ESA Climate Change Initiative (CCI+)

Essential Climate Variable (ECV)

Greenland_Ice_Sheet_cci+ (GIS_cci+)

Algorithm Development Plan

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Change Log

Issue	Author	Affected Section	Change	Status
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 session on CFL	Delivered to ESA

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Acronyms and Abbreviations

AIS	Antarctic Ice Sheet
AMAP	Arctic Monitoring and Assessment Programme
ATBD	Algorithm Theoretical Basis Document
CAR	Climate Assessment Report
CCI	Climate Change Initiative
CEOS	Committee on Earth Observation Satellites
CFL	Calving Front Location
CMUG	Climate Modelling User Group
CPROP	Contractual Proposal
CR	Cardinal Requirement
CRDP	Climate Research Data Package
CRYOVEX	CryoSat Validation Experiment (airborne and in-situ campaigns)
CRG	Climate Research Group
CS2	CryoSat-2
C3S	Copernicus Climate Change Service
DARD	Data Access and Requirements Document
DEM	Digital Elevation Model
DInSAR	Differential Interferometric Synthetic Aperture Radar
DMI	Danish Meteorological Institute
DTU-S	DTU Geodynamics Group
DTU-N	DTU Microwaves and Remote Sensing Group
ECV	Essential Climate Variable
EO	Earth Observation
ENVEO	ENVironmental Earth Observation GmbH
ESA	European Space Agency
E3UB	End-to-End ECV Uncertainty Budget
FCDR	Fundamental Climate Data Record
FPROP	Financial Proposal
GCOS	Global Climate Observation System
GEUS	Geological Survey of Denmark and Greenland
GCP	Ground Control Point
GIA	Glacial Isostatic adjustment
GIS	Greenland Ice Sheet
GLL	Grounding Line Location
GMB	Gravimetry Mass Balance
GIS	Greenland Ice Sheet
IGOS	Integrated Global Observing Strategy

IMBIE	Ice Sheet Mass Balance Inter-comparison Exercise
InSAR	Interferometric Synthetic Aperture Radar
IOC	Intergovernmental Oceanographic Commission
IPCC	Intergovernmental Panel of Climate Change
IPP	Interferometric Post-Processing
IPROP	Implementation Proposal
IPY	International Polar Year
IV	Ice Velocity
IW	Interferometric Wideswath
MFID	Mass Flux and Ice Discharge
MPROP	Management Proposal
NBI	Niels Bohr Institute, University of Copenhagen
NERSC	Nansen Environmental Research Institute
PARCA	Polar Areas Regional Climate Assessment project (NASA)
PM	Progress Meeting/ Project Management
PMP	Project Management Plan
PROMICE	Danish Program for Monitoring of the Greenland Ice Sheet
PSD	Product Specification Document
PUG	Product User Guide
PVIR	Product Validation and Intercomparison Report
RA	Radar Altimetry
RFQ	Request For Quotation
S&T	Science and Technology AS
SAR	Synthetic Aperture Radar
SLBC cci	Sea Level Budget Closure cci project
SEC	Surface Elevation Change
SOW	Statement of Work
SSD	System Specification Document
SVALI	Stability and Variability of Arctic Land Ice (Nordic project)
SWIPA	Snow, water, Ice and Permafrost in the Arctic
SVR	System Verification Report
TBD	To Be Decided
TPROP	Technical Proposal
TSX/TDX	TerraSAR-X/TanDEM-X SAR mission
TUDr	Technische Universität Dresden
UL	University of Leeds
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
URD	User Requirement Document

WBS	Work Breakdown Structure
WMO	World Meteorological Organization

1 Introduction

1.1 Purpose and Scope

This document contains the updated Algorithm Development Plan for the Greenland_Ice_Sheet_cci (GIS_cci) project for CCI+ Phase 2, in accordance to contract and SoW [AD1 and AD2]. The purpose of the document is to outline the conceptual principles for algorithm developments, especially for novel ECV products which include [RD1]:

- SEC from IceSat-2 photon counting
- GMB for GRACE-FO satellite
- IV improvements in interior, slow-moving regions,
- lakes products,
- MFID principles for estimating mass discharge.
- CFL for Sentinel+2 satellite

The ADP will be delivered as an annex to the PMP [RD1].

