SMOS Freeze and Thaw Processing and Dissemination Service

Algorithm Theoretical Baseline Document

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Prepared by

Kimmo Rautiainen, Juha Lemmetyinen, Jaakko Ikonen, Jouni Pulliainen

Finnish Meteorological Institute (FMI)

FINNISH METEOROLOGICAL INSTITUTE

GAMMA REMOTE SENSING

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Document change log

Issue/ Revision	Date	Observations
1.0	22-Dec-2015	First issue
1.1	18-Aug-2016	Updated version
2.0	13-Nov-2018	First version for SMOS Freeze and Thaw Processing and Dissemination Service
2.1	26-Nov-2018	Table 1 and Figure 3 updated
2.2	28-Feb-2019	Table 1: soil state values updated + minor updates

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Table of Contents

1 INTRODUCTION 1

2 INPUT DATA 2

2.1 SMOS DATA 2
2.2 ANCILLARY DATA 2

3 ALGORITHM DESCRIPTION 2

3.1 PHYSICAL BASIS 2
3.2 IMPLEMENTATION 4
3.2.1 IMPORT AND PROCESSING OF CATDS DATA 4
3.2.2 IMPORT AND PROCESSING OF ANCILLARY DATA 4
3.2.3 PROCESSING OF SMOS BRIGHTNESS TEMPERATURE DATA 4
3.3 DEFINITION OF WINTER AND SUMMER REFERENCES 5
3.4 DEFINITION OF THRESHOLD VALUES 6
3.5 PROCESSING MASK 7
3.6 SOIL STATE PRODUCT GENERATION 8

1 Introduction

This document presents the soil freeze and thaw state detection algorithm originally developed within the SMOS+ Innovation Permafrost (ESA ESRIN Contract no: 4000105184/12/I-BG) project and development continued within SMOS+ Frost2Study (ESRIN Contract no: 4000110973/14/NL/FF/lf). The latest version of the algorithm has been finalised within SMOS Freeze and Thaw Processing and Dissemination Service contract (ESRIN Contract no: 4000124500/18/I-EF).

The soil freeze/thaw state algorithm uses a threshold detection approach to determine the average soil state of each SMOS observation grid cell. Reference signatures for frozen and thawed states are defined for each cell from the historical database of observations. Based on comparisons to these references, soil state is categorized into three states: *thawed*, *partially frozen* or *frozen*. Ancillary data on 2 meters air temperature and snow cover are applied to regulate the detection. The ancillary data are used to (1) automatically determine the periods during which the frozen and thaw references can be defined, and to (2) remove obvious errors from the product output.

The soil state detection algorithm uses as input data CATDS (Centre Aval de Traitement des Données SMOS) level 3 brightness temperatures T_B^p, incidence angle range from 50 degrees to 55 degrees (CATDS, 2016).

The theoretical basis of the algorithm has been published in several journal articles (Rautiainen et al., 2012; Rautiainen et al., 2014; Rautiainen et al., 2016)

2 Input data

2.1 SMOS data

The algorithm uses CATDS (Centre Aval de Traitement des Données SMOS) data (level 3 brightness temperatures T_B^p). Current CATDS processor version is 310, which correspond to the level 1 SMOS DPGS version v620. The daily data is gridded and transformed to the ground polarisation reference frame p = H (horizontal), V (vertical). The final product is provided in the global cylindrical Equal-Area Scalable Earth (EASE) Grid 2 projection (1388 x 584 pixels in longitude and latitude direction, respectively). The original SMOS level 3 brightness temperature data are averaged into fixed observation angles θ and binned at 5-degree intervals. The final product is provided as NetCDF files. CATDS (2016).

2.2 Ancillary data

Two ancillary datasets are needed: daily average 2m air temperature data, and daily snow cover data.

The daily 2 m air temperature data is downloaded from the ECMWF database; ERA Interim re-analysis surface layer air temperature data (Dee et al. 2011) for period from 1-June-2010 to 31-July-2018, and NRT data since 1-August-2018. Data are gridded at a spatial resolution of 0.25 $\times$ 0.25 degrees. For both datasets the daily temperature information is given in 6 hour intervals at 00, 06, 12, and 18 hours.

The daily snow cover data consists of the National Oceanic and Atmospheric Administration's (NOAA) / National Environmental Satellite and Information Service (NESDIS) data as well as data from the Interactive Multi-sensor Snow and Ice Mapping System, IMS. The IMS dataset provides daily information on snow cover (Helfrich et al, 2007) at a spatial resolution of 4 km.

