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

D2.5 Product Validation Plan (PVP)

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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 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 in 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 induces 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 Product Validation Plan (PVP) describes the in-situ data collections and measurement techniques available for the validation of the *IceInSAR* Option 7 products. As a standard, quality assessments of Permafrost_cci products are carried out by point-wise match-ups at the locations of reference stations (boreholes and thaw depth probing networks) using standard statistics (such as bias, absolute error, relative percentage error, root mean square error). Option 7 will also benefit from the availability of additional field data documenting the active layer ground stratigraphy in the Adventdalen study area. Acquired in 2023 thanks to ongoing parallel projects, these datasets will be valuable to evaluate the use of InSAR SD data as indicator of the subsurface properties.

1 INTRODUCTION

1.1 Purpose of the document

This document describes the procedure and reference data used to validate the products generated by the Permafrost_cci *IceInSAR* Option 7. It has to be read as a complement to the PVP from the baseline project [RD-9].

1.2 Structure of the document

Section 2 presents the validation strategy and criteria used in the *IceInSAR* Option 7. Section 3 describes the reference data and validation activities performed as part of the Option 7. Section 4 gives information on Option 7 validation documents and their endorsement.

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.

[RD-3] Bartsch, A., Matthes, H., Westermann, S., Heim, B., Pellet, C., Onaca, A., Strozzi, T., Kroisleitner, C., Strozzi, T. 2023. ESA CCI+ Permafrost Phase 2. D1.1 User Requirement Document (URD). Version 3.0. European Space Agency.

[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 RULES FOR UNBIASED VALIDATION AND VALIDATION CRITERIA

2.1 Unbiased validation procedure

The CCI project team shall ensure independence for the validation, implying that the assessment of the Permafrost_cci product, as well as its uncertainties, is established with independent data sets and suitable statistical approaches. In the *IceInSAR* Option 7, we use independent validation datasets from the global GCOS Global Terrestrial Network for Permafrost (GTN-P) program and additional regional measurement stations (SIOS, UNIS, AWI). WMO/GCOS GTN-P managed by the International Permafrost Association (IPA) provides in situ measurements for the Permafrost ECVs from the Thermal State of Monitoring (TSP) and the Circumpolar Active Layer Monitoring program (CALM), including community standards for measurements and data collection (Brown et al., 2000, Clow, 2014).

In addition to the community permafrost temperature data, the *IceInSAR* Option 7 aims to evaluate the assumption that InSAR data is a relevant indicator for variability of the ground stratigraphy in permafrost regions. This requires additional field data documenting the ground stratigraphy of different sediment and landform types, exhibiting various InSAR displacement rates. Thanks to a parallel project funded by an Arctic Field Grand (Norwegian Research Council) as part of the ongoing M.Sc. work of Lotte Wendt (UiO), shallow cores were collected and analyzed in the valley bottom of Adventdalen, and thaw depth probing was performed at similar locations. The PVIR of Option 7 will refer to the results of this work (Wendt, in prep.) to discuss the value of InSAR as constraining dataset in the permafrost model.

The results of the product generation and validation will be disseminated to the team members of the baseline project, the contributors of CryoGrid Community and the CRG. The outcomes will be discussed during a user workshop, organised in synergy with the baseline project. The *IceInSAR* team will analyse CRG feedback and provide recommendations for the next Permafrost_cci phases. We will take advantage of the CRG from the baseline project with extension to the Svalbard community for the evaluation of the dedicated products (e.g. member institutions and main partners of the Svalbard Integrated Arctic Earth Observing System SIOS: https://sios-svalbard.org/). NORCE is currently involved in a project for the development of an InSAR Ground Motion Service (GMS) in Svalbard that is establishing a reference group for the definition of user requirements and the evaluation of pilot products. The project is at an early stage (started in Spring 2023) and includes several user workshops. Option 7 will take advantage of this synergy and may ask for evaluation of the generated products by the InSAR Svalbard reference group.

2.2 Validation criteria

We performed the assessment of Option 7 products by compiling a reference dataset in the Svalbard study areas and using common statistical approaches. The characterization of errors and uncertainties is carried out using conventional evaluation measures of mean, bias, absolute error difference and Root Mean Square Error (RMSE). In the *IceInSAR* Option 7, the validation will consist of:

- Point-wise site-specific match-up analyses of the ground temperature profile at standardized depths with a daily time stamps providing averaged bias, mean absolute error and RMSE for the GT time series, with in-depth analyses of performance.

- Point-wise site-specific match-up analyses of the thaw depth with daily time stamps providing averaged bias, mean absolute error and RMSE for the Permafrost_cci ALT time series, with in-depth analyses of performance.
- Correlation analysis of InSAR movement amplitude, ice content and ALT at selected locations in Adventdalen to evaluate the assumption that InSAR can document the spatio-temporal variability of the active layer water/ice content in the thawing/freezing layers and may therefore contribute to constrain the parametrization of the ground stratigraphy in the model.

