Brief communication: Classification of thawed/frozen topsoil state by spectral gradient methods based on SMAP and GCOM-W1 radiometric data

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Abstract. From 2015 to 2020, using spectral gradient radiometric methods, the possibility of frozen/thawed state identification of tundra soils was investigated based on SMAP and GCOM-W1 satellite observations of ten test sites located in the Arctic regions of Canada, Finland, Russia, and U.S.. It is shown that the spectral gradients of brightness temperature and reflectivity, measured on the frequency range from 1.4 GHz to 36.5 GHz on horizontal polarization with a determination coefficient from 0.775 to 0.834, root-mean-square-error from 6.6 days to 10.7 days, and bias from -3.4 days to +6.5 days, make it possible to identify the thawed/frozen state of the tundra soils. Spectral gradient methods have a significantly higher accuracy for identification of frozen and thawed state of tundra soils in relation to single-frequency methods based on the calculation of polarization index.

1 Introduction

Microwave radiometry is a promising all-weather method for remote sensing of seasonal soil thawing and freezing cycles in the Arctic region. The microwave emission changes significantly at the phase transitions of water in wet soil, that makes it possible to identify the thawed/frozen (FT) state of the soil. Recently, both single- and multifrequency radiometric methods for the identifying of FT soil state have been proposed. In single-frequency methods implemented in the algorithms of Soil Moisture and Ocean Salinity (SMOS) (Rautiainen et al., 2016, 2014; Roy et al., 2015) and Soil Moisture Active Passive (SMAP) (Derksen et al., 2017; Dunbar et al., 2016) satellites, the polarization index $PR = \frac{1}{2} \frac{Tb_V(1.4) - Tb_H(1.4)}{Tb_V(1.4) + Tb_H(1.4)}$ is used as an indicator of FT soil state. Here $Tb_H(1.4)$ and $Tb_V(1.4)$ are the brightness temperatures measured at horizontal (H) and vertical (V) polarizations, on a frequency of 1.4 GHz (at a viewing angle of ~40°). The time series of the polarization index PR are normalized to average seasonal maximum (winter) and minimum (summer) PR values, which are determined for specific

landscape types (Rautiainen et al., 2014). The decision on FT state of the soil is made when the normalized PR passes through 0. Hitherto, a space product for identifying FT soil state based on multifrequency radiometric measurements has not been created.

35   However, the possibilities of identifying FT soil state have been studied using the polarimetric data of multifrequency radiometers, such as Scanning Multichannel Microwave Radiometer (SMMR), Special Sensor Microwave/Imager (SSM/I), Advanced Microwave Scanning Radiometer for EOS (AMSR-E), AMSR-2 (at a viewing angle of ~50°-55°). Multifrequency methods for the identifying of FT soil state are based on the assessment of effective temperature, emissivity (Zhao et al., 2011, 2017; Hu et al., 2017, 2019) or reflectivity (Muzalevskiy and Ruzicka, 2020, 2021), as well as the spectral gradient of

40   brightness temperature ($\Delta Tb/\Delta f$) in a wide frequency range from f=10.7 GHz to f=37 GHz (Zuerndorfer et al., 1989, 1990, 1992). Research (Zuerndorfer et al., 1989, 1990, 1992) shows that the correlation diagram between $\Delta Tb/\Delta f$ in the frequency range 10.7 GHz - 37 GHz and the brightness temperature Tb(37) measured on a frequency of 37 GHz is a good indicator of FT soil state (testing mainly for the Great Plains area U.S.). In this method, the brightness temperatures, measured by SSM/I (SMMR), were averaged between horizontal and vertical polarizations. Results showed that low values of Tb(37) and negative

45   values of $\Delta Tb/\Delta f$ are an effective criterion for assessing the frozen state of topsoil. In a study by (Zhao et al., 2011) of agricultural areas in the Haihe River valley, China, ground radiometric measurements showed, that identification of FT soil state using the effective emissivity had higher confidence compared to the spectral gradient of radio brightness temperature. In this case, the effective emissivity was calculated as the ratio of brightness temperatures $Tb_H(18.7)/Tb_V(36.5)$, measured on a frequency of 18.7 GHz in the horizontal polarization (H) and on a frequency of 36.5 GHz in the vertical (V) polarization.

