Temperature Dependence of SMOS/MIRAS, GCOM-W1/AMSR2 Brightness Temperature and ALOS/PALSAR Radar Backscattering at Arctic Test Sites

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Abstract— In this study we investigated correlations between soil temperature and radar backscattering coefficient (HH-pol) measured by the ALOS PALSAR at the frequency of 1.26 GHz, and brightness temperatures measured by SMOS/MIRAS (viewing angle 55°, V-pol) at the same frequency and GCOM-W1/AMSR2 (V-pol) in the range of frequencies from 6.9 GHz to 18.7 GHz near Vaskiny Dachi weather station (70.2955N, 68.8835E) over the territory of the Yamal Peninsula. Empirical relationships between brightness temperature, backscattering coefficient and soil temperature have been found, which allow to predict the soil surface temperature on the test site from GCOM-W1 and ALOS PALSAR measurements.

1. INTRODUCTION

Analysis of the literature [1–3] showed that existing empirical models associate the surface soil temperature with brightness temperature, measured at the frequency range from 18.7 GHz to 89 GHz. At the same time, we have not found the studies in which the correlation between the brightness temperature measured by microwave radiometers at the frequency range from 1.4 GHz to 18.7 GHz and the real soil temperature in the Arctic tundra are investigated. In literature, we have not found also experimental studies in which the correlation between the ALOS PALSAR backscattering coefficient and the soil temperature in the Arctic tundra was investigated. This work is devoted to the experimental establishment of such relationships in order to study the possibility of predicting the soil temperature in the Arctic tundra based on microwave radar and radiometric observations.

2. TEST SITE AND DATA

As a test site, the area of Vaskiny Dachi (VD) weather station located in the center of the Yamal Peninsula was selected. The VD coordinates are 70.2955N, 68.8835E. The test site is a typical tundra, covered with non-tussock sedge, moss, lichens, and dwarf shrubs with the height less than 40 cm. The area within the test site was occupied by soils covered with vegetation ($\sim 98.0\%$) and open water bodies ($< 2.0\%$). The vegetation cover was comprised of the areas of erect dwarf-shrub (5.3%), a low-shrub tundra (91.3%) and non-tussock sedge, dwarf-shrub, and moss tundra (3.4%). These data were obtained based on electronic maps for vegetation and water of the Yamal Peninsula from the Institute of Arctic Biology of the University of Alaska [4]. For the area of the test site, the maximum vegetation biomass was equal to 0.3 kg/m^2, which was calculated based on the NDVI index (two-week product of MODIS MOD13Q1) over the time period from July 6 to September 28, 2013. The predominant soils are sand, and sandy loam with the texture (sand 44.5%, silt 41.5% and clay 14.0%) in the near-surface active layer (0–30 cm) of the test site [5]. The predominant soils are sand, and sandy loam with the texture (sand 44.5%, silt 41.5% and clay 14.0%) in the near-surface active layer (0–30 cm) of the test site [5]. The average bulk density of upper organic layer of soil samples was found to be approximately 0.3 g/cm^3. At the test site the average daily soil surface temperatures were provided by the Vaskiny Dachi weather station [6] over the period from January 1 to December 31, 2013. The brightness temperature data on viewing angle of 55 degrees at vertical polarization for frequencies from 1.4 GHz to 18.7 GHz were acquired from Soil Moisture and Ocean Salinity (SMOS) and Global Change Observation Mission-Water (GCOM-W1) at the same time interval and for closest pixels to the VD coordinates. The daily product of brightness temperature for night and day orbits was acquired from GCOM-W1 (JAXA) and SMOS (CATDS).

The twenty four ALOS PALSAR's scenes at a frequency of 1.26 GHz in the wide observation mode (WB1) using HH-polarization over the period from January 15, 2010 to January 18, 2011 were acquired in framework of 4th ALOS Research Announcement, project No. 1422. The descending orbits were used, and the off-nadir angle and pixel spacing were of 27.1° and 100 m, respectively. The used PALSAR data corresponds to the Level 1.5 product. The observation time was around 7 a.m.

(UTM). The PALSAR data were processed using the Next ESA SAR Toolbox. All of the PALSAR scenes were processed with a median filter, the size of window was 100 pixels. As a result, the values of backscatter coefficient corresponded to a pixel size of 10×10 km. Backscatter coefficients were calculated from the PALSAR HH-intensities using the standard calibration formula.

