

SMOS Freeze and Thaw Processing and Dissemination Service

ReadMe-first Technical Note

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Document change log

Issue/ Revision	Date	Observations
0.1	26-Jun-2018	Draft issue for Kick-Off meeting
1.0	28-Nov-2018	Updated version
1.1	28-Feb-2019	Updated based on ESA comments
1.2	05-Mar-2019	Minor modification in Section 1.1 Data access; and in table 2, FT values corrected
1.3	10-Jul-2019	Processor version updated to 2.01, text updated accordingly
2.0	19-Sep-2023	Major update all sections updated
2.1	16-Oct-2023	Minor updates to links and dates
2.2	02-Nov-2023	Table 1 updated

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1 Information on the current data product

Processor version	v3.0 (Level 3 F/T product – L3FT)
Release date	30 October 2023
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Accepted by	Raffaele Crapolicchio Serco Italia SpA - for European Space Agency (ESA)
Further information	Product Description Document (PDD) Algorithm Theoretical Baseline Document (ATBD) https://earth.esa.int/eogateway/catalog/smos-soil-freeze-and-thaw-state
Data access	Data access from FMI dissemination service: http://nsdc.fmi.fi/services/SMOSService Data access from ESA dissemination service: https://smos-diss.eo.esa.int/oads/access
Contact for help	Issues related to data access at FMI servers, please contact : smos.dissemination.support@nsdc.fmi.fi Issues related to data access at ESA servers, please contact EOHelp@esa.int
Feedback comments to	The FT Service webpage in FMI has a user feedback channel: http://nsdc.fmi.fi/services/SMOSService Feedback related to science can also be sent to: kimmo.rautiainen@fmi.fi

This Read-me-first technical note introduces level 3 SMOS Soil Freeze and Thaw (F/T) product (SMOS L3FT). The SMOS L3FT product is generated from SMOS CATDS (Centre Aval de Traitement des Données SMOS) daily gridded level 3 brightness temperature data. The F/T product uses two-meter air temperature as auxiliary data. The reprocessed product uses ERA5-Land surface layer air temperature data (from 1 June 2010 to 10 October 2023), and the nominal operational product (from 11 October onwards) uses ECMWF IFS forecast data.

The SMOS L3FT product is based on the earlier work performed within the frame of SMOS+ Innovation Permafrost and SMOS+ Frost2 studies. Within these studies, several demonstrator datasets were published. The versions numbers of the operational F/T product and the demonstrator products and their corresponding CATDS and DPGS versions are collected in Table 1

The first version of the operational SMOS L3FT product (v 2.0) was released in March 2019 (official announcement in April 2019). The current product version is 3.00

L3FT FMI	L3 CATDS	L1 DPGS	Release date	Notes
v0.1	2.5	v500	March 2013	First official global F/T product, outcome of SMOS+ Innovation Permafrost project.
v1.0	2.7	v600	July 2015	Updated algorithm based on outcome Frost2Study.
v2.0	3.1	v620	March 2019	First version of the operational F/T product.
v2.01	3.1	v620 (until May-21) v724 (since May-21)	23-May-2019	Minor bug related to the orientation of the fixed data matrix.
v3.0	3.31	v724	30-Oct-2023	Major updates to the algorithm: Temporal filtering changed to Kalman filtering algorithm, improved use of input data RFI flag, ascending and descending orbit products, improved information on the quality of the FT estimate.

Table 1: SMOS L3FT product versions and their correspondence to CATDS and DPGS products versions

2 Data access

The SMOS L3FT product is accessible through FMI and ESA ftp and http dissemination services. Table 2 summarizes the available data access URLs. Please refer to the Product Description Document (PDD) for the contents of the data files.

Information	URL
FMI dissemination server	http://nsdc.fmi.fi/services/SMOSService/
FMI ftp access, username="anonymous", password=your email address	ftp://litdb.fmi.fi/outgoing/SMOS-FTService/
ESA dissemination server	https://smos-diss.eo.esa.int/oads/access/

Table 2: SMOS L3FT data access URLs.