3 VALIDATION ACTIVITIES

3.1 Reference datasets

The three selected study areas (see PSD, [RD-2]) have in-situ permafrost monitoring sites. Ground temperature (GT) measurements from the boreholes of the Global Terrestrial Network for Permafrost (GTN-P) and estimated active layer thickness (ALT) from thaw depth measurements from the Circumpolar Active Layer Monitoring (CALM) program are the main reference datasets from validation of Option 7 products.

In Adventdalen, Permafrost ECV observations have been carried out since 2000 (Strand et al., 2020) and a dense network of boreholes is available for model calibration and validation (Christiansen et al., 2021). In Ny-Ålesund, Permafrost ECV observations have been carried out since 1998 at the intensively studied Bayelva area, a permafrost research site where environmental data series have been collected (Boike et al., 2018). In Kapp Linné, Permafrost ECV observations have been carried out since 2008 and several boreholes are available for model calibration and validation (Christiansen et al., 2010; 2021). The locations and characteristics of the GTN-P/CALM sites available in the study areas are summarized in **Table 1**.

For point-scale simulations, land surface temperatures measured at the borehole location will also be used as forcing data in the model (see ATBD), while ground temperatures are used to validate the model at depth.

Table 1. Reference datasets in the Adventdalen, Ny- Ålesund and Kapp Linné study areas: Ground Temperature from boreholes (GT) and Active Layer Thickness from manual probing (ALT) from GTN-P and CALM networks with data during the period 2015–2023. The sites are shown in the maps in **Figure 1**.

Study area	Site name	Lat/long	Measured parameters	Available years	Monitoring network	Responsible institution	Comment and data access
ADV	ADV-B-1	78.189466, 16.149151	GT	2013–2023	GTN-P	UNIS	
ADV	ADV-B-2	78.194756, 15.985393	GT	2013–2023	GTN-P	UNIS	
ADV	AS-B-2	78.20146, 15.83465	GT	2008–2019	GNT-P	UNIS	
ADV	Adventdalen – Loess Terrace	78.2010, 15.8368	GT	2019–2023	SIOS	UNIS	Data access through MET
ADV	EN-B-1	78.190206, 15.78158	GT	2008–2021	GTN-P	UNIS	
ADV	EN-B-2	78.190456, 15.781619	GT	2013–2020	GTN-P	UNIS	
ADV	Endalen	78.1905, 15.7815	GT	2021–2023	SIOS	UNIS	Data access through MET
ADV	JAN-B-1	78.184726, 16.285834	GT	2013–2021	GTN-P	UNIS	
ADV	Innerhytte Pingo	78.1889, 16.3455	GT	2008–2020	GTN-P	UNIS	

ADV	Adventdalen – Innerhytta Pingo	78.1888, 16.3442	GT	2020–2023	SIOS	UNIS	Data access through MET
ADV	Ice Wedge	78.18583, 15.923572	GT	2012–2019	GTN-P	UNIS	
ADV	Adventdalen – Ice Wedge	78.18580, 15.92362	GT	2019–2023	SIOS	UNIS	Data access through MET
ADV	Snow-patch-lower	78.18752, 15.91324	GT	2008–2013	GTN-P	UNIS	
ADV	Snow-patch-upper	78.18752, 15.91324	GT	2008–2020	GTN-P	UNIS	
ADV	Adventdalen Upper Snowdrift	78.18752, 15.91328	GT	2019–2023	SIOS	UNIS	Data access through MET
ADV	Janssonhaugen – Vest	78.1794, 16.3686	GT	2019–2023	SIOS	MET	Data access through MET
ADV	Janssonhaugen	78.1793, 16.3805	GT	1998–2023	PACE	MET	Data access through MET
ADV	UNIS-CALM	78.2005, 15.8386	ALT	2000–2023	CALM	UNIS	
NYA	Bayelva	78.92086, 11.83345	GT	2009–2023	GNT-P	AWI	Data access through PANGEA
NYA	DBNyAlesund	78.92194, 11.86583	GT	2016–2019	GNT-P	UNIS	
NYA	Ecogrid	78.92, 11.86	ALT	2014–2019	CALM	University of Insubria	
KAP	KL-B-1	78.05663, 13.641478	GT	2008–2021	GNT-P	UNIS	
KAP	KL-B-2	13.636671, 78.054605	GT	2008–2021	GNT-P	UNIS	

3.2 Additional datasets

The composition of soil/rock, ice, air, unfrozen water, organic content, its cryotexture and -structure influence the thermal subsurface properties of the permafrost and the active layer. The seasonal thawing and freezing of the upper ground layers induce cyclic subsidence and heave of the ground surface due to ice formation and melt in the active layer. The movement amplitude in permafrost environment is highly related to the frost-susceptibility of the ground material, i.e. the ability for water to turn into ice lenses and lift up the ground surface during the freezing period. The main assumption of the Option 7 is that InSAR-based surface displacements can document the spatio-temporal variability of the active layer water/ice content in the thawing/freezing layers and may therefore contribute to constrain the parametrization of the ground stratigraphy in the model. To validate this assumption, we need to compare InSAR products with field data documenting need to confirm that the magnitude of the InSAR-measured subsidence/heave relate to the ground parameters.

