ESA Climate Change Initiative (CCI)

Greenland Ice Sheet (GIS) Essential Climate Variable (ECV)

System Specification Document (SSD)

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Change Log

Issue	Author	Affected Section	Reason	Status
1.0	S&T	All	Draft version	
1.1	GEUS	5	Updated MFID	
1.2	ENVEO, S&T	3	Updated IV	Reseased to ESA on 6 July 2021
2.0	All	All	Update for CCI+ Phase 2	Released to ESA on 1 December 2023

Acronyms and Abbreviations

Acronyms	Explanation
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
MEaSUREs	Making Earth System Data Records for Use in Research Environments (NASA)
MFID	Mass Flow Rate and Ice Discharge
MPROP	Management Proposal
NBI	Niels Bohr Institute, University of Copenhagen
NERSC	Nansen Environmental Research Institute
NU	Northumbria University
OLI	Operational Land Imager
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

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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 System Specification for the Greenland_Ice_Sheet_cci (GIS_cci) project for CCI+ Phase 2, in accordance with contract and SoW [AD1 and AD2].

The purpose of the document is to specify the characteristics of the ESA GIS_cci ECV processing systems.

This SSD document builds on the Phase 1 SSD [RD1] of the 'Greenland_Ice_Sheet' CCI+ project.

1.2 Document Structure

This document is structured into an introductory chapter followed by five chapters describing the processing system for the CCI+ ECV parameters, which are:

- Surface Elevation Change (SEC)
- Ice Velocity (IV)
- Gravimetric Mass Balance (GMB)
- Mass Flux and Ice Discharge (MFID)
- Supraglacial Lake (SGL)

Each ECV chapter provides:

- A specification of the purpose of an operational ECV production system and its intended use.

- An overview of the context of the system, defining all significant interfaces among system components and crossing the system's boundaries.

- A definition of the fundamental operations to be performed within the system to accept and process the inputs and to process and generate the outputs.

- A description of the major constraints of the system.

- A description of operational scenarios for the system including data sources, valid ranges of values, timing considerations, operator requirements, and special interfaces.

- Specification of the environmental characteristics of where the system will be installed.

- Specification of the growth, expansion, and capability characteristics, as well as limitations of the system.

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

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

2 Surface Elevation Change (SEC)

2.1 System overview

The SEC operational ECV production system takes as input all available elevation data from the Level-2 products of radar altimetry missions since 1991 and processes these to produce 5-year (and for CS2 2-year) mean rate of surface elevation change products over the Greenland ice sheets. Input data for the SEC production system consists of multi-mission radar altimetry data (Table 2.1), auxiliary correction data, ice sheet DEM, and ice mask. The SEC system is described in detail in the DPM and the GIS CCI project and any updates are also reported in the current ATBD.

Table 2-1: Current Radar Altimetry Data Sets

Mission	Product Level	Baseline	Source	Operational Dates
CCI+ GIS				
ERS-1	L2	REAPER v2.0	ESA	02-Aug-91 to 02-Jun-96
ERS-2	L2	REAPER v2.0	ESA	13-May-95 to 04-Jul-03
ENVISAT	L2	GDR v2.1	ESA	09-Apr-02 to 18-Oct-10
CryoSat-2	L2i SIN	Baseline-E	ESA	16-Jul-10 to present
CryoSat-2	L2i LRM	Baseline-E	ESA	16-Jul-10 to present
Sentinel-3B	L2	Baseline-005	ESA	01-Mar-16 to present
Sentinel-3B	L2	Baseline-005	ESA	01-May-18 to present

2.2 Operational scenarios

The SEC processor works in four distinct modes: True repeat track, along track, cross-over and Plane-fit. The choice of mode depends on the data used as input. We refer here to the ATBD for further information.

Table 2-2: User-defined input for the SEC system

User input	Format	Note
START TIME	ddmmyyyy	Start date of the chosen SEC period
END DATE	ddmmyyyy	End date of the chosen SEC period
GRID SIZE	X [km]	Grid cell size of final SEC grid
CORR. LENGTH	Y [km]	Correlation length of dh/dt data. This controls the smoothness of SEC grid
MIN #DATA	Z [number]	Number of data points required in each grid cell/segment.
DEM	Name of DEM	Choice of DEM to use in the relocation
Model	#	Defines which model to solve for in the least squares regression
Flags	binaries	1 for use this parameter. 0 do not use this parameter. Number of relevant flags depends on mission data.

2.3 Hardware and software platform

The SEC operational ECV production system runs on most UNIX servers with adequate memory and disk storage space. The current SEC processing system is developed and tested in Mac-OS, and is transferred for operational runs to a server system running ax86_64 GNU/Linux UNIX operating system.

2.3.1.1 Hardware

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Table 2-3: Processing Hardware at for the SEC processor

Model	Supermicro 848A-R1K62B
Processor	4 X AMD Opteron 6376 (64 cores), 64 bit
Memory (RAM)	256 GB
Local Hard Drive	30TB
Network Attached Storage	>100TB

2.3.1.2 Operating system

The system currently runs on the UNIX operating system x86_64 GNU/Linux. The system has been tested and runs on other Unix/Linux systems as well, including Mac OS X.

2.3.1.3 Tools and libraries

The SEC processor is written in Python. Python 3.5 packages: numpy, tables, scipy, matplotlib, os, sys, multiprocessing, shapefile, netCDF4, rasterio.

2.4 Future concerns and developments

We are currently working on porting all the processing of the SEC solutions to run on the HPC.

2.5 References

Sørensen, L. S., B. Simonsen, S., Forsberg, R., Khvorostovsky, K., Meister, R., & E. Engdahl, M. (2018). 25 years of elevation changes of the Greenland Ice Sheet from ERS, Envisat, and CryoSat-2 radar altimetry. *Earth and Planetary Science Letters*, 234–241.

3 Ice Velocity

3.1 SAR Ice Velocity (SAR IV)

3.1.1 System overview

In this section we describe the processing system for deriving ice velocity maps from repeat pass SAR data applying both offset tracking and SAR interferometry (InSAR) techniques. The ENVEO SAR Software Package (ESP) Version 2.1 is used for the generation of ice velocity maps. ESP 2.1 applies incoherent and coherent offset tracking for mapping displacements in range and azimuth on repeat pass SAR SLC data. It also measures line-of-sight displacements with InSAR and combines these to derive ice velocity from crossing-orbit measurements. The IV processor supports the common space-borne SAR missions including Sentinel-1 , Radarsat-2, ERS 1/2, ENVISAT, ALOS, and TerraSAR-X, and could readily be adapted for SAOCOM in this phase of the project. Auxiliary data needed are a DEM and (optional) ocean/ice/land mask. For interferometry, an external a-priori ice velocity map can also be used for coregistration and calibration. Figure 3-1 shows the high-level processing line for the IV production. It includes the following three modules:

- MODULE IV: within this module, SAR data are imported into the system and velocity maps are generated for pairs of repeat pass SAR data of the same track. This module corresponds either to offset tracking or InSAR processing. The output is IV maps in map projection as defined by the user. Each IV product includes a quality map.

- MODULE MERGE: this module combines the IV products from various tracks and image pairs. The output is a merged large/regional scale ice velocity map and a quality map.

- MODULE VAL: the validation module is an associated module, which enables the inter-comparison and validation of the generated ice velocity map with in-situ velocity measurements. The output is statistical information on the inter-comparison and scatterplots compiled in a quality assessment report.