3 Updates to this version

Version 3.0 processor has several major updates. These are:

- Output data contains more information: there are now separate products for ascending and descending orbit data. Number of days since last observation is a new variable.
- Input data has been changed to polar gridded version of the CATDS L3TB data.
- Improved use of RFI information provided in the CATDS L3TB data.
- Temporal filtering changed to use Kalman filtering algorithm.
- Product quality flag has been updated.

3.1 Output data format

The SMOS L3FT product daily output data package contains information on soil state, processing mask, data quality, date of the last acquisition, latitude and longitude. A detailed description of each variable is given in the PDD. Data are provided in netcdf format. The format is the same as in the previous version, but data files contain more information. The FT product of the previous version (v2.01) used data only from the descending orbits. New version (3.0) has two soil FT products, one derived from the ascending (6 AM) orbit data, another from the descending (6 PM) orbit data. Additionally, the number of days since last acquisition is a new variable.

3.2 Input data

The input data for the SMOS FT processor has been changed. SMOS FT processor v3.0 uses the CATDS level 3 gridded brightness temperatures in EASE-2 polar projection (CATDS v3.31). Previous FT processor (v2.01) used the cylindrical projection data (CATDS v3.1). The FT estimates are provided in the EASE-2 polar projection. As the input data are now in the same projection no additional re-projection routines are required.

3.3 RFI

CATDS L3TB data includes RFI information indicating the number of views potentially contaminated by RFI. The new version of the SMOS L3FT product uses this information to (a) remove the RFI contaminated observations and to (b) provide information on the data quality.

3.4 Kalman filtering method

The previous version (v2.01) used 20-day moving average for temporal filtering and noise reduction. It has been replaced by the Kalman filtering algorithm. The use of Kalman filtering allows to take into account measurement uncertainty and will result in improved response of the signal to the true FT transition.

3.5 Quality flag

The quality information is coded into an 8-bit unsigned integer in the following manner

$$Rwwxxyyz$$

where **z** indicates if data are available, **yy** the number of days since the last acquisition, **xx** the amount of suspected RFI, and **ww** the estimated probability of the given freeze-thaw state. More detailed description is provided in PDD.

4 Spatial coverage

The full spatial coverage of the product is 0°N - 85°N; 180°W - 180°E. The SMOS satellite covers the Earth in 3 days. The revisit time depends on latitude, with observations being received more frequently at high latitudes. The spatial coverage is reduced in some areas due to RFI (e.g. parts of Asia, Russia, Middle-East, and Southern Europe). Figure 1 shows the average observation frequency for 1 January 2015 - 30 June 2022. These figures clearly show the higher frequency of observations at high latitudes due to the sun-synchronous SMOS orbit. There are areas of the Eurasian continent that are severely affected by man-made RFI. In these areas, the frequency of observations is significantly reduced, resulting in a reduced number of good quality observations. The user should be aware of this problem. On the Eurasian continent, areas marked in blue (observation frequency less than 20%), are

Bit	Name	Coded information
z	Data available	0 - no data available 1 - data available
yy	Days since last observation	00 - maximum of one day since last observations was acquired 01 - two to three days since last observation was acquired 10 - four to seven days since last observation was acquired 11 - more than seven days since last observation was acquired
xx	Presence of suspected RFI in the acquisitions	00 - less than 5% suspected to be affected by RFI 01 - from 5% to 15% suspected to be affected by RFI 10 - from 15% to 30% suspected to be affected by RFI 11 - more than 30% suspected to be affected by RFI
ww	Probability of the estimated freeze-thaw state	00 - more than 90% 01 - between 70% and 90% 10 - between 50% and 70% 11 - less than 50%
R	Not used	Reserved for further use

Table 3: Quality flag information included in the SMOS L3FT product.

most likely to have high uncertainties. When using SMOS L3FT data on areas with less frequent revisit time, users are advised to use the number of days since last observation information. The variables are `delta_dnum_asc` and `delta_dnum_dsc` for ascending and descending orbit data, respectively. Detailed information are given in PDD.