In addition to the GT and ALT data collection described in Section 3.1, a field campaign supported by an Arctic Field Grant was carried out in Spring-Summer 2023 as part of Wendt's master thesis to characterize subsurface parameters in Adventdalen. A total of 12 cores between 0.6 and 2 m depth were collected (**Figure 1**, ADV) to document the geocryological properties of the active layer and upper permafrost (stratigraphy, organic content, ground ice content, dominating lithology and texture). Different geomorphological landforms assumed to represent a variety of subsurface conditions were covered. The site selection also represents a variety of InSAR seasonal displacement amplitudes. At similar locations, the active layer thickness is estimated by manually probing the thaw depth in late summer.

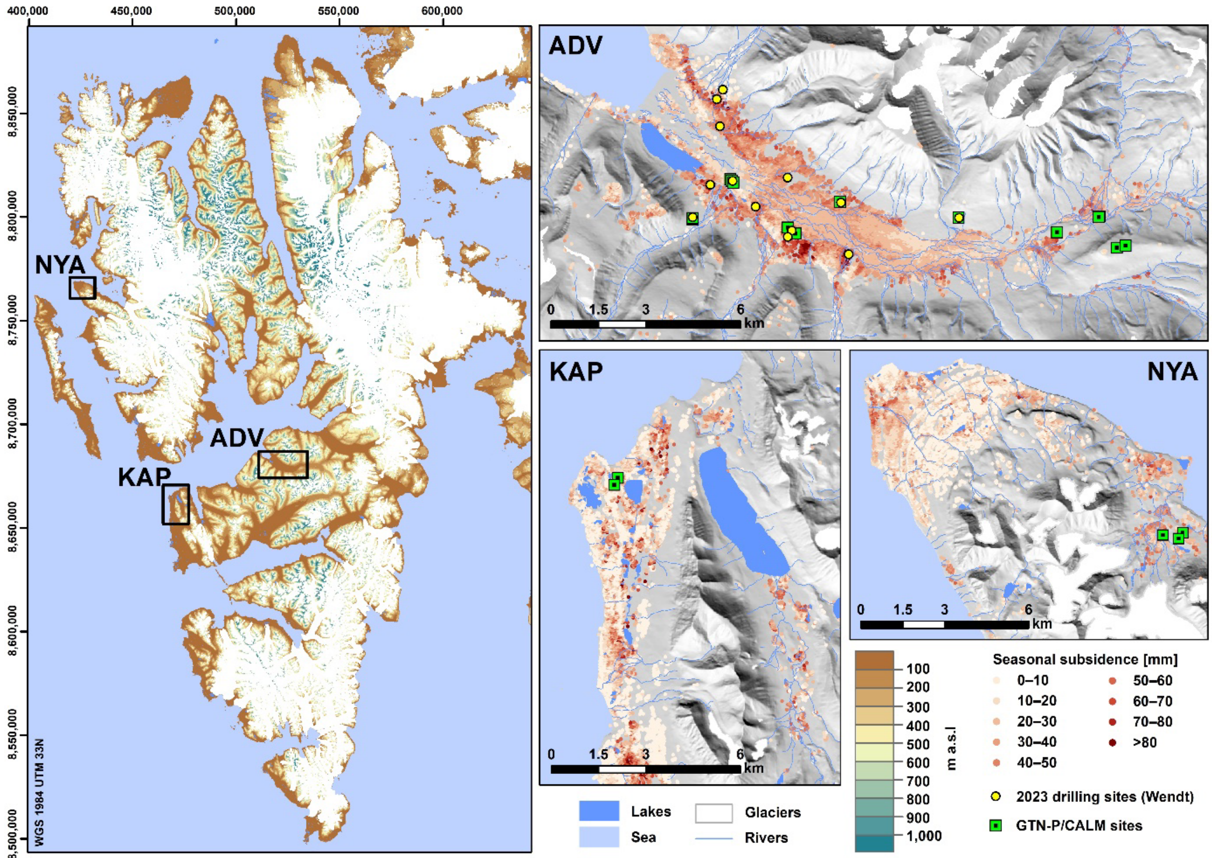

Figure 1. Locations of reference data from boreholes and CALM sites in the three study areas (Adventdalen ADV, Ny-Ålesund NYA and Kapp Linné KAP). In ADV, the location of cryostratigraphic and ALT data from Wendt's thesis are also shown (drilling sites and thaw depth probing in the valley bottom). Note that the extents of the maps are slightly different than the study areas presented in the PSD [RD-2] for sake of visualisation (zoom in on areas with reference sites for validation). Seasonal InSAR-based subsidence maps in the background are based on past results (2017 season) from Rouyet et al., 2021.

