square error (RMSE) of 0.04 allows to predict the experimental values of the reflection coefficient and with RMSE of less than 0.09cm^3/cm^3 allows to retrieve the soil moisture in the layer of 0-6cm.

Index Terms— GNSS-R, Arctic tundra, Soil moisture.

1. INTRODUCTION

To simulate angular dependencies of brightness temperature in L-band, semi-empirical soil emission *H-Q* model was proposed in [3] and lately was improved in [1], for the purpose of relating the SMOS observations. The emission model in [3] was tested on experimental data from the PORTOS 1993 campaign with predominantly mineral solids in the thawed condition. The emission model was allowed to simulate brightness temperatures with a RMSE of 6 K–7 K and to retrieve of soil moisture with a RMSE of 0.03–0.04 cm^3/cm^3. The emission model [3] has not been previously tested during under satellites field companies in Arctic tundra regions for soil moisture retrieval. In this paper to test the emission model [3], the main element of which is a model of reflection coefficient, is proposed to use the method of Global Navigation Satellite System (GNSS) reflectometry (GNSS-R). The error of model of reflection coefficient will be evaluated from comparing measured in situ to retrieved values of soil moisture. Soil moisture will be retrieved from minimizing the norm of the difference between the measured reflection coefficient and calculated one, with using model of [3]. The reflection coefficients were measured by GNSS-receiver on the test site in the Yamal Peninsula, with using processing method, proposed in [4].

2. TEST SITE AND DATA

As a test site of Arctic tundra was chosen the territory of polar weather station Marresale (WS), which is placed (69.7164 N, 66.8125 E) in the west coast of the Yamal Peninsula (Yamalo-Nenets Autonomous District). The landscape of the test site is predominantly formed by a grassy Arctic tundra with various kinds of herbs and moss growing in moist soils with low shrubs, heights of which is less than 40cm. The total thickness of organic cover (moss, lichen, turf, and peat) is order of 0.1m. Sand and sandy-loam soils predominate in the near-surface (0-30cm) of active layer, which have the following percentages by weight: sand 26-37%, silt 46-63% and clay 11-17% [5]. The chosen test site was relatively flat area 40x40m, with deviation of soil surface heights from the horizontal plane, which does not exceed 0.3m. Average height of soil surface on the test site was ~ 33m above sea level.

In the center of the test site (69.71647N, 66.81073 E) was installed dipole antenna of the GNSS receiver on the height of 4.61m, above ground surface. For receiving of GNSS signal was used GPS and GLONASS L1 MRK-32R receiver, which was made by the SPE "Radiosvayz" (Krasnoyarsk, Russia). Recordings of GLONASS and GPS signals were made daily in August from 12 to 20, 2015. The beginning of the recordings were about 11 o'clock (UTC+3) and duration ones were about 7 hours. In the middle of each recordings, the soil temperature at depths of 0.0cm, 2.5 cm, 5.0cm, 10.0cm and 20.0cm was measured with using an electronic thermometer Testo905-T1; volumetric soil moisture (at three different points of the test site) was measured with using thermogravimetric method in three soil layers: 0-3cm, 3-6cm, 6-9 cm. Mean value and standard deviation of soil moisture, measured at the test site in the layer thickness of 0-3cm, 3-6cm и 6-9 cm, appeared to be 0.32±0.07cm^3/cm^3, 0.68±0.06cm^3/cm^3 и 0.65±0.14cm^3/cm^3, respectively. Mean value and standard deviation of dry bulk density, measured at the test site in the layer thickness of 0-3cm, 3-6cm и 6-9 cm, appeared to be 0.17±0.05 g/cm^3, 0.47±0.18 g/cm^3, 0.74±0.35 g/cm^3, respectively.

