ESA Climate Change Initiative (CCI)

Antarctic Ice Sheet (AIS) Essential Climate Variable (ECV)

Product Specification Document (PSD)

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Change Log

Issue	Author	Affected Section	Reason	Status
0.1	Anna Hogg	All	Document creation (Doc. Id: ESA_AIS_cci_PSD)	Released to AS on 27.11.2013
0.2	Andrew Shepherd	All	Science lead approval (Doc. Id: ESA_AIS_cci_PSD)	Released to consortium on 04.03.2013
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1.1	Anna Hogg, UL	All	Update from Antarctic_cci Scoping Study in Phase 1 to Phase 2 No changes from review.	Issued to ESA on 16.07.2015 for review Released to ESA on 2015-09-11
1.2	K. Hauglund, S[&]T T. Nagler, ENVEO	Intro 1.3 6.1.1.1 + 6.1.1.2	Updated distribution list Updated RD list Added last paragraph descriptions	Released to ESA on 2017-06-14
2.0	Anna Hogg, UL	3.2 Table 3.1 and 5.2 Table 5.2 6.1.1.1 8.3.1 Table 8.1 a and b 9	Updated for Year 3: Replaced SEC temporal frequence from monthly to 140 days Added ref to Annex 1 on IV metadata Replaced GLL metadata tables and content descriptions Added Annex 1 Table 9.1 Text view of metadata for the velocity product	Released to ESA on 2017-10-23
3.0	D. Floricioiu	All	Updated at the beginning of Phase 2	Released to ESA

Acronyms and Abbreviations

AIS	Antarctic Ice Sheet
AMAP	Arctic Monitoring and Assessment Programme
ATBD	Algorithm Theoretical Basis Document
ATLAS	Advanced Topographic Laser Altimeter System
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
DLR	German Aerospace Center
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
GLL	Grounding Line Location
GMB	Gravimetry Mass Balance
GrIS	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
MPROP	Management Proposal
NBI	Niels Bohr Institute, University of Copenhagen
NERSC	Nansen Environmental Research Institute
NU	Northumbria University
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 satellites
TUDr	Technische Universität Dresden
UCL	University College London
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

This document contains the Product Specification Document (PSD) for the Antarctica_Ice_Sheet_cci+ project for CCI+ phase 2, in accordance with the contract and SoW [AD1 and AD2].

This document is an update according to the description in the Technical Proposal of the AIS_cci+ phase 2 proposal [RD1]. It is based on the AIS_cci+ phase 2 User Requirement Document [RD2], and developed from the Product Specification Document (PSD) version 2.0 which was produced during the AIS_cci (2015-2018) project [RD3]. PSD version 1.0 resulted in the first iteration of Task 1, while PSD version 2.0 in the second iteration. To be mentioned that no PSD update was requested during AIS_cci+ phase 1 (2019 – 2022) of the project.

The present PSD document is part of Task 1 Requirements Analysis deliverables of AIS_cci+ phase 2, with deliverable id: D1.2.

1.1 Purpose and Scope

The aim of PSD is to document the technical feasibility of meeting the updated user requirements described in the URD. These refer to the temporal frequency, spatiotemporal coverage and resolution and the associated uncertainty of each parameter product.

In addition to the updated definitions of the existing products over the Antarctic Ice Sheet ECV, the PSD indicates the
new EO data products that will be produced in phase 2 of the AIS_cci+ project. The specifications are also included.

The geophysical parameters of the Antarctic Ice Sheet (AIS) in the AIS_cci+ project taken over from phase 1 are:

- Surface elevation change (SEC)
- Ice velocity (IV)
- Grounding Line Location (GLL)
- Gravimetric Mass balance (GMB)

The new data products in AIS_cci+ phase 2 are:

- Ice Velocity Change (IVC)
- Grounding Line Migration (GLM)
- Ice Shelf Coast Line (ISCL)

This document provides detailed information about geophysical content, data format, spatial and temporal coverage and sampling, quality flags, grid and geographic projection, annotation data, ancillary data and the error budget of the products.

1.2 Document Structure

This document is structured as follows:

- Chapter 2 provides background information on the AIS_cci project and its parameters.
- Chapter 3 specifies the SEC product specifications
- Chapter 4 specifies the IV product specifications
- Chapter 5 specifies the IVC product specifications
- Chapter 6 specifies the GMB product specifications
- Chapter 7 specifies the GLL product specifications
- Chapter 8 specifies the GLM product specifications
- Chapter 9 specifies the ISCL product specifications
- Chapter 10 contains a list of references

1.3 Applicable and Reference Documents

Table 1.1 Applicable Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
AD1	ESA/Contract No. 4000143397/23/I-NB CCI+ PHASE 2 - ANTARCTIC ICE SHEET.	CCI+ PHASE 2 - NEW R&D ON CCI ECVS for AIS CCI	13.02.2024	NA
AD2	ESA-EOP-SC-AMT-2023-12 and its appendix 2.	STATEMENT OF WORK, ESA EXPRESS PROCUREMENT – EXPRO CCI+ phase 2 – Theme II – Antarctic Ice Sheet (AIS)	14.07.2023	1.2

Table 1.2 Reference Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
RD1	UN-ESA-AIS-CCI+-P2-CCN-TPROP	Antarctic Ice Sheets cci+ Technical Proposal (TPROP)	2023.09.27	1.0
RD2	NU-UL-ESA-AISCCI+-URD-001	User Requirements Document (URD)	2024.09.09	2.0
RD3	NU-ESA-AISCCI+-PSD-001	Product Specification Document (PSD)	2017.10.17	2.0
RD4	ST-UL-ESA-AISCCI+-ATBD-001	Algorithm Theoretical Basis Document (ATBD) for CCI+ phase 1	2020-03-09	1.0
RD5	ST-UL-ESA-AISCCI+-PUG-001	Product User Guide (PUG)	2021-06-03	1.0

RD6	ST-UL-ESA-AISCCI+-CAR-001	Climate Assessment Report (CAR)	2022-05-03	1.0
RD7	ST-UL-ESA-AISCCI+-ADP-002	Algorithm Development Plan (ADP)	2024-06-10	2.0
RD8	ST-UL-ESA-AISCCI+-SSD-001	System Specification Document (SSD)	2020-09-14	1.1
RD9	ST-UL-ESA-AISCCI+-PUG-001	Product User Guide	2021-06-03	1.1

2 Background and parameter information

2.1 Background of Antarctic Ice Sheet ECV parameters and the scientific added value

The Antarctic Ice Sheet CCI project (AIS_cci) was launched in Phase 2 of the ESA CCI programme as an extension to the Ice Sheets ECV which at that time included only Greenland and the need to generate parameters specific for the Antarctic Ice Sheet ECV. Currently, the AIS_cci+ generates a set of products for ECV parameters based on data acquired by ESA EO satellite missions over the last 3 decades.

The geophysical products over Antarctica generated within AIS_cci+ are crucial for ice sheet monitoring and modelling, glaciological research and climate modelling. These data sets aim to contribute to the understanding of

- the current AIS mass loss and the involved contributing processes
- the consequences of the present and future climate changes on AIS mass change
- how to improve the predicted sea level change contribution.

Added values for AIS_cci+ data products:

SEC

seamless, bias-free, gridded elevation change product, processed in a transparent and consistent way, across a diverse set of different satellites FCDR's from radar altimetry satellites. This relieves the users of having to deal with different orbits, periods and cross-over difference schemes, and makes the data much more available to a larger non-expert community. The CCI+ SEC product covers a long time period (1992-) which makes it possible to detect large changes in the ECV over time. The SEC product offers the high spatial resolution needed for regional analysis and process studies for individual glaciers.

IV /IVC

provision of basic ice velocity time series provides important data on glacier dynamics changes, and – combined with ice thickness data and accumulation data in the interior – another source of the overall mass balance of the ice sheets. The scientific usefulness of such data has been demonstrated in the ESA/NASA IMBIE exercises [The IMBIE team (2020); The IMBIE team (2018)] for intercomparison of different EO data for estimating the overall mass balance of Greenland and Antarctica.

