permafrost
cci

CCI+ PHASE 2
PERMAFROST

CCN4 OPTION 7
ICEINSAR: INFERRED ACTIVE LAYER WATER/ICE CONTENT AND FREEZE-THAW PROGRESSION FROM ASSIMILATING INSAR IN PERMAFROST MODEL

D1.1 USER REQUIREMENT DOCUMENT (URD)

VERSION 1.0

31 MARS 2023

PREPARED BY

b·geos GAMMA REMOTE SENSING

NORCE UiO : University of Oslo

Document Status Sheet

Issue	Date	Details	Authors
0.1	15.03.2023	Template based on baseline URD	L. Rouyet (NORCE)
0.2	23.03.2023	First draft CCN4 Option 7 D1.1	L. Rouyet, L. Wendt (NORCE)
0.3	27.03.2023	Updated/corrected version CCN4 Option 7 D1.1	S. Westermann (UiO), A. Bartsch (B.GEOS), Strozzi (GAMMA)
1.0	31.03.2023	Final version CCN4 Option 7 D1.1	L. Rouyet (NORCE), L. Wendt (NORCE), S. Westermann (UiO), A. Bartsch (B.GEOS), Strozzi (GAMMA)

Author team

Line Rouyet and Lotte Wendt, NORCE

Sebastian Westermann, UiO

Annett Bartsch, B.GEOS

Tazio Strozzi, GAMMA

ESA Technical Officer

Frank Martin Seifert

EUROPEAN SPACE AGENCY CONTRACT REPORT

The work described in this report was done under ESA contract.
Responsibility for the contents resides in the authors or organizations that prepared it.

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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 modelling and climate user community. The two main products associated to the ECV Permafrost are Ground Temperature (GT) and Active Layer Thickness (ALT). GT and ALT are documented by the Permafrost_cci project based on thermal remote sensing and physical modelling.

The Permafrost_cci models take advantage of additional datasets, such as snow cover and land cover, to estimate the heat transfer between the surface and the underground. However, several challenges remain due to spatially variable subsurface conditions, especially in relation to unknown amounts of water/ice in the active layer that modify the effective heat capacity and the thermal conductivity of the ground. In complex terrain with large spatial heterogeneities, coarse and partly inadequate land cover categorisation, the current results show discrepancies with in-situ measurements, which highlight the need to assimilate new data sources as model input. Although the ground stratigraphy is not directly observable from space, it impacts the dynamics of the ground surface. The seasonal thawing and refreezing induce cyclic subsidence and heave of the ground surface due to ice formation and melt in the active layer, and can therefore be used as indirect indicator of the ground conditions.

Synthetic Aperture Radar Interferometry (InSAR) based on Sentinel-1 images can be used to measure the amplitude and seasonal progression of these displacements. The movement amplitude is related to the amount of water/ice that is affected by a phase change, whilst the timing of the displacement patterns reflects the vertical progression of the thawing/freezing front. Considering the fine to medium spatial resolution of Sentinel-1 images, InSAR time series therefore have the potential to enhance the characterisation of subsurface hydrogeologic and thermal parameters and adapt the existing Permafrost_cci models to improve their performance at the local to regional scale. The *IceInSAR* pilot project (Option 7) will develop a prototype for permafrost model adjustment by assimilating Sentinel-1 InSAR surface displacement maps and time series into the model to constrain stratigraphy parameters. *IceInSAR* will provide pilot products, expected to be used for adjustment of the ECV processing chain of the baseline project in a next phase.

This User Requirement Document (URD) has to be read as a complement of the recently updated URD from the Permafrost_CCI baseline Phase 2 (RD-1). The present document describes the background of the *IceInSAR* pilot project (Option 7) and how it can contribute to address identified URq currently considerably beyond the state-of-the art in remote permafrost ECV assessment. Specifically, we aim to evaluate the potential of assimilating InSAR data into permafrost models to work towards a fulfilment of “breakthrough” or “target”/”goal” user requirements for:

1. High spatial and temporal resolution (URq_09, URq_12, URq_13, URq_18);
2. High data quality and product accuracy (URq_4, URq_9, URq_12, URq_13, URq_19);
3. Enhanced ground stratigraphy product and representation of the subgrid variability (URq_11, URq_12, URq_13, URq_21, UR1_22);
4. Surface displacement (SD) as potential new permafrost product (URq_3, URq_18, URq_20).