3. METHOD OF MEASURING THE REFLECTION COEFFICIENT AND SOIL MOISTURE

The measurement of angular dependence of the reflection coefficient of electromagnetic waves from soil surface is based on the method described in [4]. In accordance with this technique, the angular dependence of signal power at the output of GNSS-receiver are measured. Typical signal power at the output of GNSS-receiver due to as satellites rises above the horizon are depicted in Fig. 1.

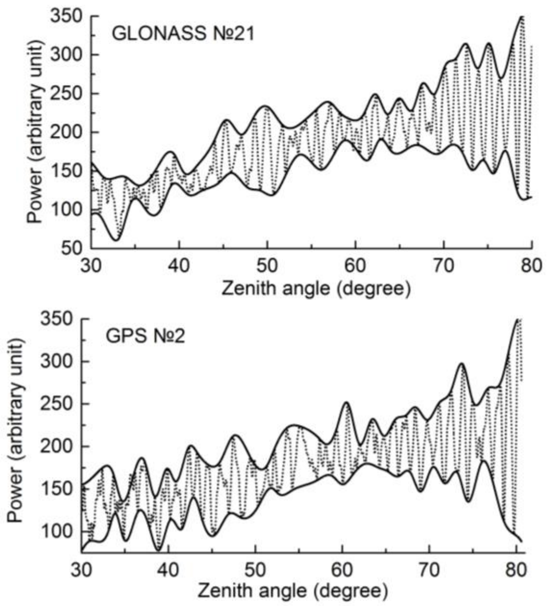

Fig. 1. Interference patterns of GLONASS №21 and GPS №2 signals. Recording of signals were made August 17, 2015 from 10h 02m 09s to 19h 36m 17s (UTC+3).

The total power recoded by GNSS-receiver, equipped antenna with vertical polarization, placed above the bare soil surface, can be calculated using the formula [4]:

$$P(\theta) = F(\theta) \cdot \left|1 + \left|\Gamma_V(\theta)\right| e^{i\Delta\Phi(\theta)}\right|^2, \qquad (1)$$

where $F(\theta)$ – antenna pattern, $|\Gamma_V(\theta)|$ – module of complex reflection coefficient, $\Gamma_V(\theta)$, $\Delta\Phi(\theta)=\gamma(\theta)+\varphi(\theta)$, $\gamma(\theta)$ – phase of complex reflection coefficient, $\varphi(\theta)=2k_0\,h\cdot\cos(\theta)$ – the phase difference between the direct wave (propagating in a straight line from the satellite to the receiver) and the reflected wave from the soil surface, $k_0=2\pi f/c$ – wave number of vacuum, f is the GPS and GLONASS working frequency, h – antenna height of GNSS receiver, θ – zenith angle, c – velocity of light in vacuum. A simple model (1) allows to derive expression for upper, $P_{up}(\theta)$, and lower, $P_{low}(\theta)$, envelopes of an interference pattern

$$P_{up}(\theta)=F(\theta)\cdot(1+|\Gamma_V(\theta)|)^2, \qquad (2a)$$

$$P_{low}(\theta)=F(\theta)\cdot(1-|\Gamma_V(\theta)|)^2. \qquad (2b)$$

From (2) can easy obtain an analytical expression for the square of module of the reflection coefficient:

$$|\Gamma_V(\theta)| = \left(\frac{\sqrt{P_{up}(\theta)} - \sqrt{P_{low}(\theta)}}{\sqrt{P_{up}(\theta)} + \sqrt{P_{low}(\theta)}}\right)^2. \qquad (3)$$

Using the formula (3) and the interference diagrams, which have been measured during the expedition in August 12-20, 2015, similar to that shown in Fig. 1, the reflection coefficients were retrieved. As can be seen from Fig.1 envelopes of interference patterns oscillates and have many local maximum and minimum. The oscillations in the envelopes of interference patterns can be attributed to local changes in amplitude of reflection coefficient, and to local changes zenith angle (due to topography). On average, in every day, 20 and 24 of the angular dependence of reflection coefficients were obtained from interference patterns of GLONASS and GPS satellites, respectively. From the measured angular dependence of reflection coefficients, the soil moisture was retrieved. The retrieving algorithm was based on minimizing the norm of the difference between the measured reflection coefficient and calculated one, with using model which is described in the next section.

