


# **ESA Climate Change Initiative (CCI+) Essential Climate Variable (ECV) Antarctica\_Ice\_Sheet\_cci+ (AIS\_cci+) System Specification Document (SSD)**

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DTU Geodynamics Group (DTU-S)  
ENVironmental Earth Observation GmbH (ENVEO)  
Deutsches Zentrum für Luft- und Raumfahrt (DLR) Remote Sensing Technology  
Institute (IMF)  
Science [&] Technology AS (ST)  
Technische Universität Dresden (TUDr)  
University College London (UCL/MSSL)  
University of Leeds, School of Earth and Environment (UL)

 <b>antarctic ice sheet</b> cci	Greenland_Ice_Sheet_cci+ System Specification Document (SSD)	Reference : ST-DTU-ESA-GISCCI+-PMP-001 Version : 1.0 page Date : 14 Sep 2020 2/50
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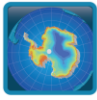
## Signatures page

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## Change Log

Issue	Author	Affected Section	Change	Status
1.0	D. Fantin	All	Document Creation	
1.1	A.Muir	All	First update for CCI+	

## Acronyms and Abbreviations

Acronyms	Explanation
<b>AIS</b>	Antarctic Ice Sheet
<b>ATBD</b>	Algorithm Theoretical Basis Document
<b>CCI</b>	Climate Change Initiative
<b>CECR</b>	Comprehensive Error Characterisation Report
<b>DEM</b>	Digital Elevation Model
<b>DInSAR</b>	Differential SAR Interferometry
<b>DLR</b>	Deutsches Zentrum für Luft- und Raumfahrt
<b>DTU</b>	Danmarks Tekniske Universitet
<b>ECV</b>	Essential Climate Variables
<b>ENVEO</b>	Environmental Earth Observation
<b>ERS</b>	European remote sensing satellite
<b>IBE</b>	Inverted Barometer Effect
<b>IV</b>	Ice Velocity
<b>IVonIS</b>	Ice Velocity on Ice Shelves
<b>LRM</b>	Low Resolution Mode
<b>OCOG</b>	Offset Centre of Gravity (OCOG) re-tracker
<b>PUG</b>	Product User Guide
<b>RA</b>	Radar Altimetry
<b>RMSE</b>	Root-Mean-Square Error
<b>RR</b>	Round Robin
<b>S3MPC</b>	Sentinel-3 Mission Performance Center
<b>SAR</b>	Synthetic Aperture Radar
<b>SEC</b>	Surface Elevation Change
<b>SoW</b>	Statement of Work
<b>TCM</b>	Tidal Correction Module
<b>TFMR</b>	Threshold First Maximum Retracking
<b>TUDr</b>	Technische Universität Dresden
<b>UCL</b>	University College London
<b>UL</b>	University of Leeds
<b>UTC</b>	Coordinated Universal Time

# 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 1, in accordance to 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 four chapters describing the processing system for the AIS\_cci ECV parameters which are

- Surface Elevation Change (SEC),
- Ice Velocity (IV),
- Grounding Line Location (GLL), and
- Gravimetric Mass Balance (GMB).


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. 4000126813/18/I-NB, and its Appendix 2	CCI+ PHASE 1 - NEW R&D ON CCI ECVS, for Antarctic_Ice Sheet_cci	2019.09.30	

 <b>antarctic ice sheet cci</b>	Greenland_Ice_Sheet_cci+ System Specification Document (SSD)	Reference : ST-DTU-ESA-GISCCI+-PMP-001 Version : 1.0 page Date : 14 Sep 2020 8/50
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AD2	ESA-CCI-EOPS-PRGM-SOW-18-0118 Appendix 2 to contract.	Climate Change Initiative Extension (CCI+) Phase 1, New R&D on CCI ECVs Statement of Work	2018.05.31	Issue 1 Revision 6
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**Table 1.2: List of Reference Documents**

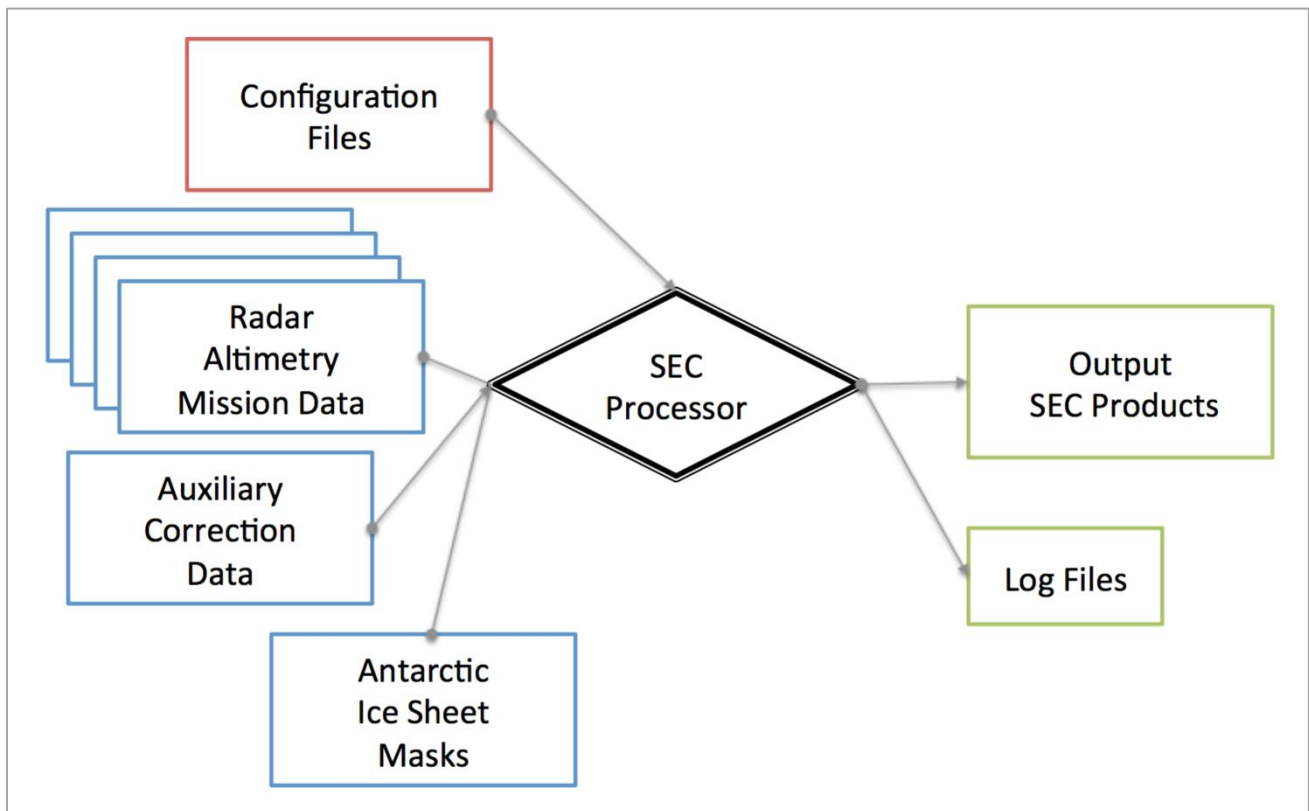
No	Doc. Id	Doc. Title	Date	Issue
RD1	ST-UL-ESA-AISCCI-URD-001	User Requirement Document (URD)		
RD2	ST-UL-ESA-AISCCI-PSD-001	Product Specification Document (PSD)		
RD3	ST-UL-ESA-AISCCI-DARD-001	Data Access and Requirements Document (DARD)		
RD4	ST-UL-ESA-AISCCI-ATBD-001	Algorithm Theoretical Basis Document (ATBD)		
RD5	ST-UL-ESA-AISCCI-ATBD-002_RR	Algorithm Theoretical Basis Document (ATBD), Appendix Round Robin Experiments		
RD6	ST-UL-ESA-AISCCI-CECR-001	Comprehensive Error Characterisation Report (CECR)		
RD7	ST-UL-ESA-AISCCI-SSD-001	System Specification Document (SSD)		
RD8	ST-UL-ESA-AISCCI-SVR-001	System Verification Report (SVR)		
RD9	ST-UL-ESA-AISCCI-PUG-001	Product User Guide (PUG)		
RD10	ST-UL-ESA-AISCCI-PVIR-001	Product Validation and Inter-comparison Report (PVIR)		
RD11	ST-UL-ESA-AISCCI-CRDP-001	Climate Research Data Package (CRDP)		
RD12	ST-UL-ESA-AISCCI-CAR-001	Climate Assessment Report (CAR)		
RD13	N/A	ESRI Shapefile Technical Description	July 1998	N/A

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



## 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.



**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.

## Radar Altimetry Data

Input data from radar altimeter missions are chosen from the latest fully reprocessed and validated baseline archive of operational Level-2 or Level-2i products from ESA. Data highlighted in bold represents baselines or missions that were not available in CCI, are new to this phase of CCI+.

