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

Antarctica_Ice_Sheet_cci+ (AIS_cci+)

System Specification Document (SSD)

Prime & Science Lead: Andrew Shepherd

Northumbria University, Newcastle upon Tyne, United Kingdom

Technical Officer: Anna Maria Trofaier

ESA ECSAT, Didcot, United Kingdom

Consortium:

DTU Microwaves and Remote Sensing Group (DTU-N)

DTU Geodynamics Group (DTU-S)

Environmental Earth Observation IT GmbH (ENVEO)

Deutsches Zentrum für Luft- und Raumfahrt (DLR) Remote Sensing Technology Institute (IMF)

Northumbria University (NU)

Science [&] Technology AS (ST)

Technische Universität Dresden (TUDr)

University College London (UCL/MSSL)

Signatures page

Prepared by	Alan Muir Lead Author, UCL	
Checked by	Andrew Shepherd Science Leader, NU	
Issued by	Daniele Fantin, Project Manager, S&T	Digitally signed by Daniele Fantin Date: 2025.02.19 12:13:15 CET
Approved by	Anna Maria Trofaier ESA Technical Officer	Digitally signed by Anna Maria Trofaier Date: 2025.02.19 13:05:32 Z

Table of Contents

Change Log

Issue	Author	Affected Section	Change	Status
1.0	A. Muir, Lead Author, UCL	All	Updated for Phase 2	Released to ESA

Acronyms and Abbreviations

Acronym	Explanation
AIS	Antarctic Ice Sheet
ADP	Algorithm Development Plan
AIS_cci+	Antarctic Ice Sheets CCI project Extension
API	Antarctic Peninsula
ATBD	Algorithm Theoretical Basis Document
CAR	Climate Assessment Report
CCI(+)	Climate Change Initiative (Extension)
CFL	Calving Front Location
CONAE	Comisión Nacional de Actividades Espaciales
DEM	Digital Elevation Model
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DTU	Danish Technical University
EAIS	East Antarctic Ice Sheet
ECV	Essential Climate Variable
ENVEO	ENVironmental Earth Observation GmbH
EO	Earth Observation
ESA	European Space Agency
GLL	Grounding Line Location
GLM	Grounding Line Migration
GMB	Gravimetric Mass Balance
ISCL	Ice Shelf Coast Line
IV	Ice Velocity
IV-TDM	Ice Velocity Tidal Correction Module
IVC	Ice Velocity Change
MFID	Mass Flux Ice Discharge
MPC	Mission Performance Cluster
SEC	Surface Elevation Change
SL	Science Lead
SOW	Statement of Work
ST	Science & Technology AS
TOPS	Terrain Observation by Progressive Scans
TUD	Technical University of Dresden
UB	University of Bristol
UCL	University College London
UL	University of Leeds
UN	University of Northumbria
WAIS	West Antarctic Ice Sheet
NASA	National Aeronautics and Space Administration

SAR	Synthetic Aperture Radar
InSAR	Interferometric SAR
ML	Machine Learning

1 Introduction

1.1 Purpose and Scope

This document contains the System Specification Document for the Antarctica_Ice_Sheet_cci (AIS_cci) project for CCI+ Phase 2, in accordance to the contract and SoW [AD1 and AD2].

This is the System Specification Document (SSD), which specifies the characteristics of the ESA AIS_cci+ ECV processing systems.

1.2 Document Structure

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

- Surface Elevation Change (SEC)
- Ice Velocity (IV) and Ice Velocity Change (IVC)
- Grounding Line Location (GLL) and Grounding Line Migration (GLM)
- Gravimetric Mass Balance (GMB)
- Ice Shelf CoastLines (ISCL)

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 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 of the system.
- Description of the life cycle sustainment activities to be executed during the life cycle 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. 4000143397/23/I-NB CCI+ PHASE 2 - AIS	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
AD-3	NU-ESA-AISCCI+-ATBD-002	Algorithm Theoretical Basis Description	07.02.2025	1.0

2 Surface Elevation Change (SEC)

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 surface elevation change products over Antarctic ice sheets. In this phase of the project, level-2 products from the laser altimetry mission ICESat-2 are also used to produce SEC.

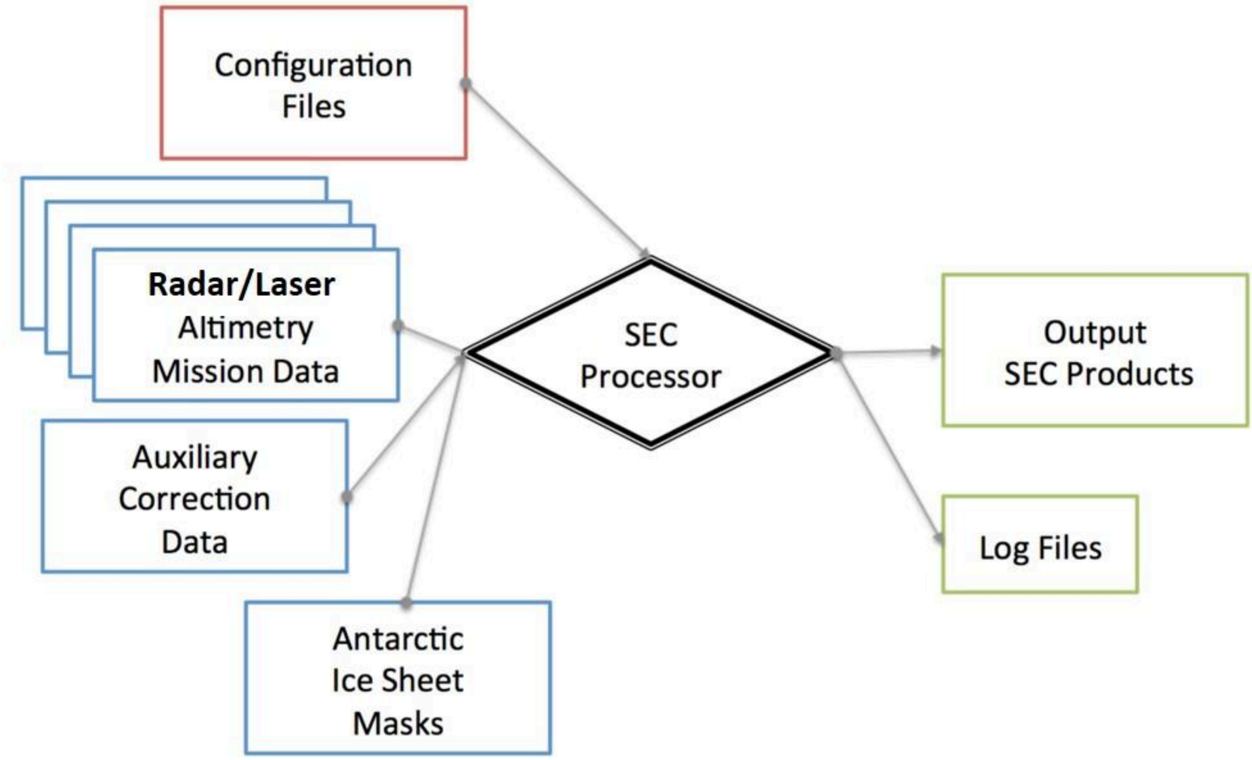

Figure 2.1: SEC ECV Processor Input/Output

Input Data Sources

Input data for the SEC production system consist of multi-mission altimetry data, auxiliary correction data, ice sheet masks and configuration files.

Satellite Altimetry Data

Input L2 data from radar altimeter missions are chosen from the latest fully reprocessed and validated baseline archive of operational Level-2 products from ESA. **All data sets are new to this phase of CCI+**, and replace previous L2 baselines used in previous phases. Use of laser altimetry from ICESat-2 is new to this phase.

Table 2.1: Current Altimetry Data Sets

Mission	Type	Baseline	Version	Source	Operational Dates
ERS-1	RA	FDR4ALT LI	1.0	ESA	2-Aug-91 to 2-Jun-96
ERS-2	RA	FDR4ALT LI	1.0	ESA	13-May-95 to 4-Jul-03
ENVISAT	RA	FDR4ALT LI	1.0	ESA	9-Apr-02 to 18-Oct-10
CryoSat-2	RA	CryoTEMPO	C001	ESA	16-Jul-10 to (now-30days)
Sentinel-3A	RA	Thematic LI	BC05	ESA	07-Dec-16 to (now-30days)
ICESat-2	LA	ATL06	006	NASA	14-Oct-18 to (now-180days)
Sentinel-3B	RA	Thematic LI	BC05	ESA	23-Nov-18 to (now-30days)

Auxiliary Correction Data

Some L2 product data sets also require auxiliary data files to correct known instrument drifts or to provide updated geophysical or atmospheric corrections that have not yet been incorporated into the latest operational baseline data sets.

Table 2.2: Auxiliary Data Sources

Mission/Baseline	*Auxillary Correction*	*Source*	*Auxiliary File Pre-processing*
All	GIA (Glacial Isostatic Adjustment) Correction	IJ05_R2 model (Ivans & James 2005)	none

Antarctic Basin Masks

To process SEC data over the Antarctic ice sheet it is necessary to provide a mask to filter the input altimeter and processed data to include only elevation change over the grounded ice sheet. To produce a SEC time series for individual Antarctic drainage basins it is necessary to provide a set of basin masks. In this project we use the glaciological basins defined for Antarctica by Rignot (2016), and as recommended by the ESA/NASA IMBIE project.

Table 2.3: Antarctic basin mask

Mask	*Source*	*Auxiliary File Pre-processing*
Antarctic Basin Mask	Rignot et al, 2016/IMBIE (imbie.org)	CPOM/IMBIE

Output Data Products

The output of the SEC operational ECV processor are NetCDF v4 format files containing gridded SEC and error values for each full mission and from cross-calibrated combined mission 5-year periods, and CSV format files containing Antarctic drainage basin time series at a monthly interval.

Table 2.4: Output Data Products

Product	*Grid Resolution*	*Mission*	*Period*	*Format*
SEC	5km	ERS-1	2-Aug-91 to 2-Jun-96	NetCDF v4 (Classic)
SEC	5km	ERS-2	13-May-95 to 4-Jul-03	NetCDF v4 (Classic)
SEC	5km	ENVISAT	9-Apr-02 to 18-Oct-10	NetCDF v4 (Classic)
SEC	5km	CryoSat-2	16-Jul-10 to (Now-90-days)	NetCDF v4 (Classic)
SEC	5km	Sentinel-3A	07-Dec-16 to (Now-90-days)	NetCDF v4 (Classic)
SEC	5km	ICESat-2	14-Oct-18 to present	NetCDF v4 (Classic)
SEC	5km	Sentinel-3B	23-Nov-18 to (Now-90-days)	NetCDF v4 (Classic)
SEC	5km	All RA missions	5-year periods since 1991	NetCDF v4 (Classic)
DEM	5km	All Ra missions	Annual	NetCDF v4 (Classic)

Processing Timeliness

SEC products are updated quarterly when there is availability of new altimetry data from current satellites (such as CryoSat-2, Sentinel-3A, Sentinel-3B, ICESat-2) in the latest operational baseline validated for the SEC processor. There is normally a delay of approximately 32 days after satellite acquisition before ESA releases L2 products (with a precise orbit). NASA releases L2 ICESat-2 products in tranches with a delay of 90 to 180 days.

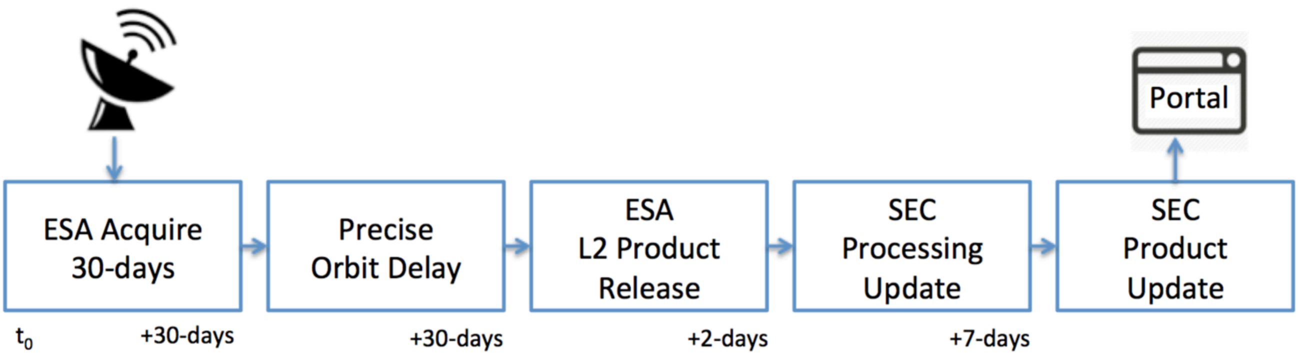

Figure 2.2: SEC Product Update Time Line for new CryoSat or Sentinel-3 data.

Should ESA or NASA update the L2 product baseline for a mission, then there will be no new SEC product updates using the new baseline until it has been validated and calibrated for use in the SEC processor.

Portal Access

SEC products are made available on the SEC product web portal, a service hosted by CPOM, UCL's Operational Polar Monitoring Portal http://www.cpom.ucl.ac.uk/landice.

Users must register their details (Name, Email Address, Affiliation, Sector, Country) and tick a box indicating that they will site publication XX, DOI YY, and whether they wish to be informed of new versions of the dataset, before accessing the data for the first time.

SEC and DEM product NetCDF files, quicklook images, and documentation are packaged and compressed in to zip archive files. Separate archive files are provided for each individual mission period, each 5-year cross-calibrated multi-mission period and a single archive containing all period files.

2.1 System overview

The SEC operational ECV production system comprises of 6 main top level processes (shown in Figure 2.3) to manage ingest and archive of radar and laser altimetry data sets, process scheduling, log, error management and operator notification, processing of individual missions to produce SEC time series, cross-calibration to produce multi-mission data sets, product production, and portal data management.

