Soil Moisture Retrieval in the North Slope of Alaska From GCOM-W1/AMSR2 and Meteor-M No. 2/MTVZA-GYa Radiometers Data

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Abstract— In this paper, for the Arctic tundra region in the North Slope of Alaska, calibration of microwave emission model on the basis of AMSR2 and MTVZA-GYa radiometric data of the GCOM-W1 and Meteor-M No. 2 satellites, respectively were carried out. The GCOM-W1 and Meteor-M No. 2 brightness temperature data covered the period from January 1, 2012 to December 31, 2016 and January 1 to December 31, 2015, respectively. The peculiarity of the proposed calibration lies in the use of biomass vegetation and soil temperature estimations from the AMSR2 and the MTVZA-GYa radiometers observations with using empirical relationships. To estimate the vegetation biomass and soil temperature were proposed calibration curves linking brightness temperatures, measured by the radiometers, with the aboveground phytomass which was estimated from MODIS NDVI data, and with soil temperature which was measured by weather stations in-situ. As a result was shown that the proposed calibration allows to retrieve soil moisture at the test sites in North Slope of Alaska with determination coefficient of 0.46–0.52 and RMSE of 0.06–0.1 cm^3/cm^3. The study shows the potential possibility of carrying out the calibration of emission model, which improves the accuracy of the measurement of soil moisture in the Arctic region compared to existing satellite information products. This study demonstrates the possibility of using radiometer MTVZA-GYa on aboard of the Russian satellite Meteor-M No. 2 to measure soil moisture in the Arctic region. Found empirical relationships between brightness temperatures and surface soil temperature and aboveground phytomass at the test sites allows to predict these values from GCOM-W1 and Meteor-M No. 2 observations in the range of RMSE 53–54 g/m^2 and 1–1.5 K, respectively.

1. INTRODUCTION

Soil moisture is a key parameter characterizing the integral effect of man-made and natural factors on water, energy and carbon cycles through the land surface in the Arctic ecosystem and is one of fifty essential climate variables recommended by the WMO for observation [1]. In the northern regions (the Russian Federation, the U.S., Canada, and others), measurement of soil moisture is carried out by means of highly rarefied, spatially distributed network of meteorological stations. A small number of these weather stations severely limits the ability to observe climate change and does not provide sufficient numbers of input data into weather and climate models. Modern remote sensing satellites, moving at close to the polar orbits, are capable up to several times a day observe the vast Arctic territories with high spatial resolution, and are an alternative source of soil moisture data, complementing ground-based measurements.

Information products "soil moisture" were created by Japanese, European and American space agencies on the basis of radiometric measurements: AMSR2 radiometer on board GCOM-W1 satellite (multi-frequency, polarimetric method, 10.7 GHz and 36.5 GHz), MIRAS radiometer on board SMOS satellite (multi-angular, polarimetric, one frequency method, 1.4 GHz), and SMAP satellite (one viewing angle, one frequency, 1.4 GHz, polarimetric method), respectively. However, in the most recent studies [2–4] large errors of the satellite information products were shown for the greater part of northern regions in the Russian Federation, U.S. and Canada concerning to the ground truth measurements (standard deviation reaches $\sim 0.25\,cm^3/cm^3$, the determination coefficient ~ 0.3). The authors of the articles associates not sufficient accuracy of these information products with the need to improve emission models with taking into account the specific geophysical conditions in the Arctic regions, with using specific calibration of emission model and physical models of the dielectric constant for the dominant type of soil.

In this paper, we attempt to calibrate the microwave emission model for the test sites in the Arctic tundra on the basis of microwave radiometric data of the GCOM-W1 and Meteor-M No. 2 satellites. Calibration of soil emission model for MTVZA-GYa radiometer on board of the Russian

Meteor-M No. 2 satellite will be carried out for the first time. Based on modified emission model, the soil moisture was retrieved on test sites Toolik Lake and Happy Valley, located in the North Slope of Alaska, U.S. from GCOM-W1/AMSR-2 and Meteor-M No. 2/MTVZA-GYa observation at H-pol and frequency of 10.7 GHz during period from 2012–2016 and 2015, respectively. As a result was shown that modified soil emission model allows more properly retrieve soil moisture in arctic region than full-time satellite model.

