CCI+ PHASE 1 – NEW ECVS
Permafrost

CCN3 Option 3
TOWARDS A MULTI-PURPOSE FREEZE/THAW CDR

D2 Design Justification (DJ), Technical Specifications (TS),
Design Definition (DD)
D3.2 Observation Strategy (OS);
D4 Product Validation Report (PVR)

Version 2.0

13 September 2024

Prepared by

Document Status Sheet

Issue	Date	Details	Authors
1.0	31.05.2023	First separate versions of TS, DD, OS and PVIR	Annett Bartsch
2.0	13.09.2024	Fusion of TS, DJ, DD, OS and PVIR with reference to publications	Annett Bartsch

Author team

Annett Bartsch, BGEOS

Thomas Nagler, ENVEO

Jan Wuite, ENVEO

Kimmo Rautiainen, FMI

Tazio Strozzi, GAMMA

ESA Technical Officer:
Frank Martin Seifert

TABLE OF CONTENTS

Executive summary

Within the European Space Agency (ESA), the Climate Change Initiative (CCI) is a global monitoring program which aims to provide long-term satellite-based products to serve the climate modeling and climate user community. Permafrost has been selected as one of the Essential Climate Variables (ECVs) which were elaborated during Phase 1 of CCI+ (2018-2021).

CCN3 option 3 addressed the need for a FT climate data record of relevance for Permafrost monitoring and as well as further applications. The specific aim of this CCI+ Permafrost subproject is to identify algorithms and datasets which are suitable for the production of a consistent time series. It builds on algorithms developed in the framework of ESA DUE Permafrost, GlobPermafrost and ESA SMOS FT.

A potential multi-purpose freeze/thaw CDR should have 25km resolution, polar stereographic projection, covering the northern hemisphere (global as target) and representing 2010-2020 as threshold and back to 1979 as target. Product levels are 4: The data sets are created from the analysis of lower level data, resulting in gridded, gap-free products.

This document summarizes the design engineering process (D2), observation strategy (D3.2) and product validation (D4). This includes the justification for the choice of methods with respect to user needs. Product specifications are documented and information on levels of system design, engineering results and final selected algorithms provided. Issues relevant for the observation strategy of a potential multipurpose freeze/thaw CDR are summarized. Seasonal transition periods and mid-winter thaw and refreeze are discussed separately.

Full details are available in:

Bartsch, A., Bergstedt, H., Pointner, G., Muri, X., Rautiainen, K., Leppänen, L., Joly, K., Sokolov, A., Orekhov, P., Ehrich, D., and Soininen, E. M. (2023): Towards long-term records of rain-on-snow events across the Arctic from satellite data, The Cryosphere, 17, 889–915, https://doi.org/10.5194/tc-17-889-2023

Bartsch, A., Muri, X., Hetzenecker, M., Rautiainen, K., Bergstedt, H., Wuite, J., Nagler, T., and Nicolsky, D.: Benchmarking passive microwave satellite derived freeze/thaw datasets, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2024-2518, 2024.

1 Introduction

1.1 Purpose of the document

This document provides the design engineering, validation and user observation strategy for CCN 3 Option 3 (option led by b.geos).

1.2 Structure of the document

Section 2 details the design engineering, section 3 the observation strategy and section 4 the validation.

1.3 Applicable documents

[AD-1] ESA 2017: Climate Change Initiative Extension (CCI+) Phase 1 – New Essential Climate Variables - Statement of Work. ESA-CCI-PRGM-EOPS-SW-17-0032

[AD-2] Requirements for monitoring of permafrost in polar regions - A community white paper in response to the WMO Polar Space Task Group (PSTG), Version 4, 2014-10-09. Austrian Polar Research Institute, Vienna, Austria, 20 pp

[AD-3] ECV 9 Permafrost: assessment report on available methodological standards and guides, 1 Nov 2009, GTOS-62

[AD-4] GCOS-200, the Global Observing System for Climate: Implementation Needs (2016 GCOS Implementation Plan, 2015.

