D3.3: Algorithm Theoretical Basis Document (ATBD) of the Process Specification

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1. Introduction

1.2. Purpose and scope

This document is the Algorithm Theoretical Baseline Document (ATBD) detailing the high level specification of the process developed in the frame of the LOTUS project from Level 1.0 up to higher levels. Each processing chain is an independent process which consists of a sequence of scientific algorithms. All the focussed areas are considered in this document : Open Ocean, Polar Ocean, Coastal Zone and hydrological zones.

1.3. Document structure

This document is structured into two chapters describing:

- Architecture of the LOTUS processing chains
- Detailed description of each processing level

2. Architecture of the LOTUS processing chains

2.1. General processing level conventions in altimetry

A complete ground processing chain has been defined and developed in the frame of the LOTUS project. As for all altimeter processing chains, the processing has been split in different levels (from 0 to 4) which correspond to the following standard definitions.

Level 0 : It corresponds to the raw telemetry for the particular source packet (altimeter measurements in our case)

Level 1 : Telemetry is processed to obtain level 1 data, i.e., data that are time tagged and located, expressed in the appropriate units, and checked for quality. This task is generally performed by the Instrument Control Center. Level 1 data are corrected for instrumental errors and errors due to atmospheric signal propagation and perturbations caused by surface reflection. Geophysical corrections are then applied (solid earth, ocean and pole tides, etc.). For delay doppler altimetry, the SAR processing is performed, the tracker ranges and the scaling factor are computed. The multilooked waveforms are computed (level 1 data are formed at 20Hz)

Level 2 : At this level, the waveforms computed at Level 1, are retracked. Different retracking algorithms can be applied to calculate the final altimeter range, backscatter coefficient, wind speed over ocean and SWH. There are different types of retracking algorithms according to the type of waveforms (ocean, ice, sea-ice). Geophysical corrections depending on the retracker output are computed. Level 2 products are generally provided to the users for validation purposes.

Level 3 : Level 3 data are validated (off-record data are edited), along-track data. Further computation is performed on level 2 geophysical data (e.g. SSH or SLA). There may be cross-calibration between missions.

Level 4 : In general, Level 4 data are multi-satellite (cross-calibrated), gridded data for the ocean products. For the other surfaces, they have never been defined but we can consider that time series at a given point (virtual station for example) can be considered as level 4 products.

2.2. LOTUS processing chains

The aim of the LOTUS project is to define and develop new methodologies to process the Cryosat-2 data (and in the future, Sentinel-3 data) over the different surfaces identified : open ocean, coastal ocean, polar ocean and hydrological zones. A classical processing architecture has been developed for the LOTUS project according to the following diagram in which processing chains and products have been identified.

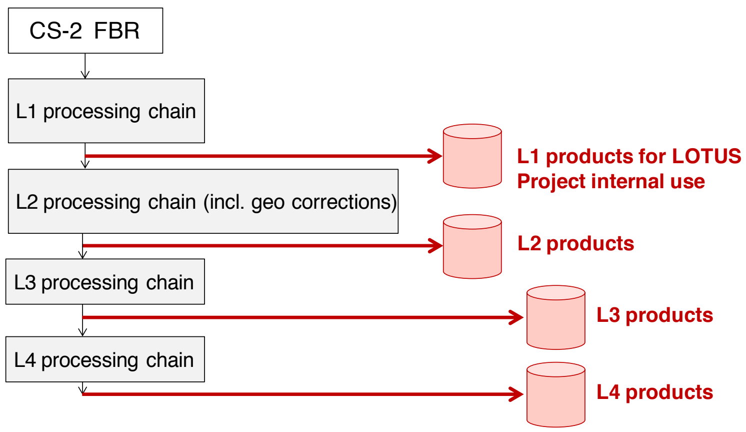

Figure 1: General flowchart of the LOTUS processing chain

Dedicated processing chains have been defined and implemented in the frame of the LOTUS project with the aim to provide the higher level products that will be used for applications of new GMES value-adding services but also with the aim to provide the LOTUS partners with the data required for their studies depending on the product level and depending on the applications.