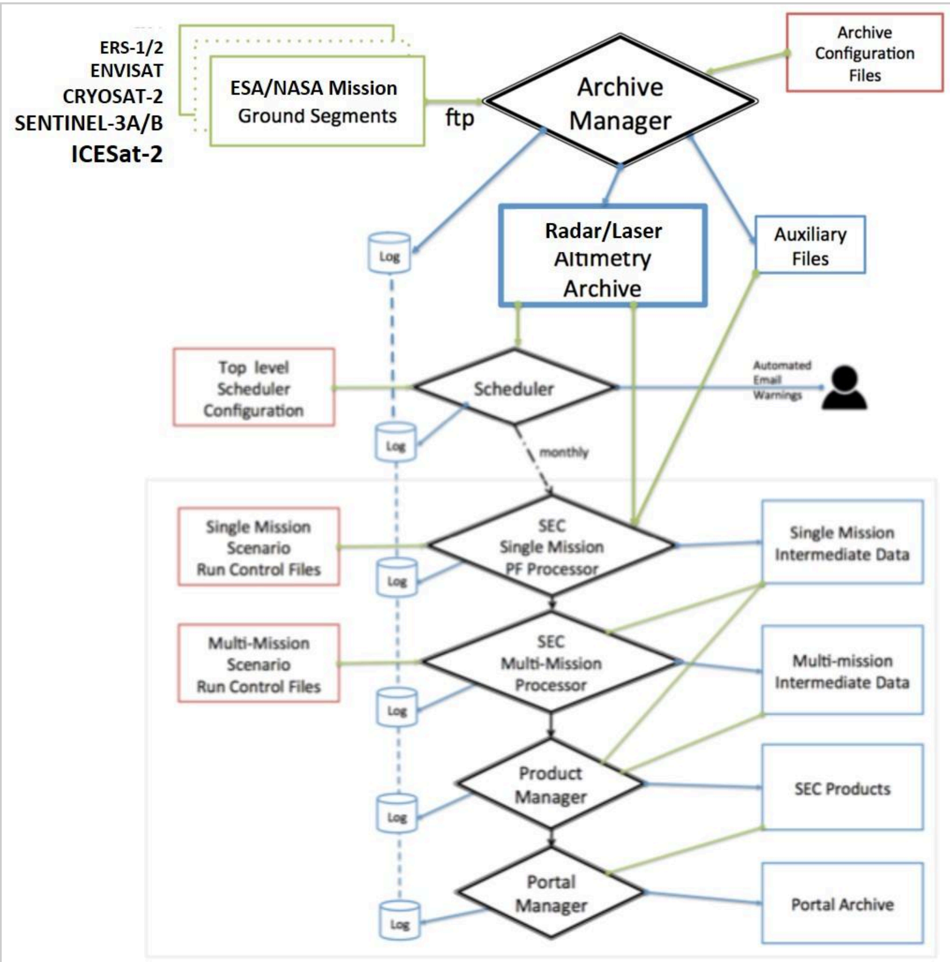

Figure 2.3: SEC ECV Production System Top Level Processes

Each top level process is described in more detail below.

2.1.1 SEC Archive Manager

The Archive Manager controls the process of archiving and updating all current (CryoSat-2, Sentinel-3a, 3b, ICESat-2) and historic (ERS-1, ERS-2, ENVISAT) satellite altimetry data sets required for the SEC processor. Its primary aim is to ensure that the SEC processor has access to the most up to date set of radar altimetry data (from validated baselines) available and to report on availability for each mission.

It has two main functions:

a) Generate statistics of RA/LA data sets held in its archive and report anomalies.

b) Manage the ingest from ESA/NASA ground segment ftp sites of new data (from validated baselines).

The Archive manager is configured by a set of configuration files which detail the location of each mission L2 or L2i data set in the file system, and the required update frequency, and ftp details.

A separate update manager process runs for each live mission such as CryoSat, Sentinel-3a, 3b and ICESat-2. Historic missions such as ENVISAT, ERS-2 and ERS-1 are updated by manual process in the event of a new validated ESA L2 product baseline becoming available.

The Archive Statistics Manager process reports on data availability and any availability anomalies or disk errors from all missions.

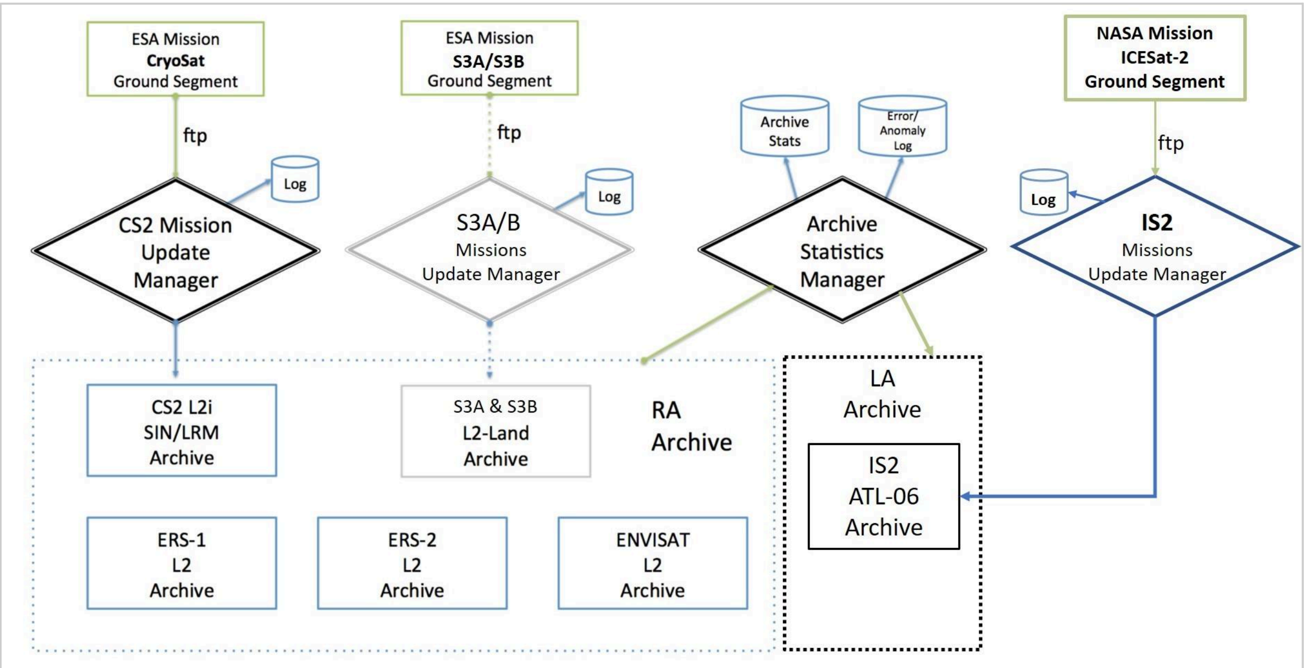

Figure 2.4: SEC Archive Manager

2.1.2 SEC Process Scheduler

The SEC process scheduler is the top level process which automates the scheduling of all SEC processing and product production (except radar and laser altimetry archive management) according to its schedule configuration file.

By default the scheduler automatically runs monthly (on the 1st day of each month) and will initiate the single mission plane fit processor for each live mission that has new validated data. It will then run the multi-mission processor, product manager, and portal manager to generate and export updated products.

Each process stage is checked for fatal errors before continuing and their success, failure and timing are logged. At the end of each scheduled monthly processing, the scheduler log is emailed to the operator or can be inspected manually.

The process scheduler, and individual processes can be run manually by the operator. This may be necessary if new SEC processor versions are implemented or new altimetry baselines become available. Single mission plane fit processing may be run in parallel if required.

2.1.3 Single Mission Plane Fit Processor

The SEC single mission plane fit processor performs three main tasks to convert raw L2 radar altimetry data to gridded SEC parameters:

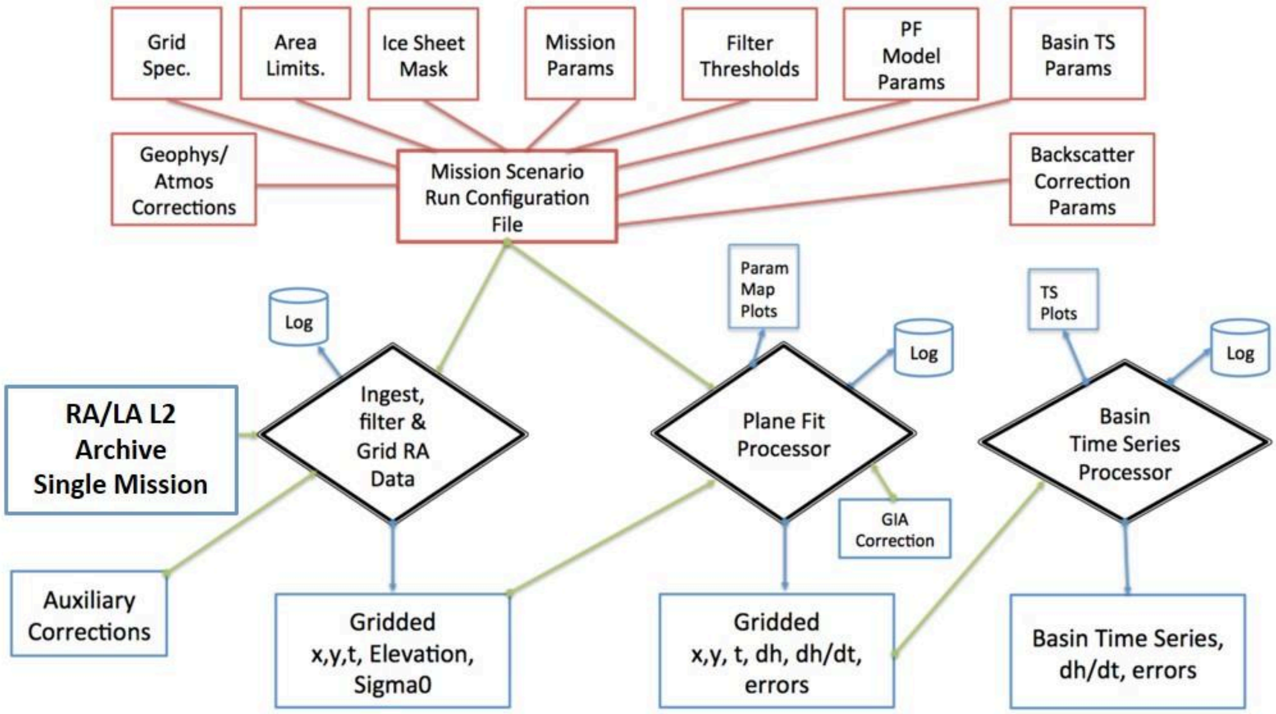

Figure 2.5: SEC Single Mission Plane Processor

i) **Ingest and Gridding**. This is the process of ingesting single mission RA and LA L2 or L2i data from the RA and LA Archive, performing any masking, filtering, processing or correction steps necessary to extract fully corrected high rate measurements of slope corrected location, ice sheet elevation, backscatter and time. The resulting measurements are then stored in a 5km polar stereographic dynamic grid array saved as python .npz format files. Statistics of the number of RA/LA orbit files read, measurements accepted and rejected, and the reasons for rejection are saved to a log file.

ii) **Surface Fit Processing**. The Surface Fit processor fits a modelled surface to each grid cell using the method described in *McMillan et al, 2014*., and then removes the topographic and anisotropic components of each elevation measurement, leaving the temporal variation. It also corrects for volume penetration of the ice by performing a backscatter correction, applies a GIA correction, and calculates dh/dt and residuals. All the results and model fit parameters from this process are stored in new python .npz grid array files. Statistics of the number of grid cells and measurements successfully processed and those rejected are stored in a log file. Maps of each model parameter, dh/dt, and surface slope are automatically plotted and stored.

iii) **Basin Time Series Processing.** The basin time series processor calculates the mean surface elevation change within an Antarctic drainage basin or region (IMBIE basin definitions, *Rignot et al, 2016*) at 30 day epochs, since the start of the mission. Grid cells within a basin that do not contain measurements at an epoch are filled using an area interpolation algorithm. Resulting time series data are stored in CSV format files. Statistics of the % area filled within each basin at each epoch, before and after interpolation are saved in a log file. Time series plots for each basin are automatically produced and stored.

Each single mission plane fit processing scenario is controlled by a run control configuration file, stored in $RT_HOME/conf/rcfs/<scenario_name>.rcf

Each run control file calls a set of mission default configuration files stored in $RT_HOME/conf/rcfs/defaults. There are a set of default configuration files for each mission that control all aspects of data ingest and processing. Scenario run control files can also override any default settings.

Directory	*Description*
TIMESERIES/	contains all output data files in CSV format
LOGS/	contains all processing log and stats files
CONF/	contains a copy and record of all configuration parameters used in the processing as set in the RCF.
FOFS/	contains an ASCII text list of all RA and LA L2 file names read
IMAGES/	contains all auto generated plots and parameter maps in jpg format.

All intermediate data output and log files for a processing scenario is stored in the scenario directory:

$RT_HOME/scenario_data/<scenario_name>/

2.1.4 SEC Multi-mission dh/dt Processor

The SEC multi-mission processor combines individual mission SEC time series by performing a cross-calibration step at the grid pixel level.

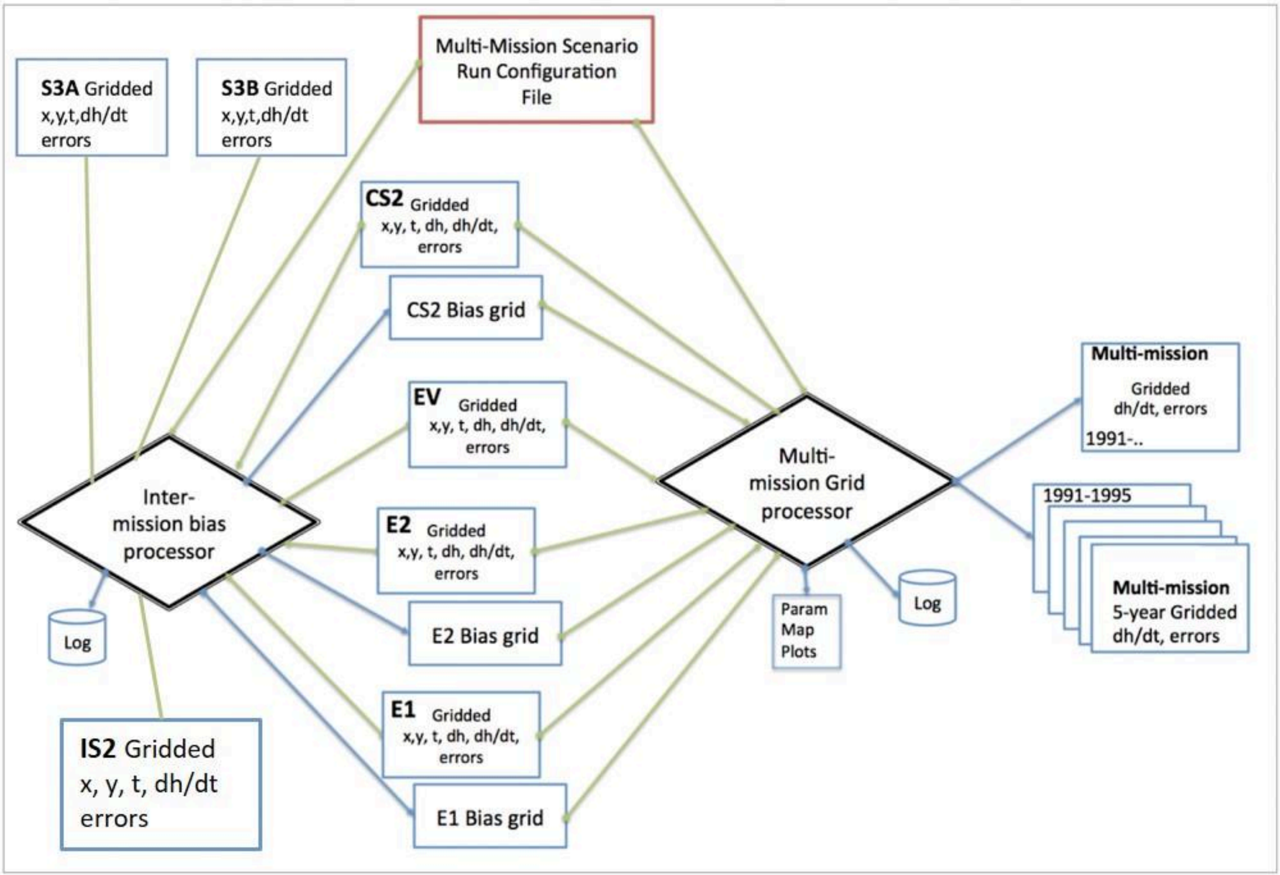

Figure 2.6: SEC Multi-mission dh/dt processor

Directory	Description
TIMESERIES/	contains all output data files in CSV format
LOGS/	contains all processing log and stats files
CONF/	contains a copy and record of all configuration parameters used in the processing as set in the RCF.
IMAGES/	contains all auto generated plots and parameter maps in jpg format.