50   The algorithm created for identifying FT soil state (Zhao et al., 2011, 2017; Hu et al., 2017, 2019) was implemented on the basis of Fisher's discriminant analysis (Fisher 1936), where the discriminant function was a linear combination of two attributes: effective emissivity $Tb_H(18.7)/Tb_V(36.5)$ and brightness temperature $Tb_V(36.5)$. In the article by (Muzalevskiy and Ruzicka, 2020), the $MPR = \frac{1}{2}\frac{\Gamma_H(1.4)+\Gamma_V(1.4)}{\Gamma_H(1.4)-\Gamma_V(1.4)}$ polarization index was proposed as an indicator of topsoil FT state, where $\Gamma_H(1.4)$ and $\Gamma_V(1.4)$ are the effective reflectivity of topsoil at horizontal and vertical polarizations, estimated on a frequency of 1.4

55   GHz. In contrast to the effective emissivity in the methods (Zhao et al., 2011, 2017; Hu et al., 2017, 2019), the ratio of reflectivities in the MPR index minimizes the effect of soil roughness and canopy optical thickness. Effective reflectivities $\Gamma_{H,V}(1.4) \equiv 1 - \frac{Tb_{H,V}(1.4)}{Tb_V(6.9)}$ were estimated based on brightness temperatures, measured by SMAP on a frequency of 1.4 GHz and GCOM-W1 at a vertical polarization and a frequency of 6.9 GHz (as an estimation of the effective temperature of topsoil (Muzalevskiy et al., 2016)). A threshold level ~1.0-1.2 in the proposed MPR index, showed a significant correlation with the

60   transitions of the topsoil temperature through 0°C at twelve test sites in the North Slope of Alaska, U.S., the North of Canada, Finland and Russia (Muzalevskiy and Ruzicka, 2020; Muzalevskiy et al., 2021). The proposed method is about 10 days more accurate (Muzalevskiy et al., 2021) to determine the thawed soil state in relation to the standard SMAP-SPL3FTP_E product (Dunbar et al., 2016), when compared with weather station data. Until now, the possibility of reflectivity spectral gradients as indicator of FT soil state has not been studied. In addition, the advantages of wide frequency range brightness temperature

65 spectral gradient, in the L-band is as an indicator of topsoil FT state have not been studied. The development of multifrequency algorithms for classifying topsoil FT state is topical, taking into account that the Copernicus Imaging Microwave Radiometer (Kilic et al. 2018), equipped with a high spatial resolution multispectral polarimetric radiometer 1.4-36.5 GHz (55-5 km) is expected to be launched in 2028.

2 Test sites, ground truth and satellites data

70 Ten test sites equipped with soil-climatic weather stations and located in the Northern regions of U.S., Canada, Finland, and Russia were selected to investigate spectral gradient methods for identifying FT state of tundra and boreal forest topsoil. The coordinates of the test sites and their landscape classification are summarized in Table 1 The landscape classification of the test sites is based on a database from (ESA, 2017). The statistics are given for the averaged pixel footprint area (44 km x 44 km), the centers of which coincided with the coordinates of the weather stations at the test sites.

75 **Table 1** Characteristics of test sites.

Test sites	Region	Longitude/Latitude	Land cover types (%)	Period of observation
Franklin Bluffs (FB)	U.S.	148.7208°W/69.6741°N	e: 81, b: 6, g: 6, f: 4, d: 2	24.08.16-30.31.20
SagMAT/MNT (SG)		148.6739°W/69.4330°N	e: 71, b: 20, g: 3, f: 3, d: 3	01.04.15-22.08.18
Happy Valley (HV)		148.8483°W/69.1466°N	e: 57, b: 38, d: 2, g: 1, f: 1	01.04.15-30.31.20
Imnaviat (IM)		149.3523°W/68.6397°N	e: 78, b: 16, f: 2, d: 2, g: 2	
Banks Island (BI)	Canada	119.5615°W/73.2200°N	e: 97, g: 3	01.04.15-30.06.19
Lake Chisapaw (KJ)		76.3141°W/54.9731°N	a: 60, d: 20, g: 10, e: 9	30.08.16-19.05.19
Sodankylä (SO)	Finland	26.6333°E/67.3621°N	a: 85, c: 12, g: 3	01.04.15-31.05.19
Saariselka (SA)		27.5506°E/68.3302°N	a: 70, c: 23, e: 5, b: 1	
Maresale (MS)	Russia	66.8100°E/69.7100°N	e: 69, g: 11, b: 12, d: 5, a: 3	18.08.15-18.05.19
Cherski (CH)		161.4819°E/68.7475°N	a: 53, c: 20, g: 19, f: 5	01.04.15-31.03.18

a – Forest; b – Grassland; c –Wetland; d – Shrubland; e – Sparse vegetation; f – Bare area; g – Water.

