ESA Climate Change Initiative (CCI+)
Essential Climate Variable (ECV)

Greenland_Ice_Sheet_cci+ (GIS_cci+)

Algorithm Development Plan

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Issued by	Daniele Fantin, Project Manager, S&T		Date: 08.05.2023
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Change Log

Issue	Author	Affected Section	Change
1.0	L.Sørensen	All	Document Creation
	L. Sørensen	All	Input on ECVs
2.0	R. Forsberg	All	Update for 2nd cycle of CCI+
2.1	M. Vege, D. Völgyes	2.2, 2.6	Update on Opt IV, new section on CFL
3.0	J. Wuite	All	New version for CCI+ Phase 2

Contents

Acronyms and Abbreviations

ASIAQ	Arctic Science Integration Quest
ATBD	Algorithm Theoretical Basis Document
C3S	Copernicus Climate Change Service
CCI	Climate Change Initiative
CFL	Calving Front Location
CONAE	Comisión Nacional de Actividades Espaciales
CS2	CryoSat-2
DEM	Digital Elevation Model
DMI	Danish Meteorological Institute
DTU	Technological University of Denmark
DTU-N	DTU Microwaves and Remote Sensing Group
DTU-S	DTU Geodynamics Group
E3UB	End-to-End ECV Uncertainty Budget
ECV	Essential Climate Variable
ENVEO	ENVironmental Earth Observation GmbH
EO	Earth Observation
ESA	European Space Agency
GCOS	Global Climate Observation System
GEUS	Geological Survey of Denmark and Greenland
GIA	Glacial Isostatic adjustment
GIMP	Greenland Mapping Project
GIS	Greenland Ice Sheet
GMB	Gravimetry Mass Balance
GPS	Global Positioning System
GRACE(-FO)	Gravity Recovery And Climate Experiment(-Follow On)
InSAR	Interferometric Synthetic Aperture Radar
IV-SAR/OPT	Ice Velocity (-Sar/-Optical)
LoS	line-of-sight
LRI	Laser Ranging Interferometer
MFID	Mass Flux and Ice Discharge
NBI	Niels Bohr Institute, University of Copenhagen
OT	Offset tracking
RA	Radar Altimetry
RMS	Root Mean Square
S&T	Science and Technology AS

SAR	Synthetic Aperture Radar
SDS	Science Data System
SEC	Surface Elevation Change
SGL	Supraglacial Lakes
SOW	Statement of Work
TOPS	Terrain Observation by Progressive Scans
TPROP	Technical Proposal
TUDr	Technische Universität Dresden
UL	University of Leeds

1. Introduction

1.1 Purpose and Scope

This document contains the Algorithm Development Plan for the Greenland Ice Sheet CCI project for CCI+ Phase 2, in accordance with contract and SoW [AD1 and AD2]. The purpose of the document is to outline the conceptual principles for further algorithm developments of the following ECVs:

- SEC: high spatial and temporal resolution, reference DEM grid, dh(t) grids;
- GMB: ellipsoidal correction, LRI solutions, GIA correction;
- IV-SAR: SAOCOM, InSAR, time-series of LoS velocities;
- IV-Opt: multiple spectral bands, improved filtering;
- MFID: new DEMs and ice thickness.
- SGL: new proof of concept ECV on supraglacial lakes.

1.2 Document Structure

This document is structured as follows:

- Chapter 1 provides an introduction to the document.
- Chapter 2 provides short descriptions of planned new algorithm developments for each ECV

1.3 Applicable and Reference Documents

Table 1.1: List of Applicable Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
AD1	ESA/Contract 4000126523/18/I-NB	Climate Change Initiative Extension (CCI+) Phase 2), New R&D on CCI Essential Climate Variables		
AD2	ESA-EOP-SC-AMT-2021-53	Climate Change Initiative Extension (CCI+) Phase 2), New R&D on CCI Essential Climate Variables, Statement of Work	10/06/2022	1
AD3	ATBD	Algorithm Theoretical Basis Document		