A primary added value of the AIS_cci+ is to support the continued utilization of ESA SAR mission data, with an established long-term consistency in grid spacing, coverage and methodology. The added scientific value of the AIS_cci+ project is the guaranteed public availability of the ESA time series of IV, independent of short-lived project-based efforts. The temporal and spatial coverage of the Antarctic Ice Sheet derived from Sentinel-1 data within the AIS_cci is unprecedented and represents a great added value to the scientific community.

GMB

This data product is based on GRACE and GRACE-FO data, which is the only sensor to directly measure mass change (or equivalent sea-level rise.). An added value of the GMB product is its monthly resolution. An added value from the AIS_cci+ Phase 2 product will be not only the continuation of the time series into the recent past but also the filling of the 11-month gap between the lifetime of the GRACE and GRACE-FO missions.

GLL/GLM

Mapping the GLL is based on Synthetic Aperture Radar (SAR) data from different satellites e.g. Sentinel-1, ERS-1/2, TerraSAR-X by the DInSAR method. The upper limit of flexure of the floating ice detected is taken as a proxy of the actual grounding line and is provided as the GLL product. The metadata includes information about model-based ocean tide level and air pressure at satellite acquisition times for meaningful and interpretable comparison of GLLs. None of the existing GLL databases of Antarctica contain this information. Comparisons between recent GLLs and older ones derived from ERS-1/2 tandem data with the same technique enable the detection of possible migrations of the grounding line.

ISCL

An updated version of the IceLines data from DLR (Baumhoer et al.) using not only Sentinel-1 SAR images but also CryoSat-2 altimetry data. The combination provides more certainty to the products and less confusion with sea ice. That is due to the elevation data's certainty and ability to distinguish between the ice shelf and sea ice. That combined with the high spatial resolution and large coverage of SAR data can produce more accurate results for the studied ice shelves. Since the training data is generated from the IceLines model (it is not manually delineated and has many errors), this project focuses on establishing how the added altimetry data can be beneficial but is limited in performance by the inherent limitations of the training data.

2.2 Format and sampling of the ECV products based on user requirements

The selection of the ECV parameters occurred in the initial phases of the project after consultation with the user community. This process and its updates are described in the User Requirement Document [RD2].

An overview of the planned data production in phase 2 of the AIS_cci+ project is given in Table 1. For the existing data products, the specifications are based on user requirements that resulted previously to phase 2015-2018 and have now extended temporal range and were adjusted to EO data availability and additional EO data. The specifications of the new data products planned for phase 2 (Table 2) will be updated at the end of Task 1.

Table 1 Overview of the Antarctica cci+ phase 2 data products taken over from phase 1.

Product	EO Input Data	Temporal Range cci/cci+	Temporal Frequency	Extent	Spatial Resolution
SEC	Cryosat-2, Sentinel-3, *ICESat-2*[1]	1991 - 2021	monthly	AIS	5 km grid + basins
IV	Sentinel-1 A/B, *SAOCOM*[1]	2014 - 2021	Annual, monthly & sub-monthly	AIS margins (incl. ice shelves)	200 m grid
GMB	GRACE/GRACE FO	2002 - 2021	monthly	AIS	50 km grid, basins
GLL	Sentinel-1 A/B, TSX SAR	1992 - 2021	decadal	20 ice streams	< 250 m

[1]additional EO data to be used in phase 2.

Table 2 Overview of the new data products in Antarctica cci+ phase 2. The requirements will be updated after the user consultation meeting.

Product	Product description	EO Input Data	Temporal Range cci/cci+	Temporal Frequency	Extent	Spatial Resolution
IVC	Ice Velocity Change	Sentinel-1 A/B, TerraSAR-X, ERS-1, ERS-2, ENVISAT	TBD	TBD	TBD	TBD
GLM	Grounding Line Migration	Sentinel-1 A/B, TSX SAR	TBD	TBD	TBD	TBD
ISCL	Ice Shelf CoastLine	Sentinel-1 and Cryosat-2	2017-2022	Monthly	Larsen-C, Ronne, Filchner ice shelves	up to 20m (dependent on the S1 image used)

2.3 Basic grid and line formats

The basic product formats recommended initially in the CCI general recommendations, adapted here for the AIS_cci products, are as follows:

1. Grid files (GMB, SEC, and IV/IVC) are to be stored in *NetCDF format*. IV files to be stored as Cartesian velocity components (i.e., north and east velocity in m/s). We suggest using the widespread NetCDF-4 version, readily supported by MATLAB, GMT and Python. See https://unidata.github.io/netcdf4-python/

2. Line files (GLL, GLM, ISCL) to be stored as *ESRI Shapefiles*. About 1/3 of the respondents reported to prefer GIS formats (RD2), since the NetCDF is not optimal for vector data. This ensures a useful consistency with the glaciers CCI project, which also maps outlines of isolated Greenland glaciers. See http://www.esri.com/library/whitepapers/pdfs/shapefile.pdf

2.4 Map projection for grid data

The preferred map projection for the grid products (SEC, IV/IVC, GMB) resulted from the initial Ice_Sheets_cci user survey (RD2) is Polar Stereographic As this projection is also the projection of choice for SCAR, the AIS_cci products will be produced in the Polar Stereographic projection.

Stereographic projections used for public domain data sets include both data with reference parallels of 70°S and 71°S, (e.g., US ICESat DEMs and MEaSUREs SAR IV data sets). Even if the Ice_Sheets_cci project used a reference parallel of 70°N, the AIS_cci project will use the more common Antarctic Polar Stereographic Map Projection EPSG:3031 (http://spatialreference.org/ref/epsg/wgs-84-antarctic-polar-stereographic/) which refers to a latitude of true scale of **71°S**. The reference meridian (longitude) for this projection is 0°.

Since some products such as GLL may also provide kml output files, geodetic coordinates will additionally be required. They will refer to WGS84 using the reference projection EPSG:4326 (http://spatialreference.org/ref/epsg/wgs-84/).

With simplicity and consistency in mind, the convention for the AIS_cci standard projection is:

EPSG: 3031

Antarctic Polar Stereographic, reference latitude 71°S, reference meridian 0°, ellipsoid WGS84

2.5 File naming conventions

The Antarctic Ice Sheet CCI ECV products will follow the standard file naming convention of the CCI products.

3 Surface Elevation Change (SEC) Product

3.1 SEC Product Overview

Satellite radar altimetry provides estimates of surface elevation change (SEC) through repeated measurements of ice sheet surface elevation. The Antarctic Ice Sheet (AIS) CCI+ SEC product is produced using the latest Level-2 input data from radar altimetry (RA) missions operational since 1991. The SEC product has been evaluated and applied in numerous studies e.g. [Shepherd et al. (2019)].

Averaging SEC over short temporal periods would mostly represent rapid snowfall events and seasonal cycles and are more difficult to estimate due to data constraints. Averaging over a very long temporal period (e.g. since the beginning of the RA time series in 1991) is not appropriate as the surface elevation change in some regions in Antarctica (West Antarctica in particular) has accelerated over time. Therefore we produce SEC grids based on 5-year running means of RA measurements. SEC is defined as dh/dt in units of m/yr and the spatial and temporal resolution of the SEC product aligns with the Global Climate Observing System (GCOS) 2022 targets for the Essential Climate Variables (ECVs) for ice sheets [GCOS (2022), Table 1; AD2(SoW), p. 12].

In phase 2, SEC processing chains will integrate new thematic land ice product baselines with improved measurement coverage, accuracy, and precision in elevation measurements. It will also use measurements from new sensors such as the NASA Laser Altimetry mission ICESat-2. The updated processing chain will also include a backscatter correction upgrade by exploring the use of additional waveform parameters such as the leading edge width and trailing edge slope within the processing system.

3.2 Background on Product Generation

The SEC product will be generated from a new range of improved level-2 data products (FDR4ALT for ERS-1 and -2, ENVISAT, CryoTEMPO Baseline-C for CryoSat-2 and ESA Thematic Land Ice for Sentinel-3A/B). These new thematic land ice product baselines will be integrated into the SEC processing chain so the product will benefit from their improved measurement coverage and accuracy.

