

ESA Climate Change Initiative (CCI)

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

System Specification Document (SSD)

Prime & Science Lead: Andrew Shepherd

University of Leeds, UK

A.Shepherd@leeds.ac.uk

Technical Officer:

Marcus Engdahl

ESA ESRIN, Frascati, Italy

Marcus.engdahl@esa.int

Consortium:

British Antarctic Survey (BAS)

Deutsches Zentrum für Luft- und Raumfahrt, Institut für Methodik der Fernerkundung (DLR-IMF)

DTU-Space, Department of Geodynamics (DTU-GDK)

DTU-Space, Department of Microwaves and Remote Sensing (DTU-MRS)

ENVironmental Earth Observation IT GmbH (ENVEO)

Science [&] Technology AS (S[&]T)

Technische Universität Dresden (TUDr)

Technische Universität München (TUMu)

University College London (UCL)

University of Leeds, Centre for Polar Observation and Modelling (CPOM), (UL)



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Signatures page



Prepared by	D. Fantin Lead Author, Task 3 Lead, S[&]T	Date: 2017-10-20
Issued by	K. Hauglund Project Manager, S[&]T 	Date: 2017-11-01
Checked by	Andrew Shepherd Science Leader, UL 	Date: 2017-11-01
Approved by	Marcus Engdahl Technical Officer, ESA	Date:

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Change Log

Issue	Author, Org.	Affected Section	Reason/Description	Status
1.0	D. Evensberget / S[&]T	All	First issue, year 1	Released to ESA 2016-05-05
1.1	D. Floricioiu / DLR A. Groh / TUDr	4 5	Update for Year 2: Section on GLL updated Section on GMB updated	Released to ESA 2016-10-11
1.2	A. Muir / UCL J. Wuite / ENVEO D. Floricioiu / DLR	2 3.1 – 3.2 4	Update for Year 3: Updates on SEC Updates on IV Minor updates on GLL	Released to ESA 2017-11-01

Distribution List

Organization	Consortium Member
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DLR	Tanvir Chowdhury
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S[&]T	Daniele Fantin
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TUDr	Martin Horwath
TUDr	Andreas Groh
TUM	Alexander Horvath
UCL	Alan Muir
UCL	Steven Baker
UL	Andrew Shepherd
UL	Anna Hogg

Acronyms and Abbreviations

Acronym	Explanation
ADD	Antarctic Digital Database
AIS	Antarctic Ice Sheet
AIS_CCI	Antarctic Ice Sheet CCI project
ATBD	Algorithm Theoretical Basis Document
CCI	Climate Change Initiative
CSR	Center for Space Research
DLR IMF	Deutsches Zentrum für Luft- und Raumfahrt (DLR) Remote Sensing Technology Institute (IMF)
DTU-GDK	DTU Geodynamics Group
DTU-MRS	DTU Microwaves and Remote Sensing Group
ECV	Essential Climate Variable
ENVEO	ENVEO ENVironmental Earth Observation IT GmbH
EPSG	European Petroleum Survey Group Geodesy
FM	Forward Modelling
GFZ	GeoForschungsZentrum Potsdam
GIA	Glacial Isostatic Adjustment
GIS	Greenland Ice Sheet
GLL	Grounding Line Location
GMB	Gravimetric Mass Balance
GRACE	Gravity Recovery and Climate Experiment
GRACE SDS	GRACE Science Data System
ITSG	Institute of Theoretical Geodesy and Satellite Geodesy
JPL	Jet Propulsion Laboratory
IV	Ice Velocity
NSIDC	National Snow and Ice Data Center
PIG	Pine Island Glacier
RA	Radar Altimetry
RI	Regional Integration
RR	Round Robin
RRR	Rapid Round Robin
SAR	Synthetic Aperture Radar
SEC	Surface Elevation Change
SLC	Single Look Complex
SLR	Satellite laser ranging
SMB	Surface Mass Balance

TAM	Transantarctic Mountains
TSX	TerraSAR-X
TUDr	Technische Universität Dresden
TUM	Technische Universität München
UCL	University College London
UL	University of Leeds

1 Introduction

1.1 Purpose and Scope

This document is part of Task 3 Systems Evolution within the Antarctic_Ice_Sheet_cci (AIS_cci) project, as part of ESA Climate Change Initiative (CCI) program.

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

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
AD1	ESA/Contract No. 4000112227/15/I-NB, and its Appendix 1	Phase 2 of the ESA Climate Change Initiative, Antarctic_Ice Sheet_cci	2015.04.14	-
AD2	CCI-PRGM-EOPS-SW-12-0012 Appendix 2 to contract.	Climate Change Initiative – SoW Phase 2	2014.06.11	Issue 1 Revision 3
AD3	CCI-PRGM-EOPS-TN-12-0031	CCI System Requirements	2013.06.13	Version 1
AD4	CCI-PRGM-EOPS-TN-13-0009	Data Standards Requirements for CCI Data Producers	2015.03.09	Version 1.2

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.

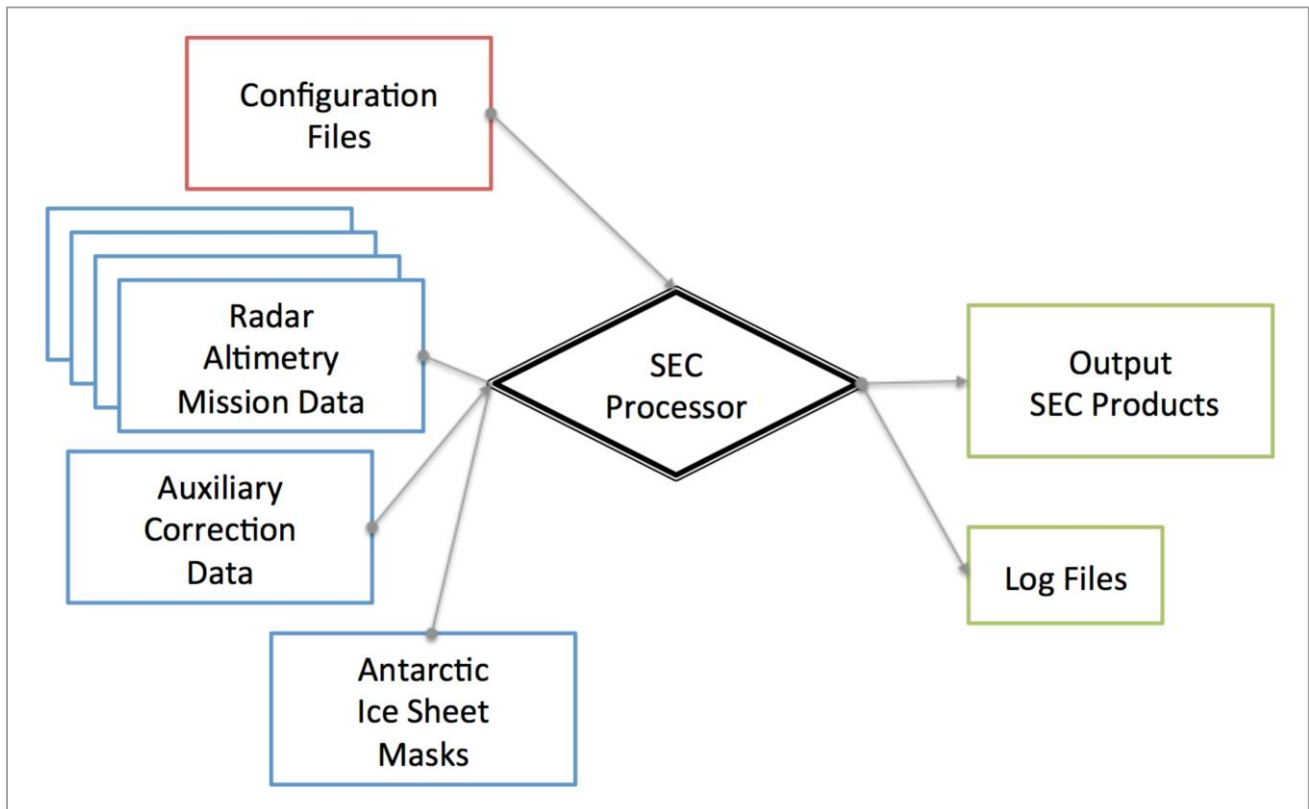


Figure 2.1: SEC ECV Processor Input/Output

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.

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	GDR v2.1	ESA	9-Apr-02 to 18-Oct-10
CryoSat-2	L2i SIN	Baseline-C	ESA	16-Jul-10 to (now-90days)
CryoSat-2	L2i LRM	Baseline-C	ESA	16-Jul-10 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
ENVISAT/ GDR v2.1	PTR Correction	ESA/UCL	UCL
ENVISAT/ GDR v2.1	Dry Tropospheric Correction	ECMWF/UCL	UCL
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-90-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** when there is availability of new altimetry data from current satellites (such as CryoSat) 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).

