ESA Climate Change Initiative (CCI+)

Essential Climate Variable (ECV)

Greenland_Ice_Sheet_cci+ (GIS_cci+)

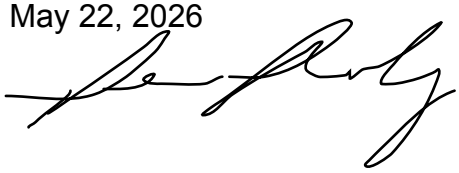
Algorithm Development Plan

Prime & Science Lead: Louise Sandberg Sørensen
DTU Space, Copenhagen, Denmark

Technical Officer: Anna Maria Trofaier
ESA ECSAT, Didcot, United Kingdom

Consortium: Asiaq Greenland Survey (ASIAQ)
DTU-Space, Department of Geodynamics (DTU-S)
DTU-Space, Department of Microwaves and Remote Sensing (DTU-N)
Danish Meteorological Institute (DMI)
ENVironmental Earth Observation IT GmbH (ENVEO)
S&T Norway AS (S&T)
Technische Universität Dresden (TU Dresden)
The Geological Survey of Denmark and Greenland (GEUS)
The Niels Bohr Institute (NBI)
Shepherd Space (SS)

Signatures page

Prepared by	Jan Wuite ENVEO	
Reviewed by	Louise Sørensen, Science Lead, DTU-S	May 22, 2026 
Issued by	Daniele Fantin, Project Manager, S&T	 Digitally signed by Daniele Fantin Date: 2026.05.22 10:01:44 CEST
Approved by	Anna Maria Trofaier ESA Technical Officer	Anna Maria Trofaier Digitally signed by Anna Maria Trofaier Date: 2026.06.04 10:08:30 +01'00'

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
4.0	J. Wuite	All	New version for CCI+ Phase 3

Contents

Signatures page 2
Change Log 3
Contents 4
Acronyms and Abbreviations 5
1. Introduction 7
    1.1 Purpose and Scope 7
    1.2 Document Structure 7
    1.3 Applicable and Reference Documents 8
2. Planned Algorithm Developments 9
    2.1 Surface Elevation Changes 9
    2.2 Ice Velocity from SAR 11
    2.3 Ice Velocity from Optical 14
    2.4 Gravimetric Mass Balance 16
    2.5 Mass Flow Rate and Ice Discharge 17
3. References 19

Acronyms and Abbreviations

Acronyms	Explanation
ATBD	Algorithm Theoretical Basis Document
C3S	Copernicus Climate Change Service
CCI	Climate Change Initiative
CS2	CryoSat-2
CSR	Center for Space Research, University of Austin
DEM	Digital Elevation Model
(D)InSAR	(Differential) Interferometric Synthetic Aperture Radar
DMI	Danish Meteorological Institute
DTU-N	DTU Microwaves and Remote Sensing Division
DTU-S	DTU Geodesy and Earth Observation division
ETAD	Extended Timing Annotation Dataset
ECV	Essential Climate Variable
ENVEO	ENVironmental Earth Observation IT GmbH
EO	Earth Observation
ESA	European Space Agency
GCOS	Global Climate Observation System
GCP	Ground Control Point
GEUS	Geological Survey of Denmark and Greenland
GFZ	Deutsche GeoForschungsZentrum
GIA	Glacial Isostatic Adjustment
GIS	Greenland Ice Sheet
GLL	Grounding Line Location
GMB	Gravimetry Mass Balance
GRACE(-FO)	The Gravity Recovery and Climate Experiment (Follow On)
InSAR	Interferometric Synthetic Aperture Radar
IPP	Interferometric Post-Processing
IV	Ice Velocity
JPL	NASA Jet Propulsion Laboratory
LOS	Line of sight

MFID	Mass Flux and Ice Discharge
NBI	Niels Bohr Institute, University of Copenhagen
NEGIS	North East Greenland Ice Stream
OT	Offset tracking
PROMICE	Danish Program for Monitoring of the Greenland Ice Sheet
S2	Sentinel-2
SAR	Synthetic Aperture Radar
SDS	Science and Data System
SEC	Surface Elevation Change
SLC	Single look complex
SMB	Surface Mass Balance
SOW	Statement of Work
TOA	Top of Atmosphere
TPROP	Technical Proposal
TU Dresden	Technische Universität Dresden
URD	User Requirement Document
TOPS	Terrain Observation by Progressive Scans
OT	Offset Tracking

1. Introduction

1.1 Purpose and Scope

This document contains the Algorithm Development Plan for the Greenland Ice Sheet CCI project for CCI+ Phase 3, in accordance with the contract, SoW, and CCN5 proposal [AD1, AD2, AD3].