The processor has two main tasks:

1. Calculate an intermission bias with respect to Envisat for each mission at each grid cell by analyzing the time series around mission overlap periods. The bias grid is saved for each mission. A log containing the statistics of bias generation success or failure for each grid is saved.
2. Combine the mission times series at each grid cell by applying the bias. Calculate dh/dt and residual errors of the combined multi-mission time series for 5 year periods from 1991, and for the whole period. The resulting grid files are stored as python .npz format files. Maps of stored parameters are automatically generated and saved.

Each multi-mission processing scenario is controlled by a run control configuration file, stored in $RT_HOME/conf/multi_mission_ts_rcfs/<scenario_name>.rcf

The run control file contains the set of single mission scenario names to combine, as well as any threshold parameters used in inter-mission bias determination.

All intermediate data output and log files for the multi-mission processing scenario are stored in the scenario directory:

$RT_HOME/scenario_data/<multi-mission scenario_name>/

2.1.5 SEC Multi- Mission Basin Time Series Processor

The SEC multi-mission basin time series processor combines individual mission SEC basin (IMBIE basin definitions, *Rignot et al, 2016*) time series by performing a cross-calibration step at the basin and sector level.

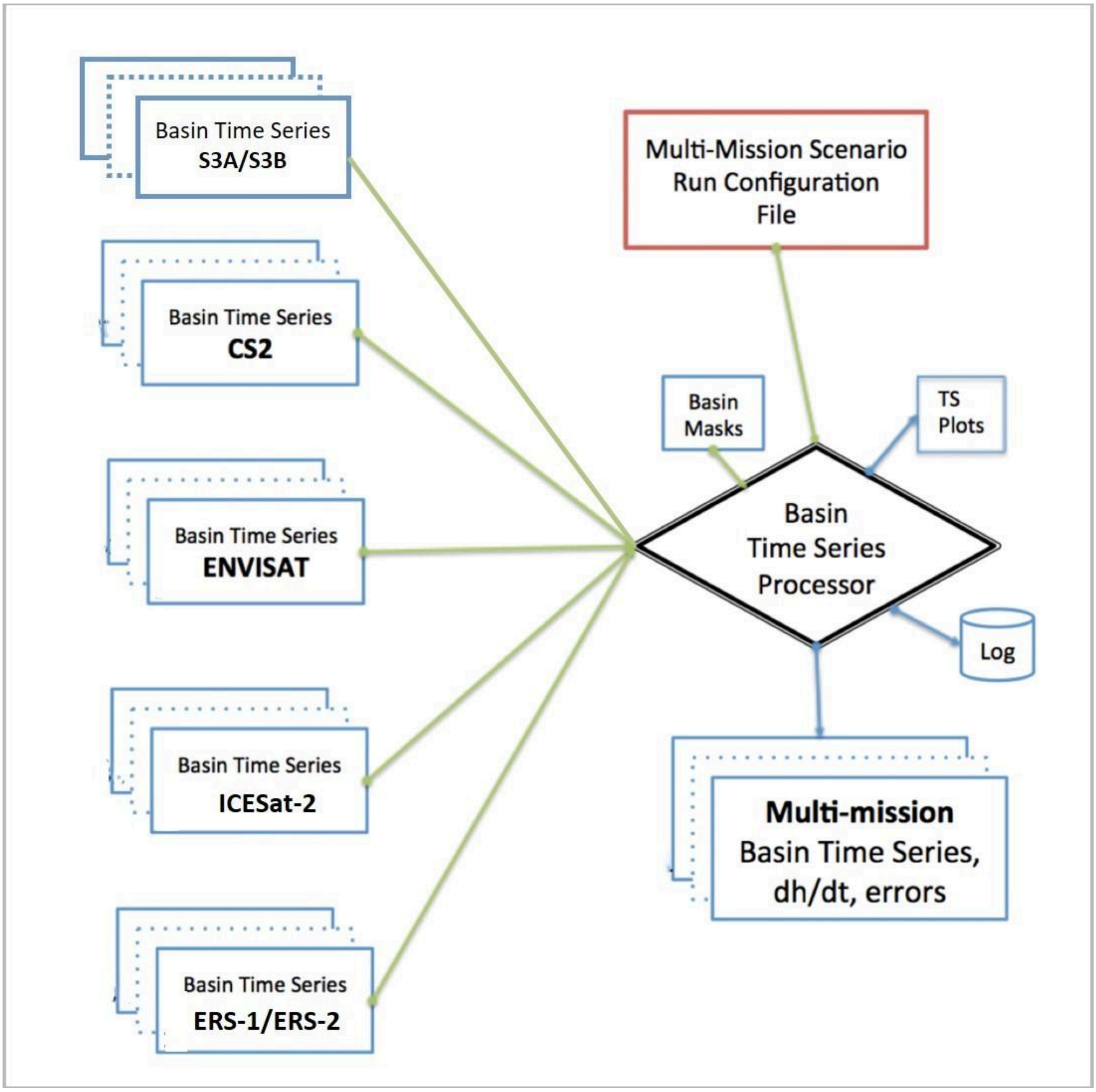

Figure 2.7: Multi-mission Basin Time Series Processor

The basin and sector numbering definition is as follows:

Basins range from A-Ap to Ipp-J (figure 2.8) as per IMBIE - Rignot et al, 2016.

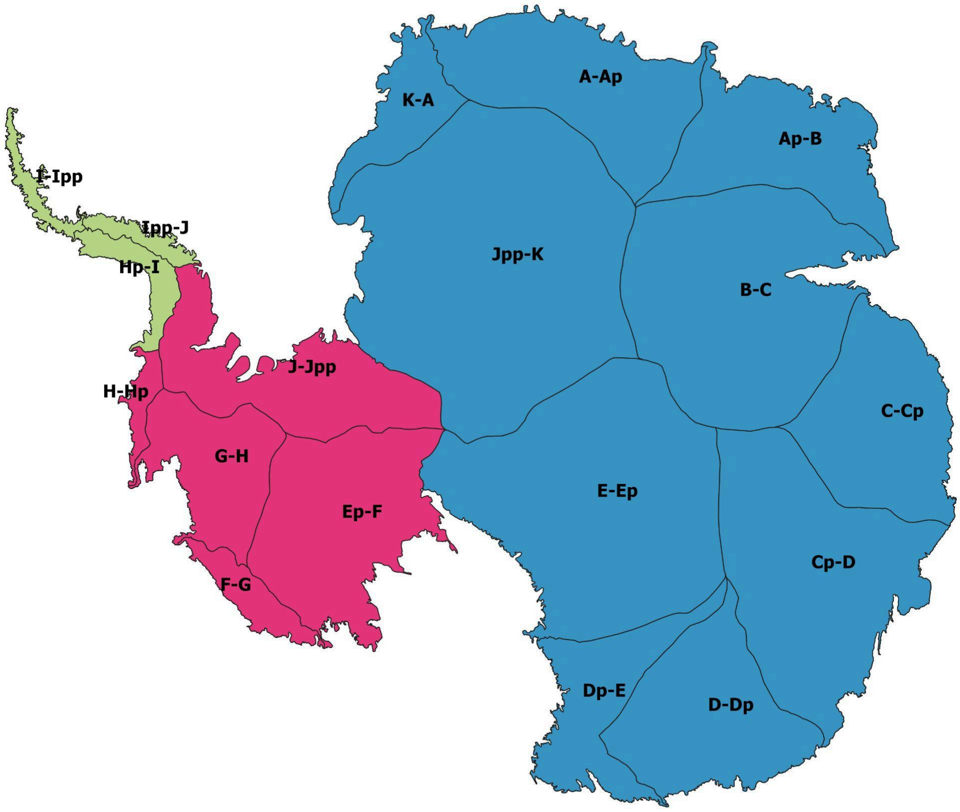

Figure 2.8: Antarctic Drainage Basins

The multi-mission basin time series processor is controlled by a run control configuration file, stored in:

$RT_HOME/conf/multi_mission_ts_rcfs/<scenario_name>.rcf

The run control file contains the set of single mission scenario names to combine, as well as any threshold parameters used in inter-mission bias determination.

Input Files for the processor are taken from the single mission scenario basin time series files stored in:
$RT_HOME/scenario_data/<single-mission scenario_name>/TIMESERIES/basin_z<basin name>.<fill_type=0-3>.sav

Directory	Description
TIMESERIES/	contains all output data files in CSV format
LOGS/	contains all processing log and stats files
CONF/	contains a copy and record of all configuration parameters used in the processing as set in the RCF.
IMAGES/	contains all auto generated plots and parameter maps in jpg format.

All intermediate data output and log files for the multi-mission processing scenario are stored in the scenario directory:

$RT_HOME/scenario_data/<multi-mission scenario_name>/

2.1.6 SEC CCI Product Manager

The Product Manager's function is to process the intermediate data output (in IDL format) from the SEC single mission, multi-mission and time series processors to produce products in the formats and time frames required by the CCI product specification. The product manager also maintains unique product version numbers.

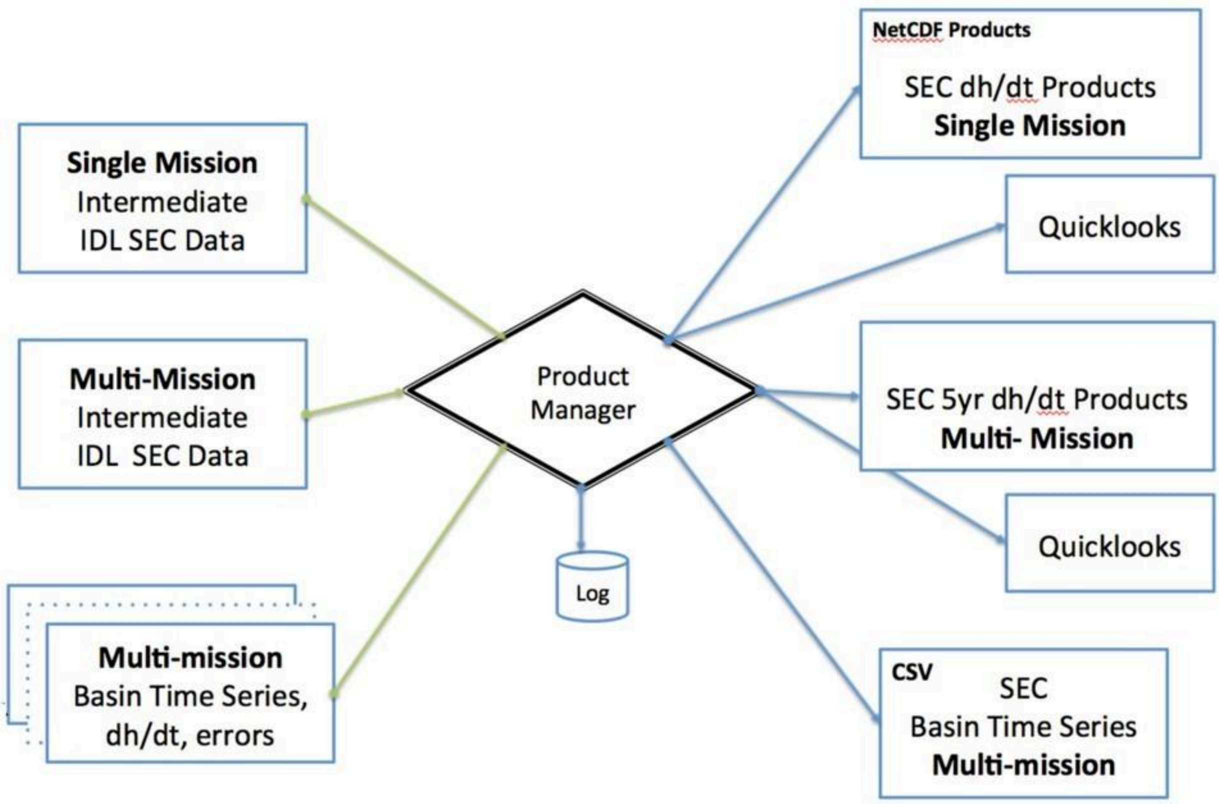

Figure 2.9: SEC CCI Product Manager

2.1.7 SEC Portal Manager

The SE Portal Manager updates the Web Portal data archive. The Web Portal data archive has a secure data area (located outside the website's root directory) which is used for CCI products, and is only accessible by registered users through the portal interface. It also has a public web directory which is used for data, plots and maps available on the portal without registration.

