CCI+ PHASE 2 – NEW ECVS
PERMAFROST

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

D2.4 ALGORITHM DEVELOPMENT PLAN (ADP)

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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 model takes 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 Algorithm Development Plan (ADP) reminds the rationale behind the implementation of the *IceInSAR* pilot study and describes the potential future developments beyond the initial timeline of the project (2023–2025).

1 INTRODUCTION

1.1 Purpose of the document

This document provides an overview over the planned development of the algorithm within and beyond the duration of the *IceInSAR* Option 7. It has to be read as a complement to the ADP from the baseline project [RD-8].

1.2 Structure of the document

Section 2 reminds the rationale behind the development of the *IceInSAR* Option 7 and justifies the chosen processing strategy. Section 3 summarizes the implemented processing lines and specified products within the Option 7. Section 4 describes expected future developments if the results are promising at the end of the project duration.

A bibliography complementing the applicable and reference documents (Sections 1.3 and 1.4) is provided in Section 5.1. A list of acronyms is provided in Section 5.2. A glossary of the commonly accepted permafrost terminology can be found in [RD-12].

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] Rouyet, L., Wendt, L., Westermann, S., Bartsch, A., Strozzi, T. 2023. ESA CCI+ Permafrost Phase 2. CCN4 Option 7. IceInSAR: Inferred Active Layer Water/Ice Content and Freeze-Thaw Progression From Assimilating InSAR in Permafrost Model. D.1.1 User Requirement Document (URD). Version 1.0. European Space Agency.

[RD-2] Rouyet, L., Wendt, L., Westermann, S., Bartsch, A., Strozzi, T. 2023. ESA CCI+ Permafrost Phase 2. CCN4 Option 7. IceInSAR: Inferred Active Layer Water/Ice Content and Freeze-Thaw Progression From Assimilating InSAR in Permafrost Model. D.1.2 Product Specification Document (PSD). Version 1.0. European Space Agency.

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[RD-4] 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-5] Bartsch, A., Westermann, S., Strozzi, T. 2023. ESA CCI+ Permafrost. D.2.1 Product Validation and Algorithm Selection Report (PVASR). Version 4.0. European Space Agency.

[RD-6] Westermann, S., Bartsch, A., Strozzi, T. 2023. ESA CCI+ Permafrost. D.2.2 Algorithm Theoretical Basis Document (ATBD). Version 4.0. European Space Agency.

[RD-7] Westermann, S., Bartsch, A., Heim, B., Strozzi, T. 2023. ESA CCI+ Permafrost. D.2.3 End-To-End ECV Uncertainty Budget (E3UB). Version 4.0. European Space Agency.

[RD-8] Westermann, S., Bartsch, A., Heim, B., Strozzi, T. 2023. ESA CCI+ Permafrost. D.2.4 Algorithm Development Plan (ADP). Version 4.0. European Space Agency.

[RD-9] Heim, B., Wieczorek, M., Pellet, C., Delaloye, R., Barboux, C., Westermann, S., Bartsch, A., Strozzi, T. 2023. ESA CCI+ Permafrost. D.2.5 Product Validation Plan (PVP). Version 4.0. European Space Agency.

[RD-10] Bartsch, A., Westermann, S., Strozzi, T. 2023. ESA CCI+ Permafrost. D.2.1 Product Validation and Algorithm Report (PVASR). Version 4.0. European Space Agency.

[RD-11] Heim, B., Lisovski, S., Wieczorek, M., Pellet, C., Delaloye, R., Bartsch, A., Jakober, D., Pointer, G., Strozzi, T. 2021. ESA CCI+ Permafrost. D.4.1 Product validation and intercomparison report (PVIR). Version 3.0.

[RD-12] 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).

1.5 Bibliography

A complete bibliographic list that supports arguments or statements made within the current document is provided in Section 5.1.

1.6 Acronyms

A list of acronyms is provided in Section 5.2.

2 JUSTIFICATION ON THE ALGORITHM CHOSEN

2.1 InSAR processing

Multi-temporal Synthetic Aperture Radar (SAR) Interferometry (InSAR) is an established remote sensing technique to measure surface displacements with high accuracy (mm–cm). Due to the impact of the ground stratigraphy and the ground thermal regime on the dynamics of the ground surface, InSAR products have proven to be a valuable indicator of the subsurface hydrogeologic and thermal parameters in permafrost regions (Bartsch et al., 2019; Strozzi et al., 2018; Reinosch et al., 2020; Rouyet et al., 2019; Rouyet et al., 2021; Wang et al., 2020; Zhang et al., 2019; Zwieback et al., 2021). Our assumption is that InSAR may therefore be able to improve the parametrization of the subsurface properties in permafrost models.

Operational InSAR Ground Motion Services (GMS) delivering surface displacement (SD) products at the national to continental scales are becoming available all around the World. While no such service is currently available in the main permafrost regions, initiatives in that direction are being implemented (e.g. 2023–2025 InSAR Svalbard GMS development project funded by the Norwegian Space Agency and the Geological Survey of Norway). When the pilot products developed in the Option 7 show the potential of InSAR products to improve the performance of permafrost model at the local–regional scales, it will open the door to possible operational exploitation of InSAR SD data at the larger scale.