[AD-5] b.geos, Proposal , CCI+ PHASE 1 – NEW ECVS PERMAFROST OPTION 3 - TOWARDS A MULTI-PURPOSE FREEZE/THAW CDR, 2017.

1.4 Reference Documents

[RD-1] van Everdingen, Robert, ed. 1998 revised May 2005. Multi-language glossary of permafrost and related ground-ice terms. Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology. (http://nsidc.org/fgdc/glossary/; accessed 23.09.2009)

[RD-2] Bartsch, A., Wuite, J., Rautiainen, K., Nagler, T., Strozzi, T. (2022): ESA CCI+ Permafrost CCN3 Option 3 - User Requirements Document, v1.0

[RD-3] Bartsch, A., Wuite, J., Rautiainen, K., Nagler, T., Strozzi, T. (2022): ESA CCI+ Permafrost CCN3 Option 3 – Product Specification document, v1.0

[RD-4] Nagler, T., Schwaizer, G., Keuris, L., Luojus, K., Malnes, E., Small, D., Metsämäki, S. (2020): SEOM S1-4SCI SNOW Development of Pan European Multi-Sensor Snow Mapping Methods Exploiting S-1 - Algorithms Theoretical Basis Document, v2.0, February 2020.

[RD-5] Schwaizer, G., S. Metsämäki, M. Moisander, K. Luojus, S. Wunderle, K. Naegeli, T. Nagler, J. Lemmetyinen, J. Pulliainen, M. Takala, R. Solberg, L. Keuris, P. Venäläinen, and N. Mölg (2022): ESA CCI+ Snow ECV: Algorithm Theoretical Basis Document, v3.0, January 2022.

[RD-6] Bartsch, A., Muri, X., Bergstedt, H., Wuite, Hetzenegger, M., J., Rautiainen, K., Nagler, T., Strozzi, T. (2023): ESA CCI+ Permafrost CCN3 Option 3 – Design Engineering document, v1.1

[RD-7] Bartsch, A., Muri, X., Bergstedt, H., Wuite, Hetzenegger, M., J., Rautiainen, K., Nagler, T., Strozzi, T. (2023): ESA CCI+ Permafrost CCN3 Option 3 – Product validation and intercomparison report, v1.0

[RD-8] Bartsch, A., Muri, X., Bergstedt, H., Wuite, Hetzenegger, M., J., Rautiainen, K., Nagler, T., Strozzi, T. (2023): ESA CCI+ Permafrost CCN3 Option 3 – Observation strategy report, v1.0

[RD-9] Bartsch, A., Bergstedt, H., Pointner, G., Muri, X., Rautiainen, K., Leppänen, L., Joly, K., Sokolov, A., Orekhov, P., Ehrich, D., and Soininen, E. M. (2023): Towards long-term records of rain-on-snow events across the Arctic from satellite data, The Cryosphere, 17, 889–915, https://doi.org/10.5194/tc-17-889-2023

[RD-10] Bartsch, A., Muri, X., Hetzenecker, M., Rautiainen, K., Bergstedt, H., Wuite, J., Nagler, T., and Nicolsky, D.: Benchmarking passive microwave satellite derived freeze/thaw datasets, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2024-2518, 2024.

2 Design engineering documentation

The development of a freeze/thaw CDR has been separately investigated for seasonal transition periods and mid-winter. Target applications are primarily permafrost, carbon flux, soil moisture and rain-on-snow and seasonal snow melt studies [RD-3]. Seasonal snowmelt is addressed already in several initiatives and is therefore not covered.

Several existing freeze/thaw products were considered for fusion. In case of mid-winter freeze/thaw, no products for the recent decade are available. An existing method for time series production has been investigated and adapted for the purpose of climate data record production [RD-5].

2.1 Seasonal transition periods

Three freeze/thaw datasets based on relatively coarse spatial resolution passive microwave information have been available for benchmarking [RD-5, RD-10].

