CryoSat2 : L2 Design Summary Document

Technical details of the processing performed by the IPF2 Specialised processors

Author:	D. J. Brockley, UCL
Checked:	S. Baker, UCL
Approved:	J. Bouffard, ESA

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MSSL UCL Mullard Space Science Laboratory

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Document History

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Iss D v0	5/7/2018	DJB	Created issue D for vN 1.1 release – Baseline D
Iss D v1	28/3/2019	DJB	Formulae in all sections clarified and notation harmonised. All sections edited such that this version is cleared by UCL for release to CS2 data users by ESA, for the purpose of understanding the products and processing only.
Iss D v1.1	3/4/2019	DJB	Updated following ESA review. References corrected.

Entries in italics denote non-deliverable versions provided internally

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1 Introduction

1.1 Purpose

This document is the Design Summary Document [DSD] for the CryoSat Level 2 IPF2 processing system, developed by University College London's Mullard Space Science Laboratory. The code runs under the Linux operating system, specifically CentOS. The purpose is to enable those using the chain, or the data that it produces, to understand how the data is processed.

1.2 Scope

The scope of this document is to:

- describe the design of the processor at high level
- describe the key processing steps of each L2 specialised processing chain at high level
- identify at high level all the inputs and outputs required

This document is not a complete description of the L2 processing as some component algorithms and models are provided by ESA as 'black box' library functions.

For further information, or to request clarifications, contact: eohelp@esa.int

1.3 Acronyms and Abbreviations

ACS	Advanced Computer Systems
ADF	Auxiliary Data File (used in the IPF/PDS)
ANX	Ascending Node crossing
ARESYS	Advanced Remote Sensing Systems
BD	Box Discriminator
CFI	Customer Furnished Item
CLS	Collecte Localisation Satellites
CNES	Centre National D'Etudes Spatiales
CoG	Centre of Gravity
CS2	CryoSat 2
DAC	Dynamic Atmosphere Correction
DEM	Digital Elevation Model
DSD	Design Summary Document
EASE	Equal-Area Scalable Earth
ENVISAT	Environmental Satellite
ERS	European Remote Sensing satellite
ESA	European Space Agency
GDR	Geophysical Data Record
GIF	Graphics Interchange Format
GIM	GPS Ionospheric Map
HDF	Hierarchical Data Format
IPF	Instrument Processing Facility
IPFDB	IPF Database File (aka SIRDBF previously)
L1/L1b/L2	Processing Levels 1/1b/2
LI	Lead Investigator

LIP	Level 2 Ice Processor (ESL reference processor for RA-2 Ice algorithms)
LOP	Level 2 Ocean Processor (ESL reference processor for RA-2 Ocean algorithms)
LRM	Low Resolution Mode (mode of CryoSat SIRAL)
MSS	Mean Sea Surface
MSSL	Mullard Space Science Laboratory
netCDF	Network Common Data Form
NOAA	National Oceanic and Atmospheric Administration
OCOG	Offset Centre of Gravity
ODLE	Ocean Depth and Land Elevation
PCONF	Processor Configuration File
PDS	Payload Data Segment
RA	Radar Altimeter
SAR	Synthetic Aperture Radar (mode of CryoSat SIRAL)
SARin	Synthetic Aperture Radar Interferometry (mode of CryoSat SIRAL)
SHA	Surface Height Anomaly
SID	SARin mode Degraded case
SIRAL	SAR/Interferometric Radar Altimeter
SWH	Significant Wave Height
UCL	University College London

1.4 References

[R1] CryoSat IPF1 SAR/SARin specialised processors: Detailed Processing Model C2-DD-ARS-GS-5101

[R2] RA2/MWR LOP Algorithms Definition and Accuracy PO-NT-RAA-0004-CLS Issue 2rev1

[R3] CS2 Product Handbook https://wiki.services.eoportal.org/tiki-index.php?page=Cryosat+Documents

[R4] Peacock, N.R. and Laxon, S. W. (2004), Sea surface height determination in the Arctic Ocean from ERS altimetry, J. Geophys. Res., 109, C07001, doi:10,1029/2001JC001026

[R5] Numerical Recipes in C: The Art of Scientific Computing. Section Edition, 1992. William H. Press and Saul A. Tukolsky and William T. Vetterling and Brian P. Flannery

[R6] Angle measurements with a phase monopulse radar altimeter. Jensen, J. R. IEEE Transactions on Antennas and Propagation, vol 47, issue 4, 1999, pp. 715-720

[R7] R. L. Tilling, A. Ridout, and A. Shepherd, "Estimating Arctic sea ice thickness and volume using CryoSat-2 radar altimeter data," *Advances in Space Research*, 2017.

1.5 Other sources of information

- CryoSat Product Handbook
- CryoSat L1 Product Format Specification C2-RS-ACS-ESL-5264
- CryoSat L2 Product Format Specification C2-RS-ACS-ESL-5265

2 Overview of the IPF2 Processor

The key design philosophy of the IPF2 processor is to *never* throw away data, however degraded, that a user may find useful. If a correction to range is missing, or a retracking result is potentially of low accuracy, the height is still output, but a flag is raised. Users should *always* check flag bits and filter the results according to their domain-specific requirements.

The CryoSat SIRAL instrument produces data in 3 primary measurement modes:

- Low Resolution Mode (LRM) is analogous to the pulse limited operation of previous missions, and is used to return data from the flatter ice sheet regions and open ocean
- SAR mode, which uses coherent echo processing to return higher resolution along track data from sea-ice and sea-ice contaminated ocean surfaces
- SARin mode, which uses coherent echo processing and interferometry to return higher resolution along track data, and across track echo direction from ice sheet margins. This mode also operates over selected sea-ice regions, to gauge the applicability of interferometry to these areas

The Level-0 data are processed to Level-1b by the IPF1 processor [R1]. The IPF1 processor was defined and built by University College London and is maintained and further developed by industry (ACS/ARESYS).

The resulting Level-1b data products carry more complex information than data from previous missions such as ERS and ENVISAT, and each mode requires specific processing. The Level-2 processing is therefore more complex, although the basic goal of converting the Level-1b waveforms and parameters into geophysical quantities is similar to previous missions.

The Level-2 processing is performed by the operational IPF2, consisting of a specialised processor for each mode (built by UCL) and pre-processing, post-processing and PDS interfacing components (built by ACS). It is the specialised IPF2 processor that is addressed by this DSD. It describes the design of the processor sub-system and describes the 3 chains that address the LRM, SAR, and SARin processing modes from L1b to Level 2.

The primary output quantities from all of the Level-2 processing chains are:

- geophysically corrected ice sheet elevations, measurement locations and associated parameters
- geophysically corrected sea-ice elevations and associated parameters
- sea-ice freeboard and associated parameters
- ice-free ocean elevation and associated parameters
- associated auxiliary and geophysical correction data

These outputs are delivered in L2 and L2I (in-depth) product files which contain data collected in a single mode, and which correspond to 1 input L1b file.

These quantities are also delivered in a Level-2 GDR (Geophysical Data Record) consolidated product format that is mode-independent and segmented into whole orbits, from ascending node to ascending node (ANX). The interpretation of the data is to some extent dependent on the instrument mode, but the format itself is mode independent, and all measurements are presented at the same rate. To produce these data, 3 chains must separately process the LRM, SAR, and SARin L1b mode data segments to Level 2. The segments are subsequently joined to full orbit products by an IPF-2 consolidation processor.

Although most aspects of the L2 processing are largely analogous to traditional pulse limited Level-2 processing, there are significant differences in the detail which require different approaches. For example, the Level-1b coherent echo processing (from SAR and SARin mode) results in markedly different echo shapes which do not conform to the Brown/Hayne model, and existing echo analysis or 'retracking' methods are largely unsuitable. Also, most processing has terrain-specific and beam-formation-specific aspects that require an echo discrimination step to select appropriate subsequent processing or rejection of data. The sea-ice freeboard determination is a completely new addition to operational Level-2 processing.

3 Level-2 Processor Design

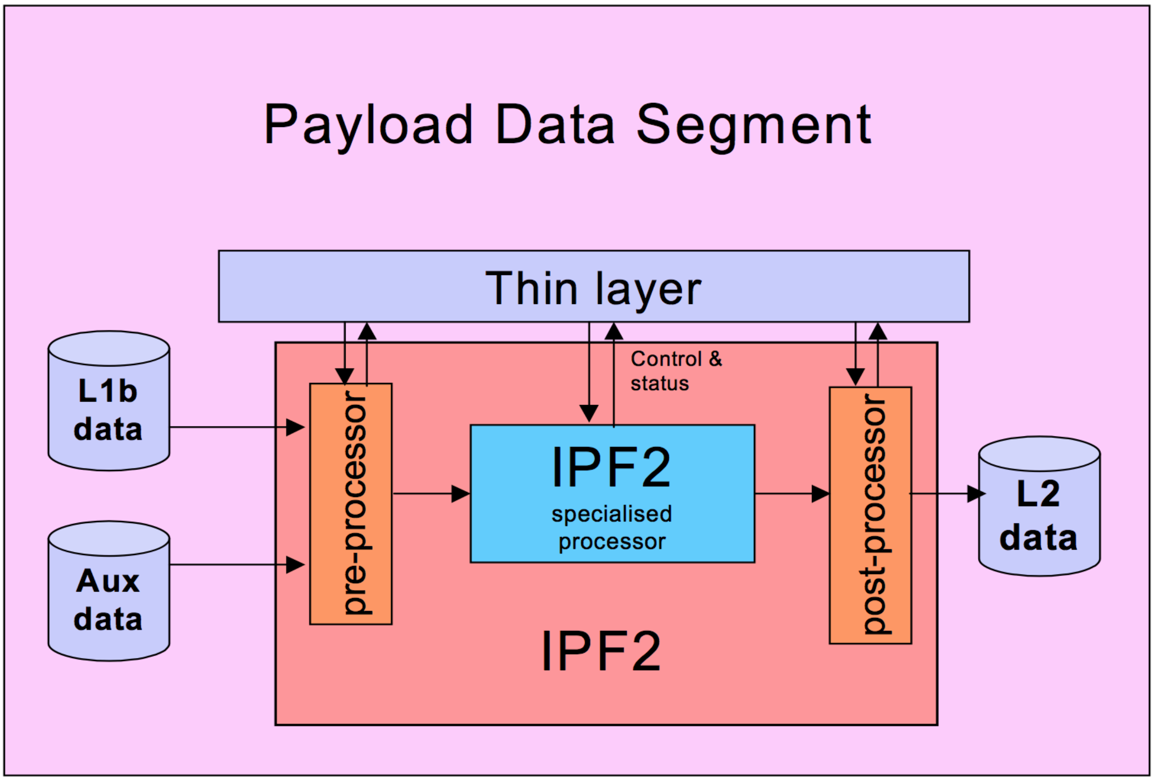

Figure 1: Context of the IPF2 processor

The IPF2 processor sits within the overall Payload Data Segment (PDS) as shown in Figure 1, and is interfaced via the so-called 'Thin Layer'. The core of the IPF2 is the IPF2 'specialised processor' built by UCL. This is controlled by the thin layer, and receives data via the pre-processor, and delivers completed products via the post-processor.

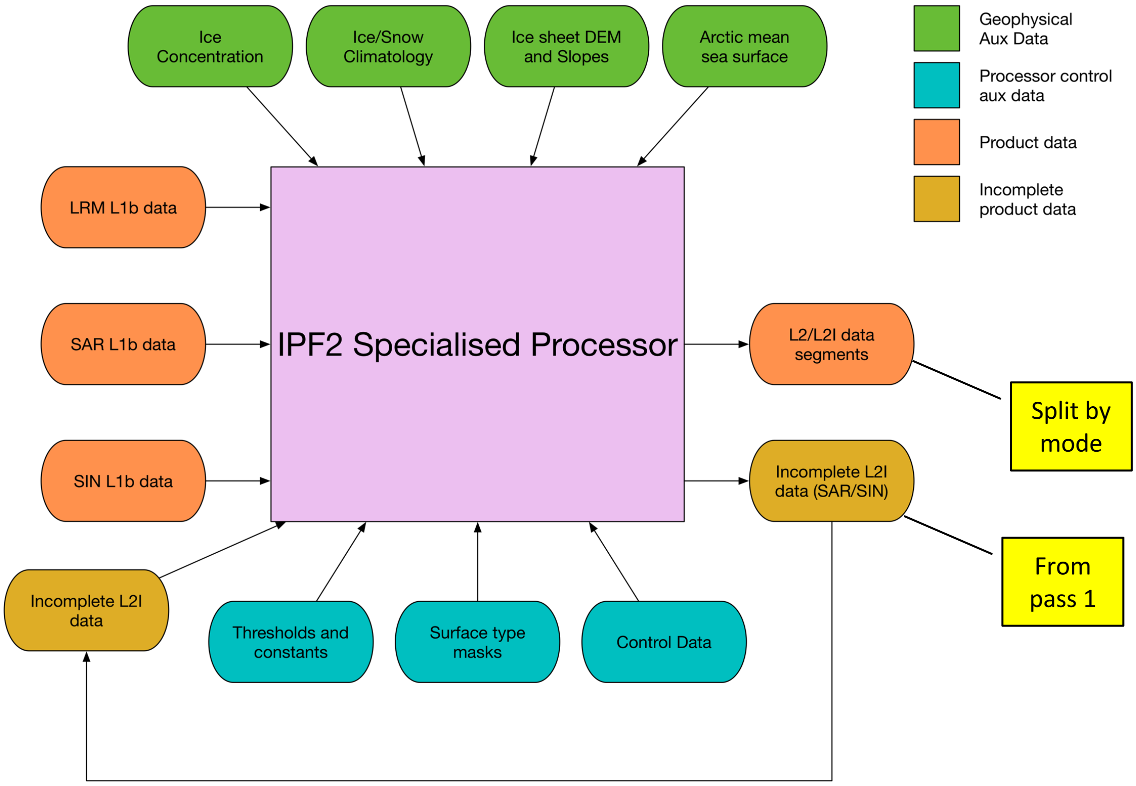

Figure 2: The context of the Level 2 specialised processor

Figure 2 shows how products and auxiliary data are interfaced to the IPF2 specialised processor. The 'feedback' link represents the two-pass processing required by the SAR chain, and is clarified by the next diagram, Figure 3.

3.1 Operational IPF-2 details

The Level 2 processor consists of 3 primary sub-chains that are to be used to process Level-1b data from the corresponding 3 primary instrument modes, plus the previously discussed SID chain. The three primary sub-chains are exposed in Figure 3. A specific executable chain is called according to the instrument mode within the Level 1b data. An input algorithm manages the Level 1b data. It orchestrates the flow of data through the chain accordingly. The algorithms execute in sequence for each input data record and output data are placed in the global shared data area. The output module outputs a completed Level 2 data record and performs any formatting and consolidation. Output is in netCDF format.

The IPF-2 specialised processor outputs segments of data in a single instrument mode corresponding to that of the input level 1b product. The LRM and SARin chains are single-pass chains, but the SAR sea ice chain is a two-pass chain which outputs a basic ocean/ice elevation product on the first pass ('incomplete' SAR products), which is normally processed in a second stage to add ice freeboard parameters. It is intended that the incomplete SAR product, which is identically formatted to the full product, can be output as a GDR product if required.
These basic Level 2 product segments are managed by the Post-processor, which adds appropriate mission headers. A consolidation processor then concatenates

the data into whole orbit products (GDR), from ascending node to ascending node (ANX).