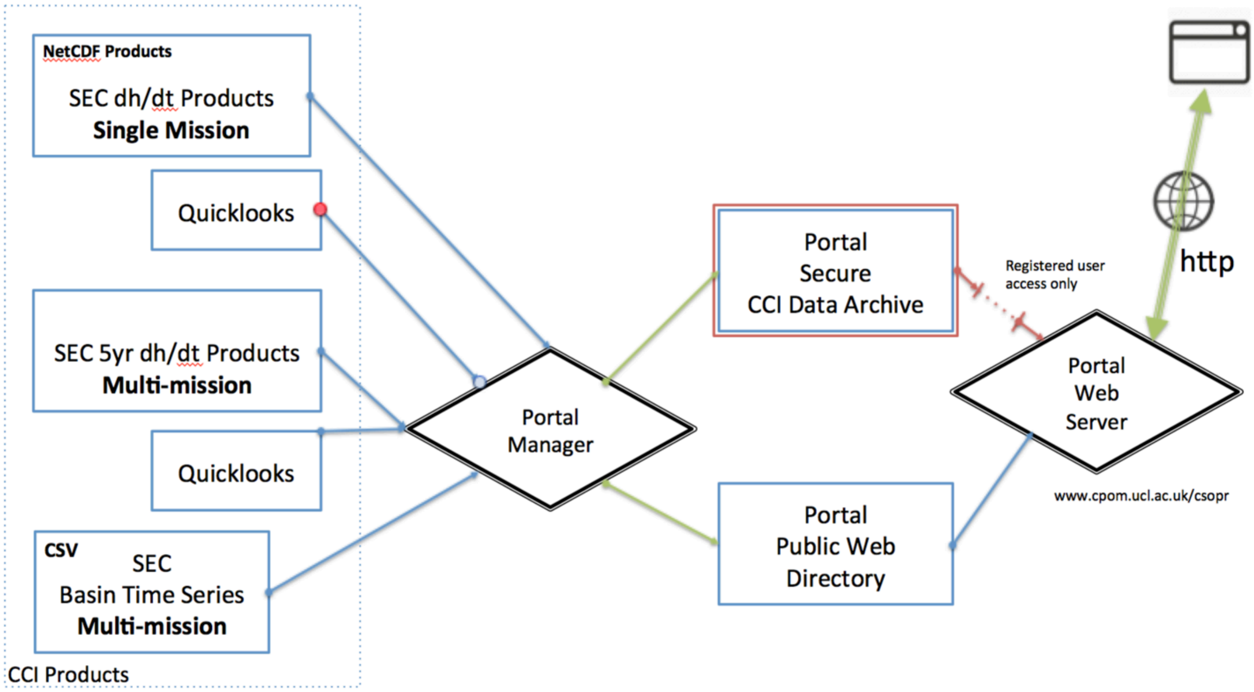

Figure 2.10: SEC Portal Manager

2.2 Operational scenarios

The following configurations and threshold values are used for operational SEC scenarios. All configuration files are stored under configuration control in $RT_HOME/conf

2.2.1 Single Mission Scenarios

Single mission scenario configurations (run control files) are maintained in $RT_HOME/conf/rcfs. These consist of common and per mission thresholds and parameters settings.

2.2.1.1 Common Settings

Geophysical Correction Failure Thresholds:

Warnings are logged if the % availability of geophysical corrections corresponding to radar altimetry measurements over the Antarctic Ice Sheet falls below the following values (per orbit file):

Dry Tropospheric	100 %
Wet Tropospheric	100 %
Ionospheric	100 %
Solid Earth	100 %
Ocean Loading Tide	100 %
Geocentric Polar Tide	100 %

Geophysical Corrections

The following geophysical corrections are applied to correct the L2 elevation data over the ice sheet for radar altimetry:

Geophysical Corrections Applied	Dry Tropospheric, Wet Tropospheric, Ionospheric, Solid Earth, Geocentric Polar Tide, Ocean Loading Tide

Grid Projection

The projection and grid definition used to bin altimetry measurements, calculate plane fit model parameters and SEC values.

Projection	Polar Stereographic (EPSG: 3031)
Latitude with no distortion	71S
Bottom left corner x coordinate of grid in m	-2820e3 m
Bottom left corner y coordinate of grid in m	-2420e3 m
Grid width (in x)	5640e3 m
Grid width (in y)	4840e3 m
Bin Size	5km

Plane Fit Thresholds

Min number of measurements in bin for plane fit	15
n*stdev(modeled heights-heights)	n=2

Basin Masks

Basin Masks Applied	Rignot et al, 2016

Basin Time Series

Basin Time Series Epoch Length	30 days
Epoch Area Interpolation Method	Inverse Distance
Min Percentage Area Filled (after interpolation)	25%
Min Percentage Area Filled (before interpolation)	15%

GIA Correction

GIA Correction	IJ05_R2 model (Ivans & James 2005)

dh/dt Filters

Maximum Slope (from model fit)	5 degrees
Maximum dh/dt	10 m/yr
Maximum r.m.s (m) of residuals	10.0 m
Filter for maximum allowed chisq of dh/dt residuals	120000
Filter for maximum allowed sigma of dh/dt residuals	0.4
Minimum time range (in years) of grid time series	Set for individual missions
Median Filter width for dh/dt plot	3

2.2.1.2 Individual Mission Settings

ERS-1

This section shows the individual settings used for ERS-1.

Ingest Read Checks

Warnings are logged if the number of L2 orbits successfully read in per repeat cycle are less than the following thresholds:

Threshold Number of L2 Orbits per 3-day cycle (Phase A)	35
Threshold Number of L2 Orbits per 3-day cycle (Phase B)	35
Threshold Number of L2 Orbits per 35-day cycle (Phase C)	400
Threshold Number of L2 Orbits per 168-day cycle (Phase EF)	500
Threshold Number of L2 Orbits per 35-day cycle (Phase G)	400

Scenario Settings

Scenario Name	ant_e1_5km
Mission	ERS-1
L2 Data Source	FDR4ALT LI L2
Operational Start Date	4/4/1992
Operational End Date	2/6/1996
Number of Expected L2 Files Read	21158
Tracking Mode	Ice Mode
Surface Type	Continental Ice
Retracker Selected	Ice-1
Filter on Retracking Flag	ICE1_QUAL_FLAG_20HZ
Backscatter correction period	18 months
Backscatter correction start/stop	1992.33 1993.83
Minimum time range (in years) of grid time series	2 years

ERS-2

This section shows the individual settings used for ERS-2.

Ingest Read Checks

Warnings are logged if the number of L2 orbits successfully read in per repeat cycle are less than the following thresholds:

Threshold Number of L2 Orbits per 35-day cycle (Phase A)	400

Scenario Settings

Scenario Name	ant_e2_5km
Mission	ERS-2
L2 Data Source	FDR4ALT LI L2
Operational Start Date	13/5/1995
Operational End Date	4/7/2003
Number of Expected L2 Files Read	43038
Tracking Mode	Ice Mode
Surface Type	Continental Ice
Retracker Selected	Ice-1
Filter on Retracking Flag	ICE1_QUAL_FLAG_20HZ
Backscatter correction period	18 months
Backscatter correction start/stop	1995.5 1997.0
Minimum time range (in years) of grid time series	4 years

ENVISAT

This section shows the individual settings used for ENVISAT.

Ingest Read Checks

Warnings are logged if the number of L2 orbit pass files successfully read in per repeat cycle are less than the following thresholds:

Threshold Number of L2 Pass Files per 35-day cycle (Phase A)	930

Scenario Settings

Scenario Name	ant_env_5km
Mission	ENVISAT
L2 Data Source	FDR4ALT LI L2
Operational Start Date	14/5/2002
Operational End Date (of repeat period)	18/10/2010
Number of Expected L2 Files Read	83513
Tracking Mode	320Mhz
Surface Type	Continental Ice
PTR Correction Anomaly Applied	Y (source ESA/UCL)
Dry Tropospheric Anomaly Correction Applied	Y (source ECMWF/UCL)
Retracker Selected	Ice-1
Filter on Retracking Flag	KU_ICE1_RETRACKER_QUA_FLAG
Filter on Chirp ID error	Y
Backscatter correction period	18 months
Backscatter correction start/stop	2007.9 2009.4
Minimum time range (in years) of grid time series	4 years

CryoSat

This section shows the individual settings used for CryoSat. For CryoSat we use separate scenarios for LRM and SIN mode. The resulting grids are then merged (with SIN data taking precedence in mixed bins) to form a single grid.

Ingest Read Checks

Warnings are logged if the number of L2 orbit pass files successfully read in per sub-cycle are less than the following thresholds:

Threshold Number of L2 Files per 30-day sub-cycle (LRM)	3000
Threshold Number of L2 Files per 30-day sub-cycle (SARin)	1500

Scenario Settings

LRM

Scenario Name	ant_cs2_lrm_5km
Mission	CryoSat
L2 Data Source	CryoTEMPO Baseline C001
Operational Start Date	1/7/2010
Operational End Date	Now-30 days
Tracking Mode	LRM
Apply LRM Time Tag Bias for Baseline-B	Y
Surface Type	grounded ice
Filter on Retracking Flag	No
Filter on MCD Flag	No
Filter on Overall Measurement Quality Flag	No
Backscatter correction period	5years
Backscatter correction start/stop	2010.9 2015.9
Minimum time range (in years) of grid time series	4 years

SARin

Scenario Name	ant_cs2_sin_5km
Mission	CryoSat
L2 Data Source	CryoTEMPO Baseline C001
Operational Start Date	1/7/2010
Operational End Date	Now-90 days
Number of Expected L2 Files Read	362041
Tracking Mode	LRM
Apply LRM Time Tag Bias for Baseline-B	Y
Surface Type	grounded ice
Filter on Retracking Flag	Y
Filter on MCD Flag	Y
Filter on Overall Measurement Quality Flag	Y
Backscatter correction period	3years
Backscatter correction start/stop	2010.9 2015.9
Minimum time range (in years) of grid time series	4 years

Sentinel-3A

This section shows the individual settings used for Sentinel-3A.

Scenario Settings

Scenario Name	ant_s3a_5km
Mission	Sentinel-3A
L2 Data Source	Thematic LI L2 (BC05)
Operational Start Date	1/3/2016
Operational End Date	Now-30 days
Number of Expected L2 Files Read	
Tracking Mode	SAR closed loop
Surface Type	Land & Ice (from parameter in L2)
Filter on Retracking Flag	No
Filter on MCD Flag	No
Filter on Overall Measurement Quality Flag	No
Backscatter correction period	5 years
Backscatter correction start/stop	Start of mission/5 years
Minimum time range (in years) of grid time series	4 years

Sentinel-3B

This section shows the individual settings used for Sentinel-3B.

Scenario Settings

Scenario Name	ant_s3a_5km
Mission	Sentinel-3B
L2 Data Source	Thematic LI L2 (BC05)
Operational Start Date	23/11/2018
Operational End Date	Now-90 days
Number of Expected L2 Files Read	
Tracking Mode	SAR closed loop
Surface Type	Land & Ice (from parameter in L2)
Filter on Retracking Flag	No
Filter on MCD Flag	No
Filter on Overall Measurement Quality Flag	No
Backscatter correction period	5-years
Backscatter correction start/stop	start of mission/5-years
Minimum time range (in years) of grid time series	4-years

ICESat-2

This section shows the individual settings used for ICESat-2.

Scenario Settings

Scenario Name	ant_is2_5km
Mission	ICESat-2
L2 Data Source	ATL-06 version 006
Operational Start Date	14/10/2018
Operational End Date (of repeat period)	Now-180 days
Surface Type	grounded ice
Beams Used	6 (GT1L, GT1R, GT2L, GT2R, GT3L, GT3R)

2.3 Annual DEM

In addition to the fundamental ECV from the satellite altimetry datasets, annual digital elevation models (DEM) will be produced for the full altimetry timeframe. The module to produce annual DEM covering altimetry timeframe is currently under development. This will involve using measurements from all radar and laser altimetry missions and performing spatio-temporal fits to produce the DEM at appropriate spatial resolution.

2.4 Hardware and software platform

The SEC operational ECV production system will run on most Linux servers with adequate memory, disk storage space. The current SEC processing system is operated and tested on a server system running the Linux CentOS 7 operating system.

2.4.1 Hardware

Table 2.5: Processing Hardware at for the SEC processor

Make	**Dell**
Processor	**2x2.3GHz 8-core Xeon E5-2470**
Memory (RAM)	386GB
Local Hard Drive	200TB
Network Attached Storage	164 TB

2.4.2 Operating system

The system currently runs on the Rocky Linux 9.2 operating system.

2.4.3 Tools and libraries

The system requires:

i) Python v3.11+

ii) CPOM Python Package environment

Note that this list does not include tools and libraries required by the web portal. The web portal configuration is not part of the CCI project.

2.4.4 Version Control

The system uses git/GitHub for version control.

2.5 Future concerns and developments

The SEC production system will be developed further during the Antarctic Ice Sheets CCI+ Phase 2 project to include some or all of the following features:

New Altimetry Data Sets and Missions scheduled during 2025:

i) New baselines of CryoTEMPO (Baseline-D, Q2 2025)

ii) New baselines of ICESat-2 (ATL-07), subject to release data and validation

3 Ice Velocity (IV) and Ice Velocity Change

3.1 System Overview

In this section we describe the processing system for deriving Ice Velocity (IV) and Ice Velocity Change (IVC) from repeat pass SAR data. The main input for IVC are the IV maps and the same processing system is shared hence the system for both is described in this chapter. The ENVEO SAR Software Package (ESP) Version 2.1 is primarily used for 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 sensors including Sentinel-1, Radarsat-2, ERS 1/2, ENVISAT, ALOS, TerraSAR-X, and TanDEM-X and is adapted to include newer sensors including SAOCOM and ICEYE. Auxiliary data include a DEM, a tide model, atmospheric pressure data and an ocean/ice/land mask. Figure 3.1 shows the high-level processing line for the IV & IVC production. It includes the following modules:

- IV MODULE: 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. The module applies either offset-tracking or InSAR processing. The InSAR processing line has been expanded in Greenland Ice Sheet CCI and for further details the reader is referred to the SSD for GIS CCI. The output of the IV module are IV maps in map projection as defined by the user.
    - IV TIDAL CORRECTION MODULE: The key novel development for the ice velocity (IV) retrieval algorithm in Antarctic Ice Sheet CCI+ Phase 1 was the implementation of an Ice Velocity Tidal Correction Module (IV-TCM), which is embedded in the IV module. The IV-TCM corrects the ice velocity on ice shelves and floating extensions of outlet glaciers (e.g. ice tongues) for tidally induced vertical motion using an external tide model and atmospheric pressure reanalysis data.
- MERGE MODULE: this module combines the IV products from different tracks and image pairs for a user defined AOI and time period (e.g. monthly, seasonal, annual). The output is a merged regional scale averaged ice velocity map, including a valid pixel count and error map.
- VALIDATION MODULE: 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 and ice velocity products from other sources (e.g. Measures). The output is statistical and graphical (scatterplot, difference map etc.) information on the inter-comparison.
- ICE VELOCITY CHANGE MODULE: In phase 2 of the project the ECV product portfolio is expanded by including Ice Velocity Change (IVC). The processing line is currently in development and built as a separate IVC module which is planned to be embedded in the overall processing line for ice velocity. Demonstration products showing ice velocity change for different regions will be generated. IVC is provided as gridded maps with the same grid size and extent as the IV maps on which they are based.