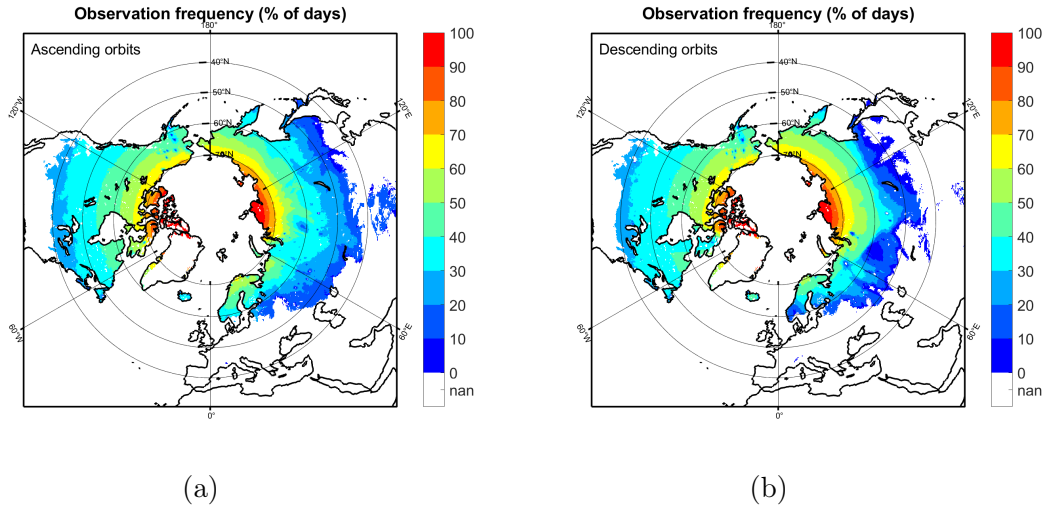


Figure 1: Maps of the average observation frequency after data quality filtering for the time period 1 January 2015 - 30 June 2022, (a) ascending orbits and (b) descending orbits.

5 Known caveats and shortages

The algorithm has the best performance at high latitudes (above 60 degrees) due to many reasons: (1) the seasonal changes are typically very evident, (2) vegetation cover if existing, is typically sparser compared to vegetation cover at lower latitudes, and (3) due to orbit configuration the SMOS instrument is observing the high latitudes more frequently (sun synchronous orbit).

Areas that are typically dry are challenging as the permittivity change due to soil freezing is very small. On areas with very thin or non-existing soil layer (e.g. rocky areas and mountains), frozen soil conditions cannot be distinguished from the thawed soil conditions; the estimation of the algorithm is mostly defined by the processing mask (PM), which is determined by the ancillary input data. On other regions, PM is used to omit the obvious omission and commission errors, more detailed description is provided in ATBD.

The user should also be aware that large open water bodies provide a very large dynamic range between summer and winter conditions: there is a high difference in observed signal between an open water target and a thick ice target. For areas with high open water percentage, the estimation of the soil freezing may be dominated by the freezing of the open water rather than the freezing of soil. It is recommended to use land cover data (e.g GlobCover 2009, Global Land Cover 2000 and Land Cover CCI) and be critical to results on such pixels that have an open water coverage higher than 20%.

6 Product validation

We have compared SMOS freeze and thaw estimates with in-situ measurements from the International Soil Moisture Network (ISMN). The two datasets have very different spatial scales, the SMOS L3FT state is estimated over the EASE-2 grid at

25 km \times 25 km resolution while each in-situ observation provides information on the sensor location. In many cases, only one sensor was located within a large SMOS L3FT pixel. We have removed data from those in-situ sensors that do not represent their surrounding SMOS L3FT pixel. This was done using land cover data, air temperature data (ECMWF ERA5 Land) and snow extent data from the Interactive Multisensor Snow and Ice Mapping System (IMS). If the land cover type at the sensor location did not match the dominant land cover type of the SMOS L3FT pixel (EASE-2 grid), the sensor data were discarded. Air temperature and snow extent data were gridded over the EASE-2 grid. Sensor data was also screened out if the sensor indicated soil freezing even though the average air temperature for the EASE-2 pixel remained above zero degrees Celsius. In such cases, the sensor locations could not represent the soil freezing conditions over the entire pixel. Similarly, if the air temperature was below zero degrees Celsius and no soil freezing was detected at the sensor location, it was suspected that the sensor location did not represent the entire pixel. In such cases, the snow extent data was considered - in cases of early snow onset, the ground may not freeze even at cold temperatures due to the additional thermal insulation of the snow cover.