2.2 CryoGrid model

In the Permafrost_cci baseline model scheme, CryoGrid is applied to generate products at the global scale. In parallel, continued model development with a community of mainly European permafrost researchers recently led to the establishment of a CryoGrid community model (Westermann et al., 2023), which comprises the functionalities of other modules applicable at various scales and accounting for different levels of complexity. The community model includes the Permafrost_cci model used for the baseline project, as well as more sophisticated process models accounting for the complex water cycle of the permafrost, i.e. well suited for simulating the variability of active layer water/ice content (e.g. Westermann et al., 2016). The community model is also supplemented by new functionalities for generating model ensembles and ingesting various spatially distributed datasets.

The Option 7 takes advantage of these recent developments. Setting up the adjusted Option 7 model within the CryoGrid community model makes it possible to take advantage of the recent advances made by the community, while allowing future test of transferability to other permafrost regions and applying it to larger scales in the future.

3 EXISTING PRODUCTION LINES

3.1 InSAR production line

The Option 7 SD products are processed with Sentinel-1 InSAR using a SBAS algorithm (Berardino et al., 2002) implemented in the NORCE GSAR software (Larsen et al., 2005). With the objective of using InSAR to indirectly document the ground stratigraphy and constrain the parametrization of the ground stratigraphy in CryoGrid, the current project focuses on generating two types of products: seasonal surface displacement time series (SSD) and multi-seasonal surface displacement maps (MSD products) (see PSD, [RD-2]). The later can be used to produce inferred InSAR-based geocryological maps potentially exploitable for model assimilation at the larger scale.

3.2 CryoGrid production line

In the Option 7, we will generate the traditional Permafrost_cci variables (ground temperature at a certain depth GTD and active layer thickness ALT) at different spatial scales than the baseline project (see PSD, [RD-2]). Due to the pilot nature of the project, we first focus on one-dimensional point-scale simulations to evaluate the effect of InSAR data assimilation and be able to directly compare the results against in-situ GT and ALT variables acquired at similar locations (see Option 7 PVP). At the regional scale, experimental downscaled products assimilating InSAR SD data will be compared with traditional Permafrost_cci outputs (1-km grid).

At this stage, the Option 7 focuses on study areas in Central and Western Spitsbergen (Svalbard), where both project partners (NORCE and UiO) have extensive experience. If successful (improved performance after InSAR assimilation), the results may be transferred to other study areas and applied to larger regions.

4 ALGORITHM DEVELOPMENT PLANS

Based on the conclusions from the Option 7, we may evaluate the potential for model transferability in another Arctic region. If promising in Svalbard, the procedure developed in Option 7 will be tested in other permafrost regions to evaluate the transferability of the InSAR-constrained model in different environments. The actual candidates for this exercise are Siberia, Mongolia, Greenland or Alaska, building also on products developed in DUE Permafrost and DUE GlobPermafrost. The choice of the study area(s) will depend on the actual project synergies and collaborations with international institutions (to maximise the knowledge of the study area) and the data availability and quality (both remote sensing and in situ for validation).

With the long-term objective to upscale the processing to larger areas, strategies to simplify the InSAR-based information and reduce the size of the input datasets are needed. A natural continuation of the project is to test the generation and assimilation of SSD/MSD subproducts with a few categories of ground movement amplitude/patterns that effectively represent various ground conditions while avoiding injecting unnecessary complexity having minor impact on the modelling results. The categorisation of different subsidence patterns assumed to represent different levels of ground ice contents may be performed with traditional geospatial clustering techniques. This part of the project is at a research stage. The methodology for developing such maps may therefore evolve throughout and beyond the project duration. Other studies using clustering applied to InSAR data will be reviewed to define an appropriate strategy (e.g. Costantini et al., 2018; Crippa et al., 2021; Festa et al., 2022; Khalili et al., 2023).

In Option 7, we test the direct assimilation of InSAR products in the model to provide experimental products at the regional scales. An alternative solution to take advantage of InSAR capability of documenting the subsurface properties in permafrost regions is to use the SD products to refine the landcover products used as model input (indirect exploitation). In this context, it is important to highlight that Option 7 meets the objective of Option 6 (*Improved soil description through a landcover map dedicated for the Arctic*), by providing new datasets that more realistically represent the ground stratigraphy than the current landcover model input. We therefore aim to compare the InSAR-based geocryological maps from Option 7 to the Permafrost_cci Circumarctic Landcover Units (CALU) from Option 6. If these two products can be proven complementary, a natural continuation of the project would be to combine our results with the products developed in Option 6.

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5.2 Acronyms

AD	Applicable Document
ADP	Algorithm Development Plan
ALT	Active Layer Thickness
ATBD	Algorithm Theoretical Basis Document
B.GEOS	b.geos GmbH
CCI	Climate Change Initiative
ECV	Essential Climate Variable
EO	Earth Observation
ESA	European Space Agency
E3UB	End-To-End ECV Uncertainty Budget
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
NORCE	Norwegian Research Centre AS
PE	Permafrost Extent
PF	Permafrost Fraction
PSD	Product Specification Document
PVASR	Product Validation and Algorithm Selection Report
PVP	Product Validation Plan
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