1 INTRODUCTION

1.1 Purpose of the document

This document summarizes the user requirements targeted by the *IceInSAR* pilot project (Option 7), based on the recently updated URD from the Permafrost_cci baseline Phase 2 (RD-1). Elements that do not apply to Option 7 or overlap with the baseline URD are not repeated.

The URD assesses the requirements of relevant organisations from the Climate Research Community and the International Permafrost Community; the requirements will be used to guide the product specifications of the Permafrost_cci project.

A concise reference code 'URq_XX' has been assigned to each User Requirement in the Permafrost_CCI baseline. For cross-referencing and traceability purpose, we use here the same numbering.

1.2 Structure of the document

Section 2 describes the types of expected uses for the Option 7 outcomes and summarizes which users can benefit from the results. Section 3 identifies the user requirements that the project is targeting. A discussion of the potential issues to fulfil them is presented in Section 4. Section 5 summarizes the user requirements relevant for the project. A bibliography complementing the applicable and reference documents (Sections 1.3 and 1.4) is provided in Section 6.1. A list of acronyms is provided in Section 6.2. A glossary of the commonly accepted permafrost terminology can be found in [RD-9].

1.3 Applicable documents

[AD-1] ESA. 2022. Climate Change Initiative Extension (CCI+) Phase 2 – New Essential Climate Variables – Statement of Work. ESA-EOP-SC-AMT-2021-27.

[AD-2] GCOS. 2022. The 2022 GCOS Implementation Plan. GCOS – 244 / GOOS – 272. Global Observing Climate System (GCOS). World Meteorological Organization (WMO).

[AD-3] GCOS. 2022. The 2022 GCOS ECVs Requirements. GCOS – 245. Global Climate Observing System (GCOS). World Meteorological Organization (WMO).

1.4 Reference Documents

[**RD-1**] Bartsch, A., Matthes, H., Westermann, S., Heim, B., Pellet, C., Onaca, A., Kroisleitner, C., Strozzi, T. 2023. ESA CCI+ Permafrost Phase 2. D1.1 User Requirement Document (URD), v3.0. European Space Agency.

[**RD-2**] IPA. 2016. Specification of a Permafrost Reference Product in Succession of the IPA Map. 2016. Final report. IPA Action Group. https://www.permafrost.org/group/specification-of-a-permafrost-reference-product-in-succession-of-the-ipa-map/

[RD-3] OSCAR. Requirement defined for Permafrost. Observing System Capability Analysis and Review Tool. https://www.wmo-sat.info/oscar/variables/view/124

[**RD-4**] Duchossois G., P. Strobl, V. Toumazou, S. Antunes, A. Bartsch, T. Diehl, F. Dinessen, P. Eriksson, G. Garric, M-N. Houssais, M. Jindrova, J. Muñoz-Sabater, T. Nagler, O. Nordbeck. 2018. User Requirements for a Copernicus Polar Mission - Phase 1 Report, EUR 29144 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-80961-3, https://doi.org/10.2760/22832, JRC111067.

[**RD-5**] Heim, C., Lisovski, S., Wieczorek, M., Pellet, C., Delaloye, R., Bartsch, A., Jakober, D., Pointner, G., Strozzi, T. CCI+ Phase 1 – New ECVS Permafrost. D4.1 Product Validation and Intercomparison Report (PVIR). Version 3.0. European Space Agency.

[**RD-6**] Bartsch, A., Westermann, S., Strozzi, T., Wiesmann, A., Kroisleitner, C., Wieczorek, M., Heim, B. 2023. ESA CCI+ Permafrost Phase 2. D1.2 Product Specification Document (PSD). Version 3.0. European Space Agency.

[RD-7] National Research Council. 2014. Opportunities to Use Remote Sensing in Understanding Permafrost and Related Ecological Characteristics: Report of a Workshop. Washington, DC: The National Academies Press. https://doi.org/10.17226/18711.

[RD-8] Bartsch, A., G. Hugelius, Strozzi, T. 2021. ESA CCI+ Permafrost CCN3 Option 6: improved soil description through a landcover map dedicated for the Arctic. User Requirements Document, v1.0.

[**RD-9**] 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/.

1.5 Bibliography

A complete bibliographic list that supports arguments or statements made within the current document is provided in Section 6.1.

1.6 Acronyms

A list of acronyms is provided in Section 6.2.