3 Algorithm description

3.1 Physical basis

The physical basis of soil F/T detection at passive microwave observations is based on the difference in emissivity between unfrozen and frozen soil. The presence of free liquid water in unfrozen soils increases the effective dielectric constant compared to situation when frozen, thus decreasing emissivity and brightness temperature. On the other hand, freezing of the liquid soil water-phase affects the detected emission in the same way as drying does, *i.e.* emissivity is increased. Figure 1 shows the calculated spectra of the real and imaginary parts of the complex dielectric constant $\varepsilon = \varepsilon' + i \cdot \varepsilon''$ for pure ice and pure water (Mätzler et. al 2006). For liquid water, the real part of the relative dielectric constant is close to $\varepsilon' \approx 90$ at L-band; for fast pure ice it is $\varepsilon' \approx 3.2$ across the microwave range. For higher microwave frequencies, ε of free water is increasingly closer to that of ice, as a consequence of relaxation at $f_r \approx 8$ GHz, thus decreasing the potential contrast in emissivity between water and, for example, moist soils in frozen or unfrozen states.

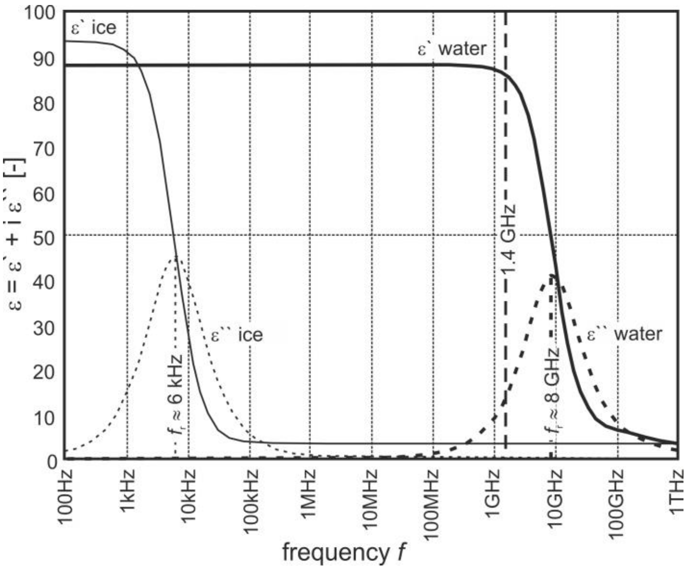

Figure 1. Spectra of the complex relative dielectric constant of pure ice at T = 270 K and pure water at 273 K. Real parts are shown as solid lines and imaginary parts as dashed lines. At L-band (1.4 GHz) the permittivity contrast between the liquid water and ice is very large (figure from Rautiainen et al. 2014)

Changes in the permittivity of soil affect the measured brightness temperatures. The lower the permittivity of the target is, the higher emissivity it has. Following from the Fresnel equations the change of a dielectric contrast between two media will affect the two linear polarizations, horizontal and vertical, differently at incidence angles greater than zero. The power difference of emitted signals between vertical and horizontal polarizations can be expected to be smaller for frozen soil than for unfrozen soil. As a result, the polarization difference ($T_B^V - T_B^H$) is decreased for frozen soil compared to thaw soil situation. The core of the algorithm is based on calculating the normalized polarization ratio (NPR) for each observation. This parameter, following earlier conventions, is called henceforth the Frost Factor (FF_{NPR}), given by:

$$\boldsymbol{FF}_{\mathbf{NPR}} \equiv \frac{\boldsymbol{T}_{\mathbf{B}}^{\mathbf{V}} - \boldsymbol{T}_{\mathbf{B}}^{\mathbf{H}}}{\boldsymbol{T}_{\mathbf{B}}^{\mathbf{V}} + \boldsymbol{T}_{\mathbf{B}}^{\mathbf{H}}}. \quad (1)$$

One advantage of the FF_{NPR} is the inherent insensitivity to physical temperature; which would be required for the direct observation of brightness temperature

3.2 Implementation

The practical implementation of the algorithm is described. The main script of the processing software is written in matlab code. All the re-projection routines are made with GDAL GIS software. GDAL commands use also some Python code extensions.