2. Planned Algorithm Developments

2.1 Surface Elevation Changes

In Phase 1 of the Greenland CCI+ project, we continued the delivery of a 5-year running mean SEC for the Greenland ice sheet, with the focus of providing the highest possible spatial resolution (5 km). Within the C3S project, which relies on the R&D carried out in the CCI projects, the focus is on increasing the temporal resolution of the delivered products (monthly). Therefore, R&D efforts within CCI+ GIS phase 2 will focus on providing data at both high spatial and temporal resolution. The algorithm development will focus on the recent missions (CryoSat-2 and Sentinel-3), where especially progressing to CryoSat-2 Swath processed data is expected to increase observational coverage within the SARIn area (Gourmelen et al., 2018, Andersen et al., 2022). Further, in contrast to Phase 1 of the Greenland CCI+ project, the SEC data product will progress from a dh/dt grid to a reference DEM grid and multiple dh(t) grids, which strives to meet the GCOS requirements. We see multiple approaches to reach this which will be investigated during the early phase of phase 2. One approach could be that the traditional regression of dh/dt

$$
\begin{aligned}
H(x,y,t) = H_0(\bar{x},\bar{y}) &+ dH/dt(t-\bar{t}) \\
&+ dLeW(LeW - \bar{LeW}) \;\; + dB_s(Bs - \overline{Bs}) \\
&+ sx(x-\bar{x}) + sy(y-\bar{y}) + cx(x^2 - \bar{x}^2) \\
&+ cy(y^2 - \bar{y}^2) + cc(x^2 - \bar{x}^2)(y^2 - \bar{y}^2) \\
&+ \alpha\cos(\omega t) + \beta\sin(\omega t) \\
&+ b_{AD}(-1)^{AD} \\
&+ \epsilon(x,y,t),
\end{aligned}
$$

where overbars are the average, H is the elevation at location (x,y), and time t, LeW is leading edge width, Bs is backscatter, (sx, sy, cx, cy, cc) is curvature parameters, (α, β, ω) is parameters for interannual variability in the elevation, and ε is the residuals, can be used to correct the satellite observed elevations for local topography. Thereby a time series of elevations can be constructed at a common location on the ice sheet, with the temporal evolution of satellite passes within the chosen influence kernel. Another approach that will be investigated is to increase the dimensions of the kriging procedure to also include the time dimension and not only as done in the past on the gridded solutions to dh/dt.

Having established the most optimal method of deriving reference DEM and the dh(t), the processing algorithm will be made to accommodate interchanging input data, which will allow for an experimental product release using ICESat-2**.** Further, operationalization of the R&D within the Greenland CCI+ phase 2 will be conducted within the C3S, and we strive to ensure the quality and uptake of CCI+ phase 2 developments into C3S**.**

The product validation will build on lessons learned during the previous phases of the CCI project but evolve by replacing the Operation IceBridge L4 data previously used with the ICESat-2 elevation change product (ATL15) to ensure a full end-to-end uncertainty characterization (E3UB) can be performed in the years to come.

2.2 Ice Velocity from SAR

In Phase 1 of the Greenland CCI+ project we have been working on the evolution of the processing line for advancing the IV products. This included the extension of the IV processor for supporting Sentinel-1 Terrain Observation by Progressive Scans (TOPS) mode InSAR, using ascending and descending crossing orbit pairs. Based on this system we generated a comprehensive high-resolution ice velocity map at 50 m posting over the ice sheet by combining SAR interferometry (InSAR) and offset-tracking (OT) (Figure 2.1a; Nagler et al., 2022). The InSAR method provides improved accuracy particularly in the slow-moving interior of the ice sheets and at higher resolution, but requires crossing satellite acquisitions as well as image pairs with adequate coherence. On zones without crossing orbits the processing line combines the velocity vector derived from InSAR with flow direction derived from OT to optimally fill in gaps. Fast moving areas, where coherence is not preserved, are filled with OT velocity observations. The added value of the new ice velocity map was assessed by intercomparison with operational ice velocity products and in-situ GPS data, showing significant improvements compared to existing operational products. In the proposed project we aim on further developing, extending and streamlining this system for optimally generating and merging data from different techniques (InSAR, SAR OT) for routine generation of advanced Greenland-wide ice velocity maps.