2 USERS OF PERMAFROST DATA AND RELATED INITATIVES

2.1 Specific use of the *IceInSAR* outcomes

The *IceInSAR* Option 7 is a pilot project using selected case studies in Svalbard to test the assimilation of InSAR-based Surface Displacement (SD) product into the ESA Permafrost_cci model (CryoGrid). Thereby, the estimate of the two main ECV permafrost products will be constrained based on the SD product: Ground Temperature (GT) and Active Layer Thickness (ALT). The expected use of the project outcomes is two-sided, following two temporalities:

- **Short-term objective:** *IceInSAR* will provide new local to regional products, complementary to existing 1-km Permafrost_cci products that may be directly valuable for scientific and operational applications in Svalbard.
- **Long-term objective:** *IceInSAR* will provide enhanced modelling products at a prototype level, based on the assimilation of new data sources and is expected to be used for adjustment of the ECV processing chain of the baseline project in a next phase.

2.2 User community of the *IceInSAR* outcomes

The SD product is primarily developed for applications considered within the ESA Permafrost_cci model (CryoGrid) but further use beyond is considered in addition. According to the two previously defined objectives/data uses (Section 2.1), the following user communities are identified:

User community targeted by the short-term objective:
To perform test of InSAR assimilation into the permafrost models and generate InSAR-constrained modelling products, the *IceInSAR* Option 7 has selected cases studies in three regions of Spitsbergen, Svalbard. The SD, GT and ALT products will therefore benefit the Svalbard community:

- Norwegian and foreign research and educational institutions, studying the impacts of climate change in the Arctic environment of Svalbard.
- National agencies (e.g. the Norwegian Polar Institute, The Norwegian Environment Agency, the Geological Survey of Norway NGU, the Norwegian Water Resources and Energy Directorate NVE) and local–regional authorities (e.g. The Governor of Svalbard and Longyearbyen Municipality Council) in charge of infrastructure stability and geohazards management.
- The National Meteorological Institute (MET Norway) conducting permafrost monitoring programmes and research in climatology and permafrost-climate interactions in the Earth System.
- A large public (e.g. mountaineers, local community) having an interest in changing permafrost conditions, in relation with climate change.

User community targeted by the long-term objective:
Considering the long-term objective to enhance the characterisation of subsurface hydrogeologic and thermal parameters and adapt the existing Permafrost_cci models, the user community targeted by the *IceInSAR* Option 7 is similar to the one described in the Permafrost_cci baseline URD [RD-01]:

- Scientists across disciplines which work in permafrost regions, such as:
  - Climate modellers who are interested in the interactions of permafrost with the climate system and work to improve predictions of future changes.
  - Regional permafrost modellers who are using the ECV parameters to validate their models.

  - Remote Sensing scientists who are investigating land surface change from satellite observations in permafrost regions.
  - Field scientists who require information on the geo-spatial context of the in-situ measurements.
- Authorities, organisations and projects/initiatives, interested in the monitoring of permafrost for decision making, e.g. with respect to land use management and permafrost-related hazards.

Detailed description of the users from the Climate Research Community and various international initiatives is included in the Permafrost_cci baseline URD [RD-1]. The users of the Permafrost_cci data products cover a relatively broad use of topics and therefore have a relatively broad range of requirements.

3 SUMMARY OF USER REQUIREMENTS

The identification of the Permafrost_cci user requirements has been performed based on user surveys and consultations, complemented by the review of requirements from different institutions/initiatives (IPA, GTN-P, GCOS, OSCAR) and targeted interviews with climate modeller and permafrost specialists from CMUG and Obs4MIPs. The detailed results of this work are described in the Permafrost_cci baseline URD [RD-1]. The project defines the requirements for three parameters: the ground temperature (GT), the active layer thickness (ALT) and the permafrost extent/fraction (PE/PF).

Some user requirements (URq) are not directly applicable to the *IceInSAR* Option 7 due to the pilot nature of the project and the local to regional geographical extent of the study. This apply to URq_01, URq_05, URq_06 and URq_17. **Others are applicable although not especially targeted by the project**, i.e. *IceInSAR* outcomes will fulfil the requirements similarly as the baseline products. This applies to URq_02, URq_07, URq_08, URq_10, URq_14 and URq_15.

We detail here the remaining URq, targeted by the project and for which *IceInSAR* products may contribute to better fulfilling the user requirements:

Reminder: The "threshold" requirement is the minimum performance level, i.e. the value below which the observation does not yield any significant benefit for the application in question or may even deteriorate the application. The "target" or "goal" requirement is the maximum performance level is the value which, if exceeded, does not yield significant improvement in performance for the application in question. The "breakthrough" requirement is an intermediate level that represents the value that would need to be attained to provide a significant benefit for the application, compared with current performance.