- MODULE IV-DATABASE: This module connects the velocity data archive to an online portal/toolbox for easy access, data visualisation, and analysis, including the derivation of velocity profiles and calculation of ice discharge along pre-defined gates.
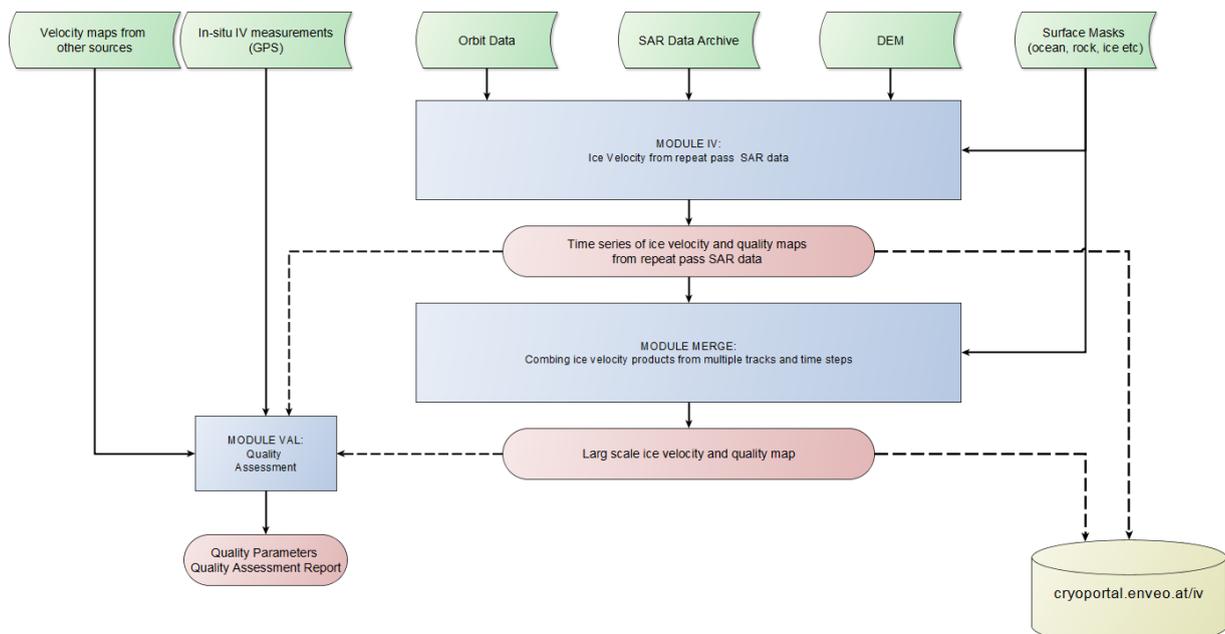

Figure 3-1: High-level flow chart of the IV processing system. Green – input data, Blue – processing modules, red - product and intermediate products.

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MODULE IV

Offset-tracking

Figure 3-2 shows a high-level flow line of the ice velocity generation module with offset tracking. Regarding Sentinel-1 Interferometric Wide (IW) Single Look Complex (SLC) data the processing is done on the burst level. In the case of SAOCOM Stripmap mode data, the processing is done on scene/frame level, which is practically very similar.

The module has access to the SAR data archive and orbit data, as well as the DEM and optionally the surface masks. The processing is done track by track, for each track image pairs are selected according to the time step. For SAOCOM processing we select the shortest repeat pass periods (either 8, 16 or 24 days). Using image geometry and a digital elevation model the local shift between the image pair is calculated which is considered in the displacement calculation using incoherent (or coherent) offset tracking. Besides the displacements in the slant range and azimuth, the quality of the matching is calculated. After outlier removal, the velocity of the 3 components is calculated using a DEM as input. Optionally, the surface masks are applied to mask ocean and unglaciated areas.

The output of this module is velocity maps (E, N, Z) in m/d per track and time step, and the quality map.
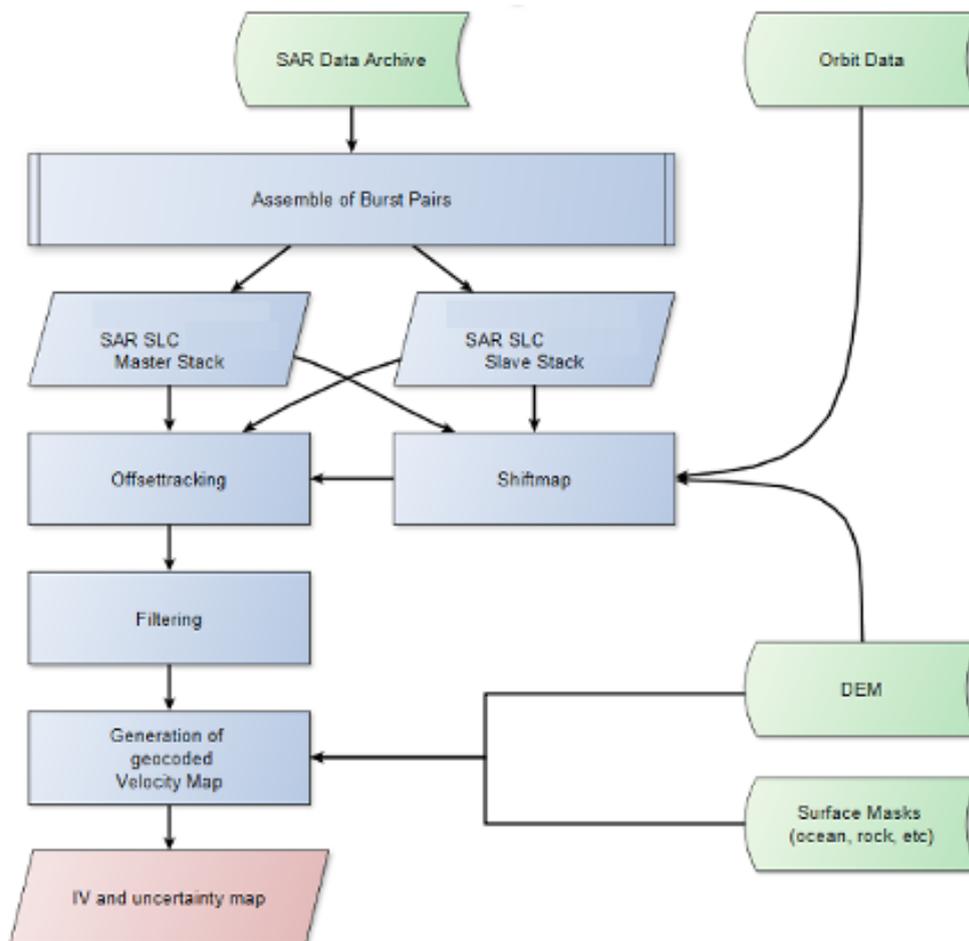

Figure 3-2: Processing steps for ice velocity generation using offset-tracking applied to SAOCOM StripMap and Sentinel-1 SLC data.

InSAR

Figure 3-3 describes the flowline of InSAR processing for ice velocity. This processing line is dedicated to Sentinel-1 acquisitions in TOPS mode. Similarly, in the offset-tracking module, the InSAR processing on Sentinel-1 data is performed at the burst level up to the phase unwrapping step. Burst-level processing includes co-registration, interferogram formation, flat-earth and topographic phase removal and coherence estimation. If working with Stripmap acquisitions, as in the case of SAOCOM, instead, these processing steps are directly applied to the whole scene and the processing line is adapted by simply skipping the debursting step.