At the North Slope of Alaska test sites soil temperature was measured at a surface (depth of 1cm). FB test site is located in the coastal plain with flat alluvial terrace in a moss tundra landscape with moist nonacidic sedges, and prostrate-shrubs. SG, HV and IM are located on hilly terrain with dominantly moist acidic and non-acidic tussock tundra to the north and considerable

80 shrub growth to the south. The BI test site is formed by gentle hills with sparse vegetation in the form of mosses and grassy meadows. Boreal forest test sites are represented by SO, SA in Finland and KJ in Canada. SO and SA are located in different density forest, non-forest area is covered with juniper, heather and thin layer of lichen and moss. KJ are located in typical Canadian taiga with low-density black spruce-lichen woodland (sandy soils). Soil temperature at the test sites SO, SA and KJ were measured at a depth of 2-5cm. MS test sites located on the Yamal peninsula in moist and dry dwarf shrub-moss-lichen

85 tundra in combination with sedge-moss mires. The soil temperature at MS was measured at a depth of 2-5 cm. The CH area is dominated by wetlands covered with larch forests of varying canopy cover (ranging from 13% to 75%). At CH test site soil temperature was measured in five test plots (which averaged for further analysis) at the interface between the organic and

mineral soil layers, at depths of 6-10 cm below the surface depending on organic layer thickness (Loranty and Alexander, 2021). At the KJ, MS and CH test sites water objects are occupied more than 10% in the pixel area.

90   The brightness temperatures of test sites were measured on vertical and horizontal polarizations by SMAP and GCOM-W1 satellites on a frequencies of 1.4 GHz and 6.9 GHz, 10.7 GHz, 18.7 GHz, 36.5 GHz, respectively. Ascending SMAP and GCOM-W1 orbits were chosen due to the greater variation in seasonal amplitudes of both soil surface temperature, according to weather stations, and brightness temperatures compared to descending orbits. SMAP polarimetric brightness temperature data (SPL3FTP_E) in Northern Hemisphere azimuthal projections on a 9 km Equal-Area Scalable Earth Grid (EASE-Grid 2.0)

95   were used over the test sites in the period of soil temperature observations by the weather stations (see Table 1). GCOM-W1 brightness temperature data were acquired from L1R product, where the brightness temperatures of high-resolution channels are resampled to the effective pixel area of lower resolution channel on a frequency of 6.9GHz, gridded with 12.5 km cell size. The difference in observation angles 40° and 55°, respectively for SMAP and AMSR2, was neglected. Pixels closest to the coordinates of weather stations, with the exception of MS, were used in the analysis. MS is located at the coast of the Kara

100 Sea, thus a pixel whose center is far more than 50 km from the sea was chosen. Daily 9 km EASE-Grid freeze/thaw SMAP product (SPL3FTP_E, both ascending and descending orbits) based on the NPR index (Dunbar et al. 2016) was used for identification freeze/thaw state of land at the test sites.

3 Spectral gradient methods for identifying the thawed-frozen state of topsoil

The spectral components of brightness temperature are formed by the emitting layers of topsoil with different thicknesses. For

105 this reason, the difference between brightness temperatures measured in the different parts of frequency spectrum is related to the vertical (in the direction of the 0z axis) gradient $\frac{\Delta T_s}{\Delta z}\Big|_{z=0}$ of soil temperature T_s, and hence with the direction of the heat flux $J_0 = K \frac{\Delta T_s}{\Delta z}\Big|_{z=0}$, where K is the thermal conductivity, through the soil surface. Indeed (Zuerndorfer and England, 1992), on the basis of the phenomenological theory of emission, the brightness temperature $Tb_p(f)$ of a dielectric half-space with a linear temperature profile can be represented as