The following scheme gives the general architecture of the LOTUS processing chains. It is coherent with the flowchart given in D3.1 (Data Product and Definition Document), providing the general structure of the products delivered by the LOTUS processing chains.

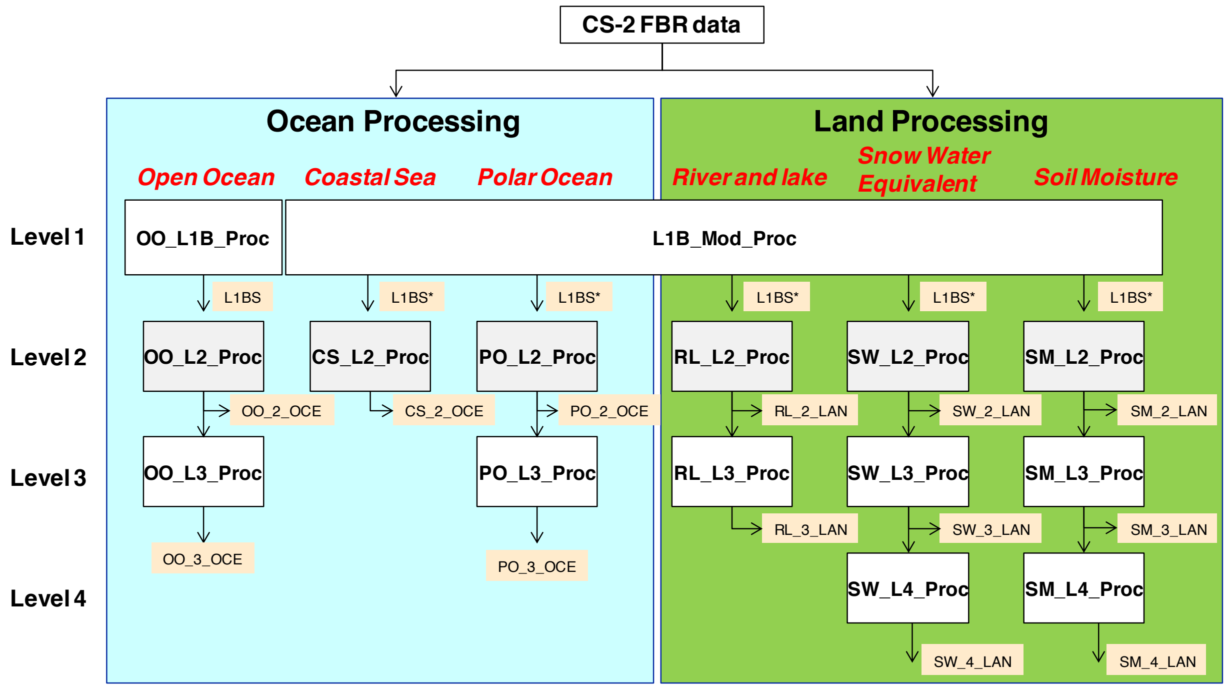

Figure 2: Overall view of the LOTUS processing chains.

The Cryosat-2 FBR data are the input data of the LOTUS processing chains. During the course of the project, it has been agreed by ESA Cryosat-2 mission manager (T.Parinello) that the LOTUS processing chain will use Cryosat-2 FBR (Full Bite Rate) data. It is indeed important for the quality of the project to be able to start from the raw data in order to construct the L1 data set independently from the official processing chains (and with the ability to develop several processing options depending on the observed target). Doing so, the LOTUS is thus able to investigate new L1 processing and new methods to provide the best exploitable data to each partner and for each application.