The SEC processor developed by the Centre for Polar Observation and Modelling (CPOM) (UCL/Northumbria) is used for product generation. This processor combines plane fit processing configured with a backscatter correction calculated over the full mission. The plane fit algorithm [Shepherd, et al., 2019] can be applied to satellites with both short (27 to 35 days such as the main operational periods of ERS-1/2, ENVISAT and Sentinel-3A/B) and long (369 days such as CryoSat-2) orbit repeat periods where measurements do not exactly repeat within monthly time scales. The actual algorithms used for SEC are outlined in the ATBD [RD4] and were shown in the CCI round-robin to perform as well as or better than other along-track missions for all missions. The plane fit method grids both ascending and descending measurements in a regular polar stereographic grid instead of gridding separately along the track. It derives a SEC estimate at the centre of each grid cell by applying a surface model to the measurements within that cell. SEC results are produced on the same grid as the SEC output product and hence do not require re-gridding which can introduce an additional error and reduce accuracy.

Elevation changes in each geographical grid cell are computed from satellite radar altimetry data using a surface model fitted with a Levenberg-Marquardt least squares method:

$$\mathbf{z}(x,y,t,h) = a_0 + a_1\mathbf{x} + a_2 y + a_3\mathbf{x}^2 + a_4\mathbf{y}^2 + a_5\mathbf{xy} + a_6\mathbf{h} + a_7\mathbf{t}$$

where z is height, x and y are polar stereographic easting and northing coordinates respectively, h is the satellite heading (set as binary, asc=1, desc=0), and t is the time in years since reference time 1-Jan-2000. Outliers two standard deviations beyond the modelled height are iteratively removed.

A second model is fitted to the slope- and satellite heading-corrected elevation anomalies emerging from the plane fit to remove residual short-term fluctuations correlated with changes in backscattered power [Wingham et al., 1998]:

$$p = a + b\mathbf{t} + c\mathbf{h}$$

where p is the backscatter power. This is applied in a separate step to ensure it does not interfere with the spatial and temporal elevation fit. The data is then aggregated into 140-day epochs for each satellite mission, with cross-calibration applied to account for biases between missions to produce the final time series of elevation changes.

3.3 Detailed SEC product specifications

NetCDF files will contain the AIS CCI+ 5 km polar stereographic grid covering the whole Antarctic ice sheet south of -56 N with multi-mission 5-year mean SEC at monthly intervals.

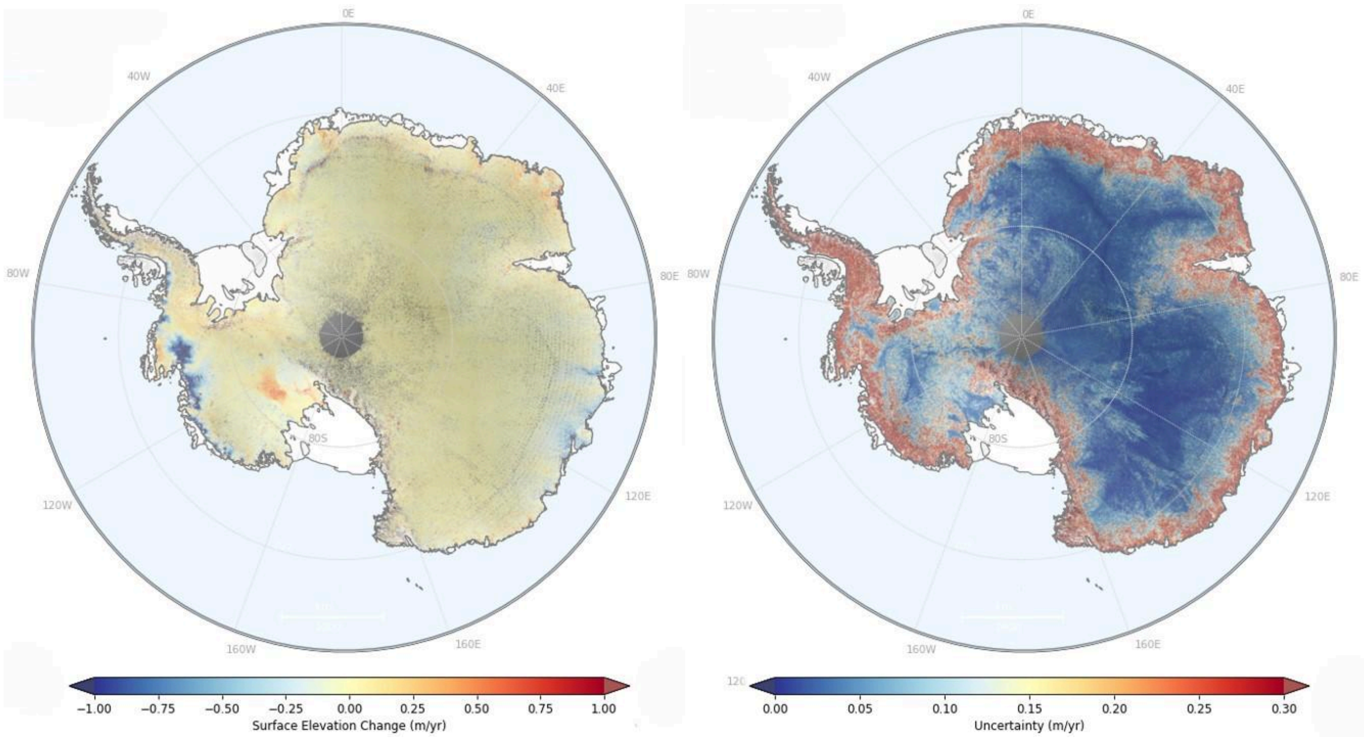

Figure 3.1: Surface elevation change (left) and uncertainty in SEC (right) at 5 km grid from 2017-2021.

Key NetCDF Attributes & Data Variables

This is the basic metadata for the SEC product and a list of key data variables used.

Attribute Name	Data Type	Description
title	String	A descriptive title for the SEC dataset
grid_projection	String	Name of the map projection used
Data Variables	**Data Type**	**Description**
sec	Float	Surface elevation change
sec_uncertainty	Float	Uncertainty in surface elevation change
lat	Float	Latitude in decimal degrees
lon	Float	Longitude in decimal degrees
x	Float	Cartesian x-coordinate - easting
y	Float	Cartesian y-coordinate - northing
start_time	Float	The start time of the 5-year time slice period
end_time	Float	The end time of the 5-year time slice period
basin_id	Int	IMBIE glaciological basin ID number
surface_type	Int	Surface type identifier

4 Ice Velocity (IV) Product

4.1 IV product overview

The Ice Velocity (IV) products produced in Antarctic Ice Sheet CCI+ contain gridded surface velocity maps of the Antarctic Ice Sheet that are derived from repeat-pass synthetic aperture radar (SAR) data using combinations of coherent and incoherent offset tracking (OT) and InSAR. A velocity grid represents the average ice surface velocity for the selected period of the image pair or merged image mosaic. The product specifications are guided by the GCOS 2022 (Global Climate Observing System) targets for the Ice Sheets Essential Climate Variable (ECV).

In this phase of the project, the IV processing chain is upgraded to accommodate SAOCOM L-Band SAR data in synergy with Sentinel-1 in order to improve the ice velocity retrieval in Antarctica. The benefits of this upgrade will be demonstrated by generating prototype products for selected periods and key areas in the Antarctic Peninsula (API) and West Antarctic Ice Sheet (WAIS).

4.2 Background on Product Generation

The primary processor for IV generation is the ENVEO software package (ESP v2.1). ESP is a state-of-the-art IV retrieval algorithm designed for SAR sensors and has been tested rigorously through intercomparisons with other packages and extensive validation efforts.

The main production line applies advanced iterative offset tracking techniques utilising long stripes of Sentinel-1 (S1) C-Band SAR data acquired in interferometric wide (IW) swath mode to generate time series of ice velocity maps (Nagler et al., 2015). These velocity maps cover all areas with S1 repeat-pass acquisitions in Antarctica, which are primarily restricted to the coastal margins. S1-derived IV retrieval over the Antarctic Ice Sheet margins is continued in this phase of the project to cover all the areas required for the product on MFID (Option-3).