110 $$Tb_p(f) = [1 - \Gamma_p(f)]T_{s0} + [1 - \Gamma_p(f)]\frac{\Delta T_s}{\Delta z}\Big|_{z=0} z_{ef}(f), \qquad (1)$$

where f is the frequency electromagnetic field, $\Gamma_p(f)$ is the soil reflectivity in vertical p=V or horizontal p=H polarization, T_{s0} is the temperature of soil surface, $z_{ef}(f)$ is the thickness of emitting layer. From equation (1) it follows, that the density of spectral gradient of brightness temperature is directly proportional to the heat flux through the boundary of the soil surface:

$$\frac{\Delta Tb_p(f)}{\Delta f} = -T_{s0}\frac{\Delta \Gamma_p(f)}{\Delta f} + \frac{1}{K}J_0\frac{\Delta(1-\Gamma_p(f))z_{ef}(f)}{\Delta f}. \qquad (2)$$

115 By analogy with the density of spectral gradient of brightness temperature (2), the density of spectral gradient of reflectivity can be introduced $\Delta\Gamma_p(f)/\Delta f$. For an isothermal and dielectric-homogeneous half-space, the reflectivity at frequency f, in

accordance with the method (Muzalevskiy and Ruzicka, 2020), can be estimated based from equation (1) assuming $\left.\frac{\Delta T_s}{\Delta z}\right|_{z=0} \equiv$ 0:

$$\Gamma_p(f) = 1 - Tb_p(f)/T_{s0}. \tag{3}$$

120   The soil surface temperature T_{s0} can be estimated based on the measurements of brightness temperature $Tb_V(6.9)$ by the GCOM-W1 satellite on a frequency of 6.9 GHz in vertical polarization, the values of which correlate with the surface temperature of tundra soil (Muzalevskiy et al., 2016). The physical basis for this effect is the observation angle of the AMSR-2 radiometer of GCOM-W1 satellite, which is close to the Brewster angle (55º) and this leads to a decreased impact of reflectivity Γ_V on measured brightness temperature $Tb_V(6.9)$. As a result, and as expected from model (3), $Tb_V(6.9)$ becomes

125   mainly directly proportional to soil surface temperature T_{s0}. For this reason, the reflectivity was further estimated only for horizontal polarization. Further, estimates of $\Gamma_H(f)$ will be considered as the apparent values of reflectivity, since the absolute value of $Tb_V(6.9)$ does not coincide with the actual values of the soil surface temperature T_{s0}, but is only proportional to them.

4 Results and Discussion

The time series of brightness temperatures Tb_H, measured by the SMAP and GCOM-W1 satellites, as well as the reflectivity

130   Γ_H, calculated based on formula (3) are shown for the HV test site in Fig. 1a, 1b. For the other test sites, such dependencies are similar. The time series of Tb_H and Γ_H (see Fig. 1a, 1b) has a pronounced seasonal variation with a periodic change in maximum and minimum values. On the dates corresponding to the moment of soil thawing or freezing, the order of brightness temperature and reflectivity values are inverted, along with an increase or decrease in frequency. Several such regions are marked by ovals with a dashed line in Fig. 1a, 1b (see the period 2015-2016). In Fig. 1, these areas are shown on a larger scale.

135   Indeed, as can be seen from Fig. 1 in winter (before May 7, 2016 and after November 1, 2015), the values of brightness temperatures decrease with increasing frequency, i.e. a negative gradient is observed, but in summer the positive gradient is observed (see Fig. 1c, 1d). The seasonal variation of reflectivity has an opposite spectral gradient (see Figs. 1e, 1f) with respect to the spectral gradient of brightness temperature. In the transition region (May 7-19, 2016 and October-November, 2015, see Fig. 1), the spectral gradient of brightness temperature and reflectivity is minimal. In these time intervals, for any pairs of

140   $Tb_H(f_1)$ and $Tb_H(f_2)$, $\Gamma_H(f_1)$ and $\Gamma_H(f_2)$ at different frequencies f_1 and f_2, there is a point of zero spectral gradient (the point of sign change in the spectral gradient), at which the direction of the heat flux must change, in accordance of formula (2). Unlike the methods in which the FT index threshold level is set on the basis of calibration or normalization (Rautiainen et al., 2016; Derksen et al., 2017; Muzalevskiy and Ruzicka, 2020; Muzalevskiy et al., 2021) the zero-threshold level of spectral gradients of brightness temperatures or reflectivity does not require calibration for identification FT topsoil state. FT classification based