- **URq_03**: In the IPA Action Group report on the Specification of Permafrost Reference Products in Succession of the IPA Map [RD-2], the experts required that **the technical form of delivery for maps and data will need to be flexible** in adapting to differing communities (e.g., engineering, climate simulation) and evolving needs.
- **URq_04**: In the IPA Action Group report on the Specification of Permafrost Reference Products in Succession of the IPA Map [RD-2], the experts required **a high data quality** to serve as a reference product for model evaluation, as model input, and as a basis for assessing landscape functioning or hazards.
- **URq_09**: Requirements for **permafrost and seasonally frozen ground extent products** dedicated to the climate land cover community are addressed in the WMO OSCAR database [RD-3]. In term of **spatial resolution**, the threshold requirement is **10–100 km**, the breakthrough requirement is **0.85–1 km** and the goal requirement is **0.1–0.25 km**.
- **URq_11**: The online survey of the ESA DUE GlobPermafrost in 2016, completed by interviews with climate modellers and permafrost specialists pointed that **a new ground stratigraphy product for the permafrost domain** needs to be compiled in close consultation with climate modelers. It is consensus in the community that currently existing classifications are heavily flawed for permafrost.
- **URq_12**: The Permafrost_cci specific user requirement survey from 2018 defined the threshold and target requirements for **ground temperature**. As threshold requirement, the users demand a precision of **0.5 K**, a RMSE **< 2.5 °C** and horizontal resolution of **10 km**. As target/goal requirement, the users highlighted the need for a precision of **0.1 K**, a RMSE **< 0.5 °C** and a spatial

resolution of **1 km**, including a **representation of the subgrid variability**. The temporal resolution should be **annual** (threshold) or **monthly** (target).

- **URq_13:** The Permafrost_cci specific user requirement survey from 2018 defined the threshold and target requirements for **active layer thickness**. As threshold requirement, the users demand a precision of **10 cm**, a RMSE **< 25 cm** and a spatial resolution of **10 km**. As target/goal requirement, the users highlighted the need for a precision of **1 cm**, a RMSE **< 10 cm** and a spatial resolution of **1 km**, including a **representation of the subgrid variability**. The temporal resolution should be **annual** (threshold) or **monthly** (target).
- **URq_18**: The JRC report on User Requirements for a Copernicus Polar Mission [RD-4] requires a **spatial resolution** of **1 m** (goal) to **10 m** (threshold) for **permafrost extent/fraction**.
- **URq_19**: GCOS defines requirements for ECV permafrost tailored for in-situ measurements [AD-2] [AD-3]. In term of **product accuracy**, GCOS requires **0.2 °C** (threshold), **0.1 °C** (breakthrough) and **0.01 °C** (goal) for the **ground temperature.** The required mechanical probing penetration accuracy / sensor accuracy is respectively **2 / 15 cm** (threshold) and **1 / 5 cm** (goal) for the **active layer thickness**.
- **URq_20**: The JRC report on User Requirements for a Copernicus Polar Mission [RD-4] specifies **"surface displacement" as key parameter** for the monitoring of changing permafrost conditions (Tables 6 and 8, p.11 and p.21 [RD-4]) based on in-situ driven recommendations [RD-7]. The required spatial and temporal resolutions for such products are **1 m** (goal) to **5 m** (threshold) and **14 days** (goal) to **1 yr** (threshold). The required vertical accuracy is **0.001 m/yr** (goal) to **0.01 m/yr** (threshold).
- **URq_21**: For **soil physical characteristics**, a target spatial resolution of **1–5 m** (regionally) and threshold spatial resolution of **100–1000 m** (circumpolar) are suggested [RD-7].
- **URq_22:** Spatial resolution requirements for CryoGrid with respect to **improvement of soil parameterization** [RD-8] are **100–300m** (threshold) and **20 m** (target). The products should document the **last decade** (threshold), ideally the **1979–present** period (target).
- **URq_23:** CryoGrid minimum sampling for the production of climate data records in Permafrost_cci is **1 km^2**, targeting **annual products based on daily input** [RD-1] [RD-6].

4 USER REQUIREMENTS FEASIBILITY

4.1 Summary of user requirement feasibility from the current state-of-the-art

The Permafrost_cci baseline URD [RD-1] highlights several challenges to fulfil some of the reviewed users demands, especially when considering the maximum (target/goal) and intermediate (breakthrough) performance levels. The users demand a combination of extensive geographical coverage, high spatial resolution, including representation of subgrid variability, high temporal resolution and long temporal coverage. Some requirements go considerably beyond the state-of-the-art in remote permafrost ECV assessment, considering published studies and recently demonstrated progress.