Mission	Product Level	Baseline	Source	Operational Dates
ERS-1	L2	REAPER v1.0	ESA	2-Aug-91 to 2-Jun-96
ERS-2	L2	REAPER v1.0	ESA	13-May-95 to 4-Jul-03
ENVISAT	L2	<b>GDR v3</b>	ESA	9-Apr-02 to 18-Oct-10
CryoSat-2	L2i SIN	<del>Baseline-C</del> <b>Baseline-D</b>	ESA	16-Jul-10 to (now- <del>90days</del> 90days)
CryoSat-2	L2i LRM	<del>Baseline-C</del> <b>Baseline-D</b>	ESA	16-Jul-10 to (now- <del>90days</del> 90days)
<b>Sentinel-3A</b>	<b>L2</b>	<b>Baseline-3/4</b>	<b>ESA</b>	07-Dec-16 to (now- <del>90days</del> 90days)
<b>Sentinel-3B</b>	<b>L2</b>	<b>Baseline-3/4</b>	<b>ESA</b>	23-Nov-18 to (now-90days)

**Table 2.1:** Current Radar Altimetry Data Sets

## 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 in to the latest operational baseline data sets.

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

**Table 2.2:** Auxillary Data Sources

## 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.

Mask	Source	Auxiliary File Pre-processing
Antarctic Basin Mask	Goddard Ice Altimetry Group, (Zwally et al, 2012)	University of Leeds/IMBIE

**Table 2.3:** Antarctic basin mask

## Output Data Products

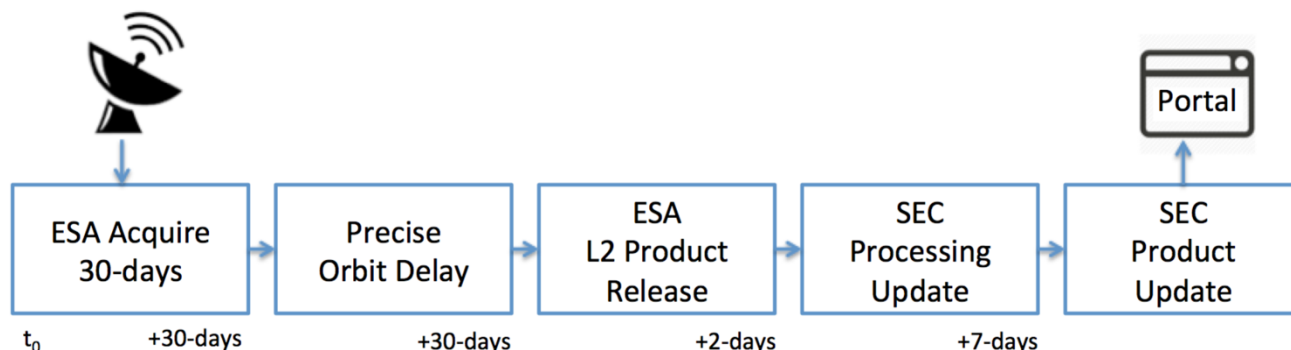
The output of the SEC operational ECV processor are NetCDF v4 (Classic) format files containing gridded SEC and error values for each full mission and from cross-calibrated combined mission 5-year periods, and CSV format files containing Antarctic drainage basin time series at a monthly interval.

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- <del>9090</del> -days)	NetCDF v4 (Classic)
SEC	5km	Sentinel-3A	07-Dec-16 to (Now- <del>9090</del> -days)	NetCDF v4 (Classic)
SEC	5km	Sentinel-3B	23-Nov-18 to (Now- <del>9090</del> -days)	NetCDF v4 (Classic)
SEC	5km	All	5-year periods since 1991	NetCDF v4 (Classic)

**Table 2.4:** Output Data Products

### Processing Timeliness

SEC products are updated ~~quarterly~~ quarterly when there is availability of new altimetry data from current satellites (such as CryoSat-2, Sentinel-3A, Sentinel-3B) 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).




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

Should ESA 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/csopr>.

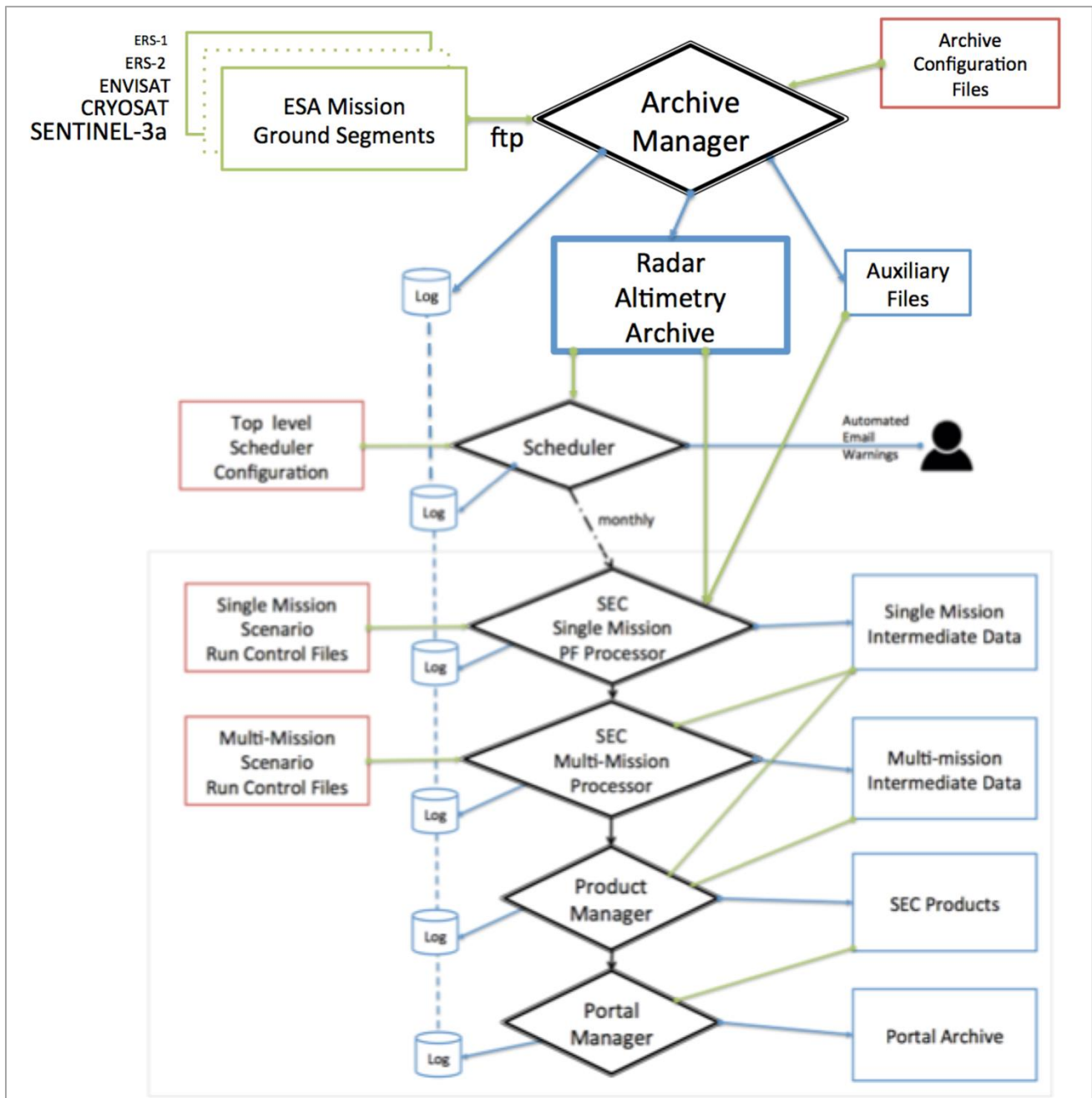
Users must register their details (Name, Email Address, Affiliation, Sector, Country) and tick a box indicating that they will site publication XX, DOI YY, and whether they wish to be informed of new versions of the dataset, before accessing the data for the first time.

 <b>antarctic ice sheet</b> cci	Greenland_Ice_Sheet_cci+ System Specification Document (SSD)	Reference : ST-DTU-ESA-GISCCI+-PMP-001 Version : 1.0 page Date : 14 Sep 2020 12/50
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SEC 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 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) and historic (ERS-1, ERS-2, ENVISAT) radar 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.

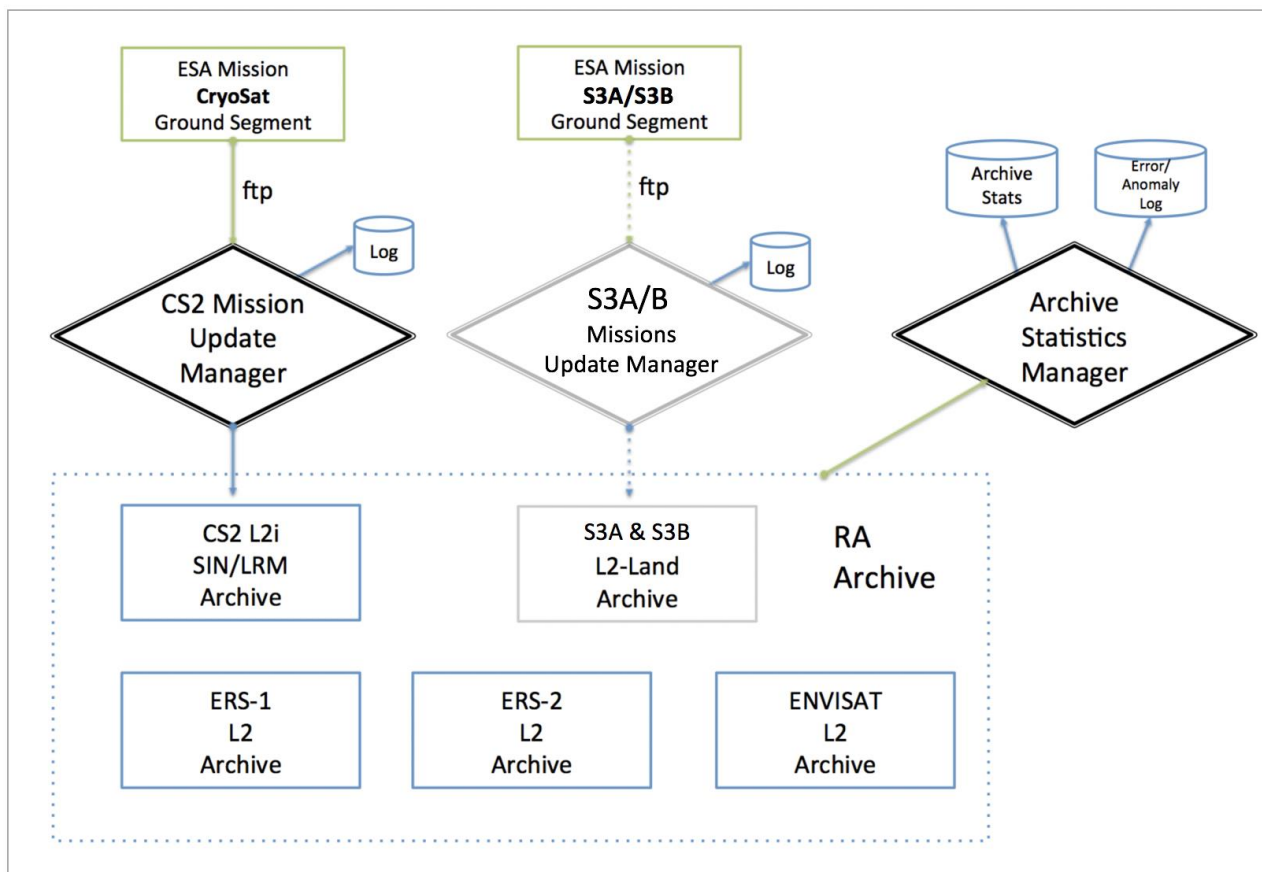
It has two main functions:

- Generate statistics of RA data sets held in its archive and report anomalies.
- Manage the ingest from ESA 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 and Sentinel-3a, 3b. 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 altimetry archive management) according to its schedule configuration file.