A significant part of the project work will be related to algorithm development and improvement. The core algorithms for all ECVs have already been developed in the framework of earlier projects. In this Phase 3, we will continue to develop and validate algorithms to meet the latest GCOS ECV requirements, involving novel implementations, sensors and corrections that meet specifications and user requirements as described in the User Requirement Document (URD, D1.1) and Product Specification Document (PSD, D1.2). The principal input for the algorithms is multi-mission satellite data from the Copernicus Sentinels and other key satellite missions, including new ones. Here, we describe the strategy for further technical algorithm development. The physical and technical basis of the algorithm improvements will next be described in the Algorithm Theoretical Basis Document (ATBD, D2.2). The purpose of the document is to outline the conceptual principles for further algorithm developments of the following ECVs:

- Surface Elevation Change (SEC and dSEC)
- Ice velocity from SAR sensors (IV-SAR)
- Ice Velocity from optical sensors (IV-Opt)
- Gravimetric Mass Balance (GMB)
- Mass Flux Ice Discharge (MFID)

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.
- Chapter 3 lists references.

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. 4000126523/19/I-NB - Greenland_Ice-Sheets_CCI+ and its Appendix 1 (incl CCN3)	CCI+ Phase 1 New R&D pm CCI ECVs for Greenland _Ice Sheet_cci (incl CCN3)	Cont: 2019.03.06 CCN3: 2022.12.05	-
AD2	ESA-EOP-SC-AMT-2021-53	Climate Change Initiative Extension (CCI+) Phase 2 - New R&D on CCI Essential Climate Variables -SoW (incl Annexes)	2022.06.10	Issue 1 Revision 2
AD3	DTU-ESA-GIS-CCI-P3-PROP-001	CCN5 FOR PHASE 3 (2025-2026) Technical, Management,Implementation and Financial Proposal (PROP)	2025.05.30	2.0

2. Planned Algorithm Developments

2.1 Surface Elevation Changes

SEC

In Phase 3 of the Greenland CCI+ project, we will continue the legacy of delivering 5-year running mean elevation changes (SEC) for the Greenland ice sheet. We do not foresee that the SEC processor will be subject to methodology updates but if new data releases become available we will invoke a full reprocessing of the affected time series.

dSEC

In Phase 3 of the Greenland CCI+ project, we aim to further develop the novel dSEC method to deliver surface elevation changes over the Greenland Ice Sheet. This method uses a State Space Model (SSM) implemented through the RTMB package in R (Kristensen et al., 2016) and analyzes L2 ESA-processed CryoSat-2 data across spatial and temporal domains.

The planned algorithm developments focus on improving the robustness of the data product through enhanced handling of noise and outliers. This will be achieved through a dedicated postprocessing framework applied to the model output. The postprocessing consists of spatial and temporal filtering techniques designed to reduce noise and suppress non-physical variability while preserving the underlying geophysical signal.