The main upgrade of the IV processing chain introduced in this phase of the project is the adaptation of the existing InSAR and OT algorithms to accommodate SAOCOM L-Band SAR data in synergy with Sentinel-1. For this, the existing processing lines developed originally for Sentinel-1 TopSAR are amended to accommodate SAOCOM data as well as the combination of SAOCOM and Sentinel-1 with ascending and descending crossing orbit pairs. New product development focuses on test areas depending on the availability of SAOCOM and S1 SAR data with short revisit times, ascending/descending coverage and scientific interest. These test regions include major outlet glaciers with high velocities and velocity gradients as well as slower-moving ice.

4.3 Detailed IV products specifications

Products are provided as either NetCDF or GeoTIFF files with separate layers for the velocity components vx, vy, vz and vv (magnitude of the horizontal components). For velocity mosaic, consisting of merged velocity maps additional maps showing the valid pixel count and uncertainty (std) are included. Only a single time slice is provided per NetCDF4/GeoTIFF. For each file, one (x, y)-grid is supplied, and the value of the time coordinate represents the midpoint time of the acquisitions used to form the given grid. The ice velocity map is provided in the Antarctic Polar Stereographic projection (EPSG: 3031, defined at https://epsg.io/3031). The horizontal velocity is provided in true metres per day, towards the easting (vx) and northing (vy) direction of the grid, and the vertical displacement (vz), is derived from a digital elevation model (REMA 200m DEM; Howat et al., 2019). For all maps, a no-data value of 3.4028235e+38 is used. The spatial and temporal resolution and coverage are provided in Table 4.1.

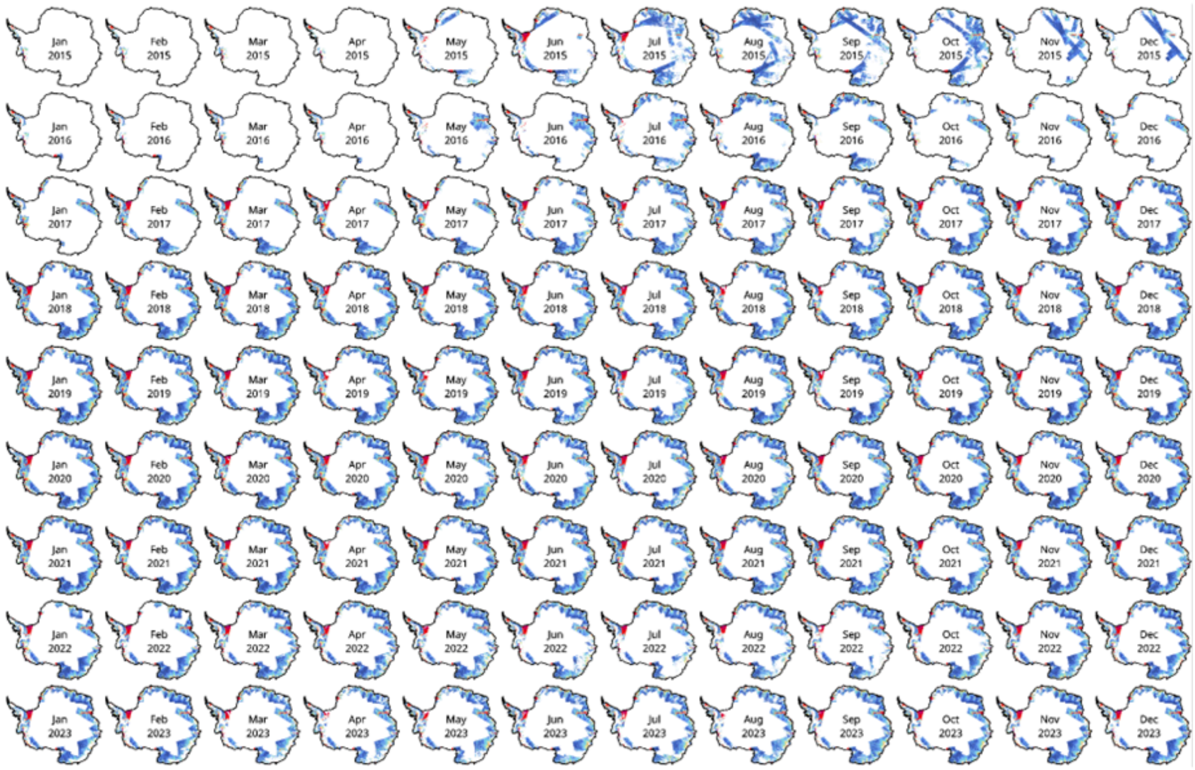

Figure 4.1: Monthly Antarctic Ice Sheet ice velocity maps since 2015 derived from Copernicus Sentinel-1.

Table 4.1: Spatial and temporal resolution and coverage of IV products generated in the project.

Sensor	Spatial Resolution	Spatial coverage	Temporal resolution	Temporal coverage
Sentinel-1	200 m	Antarctic Ice Sheet margins	6-12 days, monthly	2015-present
SAOCOM & SACOM/S1	100-200 m	Selected regions in the Antarctic Peninsula and West Antarctic Ice Sheet	8-32 days	2021-present

5 Ice Velocity Change (IVC) Product

5.1 IVC product overview

Ice Velocity Change (IVC) is a new ECV product introduced in the project and is currently not provided by any of the existing EO programs or operational services. IVC is a fundamental ice sheet parameter that is key to detect and investigate regions with dynamic instabilities or to identify short-term fluctuations and longer-term trends that may be induced by seasonal, climatic and/or oceanographic changes. The product to be developed shall utilise existing and newly generated annually averaged ice velocity maps derived from Sentinel-1 (See Chapter 4). Figure 5.1 shows a preliminary product representing the difference in velocity magnitude between 2016/17 and 2015/16.

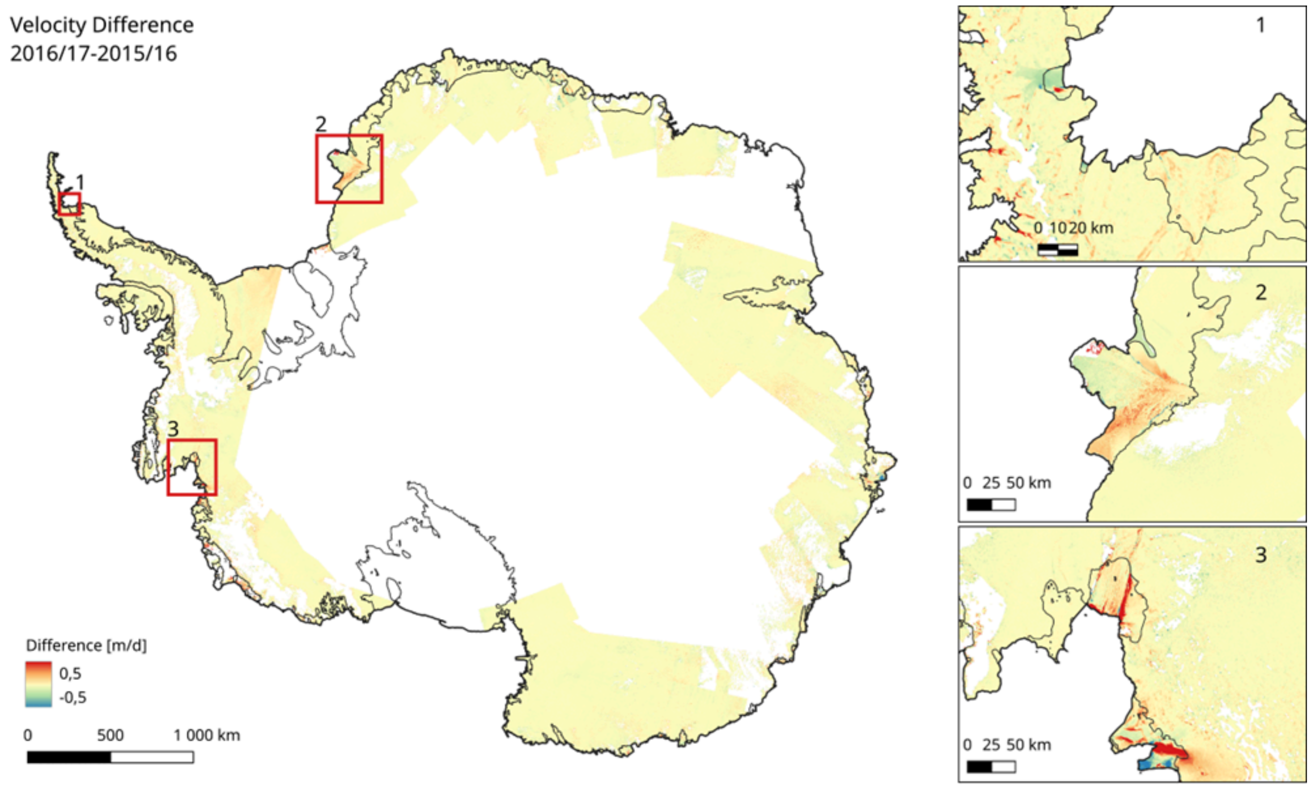

Figure 5.1: Prototype IVC product representing the difference in velocity magnitude between 2016/17 and 2015/16. Red indicates areas with increased velocity, and blue indicates areas with reduced velocity.