8-day repeat-pass L-Band SAR data over Greenland are since 2021 also acquired by SAOCOM A/B SAR mission (Figure 2.1b) as a background mission (i.e. without systematic acquisition plan). The prime payload of the dual satellite constellation is an L-band polarimetric SAR instrument, managed and operated by CONAE (Comisión Nacional de Actividades Espaciales - Argentina's Space Agency). By using L-Band SAR data the use of the InSAR method can be extended to cover faster moving areas than possible with C-band (Sentinel-1). Simulations show that L-band data have a reduced fringe frequency in shear zones and fast-moving areas, enabling reliable phase unwrapping so that the InSAR method can also be applied in zones where Sentinel-1 data decorelate. Additionally, the L-band signal coherence is less affected by variable surface conditions than C-band. Consequently, further improvement for ice velocity monitoring can be expected from the synergy of C-band and L-band InSAR data, as rendered possible by combining Sentinel-1 and SAOCOM A/B. Within the project we will develop tools for processing SAOCOM data focusing on handling large baselines, automatization of coregistering SAOCOM data combining orbital data, DEM and refinement using local matching of datasets, which is needed due to the reduced quality of the orbital state vectors. Using SAOCOM data we will investigate methods for combining L- and C-Band interferometric data for ice velocity monitoring using InSAR. The planned work will be carried out in coordination with the activities proposed in 4DGreenland and Antarctic Ice Sheet CCI+ Phase 2. The work contributes to the preparation for the upcoming NISAR L-Band Mission scheduled for Launch in Jan 2024, and the Copernicus ROSE-L Mission.

a) b)

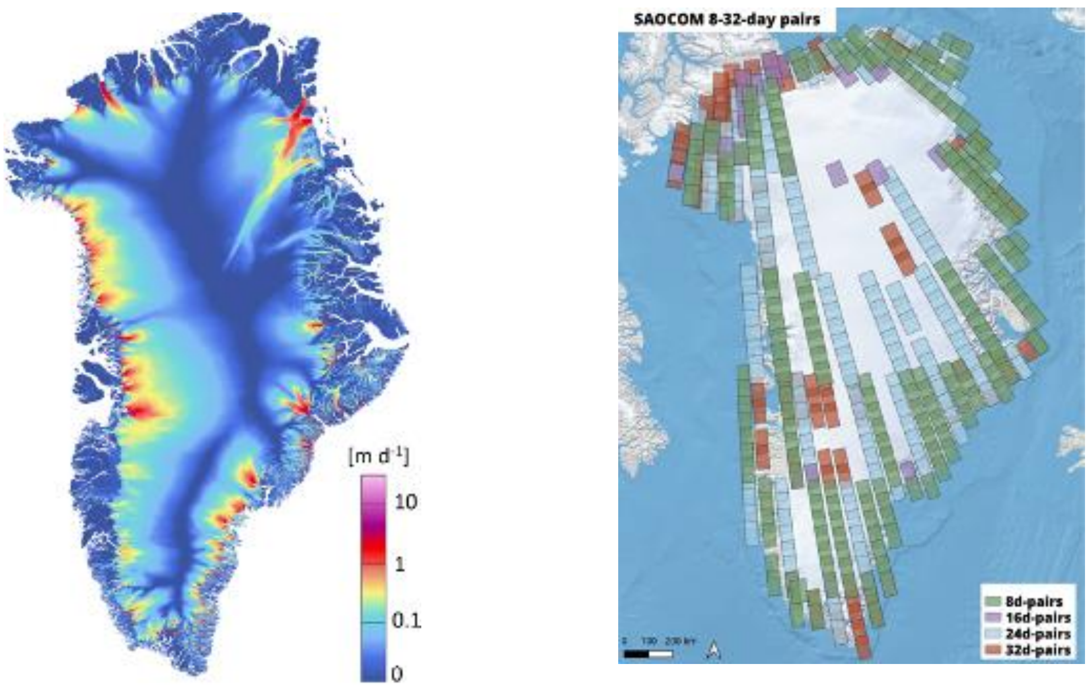

Figure 2.1a) Greenland ice sheet wide velocity map, 50 m pixel spacing, combining SAR interferometry and offset tracking, using Sentinel-1A and 1B SAR data with 6 days repeat for the period 2018-2021. b) Greenland Ice Sheet coverage of SAOCOM 1A and 1B Stripmap S4 and S5 acquisitions with 8, 16, 24 & 32 days repeat coverage (Nov 2021- Mar 2022).