In situ data are only available for the North American continent from the International Soil Moisture Network (ISMN). In total, data were available from five different networks: SNOTEL - Snow Telemetry Network, SCAN - Soil Climate Analysis Network, USCRN - The U.S. Climate Reference Network, RISMA - Real-Time In-Situ Soil Monitoring for Agriculture Network, and BNZLTER - Bonanza Creek, the Long Term Ecological Research Network. The in-situ data from all sites always include both soil moisture and soil temperature data. Data at a depth of 5 cm were compared with SMOS L3FT estimates. Figure 2 shows the locations of all SMOS pixels with in-situ observations.

The comparisons between the SMOS L3FT products and the in-situ observations are made using the Day of Freezing (DoF) information defined from these two datasets. In order to determine the DoF from in-situ observations, we have calculated the soil freeze and thaw index, hereafter referred to as the soil ft index. It is defined separately for each sensor and for each soil freezing period. The soil ft index is calculated from the soil freezing curve (SFC). The SFC represents the relationship between the volumetric soil liquid water content (LWC) and the soil temperature. The soil temperature thresholds for frozen soil ST_{fr} and thawed soil ST_{th} were calculated by finding the intersection point of the SFC with the soil LWC thresholds LWC_{fr} and LWC_{th} , respectively (Figure 3). The thresholds defining the soil ft indices were calculated separately for each soil freezing period and individually for each sensor location. All observations below the defined soil LWC and soil temperature thresholds indicated frozen soil, and similarly above these thresholds indicated thawed soil. Observations between the thresholds were considered to represent the transitional phase. The soil ft index was given a value of one if frozen and zero if thawed. For the transition phase, the soil ft index value was linearly scaled between zero and one based on the observed soil LWC with respect to the soil LWC thresholds. An example SFC is shown in Figure 3. The derived soil ft index value is a site specific interpretation of the soil condition.

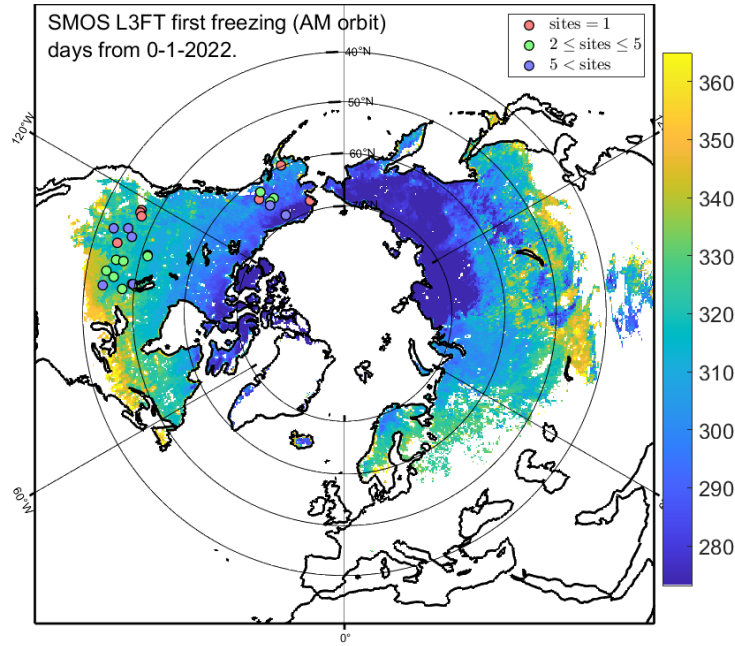


Figure 2: Locations of the ISMN stations used in the validation of the SMOS L3FT product. Markers indicate the locations of the EASE2.0 grid cells containing ISMN sites. The marker colour indicates the number of the ISMN stations inside the grid cell. The background map shows the estimated day of the freezing for the 2022-2023 winter as the number of days from the beginning of 2022.