145   on the spectral gradient method was applied for the first time by Zuerndorfer et al. (1989).
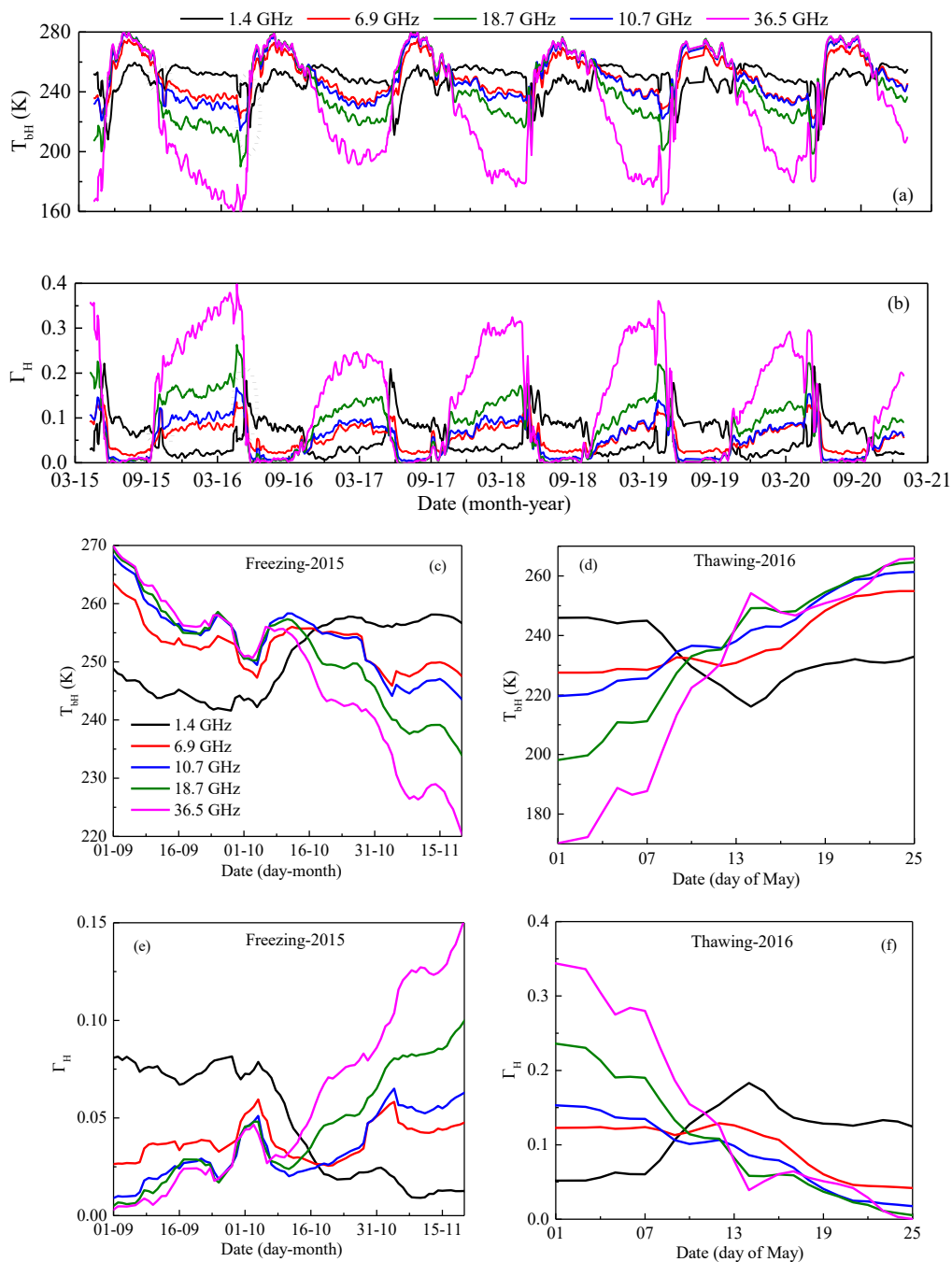
Figure 1. Time series of brightness temperatures (a), (c), (d) and reflectivity (b), (e), (f), according to SMAP and GCOM-W1 satellites data in the frequency range from 1.4 to 36.5 GHz for HV test site. (c) and (e) freezing process in 2015, (d) and (f) thawing process in 2016.