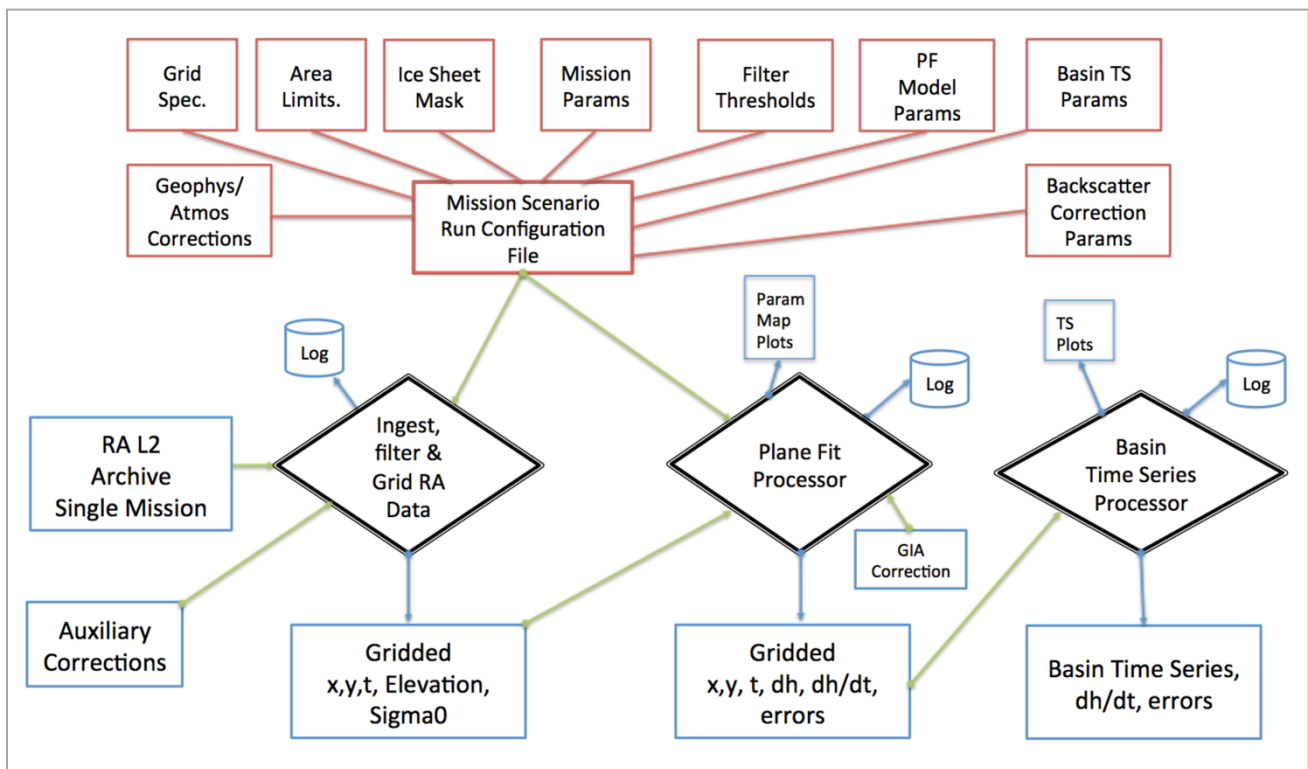
By default the scheduler automatically runs monthly (on the 1<sup>st</sup> day of each month) and will initiate the single mission plane fit processor for each live mission that has new validated data. It will then run the multi-mission processor, product manager, and portal manager to generate and export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

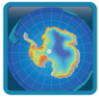
### 2.1.3 Single Mission Plane Fit Processor

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 L2 or L2i data from the RA 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 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 IDL 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, *Zwally et al, 2012*) at 30 day epochs, since the start of 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 IDL sav 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 plotted 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.

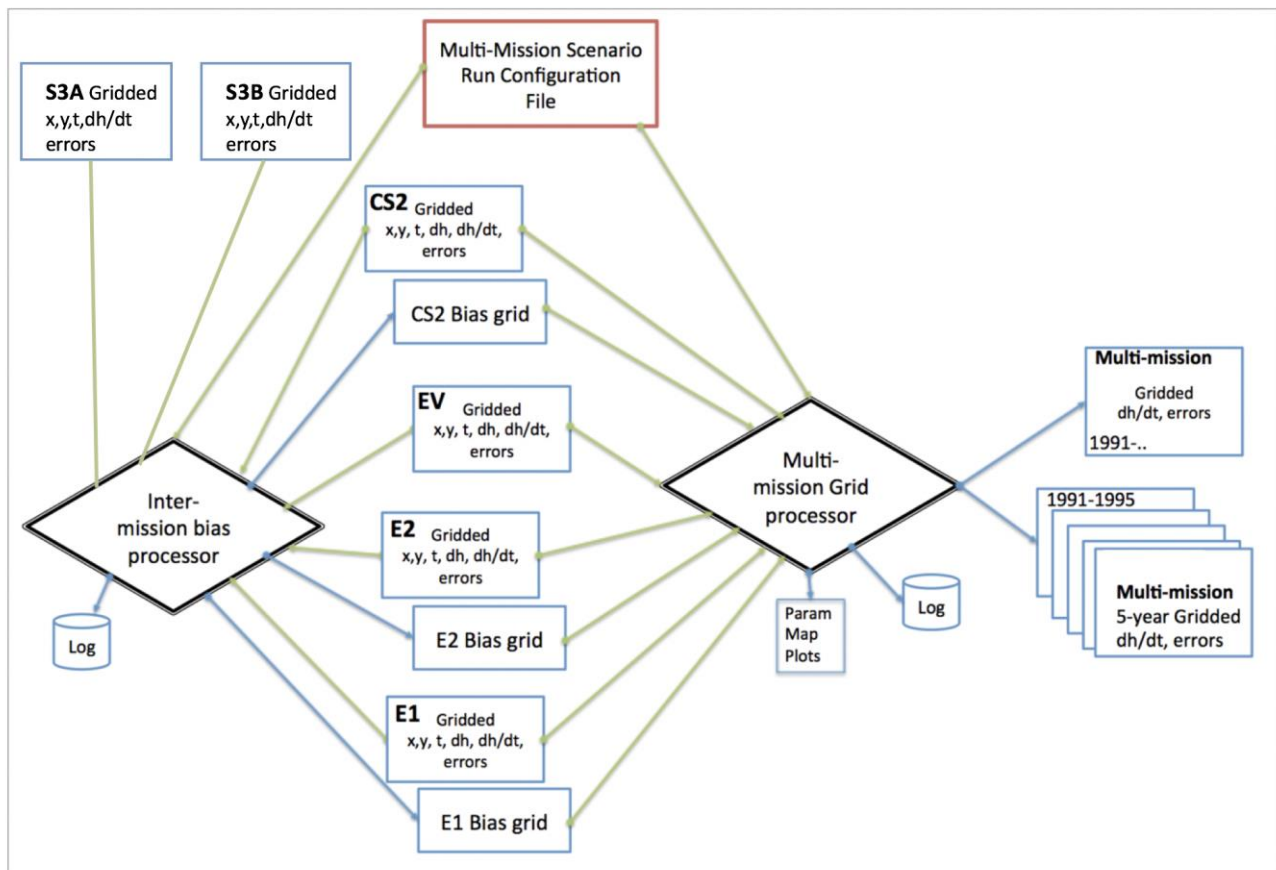


All intermediate data output and log files for a processing scenario is stored in the scenario directory:  
\$RT\_HOME/scenario\_data/<scenario\_name>/

TIMESERIES/	contains all output data files in IDL .sav 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 L2 file names read
IMAGES/	contains all auto generated plots and parameter maps in jpg format.

#### 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

The processor has two main tasks:

- i) 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.
- ii) 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.