4. MODEL OF THE REFLECTION COEFFICIENT

To calculate the module, $|\Gamma_V(\theta)|$, of reflection coefficient at vertical polarization, as a function of zenith angle, θ, we used the semi-empirical model for reflectivity in the case of bare soil introduced in [3] and further developed in [1]:

$$\left|\Gamma_V(\theta)\right| = \left((1-Q)\left|R_V(\theta,\varepsilon_s)\right|^2 + Q\left|R_H(\theta,\varepsilon_s)\right|^2\right) \cdot e^{-H_r \cos^{N_V}\theta}, \qquad (4)$$

Here parameter $Q=0{,}1771\cdot H_r$ may be interpreted as a depolarization factor, which accounts for polarization mixing effects, H_r is the soil surface roughness parameter, $R_V(\theta)$ and $R_H(\theta)$ are the reflection coefficient from smooth soil surface, $N_V=0{,}767\cdot H_r$ - 0,099. The model (4) is used for brightness temperature modeling of bare soil and was estimated from the experiments [1, Table 2] carried out with predominantly mineral solids in the thawed condition, with respect to only one specific location (PORTOS 1993 data set, Avignon, France). To link standard deviation of heights of soil surface, S_D, with the soil surface roughness parameter, H_r, the following formula was used [6]:

$$H_r=(0.9437\cdot S_D/(0.8865 S_D+2.2913))^6 \qquad (5)$$

To calculate the reflection coefficients of $R_V(\theta, \varepsilon_s)$ and $R_H(\theta, \varepsilon_s)$ in formula (4) we will be assumed that volumetric soil moisture, m_v has layered structure of $m_v(z<0$ and $z\geq -d) = m_{v1}$, $m_v(z<-d) = m_{v2}$, here z is a vertical coordinate, where an air-soil interface is at $z=0$. The reflection coefficients of $R_V(\theta, \varepsilon_s)$ and $R_H(\theta, \varepsilon_s)$ in formula (4) will be calculated with using model of reflection coefficients for single slab layer, thickness of d:

$$R_{H,V}(\theta, m_{v1}, m_{v2}, d) = \frac{r_{1,H,V}(\theta,\varepsilon_1) + r_{2,H,V}(\theta,\varepsilon_{1,2})e^{-2ik_0dw}}{1 + r_{1,H,V}(\theta,\varepsilon_1)r_{2,H,V}(\theta,\varepsilon_{1,2})e^{-2ik_0dw}}, \quad (6)$$

where $w = \sqrt{\varepsilon_1 - \sin^2\theta}$, $r_{1,H,V}(\theta,\varepsilon_1)$ and $r_{2,H,V}(\theta,\varepsilon_{1,2})$ are the Fresnel reflection coefficients at horizontal (H) and vertical (V) polarizations from z=0 and z=-d interface, $\varepsilon_1=\varepsilon(m_{v1})$ and $\varepsilon_2=\varepsilon(m_{v2})$ are the complex permittivity of soil, ε, with volumetric soil moisture m_{v1} and m_{v2}, respectively. To calculate complex permittivity of soil was used temperature dependent multi-relaxation spectral dielectric model (TD MRSDM) [7], which was created with using of soil samples collected at the area close to the test site. The sample was extracted from the organic layer at depths from 9 to 14 cm, and it consists of mineral solids and decomposed organic matter. The percentages by weight of organic matter components was about ~50%. The TD MRSDM allows to calculate complex permittivity for the given organic-rich soil as a function of soil dry density, ρ_d, gravimetric soil moisture, 0.03 g/g < $m_g=m_v/\rho_d$ < 0.55 g/g, wave frequency, 0.05 GHz < f < 15 GHz, and soil temperature, –30°C< T_s< 25°C. The values of determination coefficient for the real and imaginary parts of complex permittivity were found to be 0.997 and 0.991, respectively. While the estimates of the RMSE of the predicted values relative to the measured ones, yielded the following values 0.348 and 0.188 in the cases of real and imaginary parts of complex permittivity, respectively [7]. Soil complex permittivity was calculated using the average value (0.32 g/cm^3) of soil dry bulk density measured *in situ* at the test site in 0-6cm topsoil layer.