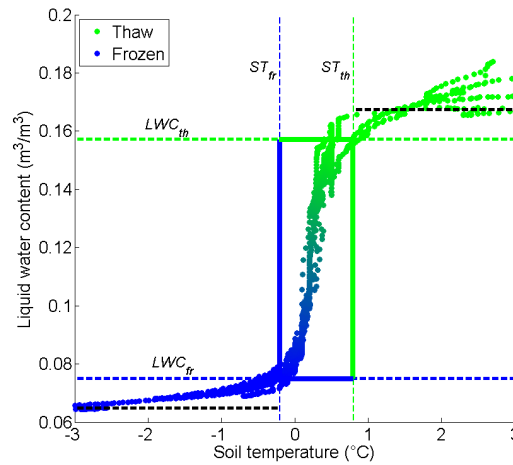


Figure 3: A soil freezing curve (SFC) showing the relation between the measured liquid water content (LWC) and the temperature of the soil, as well as the derived threshold values, for an example sensor

The results of the SMOS FT DoF comparison with in-situ data collected at 5 cm depth are shown in Figure 4 and Table 4. Five consecutive days of frozen soil were required for SMOS estimates. Similarly, five consecutive days with a probability of frozen soil of 70% were required for in situ estimates. The in-situ threshold of 70% was chosen to represent a consistent frozen soil estimate with reference to the

SMOS FT product for performance analysis. It does not necessarily represent the most optimal threshold for estimating the soil state at the sensor location. The SMOS and in-situ observations have different spatial scales (SMOS: EASE-2 pixel vs. in-situ: point location), observation depths on the soil (SMOS: top surface layer of several centimetres, depending on soil moisture conditions and vegetation above vs. in-situ: about 4-6 cm, depending on sensor type and installation) and temporal scales (SMOS: at maximum observations every day, but may be up to every 3-4 days depending on latitude and possible RFI vs. in-situ: continuous measurement). All this introduces uncertainties in the comparison results. Nevertheless, the comparison results show a good consistency.

These comparison results suggest that the SMOS product estimates later soil freezing when compared to estimates based on in-situ data. However, with different parameters for the in-situ soil ft estimation, the results would be slightly different. The agreement between the two very different data sets is good. It is interesting to note that the product derived from the ascending orbit data (6AM orbit) estimates soil freezing on average 1.3 days earlier than the descending orbit product (6PM orbit). In regions where man-made RFI has minimal effect on the SMOS observations on both orbits, such as the North American continent, both products can be used to better estimate the onset of soil freezing.

SMOS FT v3.0 vs in-situ

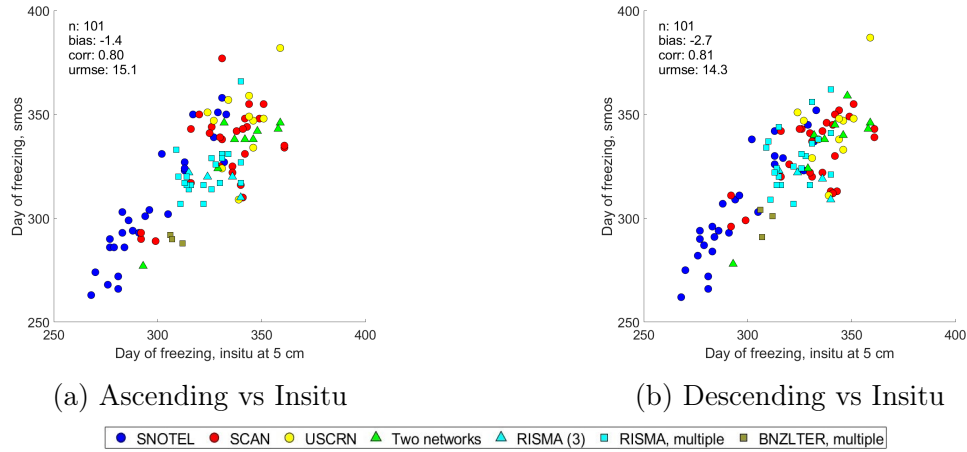


Figure 4: Comparison of the day of freezing (DoF) estimates between the SMOS v3.0 FT product and ISMN in-situ estimates (sensors at the depth of 5 cm). For both, five days of consecutive frozen soil conditions was required.

Product	Sensor depth	In-situ threshold	n	bias	corr	rmse
FT ascending	5 cm	70%	101	-1.4	0.80	15.1
FT descending	5 cm	70%	101	-2.7	0.81	14.3

Table 4: Day of freezing statistics. For SMOS FT estimate, five consecutive days of frozen soil was required and for in situ data five consecutive days of frozen soil probability of above 70% (threshold)