2. TEST SITE AND REMOTE SENSING DATA

For the calibration of microwave emission model in Arctic tundra was selected territory of the North Slope of Alaska along south to north transect, including following test sites: Toolik Lake (68.6397 N, −149.3523 W), Happy Valley (69.1466 Nm, −148.8483 W), Sagwon Hills (69.4283 N, −148.7002 W), Franklin Bluffs (69.6739 N, −148.7219 W). These test sites are located on the inner coastal plain with river terraces (Franklin Bluffs), on a north facing slope (Sagwon Hills), on the unglaciated foothills (Happy Valley and Toolik lake). Landcover units include graminoid-moss tundra and graminoid, prostrate-dwarf-shrub, moss tundra with nonacidic soils (Franklin Bluffs), moist acidic and non-acidic tundra (Sagwon Hills), tussock-graminoid, dwarf-shrub tundra and low-shrub moist acidic tundra (Happy Valley and Toolik lake). The areas within the test sites were occupied by soils with vegetation cover ($\sim 98.0\%$) and open water bodies (< 2.0–10%). In accordance with the Arctic atlas [5] on the test sites of Happy Valley and Toolik Lake, one class of vegetation cover is dominated, this is tussock-sedge, shrub, moss tundra (85.7%–98.2% within radiometer footprint). There tussock and nontussock-sedge, dwarf-shrub, moss tundra are covered test sites of the Franklin Bluffs and Sagwon Hill. Unlike Sagwon Hill, the Franklin Bluffs contains a dwarf-shrub wetland. These data were obtained based on electronic maps of vegetation and water on the North Slope of Alaska from the Institute of Arctic Biology of the University of Alaska [5]. The predominant soils are loam and sandy loam with the texture (sand 31.7–47.9%, silt 39.8–49.0% and clay 12.3–19.3%) in the near-surface active layer (0–30 cm) in the test site [6]. At the test sites, the average daily soil surface temperatures are measured by biophysical weather stations and these data are available at the web site [7, 8] over the period from 2012–2015. Moreover, Happy Valley and Toolik Lake weather stations carries out measurements of soil moisture at the depth of 11 cm and 5 cm, respectively.

The brightness temperature data for night and day orbits at vertical and horizontal polarizations at the frequencies of 10.7 GHz, 18.7 GHz, 36.6 GHz and 89.0 GHz were acquired for test sites from GCOM-W1/AMSR2 and Meteor-M No. 2/MTVZA-GYa satellites and were used to calibrate microwave emission model. More detailed information regarding MTVZA-GYa radiometer on a board of Meteor-M No. 2 satellite can be found in [9]. To estimate above ground phytomass in the Arctic tundra was used auxiliary MODIS NDVI data.

3. CALIBRATION METHOD OF MICROWAVE EMISSION MODEL

Due to the fact, that on the frequency of 6.9 GHz RFI is widespread, in this article for the creation of the soil moisture algorithm, the frequency of 10.7 GHz was selected. Since the vertical polarization is most sensitive to soil temperature, to retrieve of soil moisture was selected horizontal polarization (single channel algorithm). If effects of atmosphere, single scattering albedo are ignored, the microwave brightness temperature on the horizontal polarization, Tb_{H10}, of a land surface covered uniformly by vegetation can be expressed as follows [10]

$$Tb_{H10} = \left\{1 - \left[(1-Q)r_{oH}(W_s, C) + Q r_{oV}(W_s, C)\right] e^{-4(k_0\sigma\cos^2\vartheta)^2 - 2bW_c/\cos\vartheta}\right\} T_{\mathit{eff}}, \qquad (1)$$

where Q is the polarization mixing ratio, r_{oH} and r_{oV} is the Fresnel reflection coefficient on horizontal and vertical polarization, respectively, W_s is the volumetric water content in soil, C is the parameter depending of soil texture, k_0 is the free space wave number, σ is the root mean square of soil surface roughness heights, b is the vegetation parameter, depends on the vegetation type, W_c is the phytomass [kg/m^2], $\vartheta = 55^\circ$ and $\vartheta = 65^\circ$ is the fixed viewing angle for the AMSR2 and the MTVZA-GYa radiometers, respectively, T_{eff} is the effective temperature of soil.