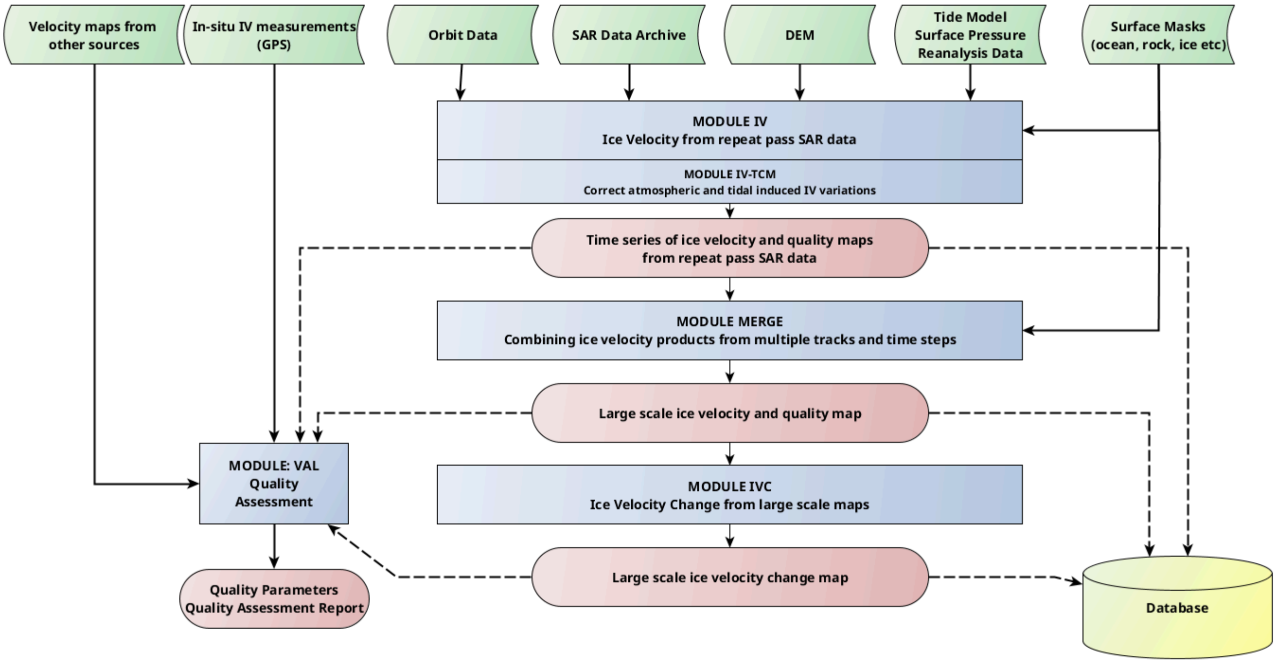

Figure 3.1: High-level flow chart of the ENVEO ESP 2.1 IV processing system. Green: input data, blue: processing modules, red: (intermediate) products, yellow: database.

3.1.1 IV MODULE (Offset-tracking)

Figure 3.2 shows the high-level flow line of the ice velocity generation module. For Sentinel-1 IW SLC data the processing is done on the burst level. In the case of Stripmap mode data (e.g. for SAOCOM) the processing is done on scene/frame level, which is very similar. Here we briefly describe the Sentinel-1 IW SLC burst processing.

The module has access to the SAR data archive and orbit data, as well as a DEM and optionally a surface mask. The processing is done track by track, for each track image bursts are selected according to the time step. For Sentinel-1 processing we select 6 and 12 day repeat pass periods. Using the image geometry and the DEM the local shift between two bursts is calculated which is considered in the displacement calculation using incoherent (or coherent) offset tracking. Besides the displacements in slant range and azimuth, the quality of the matching is also calculated. Debursting of all processed burst pairs forms the displacement map in radar geometry. The debursted displacements maps form the input for the Tidal Correction Module (IV-TCM), which corrects for tide and atmospheric pressure induced ice velocity variations on floating ice (e.g. ice shelves, ice tongues) and which is described in the next section. Finally, after outlier removal, the (tide corrected) velocity of the 3 components is calculated and geocoded using a DEM, with the option to apply a ocean/land mask. The output of the IV module are (tide corrected) velocity maps for all components (E, N, ΔZ) in m/d per track and time step.

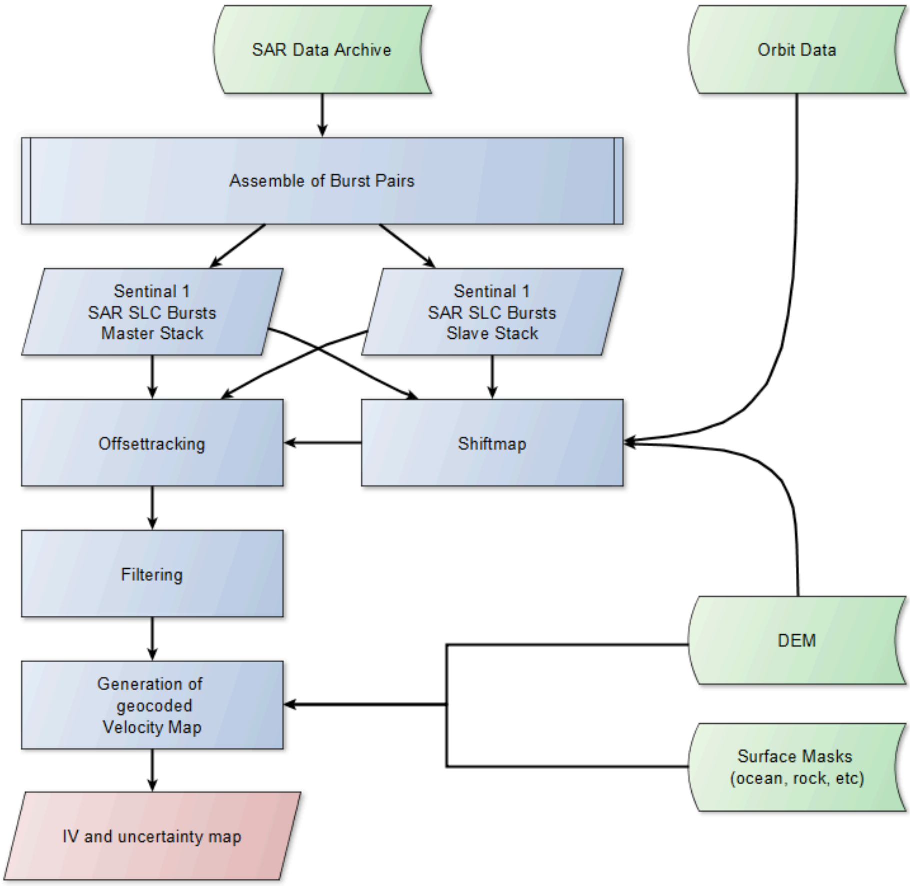

Figure 3.2: Processing steps for ice velocity generation using Sentinel-1 IW TOPS SLC data.

3.1.2 IV TIDAL CORRECTION MODULE (IV-TCM)

The processing chain to correct for tide and atmospheric pressure induced ice velocity variations is illustrated in Figure 3.3. Input to the algorithm are the uncorrected IV maps in SAR geometry on debursted stripe level, a digital elevation model covering the area of interest, a binary mask identifying the grounded ice as well as a tide model and atmospheric reanalysis dataset. First the tidal difference between the acquisition dates of the image pair forming the IV map is modelled, as well as the surface pressure difference. The model outputs are transformed into SAR geometry and then, in a second step, the elastic beam model (Vaughan, 1995) is applied to the binary mask. Finally, the IV-correction is computed using the geometric relations of the acquisition geometry.

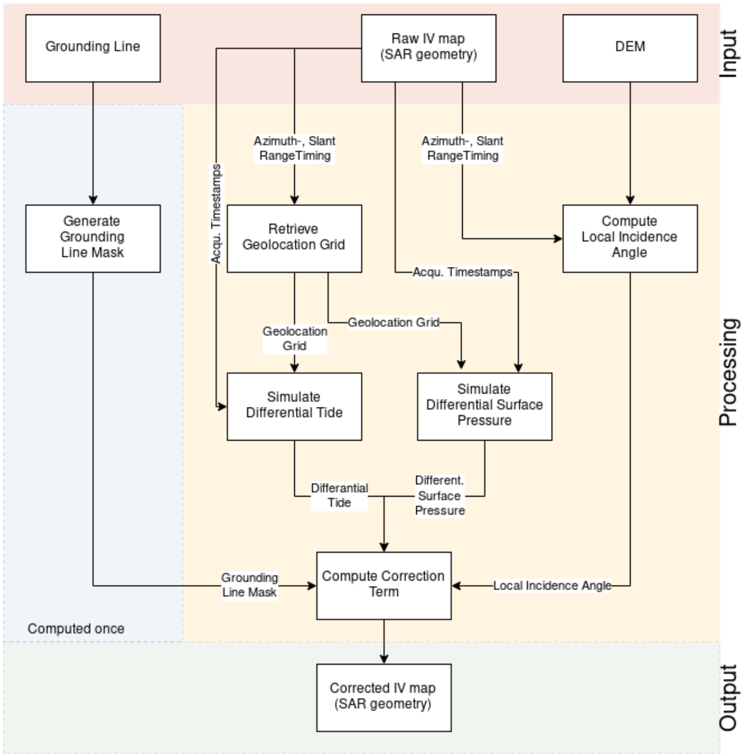

Figure 3.3 High level processing for compensating ice velocity variations induced by tides and inverse barometric effect.

3.1.3 MERGE MODULE

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 maps, 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 map, including a valid pixel count and error map based on the standard deviation.

3.1.4 VALIDATION MODULE

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. The module also allows the intercomparison with 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 difference maps.

3.1.5 ICE VELOCITY CHANGE MODULE

In Phase 2 of the project, the ECV product portfolio will be expanded to include Ice Velocity Change (IVC). Currently under development, the IVC will be built as a separate module integrated into the overall ice velocity processing line. This module aims to produce large/regional scale ice velocity change maps using the output of the MERGE IV as input.

Demonstration products showcasing ice velocity change across various regions will be produced. The IVC will be delivered as gridded maps, matching the grid size and extent of the IV maps it is derived from.

3.1.6 IV-DATABASE

The ice velocity products are linked to the IV database at https://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 visualization and download of data:

- Visualize the full time series of ice velocity profiles along predefined central flow lines of major outlet glaciers
- Visualize the full time series of velocity on fixed points along the flow line

3.2 Operational scenarios

Operational scenarios are mainly planned using Copernicus Sentinel-1 A/B/C satellites. There are currently three processing scenarios applied, the IVC scenario is in development:

- Continuous observations of Antarctic Ice Sheet margins with offset-tracking (6/12-days)
    - Applied for all continuous Sentinel-1 IW acquisitions in Antarctica. This processing scenario enables monitoring of ice velocity variations with short time intervals, e.g. in the case of Sentinel-1 with 6 to 12 days repeat. Continuous monitoring with S1 SAR is ongoing in Antarctica. At first, this was focussed on the Antarctic Peninsula and Amundsen Sea Sector, but since July 2017 this has extended to include nearly the entire ice sheet margin.
- Production of annual ice sheet wide ice velocity maps
- Production of monthly ice sheet wide ice velocity maps
- In development: production of ice sheet wide ice velocity change maps
    - IVC is a prototype product, and will be generated for a few limited areas/periods of interest

3.3 Hardware and software platform

3.3.1 Hardware

The main processing is done on 5 server machines and 22 virtual machines at the IKB cluster, which are connected to a mass storage of about 1200 TB. The system applies OPENMP to support multiple CPUs and Cores.

Table 3.1: Processing Hardware for the ENVEO SAR IV/IVC processor

	Processing	Development, Visualization, Quality Control
Model	GNU/RockyOS 9	GNU/Linux Fedora
Number of machines	5	8
Processor	AMD EPYC 7402 24-Core @ 2.80GHz 48 cores	Intel Core i7-2600 CPU @ 3.40GHz
Memory (RAM)	256 GB	32 GB
Local Hard Drive	300 GB	1 TB
Network	Ethernet 10GBASE	Ethernet 1000Base-T
Network Attached Storage	about 1200 TB network storage	about 1200 TB network storage

	Processing	
Model	GNU/RockyOS 9	
Number of nodes	22	
Processor	Intel Xeon CPU E5-2620 @ 2.00GHz 2 cores	
Memory (RAM)	10 GB	
Local Hard Drive	-	
Network	Ethernet 10GBASE	
Network Attached Storage	about 1200 TB network storage	

3.3.2 Operating system

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

3.3.3 Tools and 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

3.4 Future concerns and developments

Further improvements of the software are planned. The ESP software has been connected and tested with Cluster systems utilizing several hundreds of Cores. This is especially of interest for campaign processing of big data sets as it occurs for Antarctica.

3.5 InSAR uplift from InSAR 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.

3.5.1 System Overview

3.5.1.1 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 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.

3.5.1.2 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.

3.5.1.3 Interferogram generation and geocoding

The processing flow for a single pair is illustrated in Figure 3.4. First, the two SLCs are coregistered to the reference geometry using SLC timing, precise state vectors, the REMA digital elevation model (DEM) at a spacing of 32 m, and the AIS-CCI multiyear velocity mosaic generated by ENVEO. 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 3031 projection (Polar stereographic, with a reference longitude of 0 and a latitude of true scale of -71), 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.