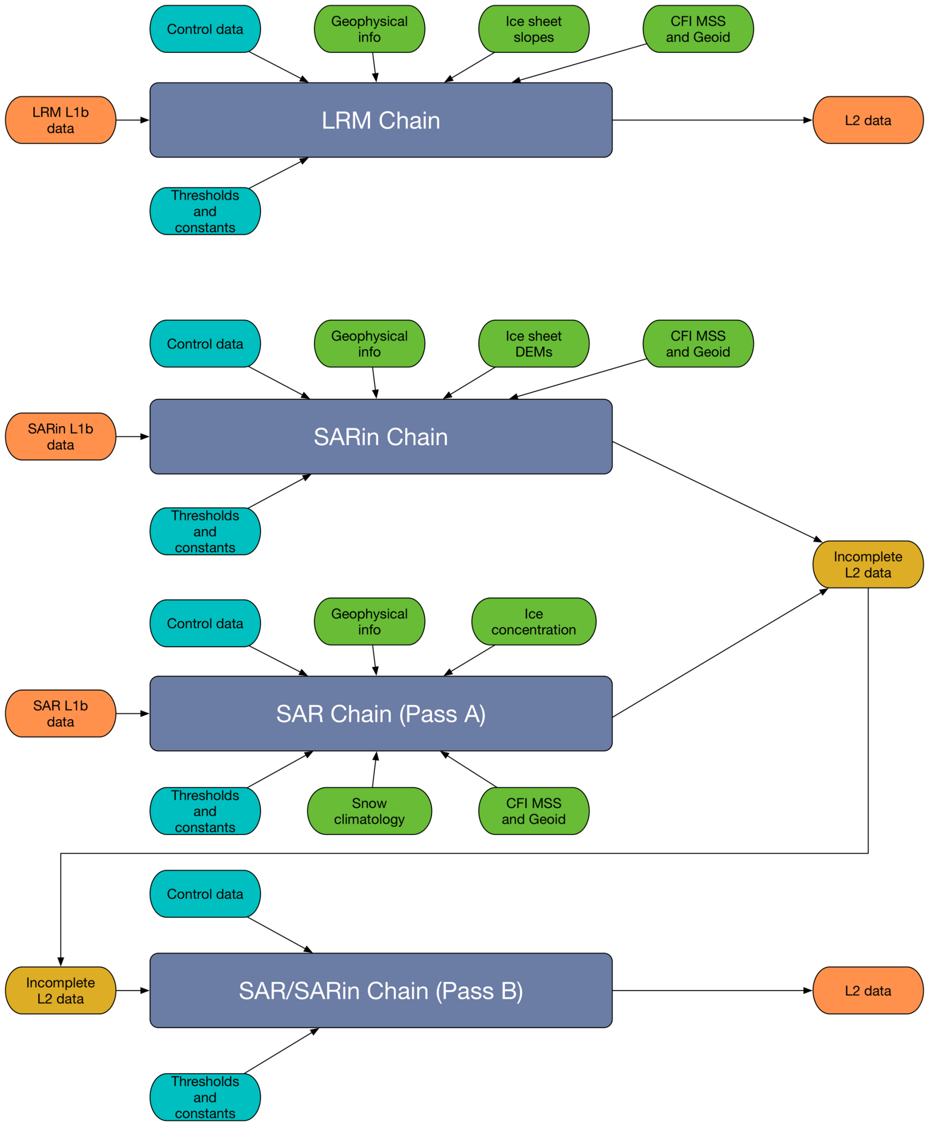

Figure 3: The processing chains within the CryoSat2 IPF2 processor

Each of the processing chains must be able to apply different processing according to scattering conditions resulting from particular terrain types – for example, the SAR chain must handle the very different returns from icy ocean and sea-ice surfaces. This implies that the chains must contain discrimination algorithms to determine the correct processing steps to execute, or to reject un-classifiable data. The high-level design of the chains is described in the following sections.

3.2 Notes of system level design issues

3.2.1 Verification of auxiliary file models

All of the model files read via CFI calls in the Level 2 processing have encoded into the file a unique identifier for the model contained within the file. This is used, for example, to determine which of the many possible mean sea-surface models is contained within the mean sea-surface model file passed to the processor. The Processor Configuration File (PCONF) contains an entry for each model file used which states the expected model identifier. If the expected model identifier and the identifier found in the file at run time do not match, the processor reports the condition into the log file and exits. The consequence of this is that model file updates must be done in parallel with a corresponding update to the PCONF file.

3.2.2 Detection of side

The SIRAL instrument can operate using the side A or B electronics. The two sets of electronics may be found to have different characteristics during commissioning phase; provision has been made for this in the IPFDB (IPF DataBase) and PCONF files. A check is made at run time to determine (from the instrument configuration flag in the L1b data) which side is in use, and the correct set of parameters is then used for the processing.

4 LRM Level-2 Processing Chain

The LRM processing chain is analogous to the Level 2 processing performed for previous missions such as ENVISAT and ERS, as the Level 1b data generated from the SIRAL instrument in LRM mode is analogous to standard pulse-limited radar altimetry data.

The processing chain is shown below in Figure 4. Firstly, the data records are discriminated, on the basis of the surface type indicator from L1b, as arising from ice covered or ocean surfaces, in order to select the appropriate subsequent processing variant.

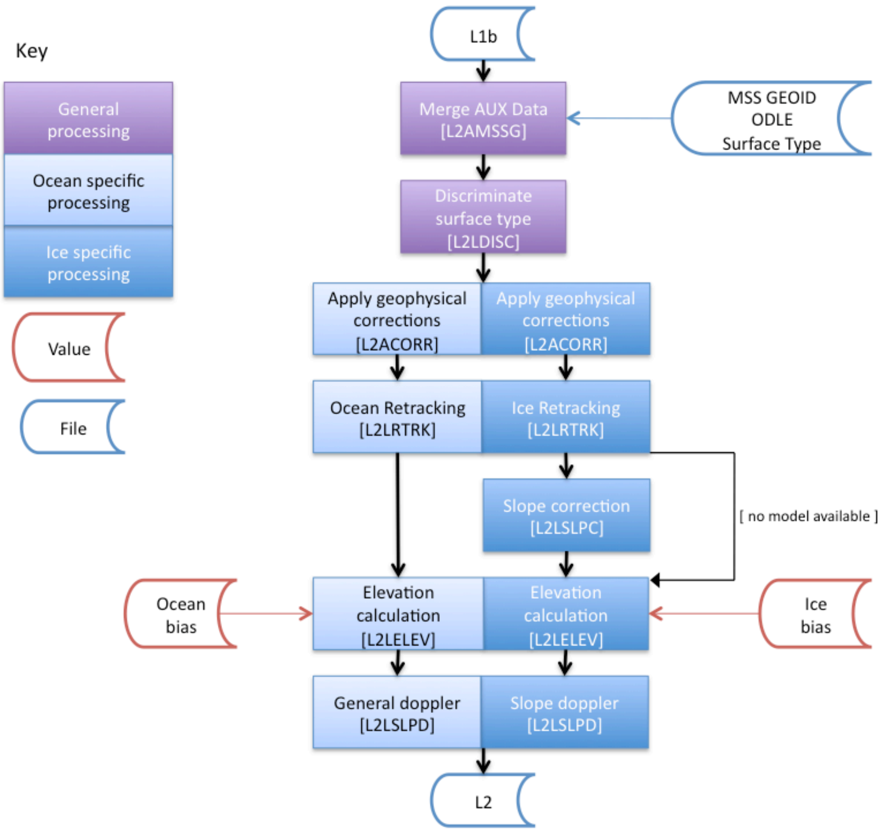

Figure 4: The CryoSa2 Level 2 LRM processing chain

Values from external model files are first merged into the data to be processed.

The surface independent corrections computed at Level 1b are applied to the parameters as appropriate for land or ocean.

The echoes must then be retracked to estimate the range error.

Retracking is performed, for all LRM echoes regardless of surface type, in five steps:

- Firstly, the echo is examined by a set of procedures to determine shape and quality, to establish whether it is suitable for further processing and to set quality flags
- Secondly, a coarse retracking is performed using the Offset Centre of Gravity (OCOG) algorithm
- The OCOG offset is then used to initialise a specialised ocean retracker (provided as a CFI by the Agency) which should provide marginally superior performance over ice sheets, and appropriate performance over the ocean surfaces
- The OCOG offset is then again used for retracker initialization, this time with a retracker designed for use over land-ice surfaces
- Finally another retracking is done using the land-ice retracker, and results from all three retrackers go on for further processing in the chain

The OCOG output also provides an additional quality check in that if the OCOG offset is very large, the CFI retracker is not called. In all cases, the OCOG values are still output if quality checks indicate that the echo is unsuitable for CFI processing or if the CFI algorithm itself indicates problems. The retracker outputs are used to compute range offset and a backscatter correction.

Over ice surfaces for which a slope model is available, corrections are then calculated for the off-ranging effects of sloping terrain using a range-slope model. This is followed by an elevation calculation that considers the echo direction derived from the slope correction. A static ice-bias correction is then applied to the elevation. The value of the ice-bias comes from the processor configuration file (PCONF) and was determined during the commissioning phase.

For the data arising from open ocean, a simplified elevation calculation is applied. This is followed by the application of a static ocean-bias to the elevation. This bias is not the same as the sea-state bias, which varies along track. Sea-state bias is not corrected for, as the algorithm was not included in the commissioning phase activities.

The static ice and ocean bias values referenced here are values read from the PCONF and intended to account for any residual system bias to elevation, which may differ by surface due to the different response of ice and ocean surfaces.

Both processing paths are then completed with a generalised Doppler correction calculation which considers both the radial component due to orbit, and the additional range error due to the change of the angle between the satellite velocity vector and the angle of the echo (point of first return) arising due to any surface slope.

4.1 Mean Sea Surface and Geoid

A mean sea-surface height (MSS), geoid height, Ocean Depth / Land Elevation (ODLE) value and surface type are calculated from standard models, using CFI routines (supplied by ESA). The surface type here is extracted at 20 Hz and is used in the processing in place of the 1 Hz value from the L1b dataset. The input to the algorithm is the spacecraft latitude and longitude from the Level 1b product. The height values extracted are placed in the L2 output product for the convenience of the user. The value of the MSS is using during the sea-ice processing (SAR/SARin mode). Flags are set to indicate the status of the computed corrections.

4.2 Surface Discrimination

For the LRM chain, it is only necessary to determine whether the underlying surface is ocean or land ice. This is to ensure, for example, that the inverse barometric correction is not applied over land. The discrimination algorithm therefore uses the surface type value extracted from the model file via a CFI call to derive a 'discriminator result' value which is used in Level 2 processing and is output to the Level 2 product.

4.3 Apply geophysical corrections and compute initial range

The geophysical corrections from the level 1b processing are applied to a range calculated from the Level 1b window delay, i.e. the round-trip time of the echo, referenced to the 'front' of the range window. Corrections are available at 1Hz in the L1b product and are not interpolated to the location of the 20Hz records when applied — the same value is applied to each of the 20 records. The set of corrections applied is also flagged. This facilitates easy removal and replacement by the user, if the user wishes to do so. The terrain type is considered so that the inverse barometric or dynamic atmospheric corrections are not applied over land.

The following 'recipes' are used to apply the corrections. Over open ocean:

C_{TOT} = DRY + WET + IBC (or DAC) + IONO + OT + LPEOT + OLT + SET + GPT

Over everything else:

C_{TOT} = DRY + WET + IONO + OLT + SET + GPT

Where:

DRY	dry tropospheric correction
WET	wet tropospheric correction
IBC	inverse barometric correction
DAC	dynamic atmosphere correction
IONO	ionospheric correction
OT	ocean tide
LPEOT	long-period equilibrium ocean tide
OLT	ocean loading tide
SET	solid Earth tide
GPT	geocentric polar tide
C_{TOT}	total correction to be applied

Each of the corrections has a corresponding flag in the PCONF that prevents it from being applied when set. The standard configuration of these flags is for IBC not to be applied and DAC to be applied instead. DAC is actually IBC plus the correction for wind effects therefore only one of them should be applied. DAC should be used over ocean free of sea ice. There is also a master flag that prevents any of the corrections from being applied.

Details of the geophysical corrections derivation are summarised in the following subsections. See http://wiki.services.eoportal.org/tiki-download_wiki_attachment.php?attId=4287 or contact the ESA project TO for further information.

4.3.1 Dry Tropospheric Correction

Refraction due to the dry gas component of the atmosphere causes a path delay in the radar return signal. The correction is calculated by a CFI library function under ESA responsibility. The correction is computed from grids of atmospheric surface pressure. Grids are non-linear with a 1.125 degree spacing in latitude and longitude. The data is sourced from ECMWF via Meteo-France. Over non-ocean surfaces a DEM must be used to convert sea-level pressures to local surface height pressure. The source of the DEM and its grid resolution are not specified.

4.3.2 Wet Tropospheric Correction

The Wet Tropospheric Correction corrects for the path delay in the altimetric return signal due to liquid water in the atmosphere. The correction is calculated by a CFI library function under ESA responsibility. The correction data is sourced from ECMWF via Meteo-France.

4.3.3 Inverse Barometric Correction

This range correction accounts for the variation in sea surface height in response to variations in the local atmospheric pressure. The correction is provided by a CFI library function under ESA responsibility. It is calculated using the same surface pressure grids used for the Dry Tropospheric correction and applies only over open ocean and over sea ice.

4.3.4 Dynamic Atmosphere Correction (DAC)

The DAC also corrects for the depression of the ocean surface caused by the local barometric pressure but additionally includes wind forcing effects. The correction is provided by a CFI library function under ESA responsibility. It should be used over ocean only where there is no sea-ice cover

4.3.5 Ionospheric Correction

The Ionospheric Correction takes into account the path delay in the radar return signal due to the free electron content of the ionosphere. The correction is provided by a CFI library function under ESA responsibility. By default the corrections is computed from the Global Ionospheric Map (GIM) created using GPS data. In the GIM data is not available the correction is derived using the Bent Model, but that is only available up to +/- 82 degrees. The choice of model can be controlled at run-time by a parameter in the PCONF file.

4.3.6 Ocean Tide

In Level 2 Offline products (from the CryoSat Ice Processor) the Ocean Tide correction is computed using a static file, derived from the Finite Element Solution 2004 (FES2004) tide model which has latitude coverage from -90 to +90 degrees and a step in latitude/longitude of 0.125 degrees. The correction is provided by a CFI library function under ESA responsibility.
The Ocean Tide does not include the Ocean Loading Tide or the Long-Period Equilibrium Tide, and these are provided separately.

4.3.7 Long Period Equilibrium Ocean Tide

The Long-Period Equilibrium Tide correction removes the effects of low frequency local tides caused by the gravitational attraction effects. The correction is provided by a CFI library function under ESA responsibility. In CryoSat Ice products the correction is derived from FES2004.

4.3.8 Ocean Loading Tide

The Ocean Loading Tide correction removes the deformation of the Earth's crust due to the weight of the overlying ocean tides. The correction is provided by a CFI library function under ESA responsibility. In CryoSat Ice products the correction is derived from FES2004.