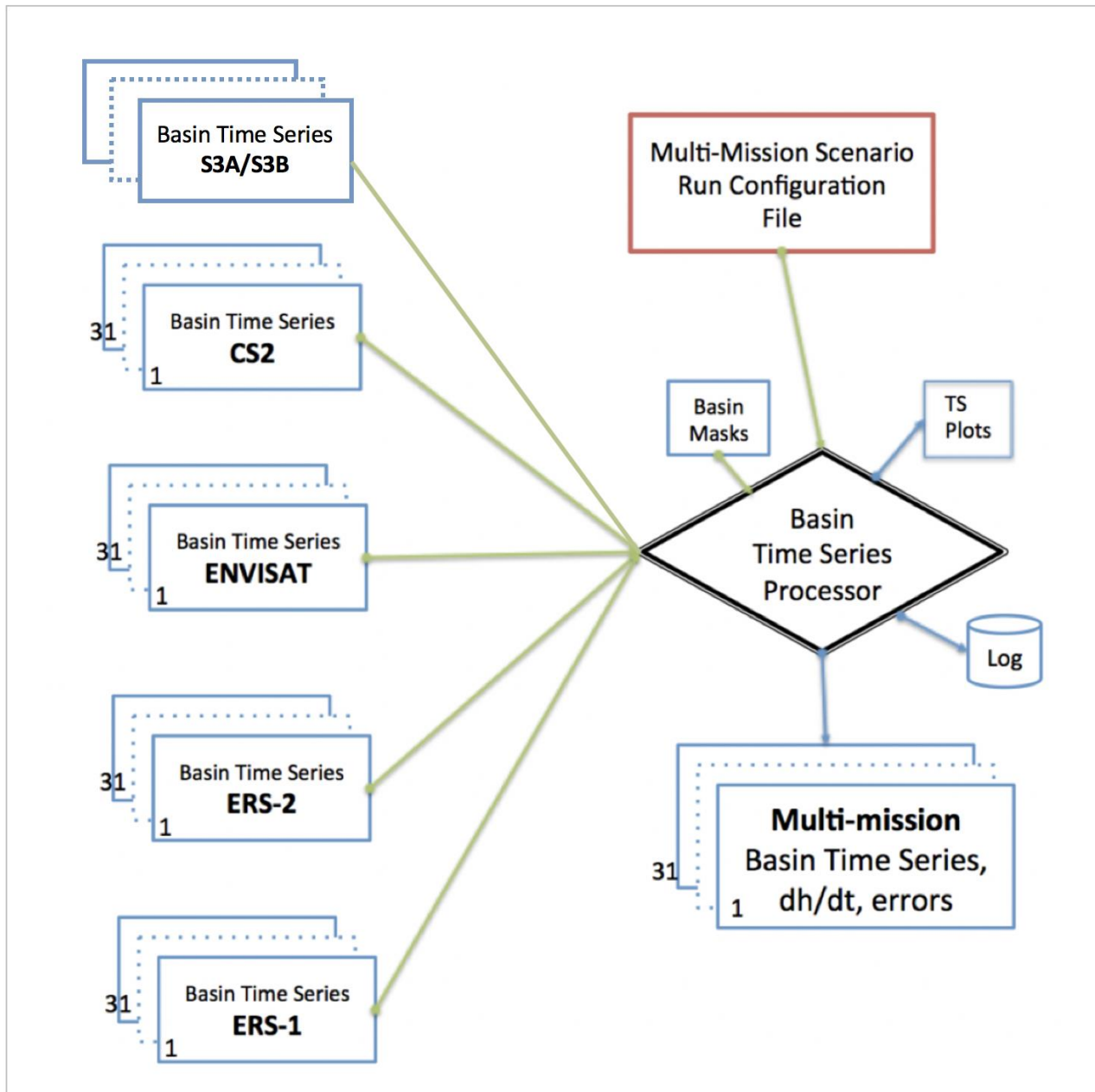
All intermediate data output and log files for the multi-mission processing scenario are stored in the scenario directory:

\$RT\_HOME/scenario\_data/<multi-mission scenario\_name>/

TIMESERIES/	contains all output data files in IDL .sav 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.

### 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, Zwally *et al*, 2012) 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:

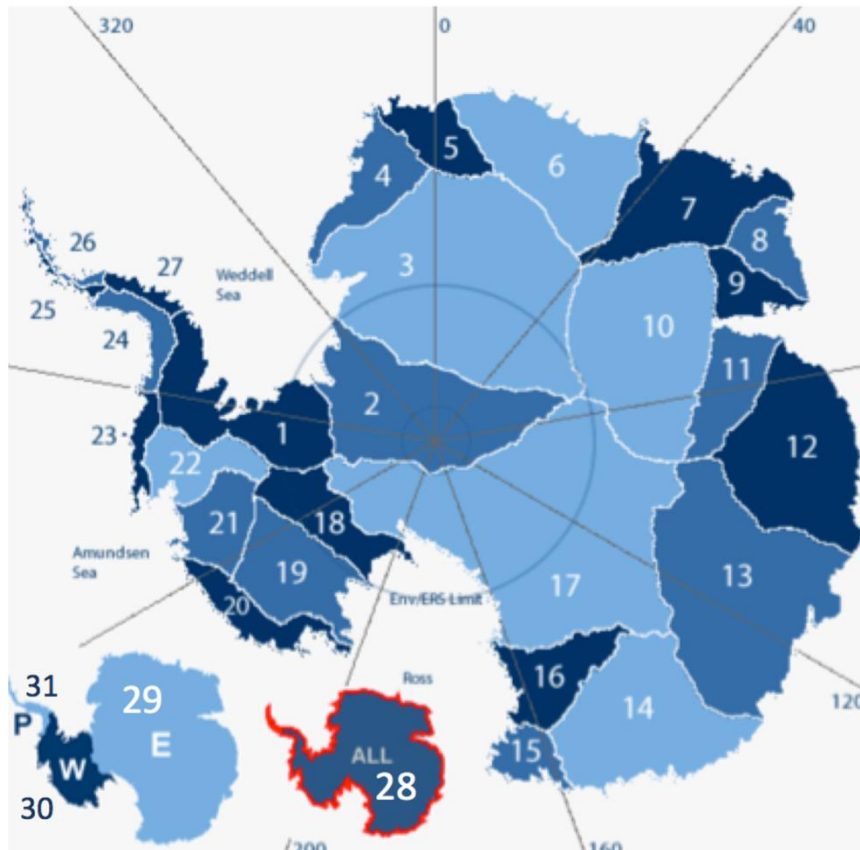
Basins 1-27 as per IMBIE - Zwally *et al*, 2012.

Basin 28 is defined as all Antarctic Ice Sheets (ie basins 1-27 combined),

Basin 29 is East Antarctica (basins 2-17),

Basin 30 is West Antarctica (basins 1,18-23)  
Basin 31 is the Antarctic Peninsular (basins 24-27).

**Figure 2.8:** Antarctic Drainage Basin and Sector Numbering



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 number=1-31>.<fill\_type=0-3>.sav

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>/

TIMESERIES/	contains all output data files in IDL .sav 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.