5.2 Background on Product Generation

One of the main outcomes of the Antarctic Ice Sheet CCI project was the development of an operational system for regular retrieval of ice velocity based on Copernicus Sentinel-1 SAR, which has since been further adapted and improved to accommodate new user requirements and increasing data coverage and temporal resolution. Based on this system, ENVEO has generated an extensive archive of IV maps covering the Antarctic Ice Sheet margins during the Sentinel-1 era (2015-onwards). In this project, this archive is exploited to study the utility of a new ECV product on ice velocity change (IVC), detailing the spatial distribution of changes in ice flow rate over specified time intervals. The aim is to develop, test and integrate an IV system module for generating IVC on a routine basis and to provide demonstration products covering key areas in the API and WAIS.

5.3 Detailed IVC product specifications

The IVC product specifications largely match those of the Sentinel-1-derived ice velocity products, which form the main input data. IVC Products are gridded at 200 m resolution and provided as either NetCDF or GeoTIFF files with separate layers representing changes in the velocity components vx, vy, vz and vv (magnitude of the horizontal components). Each NetCDF4/GeoTIFF file provides a single time slice. For each file, one (x, y)-grid is supplied. The IVC map is provided in the Antarctic Polar Stereographic projection (EPSG: 3031, defined at https://epsg.io/3031). The units represent the change in velocity in metres per day. For all maps, a no-data value of 3.4028235e+38 is used.

6 Gravimetric Mass Balance (GMB) Product

6.1 GMB product overview

The Gravity Recovery and Climate Experiment (GRACE) twin satellites and their follow-on (FO) mission GRACE-FO (Tapley et al., 2019; Landerer et al. 2020) have been measuring changes in the Earth's gravitational field since 2002. The temporal gravity variations are caused by mass redistributions within the solid Earth (such as glacial-isostatic adjustment, GIA) and at the Earth's surface (water, ice, atmosphere). If the gravity effects of solid-Earth processes are known and subtracted, the remaining temporal gravity field variations can be used to infer mass changes and mass redistributions in the Earth's subsystems, including mass changes of the AIS. The AIS_cci+ project produces Gravimetric Mass Balance (GMB) products for the AIS from GRACE and GRACE-FO Level-2 (L2) gravity field solutions. These products comprise two types of datasets: (1) Basin mass change products: monthly mass change time series for the entire AIS, and sub-regions such as the EAIS, the WAIS and the AP and 26 individual drainage basins; (2) Gridded mass change products. All products are consistent in the sense that summing up the mass changes of grid cells belonging to a particular basin is equivalent to the mass change of the pertinent basin time series.

6.2 Background on Product Generation

GRACE and GRACE-FO L2 monthly gravity field solutions are available from different processing centres, including the Centre for Space Research (CSR) at the University of Texas, the GeoForschungsZentrum (GFZ), or the Technical University Graz (TU Graz). They are provided in a spherical harmonic (SH) representation up to a maximum SH degree (typically 60 or, alternatively, 90) and can be accessed freely from https://isdc.gfz-potsdam.de/grace-isdc/.

Different processing algorithms exist in order to derive ice sheet mass changes from the SH solutions. One approach is the regional integration of areal density anomalies synthesized from the L2 gravity field solutions. An alternative approach is the mascon approach (also called the inverse approach or forward-modelling approach), where mass changes are parametrized as a set of prescribed patterns and scaling factors for each of these patterns are estimated so that the gravity effect fits the L2 solution. Döhne et al. (2023) showed that the two approaches are equivalent as long as they employ the same variance-covariance information on both the mass redistribution signal and the GRACE L2 errors. Hence, the method applied for the AIS_cci+ GMB product, specifically the method of tailored sensitivity kernels (Groh and Horwath 2021) can be considered from the perspective of both approaches.

Essential steps of the product generation are the following: Evaluate available L2 gravity field solution series to choose the one to use; Decide on the uncertainty characterisation of the L2 solutions; evaluate GIA models to be used for GIA correction, make the choice of one GIA model, and subtract the modelled GIA effect from the time series of L2 solutions. Currently, the model IJ05_R2 (Ivins et al. 2013) is used for GIA correction; Define (and possibly iterate) the mass-change signal covariance along a global grid with a regional refinement over the AIS. Use the signal covariance information and the GRACE and GRACE-FO L2 error covariance information to define sensitivity kernels (for each AIS grid cell) that minimize, in a least-square sense, the sum of propagated L2 solution errors and leakage errors. Apply the sensitivity kernels to the series of monthly L2 solutions; Aggregate the mass changes of grid cells to derive the basin mass change product; Perform an uncertainty assessment. More details are given in the ATBD. The sensitivity kernel is identical for all months. This implies that the details of resolution and filtering with which the actual mass variations are mapped into the GMB product remain constant over time.

6.3 Detailed GMB product specifications

The GMB product comprises two different datasets:

(1) the GMB basin product. This product provides a time series of basin-averaged changes in ice mass in units of mass [kg]. Basin averaged time series are derived for 26 drainage basins and the total areas of the Antarctic Peninsula, the East Antarctic Ice Sheet, the West Antarctic Ice Sheet and the entire Antarctic Ice Sheet. The basin definition is according to Zwally et al. (2012). In the Northern Antarctic Peninsula, Zwally basins 25 and 26 are aggregated into one basin, which is given Number 28. The basins are illustrated in Figure 6.1. Estimates of mean rates of mass change estimates for every basin complete the GMB basin product. The mean rates are estimated as the linear component of a linear, periodic (periods: 1 year, 1/2 year) and quadratic model fitted to the entire time series of basin-averaged changes in ice mass. An illustration of the GMB basin product is given in Figure 6.2

(2) the GMB gridded product. This product provides mass changes per grid cell in units of mass per surface area (kg m^{-2}). The unit is equivalent to “millimetres water equivalent height (mm w.e.) and is commonly used to map the spatial patterns of mass changes. The formal grid resolution is 50 km x 50 km on a polar-stereographic projection. It has to be emphasised that the actual spatial resolution is coarser (at the level of 200 km), which is reflected in the smooth appearance of mass change patterns in the 50 km x 50 km grid. An illustration of the GMB gridded product is given in Figure 6.3.

The temporal evolution in ice mass provided by the GMB products represents changes in mass relative to a reference value. This reference value is defined to be the GRACE-derived mass as of 2011-01-01. Technically, this value is derived from a linear, periodic (periods: 1 year, 1/2 year) and quadratic model fitted to the monthly solutions in the period 2002-08 – 2016-08.

Both GMB products exhibit a temporal resolution of one month and cover the period from 04/2002 to 2024-02 (or longer). The gap of temporal coverage between the GRACE mission and the GRACE-FO mission (11 months from 2017-07 to 2018-05) will be filled by applying methods specifically designed for the AIS mass changes.

The basin product is given with a thorough error characterisation. Uncertainties of the monthly mass anomalies are modelled as the combined effect of uncertainties of the temporal linear trend, σ^2_{trend}, and a temporally uncorrelated noise, σ_{noise}. The uncertainties of linear trends are summed up in quadrature from uncertainties due to different error sources. The trend uncertainties are given separately (in the separate file AIS_GMB_trend.dat, GIS_GMB_trend.dat). In this way, it can be propagated to monthly uncertainties w.r.t. a reference time t_0 of the user's choice. The error variance at any epoch is then $\sigma^2_{total}(t) = \sigma^2_{noise} + \sigma^2_{trend}\,(t - t_0)^2$. The gridded product is not equipped with an uncertainty characterization.