Based on the previously performed feasibility analysis, the following considerations are especially important for the *IceInSAR* Option 7 objectives:

- **High spatial and temporal resolutions:** The current Permafrost_cci products fulfil the spatial resolution requirement (1 km grid) [URq_12] [UR_13]. They also fulfil the threshold requirement of the WMO OSCAR database for the permafrost and seasonally extent products [URq_09]. However, the WMO OSCAR breakthrough/goal requirement (0.1–0.85 km) and the requirements for a Copernicus Polar Mission (1–10 m) [URq_18] are beyond the state-of-the-art. In term of temporal resolution, the current products are provided with an annual frequency, which fulfils the threshold requirements, but not the target requirements (monthly) URq_12] [UR_13]. Considering the objective of global coverage of the Permafrost_cci project and the technical requirements for running the current model at this scale, the resolution of the products can already be considered as high. The Permafrost_cci URD explains that "*although the input satellite data sets feature a high temporal resolution, e.g. diurnal for Land Surface Temperature, the employed model limits the final temporal resolution […], which would not fulfil threshold requirements stated by most users. Algorithm selection in Permafrost_cci must therefore closely consider the interplay between satellite data and employed model scheme.*" [RD-1, p.21].
- **High data quality and product accuracy**: The current accuracy of the Permafrost_cci products is within the thresholds defined by the specific user requirements [URq_12] [URq_13]. Yet, some areas, especially in warmer permafrost regions, display large outliers [RD-5]. It should be noted that the product accuracy assessment is strongly dependent on the spatial resolution of the products compared to the validation data, as well as the natural variability of the ground conditions within a resolution cell. The Permafrost_cci URD explains that the "*accuracy requirements stated by the users are strongly complicated by the fact that permafrost ECV physical variables (ground temperature and active layer thickness) often feature significant variations at spatial scales below the target requirement of 1 km, which in the few documented cases (see below) exceed even the threshold requirement of an RMSE of 2.5K (e.g. Fig. 2 in Gisnås et al, 2014). Therefore, even comparison of "perfect" 1 km average temperatures to point temperature measurements in boreholes will feature a significant RMSE which in this case rather reflects the spread of temperatures in space than the accuracy of the method (assuming that boreholes are placed at random locations within a pixel). In real-world permafrost ECV assessment, a bias introduced by the method/model and the input data will overlap with this effect, which significantly complicates the evaluation of accuracies. A straight-forward method to overcome this difficulty would be to increase the spatial resolution until the method can indeed deliver the deterministic temperature at*

the locations of individual boreholes. However, this would require a pixel resolution of about 10 m, which is several orders of magnitude smaller than what has been demonstrated in published studies." [RD-01, p.21]. The very high accuracy requested by GCOS [URq_19] is designed for datasets based on in-situ measurements and is therefore not achievable in case of modelling products based on satellite data.

- **Enhanced ground stratigraphy product and representation of the subgrid variability:** The conclusions regarding the resolution and accuracy of the products show the need for enhanced ground stratigraphy products [URq_11] and a better representation of the subgrid variability [URq_12] [URq_13]. The current Permafrost_cci products document the subgrid variably based on the median and standard deviation of the model ensemble [RD-06]. In addition to these estimates, we would benefit from the assimilation of new complementary measurements directly or indirectly documenting the ground stratigraphy at a higher resolution than the model grid, to account for subgrid variability. The Permafrost_cci URD for instance mentions that "*the challenge for permafrost fraction assessment is the poor availability of in-situ data for PF fraction at 1 km scale (see Chadburn et al., 2017). A practical method to provide uncertainty estimates at the pixel/grid level is required. Chadburn et al. (2017) suggest the use of high-resolution land cover with its classes as proxy for permafrost distribution in the transition zone. Such approaches have recently been tested also for medium resolution data (Landsat, Cable et al. 2016) and C-band SAR, see also Bartsch et al. (2016). Another way of overcoming these challenges would be to measure ECV physical variables not only at single points (as it is e.g. done in the GTN-P network), but assess the full spatial distribution or at least the magnitude of the spread with spatially distributed logger arrays.*" [RD-01, p.21–22].
- **Surface displacement (SD) as potential new permafrost product:** Additionally, the JRC report on User Requirements for a Copernicus Polar Mission [RD-03] specifies the need for additional key parameters, such as surface displacement (SD) [URq_18], as a proxy of changing hydro-thermal conditions in areas underlain by permafrost or seasonally frozen ground. This requirement is currently not covered by the Permafrost_cci, which focuses on the three traditional permafrost products (GT, ALT and PE/PF).