### 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.

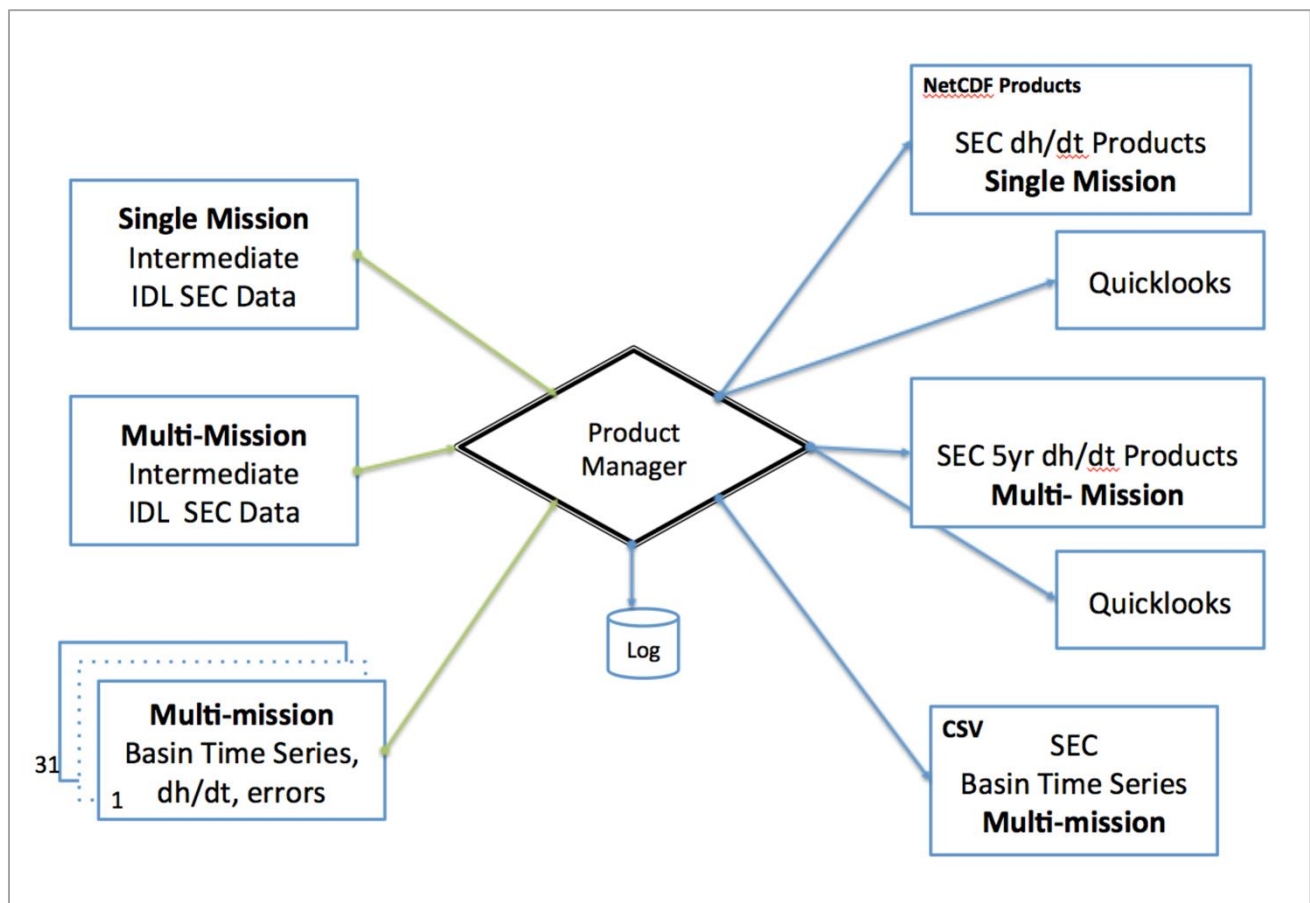


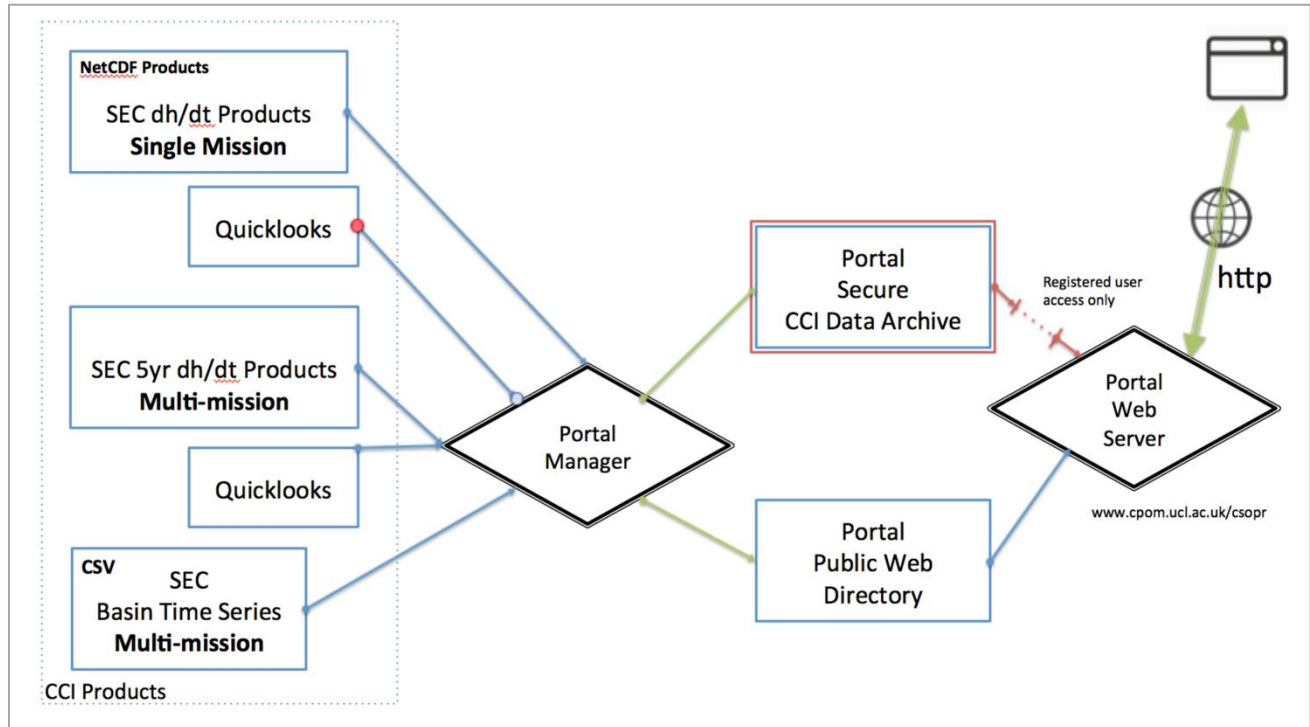
Figure 2.9: SEC CCI Product Manager

### 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 altimetry measurements over the Antarctic Ice Sheet falls below the following values (per orbit file):

<b>Dry Tropospheric</b>	100 %
-------------------------	-------

 <b>antarctic ice sheet</b> cci	Greenland_Ice_Sheet_cci+ System Specification Document (SSD)	Reference : ST-DTU-ESA-GISCCI+-PMP-001 Version : 1.0 page Date : 14 Sep 2020 23/50
---	---	--

<b>Wet Tropospheric</b>	100 %
<b>Ionospheric</b>	100 %
<b>Solid Earth</b>	100 %
<b>Ocean Loading Tide</b>	100 %
<b>Geocentric Polar Tide</b>	100 %

### Geophysical Corrections

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

<b>Geophysical Corrections Applied</b>	Dry Tropospheric, Wet Tropospheric, Ionospheric, Solid Earth, Geocentric Polar Tide, Ocean Loading Tide
--	--

### Retracker Failure Thresholds:

Warnings are logged if the % failure of the Ice-1 retracker or CryoSat SARin mode retracker over the Antarctic Ice Sheet falls below the following threshold values for a repeat cycle (or sub-cycle).

<b>% Ice-1 Retracker Failure Threshold</b>	20%
<b>% CryoSat SARin Retracker Failure Threshold</b>	10%

### Grid Projection

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

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

### Plane Fit Thresholds

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

### Basin Masks

<b>Basin Masks Applied</b>	Zwally, et al, 2012, Basin 1-27
----------------------------	---------------------------------

### Basin Time Series

<b>Basin Time Series Epoch Length</b>	30 days
---------------------------------------	---------

<b>Epoch Area Interpolation Method</b>	Inverse Distance
<b>Min Percentage Area Filled (after interpolation)</b>	25%
<b>Min Percentage Area Filled (before interpolation)</b>	15%

#### GIA Correction

<b>GIA Correction</b>	IJ05_R2 model (Ivans & James 2005)
-----------------------	------------------------------------

#### dh/dt Filters

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

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

#### Scenario Settings

<b>Scenario Name</b>	ant_e1_5km
<b>Mission</b>	ERS-1
<b>L2 Data Source</b>	REAPER v1.0 GDR L2
<b>Operational Start Date</b>	4/4/1992
<b>Operational End Date</b>	2/6/1996
<b>Number of Expected L2 Files Read</b>	21158



<b>Tracking Mode</b>	Ice Mode
<b>Surface Type</b>	Continental Ice
<b>Retracker Selected</b>	Ice-1
<b>Filter on Retracking Flag</b>	ICE1_QUAL_FLAG_20HZ
<b>Backscatter correction period</b>	18 months
<b>Backscatter correction start/stop</b>	1992.33 1993.83
<b>Minimum time range (in years) of grid time series</b>	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:

<b>Threshold Number of L2 Orbits per 35-day cycle (Phase A)</b>	400
---	-----

### Scenario Settings

<b>Scenario Name</b>	ant_e2_5km
<b>Mission</b>	ERS-2
<b>L2 Data Source</b>	REAPER v1.0 GDR L2
<b>Operational Start Date</b>	13/5/1995
<b>Operational End Date</b>	4/7/2003
<b>Number of Expected L2 Files Read</b>	43038
<b>Tracking Mode</b>	Ice Mode
<b>Surface Type</b>	Continental Ice
<b>Retracker Selected</b>	Ice-1
<b>Filter on Retracking Flag</b>	ICE1_QUAL_FLAG_20HZ
<b>Backscatter correction period</b>	18 months
<b>Backscatter correction start/stop</b>	1995.5 1997.0
<b>Minimum time range (in years) of grid time series</b>	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:

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

### Scenario Settings

<b>Scenario Name</b>	ant_env_5km
<b>Mission</b>	ENVISAT
<b>L2 Data Source</b>	GDR v2.1
<b>Operational Start Date</b>	14/5/2002
<b>Operational End Date (of repeat period)</b>	18/10/2010
<b>Number of Expected L2 Files Read</b>	83513
<b>Tracking Mode</b>	320Mhz
<b>Surface Type</b>	Continental Ice
<b>PTR Correction Anomaly Applied</b>	Y (source ESA/UCL)
<b>Dry Tropospheric Anomaly Correction Applied</b>	Y (source ECMWF/UCL)
<b>Retracker Selected</b>	Ice-1
<b>Filter on Retracking Flag</b>	KU_ICE1_RETRACKER_QUA_FLAG
<b>Filter on Chirp ID error</b>	Y
<b>Backscatter correction period</b>	18 months
<b>Backscatter correction start/stop</b>	2007.9 2009.4
<b>Minimum time range (in years) of grid time series</b>	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:

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

## Scenario Settings

<b>Scenario Name</b>	ant_cs2_lrm_5km
<b>Mission</b>	CryoSat
<b>L2 Data Source</b>	ESA Baseline-D
<b>Operational Start Date</b>	1/7/2010
<b>Operational End Date</b>	Now-90 days

<b>Number of Expected L2 Files Read</b>	<a href="#">362041362041</a>
<b>Tracking Mode</b>	LRM
<b>Apply LRM Time Tag Bias for Baseline-B</b>	Y
<b>Surface Type</b>	Land & Ice (from parameter in L2i)
<b>Retracker Selected</b>	Ice-1/CFI
<b>Filter on Retracking Flag</b>	No
<b>Filter on MCD Flag</b>	No
<b>Filter on Overall Measurement Quality Flag</b>	No
<b>Backscatter correction period</b>	<del>5</del> 5years
<b>Backscatter correction start/stop</b>	2010.9 <del>2015</del> <a href="#">2015</a> .9
<b>Minimum time range (in years) of grid time series</b>	4 years

### SARin

<b>Scenario Name</b>	ant_cs2_sin_5km
<b>Mission</b>	CryoSat
<b>L2 Data Source</b>	ESA Baseline-B
<b>Operational Start Date</b>	1/7/2010
<b>Operational End Date</b>	<a href="#">31/12/2016</a> <del>31/12/2016</del>
<b>Number of Expected L2 Files Read</b>	<a href="#">362041362041</a>
<b>Tracking Mode</b>	SARin
<b>Apply LRM Time Tag Bias for Baseline-B</b>	N
<b>Surface Type</b>	Land & Ice (from parameter in L2i)
<b>Retracker Selected</b>	SARin Retracker
<b>Filter on Retracking Flag</b>	Y
<b>Filter on MCD Flag</b>	Y
<b>Filter on Overall Measurement Quality Flag</b>	Y
<b>Backscatter correction period</b>	3 years
<b>Backscatter correction start/stop</b>	2010.9 <del>2015</del> <a href="#">2015</a> .9
<b>Minimum time range (in years) of grid time series</b>	4 years

## 2.3 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 Linux-CentOS-6.9-CentOS\\_7](#) operating system.

### 2.3.1 Hardware

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

<del>Make</del> Make	<del>Dell</del> Dell
Processor	<del>2x2.3GHz 8-core Xeon E5-2470</del> 2x2.3GHz 8-core Xeon E5-2470
Memory (RAM)	<del>132GB</del> 132GB
Local Hard Drive	<del>300GB</del> 300GB
Network Attached Storage	<del>164 TB</del> 164 TB

### 2.3.2 Operating system

The system currently runs on the ~~Linux CentOS 6.9~~Linux CentOS 7 operating system.