- Design justification: Benchmarking using a specifically developed scheme based on Sentinel-1 (workflow summarized in Figure 1) has been central for the design justification. It was carried out over sites with comparably good data availability (see Figure 2), the Alaskan North Slope and Northern Finland. Details are described in sections 3.2 and 3.3 of [RD-10].
- Technical specifications: Product specifications including file naming are provided in the PSD [RD-03]. The prototype locations are provided in Table 1 and the technical specifications are summarized in Table 2.
- Design definition: The main components of the fusion scheme are detailed in section 4.4 and Table 4 of [RD-10]. System components are:
  1. Re-gridding of data – assignment of closest centre
  2. Fusion
  3. In case of assignment of fractions from Sentinel-1 as meta-data (for prototype only)
     - Sentinel-1 ratio retrieval as for wet snow
     - State determination based on universal threshold, using landcover information (masking of water, snow, shadow, barren)
     - Subsetting to grid and fraction retrieval

  The algorithm requires selected modules of Python: numpy, pandas, geopandas, rasterio, netCDF4, h5py, pyproj, shapely, scipy

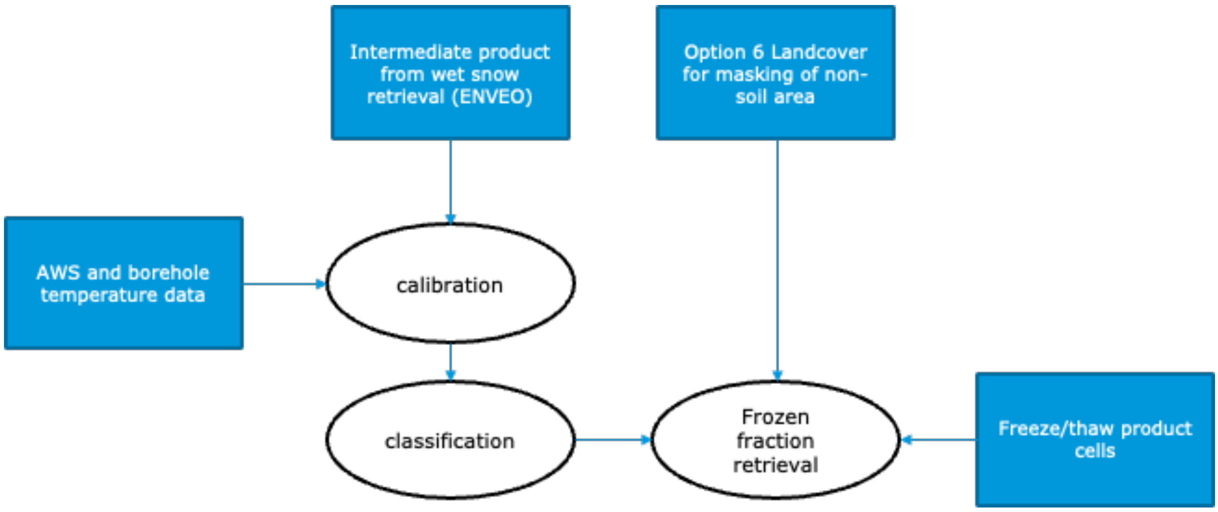

Figure 1: Workflow for benchmark dataset creation based on Sentinel-1 as described in [RD-10]