In blue, the ocean processing chains are identified. In green, the land processing chains are identified.
Ocean sub-themes : Open Ocean, Coastal Ocean, Polar Ocean
Land sub-themes : River And Lake, Snow Water Equivalent, Soil Moisture.
All processing levels are identified.
All products delivered by the LOTUS chains are identified in orange.
At some levels, it has been chosen in the course of the LOTUS project not to develop some processing chains because they have been considered not relevant or not mature enough.

The following table gives the list of processing chains that have been specified and implemented in the frame of the LOTUS project.

Processing Chain	Level	Description
OO_L1B_Proc	1	Open Ocean L1 Processing chain
L1B_Mod_Proc	1	L1 Processing chain for all surfaces except open ocean
OO_L2_Proc	2	Open Ocean L2 Processing chain
CS_L2_Proc	2	Coastal Sea L2 Processing chain
PO_L2_Proc	2	Polar Ocean L2 Processing chain
RL_L2_Proc	2	River and Lake L2 Processing chain
SW_L2_Proc	2	Snow Water Equivalent L2 Processing chain
SM_L2_Proc	2	Soil Moisture L2 Processing chain
OO_L3_Proc	3	Open Ocean L3 Processing chain ==> defined and implemented but not described in this document
CS_L3_Proc	3	Coastal Sea L3 Processing chain ==> not defined nor implemented
PO_L3_Proc	3	Polar Ocean L3 Processing chain ==> defined and implemented but not described in this document
RL_L3_Proc	3	River and Lake L3 Processing chain
SW_L3_Proc	3	Snow Water Equivalent L3 Processing chain
SM_L3_Proc	3	Soil Moisture L3 Processing chain
OO_L4_Proc	4	Open Ocean L4 Processing chain ==> not defined nor implemented
CS_L4_Proc	4	Coastal Sea L4 Processing chain ==> not defined nor implemented
PO_4_Proc	4	Polar Ocean L4 Processing chain ==> not defined nor implemented
RL_L4_Proc	4	River and Lake L4 Processing chain ==> not defined nor implemented
SW_L4_Proc	4	Snow Water Equivalent L4 Processing chain
SM_L4_Proc	4	Soil Moisture L4 Processing chain

Tableau 1: List of the processing implemented in LOTUS

2.3. Description of the LOTUS product levels

The LOTUS products are described in the D3.1.

Level-1BS, Level-2, Level-3 products are generated. Level 4 ocean products (gridded data sets for ocean applications) which were a objective at the beginning of the project, are now out of scope since this kind of products is only meaningful when merging different satellites. Moreover it is important to note the limitations of these high-level satellite products when using them, since it is not taking benefit of the improvement in the along-track resolution anymore. The objective of LOTUS is precisely to demonstrate the potential improvement brought by the SAR processing in the along-track direction.

2.4. Roles of the LOTUS partners in the development of the processing chains

The following diagram identifies the responsibilities of the different partners in the definition and development of the different processing chains. We recall that globally in the project, CLS is responsible for ocean processing chains, DTU for polar ocean and River and Lakes processing chains, Starlab for coastal ocean processing chains and NU for soil moisture processing chain.