Detailed depictions of the spectral gradient densities of brightness temperature and reflectivity are depicted in Fig. 2. To this end, the spectral gradient densities of brightness temperature and reflectivity for frequency pairs: 1.4-6.9 GHz, 1.4-10.7 GHz, 1.4-18.7 GHz and 1.4-36.5 GHz were calculated (see Fig. 2). The largest variations of brightness temperatures $\Delta Tb_H(f)$ and

150 reflectivites $\Delta\Gamma_H(f)$ with frequency (see Fig. 1) are observed in winter, while the largest variations in the spectral gradient densities of brightness temperature $\Delta Tb_H(f)/\Delta f$ and reflectivity $\Delta\Gamma_H(f)/\Delta f$ (see Fig. 2) are observed in summer. The spectral gradient of brightness temperature and reflectivity (see Fig. 1) is highest in the frequency range of 1.4-36.5 GHz, and the lowest in the frequency range of 1.4-6.9 GHz. This is due to a significant contrast of temperatures and permittivities between the shallow and deeper emitting layers of soil at frequencies of 36.5 GHz and 1.4 GHz, respectively, compared to radiation

155 layers that are close in thicknesses on frequencies of 1.4 GHz and 6.9 GHz. At the same time, per unit interval of the frequency spectrum Δf, the spectral gradient densities of brightness temperature $\Delta Tb_H(f)/\Delta f$ and reflectivity $\Delta\Gamma_H(f)/\Delta f$ seems to be larger for the narrower 1.4-6.98 GHz, than for the wider 1.4-36.5 GHz frequency band (see Fig. 2).
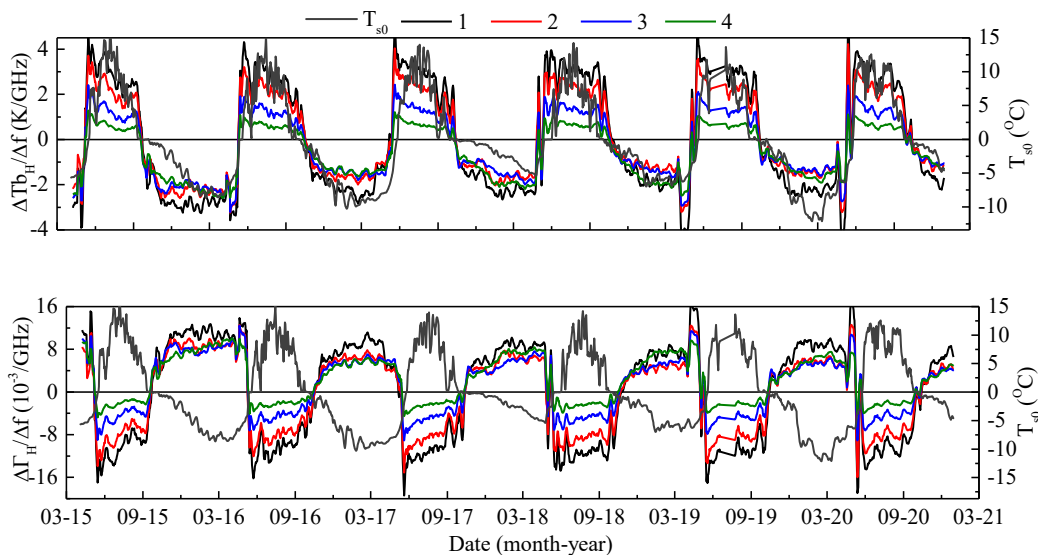
Figure 2. Density of spectral gradients of brightness temperature (a) and reflectivity (b) for HV test site, calculated for the pairs of frequencies: 1) 1.4-6.9 GHz, 2) 1.4-10.7 GHz, 3) 1 .4-18.7 GHz and 4) 1.4-36.5 GHz.