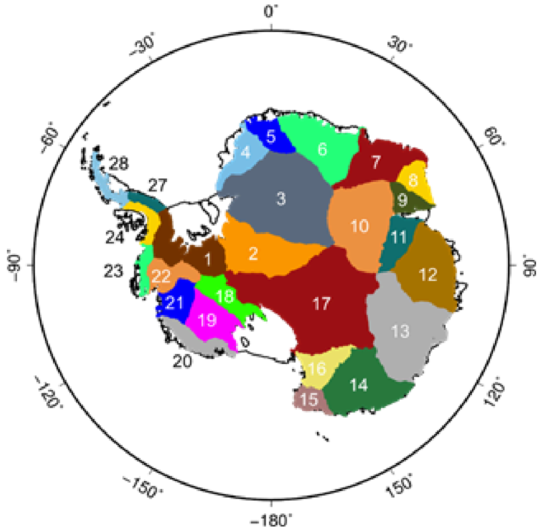

Figure 6.1: Drainage basins adopted for the GMB product. In addition, basin numbers 29-32 refer to the Antarctic Peninsula, the East Antarctic Ice Sheet, the West Antarctic Ice Sheet, and the entire AIS, respectively.

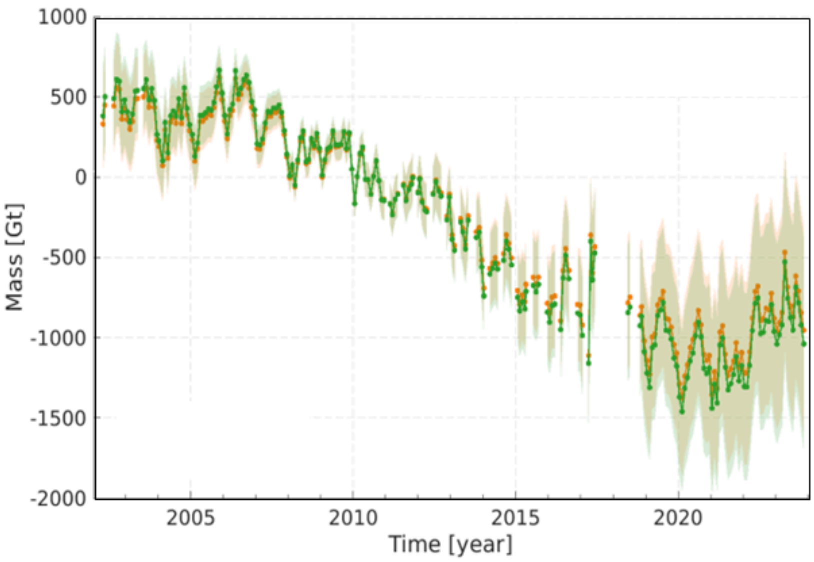

Figure 6.2: Illustration of the GMB basin product. Shown are the time series of mass changes for the entire AIS ('Basin 3'). Error bars illustrate the combination of the monthly uncorrelated noise and the uncertainties of the long-term trend. The latter becomes more expressed at the end and the beginning of the time series since the time series represents mass anomalies w.r.t. the reference time 2011-01-01. Green curves show time series with a recently incorporated ellipsoidal correction, contrasted to a previous version shown in orange.

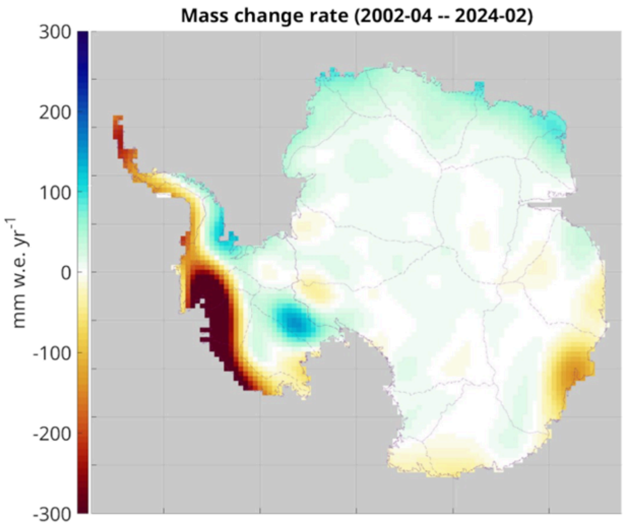

Figure 6.3: Illustration of the GMB gridded product. Mean rate of mass change over 2002-04 – 2024-02 expressed on the 50 km x 50 km grid, expressed in mm w.e. yr^{-1}, or kg m^{-2} yr^{-1}.

7 Grounding Line Location (GLL) Product

7.1 GLL product overview

The grounding line denotes all positions where the ice detaches from the bedrock and starts to float. The location of the GL varies due to different factors such as ocean tides, ice thickness, subglacial topography or sedimentation. For the AIS_cci Grounding Line Location (GLL) product the InSAR double differencing method (DInSAR), which has been identified to be the most accurate technique to identify the vertical tidal deformation of the ice sheet, is applied. The biggest limitation of mapping the GL using DInSAR is the loss of coherence. Physical changes on the ground which affect the dielectric constant of the surface such as snow accumulation, and snow drift from the wind but also melting and refreezing can alter the reflected signal in a way that phase differences are no longer coherent but result in noise. Consequently, the typical fringe pattern required for the indication of the GLL will not appear or is superimposed by noise.

At the beginning of the project, the “mapping” of the grounding line was intended as a manual delineation (digitise) of the course of the upper flexure limit. Due to the increasing number of acquired data and derived interferograms to be mapped and to the operator subjectivity regarding the position of the grounding line, in the current stage of the project, a development towards an automatic mapping of the grounding line is considered.

7.2 Background on Product Generation

The GLL production system is a two-step approach. In a first step, DLR’s Interferometric Wide Area Processor (IWAP) is used to determine interferograms and double difference interferograms SAR data. The second step is the mapping of the upper limit of flexure [RD8].

The end user can download the GLL products through the data portal, while the file formats available are described in detail in the Product User Guide (PUG) [RD9]. The GLL information is internally stored in a PostGIS database and a full database dump provides all information to the data portal.

7.3 Detailed GLL product specifications

The standard format of the GLL vector data is an *ESRI shapefile* in EPSG:3031 - WGS 84 / Antarctic Polar Stereographic coordinate system. The data product contains besides the actual linestrings additional metadata. The metadata provides information about the time of the used satellite image acquisitions, ocean tide- and air pressure levels, processing parameters, quality flags and more. Shapefiles contain multiple linestrings with each linestring having its own metadata record.

The specifications of the GLL products which are generated in AIS_cci+ phase 2 are based on the same SAR data as in the earlier phases and therefore they do not differ from the previously released products and are summarised in Table 4.2.

Table 4.2: Spatial and temporal resolution and coverage of GLL products generated in the AIS_cci+ phase 2 project.

Sensor	Spatial Resolution	Spatial coverage	Temporal resolution	Temporal coverage
Sentinel-1	< 250 m	Selected outlet glaciers and ice streams	Several times per year	2015-present
TerraSAR-X	< 250 m	Selected outlet glaciers and ice streams south of 82°S	One coverage	2008 -present

The location of the selected outlet glaciers and ice streams for GLL generation is shown in Figure 7.1. During phase 1 of the project, the focus was on dense time series in areas where the Sentinel-1 data preserve coherence.