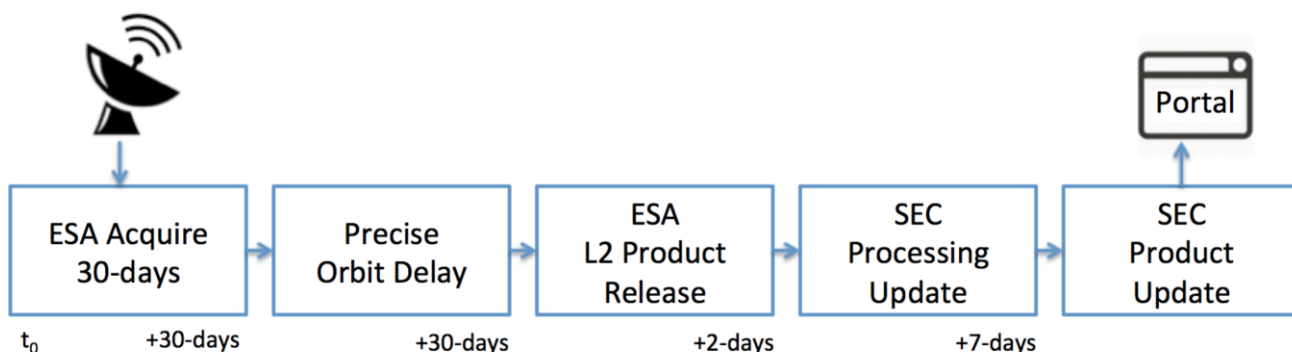


Figure 2.2: SEC Product Update Time Line for new CryoSat or Sentinel-3 data.

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.

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.

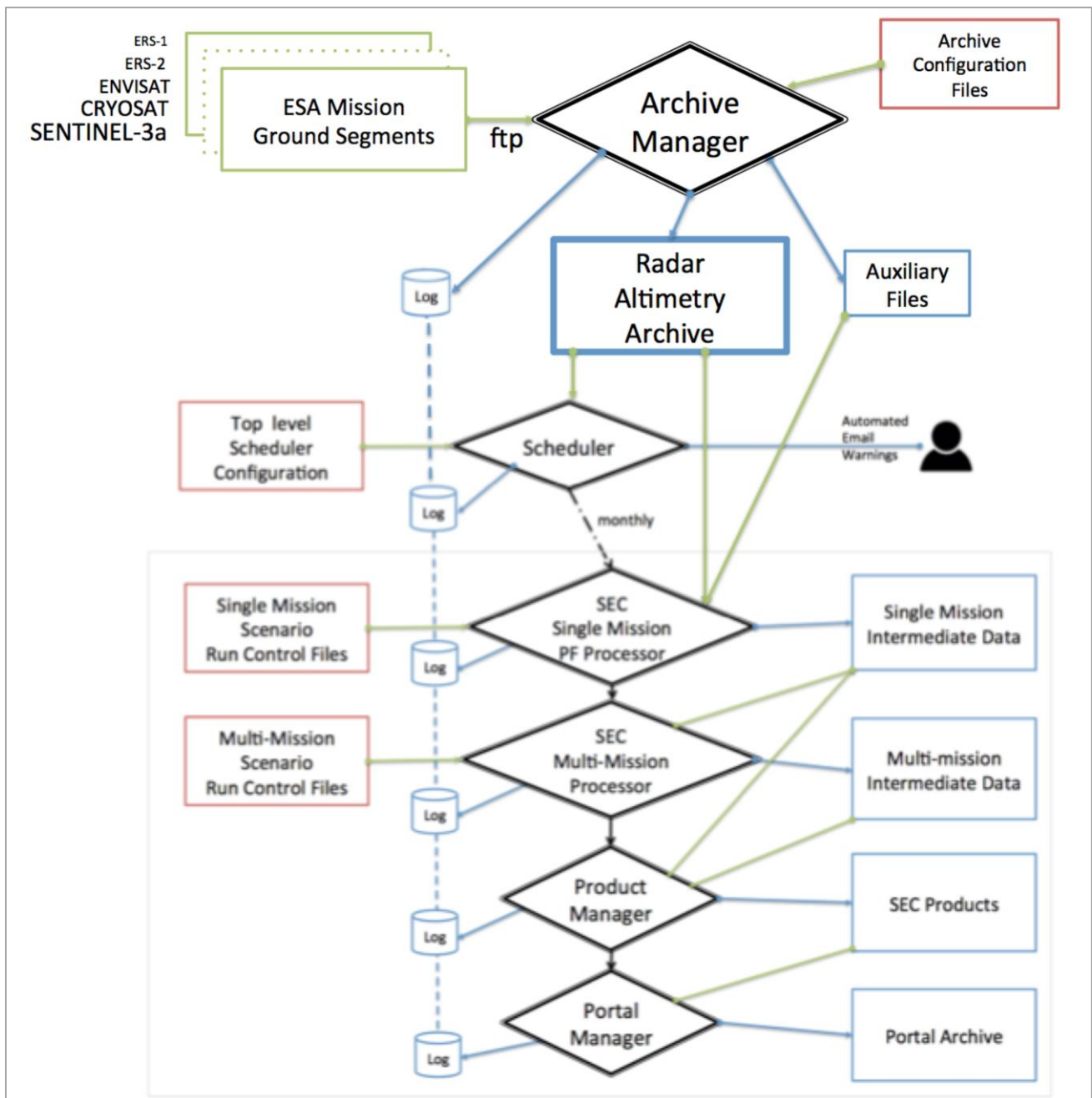


Figure 2.3: SEC ECV Production System Top Level Processes

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) 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 (after commissioning). 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.

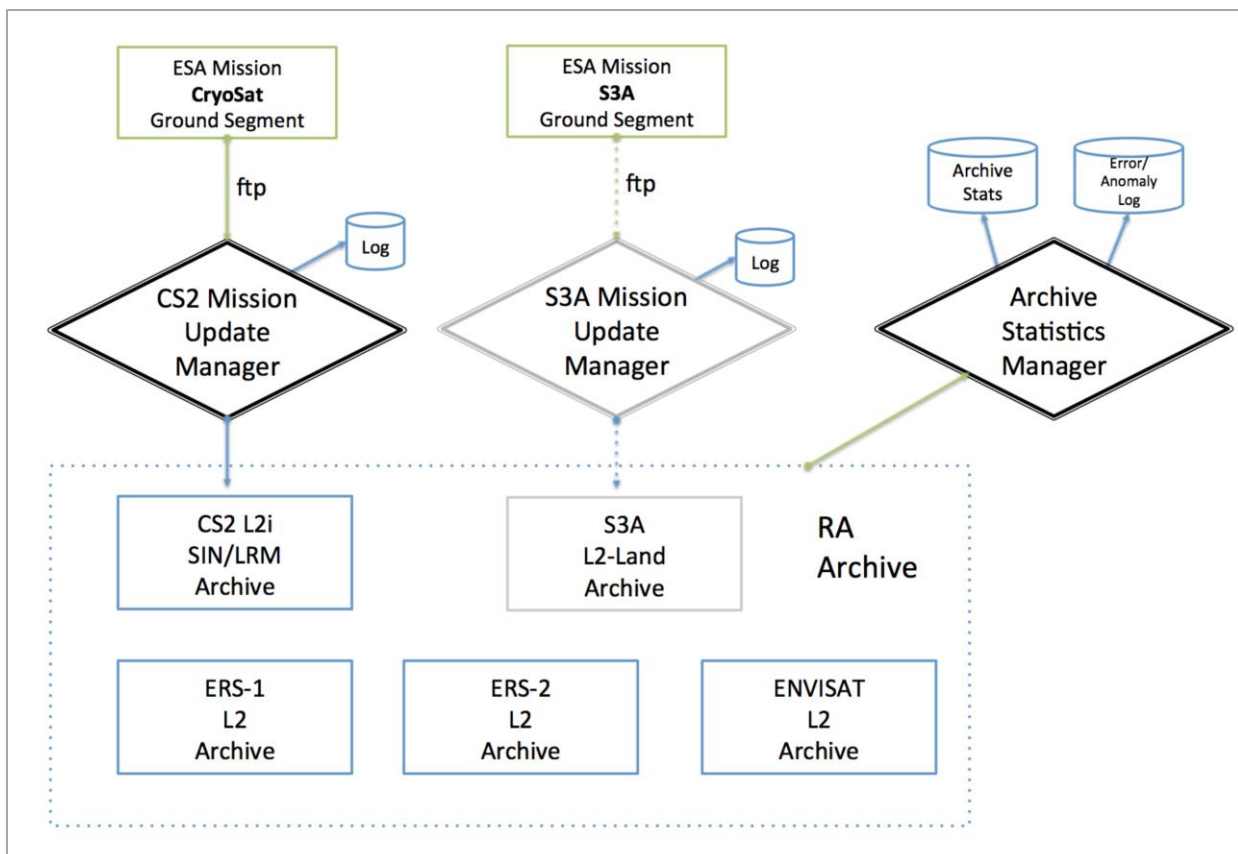


Figure 2.4: SEC Archive Manager

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 1st day of each month) and will initiate the single mission plane fit processor for each live mission that has new validated data (in 2016 this will be CryoSat, with S3A added following commissioning). 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:

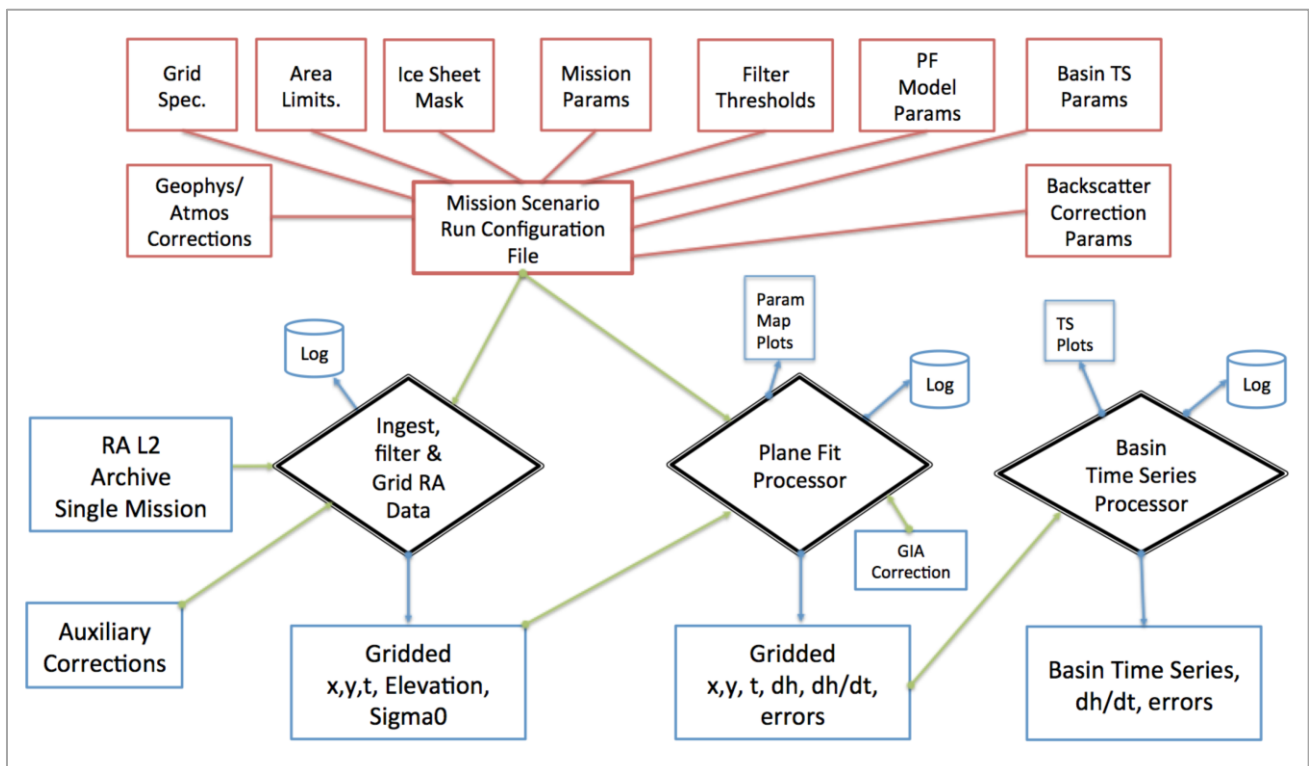


Figure 2.5: SEC Single Mission Plane Processor

- 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 as an IDL format save file. 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) **Plane Fit Processing.** The Plane 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.

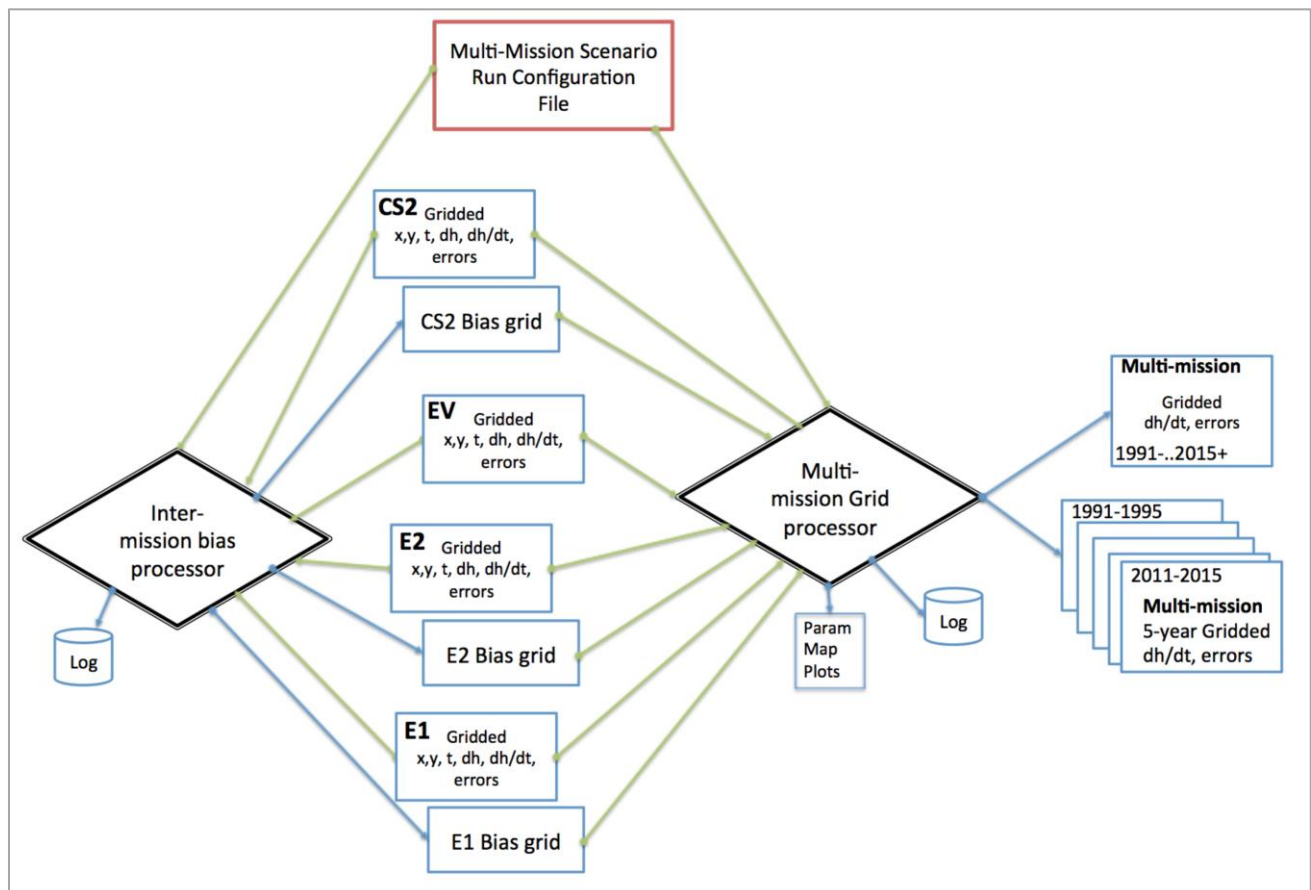


Figure 2.6: SEC Multi-mission dh/dt processor

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 IDL sav 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.

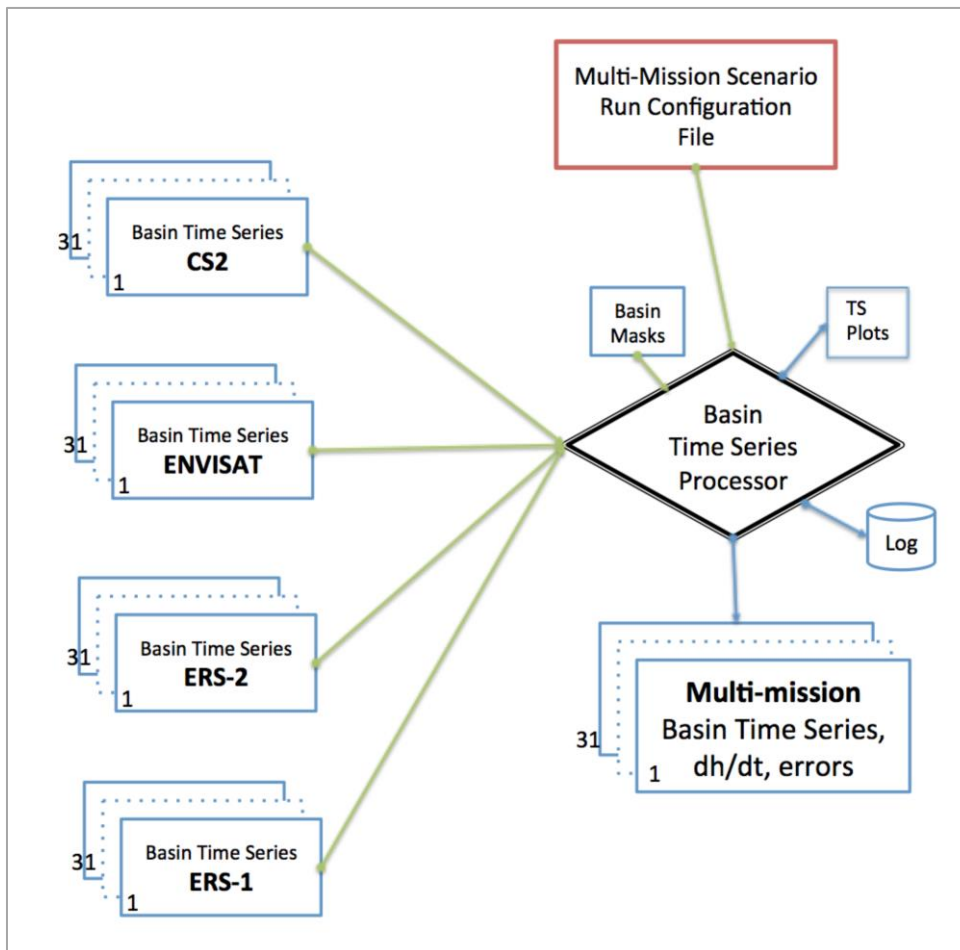


Figure 2.7: Multi-mission Basin Time Series Processor

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).