3.3 Validation strategies

3.3.1 In-situ validation of CryoGrid products

For the one-dimensional point-scale simulations, GT and ALT reference data from the in-situ permafrost monitoring sites (see Section 3.1) will be compared with the model results before and after the integration of InSAR products, to evaluate the influence of the data assimilation. Averaged bias, mean absolute error and RMSE between the modelled GT/ALT and the in-situ observations will be reported with a daily time stamps.

For the experimental products at the regional scale, discrepancies between the 1-km initial Permafrost_cci products and the downscaled products constrained by SD products will be compared and discussed during product assessment (Section 3.3.3). The spread of the model ensemble of the initial Permafrost_cci product and the spread of the downscaled results using SD-constrained model ouputs will be compared with the available in-situ data in the areas.

3.3.2 Verification of assumption of InSAR as indicator of subsurface properties

At the sites where shallow cores have been collected (see Section 3.2), the following subsurface parameters were retrieved as part of Wendt's master thesis: Excess Ice Content (EIC), Gravimetric Moisture Content (GMC), Volumetric Moisture Content (VMC) and Soil Organic Matter content (SOM). The results from the core analysis will be compared with in-situ ALT estimates and the InSAR SD measurements for the 2023 season. A correlation analysis of InSAR movement amplitude, ice content and ALT at selected locations in Adventdalen will evaluate the assumption that InSAR can document the spatio-temporal variability of subsurface parameters impacting the heat transfer and therefore contribute to constrain the parametrization of the ground stratigraphy in the model.

3.3.3 Product assessment

The results will be assessed by the Climate Research Group (CRG) and the *IceInSAR* conclusions will be discussed with the Permafrost_cci consortium and the user community to design the future phases of product development. The products and the results of the validation will be disseminated to the team members of the baseline project, the contributors of CryoGrid Community and the CRG. The outcomes will be discussed during a User Workshop, organised in synergy with the baseline project. The *IceInSAR* team will analyse CRG feedback and provide recommendations for the next Permafrost_cci phases. We will take advantage of the CRG from the baseline project with extension to the Svalbard community for the evaluation of the Option 7 products.

4 VALIDATION DOCUMENTS AND ENDORSEMENTS

Table 2 provides an overview on the Option 7 Deliverables relevant for product validation and the product assessment. Apart from the project Deliverables, we also seek for documenting the results in additional publications, such as a peer-reviewed paper in a scientific journal. If the results of the validation activities of the *IceInSAR* Option 7 products can be presented in the form of article and data publications, the largest possible endorsement is achieved.

Table 2. Documents related to validation of the Permafrost_cci products.

Deliv.	Name	Date	Content
D2.3	**E3UB**	KO+9: September 2023	defines sources of errors and uncertainties.
D2.5	**PVP**	KO+9: September 2023	outlines planned validation strategies.
D3.2	**CRDP**	KO+21: September 2024	describes the Climate Research Data Package, CRDP, the products of the pilot studies, uncertainty characterized.
D4.1	**PVIR**	KO+21: September 2024	provides a summary on quality and uncertainty of the Option 7 pilot products.
D4.2	**PUG**	KO+21: September 2024	describes delivered Permafrost_cci products in the CRDP.
D5.1	**CAR**	KO+24: December 2024	describes the Climate Science study cases using the CCI products and the user's feedback.

5 BIBLIOGRAPHY AND ACRONYMS

5.1 Bibliography

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Boike, J., Roth, K., & Ippisch, O. (2003). Seasonal snow cover on frozen ground: Energy balance calculations of a permafrost site near Ny-Ålesund, Spitsbergen. *Journal of Geophysical Research: Atmospheres*, *108*(D2), ALT-4.

Boike, J., Juszak, I., Lange, S., Chadburn, S., Burke, E., Overduin, P. P., ... & Westermann, S. (2018). A 20-year record (1998–2017) of permafrost, active layer and meteorological conditions at a high Arctic permafrost research site (Bayelva, Spitsbergen). *Earth System Science Data*, *10*(1), 355–390.

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Wendt, L. (in prep.) Assessing the relationship between ground ice contents and InSAR surface displacements for improved permafrost modelling. M.Sc. thesis. University of Oslo, Norway.

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