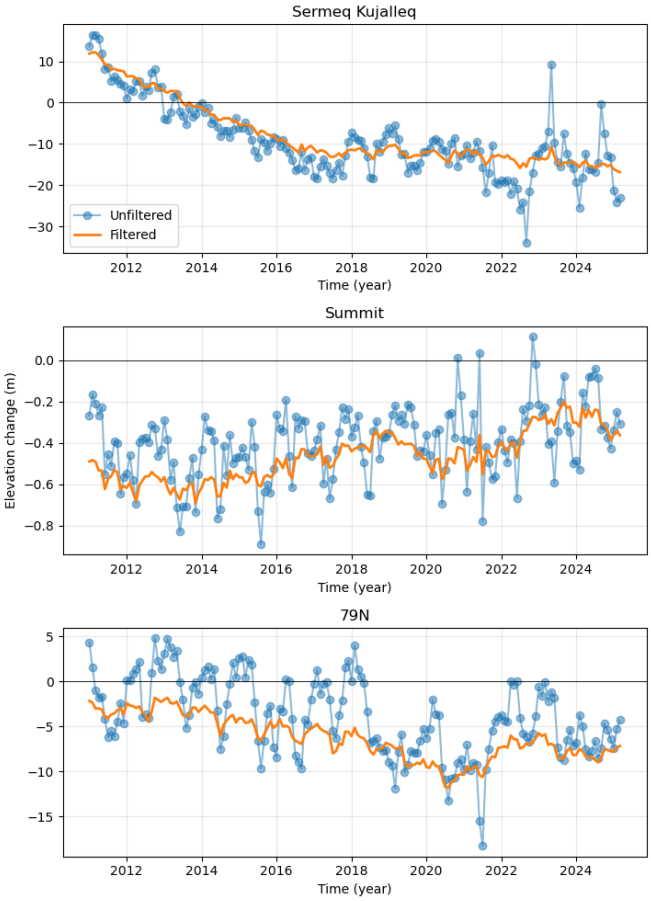


Figure 2.1: Time series of surface elevation change at three representative locations on the Greenland Ice Sheet (Sermeq Kujalleq, Summit, and 79N). Unfiltered model output (blue) is compared with the postprocessed dSEC product (orange). The postprocessing reduces noise while preserving the underlying geophysical signal and long-term trends.

We will also further develop the processing algorithm to incorporate input data from additional radar satellites, allowing the time series to be extended.

Currently, the dSEC product is produced monthly on a 5 km grid. Moving forward, the processing framework will be adapted to generate products on various spatial and temporal grids. This will support the validation of the dSEC product with the ICESat-2 elevation change product (ATL15).

We will evaluate whether dSEC can reproduce 5-year mean SEC estimates consistent with the legacy SEC product, to enable a unified processing approach.

2.2 Ice Velocity from SAR

In Phase 1 of the Greenland CCI+ project, the goal was to extend the IV processor for supporting Copernicus Sentinel-1 (S1) Terrain Observation by Progressive Scans (TOPS) mode InSAR, using ascending and descending crossing orbit pairs. In Phase 2, the focus was on further development of the velocity retrieval processing line for deriving and merging data from different techniques and sensors. For this, tools were developed for processing SAOCOM L-Band SAR data and for combining L- and C-Band interferometric data for the generation of advanced Greenland ice velocity maps.

Here, we will further enhance the routine generation of ice velocity maps from S1 by incorporating the new Extended Timing Annotation Dataset (ETAD) product in the processing line. ETAD was developed in a joint effort by the German Aerospace Center (DLR) and ESA and has been provided with the regular Sentinel-1 product since September 2023. The ETAD product provides a timing correction of the S1 SAR products, that is based on modelling and ancillary data. A significant source of velocity error arises from uncompensated propagation delays, particularly those caused by the troposphere and ionosphere, which can be misinterpreted as ice motion. The uncorrected phase delays and the approximations used during the formation of a SAR image result in an inaccurate timing of the radar signal. Since the grid sampling in a SAR image is defined by the azimuth (slow time) and slant-range acquisition time (fast time), timing errors result in inaccurate positions in the SAR image. To address these and other biases, offset tracking (OT) results are typically calibrated during postprocessing using stable or slow-moving reference areas, such as rock outcrops or ice divides. However, calibration is challenging in regions lacking stable reference points or in situ measurements, such as tracks confined to the interior of ice sheets. In such cases, ETAD products offer a valuable alternative by including the following corrections:

- Tropospheric delay correction (range timing correction)
- Ionospheric delay correction (range timing correction)
- Correction of solid-earth tidal effects (range and azimuth timing correction)
- Bistatic bias correction (azimuth timing correction)
- Doppler range shift (range timing correction)
- Frequency Modulation (FM) mismatch correction (azimuth timing correction)

The different effects and the corresponding corrections are further detailed in Gisinger et al (2021). In that study, we performed tests in Greenland and found that the corrections can enhance the absolute geolocation accuracy of the SAR images and the relative collocation accuracy of repeat pass image stacks, which improves the ice velocity retrieval (Fig. 2.2).

