First Use of the Meteor-M No. 2/MTVZA-GYa Radiometer for Remote Sensing of Soil Moisture and Temperature in the Arctic Region

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Abstract— In this paper, the results of radiothermal remote sensing of moisture and temperature of thawed soil on a test site in the Taymyr Peninsula using full-polarimetric observations of brightness temperature at the frequency of 10.7 GHz are presented. The brightness temperature data were obtained from MTVZA-GYa radiometer on a board of Meteor-M No. 2 satellite with footprint area near the Norilsk city and Khatanga, the Russia Federation. The MTVZA-GYa data covered the period from January 1 to December 31, 2015. The method to retrieve the soil moisture and temperature was based on solving an inverse problem by minimizing the norm of the residuals between the observed and predicted values of the brightness temperature. The calculation of the brightness temperature was performed using a semi-empirical model of radiothermal emission the parameters of which have been pre-calibrated at the test sites in the area of Norilsk and Khatanga, as well as using a soil dielectric model with high in organic matter. The dielectric model was especially designed based on laboratory measurements of the complex permittivity of the organic-rich soil samples, which were collected at the test site near Norilsk city. As a result, the values of the root-mean-square error between the retrieved and measured soil temperatures and soil moisture were not exceed 6.5$\circ$ 0.06 cm^3/cm^3, respectively for both test sites. These results indicate the perspectives of using the full-polarimetric observations of MTVZA-GYa radiometer on a board of Meteor-M No. 2 satellite in the X-band for the purpose of measuring the soil temperature and soil moisture in the Arctic region.

1. INTRODUCTION

In recent years reliability of the hydrometeorological remote sensing satellites Meteor-M series significantly increased. Preliminary analysis of the measurements of the Meteor-M No. 2/MTVZA-GYa radiometer on Amazon and Antarctic plateau, made from September 1, 2014 to May 30, 2015 shows that the radiometer is stable, radiometric scene have good binding to the terrain [1]. External absolute calibration of the microwave radiometer MTVZA-GYa, made from 31 July to 27 August 2014 over the Amazon forests and near from to the coast of Antarctica in the Pacific Ocean, provides to measure of brightness temperature at the frequencies of 10.65 GHz, 18.7 GHz, 23.8 GHz, 31.5 GHz, 36.7 GHz, 42.0 GHz, 48.0 GHz, 91.65 GHz, on the horizontal and vertical polarization with an error 3–5 K [2]. The main purpose of this work is to investigate the possibility of using Meteor-M No. 2/MTVZA-GYa radiometer data for the development of an algorithm for moisture and temperature retrieval in thawed Arctic tundra soil. The proposed method for moisture and temperature retrieval in thawed tundra soil from radiometric Meteor-M No. 2/MTVZA-GYa data will be based on the generally accepted physical model of soil microwave emission [3], which is currently used in the algorithm of the soil moisture retrieval from multi-frequency, polarimetric observations of brightness temperature of GCOM-W1/AMSR2 radiometer [4] and was previously used in the NASA algorithm for AMSR-E radiometer data interpretation [3]. For the purpose of improving the accuracy of soil moisture retrieval, physical model of microwave emission will be calibrated with taking into account characteristics of MTVZA-GYa radiometer and physico-geographical conditions specific for the territory of the Russian Arctic tundra in the Taimyr Peninsula.

2. TEST SITE AND REMOTE SENSING DATA

As tundra test sites, the area near the airport of Norilsk city (69.4080N, 87.1187E) and Khatanga village (71.9769N, 102.4900E) in Taimyr Peninsula, Krasnoyarsk region were chosen. Hereinafter for brevity these test sites we shall call "Norilsk" and "Khatanga", respectively. Landscape of the test sites is a forest-tundra with undergrowth, formed by dwarf shrubs, mosses and grasses. Within the footprint (89 × 198 km) of MTVZA-GYa radiometer, the landscape of the "Norilsk" test site is characterized by a percentage of: shrub tundra-31.9%, bare soil-30.7%, grass and rare shrubs-22.4%, open water objects-9.3%, forest tundra-3.1%, regularly waterlogged areas of shrub and grassy tundra-1.2%. The landscape of the " Khatanga " test site is characterized by a percentage of: shrub tundra-51.9%, grass and mosses-15.5%, grass and rare shrubs-14.2%, open water objects-6.1%, regularly waterlogged areas of shrub and grassy tundra-4.4%, forest tundra-3.3% and bare soil-3.3%. These data were obtained on the basis of electronic maps of vegetation and water bodies, Global Land Cover 2000 [5]. As a source of remote sensing data the values of brightness temperatures, measured by means of Meteor-M-No. 2/MTVZA-GYa radiometer were used. Radiometer MTVZA-GYa provides a measure of brightness temperature in the windows of atmospheric transparency at the frequency 10.6 GHz at an observation angle of 65° on the vertical and horizontal polarizations. The ascending and descending orbits of Meteor-M No. 2 crosses the equator at 9.30 and 21.30 hours (UTC), respectively. For the analysis in this article, the time series of brightness temperature measured by the radiometer MTVZA-GYa from January 1 to December 31, 2015 over the test sites "Norilsk" and "Khatanga" were used. Due to the fact that the existing network of meteorological stations "Roshydromet" does not carry out the measurement of soil moisture and temperature in the Taimyr Peninsula, as the reference information on soil moisture and temperature will be well-calibrated information products L2_SM_P — "soil moisture" from SMAP satellite and MODIS LST (MOD11A1, MYD11A1) — "the soil surface temperature" from Terra and Aqua satellites.