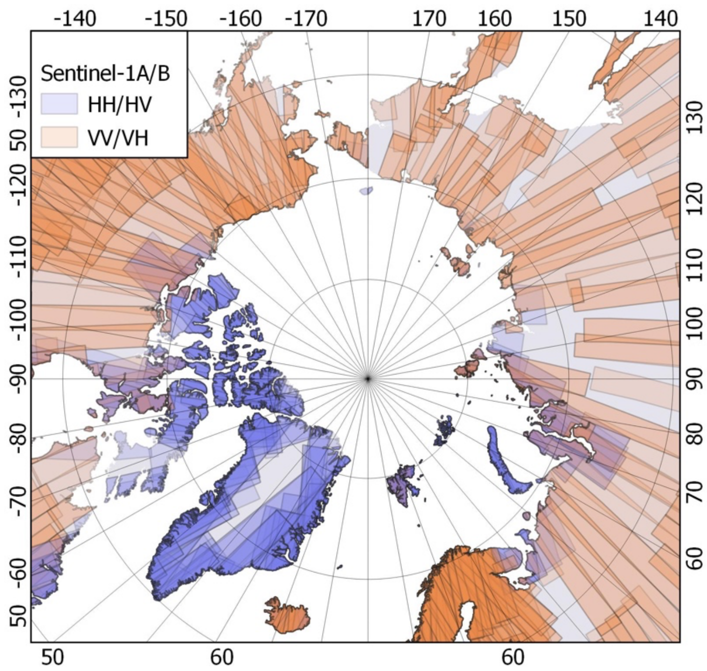

Figure 2: Example for Sentinel-1 coverage patterns across the Arctic land area. July 31 to August 20 2020 (figure source: Bartsch et al. (2021a); data source: https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-1) .

Table 1: Location of prototype grids (SMOS centre point, Polar Stereographic)

Borehole name	Region	X	Y
Kaldoaivi/ Vaisjeaggi	Finnland	1012500	3041078
Sagwon	Alaska	-1187500	1962500

Table 2: Specifications of the seasonal freeze/thaw product

Subject	Specification
Variable	Freeze/thaw status
Units	Discrete classes
Coverage	Selected grid points with in situ records
Time period	From 2017 (Finnland) and 2018 (Alaska)
Temporal frequency	Daily
Coordinate system	Polar stereographic
Spatial resolution (grid spacing)	25 km (SMOS grid)
Geometric accuracy	Subpixel
Thematic accuracy	> 80% for seasonal frozen/unfrozen flag, 81-87% for mid-winter
Auxiliary information	Subgrid state (fraction for Sentinel-1 acquisition dates)
Data (file) format	csv

2.2 Mid-winter thaw and refreeze

A mid-winter dedicated thaw and refreeze product was so far only available from Seawinds on QuikScat (Ku-band) for 1999-2009 (Bartsch 2010). A product for recent years was lacking and needed to be developed. Operationally available is C-band scatterometer information from Metop ASCAT. The C-band scatterometer regional test documented in Forbes et al. (2016) indicated applicability of the QuikScat approach, but the parameter adjustment to C-band had neither been justified so far nor had such data been applied for circumpolar retrieval.

A new dataset was created within Option 3 based on Metop ASCAT and SMOS [RD-9].

- Design justification: details are described in section 4.1 in [RD-9]
- Technical specifications: Product specifications including file naming are provided in the PSD [RD-03]. The prototype locations are provided in Table 1 and the technical specifications are summarized in Table 2.
- Design definition: The main components of the fusion scheme are detailed in sections 4.2 (preprocessing), 4.3 (midwinter freeze thaw retrieval) and 4.4 (fusion) in [RD-9]. Pre-processing steps are:
  1. Determination of November reference layer for ASCAT, determination of location specific standard deviation
  2. Retrieval of NPR at 50° incidence angle from SMOS

  Event detection:
  1. ASCAT: For each day, determination of 3 day average before and after, calculation of difference, if > location specific standard deviation, then yes (output of DeltaSigma0), otherwise 0 (no event)
  2. SMOS: maximum for three days before and after an ASCAT detection. If NPR larger than 3x high latitude standard deviation then removal of event from ASCAT record.