The amplitudes of seasonal variations of $\Delta Tb_H(f)/\Delta f$ are synchronous with variations of surface temperature of soil. The time series of $\Delta\Gamma_H/\Delta f$ varies in antiphase to the soil surface temperature (see Fig. 2). Figure 2 shows, that the time points

160 corresponding to the transitions of $\Delta Tb_H(f)/\Delta f$ and $\Delta\Gamma_H/\Delta f$ through 0 are well correlated with the time of soil surface temperature T_{s0} transition through 0°C. For further analysis, seasonal variations of $\Delta Tb_H(f)/\Delta f$ and $\Delta\Gamma_H/\Delta f$ will be used, the amplitudes of which take maximum (see Fig. 2, curve 1) and minimum (see Fig. 2, curve 4) values in the frequency ranges of 1.4-36.5GHz and 1.4-6.9 GHz, respectively. The soil will be considered frozen or thawed when the soil surface temperature transits through 0°C, according to weather stations installed at test sites. The synchronicity of transition through the zero

165 spectral gradient densities threshold of brightness temperature $\Delta Tb_H/\Delta f$ and reflectivity $\Delta\Gamma_H/\Delta f$ with the soil surface

temperature crossing 0°C were estimated (see Fig. 3).
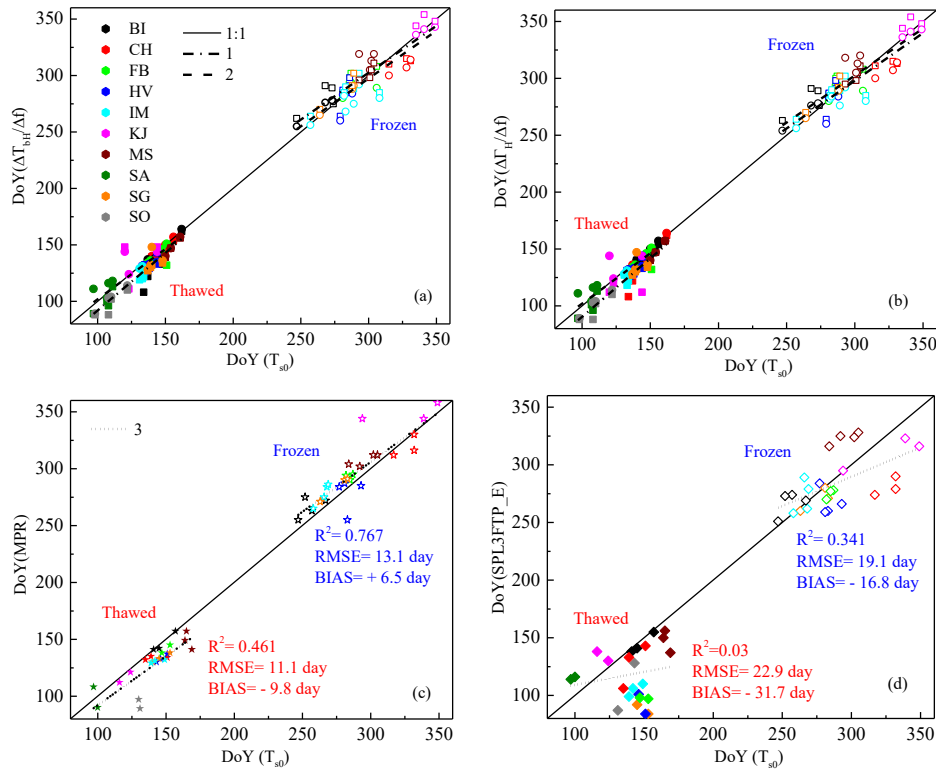
Figure 3. Days of the year (DoY) for which a thawed-frozen state was identified during the stable transition of spectral gradient densities of brightness temperature (a) and reflectivity (b) through zero, depending on the DoY for which a thawed-frozen state was identified during a stable transition of surface soil temperature through 0°C. Similar estimates in the case of index MPR (c) and SMAP SPL3FTP_E product (d). The open and filled symbols indicate the frozen and thawed topsoil state, respectively. Squares and circles indicate the density of spectral gradients in the frequency range of 6.9-1.4 GHz and 36.5-1.4 GHz, respectively. The regression lines correspond to the spectral gradients between pairs of frequencies: 1) 6.9 GHz and 1.4 GHz, 2) 36.5 GHz and 1.4 GHz; 3) regression lines to index MPR and SMAP SPL3FTP_E product.