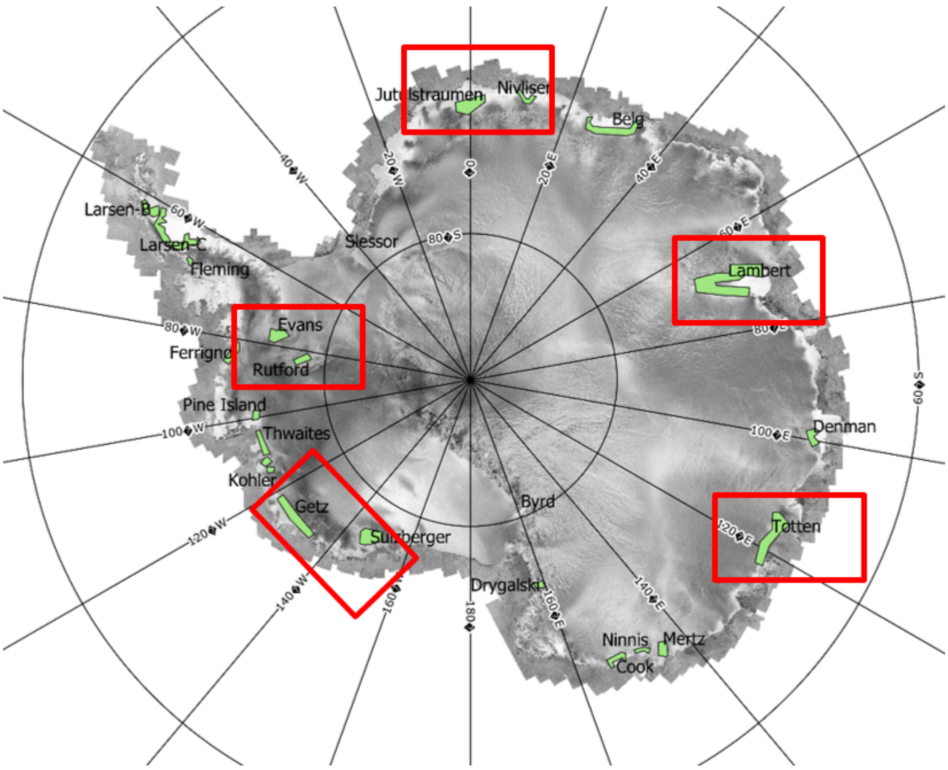

Figure 7.1 Map of the key glaciers and ice shelves selected for the GLL generation (green polygons) and the areas where the focus has been on dense time series covering various tide levels (red rectangles).

8 Grounding Line Migration (GLM) Product

8.1 GLM product overview

An important goal of the GLL mapping is the detection of grounding line retreat which involves the comparison of GLL's from different moments in time. If a higher number of delineations could be made in a semi-automatic way this opens opportunities for a new GLL-derived Grounding Line Migration (GLM) product by producing the required long time-series and filling temporal gaps in existing delineations.

8.2 Background on Product Generation

The processing system developed for the GLL parameter has been continuously adapted to the increasing SAR data volume. Consequently, dense time series of GLLs have been generated on key outlet glaciers which are considered a good database for the new AIS_cci parameter GLM. In the current stage of the baseline project, the processing chain of GLL will be extended with a prototype module exploring various metrics for GLM, e.g. (Moon, & Joughin, 2008), (Avbelj et al, 2014). Further developments through an operational GLM generation will be foreseen in the future optional activity dedicated to GLM.

8.3 Detailed GLM product specifications

The specifications of the GLM product are in the focus of a future CCN optional activity. Therefore the details of the product are still in evolution and the details will be provided according to the working plan of the optional activity.

9 Ice Shelf Coast Line (ISCL)

9.1 ISCL product overview

The objective of the proposed activity is to investigate the added benefits of combining radar measurements (Sentinel-1) with altimetry (CS2) in the delineation of ice shelf coastlines. This investigation will be conducted over three selected ice shelves (Larsen-C, Ronne, Filchner). Those three ice shelves cover a large area and have been subject to large calving events in the recent past. Furthermore, they represent challenging areas with the simultaneous presence of glaciers and islands.

Delineation of the Ice Shelf CoastLine (ISCL) will be performed using both SAR images from Sentinel-1 and elevation data from CryoSat-2 altimetry tracks. The elevation data compiled from CS2 tracks will provide an initial guess for the model based on elevation differences that can indicate the start of the ice shelf coastline. That initial guess along with corresponding SAR imagery from the designated time and location from Sentinel-1 will be fed to a Convolutional Neural Network (CNN) That will combine the 2 inputs to predict a first iteration of the location of the ISCL. Then, the model will be run iteratively as a refinement network to refine the prediction until the location converges to the predicted ISCL.

9.2 Background on Product Generation

The methodology has the following merits:

- Combination of S1 and CS2 sources exploiting their strengths
- Iteratively refining front lines explores the utility of updating a certain but outdated source (the CryoSat-2 data since the elevation change locations are certain of the location but don't have high temporal resolution or spatial coverage) by using high-resolution but ambiguous images (Sentinel-1 data which has higher spatial and temporal resolution and coverage). In the future, this approach could be used for updating previous manual delineation too.
- Iterative deep learning segmentations are less studied than traditional computer vision methods or convolutional neural network (CNN) architectures.

As can be seen in Figure 9.1, the process starts with combining the training data from 2 main sources. The first source is Sentinel-1 SAR Ground Range Detected (GRD) including both Interferometric Swath (IW) and Extra-Wide Swath (EW) image modes. The second source is altimetry data from CryoSat-2 Retracker-1. Since the latter data source has limited coverage (due to the limited swath of the altimeter), we use it to find intersection points between the along-track path of the satellite and the ice shelf. This is done by combining some tracks and finding the point where there is the most substantial elevation change, which indicates the elevation change between sea/sea ice and the ice shelf. This produces accurate -albeit scarce- geolocation points of where the ice shelf begins.

We use these points as starting delineations to construct an initial guess of where the ice shelf could be. This initial guess is generated by processing these elevation change locations and interpolating areas with missing data, then thresholding the substantial elevation change. We found such a threshold to be around 200m, but we used a dynamic threshold based on clustering to yield more accurate lines.

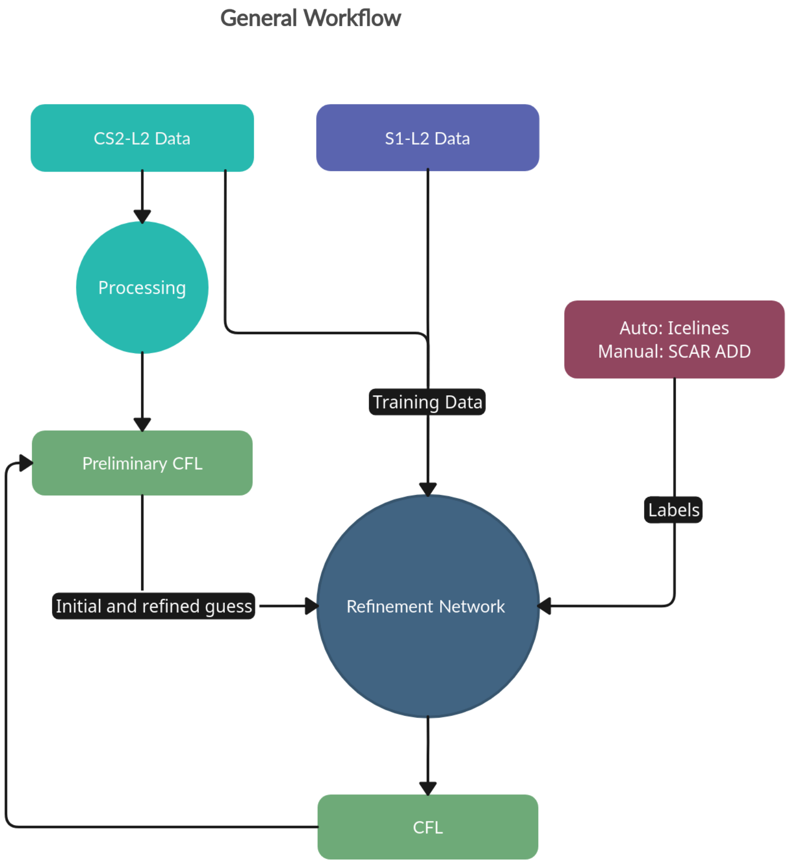

Figure 9.1: General workflow of the ISCL product generation

These lines are then fed as initial guesses to the network, along with the actual Sentinel-1 SAR images of the same scene at the same time. This is shown in Figure 9.2 (left). Sometimes when there is no data in the time range selected, we choose the image with the closest timestamp. The network then trains on detecting the lines based on labels from the IceLines dataset and a pixel-wise loss function. Since IceLines have many errors, we use them as pseudo labels and aim to not be completely restricted by them. Also, on inference, we rerun the network as a refinement network to iteratively optimise the line found based on the elevation data. This is shown in Figure 9.2 (right).