4.2 Contribution of *IceInSAR* Option 7 to fulfil the user requirements

Based on the user requirements summarized in Section 3 and the feasibility challenges identified in Section 4.1, we here discuss the expected contribution of *IceInSAR* Option 7 to fulfil the following user demands:

- **High spatial and temporal resolution (**URq_09, URq_12, URq_13, URq_18**,** URq_20): The current products fulfil the specific threshold requirements of the Permafrost_cci users (URq_12, URq_13). However, several reference documents (RD-3, RD-4) highlight the demand for higher spatial resolutions, especially valuable in areas where complex topography and heterogenous ground conditions may lead to poor model performance. Downscaling the model results can become possible for targeted regions, by including complementary high-resolution input products, such as SD maps based on InSAR (initial resolution: 20x5 m for Sentinel-1 Interferometric Wide Swath images; final resolution after multi-looking: 40–100 m). Similarly, at the regional scale, the temporal resolution can realistically be increased to the target requirement (monthly), based on Land Surface Temperature diurnal data and InSAR-based thaw subsidence / frost heave time series with a 6–12 days temporal resolution. It should however be noted that the InSAR information will be spatially and temporally discontinuous. Areas affected by typical SAR geometrical limitations (shadow/layover) and interferometric coherence loss due to wet/snow-covered surfaces or fast displacements (> ¼ the wavelength during the time interval of the interferograms, i.e. about 1.4 cm in 6–12 days) will remain undocumented. Due to coherence loss during the winter, the InSAR time series will document the displacement progression during the snow-free seasons only (typically May–June to October–November in Svalbard).
- **High data quality and product accuracy (**URq_4, URq_9, URq_12, URq_13, URq_19**)**: On average, the product accuracy of the Permafrost_cci fulfils the threshold requirements of the Permafrost_cci users (URq_12, URq_13). However, significant spatial heterogeneities and systematic biases in specific regions have been identified. Detailed analyses in the regions impacted by such bias (e.g. Svalbard) may contribute to further understand discrepancies between the model and in-situ validation data. Comparing the products from the initial model with the SD-constrained model will allow to evaluate the potential of improving the model performance based on new data inputs. The high resolution of the InSAR data will also contribute to the representation of the natural subgrid variability (see next point), that will contribute to assess if the discrepancies between model and validation data are caused by biases or rather related to the natural spatial variability of permafrost parameters within the resolution cell.
- **Enhanced ground stratigraphy product and representation of the subgrid variability (**URq_11, URq_12, URq_13, URq_21, URq_22**)**: The current models take advantage of additional datasets, such as the land cover, to estimate the heat transfer between the surface and the underground. However, several challenges remain due to spatially variable subsurface conditions, especially in relation with the unknown amounts of water/ice in the active layer that modify the effective heat capacity and the thermal conductivity of the ground. In complex terrain with large spatial heterogeneities and coarse land cover categorisation, the current results show discrepancies with in situ measurements, which highlights the need to assimilate new data sources as model input. The integration of new data sources indirectly documenting the active layer ice content, the sediment type and ground freeze/thaw patterns will be used to constrain specific ground

stratigraphy parameters in the model, at a spatial resolution much higher than the global products. The downscaled results will provide a representation of the subgrid variability that will be compared with the median and standard deviation of the model ensemble for the 1-km grid. By comparing InSAR-based SD with acquired in-situ data, Option 7 will also show how the SD product may contribute to document the sediment type and ice/water content and thus complement the generation of new ground stratigraphy products.

- **Surface displacement as potential new permafrost product** (URq_3, URq_20): In addition to their assimilation into the Permafrost_cci model, the InSAR products from Option 7 can also have a standalone value, for both scientific and operation applications in Svalbard (auxiliary data for geomorphological mapping and permafrost model, concrete use for geohazard management, etc.) (see "short-term objective and user community, in Section 2.2). In addition, the User Requirements of the Copernicus Polar Mission [RD-4] specified that surface displacement (SD) is a key parameter for monitoring permafrost regions. The required spatial resolution of such products (goal: 1 m, threshold: 5 m) is higher than the possible resolution based on Sentinel-1 images, but can be fulfilled by higher resolution satellites (e.g. TerraSAR-X, Radarsat-2). The required temporal resolution (goal: 14 days) can be met during the snow-free seasons (6–12 days InSAR time series). For the purpose of CryoGrid, threshold and target requirements for spatial resolution (100–300m and 20 m) can be however met [RD-8]. The potential of using remotely sensed displacement maps to infer the active layer thickness or the ice/water content is widely recognized [RD-7] and may complement current products. Although the use of InSAR surface displacements in permafrost regions is still at a research stage (Strozzi et al., 2018; Bartsch et al., 2019; 2023; Rouyet et al., 2019; 2021), the development of strategies for generating systematic products at the large scale are quickly advancing. The *IceInSAR* Option7 may contribute to design the procedure for delivering operational products in a future phase. The requirements for the SD product are summarized in *Tab.1*.