3. CALIBRATION METHOD OF MICROWAVE EMISSION MODEL

As a physical model of microwave emission of thawed soil, it will be used a model of soil microwave emission, which is currently used as a base model in algorithm of soil moisture retrieval on the basis of radiometric data GCOM-W1 [4]

$$Tb_p = \left\{1 - \left[(1-Q)r_{op}(\varepsilon_s) + Qr_{oq}(\varepsilon_s)\right]e^{-h_r}\right\}T_{eff}, \tag{1}$$

where Q is the polarization mixing ratio, r_{oH} and r_{oV} is the Fresnel reflection coefficient on horizontal and vertical polarization, respectively, $\varepsilon_s(W_s)$ is the complex permittivity of soil, W_s is the volumetric water content in soil, h_r is the roughness parameter, T_{eff} is the effective temperature of soil. The physical model of microwave emission [4], has been modified with using a generalized dielectric model of thawed soil with high in organic matter, which is dominant in the topsoil of Arctic tundra [6]. Calibration of microwave emission model (1) was in the finding averaged in time depolarization parameter, Q, and soil surface roughness parameter, h_r, for the two test sites. Depolarization and soil surface roughness parameters (within simplified approach, they were not dependent on polarization electromagnetic wave) were found in the course of solving the inverse problem at minimizing the norm of residual between values of brightness temperatures on vertical and horizontal polarizations at frequency of 10.7 GHz, which were calculated with using a physical model of microwave emission (1), and measured by means of MTVZA-GYa radiometer. When solving the inverse problem as independent input parameters used values of soil moisture and soil temperature on the test sites, which were taken from well-validated SMAP (L2_SM_P) and MODIS LST (MOD11A1, MYD11A1) information products, respectively. During calibration, the influence of the vegetation cover in the model (1) was neglected, $\tau_c \approx 0$. In order to reduce the influence of vegetation on the determination of the emission model parameters during it's calibration, two time period "minimum biomass" (when soil was in thawed condition) were selected. These time periods were determined as the time from increasing vegetation biomass from minimal value (05.24.2015) to value of 80% (06.18.2015) of the maximum value during growing season 2015 and from decreasing vegetation biomass from value of 80% (17.08.2015) to minimum value of biomass until (9.24.2015). Biomass of tundra cover is calculated on the basis of MODIS NDVI information products (MOD13Q1 and MYD13Q1) from Terra and Aqua with using a calibration formula [7]. Parameters of depolarization and soil surface roughness found during the calibration process are summarized in Table 1.

Values of the roughness and depolarization parameters for the two test sites are close to each other (see Table 1). At the same time, for the test site "Khatanga" observed large standard deviations from the average values of the depolarization and roughness parameters regarding to the "Norilsk" test site. This may be due to the presence at the "Khatanga" test site larger share of shrubs within the MTVZA-GYa radiometer footprint, than on the "Norilsk" test site, which could lead to additional volume scattering of waves on the vegetation elements. The values of the depolarization and roughness parameters were found also for the full vegetation season on the test sites. The values of the depolarization and roughness parameters which were found during the

Table 1: Values of parameters Q and h_r after calibration.

Test sites	$\boldsymbol{Q}$		$\boldsymbol{h_r}$	
	"Minimum biomass"	***Full vegetation cycle***	***"Minimum biomass"***	***Full vegetation cycle***
"Norilsk"	0.21±0.03	0.23±0.03	0.46±0.04	0.47±0.04
"Khatanga"	0.22±0.07	0.23±0.06	0.43±0.09	0.45±0.09

"minimum biomass" and for the full vegetation cycle, close to each other, this may indicate the weak influence of the tundra vegetation on the value of the retrieved parameters. Found values of depolarization and roughness parameters characterize integral temporal and spatial variations of the reflectivity of the soil covers with tundra vegetation, which are typical for the physical and geographical conditions in the Taimyr Peninsula. The parameters of the microwave emission model (1), found during calibration, allow to create algorithm for retrieval of soil moisture and temperature in Arctic tundra in Taimyr Peninsula using Meteor-M No. 2 radiometric data.