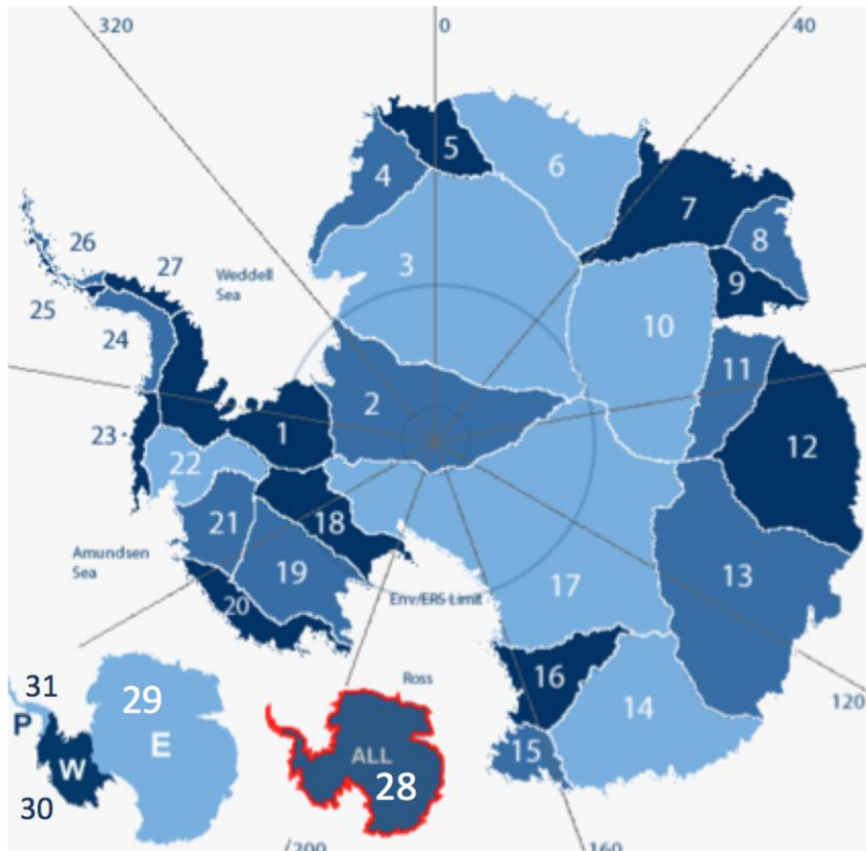


Figure 2.8: Antarctic Drainage Basin and Sector Numbering

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.

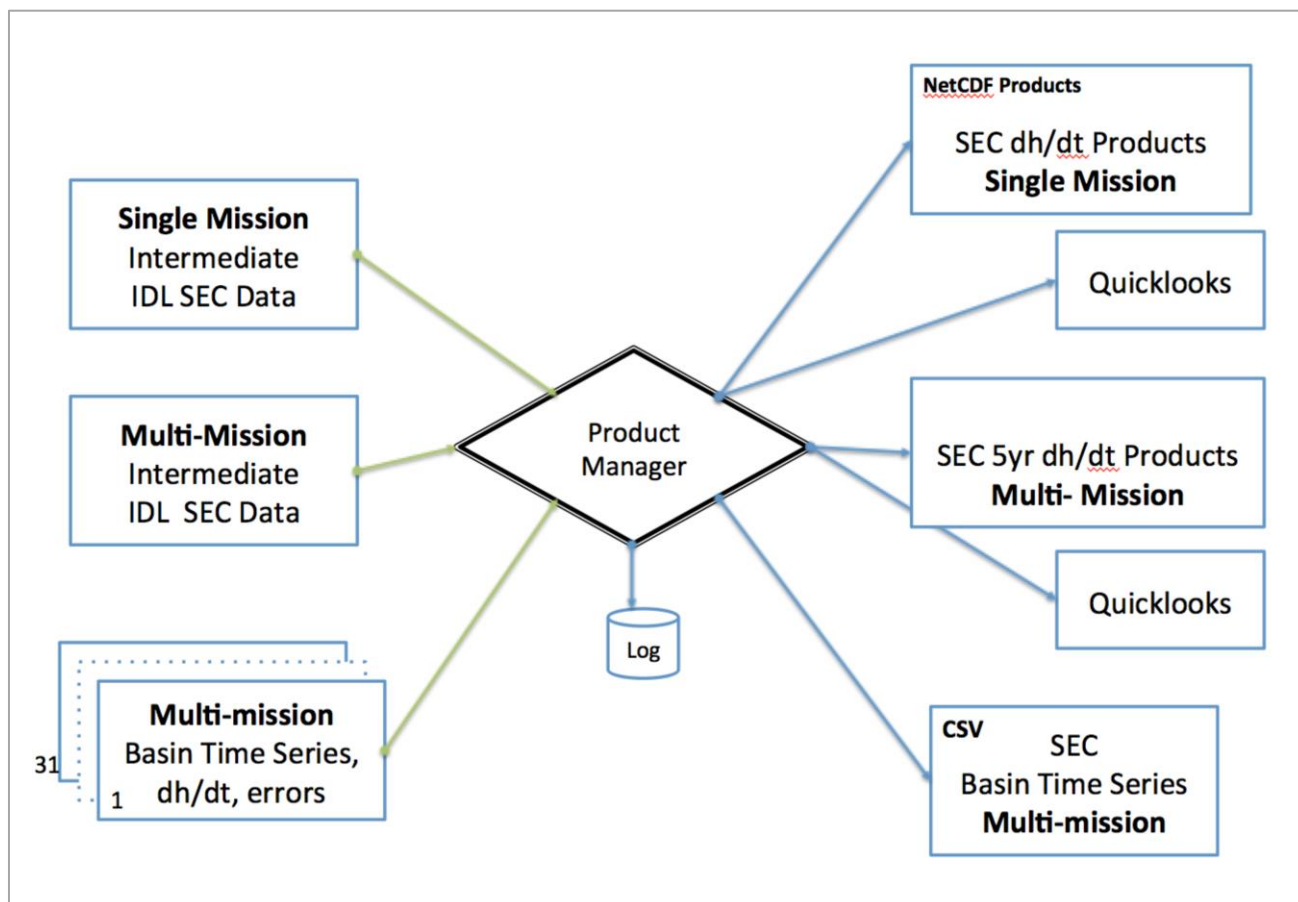


Figure 2.9: SEC CCI Product Manager

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.

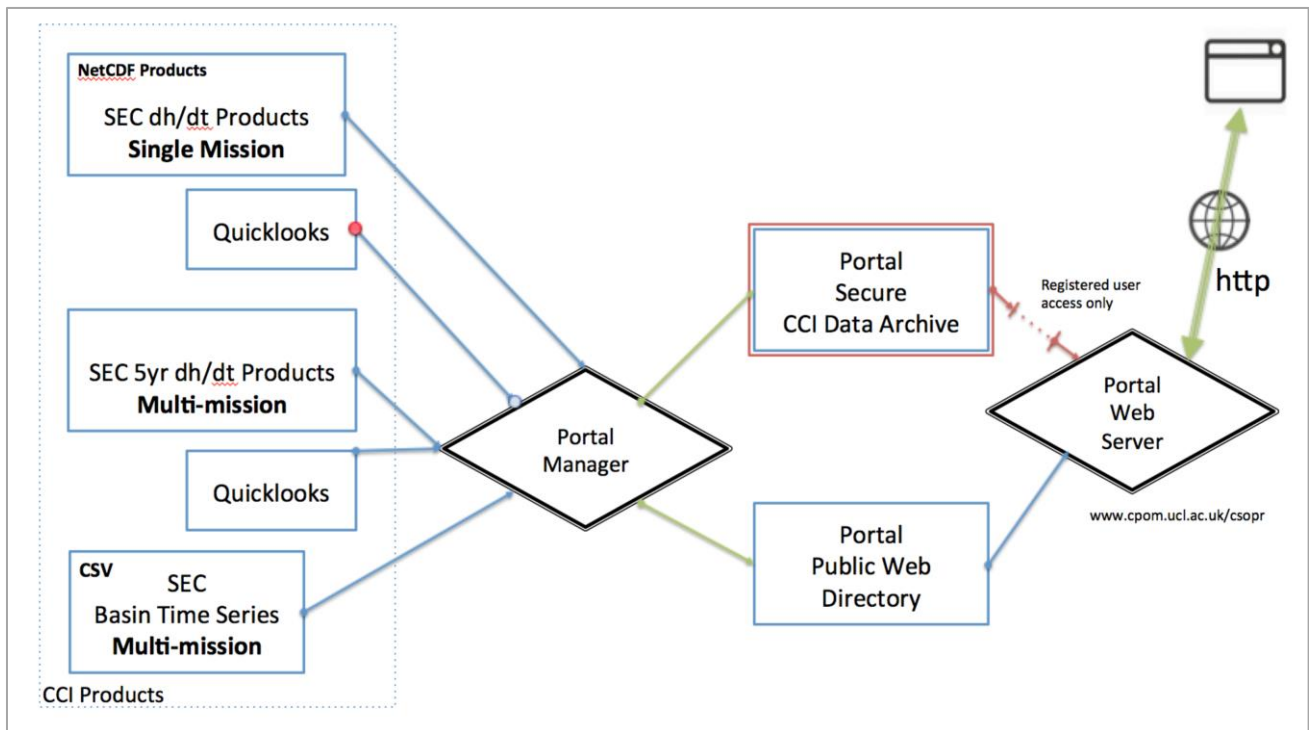


Figure 2.10: SEC Portal Manager

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):

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:

Geophysical Corrections Applied	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).