3. RESULTS OF CORRELATION ANALYSIS BETWEEN BRIGHTNESS AND SOIL TEMPERATURES

The correlation analysis between brightness temperature measured at the frequencies of 1.4 GHz, 6.9 GHz, 10.7 GHz, 18.7 GHz, and soil temperature measured at soil surface by the VD weather station at the test site was performed over the period from January 1 to December 31, 2013. The results of the correlation analysis for different frequencies only for the case of day products are presented in Fig. 1.

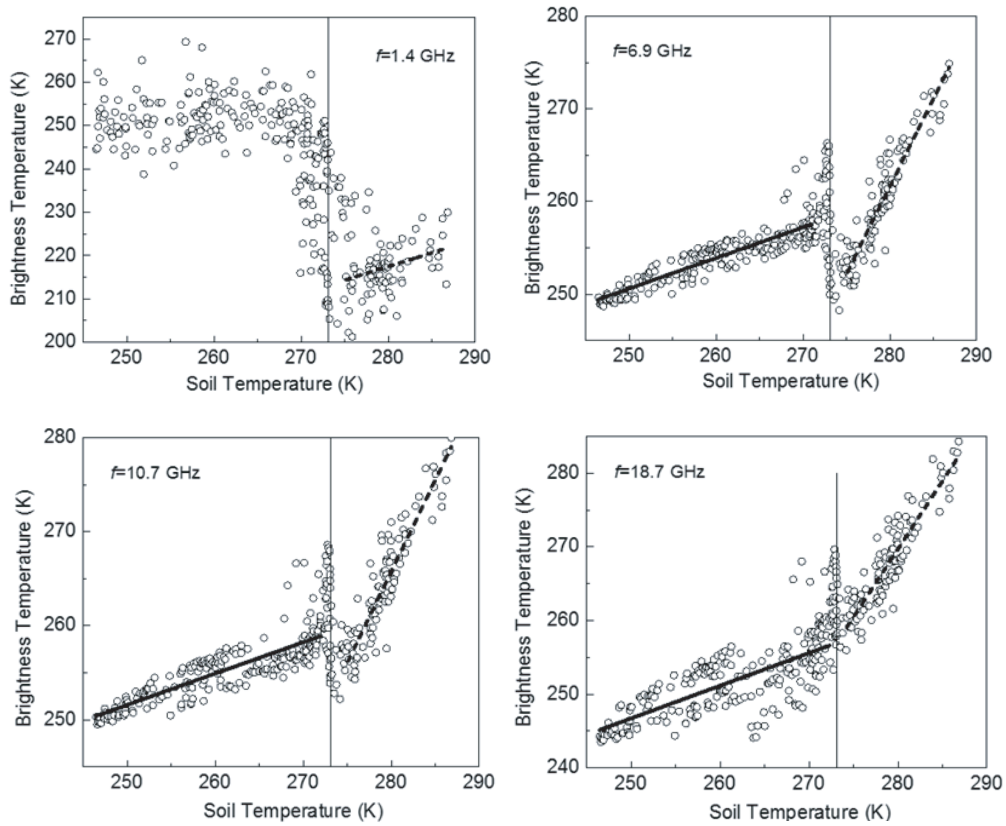

Figure 1: Frequency dependencies of brightness temperature measured at viewing angle of 55 degree for vertical polarization over the test site from January 1 to December 31, 2013 on soil temperature. The parameters of correlation analysis are presented in Table 1.

The correlation were significantly worse in the case of night products. As follow from Fig. 1, the worst correlation between brightness temperature and soil temperature is observed at a frequency of 1.4 GHz. From the GCOM-W1 data analysis follows that the depth of sensing is approximately equal to the thermal emission layer depth, which are limited by 0.5–2.8 cm in the case of thawed soil and could not exceed 6 cm in the case of frozen soil, according to [7]. As shown in [8], the brightness temperatures measured in situ by the radiometer ELBARA at a frequency of 1.4 GHz used in the SMOS mission revealed noticeable variations in the course of freezing of the topsoil layer down to 30 cm. The emission of 30 cm soil layer can not be presented the only value of surface soil temperature. Opposite, the emission have to be characterized by distribution of soil permittivity and temperature in topsoil thickness equal to depth of skin-layer. In the summer, the correlation between brightness temperature observations and soil temperature does not greatly vary at the frequency range from 6.9 GHz to 18.7 GHz. In the winter, the correlation between brightness temperature and soil temperature worsen with increasing of observation frequency due to influence of scattering and reflection of the snow cover. The numerical values of the correlation analysis based on the dependencies depicted in Fig. 1 are summarized in Table 1.