3.2.1 Import and processing of CATDS data

The relevant information imported from the CATDS input data include:

- Brightness temperatures (BT_V and BT_H in CATDS file)
- Standard deviation (Pixel_BT_Standard_Deviation_H and Pixel_BT_Standard_Deviation_V)
- Number of views (Nviews)
- Radiometric accuracies (Pixel_Radiometric_Accuracy_H and Pixel_Radiometric_Accuracy_V)

In this step data are filtered out according to the following criteria:

1. Negative polarization difference $T_{\mathrm{B}}^{\mathrm{V}} < T_{\mathrm{B}}^{\mathrm{H}}, (p = \mathrm{H}, \mathrm{V})$
2. Too large standard deviation: Pixel_BT_Standard_Deviation_*p* > 20 K
3. Low radiometric accuracy: Pixel_Radiometric_Accuracy_*p* ≥ 4 K

CATDS data includes separate daily files for ascending and descending orbits. These are read, and processed separately. Only data from the northern part of the globe is included (latitudes >= 0 degrees)

Data at incidence angle range of 50°-55° is selected.

3.2.2 Import and processing of ancillary data

The daily ECMWF 2 meters air temperature is firstly averaged (input data includes information at six hour time steps: 00, 06, 12 and 18). Secondly a re-projection is made to the Northern Hemisphere EASE2-grid projection (720x720 pixels).

The ISM snow cover data is a daily gridded information at 4 km spatial resolution. It is re-projected to the Northern Hemisphere EASE2-grid projection (720x720 pixels).

3.2.3 Processing of SMOS brightness temperature data

The main processing phases are the following:

1) Conversion from the brightness temperature data to FF_{NPR} values:

$$\boldsymbol{FF}_{\mathrm{NPR},\boldsymbol{orb}} \equiv \frac{\boldsymbol{T}^{\mathrm{V}}_{\mathrm{B},\boldsymbol{orb}}-\boldsymbol{T}^{\mathrm{H}}_{\mathrm{B},\boldsymbol{orb}}}{\boldsymbol{T}^{\mathrm{V}}_{\mathrm{B},\boldsymbol{orb}}+\boldsymbol{T}^{\mathrm{H}}_{\mathrm{B},\boldsymbol{orb}}}. \quad (2)$$

where, *orb* = ascending, descending orbit. Ascending and descending orbits are processed separately

2) Averaging of data using 20-day moving average (‹$FF_{(t-19 \ldots t0)}$›).

3) Re-projection of the data from cylindrical EASE2-grid projection to the Northern Hemisphere EASE2-grid projection (720x720 pixels).

4) Conversion to relative (rel) frost factor values $FF_{\mathrm{rel},orb}$ in units of percentage accordingly:

$$FF_{\mathrm{rel},orb}(t) \equiv \frac{FF_{orb}(t)-FF_{\mathrm{TH},orb}}{FF_{\mathrm{FR},orb}-FF_{\mathrm{TH},orb}} \cdot 100\%, \quad (3)$$

where, $FF_{\mathrm{FR},orb}$ and $FF_{\mathrm{TH},orb}$ are the empirically defined frozen (FR) and thaw (TH) soil references for each pixel, respectively. They are defined for both orbits (*orb* = ascending, descending). The $FF_{\mathrm{rel},orb}$ value of 100% equals the winter reference, and $FF_{\mathrm{rel},orb}$ = 0% equals the summer reference. The definition of frozen and thaw ground references is explained in more detail in section 3.3.

5) Soil state categorizing

The relative frost factors $FF_{\mathrm{rel},orb}$ were categorized to three soil state categories '*frozen*', '*partially frozen*', and '*thawed*' based on pre-defined threshold values. The threshold values were acquired by comparing $FF_{\mathrm{rel},orb}$ values to *in situ* frost depth *FD* data available from the SYKE (Finnish Environment Institute) frost observation network as described in more detail in section 3.4.