Burst interferograms are mosaicked at the debursting step to make a single large-scale interferogram for each master-slave pair. Phase unwrapping and phase calibration are performed at the debursted level. Once calibrated, the phase can be converted into line-of-sight (LOS) velocity and is then geocoded.

The InSAR module uses the SAR data archive in SLC format as input. For Sentinel-1 data, only data with 6-day temporal baseline are used to avoid aliasing and decorrelation caused by fast ice motion or changing surface conditions due to melt or snowfall. The InSAR module uses precise orbits provided by ESA ~20 days after the acquisition. A digital elevation model must also be given as input to the module for co-registration, estimating the topographic phase and geocoding.

Optionally, an external a-priori ice velocity map (from e.g., offset tracking) can be inserted in the module. It is then used for the co-registration and calibration steps: at the co-registration step, it is used to update the co-registration map with local displacements; at the calibration step, it is used for selecting slow-motion ground control points which are used as reference values.

The output of this module is geocoded maps of LOS velocity. These maps are produced for 6-day and 12-day repeat pass data from all available tracks. In the MERGE module, corresponding to the inversion step, these images are used to derive a velocity map. The inversion step combines LOS velocities from crossing orbits to calculate the ice flow velocity components. The merged output is a 3-D velocity map (X, Y, Z) in meters per day.
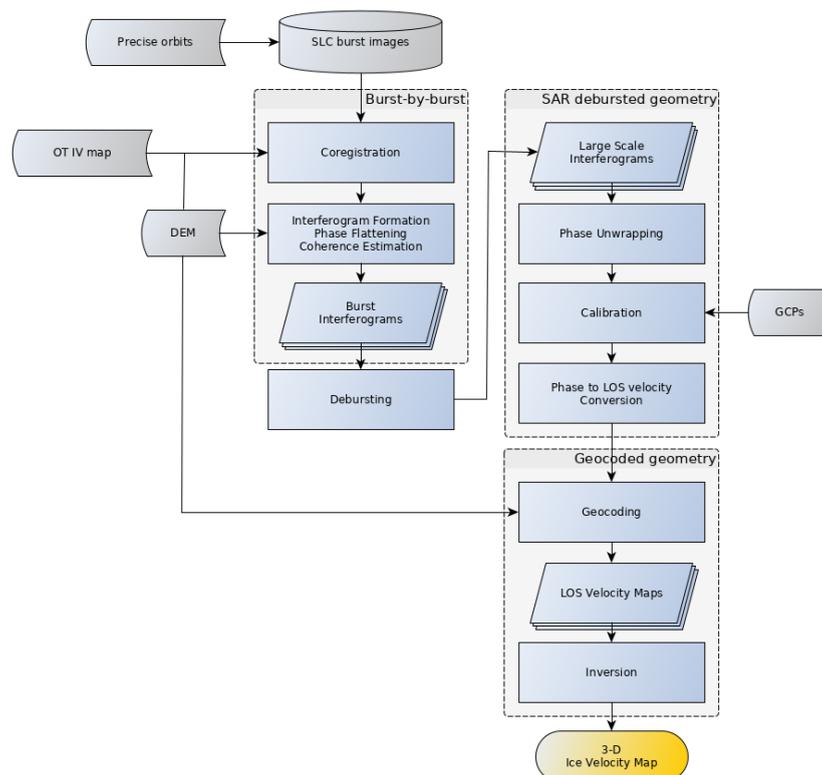

Figure 3-3: Processing steps for ice velocity generation using InSAR applied to Sentinel-1 IW TOPS SLC data. SLC – Single-Look Complex. OT – Offset Tracking. LOS – Line-of-sight. GCP – Ground Control Point.

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MODULE MERGE

This module aims to produce a large/regional scale ice velocity map using the output of the MODULE IV as input. The generation of a regional ice velocity map requires the combination of IV results, from several tracks. The long tracks are geocoded into a common map projection of the output grid, using the annotated imaging and orbit parameters and a digital elevation model as input. The merging combines the velocity components separately in m/d. The output of this module is a large-scale, regional or ice sheet-wide flow velocity and quality map.

MODULE VAL

The validation module aims for an independent validation of the ice velocity product using in-situ ice velocity data, as provided by GPS. The module inter-compares the velocity components separately but can also be applied to the velocity magnitude. Currently, the module requires manual interaction, mainly in the selection and pre-processing of the in-situ ice velocity data. Output are statistical parameters of the inter-comparison and scatter plots for visualisation. This module also allows us to inter-compare ice velocity products from other sources. The module takes different map projections into account and provides statistical parameters of the pixel-by-pixel inter-comparison, histograms, and spatial maps of the differences.

MODULE IV-DATABASE

The ice velocity products are linked to the IV database at cryoportal.enveo.at. The web-based portal allows easy access and simple analysis of all ice velocity products (single maps, monthly & annual). The current versions support the following analysis:

- Ice Velocity (IV) visualization and download of data:

  o Visualize the full-time series of ice velocity profiles along pre-defined central flow lines of all major outlet glaciers.

  o Visualize the full-time series of velocity at fixed points along the central flowline flow line.

- Mass Flux Ice Discharge (MFID) calculation:

  o For single glaciers

  o Sub basins

  o Basins

  o Ice sheet wide

3.1.2   Operational scenarios

The operational scenario for SAOCOM relies on the availability of repeat pass SOACOM-1A/B satellite acquisitions. The following operational scenarios have mainly been applied using Copernicus Sentinel-1:

1.   Continuous observations of margins and the ice sheet interior with offset-tracking.

The track-by-track offset-tracking processing is applied in regions where continuous acquisitions of S1 IW SAR data are acquired. This processing scenario enables the monitoring of ice velocity variations with short time intervals. This observation scenario has been proposed by ENVEO and implemented by ESA for the Greenland Ice Sheet margins with continuous acquisitions since June 2015.

2.   Production of annual (within C3S) and monthly ice sheet-wide ice velocity maps

Ice sheet-wide velocity maps for Greenland are generated on a monthly and annual basis and rely on the Sentinel-1 acquisition campaigns. They are performed in addition to the continuous acquisitions of S1 at the ice sheet margins. The production of an ice sheet-wide map based solely on SAOCOM is currently not possible due to the scarcity of repeat pass data over Greenland. The production of a regional IV map based on complementary SAOCOM and Sentinel-1 is foreseen.

3.   Production of (winter campaign) ice velocity map of the ice sheet interior with crossing orbit InSAR

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This scenario is currently not possible due to the decommissioning of Sentinel-1B). For a number of regions, we test and evaluate the combination of SAOCOM and Sentinel-1 crossing orbits for InSAR application . The InSAR processing generally focuses on mapping the ice sheet interior, where ice motion is slower, and conditions are more stable from one acquisition to the other. For this purpose, Sentinel-1 repeat data with short repeat time intervals acquired during the winter campaign has been used. Data in wintertime are expected to have better coherence and the coverage of overlapping ascending and descending tracks over the ice sheet interior is improved during the winter campaign. L-Band InSAR covers areas decorrelating in C-band, in particular in regions with strong velocity gradients due to reduced fringe frequency enabling reliable phase unwrapping.

3.1.3 Hardware and Software Platform

The main processing at ENVEO is performed on the processing system described below.