% Ice-1 Retracker Failure Threshold	20%
% CryoSat SARin Retracker Failure Threshold	10%

Grid Projection

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

Projection	Polar Stereographic
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	Zwally, et al, 2012, Basin 1-27
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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)
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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	REAPER v1.0 GDR 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	REAPER v1.0 GDR 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	GDR v2.1
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

Scenario Name	ant_cs2_lrm_5km
Mission	CryoSat
L2 Data Source	ESA Baseline-B
Operational Start Date	1/7/2010
Operational End Date	22/2/2015
Number of Expected L2 Files Read	362041
Tracking Mode	LRM
Apply LRM Time Tag Bias for Baseline-B	Y
Surface Type	Land & Ice (from parameter in L2i)
Retracker Selected	Ice-1/CFI
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	ESA Baseline-B
Operational Start Date	1/7/2010
Operational End Date	31/12/2016
Number of Expected L2 Files Read	362041
Tracking Mode	SARin
Apply LRM Time Tag Bias for Baseline-B	N
Surface Type	Land & Ice (from parameter in L2i)

Retracker Selected	SARin Retracker
Filter on Retracking Flag	Y
Filter on MCD Flag	Y
Filter on Overall Measurement Quality Flag	Y
Backscatter correction period	3 years
Backscatter correction start/stop	2010.9 2015.9
Minimum time range (in years) of grid time series	4 years

2.3 Hardware and software platform

The SEC operational ECV production system will run on most UNIX (Linux or Solaris x86) servers with adequate memory, disk storage space and IDL licenses. The current SEC processing system is operated and tested on a server system running the **Linux CentOS 6.9** operating system.

2.3.1 Hardware

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

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

2.3.2 Operating system

The system currently runs on the **Linux CentOS 6.9** operating system.

The system may be ported to other Unix/Linux systems that support installation of IDL 8.x or above.

2.3.3 Tools and libraries

The system requires:

- i) a licensed installation of IDL v8.x.
- ii) ImageMagick 6.9 libraries or greater.
- iii) gcc v4.9.2 or greater
- iv) NetCDF v4 library
- v) XVfb

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 year 3 of the Antarctic Ice Sheets CCI project to include some or all of the following features:

New Altimetry Data Sets and Missions scheduled during 2017-2018:

- i) Develop ingest algorithm for Sentinel-3a Radar Altimetry data. Test and process after commissioning of the satellite for land ice is scheduled to complete in Q1 2018.

New Processing Methods and Parameters:

- i) Add a firm correction to the SEC data.
- ii) Process SEC to also produce volume change and mass balance product.
- iii) Consider merging results from crossover processing and the current plane fit solution to produce a combined SEC product.
- iv) Once there are consistent L2 data sets from all missions incorporating a validated and tuned Ice-2 or equivalent retracker, the backscatter (volume scattering) correction can be improved by including data from the leading edge width in the model.
- v) Incorporate improved slope models/DEMs to improve accuracy in areas of high slope where existing models used in ESA L2 products are poorly represented.

3 Ice Velocity (IV)

3.1 System overview

In this section, we describe the processing system for deriving ice velocity maps from repeat pass SAR data applying offset tracking techniques. Figure 3.1 shows the **high-level** processing line for the IV production. It includes 3 modules:

- Module IV: within this module SAR data are imported into the system and velocity maps **are** generated for pairs of repeat pass SAR data of the same track. The output is a time series of ice velocity maps in map projection defined by the user.
- MODULE MERGE: this module combines the IV products from various tracks and image pairs. The output is a merged ice velocity map (3 components) and a quality/**error** map(**based on the standard deviation**).
- MODULE VAL: the validation module is an associated module, which enables the intercomparison and validation of the generated ice velocity map with velocity measurements **from other sources**. The output is statistical information on the intercomparison and scatterplots compiled in a quality assessment report.

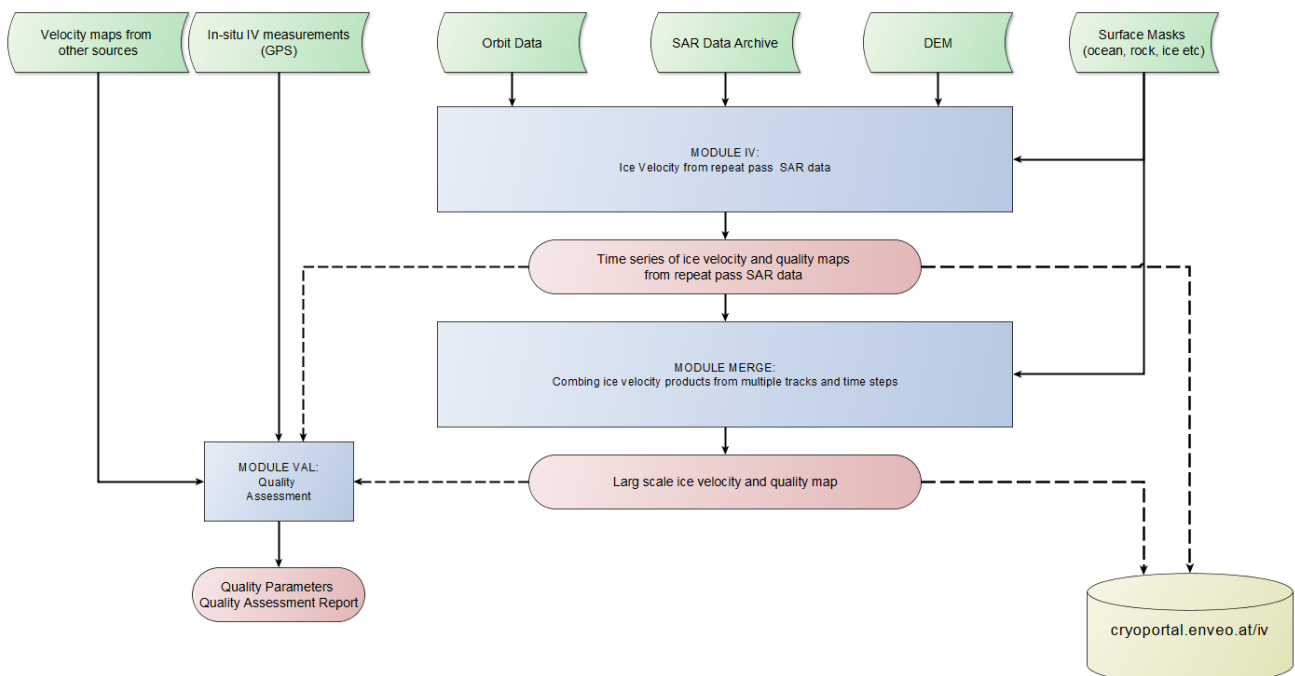


Figure 3.1: High-level flow chart of the IV processing system. Green – input data, Blue – processing modules, red - product and intermediate products.

3.1.1 MODULE IV

Figure 3.2 shows a **high-level** flow line of the ice velocity generation module. **For** Sentinel-1 IW SLC data the processing is done on burst level. In the case of Stripmap

mode data the processing is done on scene / frame level, which is very similar. Here we 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 time periods. Using image geometry and a digital elevation model the local shift between two bursts is calculated which is considered in the displacement calculation using incoherent (or coherent) offset tracking. Beside the displacements in slant range and azimuth the quality of the matching is calculated. Debursting of all processed burst pairs forms the displacement map in SLC geometry. After outlier removal, the velocity of the 3 components is calculated using a DEM. Optionally, a surface mask is applied to mask ocean and un-glaciated areas.

The output of this module are velocity maps (E, N, ΔZ) in m/d per track and time step, and a quality map. These products are useful for monitoring the short-term variations of glacier velocities.