6) Removal of obvious errors

In the final step a processing mask (*PM*) is applied to the categorized soil state dataset to remove clear errors such as soil 'frozen' results during summer conditions, or soil 'thawed' during severe winter conditions. Details on how the PM is determined are given in section 3.5 and details on applying the PM and acquiring the soil freeze/thaw product are given in section 3.6

3.3 Definition of winter and summer references

For the processing of the relative frost factor ($FF_{\mathrm{rel},orb}$), pixel-specific frozen (FR) and thaw (TH) soil references $FF_{\mathrm{FR},orb}$ and $FF_{\mathrm{TH},orb}$ (*orb* = ascending, descending) are required. First, the potential periods when the soil may be in frozen or in thawed conditions are defined. The search logic is shown in Figure 2. The ancillary input data required for this purpose are ECMWF 2m daily average air temperature data (T_{air}) and IMS snow cover data. Using the logic shown in Figure 2 each observation is identified as belonging to one of the following categories: (1) potential frozen soil, (2) potential thaw soil, or (3) not defined. A potential frozen soil condition is captured if the air temperature has been below -3°C and the pixel has a snow cover. A potential thaw soil condition is captured if the air temperature has been above +3°C and there has been over 28 days since the final snow melt-off. The temporal period during which the potential reference observations are searched and identified is from July 1st 2010 to July 31st 2018.

After defining the potential periods representing frozen and thawed conditions, the reference values are determined. First, for both frozen and thaw soil references ($FF_{\mathrm{FR},orb}$ and $FF_{\mathrm{TH},orb}$), the 50 most extreme values are collected; second, the median value is taken to represent the pixel-wise frozen and thaw soil references.

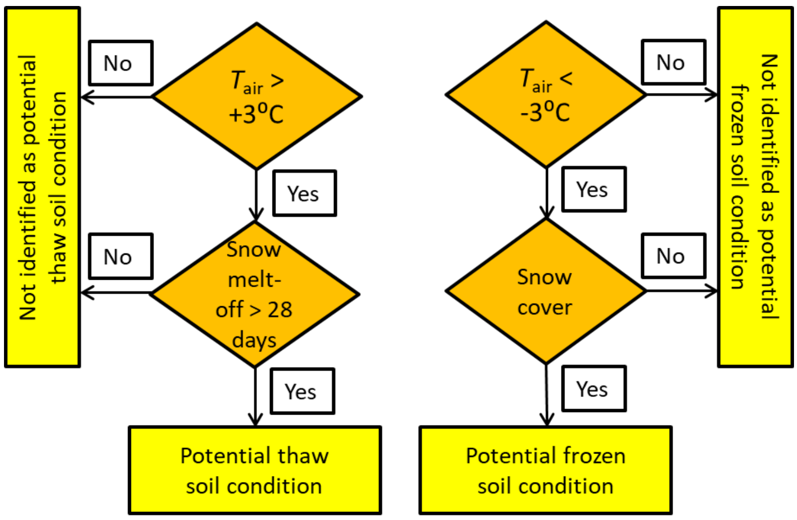

Figure 2. Selection logic for identifying potential thaw and frozen ground observations.

3.4 Definition of threshold values

An empirical exponential model is used to relate relative frost factor $FF_{\mathrm{rel},orb}(FD)$ with observed frost depth *FD*:

$$FF_{\mathrm{rel},orb}(FD) = A_{orb} \cdot (1 - \exp(-B_{orb} \cdot FD)), \quad (4)$$

where A_{orb} and B_{orb} are the fitting parameters (*orb* = ascending, descending). The frost depth observations were acquired from the Finnish Environment Institute (SYKE) network of frost tubes in Finland, selecting only tubes north of the 65 latitude.

Thresholds for soil categorizing are defined as different levels of relative frost factors $FF_{\mathrm{rel},orb}(FD)$. These thresholds are related to the value of the fitting parameter A_{orb}. The relation is given in Table 1. The threshold levels in percentages in respect to frozen and thaw soil references are also given in Table 1. Note: $FF_{\mathrm{rel},orb} = 100\%$ corresponds to frozen soil reference and $FF_{\mathrm{rel},orb} = 0\%$ corresponds to thawed soil reference.

Table 1. Thresholds for the soil state categories in respect to parameter A_{orb} (*orb* = ascending, descending) and in respect to frozen and thaw soil references

soil state: value	soil state: description	categorization condition in terms of $FF_{\mathrm{rel},orb}$ thresholds (%):	Threshold levels in respect to frozen and thaw soil references
1	thawed	$FF_{\mathrm{rel},orb} < 0.6 \cdot A_{orb}$	$FF_{\mathrm{rel},orb} < 50\%$
2	partially frozen	$0.6 \cdot A_{orb} \leq FF_{\mathrm{rel},orb} \leq 0.80 \cdot A_{orb}$	$50\% \leq FF_{\mathrm{rel},orb} \leq 70\%$
3	frozen	$FF_{\mathrm{rel},orb} > 0.80 \cdot A_{orb}$	$FF_{\mathrm{rel},orb} > 70\%$

3.5 Processing mask

For determining the *PM,* air temperatures T_{air} and snow cover ancillary data are used to distinguish the expected season for each EASE grid cell.