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 within each ECV/data

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 No. 4000126023/19/I-NB, and its Appendix 1	CCI+ PHASE 1 - NEW R&D ON CCI ECVS, for Greenland_Ice Sheet_cci		
AD2	ESA-CCI-EOPS-PRGM-SOW-18-0118 Appendix 2 to contract.	Climate Change Initiative Extension (CCI+) Phase 1, New R&D on CCI ECVs Statement of Work	2018.05.31	Issue 1 Revision 6

Table 1.2: List of Reference Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
RD1	ST-DTU-ESA-GISCCI+-PMP-001	Project Management Plan	12 May 2020	1.2
RD2	ST-DTU-ESA-GISCCI+-ATBD-001	Algorithm Theoretical Baseline Document CCI+	19 Oct 2020	1.2
RD3	ST-ESA-COLD-ML-D1D2D3-001	ST-ESA-COLD-ML-D1D2D3-001	07 Jan 2021	1.0

Note: If not provided, the reference applies to the latest released Issue/Revision/Version

2 Planned Algorithm Developments

2.1 Surface elevation changes

The algorithms implemented to derive surface elevation changes (5 yr trends) from the long time series of ESA radar missions is described in detail in the ATBD [RD2]. These include true repeat-track, along-track, plane-fit and cross-over algorithms (Sørensen et al., 2018).

The algorithms have been updated in CCI+ Phase 1 with a new unified software update (DTU RART processor), based on Python. This new suite of software replaces the software of CCI (2012-2018), and allow processing on all RA missions (ERS, Envisat and Cryosat) in the same processing suite, yielding a unified 5 km resolution SEC grid. The details of the new update are described in RD2.

The planned algorithm developments within the CCI+ project 2nd cycle 2021/22 include:

- Increasing temporal resolution to allow for 3-monthly surface change grids.
- Implement and testing a new experimental software using Kriging with constraints, to allow aiding of the elevation changes by the IV product. This product has already demonstrated the usefulness along ice stream regions in NE Greenland.
- Extracting independent SEC grids from IceSat-2 photon counting data. The algorithm will apply to the ATL06 averaged data sets (due to the very large data files for the ATL03 full photon L1 cloud data). The IS-2 algorithm will enable to fully take advantage of the 6 laser beams providing across-track topography (data set description can be found at https://nsidc.org/data/icesat-2/data-sets). We note that a SEC product (ATL15) from ICESat-2 will be directly developed by NASA and published on NSIDC as well. The CCI+ do therefore *not* plan to provide a unified CS-2/IS-2 SEC product, due to the inherent errors in radar penetration over the ice sheet. Experimental R&D data sets will be developed in CCI+, for possible future inclusion in C3S and/or CCI product portfolios.
- Alignment (e.g. bias correction) in the SEC time series with the inclusion of Sentinel-3 data, to ensure a long stable time series into the coming years. S-3 data have been implemented in the RART processor.

2.2 Ice Velocity

Ice velocity (IV) measurements will be continued using the algorithms described in the ATBD [RD2]. The main development will be related to the use of interferometry for Sentinel-1 Interferometric Wideswath (IW) data. Interferometry enables a potential order of magnitude increase in resolution and accuracy compared to the offset-tracking methods so far employed to measure IV from Sentinel-1 data. However, it provides only relative measurements of the line-of-sight component of the velocity, and works only on coherent pairs, limiting its use to relatively slow-moving regions of the ice sheet (e.g., the interior parts and the inner part of the North-East Greenland Ice Stream).

Interferometry applied to IW data, which are acquired in the Sentinel-1 specific TOPS mode, presents special challenges compared to conventional strip-map data, since the data are acquired in bursts, during which the line-of-sight of the radar beam changes from aft to forward looking. At the edge between two bursts, an unknown azimuth component of scene motion will be projected on to different line-of-sight directions in the two bursts and lead to a phase discontinuity at the burst boundary. This can affect the phase unwrapping severely if not compensated.

In the CCI+ project, and in synergy with other projects, the following developments are planned:

- Adapting the interferometric processor to ingest Sentinel-1 IW pairs.
- Development of methods for phase unwrapping across bursts. This could include use of a-priori velocities to estimate azimuth motion.
- Using combined ascending/descending tracks for deriving 2D/3D velocities from interferometry.

- Calibration of the unknown constant line-of-sight offset (absolute phase) inherent in interferometric measurements using (e.g., ground control points).
- Increasing the spatial resolution of the CCI Sentinel-1 IV products from 500m to 250m, and developments and tests towards improved spatial resolution of ~100 m pixel spacing.
- Revision of outlier removal and interpolation scheme in order to improving the accuracy and quality of the velocity field and reduce gaps.