The current IV product contains Greenland-wide 2D velocities generated from multiple observations from InSAR and/or offset-tracking. Since InSAR only measures displacements in the radar line-of-sight (LoS) direction, 2D velocities must be derived by combining InSAR measurements from crossing tracks - which are not routinely acquired - or by combining them with much noisier offset-tracking measurements. Furthermore, the ice is assumed to flow along the terrain. Many small-scale dynamic phenomena have a rapid time variation and/or a vertical displacement (subsidence/uplift) component that is not preserved in the IV product. The high resolution and low noise level of InSAR measurements provides an opportunity to study these phenomena from time series based on individual image pairs, i.e., with a 6-12 day time resolution, but this is only possible by using the LoS velocities. A prototype time-series LoS velocity product will be generated, containing also the supporting information required for users to interpret the data correctly.

The algorithm used to generate the LoS velocity product is in principle a subset of the already applied InSAR algorithm, as the line-of-sight velocities are used as input to generate the 2D velocities. However, in order to exploit the LoS velocities, some additional processing is required that will be developed and refined in the following year:

- All LoS observations from a single track (at different times) should be resampled to the same grid in order to be stacked, so that they can be delivered as a timeseries..
- Since the subsidence and uplift components of ice velocity are typically very small compared to the horizontal flow velocity, what is needed is actually the LoS velocity anomaly, i.e. the deviation from an average LoS velocity. This could be delivered as the actual product, or the full LoS velocities could be supplied, with the average velocity field supplied as an additional layer, which the user can subtract.
- The LoS vector orientation angles (i.e. elevation and azimuth angle from the observed point to the radar) are required to interpret the LoS velocity measurements, depending on the nature of the observed phenomena. In some cases, the observed anomaly is purely a vertical displacement, and only the elevation angle is required, In the general case, the anomaly is a combination of horizontal and vertical displacement. These cannot always be decoupled, but if crossing tracks with a sufficient time overlap are available, and by assuming a constant horizontal flow direction, they can be separated. A user-friendly way of supplying this information is to be developed.

2.3 Ice Velocity from Optical

The core of the optical IV pipeline is the feature tracking algorithm which is used to find ice flow velocity by deriving pixel shifts between Sentinel-2 images from different time points. The algorithmic development will focus on improving the feature tracking algorithm itself and post-processing of the resulting IV maps.

Feature tracking: Currently only the blue band is exploited by the feature tracking algorithm. The use of multiple spectral bands is expected to increase the accuracy as different features are more distinctive in a multispectral domain. Incorporating additional bands will negatively impact processing time, therefore some effort is expected in further optimization of the feature tracking algorithm. One of the optimizations could be that the feature tracking of different bands is parallelized and that the results are combined in a post-processing step. Ideally, however, the feature tracking happens directly across multiple spectral dimensions such that all spectral information is accounted for at once.

Post-processing IV maps: The output of the feature tracking algorithm is the IV map accompanied by per-pixel RMS quality values that follow from the underlying image patch matching. These quality values are currently used to filter unreliable IV values from the IV map. This way of filtering does not enforce local consistency of IV and as a result, outliers can be present in the IV maps. The filtering will therefore be extended by IV outlier detection and removal, by evaluating the neighbourhood of IV pixels and disallowing sudden jumps in IV.

2.4 Gravimetric Mass Balance

Algorithms will be based on GRACE and GRACE-FO gravity field solutions given in a spherical harmonic representation. We will continue the development of our approaches: DTU-S will follow the inversion approach based on a point mass parameterisation and pseudo-observations generated in the form of gravity changes at satellite height (Barletta et al. 2013). TUDr will follow its tailored sensitivity kernel approach (Döhne et al. 2023).

An ellipsoidal correction will be developed and implemented to make the inference of ice mass changes from gravity field changes more accurate. Recent research has highlighted some limitations of the spherical approximation applied so far (Li et al. 2017; Ditmar et al. 2018; Ghobadi-Far et al. 2019). We will review the literature, assess different novel approaches for an ellipsoidal correction and choose the most effective one.