Table 1. Requirements for a SD product in permafrost regions

	Threshold requirement	**Target requirement**
	Coverage and sampling	
Geographical coverage and sampling [URq_01] [URq_23]	1 km^2 (CryoGrid)	Pan-Arctic
Temporal sampling [URq_20] [URq_23]	Annual	Daily – biweekly
Temporal extent [URq_22]	Last decade	1979 – present
	Resolution and Uncertainties	
Horizontal resolution [URq_22] ([URq_20] [URq_21])	100–300 m (CryoGrid) (Copernicus/NRC: 5 m / 100–1000 m)	CryoGrid 20 m (Copernicus/NRC: 1 m / 1–5 m)
Accuracy	Accurate relative variability of the displacement patterns, for a better representation/parametrization of the ground stratigraphy than currently.	Accurate absolute displacements for the quantification of the ice/water content in the active layer.
Error characteristics	Relative measure of interferometric stability (coherence)	RMSE from validation against in-situ measurements.
	Thematic content	
Displacement [URq_20,21,22]	Spatial distribution of the maximum surface displacement	Seasonal surface displacement time series

5 SUMMARY AND CONCLUSION

All Permafrost_cci user requirements from the baseline URD [RD-1] are listed in Table . It provides a summary of the identified user requirements and is organised by EO data product. For each user requirement, the source and type of work to be addressed are identified. Some URq (shown in **grey**) are not directly applicable to the *IceInSAR* Option 7 due to the pilot nature of the project and the local to regional geographical extent of the case study. Others (shown in **black**) are applicable although not specially targeted by the project. In **red**, the URq targeted by the *IceInSAR* Option 7 are shown. For these the conclusion of the project may contribute to a future fulfilment of the requirements to a "target"/"goal" or a "breakthrough" level.

*Table 1: Summary of user requirements. Background (BG) means that this is a continuous activity, production (P), and dissemination (D) means that the related requirement has to be considered during production or dissemination, respectively. Parameters are Permafrost Extent (PE), Ground Temperature (GT), Active Layer Thickness (ALT) and Surface Displacement (SD). Table modified from [RD-1]. In **grey**: not directly applicable. In **black**: applicable but not especially targeted. In **red**: URq applicable/targeted by the IceInSAR Option 7.*

ID	Parameter	Requirements	Source	Type
URq_01	PE/GT/ALT	Higher spatial resolution than a map scale of 1:10,000,000	IPA Mapping group report	BG
URq_02	PE/GT/ALT	Data need to be related to a time stamp	IPA Mapping group report	P
URq_03	PE/GT/ALT	Form of delivery for maps and data need to be flexible	IPA Mapping group report	D
URq_04	PE/GT/ALT	High data quality	IPA Mapping group report	BG
URq_05	PE/GT/ALT	Benchmark dataset needs to be developed	IPA Mapping group report, GlobPermafrost/IPA mapping group workshop	P
URq_06	PE/GT/ALT	Evaluation through community	GlobPermafrost/IPA mapping group workshop	P
URq_07	PE/GT/ALT	Terminology for modelling output 'potential'	GlobPermafrost/IPA mapping group workshop	D
URq_08	GT/ALT	Depth of active layer, permafrost temperature in K and seasonal soil freeze/thaw needs to be addressed	GCOS	BG
URq_09	PE	Threshold: uncertainty 10–25 %, hor. res. 10–100 km, temp. res. 3–5 days, timeliness 5–6 days; Breakthrough: uncertainty 7–8.5 %, hor. res. 0.85–1 km, temp. res. 14–36 hours, timeliness 14–36 h	OSCAR	BG
URq_10	PE/GT/ALT	Distribution as NetCDF	CMUG	D
URq_11	PE/GT/ALT	Development of a new ground stratigraphy product for the permafrost domain	GlobPermafrost survey	P/D
URq_12	GT	Threshold: pan-arctic, yearly, last decade, 10 km, RMSE < 2.5 °C;	Permafrost_cci survey	BG