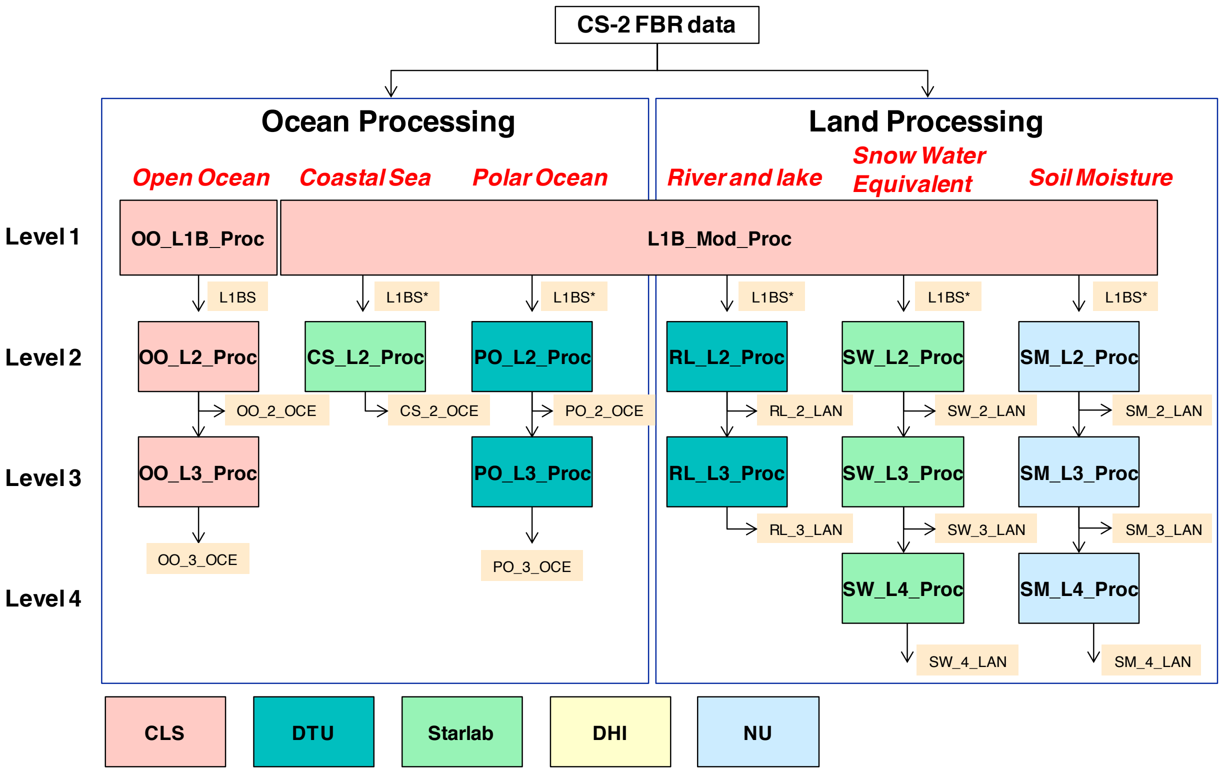

Figure 3: Role of the partners in the LOTUS development.

CLS is responsible of the global processing prototype and data distribution. Otherwise, each partner is responsible for the algorithm studies and processing chain developments linked to the specific observed surfaces.

3. Detailed description of each processing level

In this chapter, each processing of each level is described.

3.1. Ocean Processing

3.1.1. OO_L1B_Proc and L1B_Mod_Proc : Level 1 Ocean and Land processing chains

The level 1 processing chain is inherited from the CNES CPP (CNES Processing Prototype) processing chain [Boy et al., 2012], for SAR and LRM mode data. The initial aim of the CPP was to contribute to expertise studies for the Cryosat-2 mission and for the future Sentinel-3 mission (and Jason-CS mission). In the frame of LOTUS, evolutions have been implemented in the CPP. They are described hereafter.

The CPP chain is shown in Figure 4. It includes Level 1 and Level 2 data processing for both SAR and LRM telemetry. Two main functions are implemented. The first one (on the left) generates L2 data from the Cryosat-2 Full Bit Rate (FBR) data. The second one (on the right) generates LRM L2. This second function is not used in the LOTUS project which only considers SAR mode processing.

For SAR mode data, SAR and reduced SAR (RDSAR) echoes, also called "Pseudo LRM", are generated simultaneously. The SAR processor is based on the use of the aperture synthesis technique while a "conventional" processing on high PRF echoes (equivalent to on-board LRM processing) is applied to derive RDSAR-mode echoes.