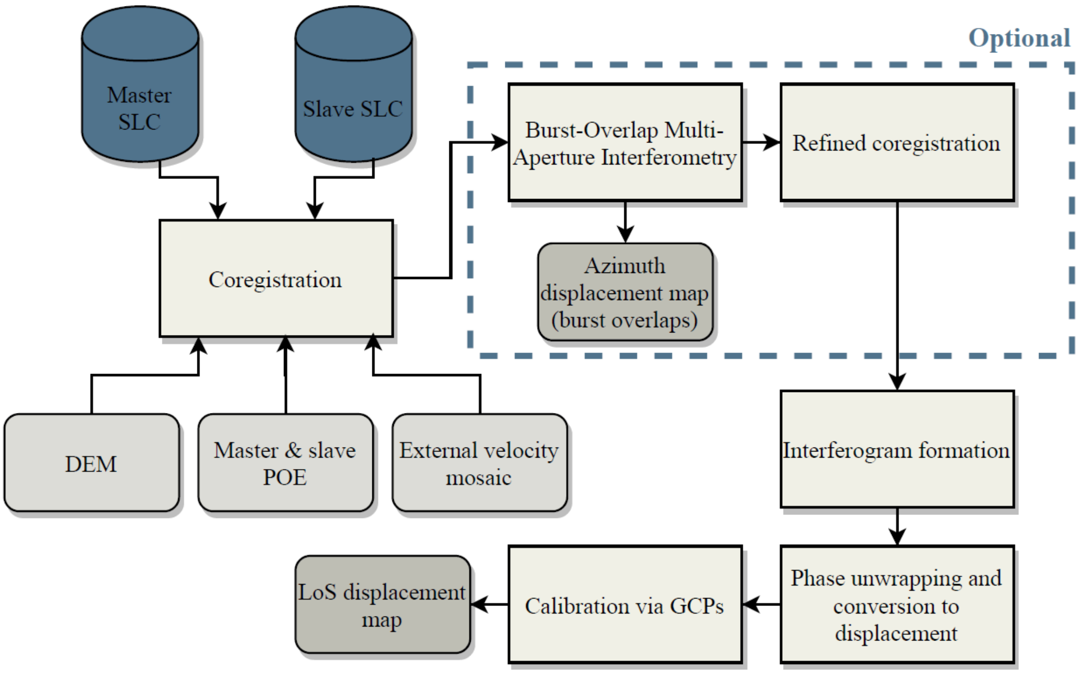

Figure 3.4: Processing flow to generate LoS-velocity for a single SLC pair.

3.5.1.4 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.

3.5.1.5 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.

3.5.2 Operational Scenario

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

3.5.3 Hardware and software platform

3.5.3.1 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).

3.5.3.2 Operating System

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

3.5.3.3 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 Grounding Line Location (GLL) and Grounding Line Migration (GLM)

This section describes the design of the GLL ECV production system and its intended use.

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, if possible, double difference interferograms from ERS-1/2, TerraSAR-X or Sentinel-1 data. The second step is the mapping of the upper limit of flexure. Since the IWAP is a separated and complex system on its own which has been documented before, it cannot be described in detail here but the respective references will be provided.

The original idea of the GLL production system was based on a manual delineation of the upper fringe belt which is usually clearly recognizable in the generated double differences interferograms. An algorithm for an automatic derivation of the GLL has recently been tested and seems promising but is not yet in an operational state. The system described in this document therefore contains elements which are not yet fully automatic or functional but in development. If changes occur during the development, this document will also be updated.

Due to the fact that in the current state manual interaction is required, it is difficult to provide a precise estimate of the timeliness. In case the system is running fully automatically, new products could be released one or two days after they appear on ESA's sentinel science hub.

The end user should download products through the ENVEO cryoportal (cryoportal.enveo.at/) or ESA cci data portal. There are different file formats (.shp, .geojson, .gpkg, .kmz) available which are described in detail in the Product User Guide (PUG). Since the GLL data portal is integrated in the ice velocity portal which allows determining velocity profiles across the grounding line, new GLL products need to be pushed to ENVEO. Since the GLL information is internally stored in a PostGIS database, a full database dump will automatically provide all information to the portal. Updated .shp, .geojson, .gpkg and .kmzproducts are equally copied.

4.1 System overview

The general design of the GLL production system is depicted in Figure 4.1. Each segment of these figures will be described in the order of the processing sequence to explain the data flow and management. At the current stage the system for automatic detection of the grounding zone (GZ) is in development but the manual tracing of upper flexure limit of GZ is possible.

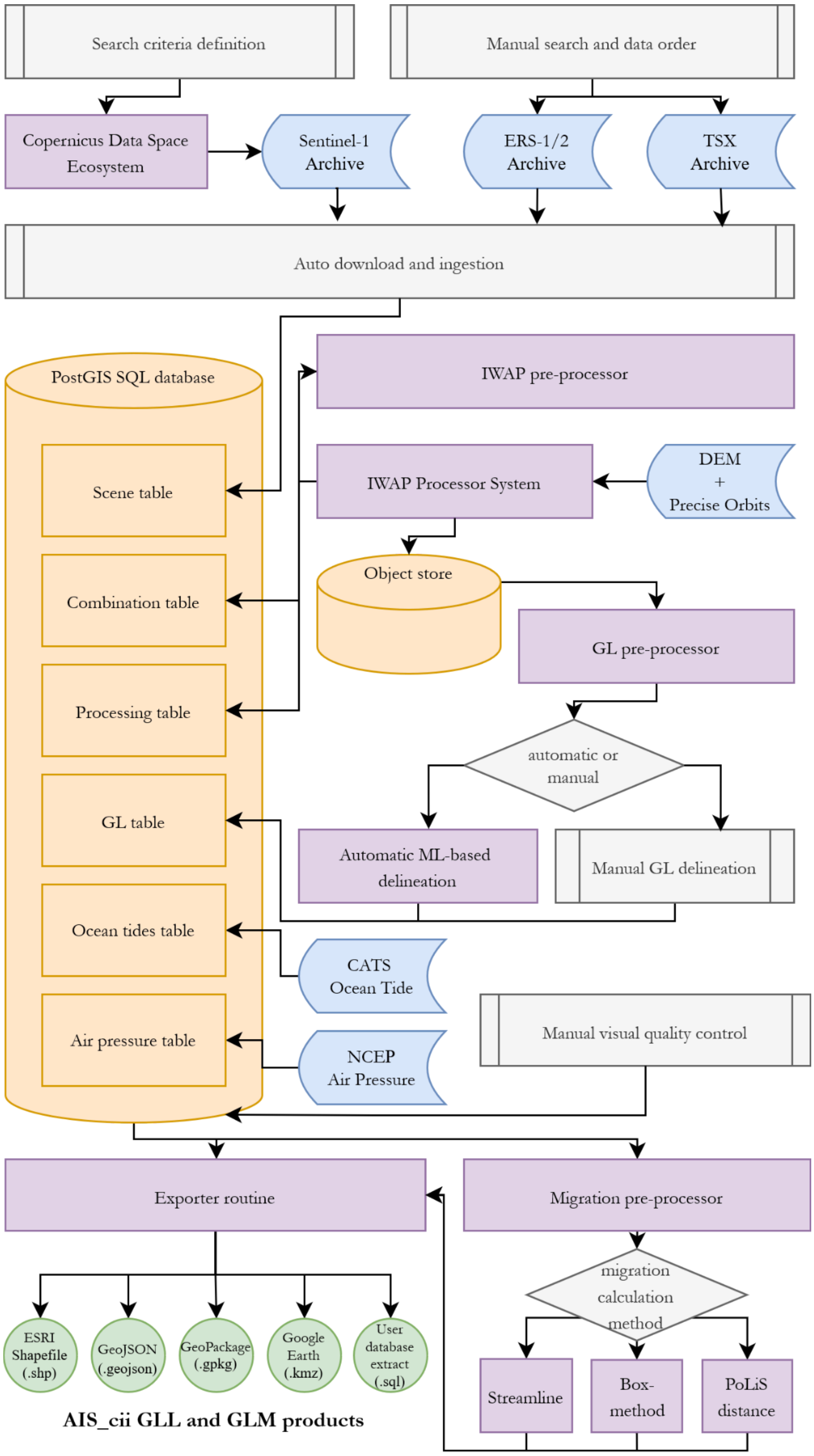

Figure 4.1: System overview flowchart. Input data in light blue, processes in violet, database systems in orange, manual processes in grey, products in green.

Manual search and data order: The system contains manual operations if ERS-1/2 and TerraSAR-X data shall be processed since searching and ordering L1b products over certain glaciers or for specific periods of time requires manual interaction with the data archives ESA Dissemination Service (https://esar-ds.eo.esa.int/oads/access/collection/SAR_IMS_1P) or EOWEB® GeoPortal (eoweb.dlr.de/egp/). These working steps are summarized with the box 'manual search and data order'.

Search criteria definition: In view of a fully automatic processing approach satellite data archives need to be monitored for newly available products. The EOWEB® GeoPortal does not support such script-based requests since there are always orders involved. But the Copernicus Data Space Ecosystem provides such functionality for Sentinel-1. Since not all newly available products may be of interest, temporal and spatial criteria need to be defined. This process only needs to be done once but could be updated occasionally.

Auto download and ingestion: When the requested data is processed at ESA or DLR, the data will be downloaded automatically and unpacked. The resulting information is saved to the PostGIS Database scene table. In this step all SLC metadata for a specified sensor (TerraSAR-X, ERS-1/2, Sentinel 1A/B/C) such as acquisition time, acquisition mode, look direction, pass direction, relative orbit number, if applicable frame and beam, spatial coverage and the path of its location for each SLC product are saved. This metadata can be read in subsequent steps.

PostGIS SQL database: Is a PostGIS database which contains the above mentioned information and therewith keeps and updates a unique record of all available SLC products and processing parameters. It also contains the derived grounding line geometries and their ocean tide and air pressure annotations. The final GLL products can be exported directly from this database.

IWAP pre-processor: The IWAP pre-processor analyzes the available scenes in the database. It will then sort all acquisitions which belong to the same relative orbit, look direction and beam and determines which interferogram pairs or triplets can be generated within the user specified temporal duration. A temporal limit can be specified e.g. maximum allowed time between passes is smaller or equal 1 day or 3 days, 11 days and 6 days or 12 days for ERS-1/2, TerraSAR-X and Sentinel 1A/B/C. If triplets are detected, they will be treated as such in order to determine the double differences directly in the satellite image system (SAR coordinates). The original SLC files are linked into a temporary processing structure which is required for the IWAP. All datasets ready for interferometric processing will be saved in a start script which is called at the end of the execution of the IWAP pre-processor in order to trigger the actual IWAP processing.

IWAP Processor System: Due to its complexity the IWAP Processor System is not covered here. The system is documented in several papers and technical notes which also cover specific topics such as TOPS interferometry required for Sentinel-1's interferometric wide swath processing. For more details please refer to [1]-[7]. After the IWAP system runs successfully, geocoded images and preview images of the interferogram, the amplitude and the coherence are copied into a S3 Object Storage.

Object Store: The object store consists of buckets which accommodate the above mentioned processing results of the IWAP. Each processing is identified by a unique id (uuid) also saved in the database.

GL pre-processor: Analog to the IWAP pre-processor, the GL pre-processor analyzes the database and object store and determines which double difference interferograms can be generated and compares this list to the already existing ones. All possible but non-existing double differences will be calculated and saved in the Object store. All datasets provide a unique double difference combination and therewith a part of the final grounding line dataset.

After running this module two options are available for mapping the location of the upper limit of the GZ.

ML based GL detector ***(working and development in progress):***

The proposed approach utilizes a pre-trained HED [8] neural network to automatically delineate GLs. By processing the wrapped interferometric phase, and additional data the model identifies the geometry of the grounding line. Moreover, the model's output is post-processed to adapt the model output to single shapefiles removing branches and spurious detections away from the established grounding zone.

Manual GL delineation: In this decision double difference maps are loaded into QGIS and the upper limit of flexure is manually digitized and saved as shapefile. The final results are stored and managed in the PostGIS database. The intermediate layer is required since the shapefiles cannot be directly entered into the database which is the task of the controller.

GL DATA controller: It updates the PostGIS database if new entries are available in the The *'GL DATA controller'* additionally contains a class which provides a wrapper to the driver functions of the CATS ocean tide model and the NCEP air pressure reanalysis datasets. The respective values will be extracted, air pressure corrections and height differences are determined and the GLL information is annotated with this information.

Exporter routine:

We have divided Antarctica into 11 different regions which include the key glaciers. The GLL products of each region (or key glacier) are updated and uploaded on the ENVEO cryoportal. Each release of GLL is named after the creation date and time and region name e.g. "AIS_CCI_GLL_20160501_162541_Fleming_Larsen" with the respective extension of the format (.shp, .geojson, .gpkg, .kmz). All the GLL products can be delivered as a portable database dump (.sql) if it is required to ENVEO.

For the Grounding Line Migration (GLM) product generation the workflow is built on the internal data representation of single grounding lines in the SQL database.

4.2 Database structure

All metadata for the grounding line products, the tide and air pressure annotation as well as the scene information are kept in a common PostGIS database. Mentioned in Section 4.1, the INPUT DATA database, the IFG DATA database and the GL DATA database are implemented in the following database schema in Figure 4.2.

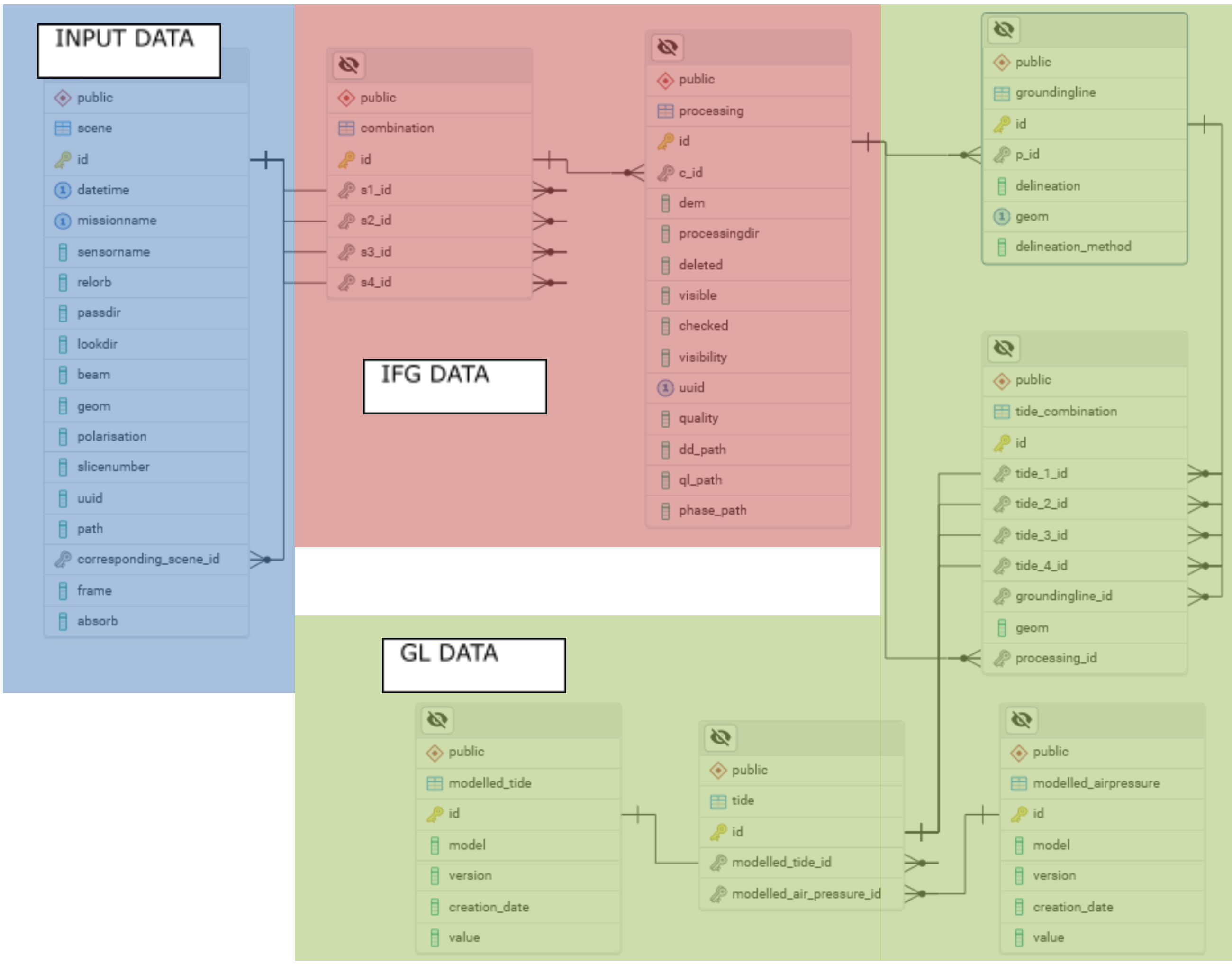

Figure 4.2: The PostGIS database structure containing information of the INPUT DATA, the IFG DATA and the GL DATA modules shown in Figure 4.1.