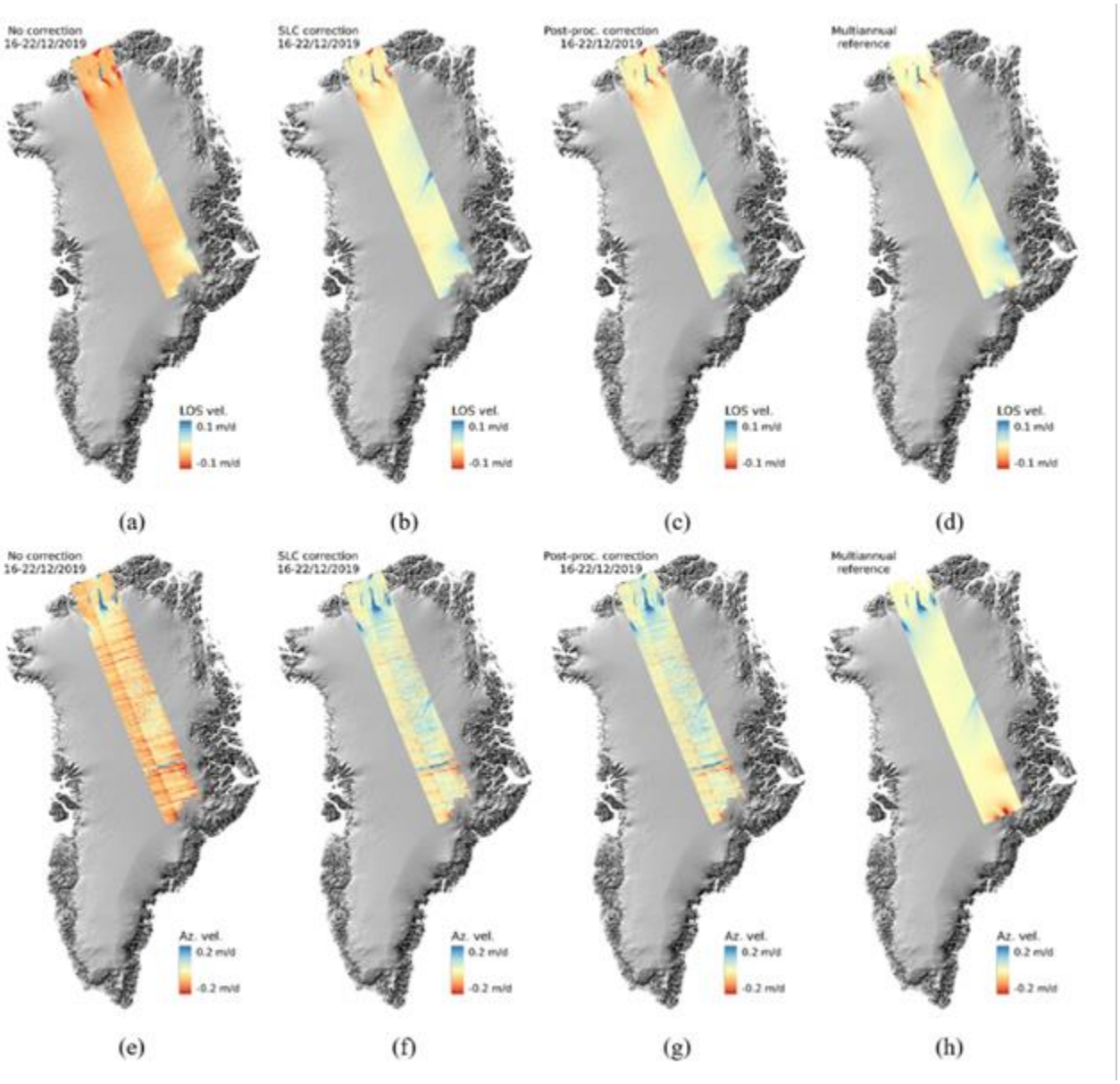


Figure 2.2: (a)–(d) Range and (e)–(h) azimuth velocity components measured with (a) and (e) uncorrected OT, (b) and (f) OT with SLC timing corrections, (c) and (g) OT with postprocessing corrections and compared with (d) and (h) multiannual velocity reference. OT is applied to a 6-day S-1A and S-1B pair acquired along track 31 (16/12/2019–22/12/2019). Figure adapted from Gissinger et al (2021).

In CCI+ GIS phase 3, we plan to develop tools for incorporating the ETAD products in the operational processing chain in order to generate a Greenland Ice Sheet-wide ice velocity map entirely based on ETAD data. The generated product will be used to explore how the timing delay corrections mitigate biases in OT IV measurements and affect the mass flux ice discharge estimation.

In phase 2 of the CCI+ GIS, a prototype InSAR product for studying the surface uplift and subsidence associated with subglacial water transport was developed, and an example product was published. The example product was used as a basis for a paper documenting the temporal progression of subglacial water transport under the North Greenland Ice sheet (Andersen,2023). In CCI+ GIS phase 3, we propose to further develop the method and apply it to other areas of the Greenland ice sheet, including areas with higher dynamics (horizontal velocity). One possible improvement, which will be

explored, is to apply double-difference InSAR as a first step to detect the presence of subglacial events directly from the interferometric phase, which can be done without the complicated steps of phase unwrapping and calibration, see Figure 2.3. The unwrapping and calibration can then be applied in a more targeted fashion to the identified areas and times of interest. To decrease the influence of atmospheric and orbit errors, as well as the influence of horizontal velocity changes, we also aim to improve the calibration methodology by basing the calibration on the immediate surroundings of the observed event rather than an image-wide calibration as is presently the case. This approach will be achieved through the following modifications to the processing pipeline:

- Identification and delineation of areas with events of interest using DDInSAR images. This is for now expected to be done by manual inspection.
- Modification of the unwrapping and calibration module to work on a limited subset of the (full-size) interferograms.
- Automated generation of calibration ground control points outside the identified uplift/subsidence regions.
- Additional calibration of uplift measurements, so that uplift rates are measured relative to the immediate surroundings, thus reducing the impact of atmospheric errors and horizontal velocity changes. This to improve uplift estimates in high dynamic regions like the Jakobshavn glacier and surrounding area.

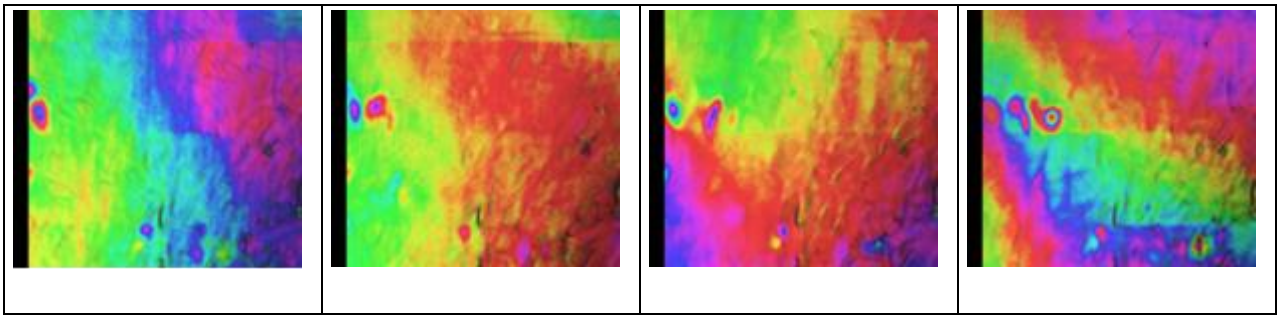


Figure 2.3: Example double-difference InSAR phase images of a propagating uplift/subsidence event, spaced 6 days apart.

2.3 Ice Velocity from Optical

Optical IV products have the potential to fill gaps in SAR IV products during summer in areas with surface melt, especially along the margins. IV retrieval from high-resolution optical data has been developed and automated during Phases 1 and 2 of the CCI+ GIS project. During Phase 1, the bulk processing of the optical IV pipeline, whose core is based on a feature tracking algorithm, was partially automated. In addition, S&T implemented several enhancements, including handling of clouded areas in the Sentinel 2 imagery to get a dense time series and avoid potential errors in the calculated IV, and improvement of the feature tracking algorithm by storing pixel values as 16 bits instead of 8 bits. These improvements were implemented within the Option “Enhancement of Optical Ice Velocity Pipeline”.

During Phase 2, the feature tracking algorithm underwent further enhancement, including transition from single-band to multi-band processing by utilising all 10-meter Sentinel-2 bands (specifically B02, B03, B04, and B08) as inputs to the algorithm, and the introduction of speckle filtering as a post-processing step to effectively reduce noise while maintaining the quality and accuracy of the algorithm's results.

During phase 3, major modifications were made to the pipeline. We start by listing the ones that were promised in the previous version of the development plan, and then proceed to further developments that were created in addition:

1. Filtering of floating ice/melange. The previous version of the data products suffers from spurious signals coming from the ice melange and icebergs floating in front of the glaciers. Being characterised by sharp, traceable edges

and a low velocity. The previous development plan recommended post-processing the products with calving fronts, but since these are not available, we tackled the issue with a more accurate masking of the data before inputting it to the algorithm. The data was only being filtered from ice masks that only existed above land areas. However, large areas of ice existed on top of water areas, which were one of the main factors leading to the problem: the mask was used to get the anchor points from land points and also filter the product. That made the masking only happen on land areas, not water areas. Instead, we used 2 masks: one for the land areas (anchor points) and one for filtering out ice and water (removing most of the floating ice) before entering the IV calculation. That was a very efficient fix to the problem. It had significant visible improvements on the homogeneity of the products and removed large areas of ice and melange. However, we still need more accurate masks and preferably calving fronts to tackle that discrepancy more accurately (the current masks used are old and need updating).