4. RETRIEVAL OF SOIL MOISTURE AND TEMPERATURE FROM METEOR-M NO. 2/MTVZA-GYA DATA

Following the calibration of the model (1), brightness temperature is observed on the vertical and horizontal polarization on frequency of 10.7 GHz over tundra, can be represented as a function of two variables: the volumetric soil moisture, W_s, and effective soil temperature, T_{eff}: $Tb_p = Tb_p(W_s, T_{eff})$. Depolarization and roughness parameters in the model (1) were set equal to the average value between two test sites 0.215 and 0.445, respectively (see Table 1). Algorithm of soil moisture and soil temperature retrieval is based on solving the inverse problem by minimizing the residual norm between the values of brightness temperature, measured, and calculated, on the vertical and horizontal polarization simultaneously. Developed algorithm was tested on the two test sites "Norilsk" and "Khatanga". As an example, Figs. 1 and 2 shows the time series of the values of soil moisture and soil temperature, retrieved from Meteor-M No. 2/MTVZA-GYa data regarding to the well-validated SMAP and MODIS LST products.

The RMSE between the retrieved values of soil temperature and soil surface temperature, obtained from MODIS LST product, was no more than 5.9 K, and determination coefficient was no better than 0.37 for the both test sites "Norilsk" and "Khatanga". The RMSE between the retrieved values of soil moisture and soil moisture, obtained from SMAP product, was no more than $0.03\,\text{cm}^3/\text{cm}^3$, at the variation of soil moisture from $0.12\,\text{cm}^3/\text{cm}^3$ to $0.30\,\text{cm}^3/\text{cm}^3$ for the both test sites "Norilsk" and "Khatanga".

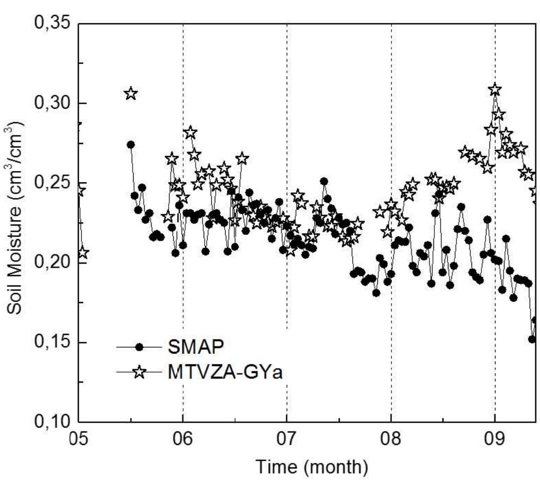

Figure 1: Soil moisture values according to the SMAP product and the retrieved soil moisture from the radiometric data MTVZA-GYa.

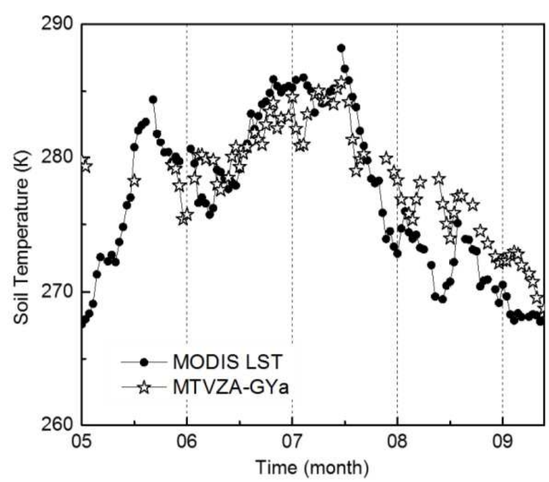

Figure 2: Soil temperature values according to the MODIS LST product and the retrieved soil temperature from the radiometric data MTVZA-GYa.

5. CONCLUSION

The main objective of this work was to study the possibility of using Meteor-M No. 2/MTVZA-GYa radiometer data for the development of the soil moisture and soil temperature retrieval algorithm for the Arctic tundra. The proposed method was based on the generally accepted physical model of microwave emission [3], which is currently used in the algorithm of the soil moisture retrieval from multi-frequency, polarimetric brightness temperature observations of GCOM-W1/AMSR2 radiometer, and was previously used in the NASA algorithm to interpret data AMSR-E radiometer. The physical model of soil microwave emission was calibrated for specific physical and geographical conditions in Russian Arctic tundra on the Taimyr Peninsula. The main element of the algorithm of soil moisture and soil temperature retrieval is the generalized dielectric model of the tundra soils with high organic matter content, the samples to create which were selected on the test site, located on the Taimyr Peninsula. Despite the significant simplification of the microwave emission model, retrieved values of soil temperature and soil moisture with RMSE of 5.9°C and $0.03\,\mathrm{cm}^3/\mathrm{cm}^3$, point to the prospect of creating information product "soil moisture and soil temperature" on the basis of the Meteor-M NO. 2/MTVZA-GYa radiometer data. The next most significant factors should be included in the microwave emission model in order to increase the accuracy of soil temperature and soil moisture retrieval: 1) the effect of vegetation cover; 2) the presence of water bodies and the different kind of soil type within the MTVZA-GYa footprint. In addition, in the future the problem of improve of emission model and algorithm of soil moisture and temperature retrieval should be solved for the active topsoil in process of freezing and thawing.

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