### 2.3.3 Tools and libraries

The system requires:

- i) Python v3.8+
- 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 Future concerns and developments

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

New Altimetry Data Sets and Missions scheduled during ~~2017~~2020:

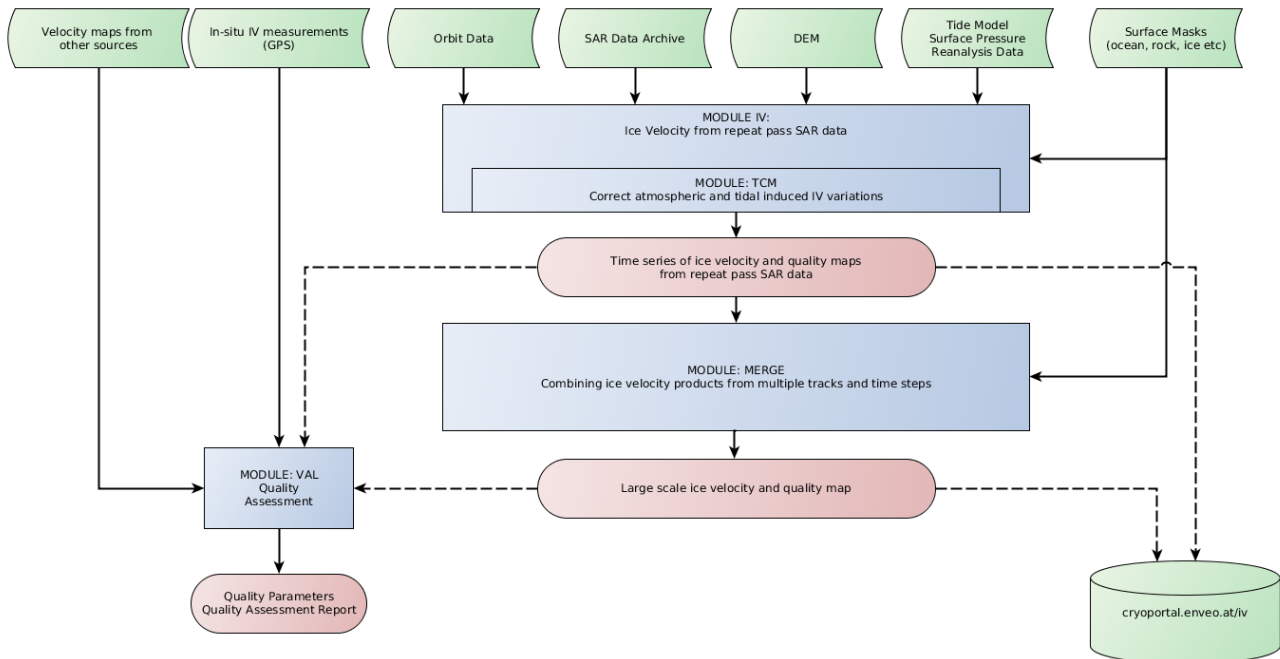
- i) Sentinel-3 Land Ice full mission reprocessing (FMR) (Baseline-5) if available. Currently S3 L2 data is a mix of baseline's 3 & 4, and requires a patch to account for changes in backscatter power between baselines.

## 3 Ice Velocity (IV)

### 3.1 System Overview

In this section we describe the processing system for deriving ice velocity (IV) maps from repeat pass SAR data. The ENVEO SAR Software Package (ESP) Version 2.1 is 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. Auxiliary data include a DEM, Tide Model and Atmospheric Pressure data and ocean/ice/land mask. Figure 3.1 shows the high-level processing line for the IV 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 is currently under development 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+ is 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.

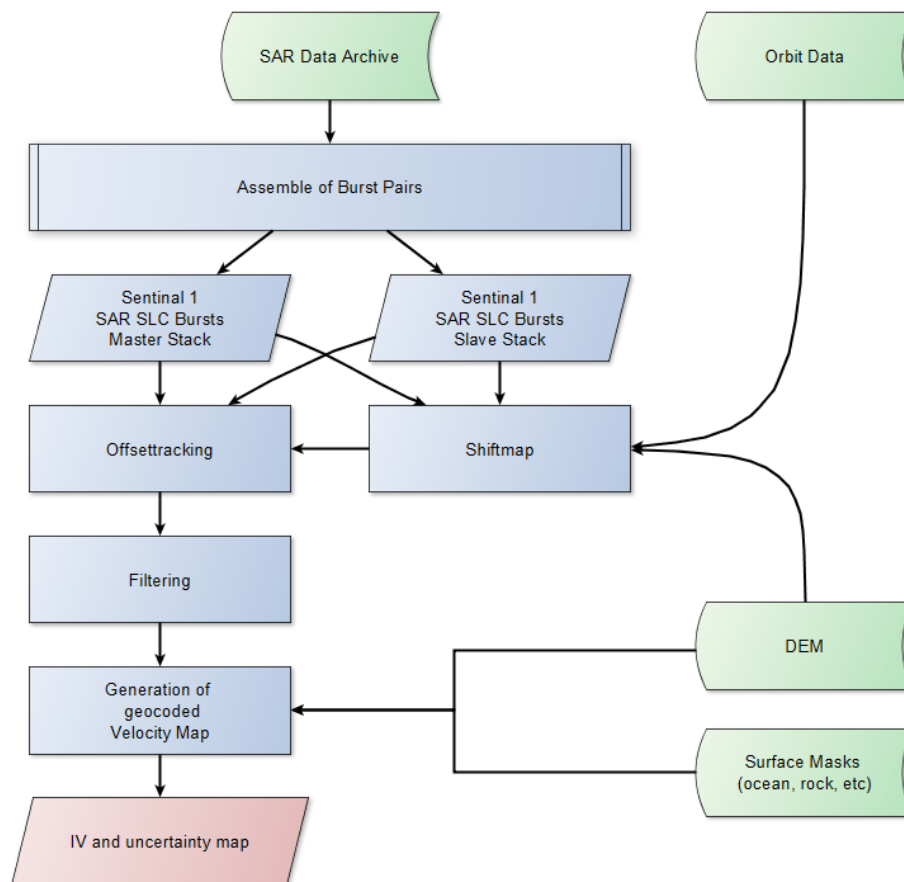


**Figure 3.1: High-level flow chart of the ENVEO ESP 2.1 IV processing system. Green: input data, blue: processing modules, red: (intermediate) products.**

### 3.1.1 IV MODULE (Offset-tracking)

Figure 3.3 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 the processing is done on scene/frame level, which is very similar. Here we briefly describe the Sentinel-1 IW SLC burst processing.

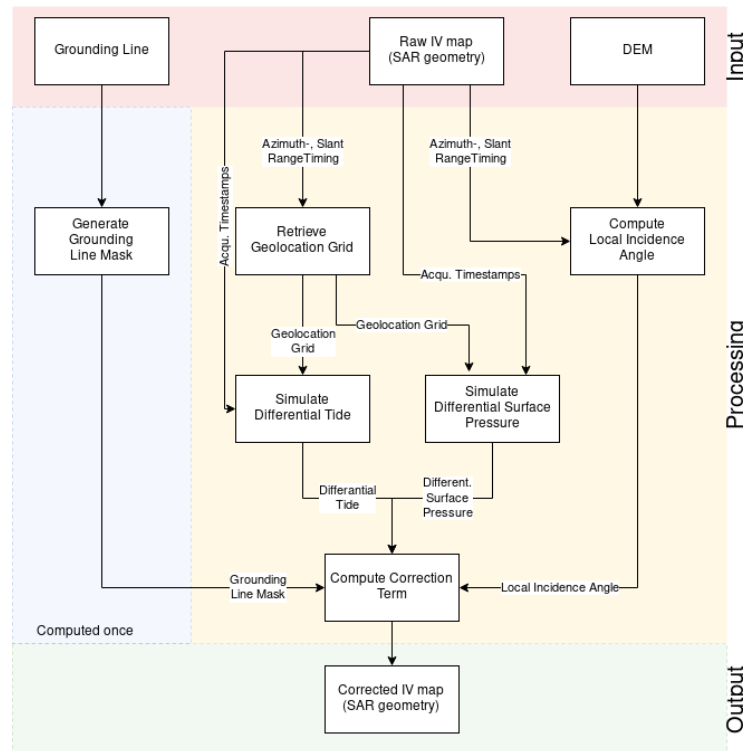
The module has access to the SAR data archive and orbit data, as well as a DEM and optionally a surface mask. The processing is done track by track, for each track image bursts are selected according to the time step. For Sentinel-1 processing we select 6 and 12 day repeat pass periods. Using the image 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,  $\Delta Z$ ) 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 deburst 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 be also applied 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 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 pre-defined central flow lines of major outlet glaciers
- Visualize the full time series of velocity on fixed points along the flow line

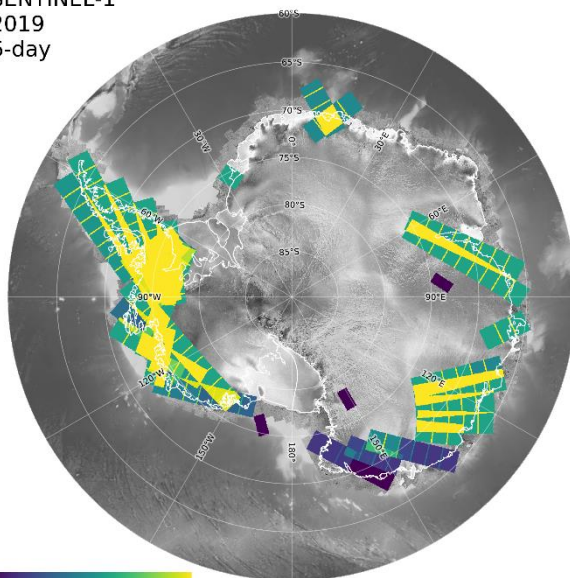
### 3.2 Operational scenarios

Operational scenarios are mainly planned using Copernicus Sentinel-1 A/B satellites. There are currently three processing scenarios applied:

- Continuous observations of Antarctic Ice Sheet margins with offset-tracking (6/12-days)
- Production of annual ice sheet wide ice velocity maps
- Production of monthly ice sheet wide ice velocity maps

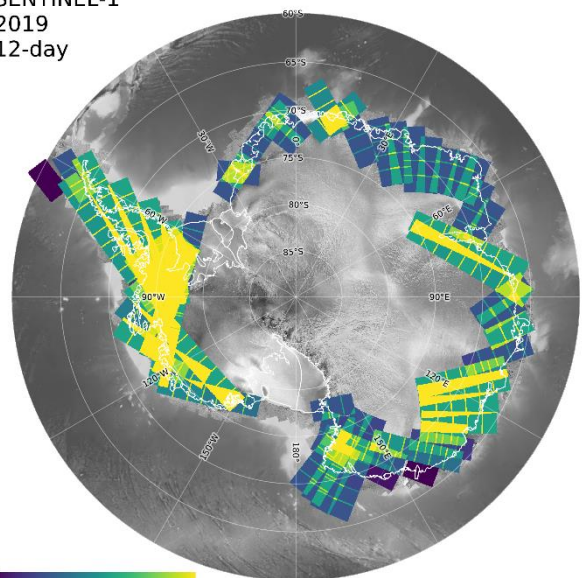
The track by track processing is applied for all continuous Sentinel-1 IW acquisitions in Antarctica. This processing scenario enables monitoring of ice velocity variations with short time intervals, e.g. in the case of Sentinel-1A with 12 days repeat (6 days using S1A and S1B). Continuous monitoring 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. Figure 3.4 shows the 6- and 12-day repeat pair coverage of Sentinel-1 IW mode data in Antarctica in 2019. The addition of additional tracks is foreseen. Antarctic wide (margin) ice velocity maps are generated on a monthly and annual basis and rely on the continuous acquisition of Sentinel-1.