2. Coregistration with neighbouring tiles: the previous development plan also mentioned the possibility of using neighbouring coastal tiles to add more data by having anchor points that help the registration, and also adding more areas being processed by the algorithm (tiles of the same orbit). We tested that in phase 3, and it did add 1 or 2 tiles to the target glaciers. However, the addition of anchor points didn't seem to add more accuracy to the algorithm since it seems that was not the main issue in it, but rather the filtering. However, that step did add 3-5 times the processing time, making it increasingly time-consuming. So we decided to keep it as an optional pipeline that can be used on request. For example, if a specific tile (of the same orbit) around a certain glacier (even if it weren't coastal) can be useful to add in the mosaic, our new improved pipeline can download these tiles automatically and mosaic them to the original 'main' glacier tiles and run it through the pipeline. We keep it under request since doing that as a main strategy consumes a lot of time and adds very little benefit under normal circumstances.
3. Weighted Average Velocity: The previous development plan suggested weighting the average velocity based on the temporal distance from the middle capture. This was also implemented in the phase 3 pipeline and was seen to have mild improvements. It was implemented as a linear weighted average. We think a Gaussian or an exponential weighted average might have more effect on the results since the linear one only had very little change on the values.

That sums up the updates recommended in the previous development plan. Here are other improvements that were added in phase 3 based on the progress we had with the mentioned updates:

1. A more rigid filtering, averaging, interpolation, and download scheme: Many of the IV maps produced in the previous phases had overestimation and many gaps and spurious values. Since we were not sure what was causing the issue and whether it was an inherent deficiency in the optical IV methodology or a bug/s in the pipeline, we performed a full restructuring and testing/evaluation of the entire pipeline. We identified many discrepancies in the download system, bands used, interpolation issues, and filtering/averaging issues that had varying effects on the performance of the algorithm. Many of which were not bugs but rather unoptimized parametric choices. Optimising the pipeline and fixing these discrepancies made significant improvements in the results: many of the gaps, overestimations and spurious values were handled. The results became smoother and more homogeneous. Figure 2.4 shows an example from the Helheim glacier highlighting the difference.

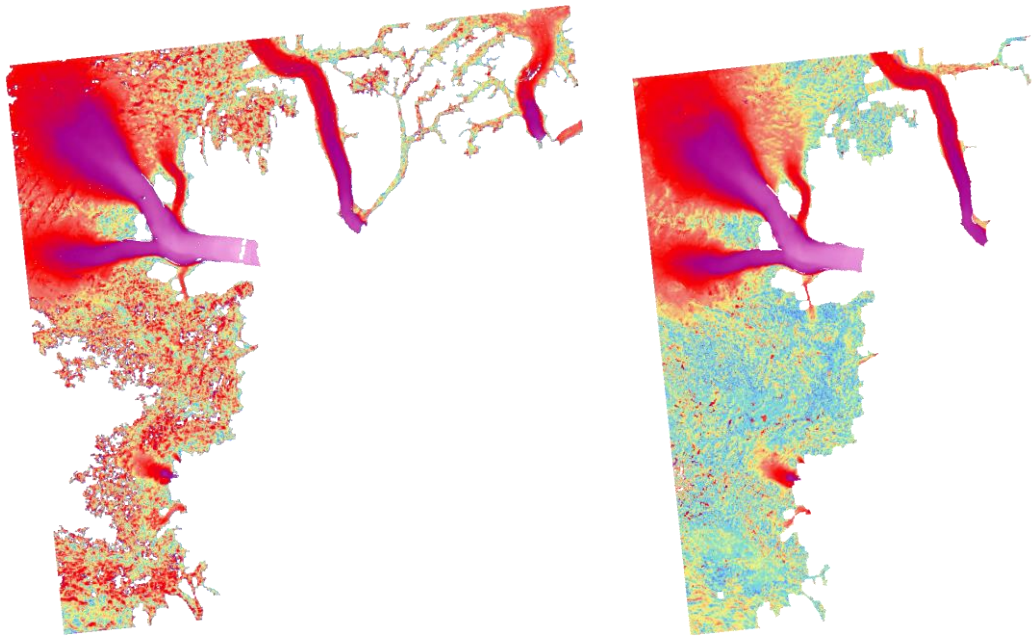


Figure 2.4: Helheim Glacier IV map from the previous phase (left) and from the improved phase 3 pipeline (right) showing fewer gaps, less overestimation, and more homogenous data and water areas filtered out.