4.3.9 Solid Earth Tide

The Solid Earth Tide correction removes the deformation of the Earth due to tidal forces from the Sun and Moon acting on the Earth's body. The correction is provided by a CFI library function under ESA responsibility. The Cartwright model is used.

4.3.10 Geocentric Polar Tide

The Geocentric Polar Tide correction accounts for the tidal response to the long-period distortion of the Earth's crust caused perturbations in the Earth's rotational axis. The correction is provided by a CFI library function under ESA responsibility.

4.4 Waveform retracking & parameter estimation

The full retracking scheme for the LRM mode is a four-part scheme, as follows:

- A series of waveform quality checks are used to assess the suitability of the input echo waveform for further processing
- An OCOG coarse retracking range error estimate is used both as an initial estimate for fine retracking, and used to produce a height measurement
- A fine range error estimation step is performed (over all surfaces) using a CFI ocean retracking package
- An alternative fine range error estimation step is performed (over all surfaces) using a least-squares fit of a Brown echo model (specifically designed for CryoSat echoes from land-ice surfaces) to the input waveform

All three results (OCOG, ocean, and land-ice) are output as height measurements.

The quality checks detailed in the sections below depend upon various thresholds and control values that are sourced from the processor configuration file (PCONF) or the IPF database file (IPFDB). The CFI retracker requires over 60 inputs, some of which must be input from or derived from the Level 1b product, and some of which are also sourced from the PCONF or IPFDB.

4.4.1 Part 1 - Echo waveform quality assessment

A series of waveform quality checks and shape calculations must be performed, whose results are used later in the processing. This allows for waveform flagging where retracking results are likely to be unreliable.

a) The noise power in the echo is estimated from the mean of a set of early range filter values (read from PCONF, as are thresholds and parameters below). For land ice echoes, these filter values may be contaminated by scattered power from the surface. A threshold is used to identify such contamination and to set a validity flag accordingly.

b) The mean power in the whole range window is determined and compared with the noise power determined above. If the mean power is smaller than a multiple of the noise power, then the echo is flagged as a low-power echo. This test finds ‘empty’ waveforms sometimes encountered in altimetry data.

c) Similarly, a test is done on variance in the waveform to eliminate spurious echoes that have no structure, despite having nominal power levels.

d) A check for the presence of an echo leading edge is performed by computing the mean power in 2 contiguous subsets of the range filters, which together span the entire range window. The nominal tracking point of the range window determines the relative fraction of the range gates in each subset. If the average power in the first range gate exceeds a multiple of the power in the second gate, the waveform is flagged as having no leading edge.

e) The “peakiness” of an echo is a useful parameter, which is output at level 2. It is also a useful quality measure on echo shape that is important for ice-free ocean retracking in particular. Peakiness can be used to identify quasi-specular echoes arising from calm water. The peakiness of the power waveform is computed using

$$pp_{LRM} = (N_s - i_{TP}) \times \frac{\max(\Phi(i), i: i \in [0, N_s - 1])}{(\overline{\Phi} \times N_s)}$$

where Φ is the power waveform. The peakiness pp is essentially the ratio of the maximum power value to the mean of the power values $\overline{\Phi}$ to the right (greater range) of the tracking point, i_{TP}. The tracking point must be included in the expression to ensure that the peakiness is correctly scaled according to the nominal position of the tracking point in the range window. N_s is the total number of samples in the range window.

4.4.2 Part 2: Coarse (OCOG) retracking

Note that the "OCOG retracker" is actually a threshold retracker with the threshold defined as a fraction of the OCOG Amplitude (defined below). It is an empirical, or model-free, retracker that is utilised because of its robust performance over surfaces with complex geometry.

A range offset and backscatter estimate are computed for all echoes using the Offset Centre of Gravity (OCOG) algorithm. The algorithm is a variant of that used for the ENVISAT RA2. The OCOG 'amplitude' is computed as follows, for a configurable sub-window of the echo from bin n_1 to n_2:

$$A_{OCOG} = \sqrt{\frac{\sum_{i=n_1}^{n_2} \Phi^4(i)}{\sum_{i=n_1}^{n_2} \Phi^2(i)}}$$

If the sum of the squares is zero, the waveform contains no power, and so defaults are applied and flags are set accordingly. The next step is then to find the range bin i_{OCOG} in the echo that first crosses the OCOG power threshold $k_{OCOG}A_{OCOG}$, where k_{OCOG} is a configurable proportion of the amplitude. A check is made that the selected bin is not the first bin as can occur with certain extreme waveforms. If all is well the echo is interpolated to find the exact range offset in mm, otherwise it is flagged and the interpolation is skipped.

$$\delta i_{OCOG} = \left(i_{OCOG} - 1 + \frac{k_{OCOG}A_{OCOG} - \Phi(i_{OCOG} - 1)}{\Phi(i_{OCOG}) - \Phi(i_{OCOG} - 1)} - i_0 \right)$$

The value i_0 is the number of the reference bin that represents zero range offset.

The quantity i_{OCOG} above is tested against a positive and negative threshold to ensure that the offset is valid. The OCOG range offset is then calculated from:

$$\delta R_{OCOG} = d_{LRM} \times \delta i_{OCOG} \quad (\mathrm{m})$$

where d_{LRM} is a parameter from the IPFDB that scales LRM mode bins to meters.

This gives (where t_{L1} is the window delay from the L1b product):

$$R_{OCOG} = \frac{ct_{L1}}{2} + C_{TOT} + \delta R_{OCOG} \quad (\mathrm{m})$$

Figure 5 shows a typical land-ice echo in LRM mode. The horizontal red line is drawn at the amplitude determined by the OCOG retrack. The green vertical line is drawn where the amplitude of the waveform first exceeds the value of the amplitude multiplied by the OCOG power threshold. In this case, the threshold was set to $k_{OCOG} = 0.3$.

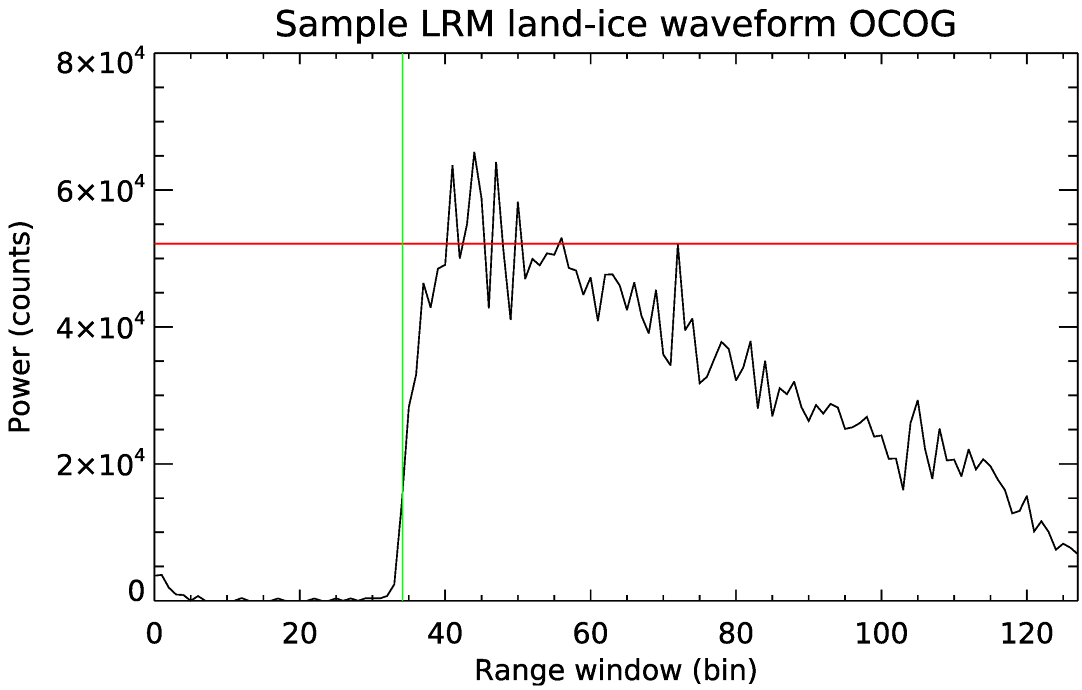

Figure 5: Example of an OCOG retrack on a land-ice echo in LRM mode

4.4.3 Part 3: Ocean CFI (fine) retracking

The values from the OCOG retracking step are fed forward to the CFI retracker routine for refinement of the tracker offset and echo amplitude, and estimation of leading edge width. The CFI retracker is run for all records that pass the waveform QA checks, regardless of surface type.

The Retracker CFI Software User Manual document states that the retracker implemented is the Ocean-1 retracker (a.k.a. the ESA/CNES/CLS algorithm).

4.4.4 Part 4: Land Ice Retracking (LIRT)

In the same way as for the CFI retracking step, all of the OCOG retracker outputs are used as an initial seed for a model-fitting retracker designed for best performance over continental ice sheets (although it is run for all records). The model (m) fitted has a noise term (N, derived by averaging a noise gate), an amplitude term (A, fitted), and a term that contains the parameters that vary the shape of the waveform (w, epoch and SWH fitted). The waveform epoch is t_0. This gives:

$$m(t) = N + Aw(t)$$

where

$$A = P_T T \exp\left[\frac{-4}{\gamma}\sin^2\xi\right]\exp\left[\frac{(\kappa_j\sigma)^2}{2}\right]$$

$$w_j(t,\kappa_j) = \frac{1}{2}\exp\left[-\kappa_j(t-t_0)\right]\left\{1+\mathrm{erf}\left[\frac{(t-t_0)}{\sigma\sqrt{2}}-\frac{\kappa_j\sigma}{\sqrt{2}}\right]\right\}$$

The time constant here is given by $T = \sigma_{\mathrm{PTR}}\sqrt{2\pi}$.

The σ term is $\sigma^2 = \sigma_{PTR}^2 + \sigma_{SWH}^2$.

ξ is the mispointing angle.

The κ_j term in the model allows the handling of mispointing to be tuned for different situations. The 1st order derivation of the term is used for CryoSat:

$$\kappa_1 = \frac{4c}{\gamma h}\left[\cos(2\xi) - \frac{1}{\gamma}\sin^2(2\xi)\right]$$

The antenna beam width parameter γ is defined as:

$$\gamma = \left(\frac{2}{\ln(2)}\right)\sin^2\left(\left\{\frac{2}{\left[{}^1\!/_{\Theta_{major}} + {}^1\!/_{\Theta_{minor}}\right]}\right\}\Big/2\right)$$

Where Θ_{major} and Θ_{minor} are the elliptical antenna beam-widths.

4.4.5 Nadir Elevation Estimation

For surfaces for which there is no slope model, the elevation estimate is produced at this stage as:
$h = hSAT - RLRM - dbias$

The same calculation is performed for all retrackers that returned a result.

4.5 Backscatter Correction

A backscatter estimation for the surface may be computed from the 'amplitude' estimate from the retracker. The expression used is of the form:

$$\sigma^0 = 10\log_{10}\left(\frac{P_R}{P_T}\right) - C + L + 30\log_{10}\left(\frac{h}{h_N}\right) - f(\vec{b}) + \sigma_{bias}^0$$

where:

P_R is the received power in Watts
P_T is the transmit power in Watts

C is a set of system constants, evaluated for a reference range h_N, and incorporating the antenna gain G, and the effective pulse length T

$$C = 10\log_{10}\left(\frac{c\pi\lambda^2 G^2 T}{(4\pi h_N)^3\eta}\right) = -151.125\ \mathrm{dB}$$

The term η in the system constants expression, corrects for the curvature of the Earth (radius R_e) and is derived as:

$$\eta = \frac{(h_N + R_e)}{R_e}$$

The value of T is taken from the PCONF file and is the effective time duration of the pulse. A definition (supplied by W. Smith, NOAA) of this parameter is:

$$T = \sqrt{2\pi}\,\sigma_{PTR} = \sqrt{2\pi}\,\frac{0.534}{B} = 4.183\times 10^{-9}\ \mathrm{s}$$

The function $f(\vec{b})$ determines the effect of mispointing (if estimated) and surface state on the estimate of σ^0.

Firstly, this function determines the roll and pitch (in micro-radians; formulas taken from [R3]) so that constant biases (nominally zero from Baseline C onwards) may be applied.

Roll $\theta = x_x$ (L1b baseline vector)
Pitch $\phi = -b_y$ (L1b beam vector)

Then mispointing $\xi^2 = (\theta + \theta_{bias})^2 + (\phi + \phi_{bias})^2$

and:

$$f(\vec{b}) = \frac{10}{\ln(10)}\left(\frac{-4}{\gamma}\sin^2\xi\right)$$

A configurable bias can be applied to the computed backscatter to bring the result into alignment with other missions.

It is possible to calculate the absolute backscatter in this manner due to the CryoSat L1b product containing the necessary parameters to convert waveforms power from counts to watts . The expression used approximates the radar equation.

4.6 Slope correction over land ice surfaces

This step is skipped for all ocean records and for records for which the lat/lon position does not correspond to an available slope model file.

The slope correction algorithm uses a slope model to determine the direction from which the echo came. The calculations transform the coordinates of the satellite position into coordinates appropriate for access to the slopes model. The slopes are then read for the position and the azimuth and attitude angles computed. This step provides the angular information necessary to estimate the so-called slope-induced error.

This algorithm follows the methodology used for the ENVISAT RA-2. Firstly, the geodetic ellipsoidal coordinates sourced from the orbit are converted to a hemispherical (i.e. the sign of latitude is ignored) Cartesian coordinate frame. The use of this artificial Cartesian (X, Y) frame allows us to specify the slopes models on a regular, equal-area grid near the poles, which would not be possible with a Lat/Lon grid. The assumption is made that LRM slopes processing will only be carried out at high latitudes (> 65°) - the current slope model files cover Greenland and Antarctica. This step does not depend on tracking performance and can always be carried out provided that the orbit data are in the L1b packets.

The coordinate conversion begins by determining the meridional radius of curvature of the ellipsoid, ρ_θ.

$$\rho_\theta = \frac{a_e(1-e^2)}{(1-e^2\sin^2\theta_0)^{3/2}} \quad \text{(m)}$$

The hemispherical Cartesian coordinates are then determined from the equations for the hemispherical equal area projection:

$$X = 2\rho_0 \cos\lambda_0 \sin\left(\frac{\frac{\pi}{2}-|\theta_0|}{2}\right) \quad \text{(m)}$$
$$Y = 2\rho_0 \sin\lambda_0 \sin\left(\frac{\frac{\pi}{2}-|\theta_0|}{2}\right) \quad \text{(m)}$$

The echo direction is found in a local Cartesian coordinate frame (x,y) which has its origin at the sub-satellite point of the ellipsoid, and the x,y plane is the tangent plane to the ellipsoid at that point. This plane may be thought of as local approximation to the ellipsoid at the sub-satellite point.