For the calculation of brightness temperature, with using formula (1), the following parameters of the model: Q, σ, b are necessary to determine during calibration on the under satellites test sites. These parameters of the model have to be found in the course of solving the inverse problem at minimizing the norm of residual between the calculated and measured values of brightness temperature. In the minimization algorithm, the average value of brightness temperature between ascending and descending satellite orbits were taken. The calibration of the model parameters was carried out on the Toolik Lake test site in period from 2012 to 2016, since the weather station has the most long lines measurements of soil temperature and moisture, which are available from the online database [8]. Parameters found in such manner describe the integral spatial and temporal characteristics of the vegetation cover and soils at the Arctic test site. During calibration process, the Fresnel reflection coefficients calculated with using dielectric model of mineral soil [11] with content of clay fraction equal of 12%. The daily soil moisture values, measured weather station at the depth of 5 cm on the test site, were used as input parameters in the dielectric model [11]. Effective soil temperature in the emission model (1) was estimated from empirical equation, described in next section. Due to the fact that the biomass value can be estimated from measurements MODIS NDVI of the Terra and Aqua satellites only every 8 days, to fill in the missing data, empirical multiple-regression approach using several T_b's channels of AMSR2 and MTVZA-GYa radiometers was proposed for fitting of the MODIS NDVI data. Method of assessing of the arctic aboveground phytomass is described in the next section.

4. EMPIRICAL METHOD FOR REMOTE SENSING ARCTIC ABOVEGROUND PHYTOMASS AND SURFACE SOIL TEMPERATURE USING AMSR2 AND MTVZA-GYA RADIOMETERS DATA

The Normalized Difference Vegetation Index (NDVI) and relationship from [12] was used to calculate an aboveground phytomass, W_c^{MODIS}, in Arctic tundra test sites:

$$W_c^{\mathrm{MODIS}} = \exp\left[(\mathrm{NDVI} - 0.994)/0.383\right]. \quad (2)$$

The regression dependence (2) with significant coefficient of determination ($R^2 = 0.94$) allows to describe relationship between Arctic phytomass, which was sampled at the middle of summer, and NDVI data averaged over 8 km area. For derive this relationship, aboveground phytomass, varied from less than 0.10 to more than 1.20 kg/m^2, was collected [12] from 2003 to 2010 along two trans-Arctic transects, one was on the North Slope of Alaska, U.S. and on the Northwest Territories in Canada and second was on the Yamal Peninsula, Russia. Phytomass for each test sites were calculated every 8 days from 2012 to 2015 with using formula (2) and MODIS NDVI products of Terra and Aqua satellites. The values of MODIS NDVI were averaged over area 43 km × 43 km and between day and night products. Empirical multiple-regression approach, with using several brightness temperature channels of AMSR2 and MTVZA-GYa, was implemented for the fitting of time series of the phytomass values. In this article, the following formula was proposed for the regression of the time series of phytomass values:

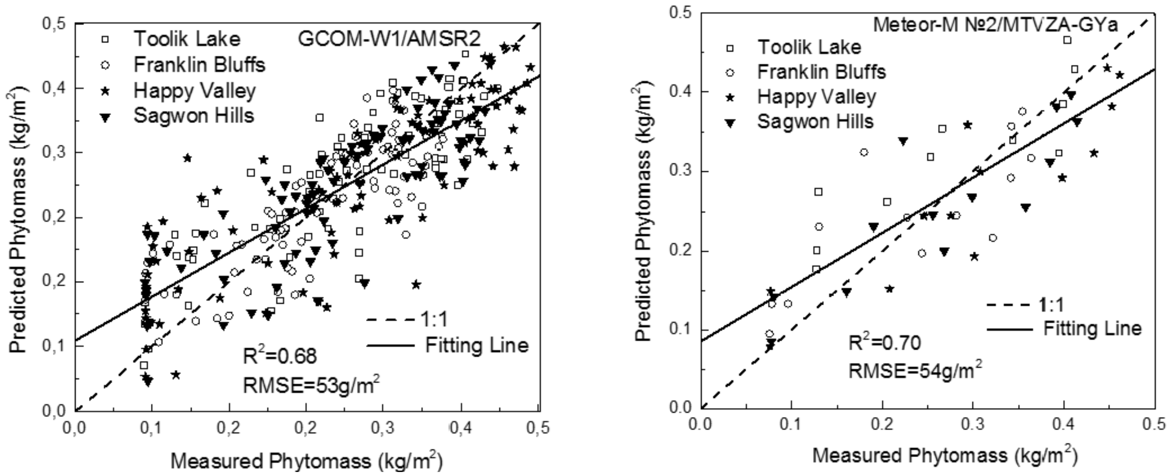
$$\mathrm{NDVI}^{\mathrm{fit}} = c_0 + c_1 Tb_{H10} + c_2 Tb_{V89}, \quad (3a)$$

$$W_c^{\mathrm{fit}} = \exp\left[\left(\mathrm{NDVI}^{\mathrm{fit}} - 0.994\right)/0.383\right], \quad (3b)$$

where Tb_{H10} and Tb_{V89} is the brightness temperature measured AMSR2 or MTVZA-GYa on horizontal polarization and frequency of 10.7 GHz and on vertical polarization and frequency of 89 GHz, respectively. The values of constants $c_0 = -3.4194$, $c_1 = 5.973 \cdot 10^{-3}$, $c_2 = 8.908 \cdot 10^{-3}$ and $c_0 = -3.4057$, $c_1 = 2.499 \cdot 10^{-3}$, $c_2 = 13.180 \cdot 10^{-3}$, respectively for AMSR2 and MTVZA-GYa, have been found in the inverse problem by minimizing the difference between the values of biomass W_c^{MODIS} and W_c^{fit}. In Fig. 1 shows values of biomass, calculated on the basis of formulas (3) using radiometric data of the GCOM-W1 and Meteor-M No. 2 satellites (indicated as predicted phytomass), and calculated based on the formula (3) using the Terra and Aqua NDVI data products (indicated as measured phytomass). To quantitatively estimate an error of the proposed approach, we calculated the RMSE and R^2 relative to the model $W_c^{\mathrm{MODIS}} = W_c^{\mathrm{fit}}$. The results of these estimations are shown in Fig. 1. A relatively high value of determination coefficient and close values of RMSE between the measured and calculated phytomass for both AMSR2 and MTVZA-GYA radiometers can be seen. Formula (3) will be used to calculate phytomass in process of calibration microwave emission model (1).

Further, in order to be able to retrieve soil moisture in areas without weather stations, an empirical formula was obtained, which allows to link the soil surface temperature with brightness temperatures, measured by AMSR2 and Meteor-M No. 2 radiometers:

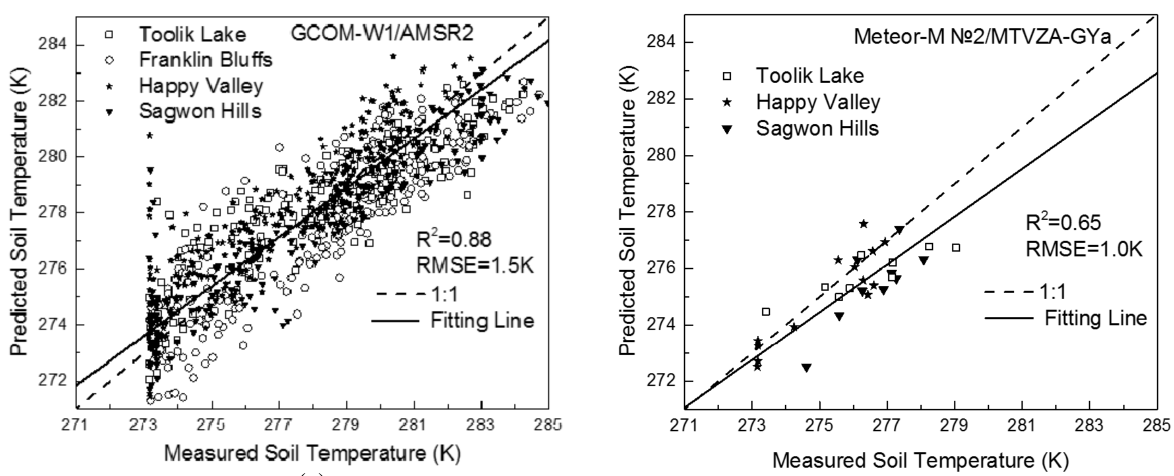
$$T_s = c_0 + c_1 Tb_{V10} + c_2 Tb_{V18} + c_3 \mathrm{MPDI}_{10} + c_4 \mathrm{MPDI}_{36}, \quad (4)$$