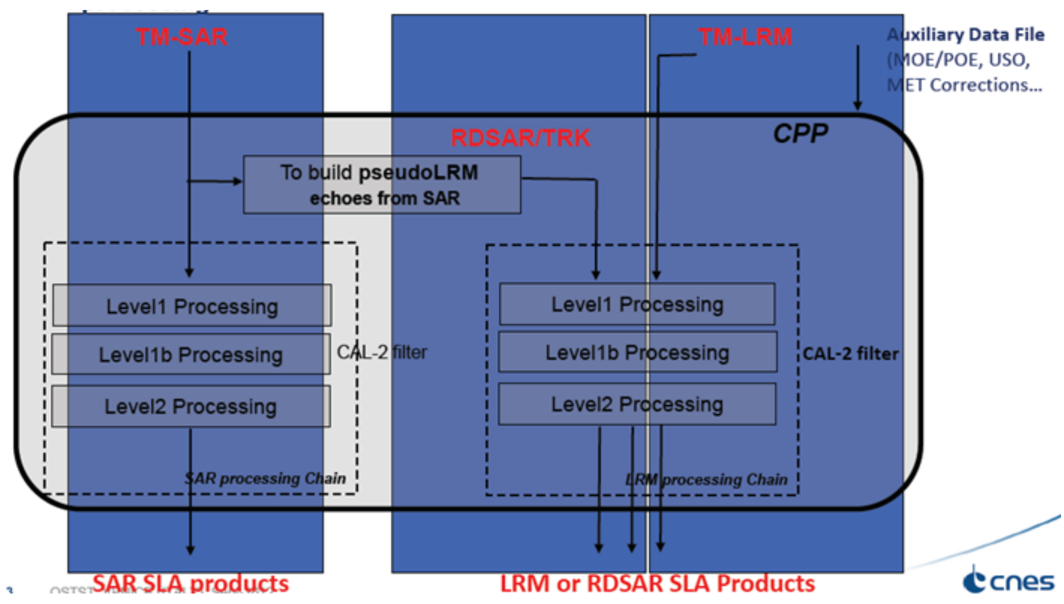

Figure 4 : General flowchart of the CPP (from Boy et al., 2012).

SAR Level 1

Level-1 products (here called L1BS, S standing for Scientific) are only used internally by the LOTUS partners in order that each partner starts from the same L1 data set to produce level 2 products with its refined algorithms depending on the focussed surface. For the LOTUS project, L1BS products are not distributed to external users.

The Level-1 processing includes geo-location and calibration of the radar echoes (i.e. stack of Doppler beams) with ancillary information (latitude and longitude coordinates, altitude, satellite velocity, roll and pitch mispointing angles of the antenna derived from the star tracker information, landmarks (land/water), tracker range, geophysical and environmental corrections) at high sampling rate (20-Hz). It should be noted that a precise orbit determination is used (the reference surface for the altitude and the orbital rate of the satellite is the T/P reference ellipsoid and not WGS84).

Two kinds of Level-1BS processing chains have been developed regarding the target end applications to be considered:

- One is intended to provide relevant information to the Level-2 processing scheme for easing the extraction of high-resolution water body quantities in regions where the impact of land and ice elements having much higher brightness temperatures than water is significant (enhancing surface topography measurements in the coastal zone, sea ice regions and over in-land rivers, their tributaries and lakes).

  1) A weighting function (e.g. Hamming function) is applied in azimuth direction in order to limit the effect of azimuth ambiguities originating from very high scattering targets that may aliased the received signal in azimuth. This function also allows cleaning the beams pointing off-nadir from spurious signals that may originate by the spread of high levels of energy contained in the main lobe through the azimuthal impulse response. Nevertheless a side effect of the weighting is to degrade the azimuthal resolution (typically ~300m to ~450m in the CryoSat-2 configuration).

  2) A second process in the chain consists in zero padding the Doppler beam waveforms doubling their extension in order to, on the one hand, broad the leading edge of the waveform and, on the other hand, avoid aliasing of the signal that would occur by squaring the detected signal typically over specular surfaces in polar ocean or coastal

- A Level-1BS product is dedicated to open ocean investigations for which the nominal CPP processing chain remains unchanged.