SENTINEL-1  
2019  
6-day



1 pairs >100

SENTINEL-1  
2019  
12-day



1 pairs >100

**Figure 3.4: 6-day (left) and 12-day (right) repeat pair coverage of Sentinel-1 IW mode data in Antarctica in 2019.**

### 3.3 Hardware and software platform

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

#### 3.3.1 Hardware

The main processing is done on 3 server machines and 18 virtual machines at the IKB cluster, which are connected to a mass storage of about 800 TB. The system applies OPENMP to support multiple CPUs and Cores.

**Table 3.1: Processing Hardware for the ENVEO SAR IV processor**

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

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

#### Tools & Libraries

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

#### Visualisation Tools

- QGIS <http://qgis.org>
- Cryoport Ice Velocity (developed by ENVEO) <https://cryoport.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.

## 4 Grounding Line Location (GLL)

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.

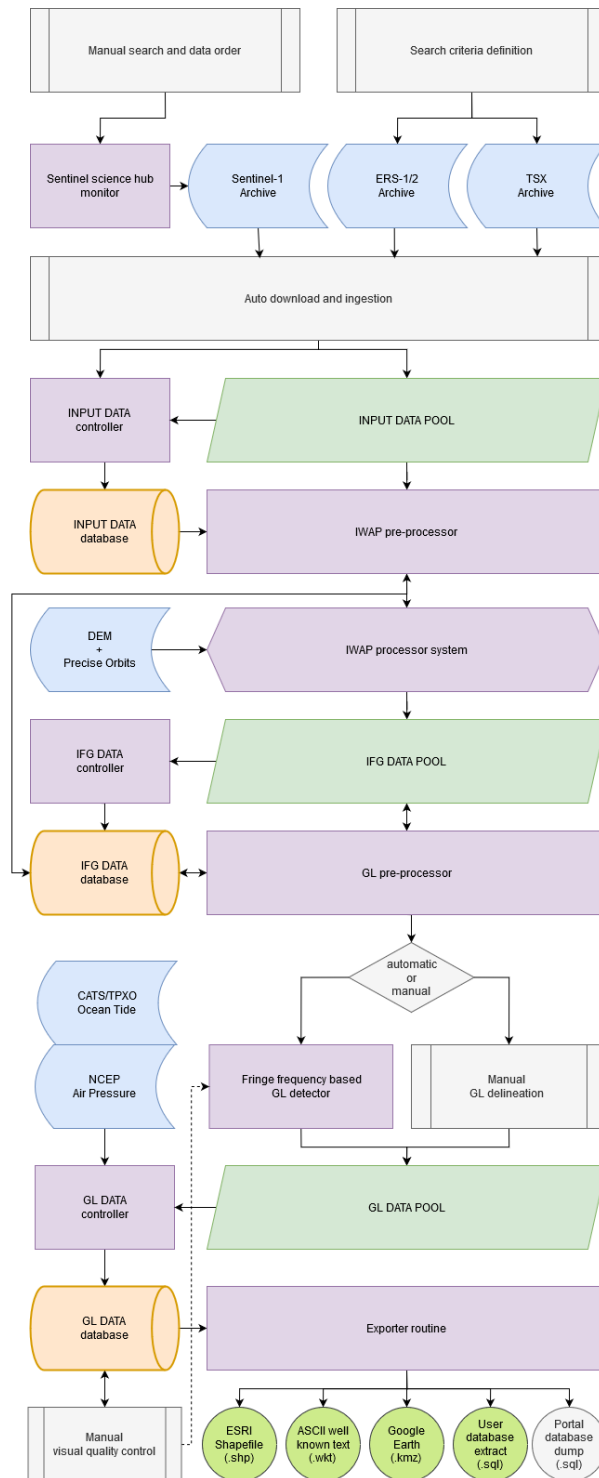
The original idea of the GLL production system was based on a manual delineation of the upper fringe belt which is usually clearly recognizable in the generated double differences interferograms. An algorithm for an automatic derivation of the GLL has recently been tested and seems promising but is not yet in an operational state. The development of this algorithm is part of the project and will continue within the next year. 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 on 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 cryoportals ([cryoportals.enveo.at/](https://cryoportals.enveo.at/)) or ESA cci data portal. There are three different file formats (.shp, .wkt, .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, .wkt and .kmz products 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 automatically 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: part one. Input data in light blue, processes in violet, database systems in orange, manual processes in grey, intermediate processing results in light green and products in lime 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 Simple Online Catalogue ([earth.esa.int/web/guest/missions/esa-operational-eo-missions/ers/news/-/article/eoli-sa-phase-out](http://earth.esa.int/web/guest/missions/esa-operational-eo-missions/ers/news/-/article/eoli-sa-phase-out)) or EOWEB® GeoPortal ([eoweb.dlr.de/egg/](http://eoweb.dlr.de/egg/)). 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. To our knowledge neither ESA Simple Online Catalogue nor EOWEB® GeoPortal support such script-based requests since there are always orders involved. But the Sentinel science hub provides such functionality. Since not all newly available products may be of interest, temporal and spatial criteria's need to be defined. This process only needs to be done once but could be updated occasionally.

**Sentinel science hub monitor:** Is a perl program which is called by a cron job in a predefined interval such as once a day or any specific time interval. It reads the '*search criteria definition*' and translates them into a respective search query request to the Sentinel science hub at ESA. The obtained available download links are temporarily saved in a text file.

**Auto download and ingestion:** When the requested data is processed at ESA or DLR, an FTP link to the pickup point is provided via email. After ordering the data, a routine which is called by a cron job in a predefined time interval such as once a week will search for this email and data will be download automatically from the FTP server and unpacked. The results are copied into the 'INPUT DATA POOL'. The cron job routine monitors for new available Sentinel-1a/b data in science hub at ESA. Once the data is available in science hub, the routine checks if the selected items already exist in the 'INPUT DATA POOL' – all new items will be downloaded, unpacked and placed in the Sentinel directory of the 'INPUT DATA POOL'. **INPUT DATA POOL:** The input data pool is one or more predefined directories which contain subdirectories for each sensor, ERS, TSX and SEN. It can spread across multiple storage systems but must be available on the machine where the IWAP processing will take place. All original SLC data products are simply dumped into the respective sensor directories (ERS, TSX, SEN) no matter at which time or over which glacier they were acquired.


**INPUT DATA controller:** Is a python program which can be called by the 'auto download and ingestion' script or by a cron job. It analyzes all SLC pool directories for a specified sensor (TerraSAR-X, ERS-1/2, Sentinel 1a/b) and updates the '*INPUT DATA database*' (Section 4.2) which contains metadata 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. This metadata can be read from the IWAP pre-processor.

**INPUT DATA database:** Is a PostGIS database which contains the above mentioned information and therewith keeps and updates a unique record of all available SLC products within all directories of the '*INPUT DATA POOL*'.

**IWAP pre-processor:** The IWAP pre-processor analyzes the '*INPUT DATA 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. 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 the '*IFG DATA POOL*' and the '*IFG DATA controller*' is launched (IFG hereby stands for Interferogram).



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**IFG DATA POOL:** Consists of directories which accommodate the above mentioned processing results of the IWAP. Subdirectories for the different sensors exist inside these directories analog to the 'INPUT DATA POOL'. On the next level results are then separated by relative orbit number, look-/pass-direction, image acquisition mode, if available its frame and generally their date/time combination.

**GL pre-processor:** Analog to the IWAP pre-processor, the GL pre-processor analyzes the 'IFG DATA database' 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 determined and saved in the 'IFG DATA POOL'. All datasets inside this directory provide a unique double difference combination and therewith a part of the final grounding line database.

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

**Fringe frequency based GL detector (working and development in progress):** The fringe frequency method aims at an automatic delineation of GLL. Estimates of the surface deformation gradient (used as a vertical tilt measurement) are derived from the wrapped interferometric phase [8]. A difference of the gradient amplitude is formed similar to a double difference interferogram which reveals the gradient differences at the glacier grounding zone. The resulting gradient amplitude differences are used both to identify (and follow) the geometry of the grounding zone and to find parameters of an elastic beam model fitting the gradient magnitude and identifying the glacier grounding line.

**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 into the 'GL DATA POOL'. The 'GL DATA POOL' is an intermediate layer; the final results are stored and managed in the 'GL DATA database'. The intermediate layer is required since the shapefiles cannot be directly entered into the database which is the task of the controller. The 'GL DATA controller' needs to be run after the manual GL delineation in order to add this dataset into the database.

**GL DATA controller:** It updates the 'GL DATA database' if new entries are available in the 'GL DATA POOL'. 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.

**GL DATA database:** is the PostGIS database which holds the final grounding line products along with the respective attributes and metadata.