(a) (b)

Figure 1: Predicted and measured values of phytomass at the test sites in Arctic tundra in period from 2012 to 2016, derived based on (a) GCOM-W1/AMSR2 radiometric data, (b) Meteor-M No. 2/MTVZA-GYa radiometric data. Fitting line: (a) $y = 0.090 + 0.684x$, (b) $y = 0.085 + 0.689x$.

where $\mathrm{MPDI}_{10,36}$ are the microwave polarization difference index at the frequency of 10.7 GHz and 36.5 GHz, $Tb_{V10,18}$ are the brightness temperatures at the frequency of 10.7 GHz and 18.7 GHz. The values of constants $c_0 = 135.7$, $c_1 = 0.2753$, $c_2 = 0.2735$, $c_3 = 4.8207$, $c_4 = -3.1665$ and $c_0 = 334.9$, $c_1 = -1.0679$, $c_2 = 0.7731$, $c_3 = 2.9324$, $c_4 = -8.6553$, respectively for AMSR2 and MTVZA-GYa, have been found in the inverse problem at minimizing the norm of residual between the values of soil temperature, measured by the weather stations at the test sites and regression formula (4). In Fig. 2 values of soil temperature calculated with using formula (4) based on the GCOM-W1 and Meteor-M No. 2 satellites data (indicated as predicted soil temperature), and measured values of soil temperature by the weather stations at the test sites are shown.



(a) (b)

Figure 2: Predicted and measured values of soil temperature at the test sites in Arctic tundra in period from 2012 to 2015. Fitting line: (a) $y = 33.3 + 0.88x$, (b) $y = 41.6 + 0.85x$.

The results of statistical estimations are shown in Fig. 2. We can see that values of determination coefficients between the measured and predicted soil temperatures are relatively high. Formula (4) will be used to calculate effective soil temperature in process of calibration microwave emission model (1).

5. RESULTS OF CALIBRATION OF THE MICROWAVE EMISSION MODEL AND DISCUSSION

Average values of the polarization mixing ratio, the root mean square of soil surface roughness heights, the vegetation parameter are appeared to be equal of $Q = 0.0$, $\sigma = 0.527$ cm, $b = 0.545$

in case of AMSR2 observations and $Q = 0.0$, $\sigma = 0.512\,\text{cm}$, $b = 0.425$ in case of Meteor-M No. 2 observations. These values were found for the period from 2012 to 2016 in the course of solving the problem of minimizing. Determination coefficient and RMSE between predicted and measured values of brightness temperature were found equal $R^2 = 0.89$ and 1.4 K, respectively in case of AMSR2 observations and $R^2 = 0.65$ and 3.2 K, respectively in case of Meteor-M No. 2 observations. In process of calibration of the emission model (1), the observations of the radiometers were only used when surface soil temperature was positive. Total number of days of AMSR2 observations were 425, MTVZA-GYa-58. It will be noticed that Meteor-M No. 2 was launched in 2014 and in the process of calibration we used only observations during 2015. As an example in Fig. 3 you can see retrieved values of soil moisture at Toolik lake and Happy Valley test sites, which were obtained based on emission model (1) with using average values of the polarization mixing ratio, the root mean square of soil surface roughness heights and the vegetation parameter, which were found in process of calibration. From Fig. 3, it is seen, that for the Toolik Lake test site where the calibration was performed, and the Happy Valley test site where calibration was not carried out, there are good agreement between the retrieved and measured values of soil moisture. Dependencies between soil moisture values, retrieved from observations of AMSR2 and Meteor-M No. 2 and measured by the