3.1.3.1 Hardware

The main (Sentinel-1) ice velocity processing is done on 3 server machines and 18 virtual machines on a cluster (IKB cluster), which are connected to a mass storage of about 800 TB. The system applies OPENMP to support multiple CPUs and Cores. For development, visualization, and quality control an additional 8 workstations are used.

Table 3-1: Processing Hardware for the ENVEO SAR IV processor.

	Processing	Development, Visualization, Quality Control
Model	GNU/Linux Centos 7	GNU/Linux Fedora
Number of machines	3	8
Processor	Intel Xeon CPU E5-2650 v2 @ 2.60GHz 16 cores	Intel Core i7-2600 CPU @ 3.40GHz
Memory (RAM)	128 GB	32 GB
Local Hard Drive	300 GB	1 TB
Network	Ethernet 10000baseT/Full	Ethernet 1000baseT/Full
Network Attached Storage	Ca 800 TB network storage	Ca 800 TB network storage

	Processing	
Model	GNU/Linux Centos 7	
Number of nodes	18	
Processor	Intel Xeon CPU-X5670 2.93GHz 2 cores	
Memory (RAM)	10 GB	
Local Hard Drive	-	
Network	Ethernet 10000baseT/Full	
Network Attached Storage	Ca 800 TB network storage	

3.1.3.2 Operating system

The ENVEO ESP Ice Velocity processing system runs on common Linux operating systems. Currently, the tested systems are CentOS release 6/7, Fedora 30 and later releases, but the software will also work on other common Linux/Unix systems.

3.1.3.3 Tools and libraries

Tools & Libraries

- GCC / OpenMP   http://gcc.gnu.org
- cmake   http://cmake.org
- PROJ.4   https://trac.osgeo.org/proj/
- Python (numpy, scipy, etc)   https://www.python.org/
- GDAL (latest version)   http://www.gdal.org/
- FFTW 3   http://www.fftw.org/
- Libxml   http://www.xmlsoft.org/
- NetCDF, HDF   http://www.unidata.ucar.edu/
- wget   https://www.gnu.org/software/wget/
- gzip   http://www.gzip.org/

Visualisation Tools

- QGIS   http://qgis.org
- Cryoportal Ice Velocity (developed by ENVEO)   https://cryoportal.enveo.at

3.1.4 Future concerns and developments

Further improvements of the software are planned. The ESP software has been connected and tested with cluster systems utilising several hundreds of cores. This is especially of interest for campaign processing of big data sets as it occurs for polar ice sheets.

3.2 Optical Ice Velocity (Opt IV)

3.2.1 System Overview

In this section we describe the processing system for deriving ice velocity maps from pairs of Sentinel-2 optical images by applying an offset tracking technique. The optical ice velocity processor developed by S&T consists of 6 modules, which are listed in Table 3-2. To run these modules, we use an automated pipeline processing manager called Dagger developed by S&T, which strings together the IV modules, manages the data streams, and handles the instantiation of the processing steps. The high-level processing line for the IV production is shown in Figure 3-5.

Table 3-2: Name and purpose of each module composing the optical IV processor

| Module name	Purpose
Product download	Queries and downloads S2 products within a given AOI and time range.
IV_pair	Finds all available pairs of S2 products between 7 and 15 days apart within the queried time range.
IV	Creates an IV map from a given S2 pair.
IV_merge	Creates a single stacked or averaged IV product of all the IV maps. Mosaicking tiles if needed.
IV_release	Prepares the final IV product in a zip file containing product description, quick look etc.
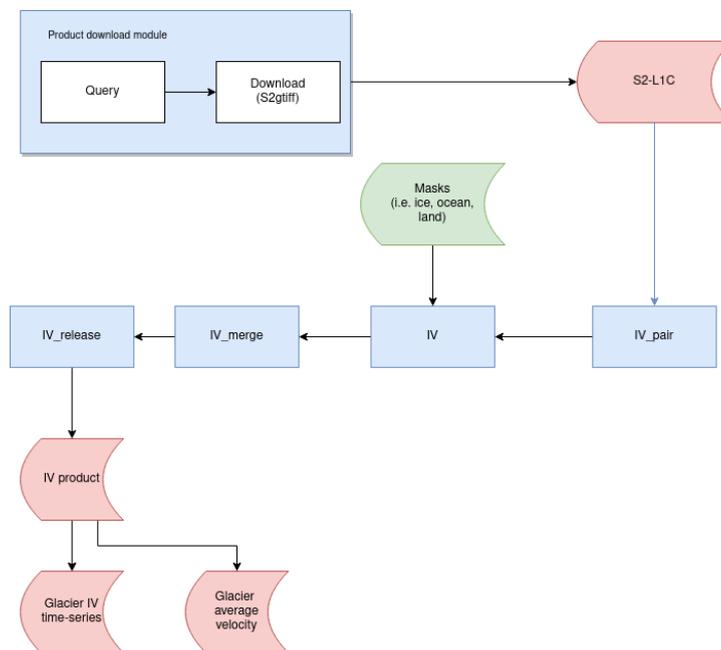
Figure 3-5: high-level flow chart of the optical IV processor. Green identifies input data, blue processing modules, grey specific processing tasks within a module and red are intermediate and final products.

3.2.2   Product download module

The product download module takes as required input an AOI and a time range, from which it queries Sentinel-2 L1C images and downloads to a local folder. Additional filtering criteria such as cloud coverage can be specified. The S2 product will be converted to the GeoTIFF format.

IV pair

All possible pairs of the retrieved S2 images that are at a minimum of seven and a maximum of 15 days apart, will be found. These pairs will then be passed on.

IV

For each pair of S2 images, we will apply a feature tracking algorithm to calculate the north and east ice velocity. Furthermore, the co-registration offset will be measured, and the root-mean-squared (rms) will be extracted from the ice velocities.

IV Merge

The IV maps generated in the previous step will be averaged, stacked and mosaiced together in the case where the AOI covers multiple tiles. Both a time series and an averaged IV map will be created.

IV Release

The final output will consist of the IV time series and the averaged IV map. These will be delivered in a zip file and NetCDF products together with a quick look image, comments, and product description as the CCI requirements have specified.

3.2.3 Operational Scenarios

The operation scenario relies on the availability of Copernicus Sentinel-2 A/B satellite acquisitions. Firstly, the observations for 9 pre-selected glaciers are retrieved based on temporal and spatial criteria through a network interface (e.g., SciHub or AWS) and stored locally. The production of the seasonal IV map is planned for the end of the summer season, after the end of the S2 satellite's observational season over Greenland.

Once the observational season is over, glacier-based IV maps are generated according to two processing scenarios:

- Production of IV time-series using observations with 6-12 days repeat.
- Production of seasonal IV map.

The scenario has been proposed by S&T and approved by ESA.

3.2.4 Hardware and software platform

3.2.4.1 Hardware

Model	Custom-built
Processor	Intel Core i7 CPU @ 3.40GHz
Memory (RAM)	32 GB
Local Hard Drive	2 TB
Network Attached Storage	1x30TB

Figure 3-6: Processing Hardware for the IV processor

3.2.4.2 Operating system

The processor operates on any Linux system.

3.2.4.3 Tools and Libraries

The Opt-IV processor requires Python 3.8 or later to run support scripts.

Linux Libraries required: gdal.

Python Libraries required(in addition to the Python standard library): click, h5py, loguru, netCDF4, numba, numpy, opencv, osr, pyproj, pytest, scipy, yaml, zipping.