  The algorithm requires selected modules of Python: numpy, pandas, geopandas, rasterio, netCDF4, h5py, pyproj, shapely, scipy

3 Observation strategy discussion summary

3.1 Seasonal transition period

The comparison with the Sentinel-1 frozen fraction and in situ data with the seasonal freeze/thaw prototypes indicated an improvement through the fusion of the different products ([RD-10]; resulting in a dataset starting 2015). A range of issues which differ between the validation sites (continuous versus sporadic permafrost) however remain. These cannot be solved based on the existing passive microwave based CDRs. The retrieval from SAR sensors such as Sentinel-1 would theoretically allow to meet the requirements for a multipurpose freeze/thaw product. The availability of Sentinel-1 data is however constrained. An alternative might be the use of historic Sentinel-1 for the calibration of a freeze/thaw fraction derived from Metop ASCAT. Freeze/thaw monitoring considering fraction could be implemented in regions with VV/VH availability, going back to 2012. Retrieval supported through Sentinel-1 HH/HV remains to be tested.

The utility of the fused dataset for permafrost, soil moisture and carbon flux applications is discussed in section 5.3 of [RD-10] considering the Option 3 user requirement survey [RD-2].

3.2 Mid-winter freeze/thaw

A fusion of Metop ASCAT and SMOS was shown applicable with some limitations due to for example data coverage (start of product 2011/12). The mid-winter freeze/thaw implementation requires both, active as well as passive microwave records in case of Metop ASCAT use [RD-9]. This relates to the issue of temperature influence on winter C-band backscatter at VV. SMOS (L-band) was tested as the passive microwave component but has been shown not to be ideal due to RFI and less dense repeat intervals south of 65°N. Sensors such as SSMI may provide an alternative. This applies to data availability as well as frequency. Snow structure changes as captured with C-band radar may also be captured with higher frequencies as available from SSMI and AMSR-E (see also discussion in [RD-9]). It could be shown that there is also potential for use of Sentinel-1 at all polarizations. This would allow a spatially more detailed analyses but cannot be implemented due to the limited Sentinel-1 data availability.

4 Product validation

4.1 Seasonal transition period

In situ near surface soil temperature and ERA5 temperature data were used. The partially frozen flag was separately analyzed from the other flags for the creation of the benchmark dataset derived from the Sentinel-1 frozen fraction (as described in [RD-4]). The frozen state retrieval from the soil and ERA5 temperature data is based on temperature thresholds. <-1°C is considered as frozen and >1°C as unfrozen. Values in between are classified as partial thaw. All comparisons of the Fusion dataset were made on the basis of the SMOS grid as the new grid. Validation datasets are described in section 2.3, methodology in section 3.5 and results in section 4.5 of [RD-10].

All global products, tested with the benchmarking dataset, are of value for freeze/thaw retrieval, although differences were found depending on seasons, in particular during spring and autumn transition. Fusion can improve the representation of thaw and freeze-up, but a multi-purpose applicability cannot be obtained since the transition periods are not fully captured by any of the operational coarse resolution products.

4.2 Mid-winter freeze/thaw

Midwinter freeze/thaw of snow results in the formation of crusts which can be documented in snowpits. Records at the end of the winter allow for an assessment of the general occurrence of events but not the exact timing. Nevertheless, such data can proof partially the number of events. Ideally sites with winters with and without events should be used in order to derive both, error of omission and commission. End of winter snowpits are most commonly available and can be used for such a purpose. Layer information with focus on high hardness was extracted, specifically the number and thickness.
In case of continuous snow pits throughout a winter, also specific events can be evaluated. Usually events occur in November. This can be evaluated with records from early December.
Further indirect assessments can be made through use of ungulate data. Common are population numbers in case of severe crust formation. An alternative are GPS collar data which can reveal change in migration patterns due to snow crust formation.
Validation records are described in section 3 and results in section 5.4 of [RD-9].
With respect to other products, the Ku-band based results (QuikSCAT and OceanSat-2) show more events than those of ASCAT–SMOS. Deviations occur specifically over southern forested regions. When compared over tundra, average results are similar between the QuikSCAT and the ASCAT–SMOS results. This includes the magnitude of events, as well as the variability from year to year. Approximately 0.31 and 0.27 events per grid cell and year have been identified with QuikSCAT and ASCAT–SMOS, respectively (standard deviation 0.06 and 0.04). The standard deviation of events was highest over Scandinavia, western Siberia and western Alaska.