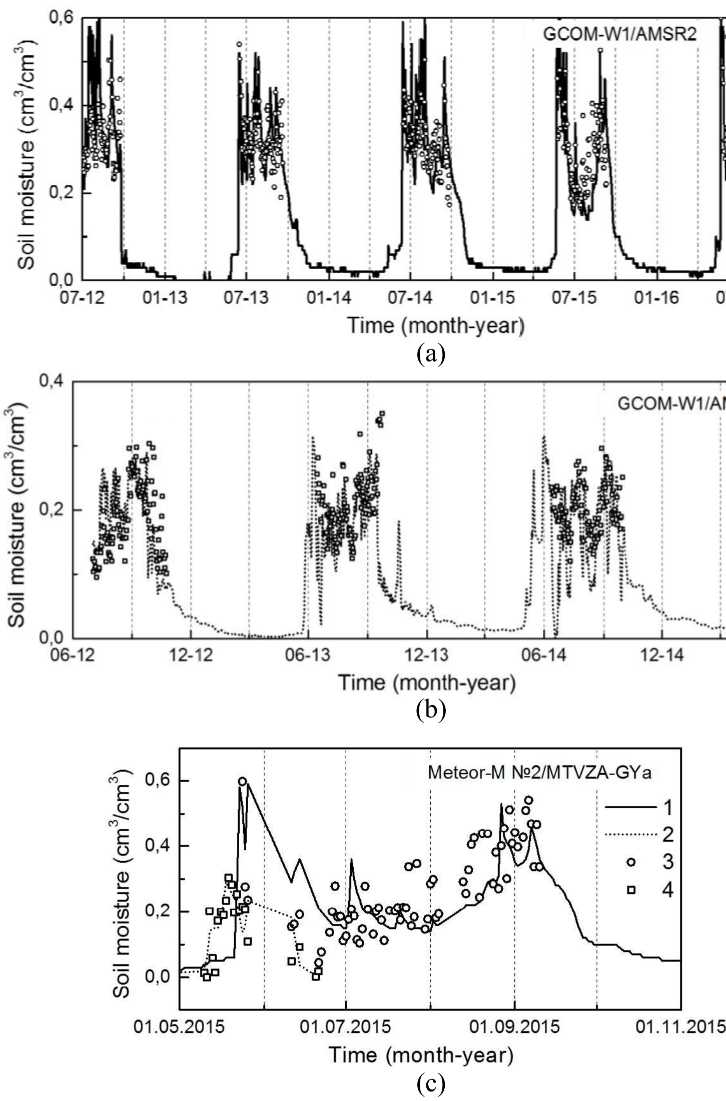


Figure 3: Time series of soil moisture values, which were retrieved from AMSR2 and MTVZA-GYa observations at Toolik lake test site (depicted on panel a and (c) as open circle) and at Happy Valley test site (depicted on panel (b) and (c) as open square), with measured ones by weather stations at the Toolik lake test site (depicted on panel (a) and (c) as solid line) and at the Happy Valley test site (depicted on panel (b) and (c) as dotted line).