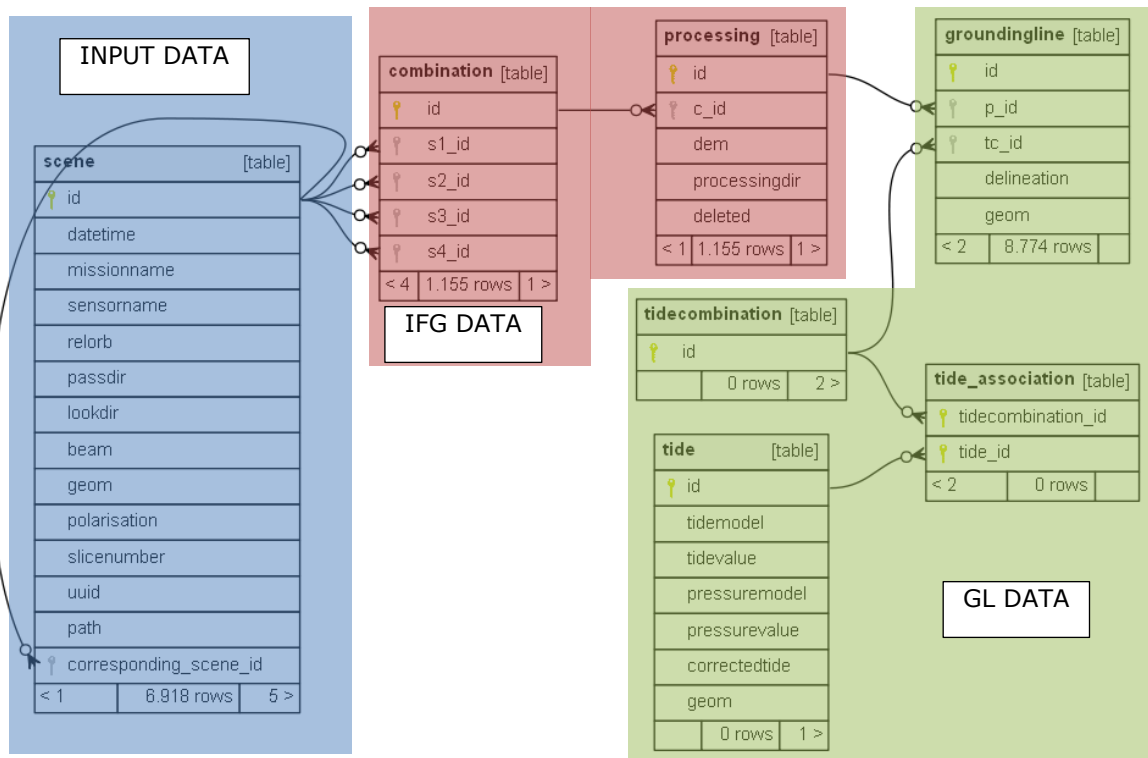
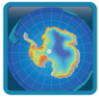
#### **Exporter routine:**

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 cryoport. 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, .csv, .kmz). All the GLL products can be delivered as a portable database dump (.sql) if it is required to ENVEO.

## **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.





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

#### 4.4.2 Operating system

Sun Fire X4800 M2: Oracle Solaris 10 x86

#### 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
- IDL
- Perl 5.8.4

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:

- CATS0201 TMD (tide model driver)
- OTPS (OSU tide prediction software)
- PostgreSQL, PostGIS, pgAdmin

## 4.5 Future concerns and developments

The GLL production system is not fully automated at present. The system is able to detect GZ automatically from gradient deformation map on some key glaciers. In order to differentiate the GZ properly from other features and noise, the threshold values of deformation gradient has to be defined. These threshold values for GZ are varied on different glaciers. Other parameters e.g. SAR sensor characteristics, imaging geometry, ocean tide model (at the time of acquisition) also influence the threshold values. We are trying to set the threshold values of GZ according to the impact of these parameters.

Most of the cases the noise, which has very low coherence, is estimated high gradient deformation values. Hence it is not suppressed completely by setting gradient threshold values. The coherence image is used to find the decorrelated areas correspond to noise and masked out from the gradient deformation map. Although the noises are removed, some areas of the GZ are disrupted. Therefore, we have to find a more sophisticated way for noise removal without any interruption of GZ.

"Fringe frequency based automatic GZ detection" module in GLL system takes less than 10 minutes to estimate magnitude of gradient deformation from ERS-1/2 or TerraSAR-X single or double difference interferogram. On the other hand almost 90 minutes is needed to estimate gradient deformation from Sentinel-1 A/B. This is due to the fact that the deformation gradient is estimated from each single burst of the beam of Sentinel-1 double difference interferogram. The estimation of gradient deformation on each beam of Sentinel-1 double difference interferogram can be minimized by utilizing multiple processors.

## 4.6 References

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## 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. Predictions from geophysical models for atmosphere, ocean, continental hydrology, and ice sheet surface mass balance (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.

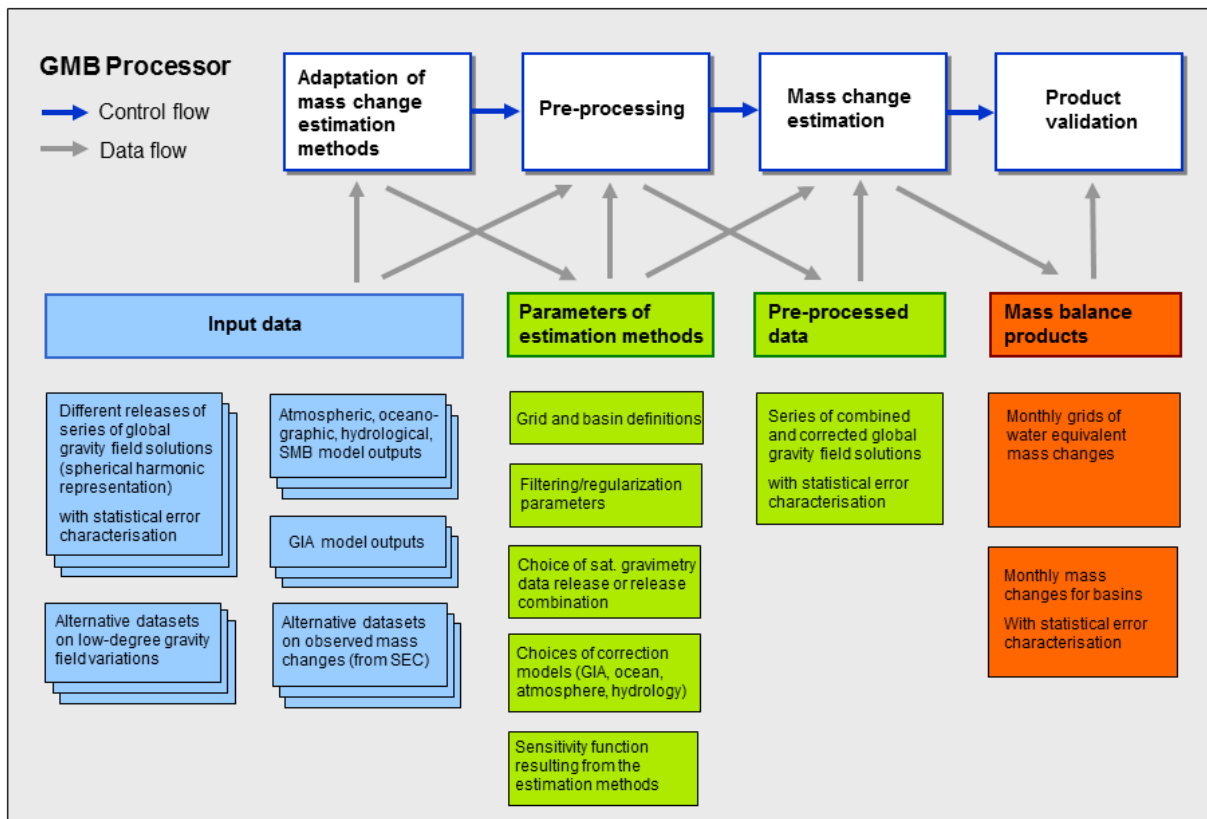
The GMB processing can be completed within a few working days, once the adaptation of the method is completed. Both the GMB basin product (ASCII format) and the GMB gridded product (ASCII, NetCDF, Geotiff format) will be generated using the most recent GRACE(FO) monthly solutions available at this time. 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](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

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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 in WP322, 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://isdctftp.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 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 case 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

<b>Model</b>	HP Pro Desk 600 G2 MT
<b>Processor</b>	Intel® Core™ i7-6700 CPU @ 3.4GHz (8 Cores)
<b>Memory (RAM)</b>	32 GB
<b>Local Hard Drive</b>	1 TB
<b>Network Attached Storage</b>	12 TB


### 5.3.2 Operating system

The operating system in use is the Linux system Ubuntu 14.04 LTS (long-term support). We foresee an update to the most recent LTS version (Ubuntu 20.04 LTS).

### 5.3.3 Tools and libraries

The core GMB production system is implemented using the commercial numerical computing environment Matlab version R2018n (9.5). 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](http://www.unidata.ucar.edu/software/netcdf)) is used. The tool `gdal_translate` from the Geophysical Data Abstraction Library ([www.gdal.org](http://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](http://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

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prepared by means of the Generic Mapping Tools (GMT) package ([gmt.soest.hawaii.edu](http://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 actual 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 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](http://cci.esa.int/sites/default/files/CCIDataStandards_v2-2_CCI-PRGM-EOPS-TN-13-0009.pdf)

**Table 6-1:** Top level CCI Data Standards Requirements

ID	Description
R-1	CCI projects shall produce data according to the CCI Data Standards Requirements: <ul style="list-style-type: none"> <li>Produced in netCDF-4 (classic) format</li> <li>Conform with the CF (Climate and Forecasting) convention</li> <li>CF standard names used for the main variables</li> <li>Include defined set of global attributes [AD4]</li> </ul>
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.

## 6.1 Line format in netCDF

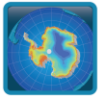
There is no line data format specification which is of relevance to GLL. The line data will be provided in NetCDF closely matching the "PolyLine" data structure of ESRI shapefiles, see [RD13].

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