According to equations (4) and (6) four values were derived for minimizing the residual norm between the measured and calculated reflection coefficients: m_{v1}, m_{v2}, H_r, and d. To matching of the retrieved values of m_{v1}, m_{v2}, with measured values of soil moisture in the layers of 0-3cm, 3-6cm, we represent the distribution of moisture in the soil at the depth of d in the form of Taylor series:

$$m_v(z)=m_{v2}+(m_{v2}-m_{v1})\cdot(z-d)/d. \quad (7)$$

If assumed a linear dependence of the change of soil moisture in the layer 0-6cm, then average values of soil moisture in the layer 0-3cm, 3-6cm can be calculated from the formula:

$$m_{v0-3} = \frac{m_{v1} + m_v(z=3cm)}{2}, \qquad m_{v3-6} = \frac{m_v(z=3cm) + m_v(z=6cm)}{2}. \quad (8)$$

With using the interference diagrams, similar to that are shown in Fig. 1, which were measured on a test site in August, 17, and formulas (4) - (6) four parameters: m_{v1}, m_{v2}, H_r, d were retrieved, and using the formulas (8) soil moisture in the layer 0-3cm and 3-6cm were calculated.

5. RESULT AND DISCUSSION

The retrieved and *in situ* measured soil moisture are shown in Fig. 2. It can be seen (Fig. 2), that the values of soil moisture measured with using both GLONASS and GPS interference patterns at different layers, are in a good agreement with each other.

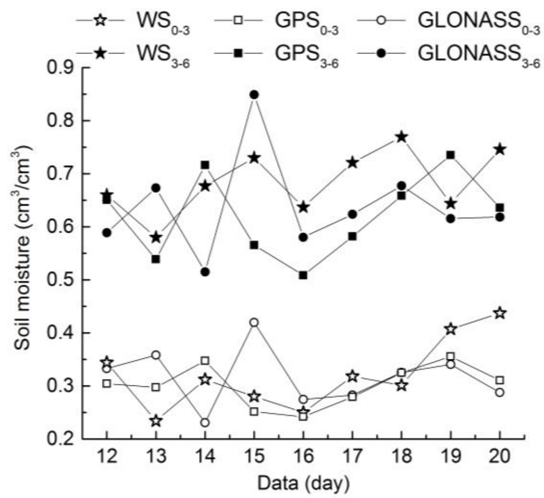

Fig. 2. Soil moisture in-situ measured and retrieved from GPS and GLONASS interference patterns at the layer of 0-3cm and 3-6cm. A date postponed in the days of August, 2015.

Correlation between retrieved and in-situ measured soil moisture are shown in Fig. 3.

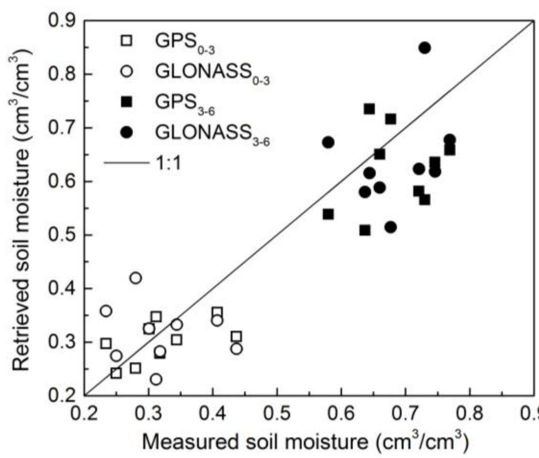

Fig. 3. Correlation between retrieved from GLONASS(GPS) interference patterns and measured soil moisture values at the test site in the layer of 0-3cm, 3-6cm.