weather stations are shown in Fig. 4. Retrieved values of soil moisture from both the AMSR2 and Meteor-M No. 2 observations have a relatively low correlation with the measured ones. The retrieved soil moisture values are overestimated and underestimated with respect to the measured ones in the ranges from $0.0\,\mathrm{cm^3/cm^3}$ to $0.1\,\mathrm{cm^3/cm^3}$ and from $0.45\,\mathrm{cm^3/cm^3}$ to $0.65\,\mathrm{cm^3/cm^3}$, respectively in the case of AMSR2 observations. Qualitative analysis for the Meteor-M No. 2 satellite undertake difficult, as the number of days of the MTVZA-GYa radiometer observations is not sufficiently. However, although the correlation is low, RMSE values are quite good, in the case of AMSR2 observations it is $0.06\,\mathrm{cm^3/cm^3}$, in the case of MTVZA-GYa observations $-0.1\,\mathrm{cm^3/cm^3}$. In this regard, we can conclude that in the range of soil moisture from 0.1 to 0.45 the proposed calibration of the radiometers allows to measure of soil moisture with errors from $0.06\,\mathrm{cm^3/cm^3}$ to $0.1\,\mathrm{cm^3/cm^3}$, in the case when the soil moisture is less than $0.1\,\mathrm{cm^3/cm^3}$ and greater than $0.45\,\mathrm{cm^3/cm^3}$ the proposed calibration can only talk about the assessment of average values of soil moisture.

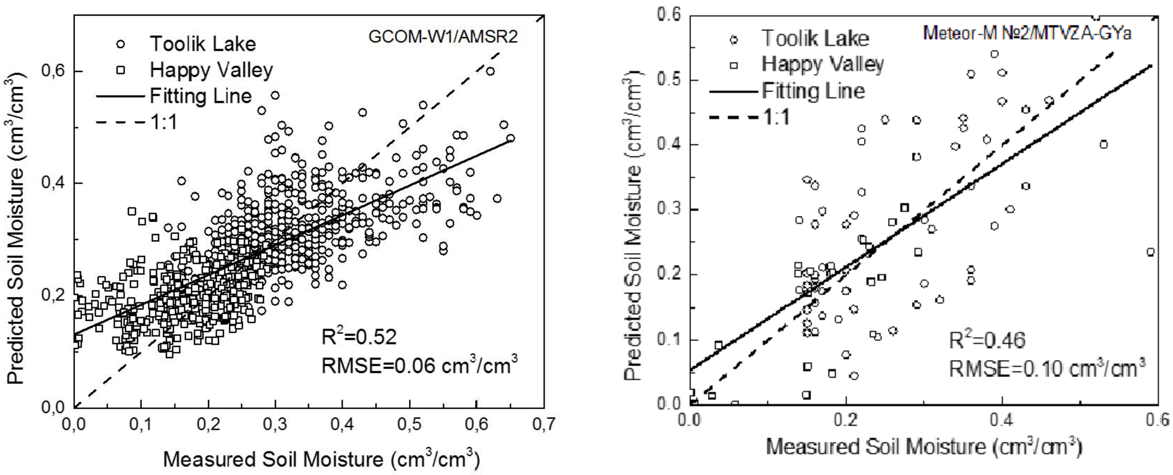


Figure 4: Retrieved values of soil moisture versus to measured ones. Fitting line in case of GCOM-W1: $y = 0.13 + 0.53x$.

6. CONCLUSION

In this paper, we attempt to calibrate microwave soil emission model for the Arctic tundra on the basis of radiometric data of the GCOM-W1 and Meteor-M No. 2 satellites. This calibration is carried out for the first time with using Meteor-M No. 2/MTVZA-GYa radiometer data. The peculiarity of the proposed calibration lies in the use of empirical relationships which to predict values of biomass and soil temperature from the AMSR2 and the AMSR2 and the MTVZA-GYa radiometers observations. For MTVZA-GYa radiometer the empirical relationships were obtained for the first time. As a result was shown that the proposed calibration allows to retrieve of soil moisture on the test sites in the North Slope of Alaska with a determination coefficient and RMSE in the range of 0.46–0.52 and $0.06–0.1\,\mathrm{cm^3/cm^3}$, respectively. It will be noticed, that the soil moisture retrieval with using MTVZA-GYa radiometer data has been performed for the first time. The study shows the potential possibility of carrying out the calibration of emission model, which improves the accuracy of the measurement of soil moisture in the Arctic region compared to existing satellite information products. This study demonstrates the possibility of using radiometer MTVZA-GYa on aboard of the Russian satellite Meteor-M No. 2 to measure soil moisture in the Arctic region.

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