2. Config-Based pipeline: The pipeline as a whole was restructured to have all the modules in one place and control their parameters in one master config file. This added a lot of flexibility for testing and production. It also allows us to implement new features, identify issues, and modify modules faster and more safely.

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 to derive monthly estimates of mass changes of the Greenland ice sheet: 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 their tailored sensitivity kernel approach (Groh and Horwath 2021). We will generate GMB products based on the full available time span from GRACE and GRACE-FO data.

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 therefore implement a line of methodological developments, which immediately concerns the long-term changes in the whole GRACE and GRACE-FO product time series – see next paragraph.
We will improve the error estimate and error representation for the GMB products from DTU and TUDr.

For the DTU inversion method, the uncertainty is estimated through a propagation of the formal error from the GRACE L2 data. Some of the solutions (months) have very high formal error, resulting in a very large error in the final mass time series. We propose to improve the analysis of such errors and devise an automatic way to handle them.

The error estimates for the TUDr method are based on the methods outlined in Groh et al. (2019). They include monthly error estimates for each month of the basin mass change time series and an error estimate for the mass trend of each

basin. It is a deliberate choice not to include the trend errors in the error estimates for each month due to the dependency on a reference time. On the other hand, it is essential to include the trend errors (which reflect main error components like the uncertainty of different GIA models and low-degree components) when the mass change time series are propagated. We propose to improve the communication of error estimates by providing temporal variance-covariance-matrices (VCM) alongside the integrated mass changes. The VCMs would include errors of multiple temporal correlation lengths (e.g., uncorrelated errors as given for each month in the current GMB product or fully correlated errors as given for the trends in the current GMB product) and would provide data users with a simple tool that can be used immediately for propagating error estimates.

2.5 Mass Flow Rate and Ice Discharge

The mass flow rate and ice discharge (MFID), is the flux of ice through gates 10 km upstream of the termini (Figure 2.4) of all glaciers flowing faster than 150 m/yr, which effectively is all Marine-Terminating glaciers of the Greenland Ice Sheet.

In phase 2, we improved the algorithm to relate the surface elevation change (SEC) to a DEM with a single year timestamp. In practice, that means that we now use an absolute annual height change (dH) instead of surface elevation change rates (dh/dt). This allows us to evaluate the impact of surface elevation changes on the MFID more directly. In Phase 3, we will continue this work by updating the algorithm to ingest the dSEC instead of the SEC as in previous versions. With the inclusion of the monthly dSEC, the surface elevation changes and ice velocity changes will now be on the same monthly timescales, and thus we will be able to resolve the seasonal evolution of MFID.

Ice thickness remains the main cause of uncertainty, and we will ensure that the basal topography estimate from BedMachine will be updated to the latest version. MFID covers the entire Greenland Ice Sheet, and with the R&D effort, the data series will be extended in time and brought up to present-day values using new monthly SEC and monthly IV products produced within the project.