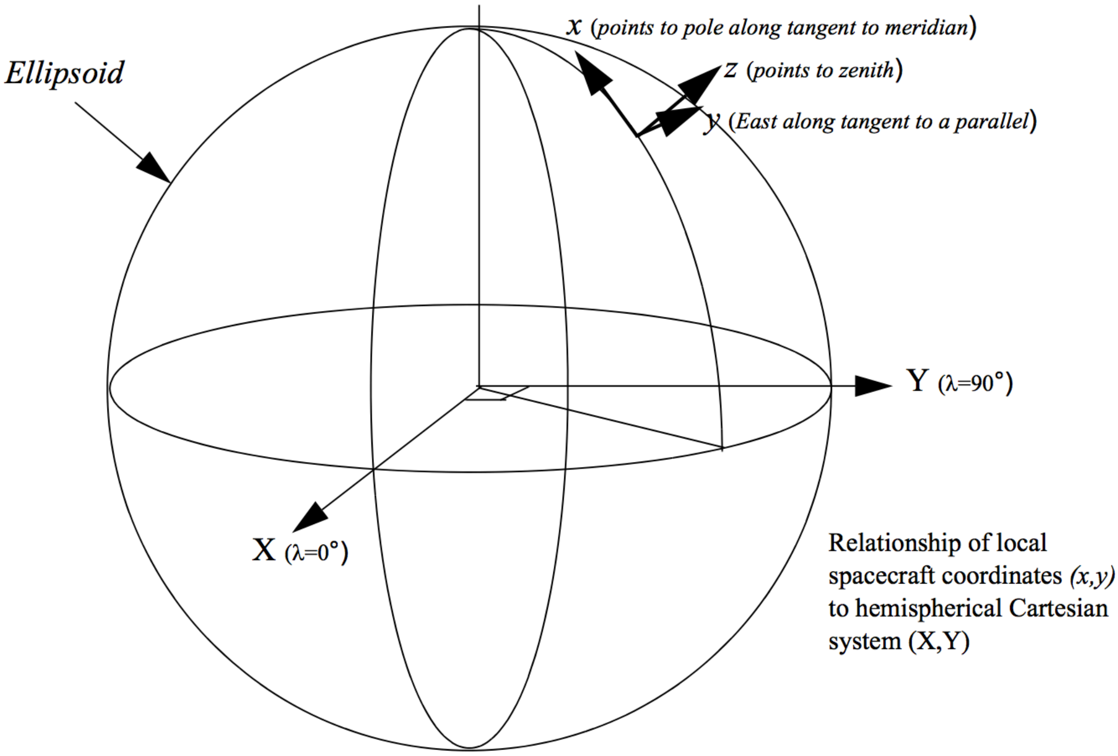

Figure 6: Coordinate systems for the slope model correction

We determine the geodetic coordinates of the ellipsoid, i.e. the meridional radius of curvature as above, and the radius of the corresponding parallel circle at the corresponding geodetic latitude:

$$\rho_\lambda = \frac{a_e \cos\theta}{\sqrt{1 - e^2 \sin^2\theta}} \quad \text{(m)}$$

The hemispherical Cartesian coordinates are used to determine if the sub-satellite point is over-flying a slopes model. If it is not, the local coordinate system elevation and azimuth are set to zero. If a slopes model is present, the slopes model is interpolated to get the X and Y coordinates of the slope as follows:

$$S_x(X,Y) = f(p,q,n,m,s_x[\,])$$
$$S_y(X,Y) = f\left(p,q,n,m,s_y[\,]\right)$$

Where f is an interpolation formula (six-point bi-variate interpolator - which is exact if second order derivatives are zero or negligible), with:

$$n = \text{Int}\left(\frac{X - X_0[i]}{\Delta_m[i]}\right) \; ; \; m = \text{Int}\left(\frac{Y - Y_0[i]}{\Delta_m[i]}\right)$$

where $\Delta_m[i]$ is the resolution of the i^{th} slope model, and $X_0[i]$ and $Y_0[i]$ are the co-ordinates of a slope value within the model. The parameters p,q are given by:

$$p = (X - X_0[i] - n\Delta_m[i])/\Delta_m[i]$$

$$q = (Y - Y_0[i] - m\Delta_m[i])/\Delta_m[i]$$

The next stage involves the computation of a set of partial derivatives of X and Y with respect to latitude, and also longitude, so that the quantities calculated in the global hemispherical Cartesian frame (X,Y) may be related to the local Cartesian frame (x,y).

$$\frac{\partial X}{\partial \theta}, \frac{\partial Y}{\partial \theta}, \frac{\partial X}{\partial \lambda}, \frac{\partial Y}{\partial \lambda}$$

The interpolated slope values (in X,Y) and the set of partial derivatives are then used to compute the range derivatives in local co-ordinates (x,y):

$$\left.\frac{\partial l}{\partial x}\right|_{x=0} \equiv s_x = \frac{1}{(\rho_{\theta_0} + h)}\left\{s_x(X,Y)\frac{\partial X}{\partial \theta} + s_y(X,Y)\frac{\partial Y}{\partial \theta}\right\}$$
$$\left.\frac{\partial l}{\partial y}\right|_{y=0} \equiv s_y = \frac{1}{(\rho_{\lambda_0} + h\cos\theta_0)}\left\{s_x(X,Y)\frac{\partial X}{\partial \lambda} + s_y(X,Y)\frac{\partial Y}{\partial \lambda}\right\}$$

The last step of the algorithm involves the calculation of the echo direction angles in local co-ordinates, thus:

$$\varphi = \operatorname{atan}\left(\frac{s_y}{s_x}\right) \equiv \operatorname{atan}\left.\left(\frac{\partial l}{\partial y}\Big/\frac{\partial l}{\partial x}\right)\right|_{\substack{x=0\\y=0}}$$

(Taking care to select the correct quadrant of the above angle.)

$$\eta = \operatorname{asin}\sqrt{s_x^2 + s_y^2} \equiv \operatorname{asin}\left.\sqrt{\left(\frac{\partial l}{\partial x}\right)^2 + \left(\frac{\partial l}{\partial y}\right)^2}\right|_{\substack{x=0\\y=0}} \quad \text{(radians)}$$

4.7 Elevation & position calculation

Over ice surfaces, the angular quantities from the slopes correction algorithm are used to compute a new elevation, latitude and longitude. The original sub-satellite latitude and longitude values are however preserved at a different location in the Level 2 product.

The corrected range and the echo direction are used to calculate the slope-corrected elevation in the geodetic (i.e. altimetric) ellipsoidal reference frame. We must transform the local co-ordinates of the echo direction using the geometry of the ellipsoid. We calculate the radius of curvature of the local ellipse in the direction of the echo azimuth using:

$$\rho = \frac{\rho_{\theta_0} - \rho_{\lambda_0}}{\rho_{\theta_0}\cos\theta_0\sin^2\varphi - \rho_{\lambda_0}\cos^2\varphi}$$

We then evaluate 3 expressions to determine the slope-corrected latitude, longitude and elevation of the echoing point, in global geodetic ellipsoidal co-ordinates, i.e. the altimeter reference frame:

$$z_e = h - l^{OCOG} \cos\eta + \frac{(l^{OCOG} \sin\eta)^2}{2\rho}$$

z_e is the height of the surface above the ellipsoid.

$$\theta_c = \theta_0 + \frac{l^{OCOG} \sin\eta \cos\varphi}{\rho_{\theta_0}} \quad \text{(radians)}$$

$$\lambda_c = \lambda_0 + \frac{l^{OCOG} \sin\eta \sin\varphi}{\rho_{\lambda_0}} \quad \text{(radians)}$$

The corrected latitude θ_c and longitude λ_c are stored in the L2 product. Only the values computed using the output of the CFI retracker are stored, but the difference in result of computing range with the LIRT or OCOG retrackers should be small.

An empirically derived ice bias correction is applied as a final step to compensate for any instrument mode-dependent processing biases. Over ocean surfaces, a simple elevation calculation is performed (no slope correction), and an equivalent empirical ocean bias correction is applied. These are static biases intended to account for any residual system bias — they do not vary along track.

The transformation equations in this algorithm are linear to a good approximation with respect to constant offsets applied to range. The atmospheric corrections are applied prior to computing the echo direction, whereas the combined Doppler correction and ice bias is applied directly to the elevation. Any components can therefore be reversed by the user if desired.

4.8 Orbit and Slope Doppler correction

This algorithm determines the generalised Doppler correction to range, due to the effects of the spacecraft orbit and due to line of sight variations arising over sloping surfaces. This is known as the generalised-Doppler range correction.

It is well known that there is a contribution to range arising from the Doppler effect due to the apparent vertical component of spacecraft orbital trajectory. However, over sloping surfaces, there is an additional contribution to range due to the Doppler effect. This arises because the echo direction (line of sight from the scattering facet) is no longer to the nadir of the spacecraft in general. This has the effect of adding in a component of the spacecraft forward orbital velocity in addition to the more generally appreciated vertical component.

For the generalised Doppler, one must perform a full vector calculation using the spacecraft velocity and position, and the echo direction. For CryoSat, the spacecraft velocity vector ($\mathbf{V}_N$) components are provided directly in the level 1b product. Also, for CryoSat LRM, it is convenient to perform a single generalised Doppler calculation following echo direction determination, which departs from the traditional methodology of determining the radial component separately.

Non-tracking data are not a problem, as the orbit information is always included, but as no elevation data are available the delta-Doppler correction is set to zero.

At several points in the processing, vectors in the spacecraft frame, i.e. in geodetic ellipsoidal co-ordinates, are converted to Cartesian co-ordinates (using CFI routines) in order to manipulate vector components:

$$(r, \theta, \lambda) \longrightarrow (X, Y, Z)$$

From the orbit parameters we obtain altitude, latitude and longitude, and transform these to Cartesian co-ordinates:

$$(h_N, \theta_N, \lambda_N) \longrightarrow (X_N, Y_N, Z_N)$$

Next, we determine the Cartesian components of the position vector of the echoing point, determined in the slope correction algorithm:

$$(z_e, \theta_e, \lambda_e) \longrightarrow (X_e, Y_e, Z_e)$$

We determine the line of sight vector from the echoing point to the altimeter, using vector arithmetic with the spacecraft position vector, and the position vector of the echoing point. For e.g. the X component we have:

$$l_x = X_N - X_e$$

The driving parameter for the Doppler range effect is the velocity component of the satellite in the line of sight of the observer. This is obtained by forming a scalar product of the spacecraft velocity vector with the line-of-sight unit vector thus:

$$V_s = \underline{V_N} \cdot \underline{\hat{l}}$$
$$V_s = V_x \hat{l}_x + V_y \hat{l}_y + V_z \hat{l}_z$$

The generalised Doppler range correction for the altimeter may now be found from:

$$d_{gdop} = -\frac{f_0 V_s}{S_c} \quad \text{(m)}$$

where:

$$f_0 = \frac{c}{\lambda_c} \quad \text{(Hz)}$$

and we note that the slope of the transmitted chirp S_c is a signed quantity which determines the sign of the Doppler correction.

As the Doppler correction has already been applied in the L1 processing that produces the window delay, the generalised Doppler correction is applied as

$$h_{gdop} = h_{dop} + d_{dop} - d_{gdop}$$

Where h_{dop} is a height estimate that includes the nadir Doppler correction and d_{dop} is the Doppler correction given in the L1b product.

5 SAR L2 sea-ice processing chains

The 2-pass SAR processing scheme is shown in Figure 7 and Figure 8. The second-pass processing shown in Figure 8 is also called for SARin data.

Firstly, the necessary values are merged into the product from the external auxiliary files. The total correction to be applied to range is calculated by adding together the individual geophysical corrections sourced from the Level 1b product. The resulting correction is then combined with the 1-way range as calculated from the window echo delay time (instrumental corrections applied) to determine the initial corrected range estimate.

Thresholds of peakiness, backscatter, waveform beam parameter array values, and daily ice concentration will be used to discriminate surface type using the waveform shapes. The discrimination attempts to determine surface type and the echoes are then further processed according to waveform shape (diffuse ocean-like or specular icy-ocean-like, i.e. from leads). Ice concentration is used to decide if a diffuse echo is from open ocean or from ice floes. Some of these algorithms are also called in the SARin processing chain (see section 6).

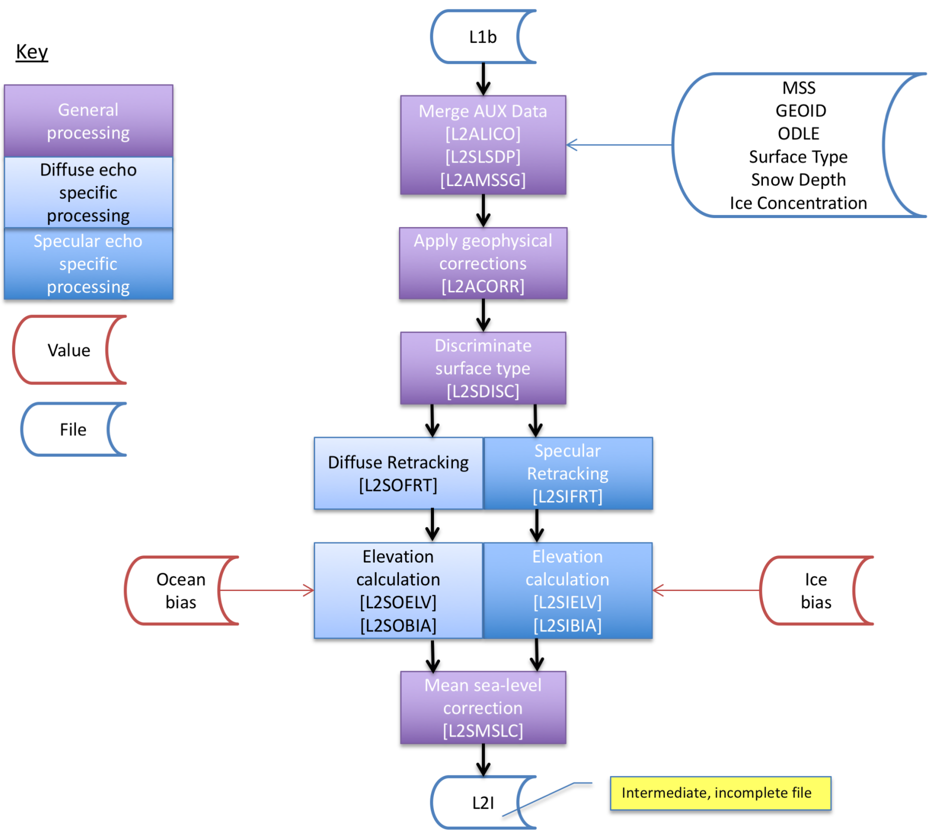

Figure 7: The SAR sea-ice pass A processing chain

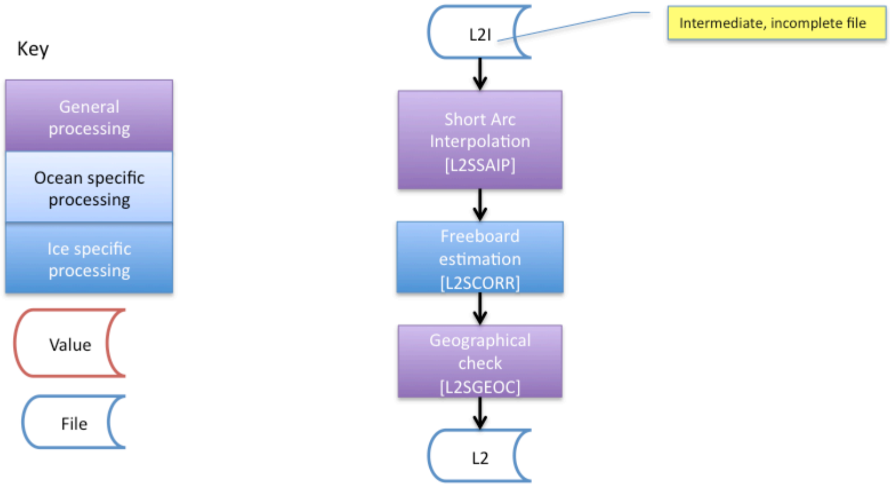

Figure 8: The SAR/SARin sea-ice pass B processing chain

For specular waveforms, the retracker algorithm uses a model fit to the power waveform to determine a range correction. For diffuse waveforms, a threshold retracker is used. For elevation estimation, the range correction is added to the initial range and the result is subtracted from the CryoSat altitude with respect to the reference ellipsoid to determine the elevations of sea-ice and leads.