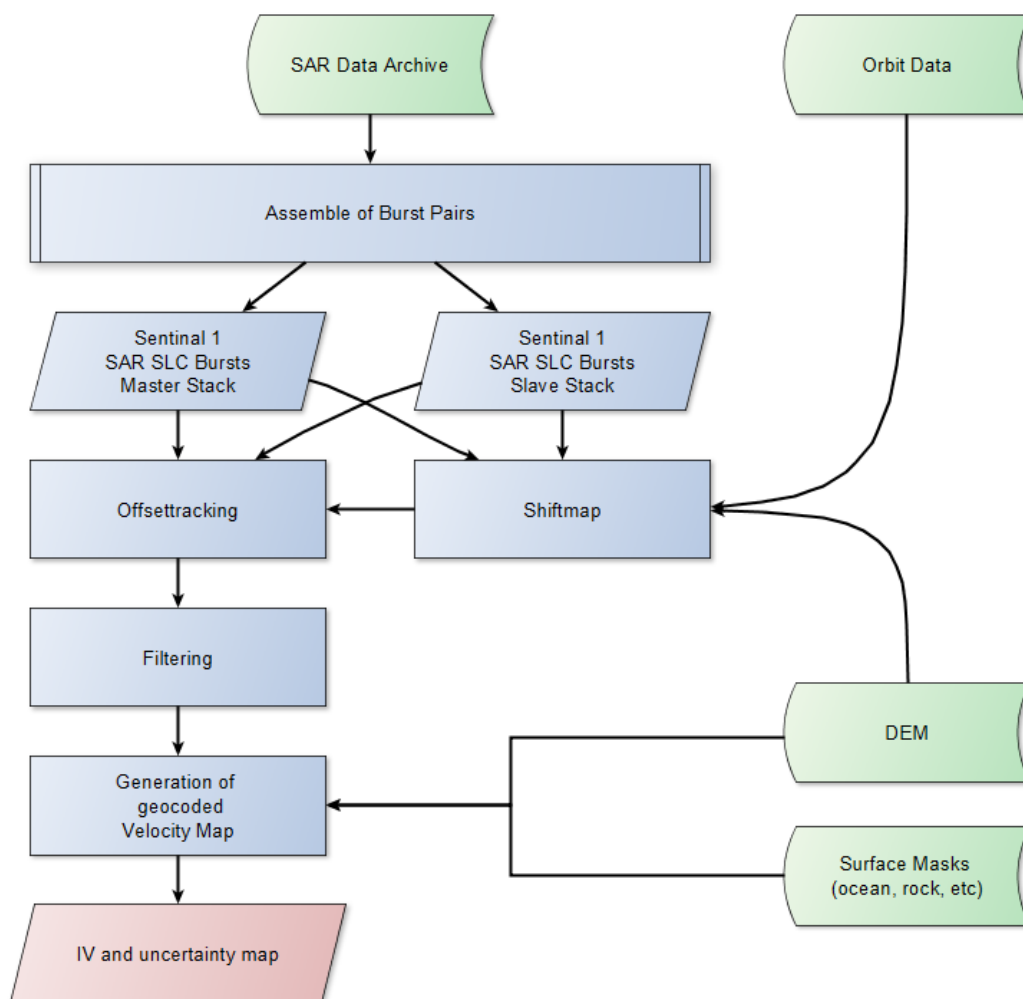


Figure 3.2: Processing steps for ice velocity generation using Sentinel-1 IW TOPS SLC data.

3.1.2 MODULE MERGE

This module aims to produce a **large-scale** ice velocity map using the output of the MODULE IV as input. The merging combines the velocity components separately in m/d. The output of this module is a large scale, regional or continental ice velocity and quality/error map **based on the standard deviation**.

3.1.3 MODULE VAL

The validation module aims for an independent validation of the ice velocity product using ice velocity data **derived from other sources (e.g. TerraSAR-X, GPS)**. The module intercompares the velocity components separately, but can be also applied to magnitude velocities. The module takes different map projections into account, and provides statistical parameters of the pixel-by-pixel intercomparison, histograms, and spatial maps of the differences.

3.1.4 MODULE IV-DATABASE

The ice velocity products are linked to the IV database at cryoportal.enveo.at. The web-based portal allows easy access and simple analysis of the time series ice velocity products and regional/ continental IV maps.

The current versions support the following analysis

- Ice velocity visualisation and download of data:
 - Visualize the **complete** time series of ice velocity profiles along pre-defined central flow lines of glaciers
 - Visualize the **complete** time series of velocity on points along the flow line
- Mass flux calculation
 - For single glaciers
 - Sub basins
 - Basins
 - Ice sheet wide
- Visualisation of time series of calving fronts

3.2 Operational scenarios

Operational observations are mainly planned using Copernicus Sentinel-1 A/B satellites. There are generally two processing scenarios applied:

- Continuous observations of key regions
- Production of regional / continental ice velocity map

The track by track processing is applied on regions where continuous acquisitions of SAR data are acquired, as for example S1 IW data over key areas in polar regions. 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). This observation scenario has been proposed by ENVEO and implemented by ESA for the Greenland margins with continuous acquisitions of S1 data acquired in 6 tracks since June 2015. Continuous monitoring with S1 SAR is also 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 3.3). The addition of additional tracks is foreseen.

Regional / continental ice velocity maps are generated on an annual basis for Greenland and Antarctica, and rely on the acquisition campaigns defined by ENVEO in agreements with CCI project partners, ESA and members of the PSTG group. They are performed additionally to the continuous acquisitions of S1.

Currently annual acquisition campaigns for Greenland Ice sheet are planned, with 4 repeat acquisitions for each track, preferable in the period December to March (Greenland) and May to September (Antarctica). To produce a complete map, ENVEO operates IV processing within 10 days after image acquisition, and provides ESA feedback on further needed acquisitions to close gaps in the IV product with low coherence. For Antarctica, a complete acquisition campaign (minus polar gap) is currently under consideration for every 3-5 years.

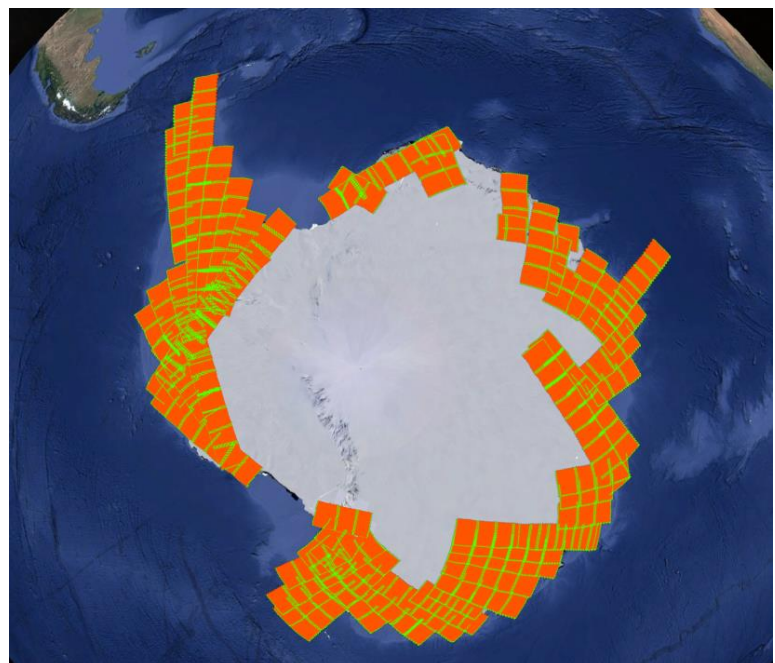
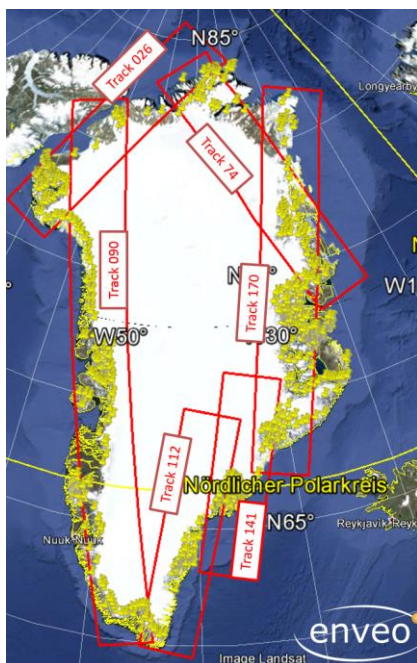


Figure 3.3: Left: Selected Sentinel-1 tracks for continues monitoring of Greenland margins (implemented since June 2015). Right: continuously acquired repeat tracks (6 & 12 days repeat interval) in Antarctica implemented since July 2017.

3.3 Hardware and software platform

The main processing at ENVEO will be performed on the processing system described below. Development, visualization and quality control is done on development machines.

3.3.1 Hardware

The main processing is done on 2 server machines, which are connected to the mass storage of about 800 TB.

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

	Processing	Development, Visualization, Quality Control
Model	GNU/Linux Centos 7	GNU/Linux Fedora
Number of WS	2	8
Processor	Intel Xeon CPU E5-2650 v2 @ 2.60GHz 32 threads	Intel Core i7-2600 CPU @ 3.40GHz
Memory (RAM)	128 GB	16 GB
Local Hard Drive	300 GB	1 TB
Network	Ethernet 10000baseT/Full	Ethernet 10000baseT/Full
Network Attached Storage	Ca 800 TB network storage	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 22 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/software/netcdf/>
- wget <https://www.gnu.org/software/wget/>
- gzip <http://www.gzip.org/>

Visualisation Tools

- QGIS <http://qgis.org>
- Web Cryoport Ice Velocity (developed by ENVEO) <https://cryoportice.enveo.at>

3.4 Future and developments

Further improvements of the software are planned. The ESP software has successfully 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 cryoportel (<http://cryoportel.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. and Figure 4.2. 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 is able to detect GZ automatically but derivation of upper flexure limit of GZ is traced manually.

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 EOLI-SA or EOWEB. These working steps are summarized with the box 'manual search and data order'.