4.3 Operational scenarios

The GLL system is designed to derive GLL on key glaciers from ERS-1/2 single interferogram and Sentinel-1 A/B double difference interferogram. Along the pole hole TerraSAR-X is used for the GLL generation. Usually the GLL is derived on each glacier yearly. But if the GLL is not continuous we try to fill the gaps with another triplet within this year. This procedure is repeated until fill the gaps of GLL.

Since the GLL system is not fully automated and ERS and TerraSAR-X SLCs are not possible to upload automatically, it is difficult to estimate the runtime. But for the GLL derivation from Sentinel-1 A/B (which is the main task in AIS cci+), it takes almost 4 hours to perform downloading Sentinel-1 A/B triplets, generating the double difference interferogram and extracting the GZ from the gradient deformation map. In the case of manual delineation an operator is required to upload the double difference interferograms into QGIS and trace a line as GLL on the upper flexure limit of GZ. Once the line was drawn and saved the GLL as a shapefile, another 3-5 minutes are needed to annotate all the attributes including CATS ocean tide model and NCEP air pressure with GLL products of different file formats.

4.4 Hardware and software platform

The main processing load will be performed on the below mentioned Sun Fire X4800 M2 (psipn3) system. Development, visualization and quality control is done on a less powerful machine with quicker graphics where tools like QGIS can be run.

4.4.1 Hardware

Table 4.1: Processing Hardware at for the GLL processor

	Processing
Model	Sun Fire X4800 M2
Processor	Intel® XEON®, CPU E7-8870 @ 2.4 GHz 8x10 = 80 Cores
Memory (RAM)	256 GB
Local Hard Drive	300 GB
Network Attached Storage	150 TB – Fibre Channel + normal NFS mounts

4.4.2 Operating system

Sun Fire X4800 M2: Rocky Linux 9.5

4.4.3 Tools and libraries

The following tools and libraries are utilized during the mentioned activities:

Development and processing:

- Git 2.17.1
- Python 2.7 and Python 3.6 with a variety of libraries such as shapely, fiona, pyproj, pygdal, sqlalchemy
- GCC 4.9.0
- DL/GDL

Analysis and visualization:

- QGIS 2.14 with GRASS GIS 7.0 plugins and others
- GMT 4.5.0
- Netcdf 4.7
- Python 2.7 and Python 3.6 and a variety of libraries such as numpy, matplotlib, pil, skimage, scipy
- GDAL 2.2.3
- Google Earth 7.1.4

Data extraction and handling tools:

- CATS2008 TMD (tide model driver) via pyTMD [9]
- PostgreSQL, PostGIS, pgAdmin

4.5 Future concerns and developments

Due to the large number of Sentinel-1 data still only a fraction of possible GLs have been delineated. In the future we will try to establish processing on the terabyte high-performance computing cluster [10] fully automatically. This would allow processing large datasets from Sentinel-1's interferometric missions to produce time-series of grounding line products.

Still, challenges persist in maintaining coherence for some of the fastest glaciers in Antarctica, which compromises the accuracy of these GL measurements or prevents us from detecting the GL completely. To address this issue, a planned revisit during the commissioning phase of Sentinel-1C could potentially restore lost coherence, similar to the 1 and 3 day repeat cycles that proved effective during the ERS mission.

4.6 References

[1] Adam, N. A., Kampes, B., & Eineder, M. (2004). Development of a Scientific Permanent Scatterer System: Modifications for Mixed ERS/ENVISAT Time Series. In ESA (Ed.), *Proceedings*. https://elib.dlr.de/8299/

[2] Adam, N., Liebhart, W., Parizzi, A., Rodriguez-Gonzalez, F., & Brcic, R. (2012). Persistent Scatter Interferometry Wide Area Product Methodology and Final Characteristics. *Terrafirma Stage*, *3*.

[3] Adam, N., Rodriguez Gonzalez, F., Parizzi, A., & Liebhart, W. (2011). Wide area persistent scatterer interferometry. *2011 IEEE International Geoscience and Remote Sensing Symposium*, 1481–1484. https://doi.org/10.1109/IGARSS.2011.6049347

[4] Gonzalez, F. R., Adam, N., Parizzi, A., & Brcic, R. (2013). *The Integrated Wide Area Processor (IWAP): A Processor For Wide Area Persistent Scatterer Interferometry*. *722*, 353. ESA Living Planet Symposium.

[5] Yagüe-Martínez, N., Balss, U., Breit, H., Rodríguez González, F., Fritz, T., Lachaise, M., & Adam, N. (2013). Operational stacking of TerraSAR-X ScanSAR and tops data. *2013 IEEE International Geoscience and Remote Sensing Symposium - IGARSS*, 888–890. https://doi.org/10.1109/IGARSS.2013.6721302

[6] Brcic, R., Adam, N. (2012). TOPS Interferometry Technical Note", DLR Remote Sensing Technology Institute.

[7] Yagüe-Martínez, N., Prats-Iraola, P., Rodríguez González, F., Brcic, R., Shau, R., Geudtner, D., Eineder, M., & Bamler, R. (2016). Interferometric Processing of Sentinel-1 TOPS Data. *IEEE Transactions on Geoscience and Remote Sensing*, *54*(4), 2220–2234. IEEE Transactions on Geoscience and Remote Sensing. https://doi.org/10.1109/TGRS.2015.2497902

[8] Xie, S., & Tu, Z. (2015). *Holistically-Nested Edge Detection*. 1395–1403. https://openaccess.thecvf.com/content_iccv_2015/html/Xie_Holistically-Nested_Edge_Detection_ICCV_2015_paper.html

[9] Sutterley, T. C., Alley, K., Brunt, K., Howard, S., Padman, L., & Siegfried, M. (2017). *PyTMD: Python-based tidal prediction software*.

[10] Eberle, J., Zeidler, J., Schwinger, M., & Zwenzner, H. (2024, April 23). *Earth Observation Exploitation Platforms to support the creation of FAIR-compliant geospatial data*. International Conference on Geoinformation, Data, Processing, and Applications, Oldenburg, Deutschland. https://elib.dlr.de/209569/

5 Gravimetric Mass Balance (GMB)

The GMB production system generates both time series of mass change grids given on a 50km x 50km grid in a polar-stereographic projection (GMB gridded product) and time series of basin-averaged mass changes for different drainage basins and aggregations (GMB basin product). Global monthly gravity field solutions derived from GRACE and GRACE-FO (hereinafter referred to as GRACE(FO)), given in the spherical harmonic domain, provided by different processing centres (e.g. ITSG, CSR, GFZ, JPL) serve as main input.

Additional datasets of low-degree spherical harmonics are required to add information not included in the GRACE(FO) monthly solutions (coefficients of degree one) or to replace inaccurate components of the GRACE(FO) dataset (C_{20} and C_{30} coefficients). GIA models are crucial for the reduction of super-imposed solid Earth mass changes. Models of surface mass balance (SMB) are needed for the GRACE/GRACE-FO gap filling procedure. Predictions from geophysical models for atmosphere, ocean, continental hydrology, and ice sheet SMB are utilized to assess leakage errors. Moreover, mass change estimates from alternative datasets, such as SEC, serve as input for the product validation.

New GRACE-FO solutions are provided on monthly intervals with a delay of four to six weeks. Being part of the GRACE(FO) de-aliasing product, model outputs for atmospheric and oceanographic mass variations are delivered together with the GRACE(FO) solutions. SLR-based monthly time series for C_{20} and C_{30} are independently generated and are regularly provided with a delay of about four weeks. In contrast, time series for degree one coefficients rely on the GRACE(FO) monthly solutions and are generated within this project shortly after their release. Additional model outputs used in the error assessment are not necessarily required to be up-to-date. The effect of GIA can be assumed constantly linear over the observational period. Hence, no regular updates of the model, specifying the linear GIA-induced mass change, are needed.

The GMB processing can be completed within a few working days, once the adaptation of the method is completed. Both the GMB basin product (ASCII format) and the GMB gridded product (ASCII, NetCDF, Geotiff format) are generated using the most recent GRACE(FO) monthly solutions available at this time. Products are available to the users via the GMB data portal hosted by TU Dresden. The data portal is accessible via https://data1.geo.tu-dresden.de/ais_gmb.

5.1 System overview

The GMB processor is a semi-automatic processing system implemented in Matlab. Figure 5.1 gives a schematic overview of the GMB processing line. It consists of four main modules, the Methods Module, the Pre-processor, the Estimation Module and the Validation Module. The control flow between the modules and between different processing routines within each model is handled by an operator. Input data procurement is done automatically. In the following, the different modules of the GMB processor are briefly described.

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(FO) 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.

All selections are based on the statistics of intermediate results as well as on a visual inspection using the built-in Matlab plotting capabilities. Intermediate results, like the empirically inferred error variance-covariance matrix used to derive the sensitivity kernels or the sensitivity kernels themselves, are stored in Matlab's binary format (mat-files) using a specific variable name. Other routines, within the same or from another module, can identify and load the variables via their unique name.

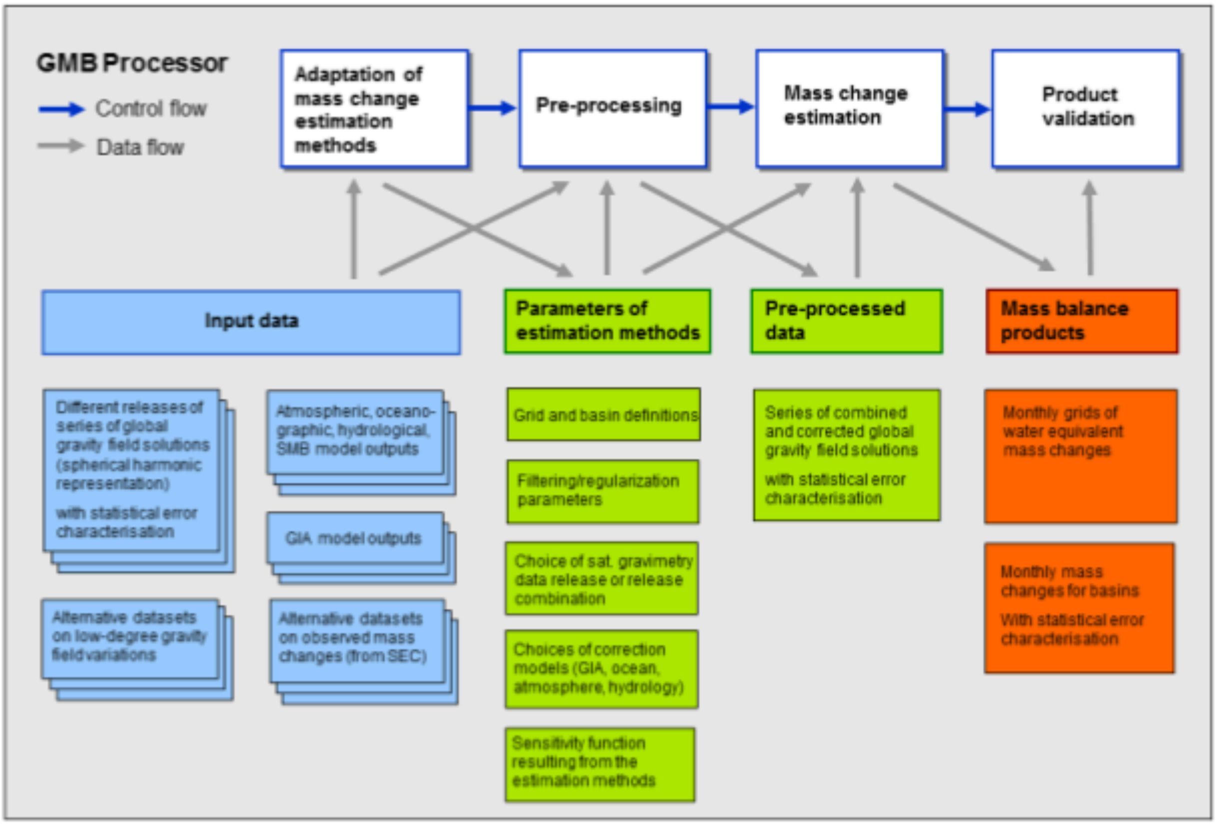

Figure 5.1.: Main modules of the GMB processor

The Methods Module comprises the most labor-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. Hence, parameter selections from the Methods Module are only altered for a new product release.

Pre-processing: Based on the selections in the Methods Module, GRACE(FO) 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), addition of degree-one coefficients, replacement of coefficients C_{20} and C_{30}, and the reduction of GIA. All monthly solutions are reduced to a specified reference value.