The processing mask *PM* has nine values as listed in Table 2. In order to determine *PM*(*t*) for each EASE grid cell for a specific time (day) *t*, a constant set of criteria were used to define each value of *PM*. As several changes from a certain value to another were considered to be unlikely, such as a change from summer (*PM*(*t*) = 1) to the first alarm of spring (*PM*(*t*) = 6) without intermediate autumn and winter periods (*PM*(*t*) = 2,3,4,5), the value given for *PM*(*t*) was restricted by *PM*(*t* - 1) for cases where *the previous value* was available. The allowed transitions between values from *PM*(*t*) to *PM*(*t* + 1) are given in Table 2. The criteria for selecting processing mask values for *PM* (only such values that differ from the previous value) are shown in a block diagram in Figure 3. If no shown criteria is matched *PM*(*t*) equals to *PM*(*t* - 1).

Table 2. The nine values of processing mask *PM*(*t*) for time *t* (day), criteria for their conditions, the respective seasons, and allowed transitions (*PM*(*t*) to *PM*(*t* + 1)). $T_{\mathrm{air}}(t)$ denotes air temperature for time (day) *t* and $\langle T_{\mathrm{air}} \rangle$ denotes average air temperature over 10 days.

PM(t)	Definition	Season	Allowed transitions (PM(t) to PM(t+1))
0	undetermined, initial value only	none	1, 3, 5, 7
1	summer	summer	1, 2
2	late summer	summer	1, 2, 3
3	freezing period, early phase	autumn	2, 3, 4
4	freezing period, longer evolved	autumn	3, 4, 5
5	winter	winter	5, 6
6	late winter	winter	5, 6, 7
7	melting period	spring	5, 7, 8
8	end phase of melting period	spring	1, 7, 8