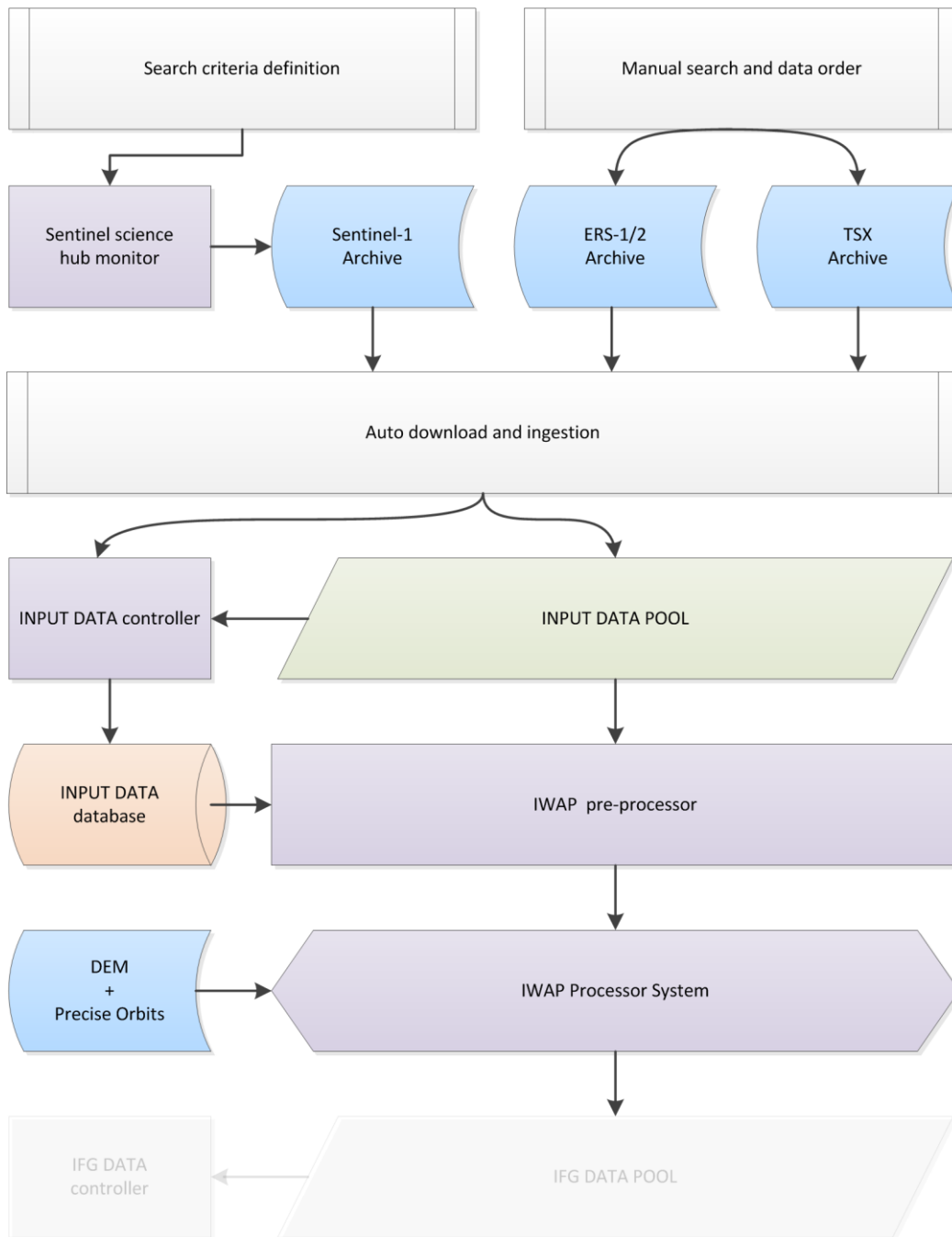


Figure 4.1: System overview flowchart: part one. Input data in light blue, processes in violet, database systems in orange, manual processes in grey, intermediate processing results in light green.

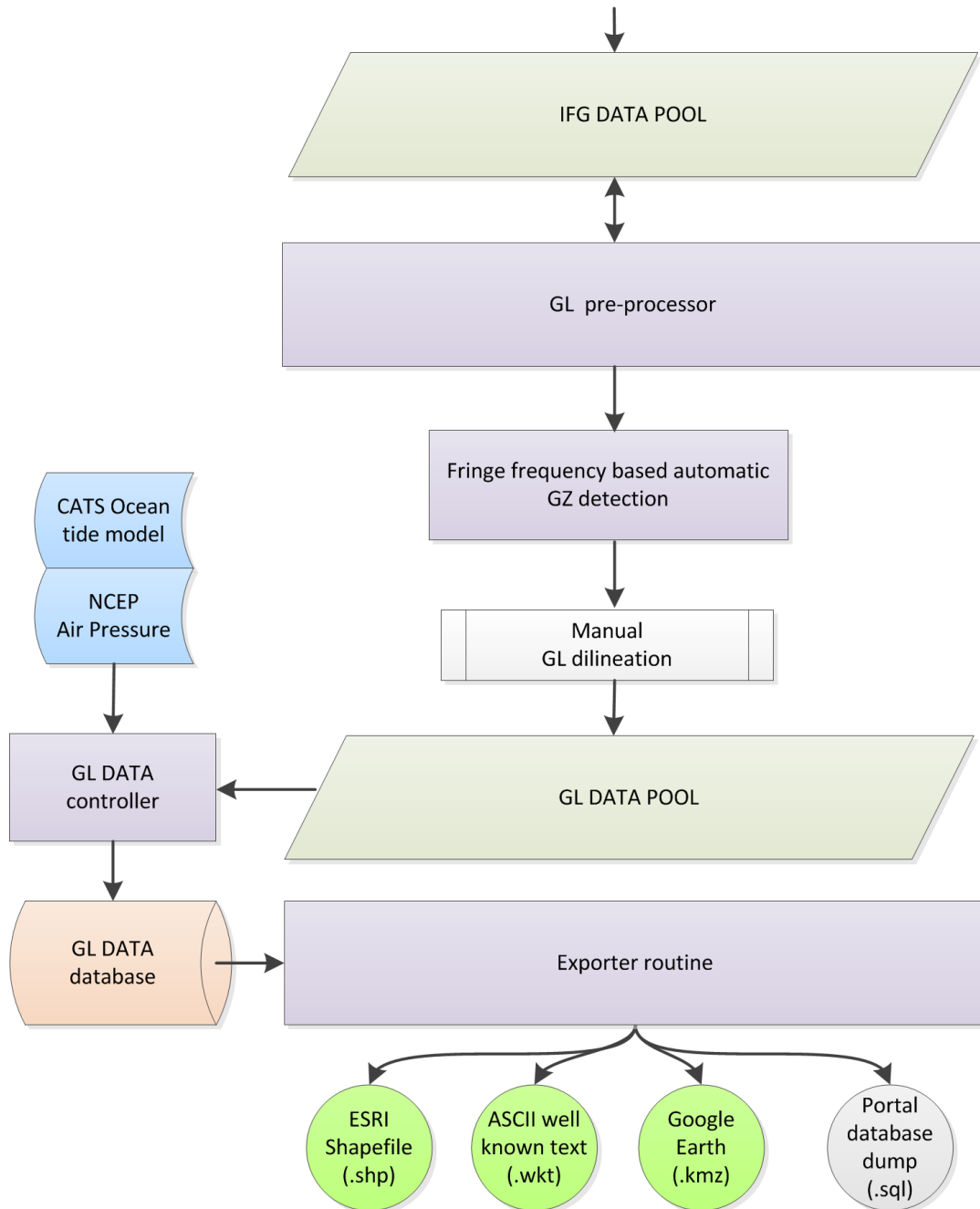


Figure 4.2: System overview flowchart: part two. Input data in light blue, processes in violet, database systems in orange, manual processes in grey, intermediate processing results in light green and products in lime green.

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 EOLI-SA nor EOWEB 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*'. Since downloading Sentinel products often causes corrupt files, the zip archives are tested for their integrity – corrupt zip files are downloaded again.

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*' which contains metadata such as acquisition time, acquisition mode, look direction, pass direction, relative orbit number, if applicable frame and beam, spatial coverage (center longitude and center latitude) 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 mysql 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, the coherence and (if applicable) the double differences are copied into the '*IFG DATA POOL*' and the '*IFG DATA controller*' is launched (IFG hereby stands for Interferogram).

IFG DATA POOL: Consists of one or more predefined directories which accommodate the above mentioned processing results of the IWAP. It contains the subdirectories 'IFG' and 'DDIFG' in order to discriminate simple interferograms and double difference interferograms. 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' and 'DDIFG' subdirectories and determines double difference interferograms. It also updates all the configuration files for running the fringe frequency based GL detector.

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

The fringe frequency method is applied to the single or double difference interferogram and estimate the deformation gradient while obtaining a measure for the noise associated with this estimate. By setting the gradient threshold values, the GZ is detected.

Manual GL delineation: The location of the upper limit flexure of GZ needs to be mapped which is so far not automatic. Gradient deformation 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 the Antarctica into 11 different regions. The GLL products of each region 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 Operational scenarios

The GLL system is performed to derive GLL on key glaciers from ERS-1/2 single interferogram and Sentinel-1a/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-1a/b, it takes almost 4 hours to perform downloading Sentinel-1a/b triplets, generating double difference interferogram and extracting GZ from gradient deformation map. After that an operator is required to upload the gradient deformation map 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.

4.3 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.

4.3.1 Hardware

Table 4-1: Processing Hardware at for the GLL processor

	Processing	Development, Visualization, Quality Control
Model	Sun Fire X4800 M2	Dell Precision T1600
Processor	Intel® XEON®, CPU E7-8870 @ 2.4 GHz 8x10 = 80 Cores	Intel® XEON®, CPU E31225 @ 3.1 GHz 1x4 = 4 Cores
Memory (RAM)	256 GB	16 GB
Local Hard Drive	300 GB	1 TB
Network Attached Storage	150 TB - Fibre Channel + normal NFS mounts	11 TB - Gigabit + normal NFS mounts

4.3.2 Operating system

Sun Fire X4800 M2: Oracle Solaris 10 x86

Dell Precision T1600: Ubuntu 14.04.3 LTS, x86_64 GNU/Linux

4.3.3 Tools and libraries

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

Development and processing:

- PyCharm 5.0.4 Community
- Eclipse Mars, CDT 8.8.1, Subclipse
- Subversion 1.8.8
- Python 2.7.6 and a variety of libraries such as shapely, fiona, pyproj, pygdal, sqlalchemy...
- GCC 4.8.5, CC
- IDL
- Perl 5.8.4

Analysis and visualization:

- QGIS 2.14 with GRASS GIS 7.0 plugins and others
- GMT 4.5.0
- Netcdf 3.6
- Python 2.7.6 and a variety of libraries such as numpy, matplotlib, pil, skimage, scipy...
- GDAL 1.11.2
- Firefox, Chrome
- Geany, Gedit, Nedit
- Google Earth 7.1.4
- GIMP 2.8.10
- gv, evince
- imagemagick

Data extraction and handling tools:

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

4.4 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-1a/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.