Specular and diffuse height biases may occur as a result of the different processing schemes applied to the data from each instrument mode. These biases were estimated as part of chain commissioning after launch and are re-estimated after updates to the platform calibration or processing scheme. The bias values are applied to correct the height estimates.

The data from the above processing are output to the Intermediate Level-2 product. The majority of the Level 2 fields are completed by this first pass and can therefore be output as a product in its own right if required. This 'incomplete' Intermediate Level 2 product is subsequently picked up by pass 2, the 'ice freeboard chain'.

In the second pass, the 'incomplete' Intermediate Level 2 product is re-ingested. Firstly, a short-arc along-track accumulation is performed, and the sea surface height anomalies are linearly interpolated between the leads and open-ocean to generate an interpolated sea-surface height anomaly for all records, including the ice discriminated regions. Anomalies are used in place of height measurements so that the linear interpolation is valid. An ice freeboard measurement is then found by subtracting the interpolated sea-surface height anomaly from the ice surface height anomalies (Freeboard Estimation). Finally, a latitude limit check is performed to output data at chosen latitude boundaries and to verify that sea-ice elevation measurements are consistent with geographic location.

The auxiliary data files specific to the SAR processing (all interpolated via the Geo CFI) are listed in Table 1:

Table 1: Auxilliary data of the SAR chain

.Data Type	Notes
Ice concentration grids	NRT dynamic ice concentration files are derived from NSIDC data and delivered to ESA as an ADF
Snow climatology	Monthly files of snow depth climatology (Warren) are used
Arctic mean sea surface	The UCL13 MSS is a merge of the CLS2011 model with high resolution CryoSat Arctic data

5.1 Pass 1 - Merge mean sea level, geoid, sea-ice concentration and snow depth

In order to facilitate post L2 ice thickness calculations, a snow depth estimate is supplied in the L2 product for each measurement position but is not applied in any way. The estimate is derived from auxiliary snow depth climatology data, read from an auxiliary file via a CFI call. A static value (a constant read from the PCONF) for snow density is also output to the L2 product. This approach can accommodate a future upgrade to include a variable snow density metric if a reliable source or model should become available.

The dynamic sea-ice concentration (SIC-D) auxiliary files are created from the Near Real-Time SSM/I EASE-Grid Daily Global Ice Concentration and Snow Extent products (http://nsidc.org/data/nise1.html). Sea ice concentration and snow extent maps are provided in two 25 km azimuthal, equal-area projections:

- Southern Hemisphere 25 km low resolution (Sl) EASE-Grid
- Northern Hemisphere 25 km low resolution (Nl) EASE-Grid

NSIDC supply the data in Hierarchical Data Format - Earth Observing System (HDF-EOS) format and browse files in GIF and HDF formats. The files are created daily and are available via FTP for two weeks after initial posting. This data is used to create the 3-day averaged files used by the IPF2 processing. Data is interpolated from these files via a CFI library call.

The values for mean sea-surface, geoid, ODLE and surface type are read in as described in Section 4.1.

5.2 Pass 1 - Apply geophysical corrections

For ice or ocean surface types, the total correction (in mm) is determined by adding together the individual corrections. These corrections are at 1Hz and are applied to the 20 Hz records that were present in the corresponding L1b block. The recipe for corrections over open-ocean, leads and sea-ice records is:

$C_{TOT} = DRY + WET + IB + IONO + OT + LPEOT + OLT + SET + GPT$

Where:

DRY	dry tropospheric correction
WET	wet tropospheric correction
IBC	inverse barometric correction
DAC	dynamic atmosphere correction
IONO	ionospheric correction
OT	ocean tide
LPEOT	long-period equilibrium ocean tide
OLT	ocean loading tide
SET	solid Earth tide
GPT	geocentric polar tide
C_{TOT}	total correction to be applied

For an overview of each of the above corrections see sections 4.3.1 to 4.3.10.

We do NOT apply the DAC for SAR as the IB is considered more appropriate correction for sea-ice covered surfaces. This is due to the DAC including the effects of wind forcing, which do not account for the presence of sea-ice on the ocean surface. Mean sea level or geoid corrections are NOT applied by this algorithm.

Each of the corrections has a corresponding flag in the PCONF that prevents it from being applied when set. There is also a master flag that prevents any of the corrections from being applied.

The initial range is then computed, i.e. the distance between the satellite and the surface. This is computed from the following:

$$R = \frac{c}{2}t + C_{TOT}$$

where,

- R initial range
- t 2-way window delay from L1b
- c speed of light
- C_{TOT} total correction

5.3 Pass 1 - Waveform discrimination

A box discrimination algorithm is used. This is a classification method for determining the surface cover type of the incoming CryoSat L1B records, using a pre-defined set of classes.

Firstly, all records that have a surface type from the mask file that is not equal to 'open-ocean' are assigned to the 'unknown class'. Then the remainder are classified on the basis of:

- the L1b beam behaviour array, that characterises the stack waveform shape

- parameters derived from the power waveform, such as peakiness
- external sea-ice concentration data (SIC-D)

The discriminator has two sets of input values. The first set is the supplied parameters, received in the L1B data file. These are contained in the beam behaviour parameter array, which has multiple parameters (beam width, beam centre and beam amplitude based on a Gaussian fit to the stack waveform shape, Skewness, Kurtosis, Stack Peakiness).

The second set is the computed parameters, either calculated from the values present in the L1B data file or read from an auxiliary file. These are echo peakiness and sea-ice concentration. The sea-ice concentration from the external SIC-D auxiliary files is used to determine if a diffuse echo originates from ice floes or from the open ocean. The value from the SIC-D is output to L2 as a reference parameter so that the discrimination result can be understood and should not be interpreted as a metric derived from the altimeter data.

Minimum and maximum values for each surface type for each of these parameters were determined by analysis of the real instrument data during commissioning.

The input values are used in a simple comparison scheme to classify surface measurements according to surface type. If all of the parameters are within the thresholds defined in the PCONF for exactly one surface type, then the record is discriminated as belonging to that surface type. Otherwise the record is discriminated as unclassified.

The peakiness (pp) above a noise estimate is defined using a waveform from which bins below the noise threshold have been removed completely:

$$pp = \frac{M\acute{\Phi}_{max}}{\sum_{k=1}^{M} \acute{\Phi}_k}$$

where:
M = number of bins above noise
Φ_{max} = is maximum power (amplitude in counts)

The noise measurement is derived from the average power contained in a window of waveform bins located near the start of the waveform window.

The skewness (Sk) is a measure of how skewed the stack waveform shape is to the right or left of the symmetrical Gaussian fit central maximum. Sk is positive >0 if the maximum is displaced to the right and negative <0 if displaced to the left.

$$Sk = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\Phi_i \mu}{\sigma}\right)^3$$

The Kurtosis (Kt) is another measure of how the stack waveform amplitude deviates from the Gaussian fit. Kt is positive >0 if the maximum is greater than the Gaussian fit and negative <0 if less.

$$Kt = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{x_i - \mu}{\sigma}\right)^4 - 3$$

where:

- N number of Doppler beams in stack
- μ mean stack power
- σ standard deviation of stack power

The Stack Peakiness (SP) is defined as:

$$SP = \frac{1}{\frac{\sum_{i=1}^{N} RIP(i)_{l,r}}{N-1}}$$

where $RIP(i)_{l,r}$ is the range integrated power the ith doppler beam to the left or right of the nadir beam, or zero for the nadir beam i.e. the nadir beam is excluded from the average.

5.4 Pass 1 - Backscatter

The SAR waveform is convolved with a weights file (an auxiliary input to the SAR chain), which results in an LRM style waveform. This waveform is then retracked with an OCOG retracker to give an amplitude estimate. A backscatter estimation for the surface may be computed from the 'amplitude' estimate from the retracker. The expression used is of the form:

$$\sigma^0 = 10\log_{10}\left(A/a_{ref}\right) - b_{ref}$$

where:

- A is the 'amplitude' estimate (in watts) from the retracker code;
- a_{ref} is a constant - an instrument characterisation parameter determined during commissioning
- b_{ref} is a constant - retracker dependent determined during commissioning

It is possible to calculate the absolute backscatter in this manner due to the CryoSat L1b product containing the necessary parameters to convert waveforms from counts to watts. The expression above approximates the radar equation.

5.5 Pass 1 - Diffuse waveform retracking

Ocean-like (diffuse) echoes (from ocean and sea-ice, and optionally from unknown classes) must be retracked to determine the offset from the window tracking reference point. Echoes received from sea-ice are typically diffuse, and often complex and multi-peaked. The figure below shows a typical waveform, overlaid with a magenta plot of the smoothed waveform which is used for retracking. The position of the first significant peak in the smoothed waveform is shown, together with the retrack point.

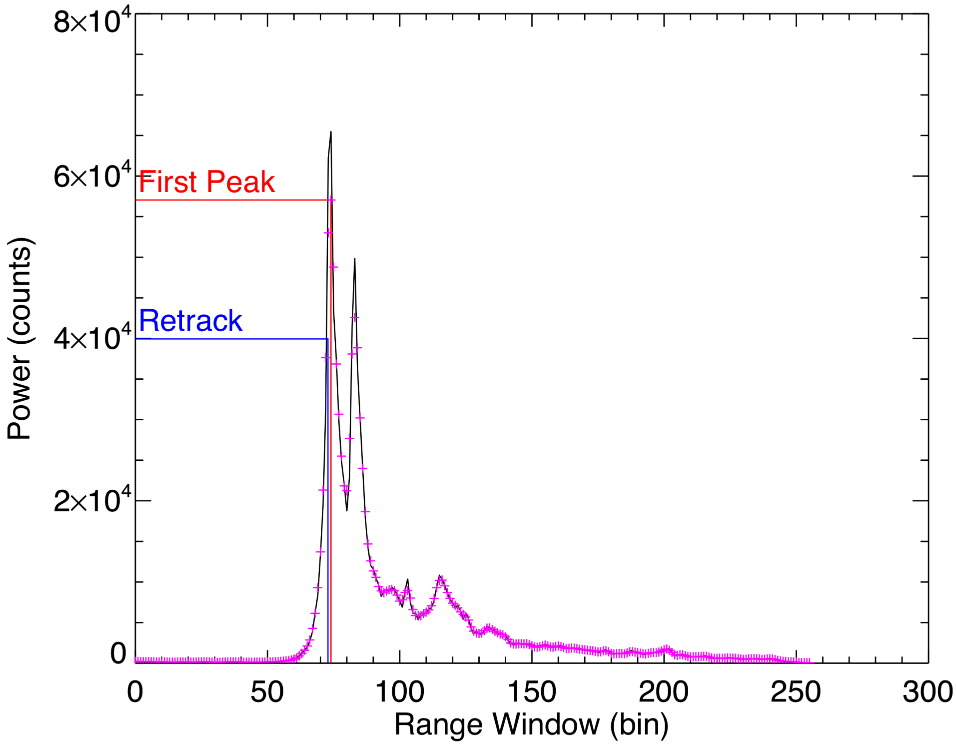

Figure 9: Typical diffuse SAR waveform from sea-ice

To obtain an accurate estimate of the sea-ice freeboard, a threshold retracker is used to minimize the effect of complex waveforms. The processing described below is performed on a waveform that has had a 3-bin moving average filter applied. The leading edge of the waveform is located by finding the first peak (defined as a bin that has greater power than both adjacent bins) where the power is greater than 20% of the peak power. A threshold retrack is then performed to locate the point where the power exceeds 70% of the power of that first peak. With $\Phi\left(i_{fp}\right)$being the power in the bin of the first peak and i_p being the first bin on the leading edge to exceed 70% of the value of $\Phi\left(i_{fp}\right)$:

$$i_{fp} = \min(\mathrm{i}) \ni \Phi(i) > 0.2\max(\Phi), \Phi(i-1) < \Phi(i), \Phi(i+1) < \Phi(i)$$
$$i_p = \min(\mathrm{i}) \ni \Phi(i) > 0.7\,\Phi\left(i_{fp}\right)$$

$$\delta i_{DIF} = \left(i_p - 1 + \frac{0.7\,\Phi\left(i_p\right) - \Phi\left(i_p - 1\right)}{\Phi\left(i_p\right) - \Phi\left(i_p - 1\right)} - i_0 \right)$$

The value i_0 is the bin number of the bin of zero range offset. The quantity δi above is further tested against a positive and negative threshold to ensure that the offset is valid. The range offset is then calculated from:

$$\delta R_{DIF} = d_{SAR} \times \delta i_{DIF}$$

where k is a parameter from the IPFDB that scales bins to meters.

5.6 Pass 1 - Icy ocean (specular) retracking and elevation estimation

For specular echoes from icy-ocean (leads), a model-fitting retracker is used. The same elevation computation scheme to that of ocean is used. A separate specular retracking processing bias may be applied on the same basis as the above diffuse processing.

The retracking is accomplished by performing a non-linear least-squares fit of a model of the SAR waveform to the L1b power waveform. The model used is given in

The fitted parameters of the model are:

- the amplitude estimate
- the epoch of the waveform model
- sigma value for the fitted Gaussian
- the exponential term for the tail

The initial values of these terms for the fitting procedure are determined by analysis of the input waveform. An example of the fit is shown in Figure 10.