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 of the GMB gridded product and every basin of the GMB basin product are 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. Basin averaged time series are used to calculate a mass balance estimate for each basin. To infer an overall accuracy measure, GRACE(FO) 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. This includes the inter-comparison between basin-averaged mass change time series from the GMB product and time series based on SEC. Moreover, all GMB products inferred from the favored GRACE release are compared with those from alternative GRACE releases. The degree of agreement between the final GMB products and the different validation datasets is evaluated visually and by means of appropriate statistics (e.g. correlation coefficients, admittance factors).

In the case of a successful validation, the GMB products are written in the final output formats. While ASCII and NetCDF output files are written using Matlab, GeoTIFF files are generated and checked by means of additional tools. After passing a final check, the files are manually uploaded to the webserver hosting the data portal.

5.2 Operational scenarios

Parameters to be set for the GMB product generation, e.g. file naming conventions and outputs are described in the following.

All routines used in the Pre-processor, the Estimation Module and the Validation Module are named following the same convention: {task}_{project}_{version}. For example, the Pre-processor routine utilized for the production of the first product release is called: prepro_aisgmb_v1.0.m. The operator needs to ensure that all scripts make use of the correct parameter selections resulting from the Methods Module. Input datasets exist in various ASCII formats. Reading routines are available for each of the formats, which include a check on the completeness of the datasets. Runtime is not a critical issue for any of the routines. None of them needs more than one hour for completion.

Data procurement: All regularly updated input datasets, i.e. GRACE-FO monthly solutions and time series for C_{20} and C_{30} are automatically downloaded by means of a python scripts executed by a weekly cron job.

GRACE(FO) solutions provided by the processing centres within the GRACE SDS (CSR, JPL, GFZ) are hosted at GFZ's ISDC archive (ftp://isdcftp.gfz-potsdam.de/grace-fo). These data are given in the same ASCII format (gzip-compressed), referred to as GRCOF2-format. Background models for atmosphere and ocean are distributed in the same format. Time series for C_{20} and C_{30} can also be procured from the ISDC archive and are given in a self-descriptive ASCII format.

Solutions generated by ITSG are provided via ftp.tugraz.at/outgoing/ITSG/GRACE. The utilized ASCII format is called gfc-format. It has been established by the International Center for Global Earth Models (ICGEM) at GFZ Potsdam and is widely used in gravity field modelling.

The data volume depends on the maximum spherical harmonic degree l_{max} (e.g. ITSG: l_{max}=60, 96, 120; CSR: l_{max}=60, 96; GFZ: l_{max}= 60, 96). Even for the release with the highest spatial resolution (i.e. ITSG l_{max}=120), the size of a single monthly solution is about 0.7MB, only. The resulting volume of all GRACE(FO) data, comprising GRACE(FO) solutions from different processing centres for the period 2002 until present and the associated background models, is clearly below 2GB.

Pre-processor: Data pre-processing is accomplished by a single routine (prepro_aisgmb_v1.0.m). This routine requires the specification of the GRACE(FO) release to be utilized, location of the input data (GRACE(FO) data and auxiliary data: degree one, C_{20}), l_{max} (l_{max}=90), the period to be considered (2002-04 until present), the GIA model to be applied (IJ05_R2) and the definition of the reference value used for the reduction of each monthly solution. Moreover, a set of degree-dependent Load-Love-Numbers is needed for the conversion of the Stokes-coefficients. GIA model outputs are given in a simple ASCII format. The pre-processed monthly solutions are arranged in a triangular scheme, widely used for spherical harmonic datasets, which is stored in a three-dimensional matrix, with the time being the third dimension. Complemented by auxiliary information, this matrix is stored in binary format (prepro_aisgmb_v1.0.mat).

Mass change estimation: The routine mass_est_aisgmb_v1.0.m loads the sensitivity kernels and the pre-processed time series from the output files generated by the Methods Module (gen_sens_eta_aisgmb_v1.0.mat) and the Pre-processor (prepro_aisgmb_v1.0.mat), respectively. Discrepancies between l_{max} specified in this module and the one used to generate the input would lead to an unexpected abortion of the routine. In case of success, quick-looks of the GMB products are immediately generated using the plotting tools provided by Matlab.

This module also requires defining the functional model applied for the error determination of the basin-averaged time series as well as for the mass balance estimation. In both cases a nine-parameter model is used. Model outputs needed for the error assessment of the mass balance estimates are loaded in terms of mass equivalent spherical harmonic coefficients. Stored in the already mentioned triangular scheme, the mass estimation approach can be applied in the same way as to the GRACE(FO) solutions.

GMB products generate at this stage as well as intermediate results, like quick-look plots, are stored in the file mass_est_aisgmb_v1.0.mat.

Product validation: The only parameters to be set in the validation routine prod_val_aisgmb_v1.0.m are the sources of validation datasets, while the GMB products are directly loaded from the estimation output available in mass_est_aisgmb_v1.0.mat. In order to compare the final GMB products with those products based on different GRACE releases, the routines prepro_aisgmb_v1.0.m and mass_est_aisgmb_v1.0.m are re-run for the releases in question. For the sake of documentation and reproduction, generated plots and statistics are stored in prod_val_aisgmb_v1.0.mat.

Finally, the routine write_prod_aisgmb_v1.0.m produces the ASCII and NetCDF outputs. No additional parameters, except of the correct input filename (mass_est_aisgmb_v1.0.mat), need to be specified. The filenames of all products to be published on the data portal are not altered between different product versions (AIS_GMB_basin.dat, AIS_GMB_grid.dat, AIS_GMB_grid.nc, AIS_GMB_trend.dat). Nevertheless, the product version is provided as part of the metadata. The same applies to the gridded product in GeoTIFF format (AIS_GMB_grid.tif), generated by the shell script netcdf2geotiff.sh.

5.3 Hardware and software platform

In the following, details on the hardware and software used to run the GMB productions system are given.

5.3.1 Hardware

Because of the moderate computational requirements of the GMB processor, high performance computing systems are not required to effectively generate GMB products. The used hardware listed in Table 5.1 is capable to host the GMB processor and to generate the products.

Table 5.1: Processing Hardware at TU Dresden for the GMB processor

Model	VMware Virtual Platform
Processor	AMD EPYC™ 7513 CPU @ 3.65GHz (16 Cores)
Memory (RAM)	64 GB
Local Hard Drive	200 GB
Network Attached Storage	12 TB

5.3.2 Operating system

The operating system in use is the Linux system Ubuntu 24.04 LTS (long-term support).

5.3.3 Tools and libraries

The core GMB production system is implemented using the commercial numerical computing environment MATLAB version R2024a (24.1.0). 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.

For inspection of the NetCDF files the ncdump tool provided by Unidata (www.unidata.ucar.edu/software/netcdf) is used. The tool gdal_translate from the Geophysical Data Abstraction Library (www.gdal.org) is utilized to convert the NetCDF file into a georeferenced TIFF file (GeoTiff). The open source Geographic Information System QGIS (www.qgis.org) is used to browse and check the GeoTIFF files. Final plots to be included in publications, presentations and the data portal are prepared by means of the Generic Mapping Tools (GMT) package (gmt.soest.hawaii.edu). All these tools are freely available.

5.4 Future concerns and developments

The GMB processor is not fully automated and needs to be operated manually. Compared to other ECV parameters (e.g. IV), the input data volume and the processor runtime are moderate. Hence, manual operation is not considered a major drawback and no full automation of the GMB processor is foreseen. Since the software and hardware in use is fully suitable for the GRACE(FO) GMB product generation, no further updates are planned in the course of the project.

6 Ice Sheet Coastal Line (ISCL)

6.1 System overview

In this section we describe the systems for processing, and delineating ISCLs from SAR and elevation data. This is done with a Deep Learning/Neural Network architecture, trained as part of a larger system that applies various processing described in detail in the ATBD [AD-3].

The network architecture is specified and built using a Python library developed by S[&]T called SNTML 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 the ISCLs from the input S1 SAR images and the altimetry CS2 tracks.
The input data consists of the following:

- SAR Ground Range Detected (GRD) from Sentinel-1 both HH and HV on IW and EW modes. Used as tif files after correction.
- Altimeter data from CS2 Retracker-1 as nc files.

The process pipeline is described in Figure 6.1 where the neural network model architecture is a U-net similar to the one used in Jiao L, et. al. (2020).

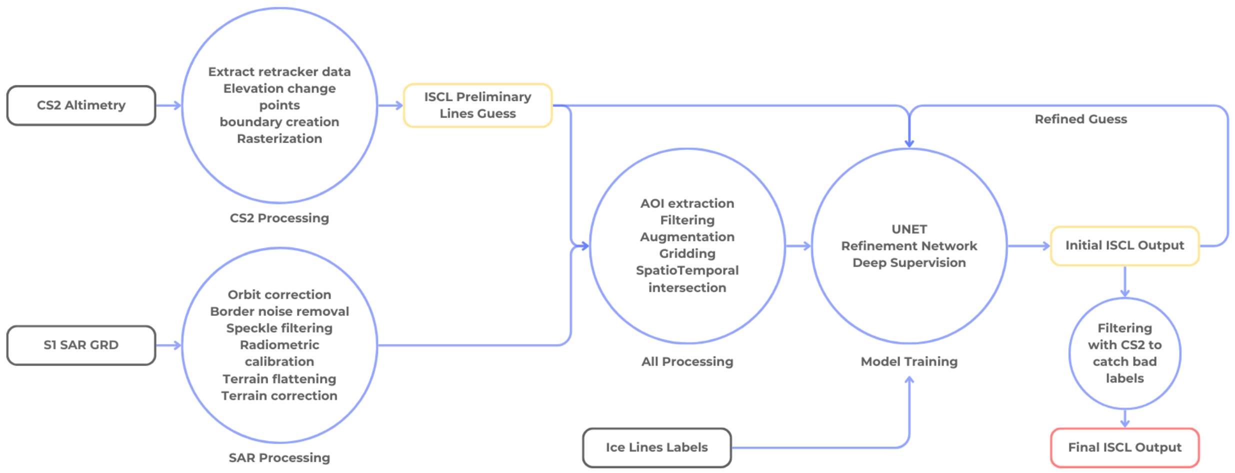

Figure 6.1 Main Workflow of the algorithm: Inputs in black borders, intermediate outputs in yellow borders, Final Output in red border. Processes in circles while data is in rectangles.

6.2 Operational scenarios

The operational scenario for this product is to generate an estimate of the location of the ISCL for any given S1 SAR image with a corresponding CS2 track (or multiple tracks) chosen to be no further than a month apart (to avoid too much error). The method can also work with only a S1 image but the CS2 tracks are preferred to complement the problems with the S1 imagery mentioned in detail in the [AD-3]. However, the output is not the model itself but the actual products (the ISCLs) of the chosen 3 ice shelves (Ronne, Filchner, and LarsenC) in a monthly frequency. These products can be viewed and used in various works.

6.3 Hardware and software platform

In the following, details on the hardware and software used to run the ISCL production system are given.

6.3.1 Hardware

In-house server machine with the following specs:

- Processor: Intel Xeon(R) Gold 6326 CPU @ 2.90GHz
- RAM: 512GB
- GPU: NVIDIA GeForce RTX 3090, 24576MiB, CUDA Version: 12.2
- Available storage: 4TB

Optional external storage also available.

6.3.2 Operating system

Ubuntu x86_64 GNU Linux

6.3.3 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.

6.4 Future concerns and developments

The main concern is the dependence on the IceLines label data which is not accurate. A great development is to use a manually delineated dataset which would provide greater accuracy and validity to the trained model.

6.5 References

Jiao L, Huo L, Hu C, Tang P. Refined UNet: UNet-Based Refinement Network for Cloud and Shadow Precise Segmentation. Remote Sensing. 2020; 12(12):2001. https://doi.org/10.3390/rs12122001

7 Appendix: CCI Data Standards

Data standards apply to the official CCI data products generated in the project. The reference document [AD4], *CCI Data Standards, v2.2* http://cci.esa.int/sites/default/files/CCIDataStandards_v2-2_CCI-PRGM-EOPS-TN-13-0009.pdf

Table 7.1: Top level CCI Data Standards Requirements

ID	Description
R-1	CCI projects shall produce data according to the CCI Data Standards Requirements: • Produced in netCDF-4 (classic) format • Conform with the CF (Climate and Forecasting) convention • CF standard names used for the main variables • Include defined set of global attributes [AD4]
R-2	Projects who have commitments to produce data in other formats, shall do this in addition to the standardized products, and shall ensure these products comply as much as possible to the CCI Data Standards (e.g. filenames, metadata)
R-3	The CCI projects shall create INSPIRE compliant metadata records for each dataset.
R-4	CCI Data Producers shall use terms from the CCI vocabulary tables [AD4] in the netCDF global attributes, or if terms are missing they shall request that they are added to the tables.
R-5	For consistency across CCI gridded products, variables shall have, as a minimum, the following dimensions: time, latitude, longitude
R-6	CCI Data Producers shall engage with the CF community to help develop the standards they require for satellite data
R-7	CCI Data Producers shall use the common directory structure [AD4] for all output data made available to users
R-8	CCI Data Producers shall use the CCI file naming convention [AD4] for all output data made available to users

The requirements R-1, R-4, R-5 pertain directly to the product data format and content.

The standard also states that projects who have commitments to produce data in other formats, shall do this **in addition** to the standardized products, and shall ensure these products **comply as much as possible** with the CCI Data Standards.

7.1 Line format in netCDF

There is no line data format specification which is of relevance to GLL. The line data will be provided in NetCDF closely matching the “PolyLine” data structure of ESRI shapefiles, see [RD13].

A PolyLine is an ordered set of vertices that consists of one or more *parts* (segments). A part is a connected sequence of two or more points. Parts may or may not be connected to one another. Parts may or may not intersect one another.

```
PolyLine
{
   Double[4] Box      // Bounding Box (if required)
   Integer NumParts    // Number of Parts
   Integer NumPoints   // Total Number of Points
   Integer[NumParts] Parts // Index to First Point in Part
   Point[NumPoints] Points // Points for All Parts
}
```

Variable	Description
Box	The Bounding Box for the PolyLine stored in the order Xmin, Ymin, Xmax, Ymax.
NumParts	The number of parts in the PolyLine.
NumPoints	The total number of points for all parts.
Parts	An array of length NumParts. Stores, for each PolyLine, the index of its first point in the points array. Array indexes are with respect to 0.
Points	An array of length NumPoints. The points for each part in the PolyLine are stored end to end. The points for Part 2 follow the points for Part 1, and so on. The parts array holds the array index of the starting point for each part. There is no delimiter in the points array between parts

As there seems to be no agreement on how to incorporate vector data in the CCI products, the official data product may simply contain a binary image of the ESRI shapefiles along one dimensional axis (unsigned char data type) and times along the other axis.

End of document