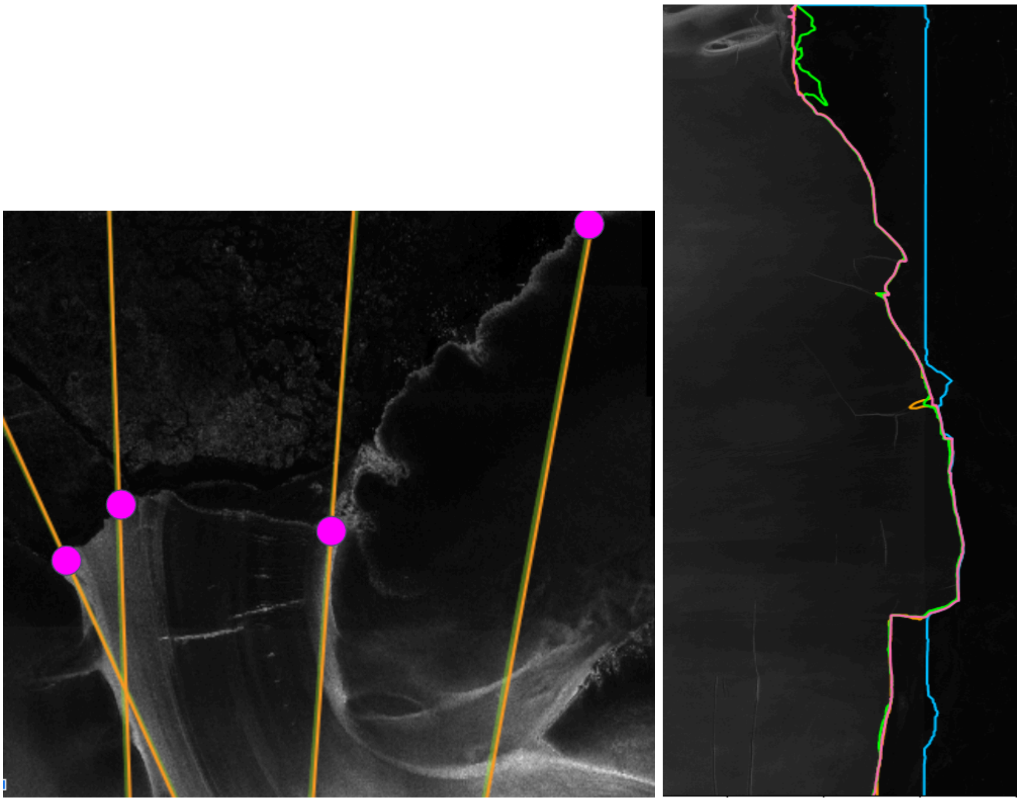

Figure 9.2: Left: Elevation change points marking the edge of the ice shelf. Right: Line refinement from the initial guess to the ice shelf front line.

9.3 Detailed ISCL product specifications

The products will consist of monthly ice shelf lines for each of the ice shelves under study. This will be a processed output where the output of the network is filtered to abide by the rules of the CryoSat-2 elevation data. If the elevation data indicates the existence (or nonexistence) of the line in a specific location (partial image), it will be more accurate than the network's output and will be used to filter out possible mistakes. This is prominent with sea ice, where the network might mistakenly assume there is a front line (and so do the IceLines labels since they are also generated from a network) but the elevation data can help remove such false positives.

The products will be in the form of GeoPackage vector data (.gpkg) for easy distribution, opening, and size requirements. Each file will contain multiple line strings which hold the data of the line in EPSG:3031 Antarctic Polar Stereographic CRS. The file will also contain metadata containing information related to the Sentinel-1 image used to obtain the line, following the CCI data standard. This data will include acquisition time, ID, mode, polarisation, and processing type. The data will extend from 2017 to 2022 across the LarsenC, Ronne(1 and 2) and Filchhner ice shelves. It will have a spatial resolution dependent on the S1 image mode used. Since we are using GRD images, it can reach 20 x 22 for IW and 50 x 50 for EW image modes.

10 References

Avbelj, J., Muller, R., & Bamler, R. (2014). A Metric for Polygon Comparison and Building Extraction Evaluation. IEEE Geoscience and Remote Sensing Letters, 12(1), 170–174. https://doi.org/10.1109/LGRS.2014.2330695

Baumhoer CA, Dietz AJ, Heidler K, Kuenzer C. IceLines–A new data set of Antarctic ice shelf front positions. Scientific Data. 2023 Mar 15;10(1):138.

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

GCOS, 2022. The 2022 GCOS Implementation Plan. Geneva: World Meteorological Organization, 85. https://gcos.wmo.int/en/publications/gcos-implementation-plan2022

Groh, A. and Horwath, M.: Antarctic Ice Mass Change Products from GRACE/GRACE-FO Using Tailored Sensitivity Kernels, Remote Sens., 13, 1736, https://doi.org/10.3390/rs13091736, 2021.

Howat, I. M., Porter, C., Smith, B. E., Noh, M.-J., and Morin, P.: The Reference Elevation Model of Antarctica, The Cryosphere, 13, 665-674, https://doi.org/10.5194/tc-13-665-2019, 2019.

Ivins, E. R., James, T. S., Wahr, J., O. Schrama, E. J., Landerer, F. W., & Simon, K. M. (2013). Antarctic contribution to sea level rise observed by GRACE with improved GIA correction. Journal of Geophysical Research: Solid Earth, 118(6), 3126-3141, DOI: 10.1002/jgrb.50208

Landerer, F. W., Flechtner, F. M., Save, H., Webb, F. H., Bandikova, T., Bertiger, W. I., Bettadpur, S. V., Byun, S. H., Dahle, C., Dobslaw, H., Fahnestock, E., Harvey, N., Kang, Z., Kruizinga, G. L. H., Loomis, B. D., McCullough, C., Murböck, M., Nagel, P., Paik, M., Pie, N., Poole, S., Strekalov, D., Tamisiea, M. E., Wang, F., Watkins, M. M., Wen, H.-Y., Wiese, D. N., and Yuan, D.-N.: Extending the Global Mass Change Data Record: GRACE Follow-On Instrument and Science Data Performance, Geophys. Res. Lett., 47, e2020GL088306, https://doi.org/10.1029/2020GL088306, 2020.

Moon, Twila and Ian R. Joughin. „Changes in Ice Front Position on Greenland's Outlet Glaciers from 1992 to 2007". Journal of Geophysical Research: Earth Surface 113, Nr. F2 (2008). https://doi.org/10.1029/2007JF000927.

Nagler, T, Rott, H., Hetzenecker, M., Wuite, J. and Potin, P., (2015): The Sentinel-1 Mission: New Opportunities for Ice Sheet Observations. Remote Sens., 7, 9371-9389.

Shepherd, A., Gilbert, L., Muir, A. S., Konrad, H., McMillan, M., Slater, T., et al. (2019). Trends in Antarctic Ice Sheet elevation and mass. Geophysical Research Letters, 46, 8174–8183. https://doi.org/10.1029/2019GL082182

Tapley, B. D., Watkins, M. M., Flechtner, F., Reigber, C., Bettadpur, S., Rodell, M., Sasgen, I., Famiglietti, J. S., Landerer, F. W., Chambers, D. P., Reager, J. T., Gardner, A. S., Save, H., Ivins, E. R., Swenson, S. C., Boening, C., Dahle, C., Wiese, D. N., Dobslaw, H., Tamisiea, M. E., and Velicogna, I.: Contributions of GRACE to understanding climate change, Nat. Clim. Change, 9, 358–369, https://doi.org/10.1038/s41558-019-0456-2, 2019.

Zwally, H. Jay, Mario B. Giovinetto, Matthew A. Beckley, and Jack L. Saba, 2012, Antarctic and Greenland Drainage Systems, GSFC Cryospheric Sciences Laboratory, https://earth.gsfc.nasa.gov/cryo/data/polar-altimetry/antarctic-and-greenland-drainage-systems

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