IV retrieval from high resolution optical data will be further developed and automated, including advancing tools for synergistic use of SAR and Optical IV. The focus will be on the time-series of key outlet glaciers during summer in areas with surface melt (Figure 1). The planned algorithm developments within the CCI+ project include:

- Upgrade of asynchronous query and download of Sentinel 2 data from Amazon Web Service archive.
- Upgrade and modernize the current mosaicking algorithm.
- Implement a fully automatic pipeline.

An automatic data download from Sentinel data hub will be implemented. Further, an investigation will be performed into cloud handling, where we will be looking at the performance of the feature tracking algorithm under different conditions.

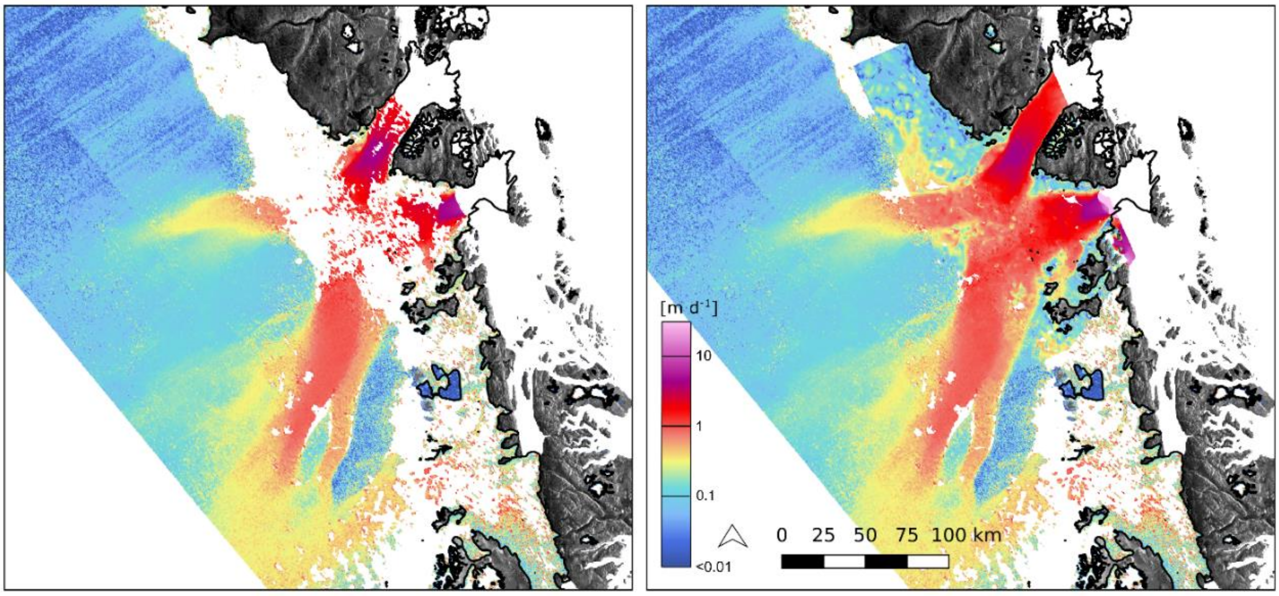

Figure 1: Synergistic S1 + S2 IV maps - main improvements expected in melting regions of glaciers during summer

2.3 Gravimetric Mass Balance

We plan to use the methods described in the ATBD [RD2] to continue the gravity mass balance (GMB) ECV with new data from the GRACE-FO. For GMB the performance of GRACE-FO will be a key factor.

We continue with a collaboration of the two consortia partners DTU and TuDr, applying different algorithms for GMB processing, to enhance the products, and cooperate on improvements. The GMB ECV implementation will be done as soon as first GRACE-FO data are available.

Planned algorithm developments within the CCI+ project include:

- Use combinations of other ECV data in combination with HIRHAM-driven PISM models and/or GNET GPS uplift data to make a "bridging" GMB product for the 2016-18 mission gap. This is still R&D based, and a product subdivided at basin scales will only be attempted in case of reasonable results corresponding to the existing error levels of current GMB products.
- Investigate the continuity of using same GRACE/GRACE-FO processing algorithms. This has been confirmed both by the CCI team and other independent researchers.
- Implementing the ellipsoidal correction both in spherical harmonic filtering and mascon products. The corrections are based on Ditmar (2018) and Ghodadi-Far et al (2019) for the TUDr method, and based on own developments in the DTU-S mascon method. This is expected to reduce the differences between the GMB products and mascon products provided by e.g. CSR and JPL.