We will follow developments in the availability and quality of monthly gravity field solutions from GRACE and GRACE-FO and adapt our algorithms accordingly. These developments concern, among other things, the recommendations of the GRACE-FO Science and Data System (SDS) on how to handle low-degree components (degree-one, C20, C30). We will also test the utilisation of monthly solutions generated by using the GRACE-FO Laser Ranging Interferometer (LRI) as soon as such solutions will be available from the GRACE-FO SDS. Testing LRI solutions for Greenland mass balance applications will give valuable feedback to the GRACE-FO processing centers and the GRACE-FO community on the quality of these solutions. At the same time we do not expect a breakthrough benefit for the GMB data product, as LRI-based solutions will cover only part of the GRACE-FO lifetime. We will therefore concentrate on a second line of methodological developments, which immediately concerns the long-term changes in the whole GRACE and GRACE-FO product time series – see next paragraph.

Glacial Isostatic Adjustment (GIA) is one of the main sources of uncertainty in the Greenland mass balance derived from GRACE, it is about +/- 7 Gt/yr. In order to reduce such uncertainty we need to tune state of the art GIA models specifically for Greenland. In Phase 1 we replaced GIA correction from ICE-6G with Caron et al. (2018). However the differences in mass equivalent GIA effects between available GIA models over Greenland are large. The relative effect (that is the ratio between the GIA correction and the ice mass change) can be large for single basins, e.g. in northeast Greenland (Kappelsberger et al. 2021) or southwest basins. Here R&D effort will focus on improving new available models and tune them for Greenland with the use of GPS uplift rates with the starting point being the semi-empirical GIA model computed in Khan et al. (2016).

2.5 Mass Flow Rate and Ice Discharge

The MFID product is derived using surface velocity and ice thickness observations, where the highest uncertainty derives from thickness estimates. The main workflow/algorithm development in this phase will include:

- Updating the reference DEM and the way to handle dh/dt
- New way of handling flux gate positions in order to reduce thickness errors

In Phase 1, SEC were imposed on the GIMP Digital Elevation Model (DEM) (Howat et al., 2014) which is composed of a mosaic of DEMs generated within the period 2003-2009, but assuming only a single timestamp with the nominal date 2007. In phase 2, we will use a DEM with a single timestamp enabling us to explore the effect of including changes in surface elevation (ice thickness) on the MFID product.

Furthermore, the MFID update will include a product extension to present day and use:

- The latest version of the bed topography model: BedMachine v5
- All ESA CCI Greenland IV including the latest IV from this project

2.6 Supra-Glacial Lakes (SGL)

Our aim is to detect supraglacial lakes within two catchment areas in North-East Greenland (79 and Zacharia). The methods are described in the GIS CCI+ ATBD [AD3], which build upon a previous Greenland CCI project aimed at extracting supraglacial lake extent for the 2019 melt season (May-October) in the northeast and southwest Greenland performed by ASIAQ. The planned algorithm developments within the CCI+ project include:

- Extraction of supraglacial lake extent in northeast Greenland from Sentinel-2 images (Bands 2, 3, 4 and 8) and supraglacial lake extent labels generated from the previous CCI (mentioned above).
- Extraction of supraglacial lake depth in northeast Greenland from Sentinel-2 images and lake bathymetry data processed by DTU, to be validated by ASIAQ. Lake bathymetry data is derived from laser altimetry data from IceSat-2.
- Production of a dataset containing lake extent and lake depth estimates for the 2019 meltwater season in northeast Greenland. If successful, the model may be rolled out onto other areas where there are sufficient labels, such as southwest Greenland. The dataset will be generated using a deep learning algorithm which uses a U-Net architecture (Ronneberger et al., 2015) which is trained on Sentinel-2 optical imagery, lake extent labels and partial lake depth labels (mentioned above). From the 13 available bands, all 10m resolution bands are selected as input channels for the model as these provide better detail for smaller lakes (bands B02, B03, B04 and B08). The algorithm is trained to “learn” features of the optical imagery in order to predict lake extent and depth. The model is known as a “multi-task” model, by which it will classify the pixels of the output as a lake or background (classification) as well as predict a depth (elevation below the surface) value for a pixel of an output image (regression).

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