4.5 References

- [1] Adam, N., Kampes, B., Eineder, M., "Development of a Scientific Permanent Scatterer System: Modifications for Mixed ERS/ENVISAT Time Series," ESA Envisat Symposium, Salzburg, September 6-10, 2004.
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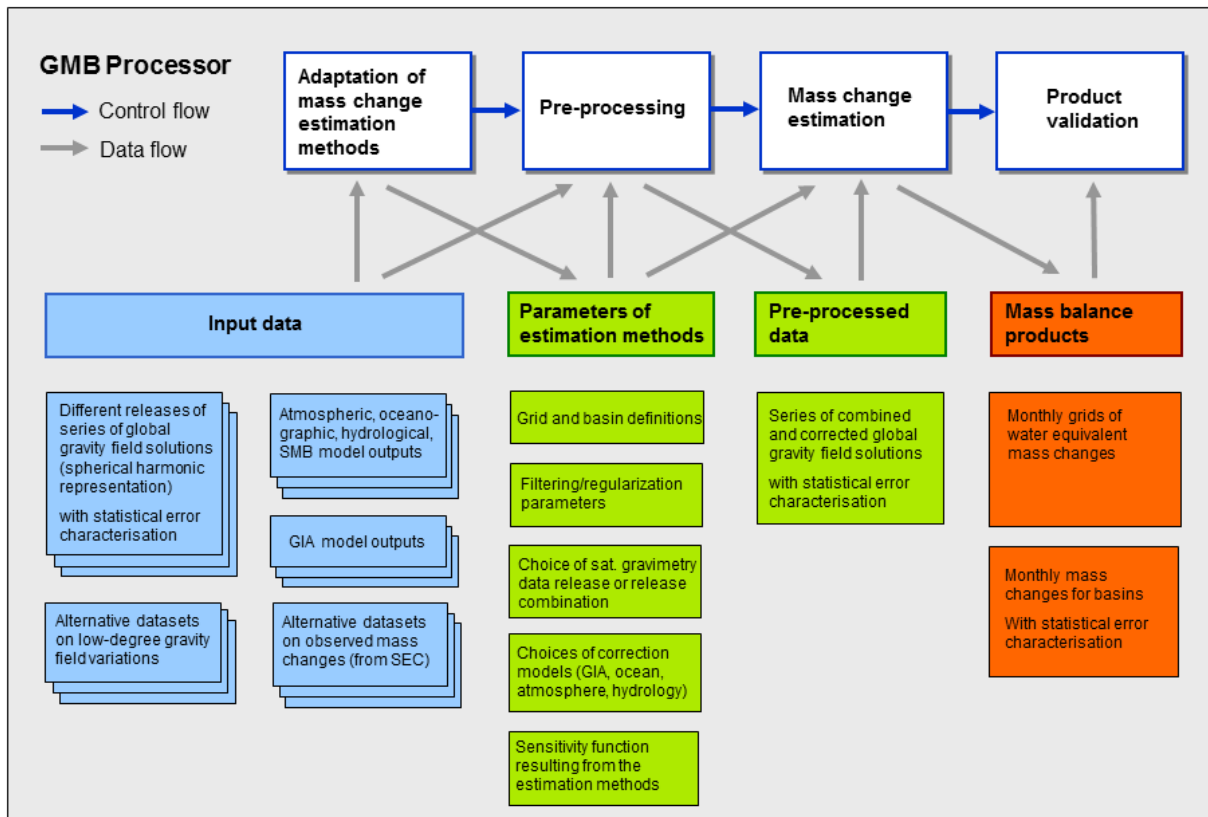
5 Gravimetric Mass Balance (GMB)

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 GRACE-derived monthly gravity field solutions, given in the spherical harmonic domain, provided by different processing centres (e.g. ITSG, CSR, GFZ) serve as main input. The release ITSG-Grace2016 (Klinger et al., 2016) was selected for the final product generation.

Additional datasets of low-degree spherical harmonics are required to add information not included in the GRACE monthly solutions (coefficients of degree one) or to replace inaccurate components of the GRACE dataset (C_{20} 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.

Nominally, GRACE solutions are provided on monthly intervals with a delay of four to six weeks. Because of the advanced age of the GRACE twin-satellites, the mission operation has been adjusted to ensure a maximum remaining lifetime. These adjustments include special orbit manoeuvres and periodic instrument switch-offs, leading to a gap in the monthly time series about every five months. Being part of the GRACE de-aliasing product, model outputs for atmospheric and oceanographic mass variations are delivered together with the GRACE solutions. SLR-based monthly time series for C_{20} 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 monthly solutions and are published 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 to be constantly linear over the observational period. Hence, no regular updates of the model, specifying the linear GIA-induced mass change, are needed.

All data required to generate GMB products from a new GRACE solution are available with a delay of two months at the very latest. 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 receive quarterly updates (cf. PUG). While these updates simply extend the existing time series, yearly updates of the algorithm will entail a complete update of the time series and a new product release. 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 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

Figure 5.1: Main modules of the GMB Processor.

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.

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 (typically once per year). Quarterly updates to the GMB products solely extend the existing time series using the same parameter selections.

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

The most common operational scenario in the GMB product generation is the quarterly update of the existing time series. Parameters to be set for this scenario, 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 monthly solutions and time series for both degree one and C_{20} , are automatically downloaded by means of a shell script executed by a weekly cron job.

GRACE solutions provided by the processing centres within the GRACE SDS (CSR, JPL, GFZ) are hosted at the PODAAC archive (<ftp://podaac.jpl.nasa.gov/allData/grace>). 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 both degree one and C_{20} can also be procured from the PODAAC archive and are given in different self-descriptive ASCII formats.

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: $l_{\max}=60, 90, 120$; CSR: $l_{\max}=60, 96$; GFZ: $l_{\max}=90$). 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 data, comprising GRACE 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 release to be utilized, location of the input data (GRACE data and auxiliary data: degree one, C_{20}), l_{\max} ($l_{\max}=90$), the period to be considered (2002-08 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 I_{\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 as to the GRACE 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 reliably generate actual and future versions of the product. Nevertheless, it is most likely that the hardware will be updated in the course of the AIS_cci project.

Table 5-1: Processing Hardware at TU Dresden for the GMB processor

Model	HP Compaq dc7900
Processor	Intel® Core™ 2 Quad CPU Q9400 @ 2.66GHz (4 Cores)
Memory (RAM)	8 GB
Local Hard Drive	100 GB
Network Attached Storage	1 TB

5.3.2 Operating system

The operating system in use is the Linux system Ubuntu 12.04 LTS (long-term support). More recent systems such as Ubuntu 14.04 LTS or the upcoming 16.04 LTS are also suitable to host the GMB data production system.

5.3.3 Tools and libraries

The core GMB production system is implemented using the commercial numerical computing environment Matlab version R2011a (7.12). All processing steps and the generation of products in ASCII and NetCDF format are carried out using Matlab. Additional tools are utilized to generate products in alternative formats, check the content and metadata of the products, and visualize the final results.

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

At present, 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 their update frequency as well as the processor runtime are moderate. Hence, manual

operation is not considered a major drawback and no full automation of the GMB processor is foreseen.

Nevertheless, specific parts of the processor could benefit from a higher degree of automation. For example, the procurement of input data will be automated in a future processor update. The automatic download of all required input data will be accomplished by a shell script periodically executed as a cron job.

For one of the future product releases, fully propagated variance-covariance models will be used in the Methods Module, replacing the currently used empirical variance-covariance model. ITSG provides these time-dependent matrices together with the GRACE monthly solutions. The maximum size of a single monthly variance-covariance matrix ($I_{\max}=120$) is about 1.2GB (gzip-compressed). The computationally extensive work on this storage consuming dataset will be carried out in joint collaboration with TUM, and can also be completed using the already available hardware and software setup.

It is also foreseen to port the GMB processor to a more up-to-date Matlab release, e.g. the already available Matlab version 2015a (8.5).

5.5 References

Klinger, B., Mayer-Gürr, T., Behzadpour, S., Ellmer, M., Kvas, A., & Zehentner, N. (2016), The new ITSG-Grace2016 release. EGU General Assembly 2016, Vienna, Austria, 17/04/16 - 22/04/16, doi: 10.13140/RG.2.1.1856.7280.

6 Appendix: CCI Data Standards

Data standards apply to the official CCI data products generated in the project. The reference document [AD4], *Data Standards Requirements for CCI Data producers, issue 1.2, March 2015*. The top level requirements are restated in Table 6-1. The document is at

http://cci.esa.int/sites/default/files/CCI_Data_Requirements_Iss1.2_Mar2015.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"> 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.

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