Table 1: Statistics for linear regression shown in Fig. 1.*

	Soil temperature $> 0°$**C**			**Soil temperature** $< 0°$**C**		
Frequency (GHz)	a	b	R^2	a	b	R^2
1.4	41.6	0.63	0.28	-	-	-
6.9	−267.0	1.89	0.93	168.1	0.33	0.89
10.7	−277.7	1.94	0.92	168.5	0.33	0.84
18.7	−246.7	1.84	0.91	135.9	0.44	0.74

*The following notations are used in the table. R^2 is a coefficient of determination; linear regression function is described by the formula: $T_{bv} = a + bT_s$, where T_{bv} is a brightness temperature measured at the vertical polarization, and T_s is a soil temperature; a and b are regression coefficients.

As follows from the data presented in the Table 1, the maximum of correlation coefficient ($R^2 = 0.93$) between soil temperature and brightness temperature measured by the GCOM-W1 was observed at the frequency of 6.9 GHz. The lowest correlation coefficient ($R^2 = 0.28$) between soil temperature and brightness temperature measured by the SMOS was observed at the frequency of 1.4 GHz. The established correlation between the soil temperature (T_s) and the brightness temperature (T_{BV}) measured GCOM-W1 at the frequency of 6.9 GHz for vertical polarization at the angle of 55 degrees allows to offer an empirical formula for the retrieving of soil temperature from the radiometric observations

$$T_s = \begin{cases} (T_{bv} - 168.13)/0.33, & T_s < 0°\text{C}; \\ (T_{bv} + 267.01)/1.89, & T_s \geq 0°\text{C}. \end{cases} \tag{1}$$

Using the formula (1) and the time series of brightness temperature measured by the GCOM-W1 for vertical polarization at the frequency of 6.9 GHz the soil temperature was retrieved in Vaskiny Dachi test site. The measured and retrieved values of soil temperature are presented in Fig. 2. The standard deviation and determination coefficient between the retrieved and measured values of soil temperature were found to be equal to 2.5°C and 0.948, respectively (see Fig. 3).

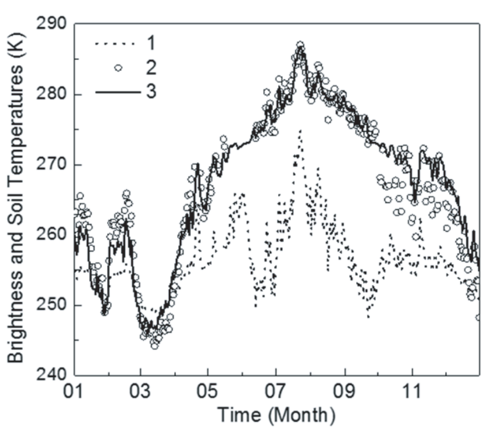

Figure 2: 1 — brightness temperature values measured by GCOM-W1 at the frequency of 6.9 GHz for vertical polarization. 2 — T_s is retrieved on the basis of the formula (1). 3 — the time series of soil temperature (T_s) measured by Vaskiny Dachi weather station at the depth of 0.6 cm (3).

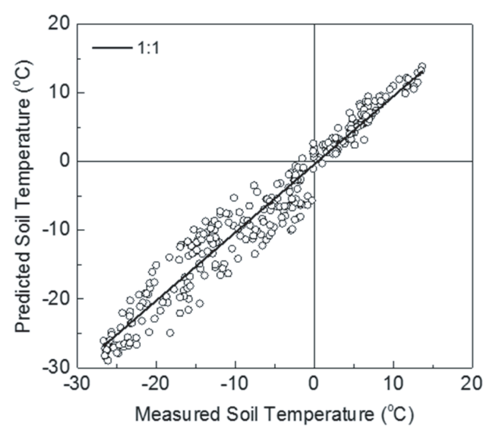

Figure 3: Retrieved values of soil temperature versus to measured ones.