3.3 SAR Line-of-Sight Velocity

The SAR line-of-sight velocity (LoS) product is derived from an intermediate product generated in the InSAR IV processing chain at DTU. This processing chain is very similar to that of ENVEO, but is implemented in the DTU IPP (Interferometric Post Processor) processor. The LoS product is a time-series product that allows the study of small-scale velocity variations at a high temporal and spatial resolution. Whereas the spatial resolution is achieved by employing InSAR, the temporal resolution is achieved because LoS velocity is derived from a single InSAR pair.

3.3.1 System Overview

3.3.1.1 Data selection and download

Due to the high temporal and spatial resolution, the LoS prototype product is produced only for selected areas of interest (AOI) where dynamic phenomena can be expected, but in the future may be produced for larger regions in order to discover and track dynamic events on a larger scale.For a selected region of interest, IW SLCs covering the AOI are searched for in the

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Copernicus Dataspace Ecosystem (CDSE). Only SLCs from tracks which are acquired continuously (i.e. every 6 or 12 days) are considered. With the current Greenland acquisition scenario, most areas are continuously imaged from only a single track. Once the data have been downloaded, each track is processed separately.

3.3.1.2 Processing Setup

To begin with, a reference SLC from the track is selected, and all bursts covering the AOI are identified. A reference (i.e. master) geometry is then defined based on these bursts and the master SLC timing and state vectors. Then, all possible 6- or 12-day pairs are identified, and each pair is processed individually, as described in the following section.

3.3.1.3 Interferogram generation and geocoding

The processing flow for a single pair is illustrated in. First, the two SLCs are coregistered to the reference geometry using SLC timing, precise state vectors, a digital elevation model (DEM) based on TanDEM-X, and a multiyear averaged (2016-2019) IV mosaic based on PROMICE ice velocity maps. The DEM is applied both to coregister and flatten the interferogram (thus removing the topographic phase component), whereas the IV is used only for coregistration, preserving the interferometric phase due to displacement. To reduce phase discontinuities at burst boundaries, burst overlap spectral diversity is used to refine the coregistration in the overlap region. The interferograms are multi-looked and phase unwrapped using a Minimum Cost Flow algorithm, calibrated using a set of pre-selected slow-moving ground control points (GCPs), and converted to LoS velocity. The LoS velocity map is subsequently geocoded to a 100 m x 100 m spaced grid in EPSG 3413 projection (Polar stereographic, with a reference longitude of -45 and a latitude of the true scale of 70), along with ancillary data (Line-of-sight vector azimuth and elevation angles, displacement error estimate), which are output to individual files. The same output grid is used for all pairs so that the data can be easily stacked in a time series.
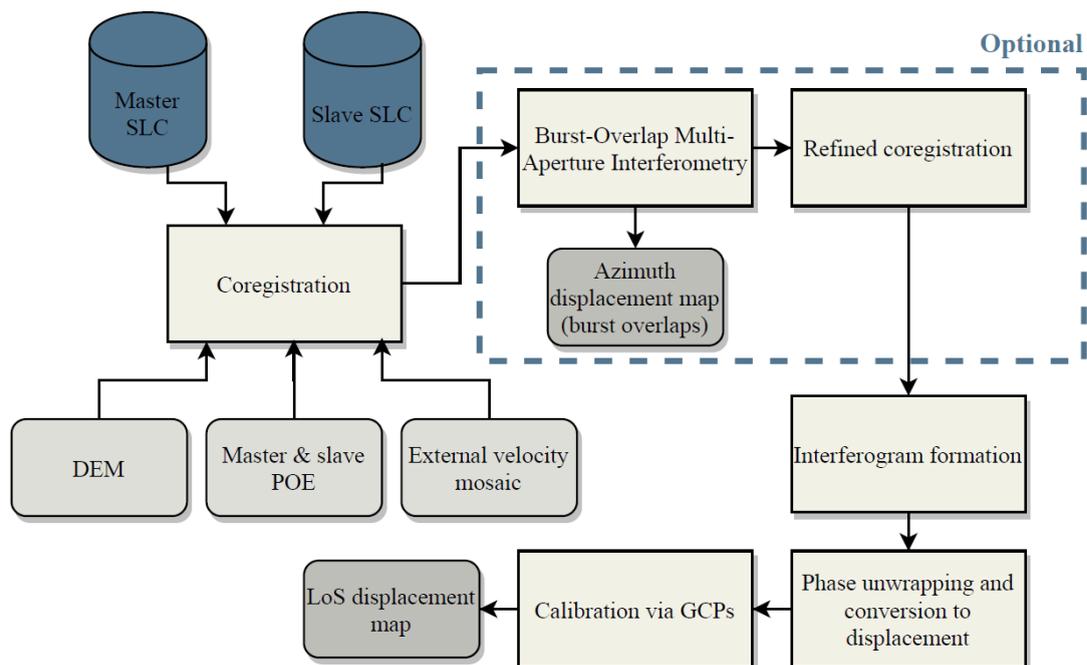

Figure 3-3: Processing flow to generate LoS-velocity for a single SLC pair

3.3.1.4 Timeseries generation

The LoS product is intended to mainly study small-scale rapidly varying vertical displacements, which are generally of much smaller magnitude than the displacements due to the overall horizontal ice flow. The latter are, on the other hand, slowly varying in time, and are typically spatially correlated on a larger scale. To partially separate the two contributions, the pixel-wise temporal median of all the velocity maps is calculated, resulting in a single velocity map, which is then subtracted

from all velocity maps in the time series. This allows the data to be analyzed directly, and the original velocity maps can be reconstructed by adding the median velocity map, which is also provided to the end-user.

3.3.1.5   Packaging

The median-corrected LoS velocity maps and associated error estimates are packaged as three-dimensional (time, x, y) variables in a NetCDF file following the CF Metadata conventions. In addition, the median velocity map, the LoS azimuth angle map, and the LoS elevation angle map are provided as two-dimensional (x,y) variables in the same file, along with all metadata about the projection and dimension variables, such that the data can be read using common GIS and geoprocessing tools.

3.3.2   Operational scenario

The LoS product is a prototype product, and will be generated for a few limited areas of interest.

3.3.3   Hardware and software platform

3.3.3.1   Hardware

The processing of individual pairs is run in parallel on the DTU Central HPC LSF cluster (https://www.hpc.dtu.dk/?page_id=2520), which comprises several different processing nodes, assigned by the HPC job scheduler. Timeseries generation and packaging are carried out on a local workstation (HP Z440 with 6-core Xeon E5-1650v4 3.6 GHz CPU, 64 GB memory, and 1TB disk)

3.3.3.2   Operating System

The HPC cluster runs Scientific Linux 7.9, whereas the local workstation runs Ubuntu 20.4.

3.3.3.3   Tools and libraries

Required linux packages:

- **GCC / OpenMP**
- **libxml2**
- **lapack**
- **hdf5**
- **fftw3**
- **Python 3.X**

Requried Python 3 libraries:

- **scipy**
- **numpy**
- **limxml**
- **dateutil**
- **netcdf4**
- **pil**
- **gdal**

4 Gravimetric Mass Balance (GMB)

4.1 DTU Space

4.1.1 System overview

The GMB system produces mass change time series of the Greenland Ice sheet as well as for pre-defined drainage basins. Also, 5-year trend (water equivalent) maps are produced.

The system algorithms and methods are described in the [ATBD], while the system input and output data including auxiliary data are described in detail in the [PSD].