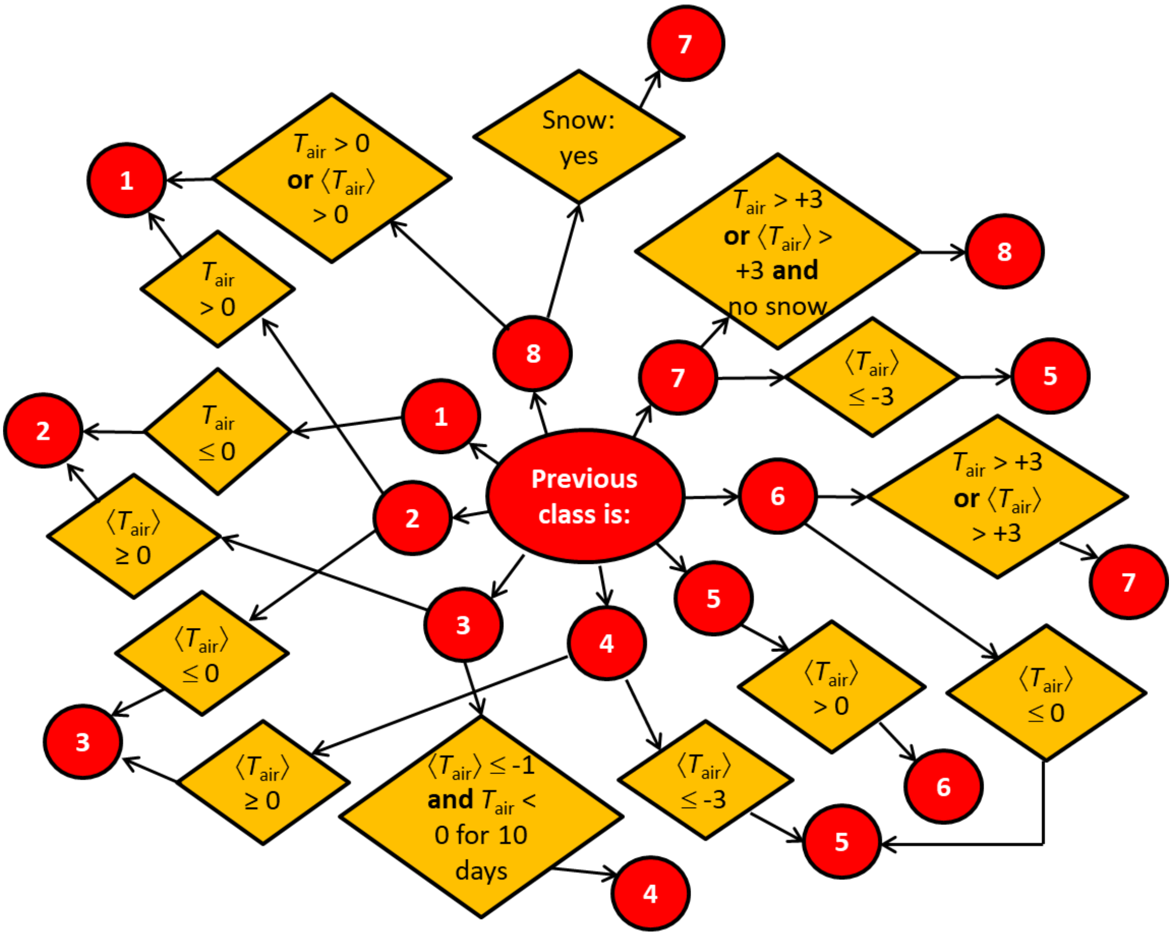

Figure 3. Block diagram of the process on defining the values for *PM*. Value *PM* = 0 is only an initial value.

3.6 Soil state product generation

The effect of applying the processing mask over the categorized soil F/T-state estimate follows the logic summarized in Table 3. For processing mask values $PM(t)$ = 3 or 4, and 7 or 8 (freezing and melting periods, respectively), the mask has no effect on the F/T-state estimates. During summer period ($PM(t)$ = 1 or 2), all soil F/T-state estimates are forced to the thawed soil state category. During the winter period ($PM(t)$ = 5 or 6), the soil state category value is not allowed to decrease; i.e. thawing is not allowed while air temperature T_{air} stays below the selected thresholds shown in Figure 3. No automatic forcing to frozen soil category is applied. It is possible that even during very low temperature conditions, the soil is not frozen due to e.g. thick snow cover that has accumulated prior to sub-zero air temperatures.

Table 3. The processing mask levels and their effect on to the final soil F/T-state estimates.

PM(t)	Effect on to the soil state estimate
1 or 2	forces the soil state to category 0
3 or 4	no effect
5 or 6	no effect, if soil state category value increases but soil thawing (i.e. category value decrease) is not allowed
7 or 8	no effect

The soil state product is a daily data matrix in provided in the Northern Hemisphere EASE grid 2.0 projection. Details on the product are given in the Product Description Document.

References

CATDS (2016). "CATDS-PDC L3TB - Daily global polarised brightness temperature product from SMOS satellite". CATDS (CNES, IFREMER, CESBIO), doi:10.12770/6294e08c-baec-4282-a251-33fee22ec67f.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137(656), 553–597. DOI: 10.1002/qj.828.

Helfrich, S., McNamara, D., Ramsay, B., Baldwin, T., & Kasheta, T. (2007). Enhancements to, and forthcoming developments in the Interactive Multisensor Snow and Ice Mapping System (IMS). *Hydrological Processes*. 21, 1576-1586.

Mätzler C., Ellison, W., Thomas, B., Sihvola, A., & Schwank, M. (2006). Dielectric properties of natural media. In C. Mätzler (Ed.) Thermal Microwave Radiation: Applications for Remote Sensing (pp. 427-539). DOI: 10.1049/PBEW052E.

Rautiainen, K., Lemmetyinen, J., Pulliainen, J., Vehviläinen, J., Drusch, M., Kontu, A., et al. (2012). L-Band radiometer observations of soil processes at boreal and sub-arctic environments. *IEEE Transactions on Geoscience and Remote Sensing*, 50(5), 1483–1497.

Rautiainen, K., Lemmetyinen, J., Schwank, M., Kontu, A., Menard, C.B., Mätzler, C., et al. (2014) Detection of soil freezing from L-band passive microwave observations. *Remote Sensing of Environment*, 147, 206–218. DOI: 10.1016/j.rse.2014.03.007.

Rautiainen, K., Parkkinen, T., Lemmetyinen, J., Schwank, M., Wiesmann, A., Ikonen, J., Derksen, C., Davydov, S., Davydova, A., Boike, J., Langer, M., Drusch, M., Pulliainen, J., (2016) SMOS prototype algorithm for detecting autumn soil freezing Remote Sensing of Environment, SMOS special issue 180:346-360