		Target: global, monthly, 1979–present, 1 km, subgrid variability, RMSE < 0.5°C.		
URq_13	ALT	Threshold: pan-arctic, yearly, last decade, 10 km, RMSE < 25 cm; Target: global, monthly, 1979–present, 1 km, subgrid variability, RMSE < 10 cm	Permafrost_cci survey	BG
URq_14	PE/GT/ALT	Monthly products	CMUG/obs4MIPs	P
URq_15	PE/GT/ALT	NetCDF format with one product per file	CMUG/Climate Data Store (CDS)	D
URq_16	PE/GT/ALT	Monthly means and daily data	CMUG/Climate Data Store (CDS)	P
URq_17	PE/GT/ALT	ERA5 spatial resolution (0.25° x 0.25°)	CMUG/Climate Data Store (CDS)	P
URq_18	PE	Threshold: global, yearly, 10 m, 85%; Goal: global, 1 year, 10 m, 95%.	User Requirements for a Copernicus Polar Mission	BG
URq_19	ALT	Threshold: RMSE 2/15 cm; Goal: RMSE 1/5 cm (mechanical probing penetration uncertainty / sensor uncertainty)	GCOS	BG
URq_20	SD	Required extra key parameter: surface displacement (SD). Threshold: 5 m, 1 yr, 0.01 m/yr Goal: 1 m, 14 days, 0.001 m/yr	User Requirements for a Copernicus Polar Mission	BG
URq_21	SD	Soil physical characteristics target resolution of 1–5 m (regionally) and threshold resolution of 100–1000 m (circumpolar)	NRC 2014	BG
URq_22	SD	100–300m (threshold) and 20 m (target), last decade (threshold), 1979 – present (target)	CryoGrid/Permafrost_cci Option 6 URD	BG
URq_23	SD	Production of climate data records in Permafrost_cci is 1 km^2, targeting annual products based on daily input	CryoGrid/Permafrost_cci	BG

To conclude, the *IceInSAR* Option 7 will develop a prototype for permafrost model adjustment, assimilating SD products from Sentinel-1 InSAR displacement maps and time series into CryoGrid model to constrain ground stratigraphy parameters at a higher spatio-temporal resolution than the global products. *IceInSAR* will provide pilot products, expected to be used for adjustment of the ECV processing chain of the baseline project in a next phase, with the general objective to better fulfil the user requirements. The specific objectives of the project in respect to the identified URqs are:

- To take advantage of high-resolution Sentinel-1 SAR satellite data (initial resolution: 20x5 m; final multi-looked resolution between 40 and 100 m) to constrain the model and provide downscaled products in specific regions (contribution to URq_09, URq_12, URq_13, URq_18).
- To develop a prototype for permafrost model adjustment by assimilating InSAR-based surface displacement to indirectly documenting subground properties, better assess the product accuracy at the regional scale and further improve the model performance (contribution to URq_4, URq_9, URq_12, URq_13, URq_19).

- To enhance the characterisation of subsurface hydrogeologic and thermal parameters based on complementary input data and contribute to a new representation of the model subgrid variability (contribution to URq_11, URq_12, URq_13, URq_21, URq_22).
- To provide a new product type (surface displacement) at the regional scale valuable for different user communities, both for operational applications in Svalbard and for model validation and development purposes (contribution to URq_3, URq_18, URq_20).

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6.2 Acronyms

AD	Applicable Document
ALT	Active Layer Thickness
B.GEOS	B.Geos GmbH
CDS	Climate Data Store
CCI	Climate Change Initiative
CMUG	Climate Modelling User Group

ECV	Essential Climate Variable
EO	Earth Observation
ESA	European Space Agency
ESA DUE	ESA Data User Element
GAMMA	Gamma Remote Sensing AG
GCOS	Global Climate Observing System
GT	Ground Temperature
GTN-P	Global Terrestrial Network for Permafrost
UIO	University of Oslo
INSAR	Synthetic Aperature Radar Interferometry
IPA	International Permafrost Association
JRC	Joint Research Centre
NetCDF	Network Common Data Format
NORCE	Norwegian Research Centre AS
Obs4MIPs	Observations for Model Intercomparisons Project
OSCAR	Observing Systems Capability Analysis and Review Tool
PE	Permafrost Extent
PF	Permafrost Fraction
PSD	Product Specification Document
RD	Reference Document
RMSE	Root Mean Square Error
SAR	Synthetic Aperture Radar
SD	Surface Displacement
URD	Users Requirement Document
URq	User Requirement
WMO	World Meteorological Organisation