4. RESULTS OF CORRELATION ANALYSIS BETWEEN ALOS PALSAR BACKSCATTERING COEFFICIENT AND SOIL TEMPERATURES

At the test site, with using ALOS PALSAR data, normalized backscattering coefficient (NBC) was calculated: $\sigma_N(t) = 0.5 + (\sigma_{HH}(t) - \sigma^{Summer})/(\sigma^{Summer} - \sigma^{Winter})$, where σ_{HH}^{Summer} and σ_{HH}^{Winter}

are mean values of BC in summer and winter, respectively, $\sigma_{HH}(t)$ is BC at the moment of time t. With using the measured values of soil temperature and the NBC, following parameters were found $T_0 = 4.28 \pm 1.38°\text{C}$, $\Delta T = -28.03 \pm 2.38°\text{C}$, $\sigma_{N0} = -0.29 \pm 0.08$, $\Delta\sigma_N = 0.27 \pm 0.09$ for calibration curve [9], $T_{sp}(T_s) = T_0 + \Delta T/(1 + \exp(\frac{\sigma_N(T_s) - \sigma_{N0}}{\Delta\sigma_N}))$, which is connect NBC with soil temperature (see Fig. 4). Retrieved values of soil temperature, which were calculated with using the calibration curve, are shown in Fig. 5. Standard deviation and determination coefficient between retrieved and measured values of soil temperatures were found to be 6.7°C and 0.51, respectively.

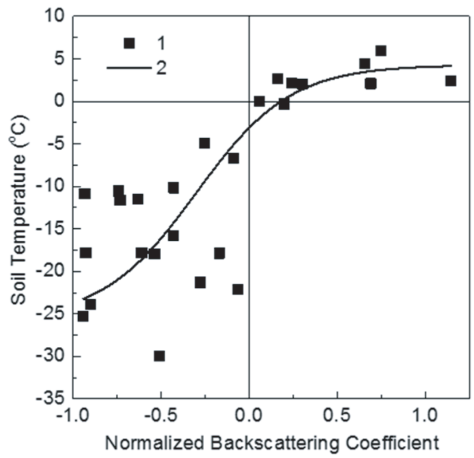

Figure 4: Dependence of the normalized backscattering coefficient (1) respect to measured soil temperature by the VD weather station. Regression curve (2) is calculated based on the calibration formula.

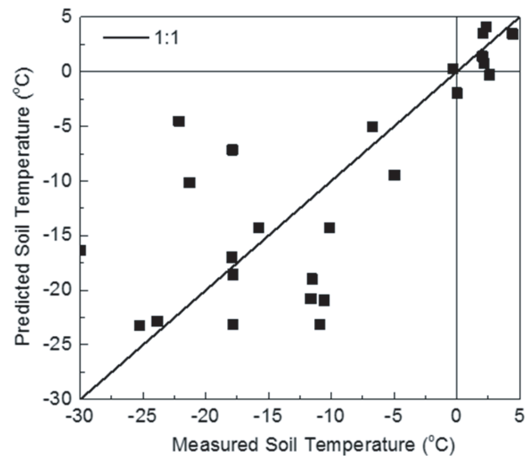

Figure 5: Retrieved values of soil temperature respect to measured ones.

5. CONCLUSION

As a result was shown, during the whole 2013, in the frequency range from 1.4 to 18.7 GHz, the brightness temperature, which was measured at the frequency of 6.9 GHz for vertical polarization and at the viewing angle of 55 degrees, has a maximum value of determination coefficient with respect to the soil surface temperature. Found correlation allowed to offer the calibration curve, based on which is possible to predict soil temperature with an error 2.5°C at the Yamal peninsula test site. In addition, it is shown, that ALOS PALSAR backscattering coefficient correlate to the surface soil temperature. The calibration curve was proposed which allows predicting the soil temperature with an error of 6.7°C The proposed calibrations are greatly simplify the procedure of remote sensing of soil temperature and the thermal state of the active layer in Arctic tundra; however, they are not universal for different territories. Developing the universal calibration curve for different areas of Arctic tundra is still a challenge.

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