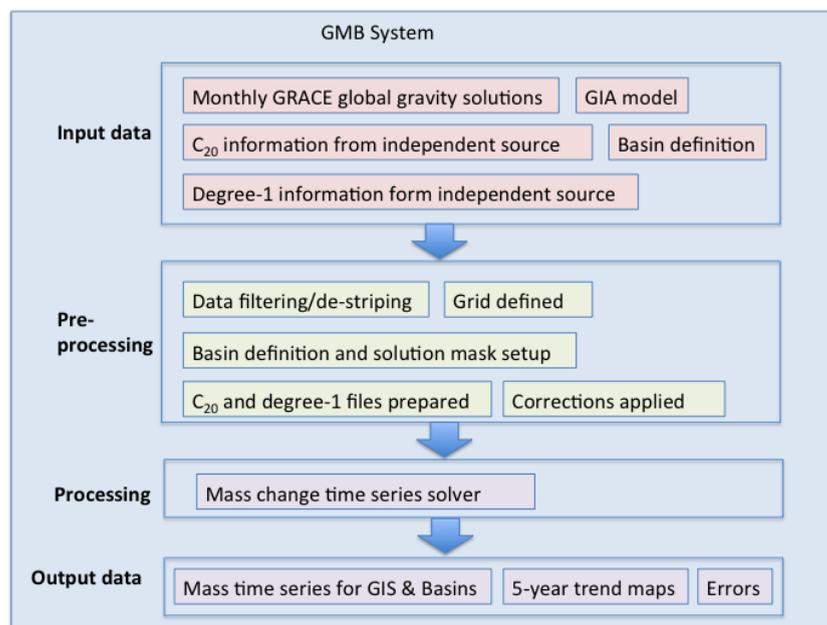The overall system overview is shown in Figure 4.1.

Figure 4.1: Overview of GMB system at DTU Space. Everywhere in the picture where we say we process C_{20}, we now process both C_{20} and C_{30}.

The GIS CCI+ GMB system is a semi-automatic processing system implemented in Fortran and gnuplot. **Figure 4.1** gives a schematic overview of the GMB processing line, which consists of two main modules: the pre-processing and processing modules. Input data download is done manually. In the following, the two modules of the GMB processor are briefly described.

Pre-processing: Based on the selections in the Methods Module, GRACE monthly solutions and time series of auxiliary datasets are pre-processed, combined and corrected. This includes the conversion from Stokes-coefficients to mass equivalent coefficients (equivalent water height), the addition of degree-one coefficients, the replacement of degree C_{20} and C_{30} and the reduction of GIA. All monthly solutions are reduced to a specified reference value.

Processing (Mass change estimation): Mass change time series for every grid cell of the GMB gridded product and every basin of the GMB basin product is produced by integrating the product of the point mass inversion (Barletta et al., 2013) of

each monthly. The statistical error characterization of the time series is derived. Basin-averaged time series are used to calculate a mass balance estimate for each basin.

4.1.2 Operational scenarios

Data procurement:

Shortly after the availability of a new monthly solution is announced via the GRACE SDS newsletter, all necessary input data are manually collected from different ftp sites.

The solution for the GRACE mission generated by the University of Texas Center for Space Research (UTCSR) is provided via ftp://isdcftp.gfz-potsdam.de/grace/Level-2/CSR/. The solution for the GRACE-FO mission generated by UTCSR is provided via ftp://isdcftp.gfz-potsdam.de/grace-fo/Level-2/CSR/. The utilized ASCII format is called GRCOF2 and it is used for the harmonic coefficients in the official GRACE GSM products format.

The data volume depends on the maximum spherical harmonic degree lmax (for CSR: lmax=60, 96). The size of a single monthly solution is only about 0.7MB. The resulting volume of all GRACE data, comprising GRACE solutions from different processing centres for the period 2002 until the present and the associated background models, is clearly below 2GB.

User-defined parameters:

User input	Format	Note
DIST	Y [km]	Distance from solution area where signal is set to zero
LAMBDA	X [number]	Smoothing parameter used in the inversion
DEG 1	Filename	Filename of the chosen degree 1 file
C20 C30 CORR	Filename	Filename of the chosen C20-C30_file
DATA SOURCE	Name	Name of data source e.g CSR, GFZ, ITGS
GIA	Name of GIA	Choice of GIA model to use.

System log

For each run of the system, a log file is created to ensure transparency for the user on what input parameters were chosen for the given run.

This log contains information on the parameters described in the table above.

4.1.3 Hardware and Software Platform

The GMB operational ECV production system will run on most UNIX servers with adequate memory and disk storage space. The current GMB processing system is operated and tested on a server system running ax86_64 GNU/Linux UNIX operating system.

4.1.3.1 Hardware

Table 4.1: Processing Hardware for the SEC processor

Model	Supermicro 848A-R1K62B
Processor	4 X AMD Opteron 6376 (64 cores), 64 bit
Memory (RAM)	256 GB
Local Hard Drive	30 TB
Network Attached Storage	100TB

4.1.3.2 Operating system

The system currently runs on the UNIX operating systemx86_64 GNU/Linux.

The system has been tested and run on other Unix/Linux systems as well, including Mac OS X and a Windows machine with Linux on a Virtual Machine.

4.1.3.3 Tools and libraries

The system requires:

    i)   gfortran

    ii)   gnuplot

    iii)   NetCDF v4 library

4.1.4 Future concerns and developments

An automatic download script could be implemented which alerts the user when / what new data is available, and download this to the server. The same applied to the additional files such as C20, C30 and degree-1 files.

4.2 TU Dresden

4.2.1 System overview

The GMB system produces mass change time series of the Greenland Ice sheet as well as for pre-defined drainage basins.

The system algorithms and methods are described in the [ATBD], while the system input and output data including auxiliary data are described in detail in the [PSD].

The overall system overview is shown in Figure 4.2. it is a semi-automatic processing system implemented in Matlab. It consists of four main modules, as described below. The control flow between the modules is handled by an operator. Input data procurement is done automatically.

Adaption of mass change estimation methods (Methods Module): In this module, the methods used to estimate mass changes are adopted to the characteristics of the latest input data (GRACE solutions and auxiliary datasets) in order to minimize both leakage errors and signal noise. Based on a quality assessment of different GRACE releases, performed in the spherical harmonic and spatial domain, the release to be used in the final product generation is selected. Moreover, the handling of low-degree spherical harmonics, GIA model reduction and additional model corrections (e.g. residual oceanic signals) are specified. Finally, the sensitivity kernels implied by the specific mass estimation method are derived [Döhne et al. 2023].

The Methods Module comprises the most labour-intensive tasks in GMB processing line. Comprehensive tests are required to verify the effectiveness of methodological amendments and modifications of the setup, resulting from the input data characteristics. These tests demand the extensive support of an operator.

Pre-processing: Based on the selections in the Methods Module, GRACE monthly solutions and time series of auxiliary datasets are pre-processed, combined and corrected. This includes the conversion from Stokes-coefficients to mass equivalent coefficients (equivalent water height), the addition of degree-one coefficients, replacement of degree C_{20}, and C_{30} if applicable and the correction for GIA. All monthly solutions are reduced to a specified reference value.

greenland ice sheet cci	Greenland_Ice_Sheet_cci+ ST-DTU-ESA-GISCCI+-SSD-001	Reference : ST-DTU-ESA-GISCCI+-SSD-001
		Version : 2.0 page
		Date : 1 December 2023 26/33

Mass change estimation (Estimation Module): The sensitivity kernels derived in the Methods Module and the time series provided by the Pre-processor serve as main inputs to this module. Mass change time series for every grid cell and every basin is produced by integrating the product of each monthly solution and the corresponding sensitivity kernel. For the basin product, the statistical error characterization of the time series is derived. To infer an overall accuracy measure, GRACE errors propagated to the mass balance estimate are complemented by leakage errors and errors in GIA models. For this purpose, the mass change estimation methods are applied to the model outputs.