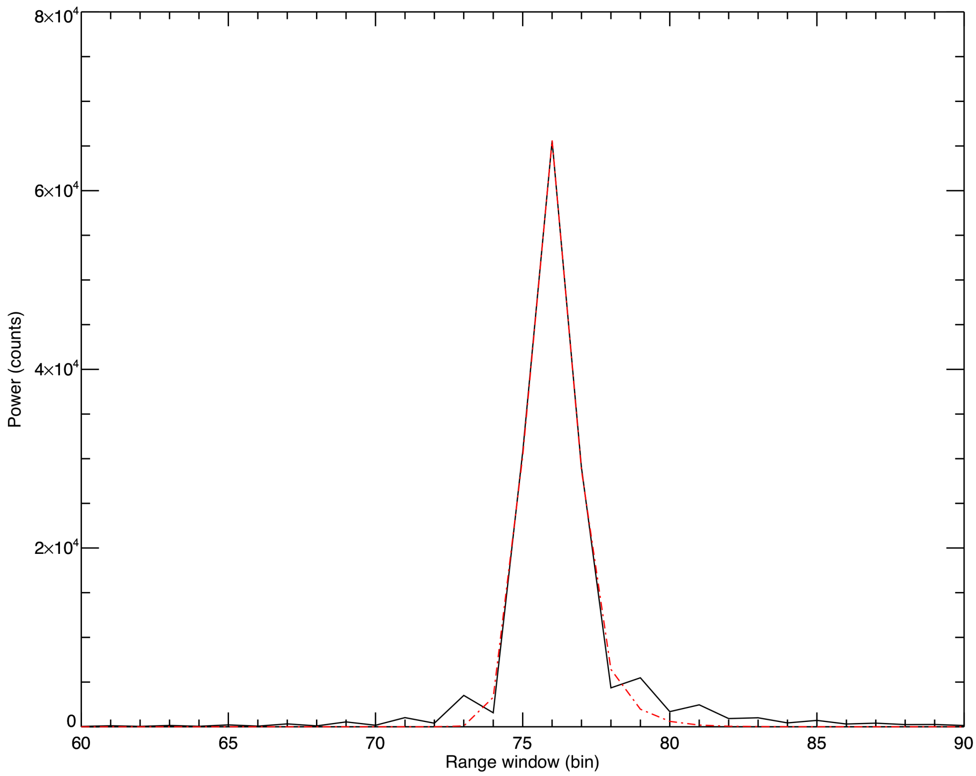

Figure 10: Typical specular SAR waveform from a lead and a corresponding model fit result (dashed)

The fitting procedure is stopped when one of the following situations occur (where all thresholds come from the PCONF):

- A χ^2 estimate of the goodness-of-fit reaches a threshold value
- The improvement of the goodness-of-fit is less than a certain threshold fraction of the previous absolute value
- A threshold number of iterations have been performed
- If the current goodness-of-fit of the current estimate is the same as or worse than the previous N attempts

The range offset is computed by converting the fitted waveform position to a bin number and differencing with the position of the zero offset bin to get δi_{SPEC} and then converting from bins to range offset:

$$\delta R_{SPEC} = d_{SAR} \times \delta i_{SPEC}$$

5.7 Pass 1 - Elevation estimation

The elevation of the records is determined from the following:

$$h_{SAR} = h_{SAT} - R_{SAR} - d_{bias}$$

where:

- h_{SAR} surface elevation above reference ellipsoid
- h_{SAT} CryoSat altitude above reference ellipsoid
- R_{SAR} Retrack-corrected range, computed using δi_{SPEC} or δi_{DIF}
- d_{bias} Retracker elevation bias for the retracker used

The retracker bias applied is dependent on which retracker was used – there are different biases for the specular and diffuse retrackers.

5.8 Pass 1 - Mean sea-level correction

The purpose of this algorithm is to determine the ice and sea surface height anomalies, using the surface discrimination flag to select the elevations and subtracting the interpolated Mean Sea Level.

$$h_{SHA} = h_{SAR} - h_{MSS}$$

where,

- h_{SAR} - the elevations with bias correction for respective surface type records
- h_{MSS} - interpolated mean sea-surface
- h_{SHA} - Surface Height Anomaly for the respective surface type records

The UCL13 mean sea surface is used here to compute the surface height anomaly. This model was specifically created for the purpose of extracting accurate surface height anomalies in the Arctic, and should not be used as a general global model.

5.9 Pass 2 - Short-arc, along-track accumulation

A fit to the height values of leads and open-ocean flagged surfaces is used to generate an interpolated sea-surface height anomaly for all records, including the ice discriminated regions. A chosen number, N, of sea surface height anomalies centred on the current record will be selected and a least-squares fit applied. Records are filtered, and surface height anomaly values outside a configurable threshold are rejected. This helps remove ocean height measurements that are anomalously high (due to the surface actually being sea-ice or land), or anomalously low (due to the lead retracked being a distance off-nadir).

Sea surface height anomaly values are selected based on the following criteria:

- Discriminated as lead or open-ocean
- Difference in timestamp from the current record less than a configurable threshold (currently chosen to correspond to ~100km)
- $|h_{SHA}| < k_{SHA}$

k_{SHA} is a threshold on surface height anomaly that excludes records for which the ocean height estimate may have been contaminated by sea-ice or off-nadir leads.

If no such records exist in the section spanning the N records, then no estimate of ice freeboard can be made and the data is flagged as not available.

The interpolated sea surface height anomaly h_{sha}' for the current record j is computed from the timestamp X_j by performing a linear least-squares fit to the selected lead heights and interpolating at the timestamp.

In principle, segments data may be concatenated to form the input file for the second pass of the SAR chain, although the PDS does not currently do this. Since there may be jumps in time between adjacent segments, we must ensure that this condition is detected and handled appropriately during the short arc interpolation.

We wish to interpolate a value of sea-surface height anomaly for a given record using known values of surface height anomaly from surrounding records. From our experience of similar processing with ERS altimeter data [R4], the interpolation will initially be based upon a nominal geographical radius of ~100km, but this radius is tuneable. We may not assume that this will correspond to a fixed number of records on either side of the current record.

The Short Arc Interpolation algorithm uses three tuneable constants to control its behaviour. The first determines the number of records that are needed for an interpolation to take place. The second threshold controls the maximum difference in time between the record at which the interpolation is taking place and any record used in that interpolation. The last is the threshold on absolute sea-surface anomaly to filter on.

5.10 Pass 2 - Freeboard estimation

An individual sea-ice freeboard measurement (excluding the overlying snow layer and assuming predominant reflection from the snow-ice interface) is found by subtracting the interpolated sea-surface height anomaly (output from Short Arc Correction), from the ice surface height anomalies (output from Ice Elevation Algorithm).

$$d_{freb} = h_{SHA}' - h_{sha}$$

where,

- d_{freb} the freeboard
- h_{SHA} the surface height anomaly
- h_{SHA}' the interpolated SHA from the fit to the ocean records about this record

5.11 Pass 2 - Geographical check

Finally, a latitude limit check is performed to verify that sea-ice elevation measurements are consistent with geographic location. Here the latitude is compared with thresholds set in the PCONF and a flag is raised if it is not within the bounds.

6 SARin L2 processing chain

The SARin processing chain is shown in Figure 11. Level-1b data in SARin mode enter from the top of the diagram. In the first algorithm, the Mean Sea Surface (MSS), Geoid, ODLE and surface type parameters are merged from auxiliary files using CFI routines. MSS and Geoid are added to the level 2 output but are not used in the processing. Next, the geophysical corrections calculated in the Level-1b processing are applied to the parameters associated with the waveforms. In the next Discriminator step, it is necessary to determine whether the radar echo is predominantly 'altimeter-like' or un-classifiable. By this we mean it is necessary to determine:

- whether the point of first return of the echo is sufficiently within the altimeter half-power foot-print to give rise to an 'altimeter like' echo with range ambiguities, and is therefore suitable for subsequent processing
- if the echo cannot be classified as above it is deemed to be un-classifiable

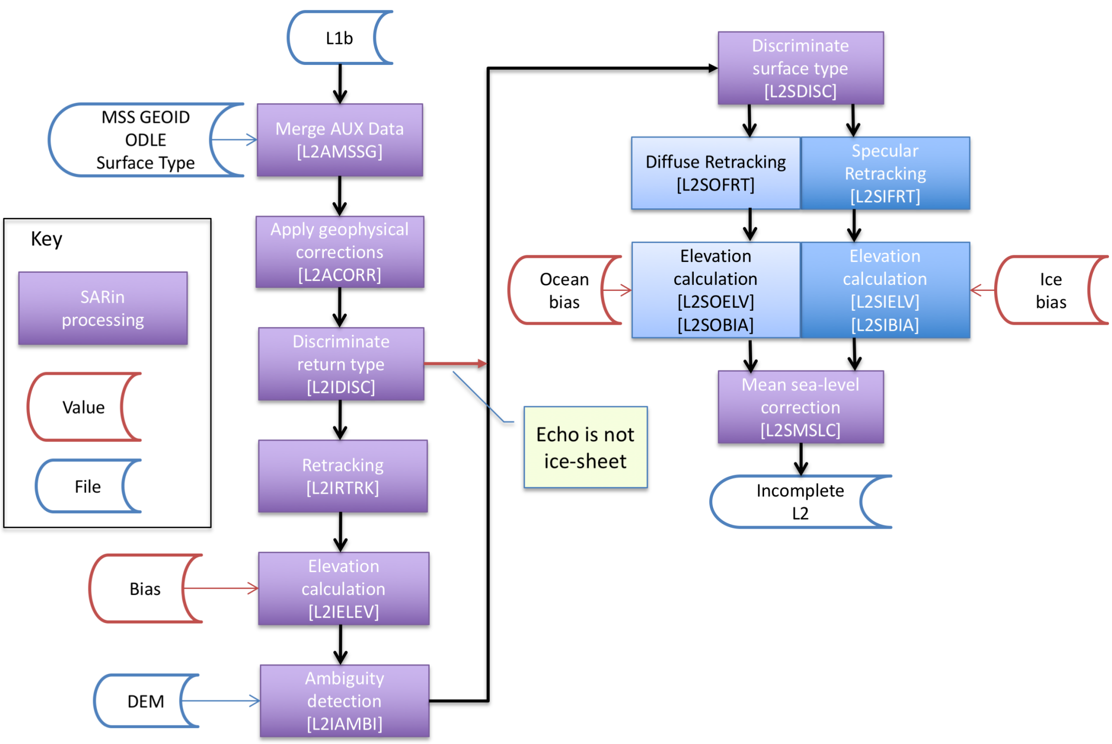

Figure 11: The SARin processing chain block diagram

Only the 'altimeter-like' echoes will be taken forward for further processing by the land ice processing (they may be sea-ice processed). The processing of the 'SAR-like' swath echoes that will be seen by the altimeter in this mode is outside the design scope.

The echoes must then be analysed in both power and phase to determine the range offset, the cross-track angle and the backscatter coefficient (a procedure analogous to the familiar 'retracking' of pulse-limited altimeter echoes). The range offset of the power echo is first determined. A suitable echo model that addresses the complex echo shapes observed has been developed and incorporated into the echo analysis procedure. Retracking the power echo allows the selection of the phase difference angle that corresponds to the first return from the surface. The corresponding phase angle is then used to derive the cross-track angle of the echo.

The information from the echo analysis is then used to determine the location and elevation of the terrain. Subsequently a check is made against a DEM to determine whether ambiguities due to phase wrapping or Doppler beam aliasing have occurred. Phase wrapping will result in a misplaced ground location, which will usually give a markedly differing height estimate to that obtained from the DEM. No attempt is made to subsequently correct the echo location in the event of phase wrapping. If the DEM check indicates that the elevation is affected by these ambiguities, the measurement will be flagged as bad.

The interferometric (SIN or SARIn) mode of the CRYOSAT SIRAL instrument uses coherent echo processing and interferometry to return higher resolution along track and across track echo direction from ice sheet margins and glaciers. The primary output quantities are the geophysically corrected ice sheet elevations, measurement locations and associated parameters.

6.1 Apply Geophysical Corrections

The following 'recipes' are used to apply the corrections.

Over Ice Sheets or any other non-ocean surface:

C_{TOT} = DRY + WET + IONO + OLT + SET + GPT

Over open ocean:

C_{TOT} = DRY + WET + IBC (or DAC) + IONO + OT + LPEOT + OLT + SET + GPT

Where:

DRY	dry tropospheric correction
WET	wet tropospheric correction
IBC	inverse barometric correction
DAC	dynamic atmosphere correction
IONO	ionospheric correction
OT	ocean tide
LPEOT	long-period equilibrium ocean tide
OLT	ocean loading tide
SET	solid Earth tide

GPT geocentric polar tide
C_{TOT} total correction to be applied

For an overview of each of the above corrections see sections 4.3.1 to 4.3.10.

6.2 Discriminator

The discriminator algorithm (see Figure 12) makes the following elementary checks on L1b data flags, and sets a failure if they are set, and sets default values of the waveform parameterisation outputs at level 2:

- Check on the level 1b measurement confidence data flag
- Check on the level 1b waveform flag

Some basic quality checks are then performed on the power echo such as:

- Check for low power in echo waveform
- Check on echo variance

The echo power noise floor is removed and the maximum power in Watts is calculated. A check is then made on the number of samples above noise power threshold. The range bin of half power maximum is then found and checked against a threshold.

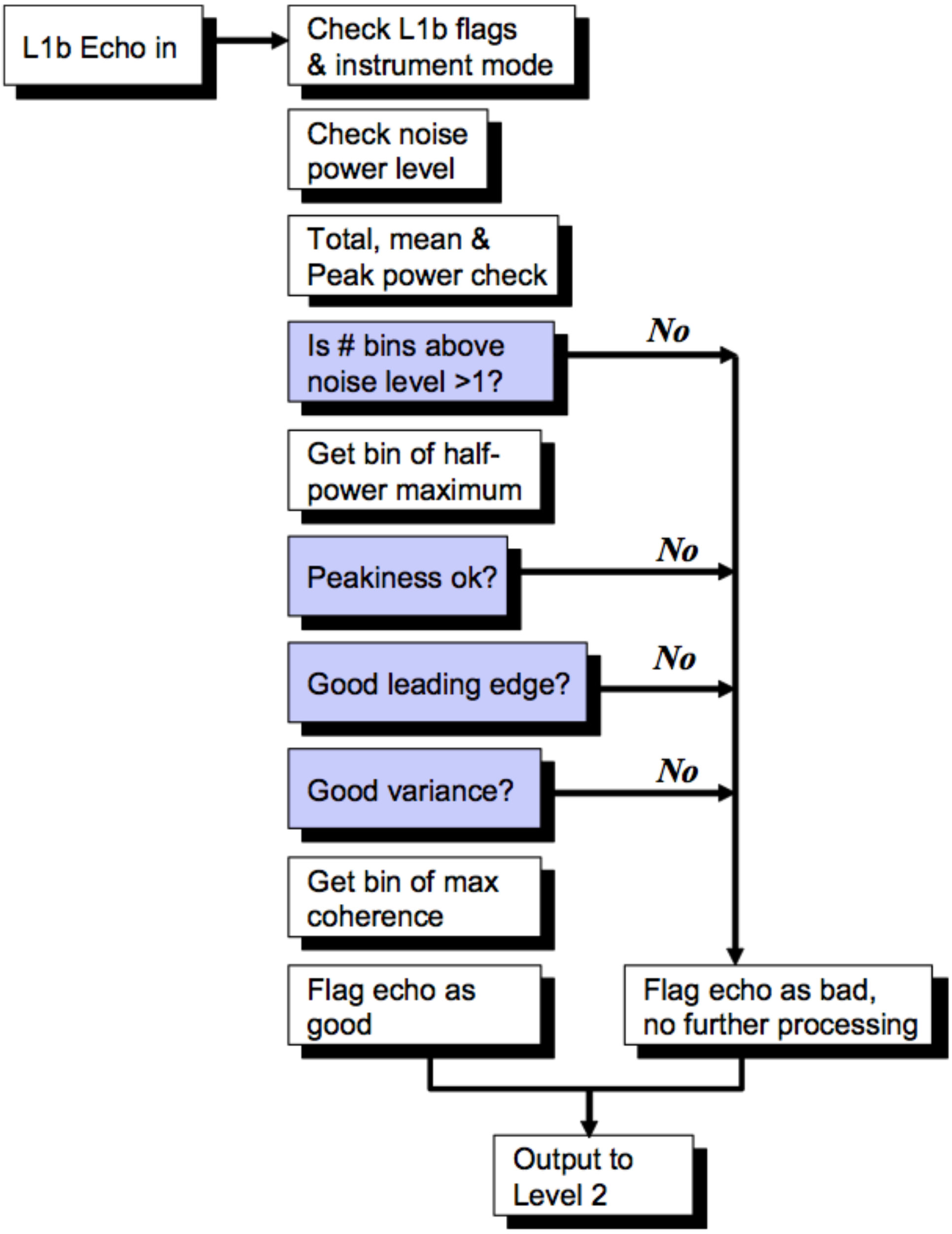

Figure 12: The SARin discriminator processing

The mean power (without noise) is then determined, and the echo peakiness is determined and checked against a threshold. A local noise gate is then used to compute and check the local noise level in Watts against a threshold.