Thus, retrieved values of the soil moisture deviated from the *in situ* measured ones by the RMSE factor equal of 0.08cm^3/cm^3 and 0.09cm^3/ cm^3 in case of using GPS and GLONASS interference patterns, respectively. Thus, retrieved values of the soil moisture deviated from the *in situ* measured ones by the RMSE factor equal of 0.08cm^3/cm^3 and 0.09cm^3/ cm^3 in case of using GPS and GLONASS interference patterns, respectively. Corresponding values of determination coefficient appeared to be 0.82 and 0.73, respectively. Mean value and standard deviation of retrieved thickness, d of soil layer with soil moisture m_{v1}, soil surface roughness, S_D are found to be 0.019±0.008m and 26±23mm for GPS, 0.017±0.006m and 28±21mm for GLONASS interference patterns. As an example in Fig. 4 the measured and calculated reflection coefficients are shown.

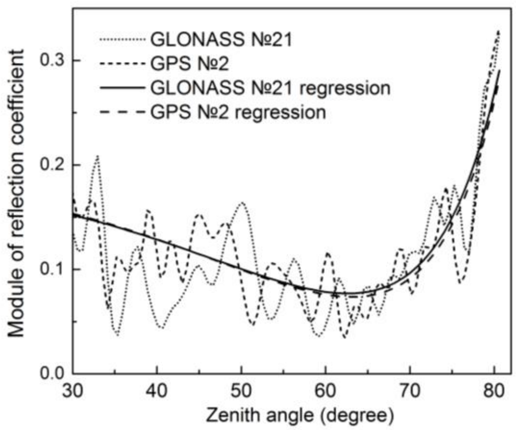

Fig. 4. Model of measured and retrieved reflection coefficients depending on zenith angle of GLONASS №21 and GPS №2 satellites.

Measured values of reflection coefficients were obtained from interference patterns, depicted in Fig. 1, after processing with using formula (3). Calculated values of reflection coefficients were obtained with using formula (4)-(6) and optimum found parameters of m_{v1}=0.08 cm^3/cm^3, m_{v2}=0.35 cm^3/cm^3, S_D=23mm, d=0.020m, and m_{v1}=0.09 cm^3/cm^3, m_{v2}=0.32 cm^3/cm^3, S_D=24mm, d=0.018m after solving of minimizing problem for GLONASS and GPS interference patterns, respectively. As can be seen from Fig.4 RMSE between measured and calculated values of reflection coefficients are significant and it is about ±0.04. The factor of oscillations in the envelopes of interference patterns (see Fig. 1) and as a consequence of changes in amplitude of reflection coefficient (see Fig.4) is a main source of error at soil moisture retrieval. Anyway, it can be concluded that the errors which are allowed in the models of reflection coefficient (6)-(7) and soil permittivity has a smaller order of smallness in compare to the error of measurement of the reflection coefficient.

7. CONCLUSION

In this paper, with using of semi-empirical model of the reflection coefficient, which is implementing to calculate the brightness temperature of the SMOS spacecraft at 1.4GHz in [1], the soil moisture was retrieved from the reflection coefficients, which were measured by GNSS-reflectometer at a test site on the Yamal Peninsula. The model of reflection coefficient with RMSE of 0.04 allows to predict the experimental values of the reflection coefficient and with RMSE of less than 0.09cm^3/cm^3 allows to retrieve the soil moisture in the layer of 0-6cm. Moreover, the proposed earlier algorithm for measurement of reflection coefficient with using interference patterns obtained by GNSS-reflectometer has been additionally validated.

6. ACKNOWLEDGEMENT

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