Product validation (Validation Module): The Validation Module summarizes all validation procedures focusing on the GMB basin product.

In the case of a successful validation, the GMB products are written in the final output formats. ASCII and NetCDF output files are written using Matlab. After passing a final check, the files are manually uploaded to the web server hosting the data portal.
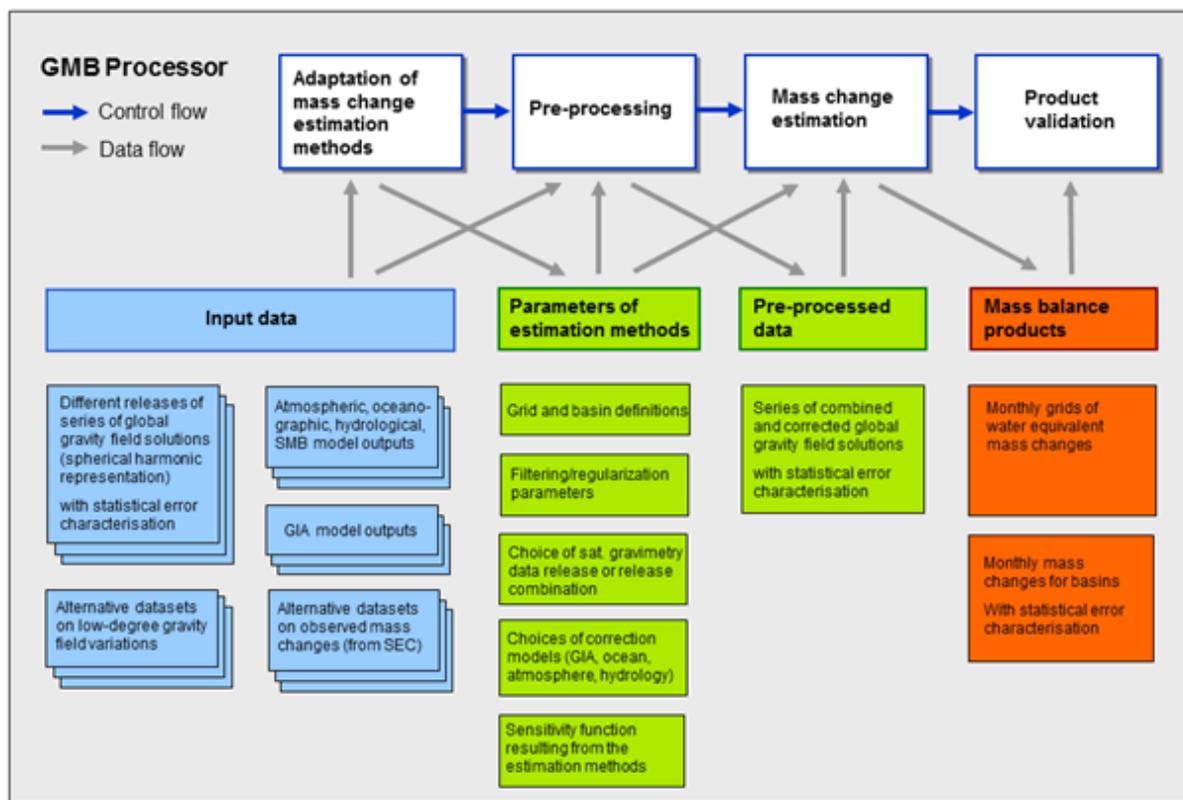

Figure 4.2: Overview of GMB system at TU Dresden.

4.2.2 Operational scenarios

Data procurement: All regularly updated input datasets, i.e. GRACE monthly solutions and time series for both degree one and C_{20}, are automatically downloaded by means of a shell script executed by a weekly cron job.

4.2.3 Hardware and software platform

4.2.3.1 Hardware

The used hardware listed in Table 4.2 is capable to host the GMB processor and to reliably generate actual and future versions of the product.

Table 4-2: Processing Hardware at TU Dresden for the GMB processor

Model	Virtual Machine hosted by TUDresden Center for Information Services and High Performance Computing, 16/32 Cores available
Processor	AMD EPYC 7513 32-Core Processor, 64 bit
Memory (RAM)	64 GiB
Local Hard Drive	200 GB
Network Attached Storage	1 TB

4.2.3.2 Operating system

The operating system in use is the Linux system Ubuntu 20.04 LTS (long-term support). More recent systems such as Ubuntu 22.04 LTS or the upcoming 24.04 LTS are also suitable to host the GMB data production system.

4.2.3.3 Tools and Libraries

The core GMB production system is implemented using the commercial numerical computing environment Matlab version R2022a (9.12). All processing steps and the generation of products in ASCII and NetCDF format are carried out using Matlab. Additional tools are utilized to generate products in alternative formats, check the content and metadata of the products, and visualize the final results.

4.2.4 Future concerns and developments

At present, the GMB processor is not fully automated and needs to be operated manually. The input data volume and their update frequency as well as the processor runtime are moderate. Hence, manual operation is not considered a major drawback and no full automation of the GMB processor is foreseen.

4.3 References

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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

5 Mass Flux and Ice Discharge (MFID)

5.1 System overview

The flow rate and ice discharge algorithms have two primary steps

- Calculation of discharge gate locations.

- Calculation of discharge through the gates.

Gate locations are calculated once using a baseline velocity product and then remain fixed in space and time. Discharge is then calculated for each time when a velocity map exists.

Note - some of the text below comes from Mankoff et al. (2019) where this algorithm was first described.

Gates are algorithmically generated for fast-flowing ice (greater than 150 m yr-1) close to the ice sheet terminus determined by the baseline-period data. We apply a 2D inclusive mask to the baseline data for all ice flowing faster than 150 m yr-1. We then select the mask edge which is near the BedMachine ice mask (not including ice shelves), which effectively provides grounding line termini. We buffer the termini 10 km in all directions creating ovals around the termini and once again down-select to fast-flowing ice pixels. This procedure results in gates 10 km upstream from the baseline terminus that bisect the baseline fast-flowing ice. We manually mask some land- or lake-terminating glaciers which are initially selected by the algorithm due to fast flow and mask issues.

We select a 150 m yr-1 speed cut-off because slower ice, taking longer to reach the terminus, is more influenced by SMB. The choice of a 10 km buffer follows from the fact that it is near-terminus and thus avoids the need for (minor) SMB corrections downstream, yet is not too close to the terminus where discharge results are sensitive to the choice of distance-to-terminus value (Mankoff et al. 2019), which may be indicative of bed (ice thickness) errors.

Discharge is calculated at each gate by multiplying the provided velocity by the thickness of the ice at the gate location. Ice thickness is calculated assuming the BedMachine basal topography as a constant bed elevation and linearly interpolated ice surface elevation based on the ESA CCI SEC relative to a fixed DEM.

5.2 Operational scenarios

The operational scenario for this product is to generate an estimate of total Greenland ice discharge for every timestep when any velocity product exits. If a velocity product does not cover all gates or all portions of all gates, velocity is linearly interpolated from the surrounding times, or forward- or backwards-filled for the last and first time, respectively.