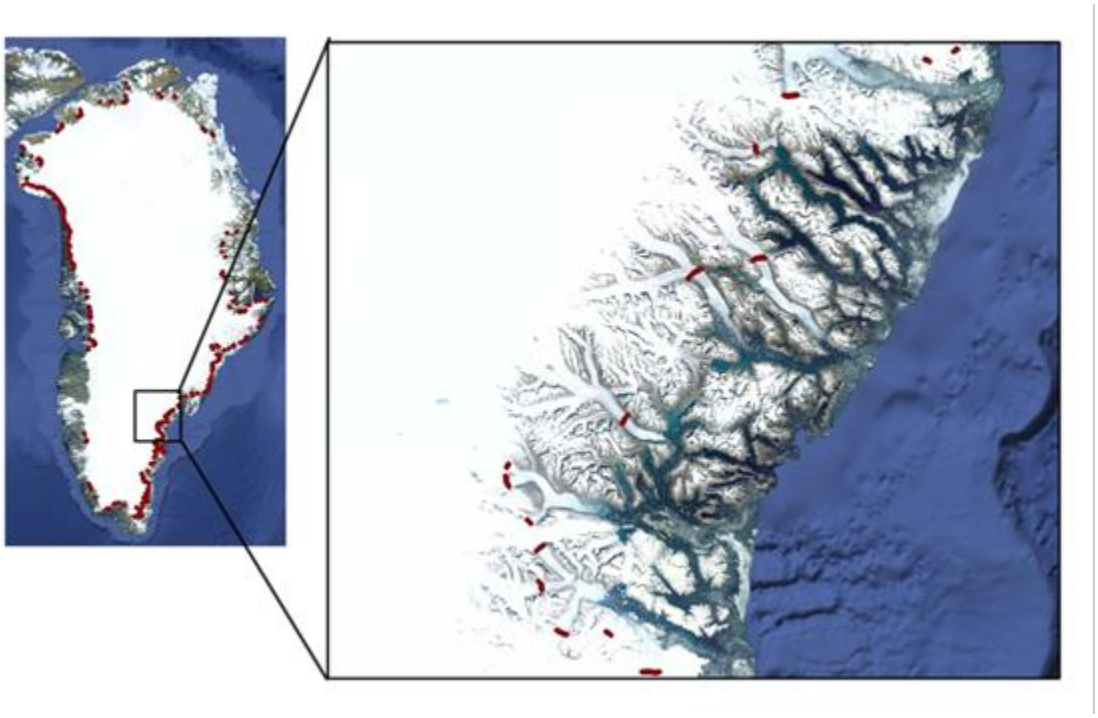


Figure 2.5: Fluxgate positions used for the MFID product.

3. References

Barletta, V R, L. S. Sørensen, and R. Forsberg: Scatter of mass changes estimates at basin scale for Greenland and Antarctica. The Cryosphere, 7, 1411–1432, 2013 doi:10.5194/tc-7-1411-2013

Caron, L., Ivins, E. R., Larour, E., Adhikari, S., Nilsson, J., & Blewitt, G. (2018). GIA Model Statistics for GRACE Hydrology, Cryosphere, and Ocean Science. Geophysical Research Letters, https://doi.org/10.1002/2017GL076644

Ditmar, P. (2018). Conversion of time-varying Stokes coefficients into mass anomalies at the Earth's surface considering the Earth's oblateness. J. Geod., 92(12), 1401–1412. doi:10.1007/s00190-018-1128-0.

Döhne, T., Horwath, M., Groh, A., & Buchta, E. (2023). The sensitivity kernel perspective on GRACE mass change estimates. Journal of Geodesy, 97(1), 11, https://doi.org/10.1007/s00190-022-01697-8

Ghobadi-Far, K., Šprlák, M., & Han, S. - C. (2019). Determination of ellipsoidal surface mass change from GRACE time-variable gravity data. Geophys. J. Int., 219(1), 248–259. doi:10.1093/gji/ggz292

Howat, I., A. Negrete, and B. Smith. 2014. The Greenland Ice Mapping Project (GIMP) land classification and surface elevation data sets. The Cryosphere. 8. DOI: 10.5194/tc-8-1509-2014.

Kappelsberger, M. T., Strößenreuther, U., Scheinert, M., Horwath, M., Groh, A., Knöfel, C., Lunz, S., Khan, S. A. (2021). Modeled and observed bedrock displacements in north-east Greenland using refined estimates of present-day ice-mass changes and densified GNSS measurements. Journal of Geophysical Research: Earth Surface, 126(4), e2020JF005860.

Khan, S. A., Sasgen, I., Bevis, M., Dam, T. V., Bamber, J. L., Wahr, J., Willis, M., Kjær, K. H., Wouters, B., Helm, V., Csatho, B. M., Fleming, K., Bjørk, A. A., Aschwanden, A., Knudsen, P., & Munneke, P. K. (2016). Geodetic measurements reveal similarities between post–Last Glacial Maximum and present-day mass loss from the Greenland ice sheet. Science Advances, 2(9), [e1600931]. https://doi.org/DOI: 10.1126/sciadv.1600931

Li, J., Chen, J., Li, Z., Wang, S.-Y., & Hu, X. (2017). Ellipsoidal correction in GRACE surface mass change estimation. Journal of Geophysical Research: Solid Earth, 122, 9437–9460. https://doi.org/10.1002/ 2017JB014033

Nagler, T., Libert, L., Wuite, J., Hetzenecker, M., Keuiris, L., Rott, H.: Comprehensive Ice sheet wide velocity mapping combining SAR interferometry and offset tracking. Proc. IGARSS 2022, pp. 3888-3891, 10.1109/IGARSS46834.2022.9884206.

Ronneberger, O., Fischer, P., Brox., T. (2015). U-Net: Convolutional Networks for Biomedical Image Segmentation. In: Navab, N., Hornegger, J., Wells, W., Frangi, A. (eds) Medical Image Computing and Computer-Assisted Intervention – MICCAI 2015. MICCAI 2015. Lecture Notes in Computer Science(), vol 9351. Springer, Cham. https://doi.org/10.1007/978-3-319-24574-4_28