From the correlation analysis of the data presented in Fig. 3, it follows that the $\Delta Tb_H(f)/\Delta f$ and $\Delta\Gamma_H/\Delta f$ in the frequency range of 6.9-1.4 GHz (36.5-1.4 GHz) determines the thawed state of the topsoil by 8.4-8.9 (1.2-3.3) days earlier, relative to soil

170 surface temperature (see Table 2, systematical error (SE)).

Table 2. Determination coefficient (R^2), root-mean-square-error (RMSE), systematic error (SE) in identifying the FT topsoil state.

	$\Delta Tb_H/\Delta f$				$\Delta\Gamma_H/\Delta f$			
	Thawed		Frozen		Thawed		Frozen	
Δf (GHz)	6,9-1,4	36,5-1,4	6,9-1,4	**36,5-1,4**	6,9-1,4	**36,5-1,4**	6,9-1,4	36,5-1,4

R^2	0,802	0,833	0,819	**0,775**	0,855	**0,834**	0,816	0,784
RMSE (day)	8,5	6,7	9,2	**10,7**	7,1	**6,6**	9,1	10,4
BIAS (day)	-8,4	-3,3	+5,7	**-3,4**	-8,9	**-1,2**	+5,6	+6,5

175   In the frequency range of 6.9-1.4 GHz, the frozen topsoil state is determined on average 5.6-5.7 days later (see Table 2, both indexes). In the frequency range of 36.5-1.4 GHz, $\Delta Tb_H/\Delta f$ makes it possible to determine the frozen topsoil state in 3.4 days earlier, and $\Delta \Gamma_H/\Delta f$ in the frequency range of 6.9-1.4 GHz in 6.5 days later (see SE in Table 2). In general, both indexes $\Delta Tb_H/\Delta f$ and $\Delta \Gamma_H/\Delta f$ have similar values of RMSE in predicting FT topsoil state. At the same time for the identification of a thawed topsoil state, $\Delta \Gamma_H/\Delta f$ has a greater accuracy (see Table 2, SE and RMSE is lower, R^2 is higher compared to $\Delta Tb_H/\Delta f$)

180   in the spectral range of 36.5-1.4 GHz. $\Delta Tb_H/\Delta f$ is more suitable for identifying a frozen topsoil state in the frequency range of 36.5-1.4 GHz (see Table 2), since it has a smaller SE (at comparable RMSE and R^2) with respect to $\Delta \Gamma_H/\Delta f$. It should be noted at correlation analysis (in the case of frozen state) did not take into account SO and SA test sites, since the indexes of $\Delta Tb_H/\Delta f$ and $\Delta \Gamma_H/\Delta f$ led to a systematic error of about 1.5 months, due to unstable soil freezing (soil surface temperature for most of the winter ranged from 0°C to -2°C-4°C according to weather stations). Spectral gradient methods have improved

185   accuracy in identifying FT topsoil state in relation to both the MPR index (see Fig. 3c and Table 2, column in bold) and to the standard SMAP product SPL3FTP_E (see Fig. 3d and Table 2, column in bold).

5 Conclusion

In this article the spectral gradient methods were used to identification FT topsoil state of northern regions based on brightness temperatures measurements from SMAP and GCOM-W1 satellites across a wide frequency range. As criteria for determining

190   FT topsoil state, the spectral gradient densities of brightness temperature and reflectivity were used in the frequency range from 1.4 GHz to 6.9 GHz and from 1.4 GHz to 36.5 GHz. Both criteria give the comparable accuracy of forecasting FT topsoil state for tundra and boreal forest regions. At the same time, to improve the accuracy of thawed topsoil state predictions, the spectral gradient density of reflectivity should be used, but for identification of frozen topsoil state, the spectral gradient density of brightness temperature should be used (the frequency range of 1.4 GHz-36.5 GHz). The methods considered in this work

195   do not fully separate the contributions of FT topsoil state from those of water bodies. The freezing processes of open water areas with the formation of ice, the description of which requires a large number of additional data on snow cover thickness, air and water temperature, and wind speed are particular difficult to account for. If we neglect the influence of water bodies (with less than 19% of the total pixel area), then, as shown in this work, FT topsoil state identification possible with determination coefficient of 0.775-0.834, root-mean-square-error of 6.6-10.7 days, and bias from -3.4 to +6.5 days. Further

200   validation of this methodology, requires expanding the number of test sites, as current analysis is limited by the small number of soil-climatic weather stations with available and up-to-date soil active layer temperature data.

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