5.3 Hardware and Software Platform

5.3.1 Hardware

The development environment is a common laptop. It currently has 32 GB of RAM and 5 TB of internal storage but can be run on a significantly smaller system. We suggest at least 8 GB of RAM and 1 TB of storage.

5.3.2 Operating system

We use the Linux operating system, specifically Ubuntu 18.04.3 LTS, with the following CPU and architecture:

Architecture: x86_64

CPU op-mode(s):   32-bit, 64-bit

Byte Order: Little Endian

CPU(s):   8

On-line CPU(s) list: 0-7

Thread(s) per core: 2

Core(s) per socket: 4

Socket(s):   1

NUMA node(s):   1

Vendor ID: GenuineIntel

CPU family: 6

Model: 142

Model name: Intel(R) Core(TM) i7-8650U CPU @ 1.90GHz

Stepping: 10

CPU MHz: 758.158

CPU max MHz: 4200.0000

CPU min MHz: 400.0000

BogoMIPS: 4224.00

Virtualization: VT-x

L1d cache: 32K

L1i cache: 32K

L2 cache: 256K

L3 cache: 8192K

NUMA node0 CPU(s): 0-7

5.3.3   Tools and libraries

We use the following tools for this workflow:

This work was performed using only open-source software, primarily GRASS GIS (Neteler et al. 2012) and Python (Van Rossum and Drake Jr 1995), in particular the Jupyter (Kluyver et al. 2016), pandas (McKinney 2010), numpy (Oliphant 2006), statsmodel (Seabold and Perktold 2010), x-array (Hoyer and Hamman 2017), and Matplotlib (Hunter 2007) packages. The entire work was performed in Emacs (Stallman 1981) using Org Mode (Schulte et al. 2012). The parallel (Tange 2011) tool was used to speed up processing. We used proj4 (PROJ contributors 2018) to compute the errors in the EPSG 3413 projection. All code used in this work is available in the Supplemental Material of Mankoff et al (2019).

5.3.4   Future concerns and developments

Development of this work is ongoing at http://github.com/mankoff/ice_discharge where we use additional IV products that support time series back to 1986, additional SEC products that cover the portions of the ice sheet where the gates are located, and other modifications.

Concerns for the future of this work are mitigated by the fact that the entire process is documented, and the code is available for anyone to replicate and improve the product. However, replicating the work has proven non-trivial so far.

Nonetheless, concerns include the quality of the ice thickness data, and the ability to generate SEC maps at regular frequency and with enough spatial coverage to cover the gate locations.

5.4   References

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6 Supraglacial Lake (SGL)

6.1 System overview

In this section we describe the systems for processing, i.e. identifying and delineating supraglacial lakes, as well as estimating the depths of said lakes. This is done with a Deep Learning/Neural Network architecture, which is trained to both provide outlines of lakes and depth estimates of these.

The network architecture is specified and built using a Python library developed by S[&]T which is specifically optimized for rapid development in a geospatial context. From this process, we generate a trained model over the available data in a deployable format (ONNX), where the trained model can be used to generate new maps of lakes with associated depth estimates.

6.1.1 Data and Model Architecture

Data is collected from Sentinel-2 and ICESat-2 over which labels are created by domain experts. Labels here refer to areas where a domain expert has taken the time to outline where on the ice one can see an actual supraglacial lake. In a similar fashion, there are tracks made by the ICESat-2 on its fly-over, estimating the depth of the ice. Where these coincide with lakes, one can get scattered points of depth data, which can be collected to create tracks across the identified lakes. The processing of the altimetry from ICESat-2 gives a reasonable estimate of the depths of the lakes that are up to 4 m deep. (ref https://tc.copernicus.org/articles/14/4253/2020/)

The Sentinel-2 data used so far has been limited to the 10 m bands, i.e. RGB and NIR.

The relative sparsity of these co-occurences means that for most lakes that appear over a period of time, before rapidly flushing through cracks formed in the ice, there will be no such depths to estimate. Similarly, there is a sparsity of how many temporary lakes one can capture by manual labelling.

Model architecture is based on a U-Net backbone, meaning that the dual task of estimating the outline of SGLs, and estimating their depths is on a certain level split into two tasks. In the first task, the model generates a semantic segmentation, marking the pixels in an input image as being either lake or not lake. The second component takes all lake components and performs a regression, to best fit a depth-estimate curve to the lake.
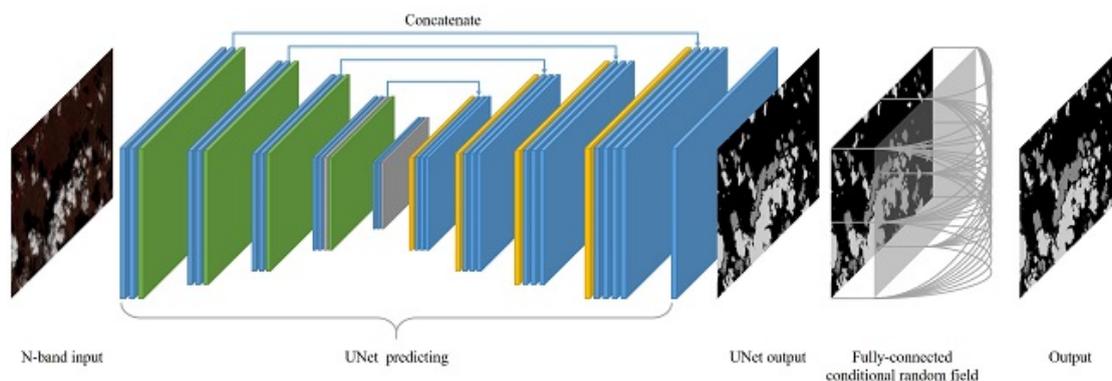

Figure 6.1: Example U-net architecture with conditional random field (CRF)
figure from Jiao L, et. al. (2020)

Data sparsity is corrected by balancing the sampling and utilising unsupervised and semi-supervised methods, e.g. Pseudo-labelling, consistency-training, contrastive learning, etc. In addition, a broad variety of data augmentations are applied, including, but not limited to rotation, cropping, flipping, rolling, mixing and scaling.

6.2   Hardware and software platform

6.2.1   Hardware

In-house server machine with the following specs:

- Processor: Intel Xeon(R) Gold 6326 CPU @ 2.90GHz

- RAM: 512GB

- Available storage: 4TB

Optional external storage also available.

6.2.2   Operating system

Ubuntu x86_64 GNU Linux

6.2.3   Tools and libraries

The programming is done in the Python programming language. We are using PyTorch and PyTorch Lightning for configuring the neural networks, with an internal library, STML, for configuration and coordination of the data pipelines. Furthermore, we use the common scientific stack of numpy, scipy, GeoPandas, etc. For manual inspection and labelling of the data we are using QGis. We also make use of the GDAL libraries for dealing with geospatial data.

6.3   Future concerns and developments

We aim to utilise the further bands from Sentinel-2. This can be done either by resampling bands, either upsampling the lower resolution bands to 10 m pixels or downsampling the higher resolution bands to 20 m pixels. We will also increase the utilisation of data to provide a better model.

In addition to the existing augmentations, we wish to use unlabelling alongside mixing, which is likely to make the model perform better on lake edges using unsupervised and/or semi-supervised training.

6.4   References

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