Left and right gates are defined on the leading edge of the echo and the relative powers and widths are computed and used to assess leading edge quality. Flags are set for use by the retracker algorithm. Finally the echo variance is checked and the bin of maximum coherence is determined.

If the echo has been flagged as good (altimeter-like) then it goes forward for further processing.

6.3 Echo analysis

The retracking algorithm has been designed to exploit least-squares fitting of a semi-analytical model of the SARin mode echo (Figure 13).

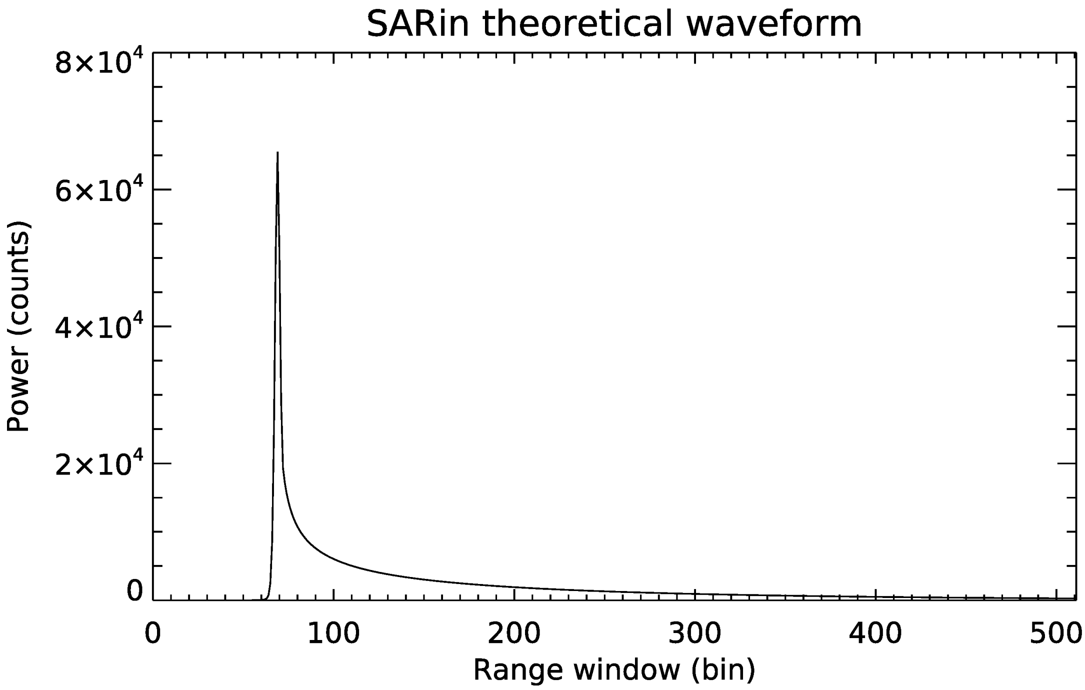

Figure 13: SARin waveform shape

The echo model is a modified Gaussian of the form:

$$m(t) = Ae^{-f^2(t)}$$

where f is a 5-part piecewise continuous function (in which a_n and b_n are polynomial functions derived from a Mathmatica model and expanded automatically into C code) whose form addresses different regions of the echo thus:

$$f_1(t) = g(t - t_0) + \big(m - g(t_0 - n\sigma)\big)$$
$$f_2(t) = b_0 - b_1(t - t_0 - t_1) - b_2(t - t_0 - t_1)^2 - b_3(t - t_0 - t_1)^3$$
$$f_3(t) = \frac{1}{\sigma(t - t_0 - t_1)}$$
$$f_4(t) = \sigma(t - t_0 - t_1) + a_2(t - t_0 - t_1)^2 + a_3(t - t_0 - t_1)^3$$
$$f_5(t) = \left(-\log\left[\frac{ce^{-\alpha(t-t_0)}}{a\sqrt{t - t_0}}\right]\right)^{1/2}$$

$$f(t) = \begin{cases} f_1(t) \text{ for } t < t_0 + n\sigma \\ f_2(t) \text{ for } t_0 + n\sigma < t < t_0 + t_2 \\ f_3(t) \text{ for } t_0 + t_2 < t < t_0 - t_1 \\ f_4(t) \text{ for } t_0 - t_1 < t < t_0 - t_3 \\ f_5(t) \text{ for } t > t_0 + t_3 \end{cases}$$

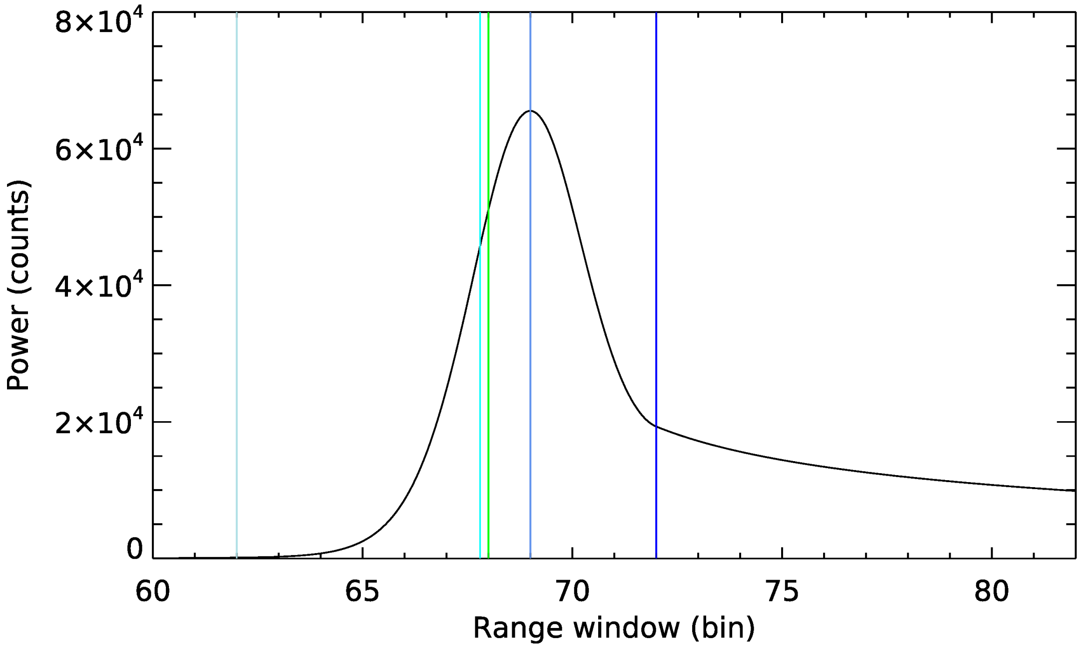

Figure 14: Domains of piecewise functions

In Figure 14, the domains of the functions are divided by the blue lines. The green line marks the retracking point, t_0.

11 parameters are involved in the fitting. These are:

- A height of the peak (the power maximum)
- σ the width of the peak
- t_0 retracking time
- c slope of the tail
- α decay of the tail due to antenna gain pattern
- n $n\sigma$ is the boundary time between $P_1(t)$ and $P_2(t)$
- t_1 centre of the peak on the time axis after t_0
- t_2 boundary between $P_2(t)$ and $P_3(t)$
- t_3 time of the tail start
- m is the tie point between $P_1(t)$ and $P_2(t)$
- g gradient of $f_1(t)$

The model depends non-linearly on the first 6 parameters. Following an initial estimate of these parameters, fitting is performed iteratively using the non-linear least squares procedure of Levenberg & Marquhardt (for an example implementation, see [R5]) and a chi-squared fit criterion. The other parameters are derived from configurable constants and the fitted values.

Following the fit to the echo power, a simple function is fitted to the phase profile to get the phase difference at the power retracking point. The scattering angle may be calculated from this phase difference. After the retracking point, the plot of the phase difference array shows a slope [R6]. This arises because the centre of the antenna pattern remains at the sub-satellite point, whilst the point of first echo return may be away from that point due to terrain slope effects. Assuming a uniform surface reflectivity, the antenna beam pattern will weight some areas more than others and produce a bias in the observed phase difference for points that are away from the retracking point. Both the phase difference and phase slope are therefore fitted. The fit is complicated slightly due to the tendency of the phase values to wrap on +/- π. The fit is therefore performed by minimising an error term defined by:

$$\sum_{i=n_1}^{n_2} \frac{c_i^{\eta}}{1-c_i^{\delta}} \sin^2\left(\varphi_i - (\text{constant+slope} \times i)\right)$$

with respect to constant and slope, where c_i and φ_i are respectively the phase difference and the coherence of the i[th] bin in the waveform. The values of n_1 and n_2 are chosen to straddle the retracking point. The values of δ and η are tunable constants, currently set to $\delta = 2$ and $\eta = 3$.

Minimising this error term results in a maximum likelihood estimate of constant and slope parameters. The use of the sine function is necessary to overcome the wrapping phase values. The term preceding the sine function gives greater weight to waveform points with high coherence. Without proper weighting, the estimate of the scattering angle is poorer, especially at low signal-to-noise ratios[Error! Bookmark not defined.].

The Levenberg-Marquardt method is again used here but the routines were modified to handle complex numbers and wrapping phase. Once this error term has been minimised, the phase difference is found as (const+slope $\times$ $n_{retrack}$) where $n_{retrack}$ is the waveform bin value of the retracking point. The processing flow for power and phase echo analysis is shown in Figure 15.

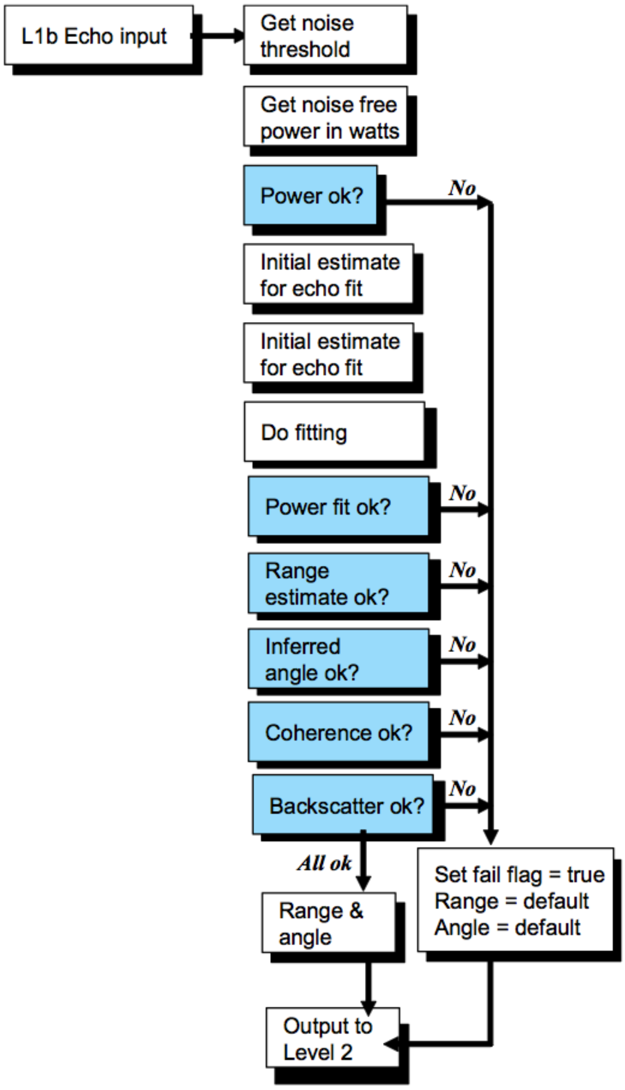

Figure 15: Echo analysis ('retracking') processing flow

6.4 Backscatter estimation

The SARin chain uses the same backscatter calculation method as the SAR - see Section 5.4. The SARin chain has its own set of tuneable constants, independent of those used for SAR.

6.5 Elevation processing

The elevation is calculated from the parameters obtained from echo analysis/retracking and from appropriate vectors supplied in the L1b data. The geometry is shown in Figure 16

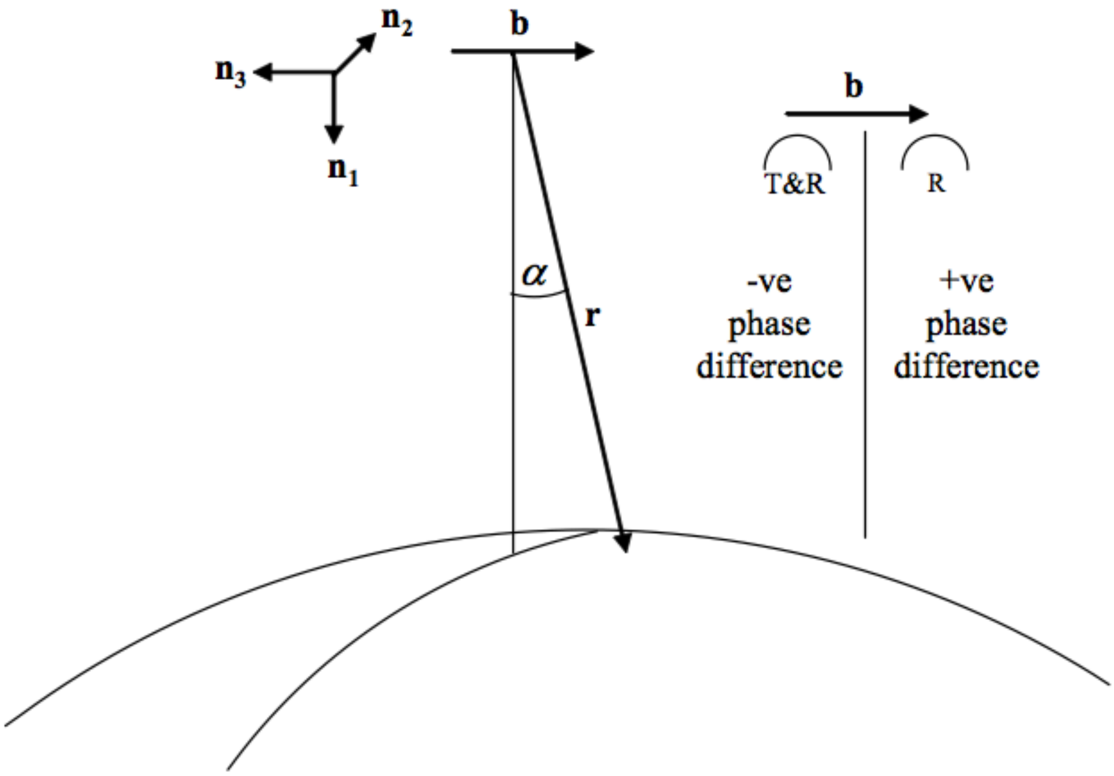

Figure 16: Estimation of elevation

From the retracking step we have the range, r, and an echo direction angle, α.