4 References

4.1 Bibliography

Bartsch Annett: Ten years of SeaWinds on QuikSCAT for snow applications. Remote Sensing 04/2010; 2(4)., DOI:10.3390/rs2041142

Bergstedt, H., Bartsch, A., Neureiter, A., Hofler, A., Widhalm, B., Pepin, N., & Hjort, J. (2020). Deriving a frozen area fraction from Metop ASCAT backscatter based on Sentinel-1. IEEE Transactions on Geoscience and Remote Sensing. https://doi.org/10.1109/TGRS.2020.2967364

Cohen, J., Rautiainen, K., Lemmetyinen, J., Smolander, T., Vehviläinen, J., Pulliainen, J. (2021). Sentinel-1 Based Soil Freeze/Thaw Estimation in Boreal Forest Environments, Remote Sensing of Environment, 254, https://doi.org/10.1016/j.rse.2020.112267

Kim, Y., J. S. Kimball, J. Du, and J. Glassy. 2021. MEaSUREs Polar Enhanced Resolution Freeze/Thaw Data Record from AMSR-E and AMSR2, Version 02 [2002 to 2020]. Boulder Colorado USA: National Snow and Ice Data Center. Digital media (https://doi.org/10.5067/WM9R9LQ2SA85).

Kouki, K., Anttila, K., Manninen, T., Luojus, K., Wang, L., & Riihelä, A. (2019). Intercomparison of Snow Melt Onset Date Estimates From Optical and Microwave Satellite Instruments Over the Northern Hemisphere for the Period 1982–2015. Journal of Geophysical Research: Atmospheres, 124, 11205– 11219. https://doi.org/10.1029/2018JD030197

Kroisleitner, C., Bartsch, A., and Bergstedt, H.: Potential permafrost distribution and ground temperatures based on surface state obtained from microwave satellite data, The Cryosphere Discuss., https://doi.org/10.5194/tc-2017-162, in review, 2017.

Naeimi Vahid, Christoph Paulik, Annett Bartsch, Wolfgang Wagner, Richard Kidd, Sang-Eun Park, Kirsten Elger, Julia Boike: ASCAT Surface State Flag (SSF): Extracting Information on Surface Freeze/Thaw Conditions from Backscatter Data Using an Empirical Threshold-Analysis Algorithm. IEEE Transactions on Geoscience and Remote Sensing 07/2012; 50(7):2566-2582.,

Park, H., Kim, Y., and Kimball, J. (2016): Widespread permafrost vulnerability and soil active layer increases over the high northern latitudes inferred from satellite remote sensing and process model assessments, Remote Sensing of Environment, pp. 349–358.

Rautiainen, K., Parkkinen, T., Lemmetyinen, J., Schwank, M., Wiesmann, A., Ikonen, J., Derksen, C., Davydov, S., Davydova, A., Boike, J., Langer, M., Drusch, M., and Pulliainen, J. (2016). SMOS prototype algorithm for detecting autumn soil freezing, Remote Sensing of Environment, 180, 346-360, DOI: 10.1016/j.rse.2016.01.012

4.2 Acronyms

CCI	Climate Change Initiative
CCN	Contract Change Notice
CRS	Coordinate Reference System
DEM	Digital Elevation Model
ECV	Essential Climate Variable
EO	Earth Observation
ESA	European Space Agency
ESA DUE	ESA Data User Element
FT	Freeze/Thaw
GAMMA	Gamma Remote Sensing AG
GCOS	Global Climate Observing System
GST	Ground Surface Temperature
GTOS	Global Terrestrial Observing System
IPA	International Permafrost Association
MAGT	Mean Annual Ground Temperature
NSIDC	National Snow and Ice Data Center
PSD	Product Specifications Document
RD	Reference Document
SAR	Synthetic Aperture Radar
URD	Users Requirement Document