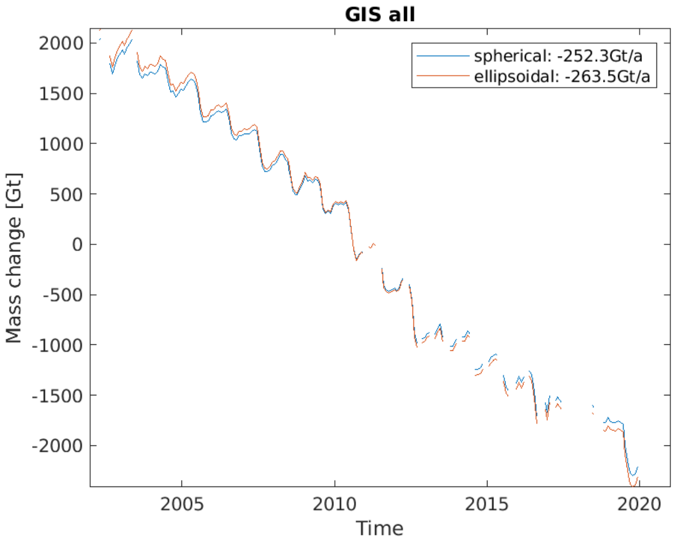

Figure 2. Estimated ellipsoidal corrections for the mascon products (A. Groh, TUDr)

2.4 Mass Flow Rate and Ice Discharge

We will use the methods described in Mankoff et al. (2019) to estimate the mass flow rate. These methods include:

- Automatic gate location selection ~5 km upstream of recent ice termini.
- Estimating ice thickness where intuition suggests reported ice thickness may be invalid.
- Estimating un-observed mass loss (coverage) at each time when any observations exist, due to spatial gaps in the velocity product.

Modifications required to make that work meet the project requirements include

- Incorporating the CCI IV product.
- Verifying that any comparison is performed using the same basin outlines – ideally based on the best estimate of basin delineation.

No major modification foreseen for the CCI cycle 2 MFID products.

2.5 Subglacial lakes

Our aim is to detect supraglacial lakes within two areas of interest (part of Jakobshavn Glacier and Nioghalvfjerds Glacier). The methods are described in the GrIS CCI+ ATBD, which build upon a previous glacier CCI project aimed at extracting ice marginal lakes. Planned algorithm developments within the CCI+ project include:

- Extraction of supraglacial lakes within the two areas of interest with Sentinel-2, validating with Landsat-8
- 6-day temporal resolution (permitting scene availability) within 2019 melting season, and size threshold of <0.02 km^2
- Examination of a possible link between ice velocity speed-ups and supraglacial lake drainage with help of other relevant ECV data produced within this project

No algorithm developments are needed for the supraglacial lakes product, only the shift in geographical area

2.6 Calving Front Locations

The aim of the machine learning-based algorithm to be developed within CCN2 (ref) is to automatically determine the position of CFL for the major outlet glaciers in Greenland using Sentinel-2 imagery. The approach strongly builds on what has been achieved during the COLD-ML project [RD3].

The following algorithmic developments are foreseen to improve the detection of CFLs:

- Increase the receptive field to the range of tens of kilometres, and use overlapping patches for model inference. These two upgrades will reduce edge artifacts at the field of view borders, allowing the model to detect more challenging structures (e.g., clouds, or long, dense ice melange).
- Develop a cloud-mixing algorithm to overlay artificial clouds over cloud free images, and train the network to detect through semi-transparent clouds or cirrus. In this way, the training labels are known, cloud level is tuneable, which promises more robust models.
- Extend the number of classes to 4: ice sheet, ocean+ice melange, land , and clouds/others. The corresponding loss function will penalize predicting incorrect classes for a given pixel, but it will give less penalty for guessing clouds than for guessing another incorrect class. This encourages the network to guess the correct class, but for hard cases, it should rather predict clouds than a wrong class. Postprocessing steps:
    - Automatically remove incorrect predictions by finding connected components, and removing items via setting a specific threshold. The primary use of this step is to remove smaller regions which are currently predicted as ice sheets, but they are actually just icebergs or ice melange regions.
    - Advance the vectorization approach of the pixelated predictions by exploring alternatives decoding besides thresholding, e.g., using Dijkstra’s shortest path algorithm where the prediction pixels are used as path weights. This approach is more computationally expensive, but it might further improve extraction quality. .
    - Use advanced decoding for removal of the small-scale noise. Given that the front locations have approximately known shapes, a shape constraint, edge smoothing, or edge filtering approach will be attempted. The average performance of the algorithm isn’t expected to significantly change, but the number of major outliers should decrease.

The development steps described above will address previous shortcomings.

References

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