The baseline vector **b** in the CryoSat {CoG, $\mathbf{n_1}$, $\mathbf{n_2}$, $\mathbf{n_3}$} reference frame is {x_b, y_b, z_b}.

The range r and angle α locate the echoing point on a circle, C, around the interferometer baseline.

The intersection of the circle and a plane defined by n_1 and n_3 gives two points. This plane is orthogonal to the velocity vector and contains the SARin footprint.

The positions of the solution points are shown in green on the following diagram (Figure 17), where:

- The satellite is in red at point S
- The point C is the centre of the circle on the baseline vector
- The potential echoing points E are in green
- The blue rectangle is the plane orthogonal to the baseline vector
- The red rectangle is the plane orthogonal to the velocity vector

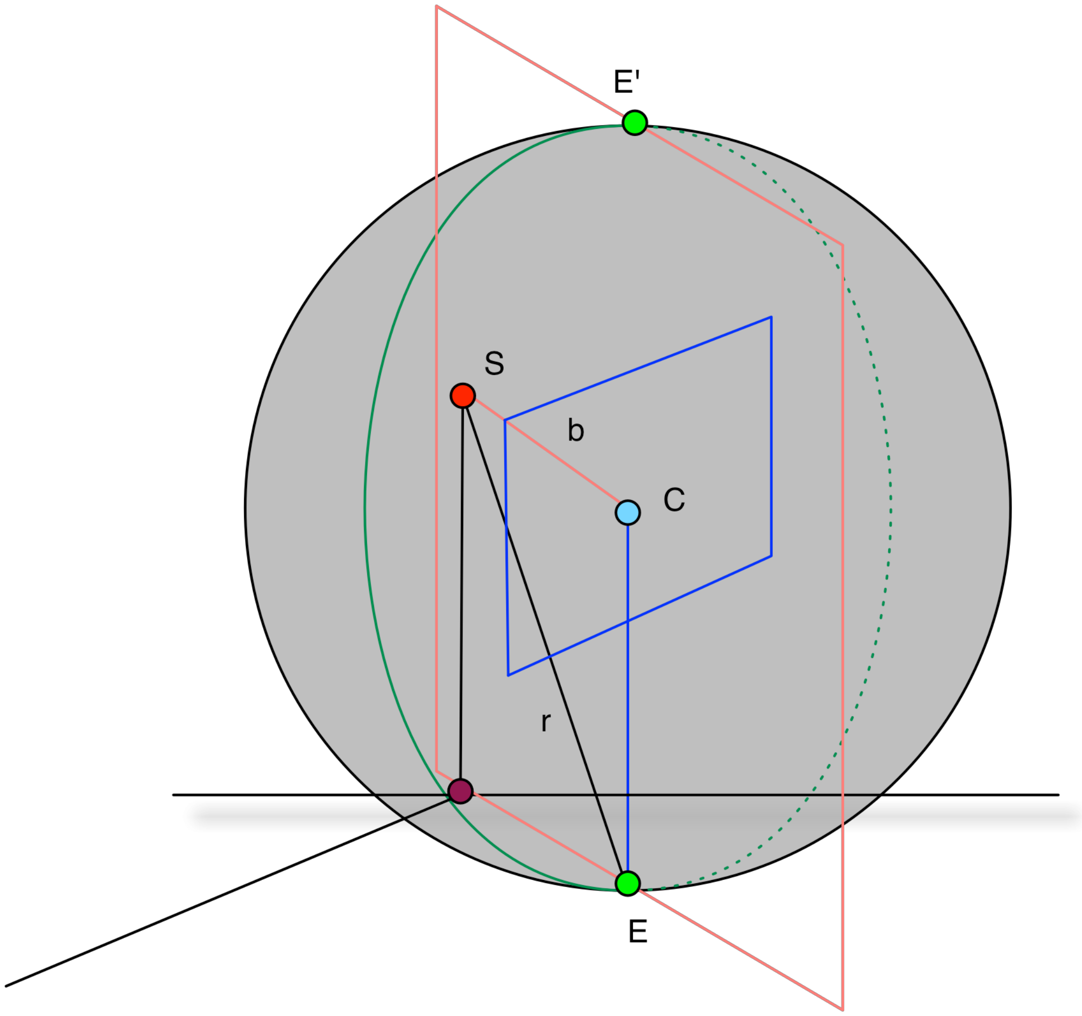

Figure 17: Geometry for SARin elevation calculation

The correct solution is the one with the greatest x value (positive on $\mathbf{n_1}$ axis).

With a satellite altitude of 700 km and an earth radius of 6400 km, an error of 1 milli-radian on the inferred angle gives an error in position of about 0.7km (6267 micro-degrees lat/lon), and this results in an error of about 334 mm on the elevation.

The processing flow is shown in Figure 18. This includes the addition of a static bias variable, read from the PCONF, to account for any residual system bias. This bias value is constant along track.

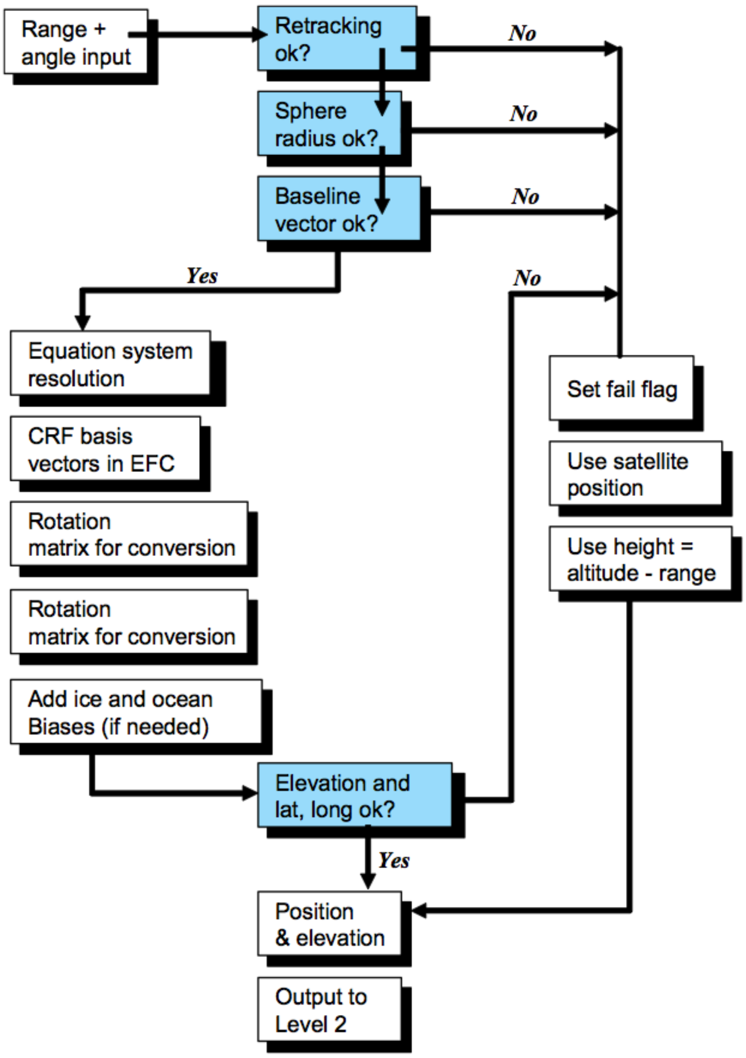

Figure 18: Elevation processing logic for SARin

6.6 Ambiguity check

This algorithm checks whether the location of the measurement point is ambiguous. This can occur across-track when the interferometric phase difference has wrapped or along-track when the Doppler beams are aliased (see Figure 19). In the event that the phase has wrapped or the Doppler beams are aliased it is likely that the elevation will be incorrect by a significant amount.

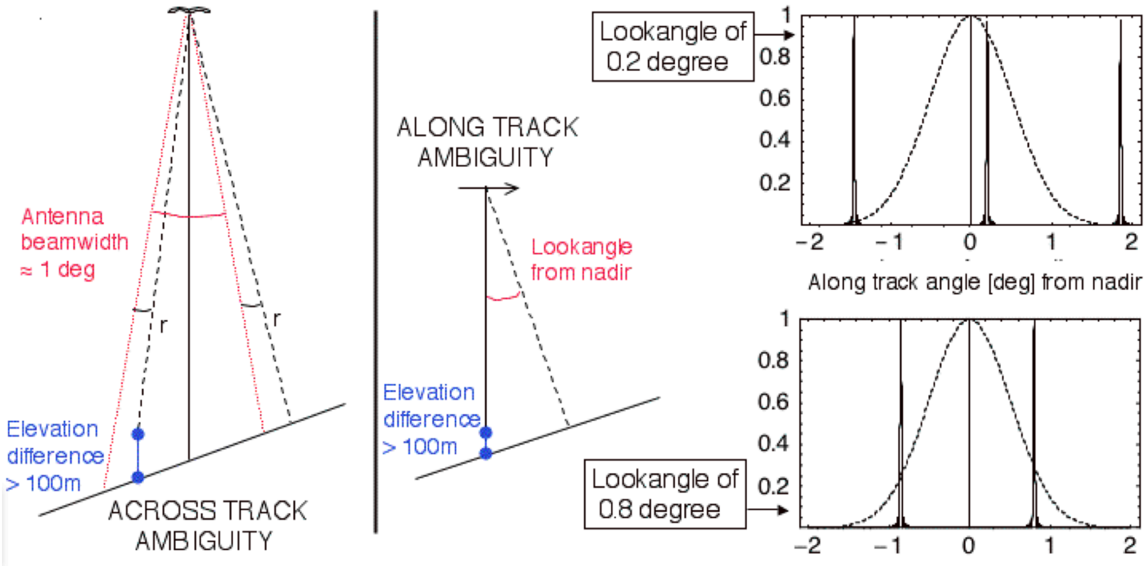

Figure 19: Across and along track ambiguities

This check uses Digital Elevation Models (DEMs) that will be updated during the mission. To determine if a measurement is ambiguous, the algorithm looks for the appropriate DEM for the current measurement position. If there is no available DEM, the algorithm sets the ambiguous flag. The algorithm adopts the methodology for Antarctic and Greenland slope model access in the ENVISAT RA-2 LOP chain. The coordinates of the measurement position are transformed into the coordinate system of the DEM. Finally, the DEM is interpolated at the measurement point and the interpolated and measured elevations are compared. There is ambiguity if the difference in elevations is greater than a threshold.

Ambiguity processing proceeds as follows:

- Read all available DEM headers and data sets.
- Get longitude (lon), latitude (lat) and height (h) of the measure from the Elevation algorithm.
- Find the DEM of the corresponding area using DEM headers.
- Transform geodetic coordinates into DEM local Cartesian coordinates (X, Y, Z).
- Interpolate DEM at the retrieved location (X,Y).
- Compare the DEM interpolated elevation with h.
- If DEM interpolated elevation is consistent with h (to within ± h, where h is a run-time tunable threshold) then there is no ambiguity.

These steps are shown diagrammatically in Figure 20.

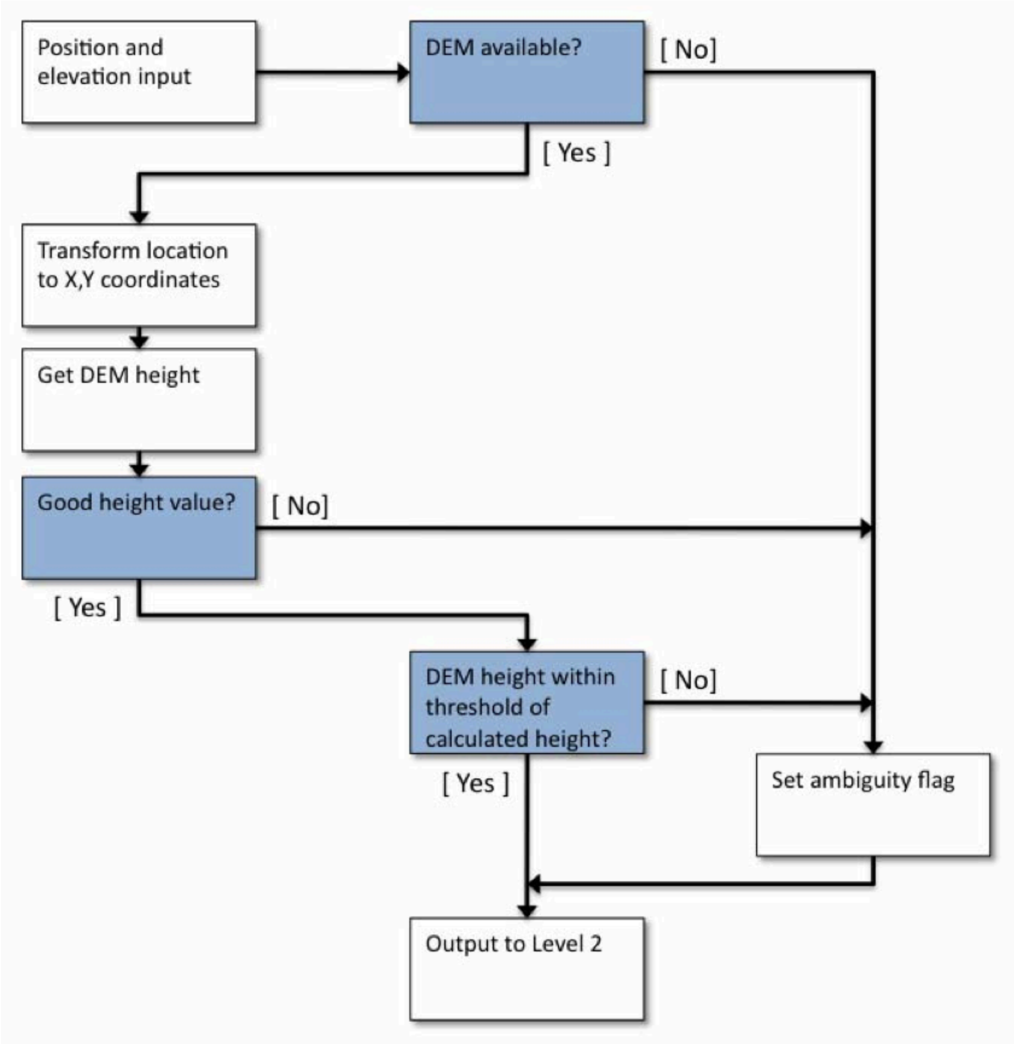

Figure 20: Ambiguity check logic for SARin

6.7 Sea-ice processing for SARin data

From this point, the sea-ice processing algorithms from section 5 are run on the SARin power waveform. The incomplete L2 SARin data is then passed through the SAR Pass B chain. No values calculated by the SARin land-ice processing algorithms are overwritten by the sea-ice processing, although additional bits in flag words may be set (none are cleared).