RDSAR-mode processing chain

The RDSAR mode echoes are obtained from the same individual returns that are used in SAR-mode (provided in FBR) but a different processing is employed to generate the waveforms.

The description of the RDSAR-mode algorithm is given in the flow chart shown in Figure 5 which outlines the key parts in the way the algorithm works.

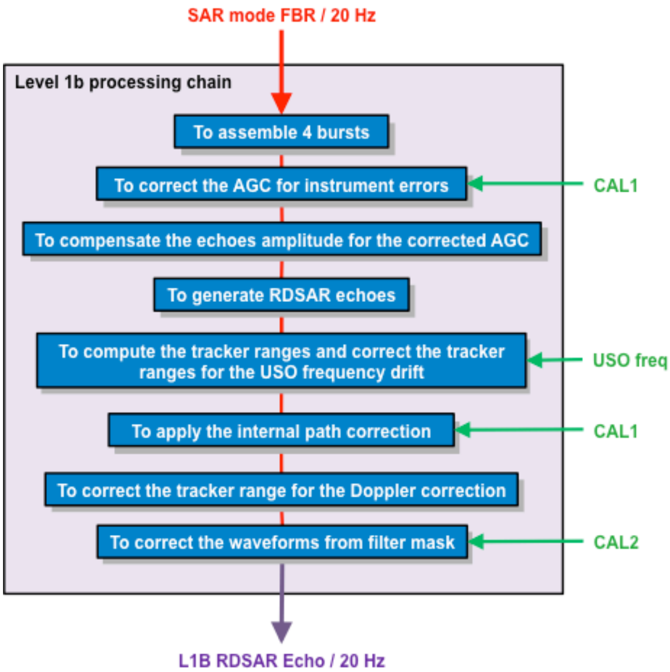

Figure 5 : Flowchart of the Level 1 RDSAR processing

3.1.1. OO_L2_Proc : Level 2 Ocean processing chains

SAR Level 2

The processing chain includes high-resolution along-track geophysical quantities (altimeter range, orbital altitude and geophysical corrections, with significant wave height and wind-speed information) derived from the processing of the measurements data provided into the Level-1BS product, then time-tagged, precisely located and corrected for geophysical and environmental effects (tropospheric correction, ionospheric correction, solid earth, ocean and pole tides, etc.). Different Level-2 processes are in use according to different targets and will thus generate more than one Level-2 product from the same Level-1BS product. Data at this level are used by scientists or engineers that already work in the field.

In SAR mode, starting from the square-law detected Doppler beams (looks) of the stack, two types of signal are exploited:

- The multi-looked SAR power echo, which is simply obtained by an incoherent summation in azimuth direction of the beam waveforms of the stack. The numerical retracking algorithm that is currently operating in the CPP chain fits the SAR echo with pre-computed echo models to retrieve the range, SWH and sigma-naught.
- The distribution of power across the beams after integrating the power in range. It is expected that this distribution of power reflects the along-track antenna gain pattern, i.e. Gaussian. Any distortion of the Gaussian shape may not be seen in the multi-look echo, but would give amount of relevant information to be analyzed, in particular the along-track mispointing angle and the ocean surface (ocean surface roughness, slope of the surface, high reflectivity surface). By fitting the distribution with a Gaussian-like model, the estimated parameters will inform about the beam behaviour. The characterization of the ocean surface (e.g. stack width, kurtosis, skewness) from stack data is one of the priorities raised by the expert team of the mid-term CP4O project [Cotton, 2014]. It has been implemented in the LOTUS processing chain.

The main algorithm implemented at Level 2 is the retracking function. Geophysical corrections are usually also computed at level 2 but for the LOTUS project, they are computed at level 1 in order to be provided to the different partners making possible for them to construct and validate the surface heights.

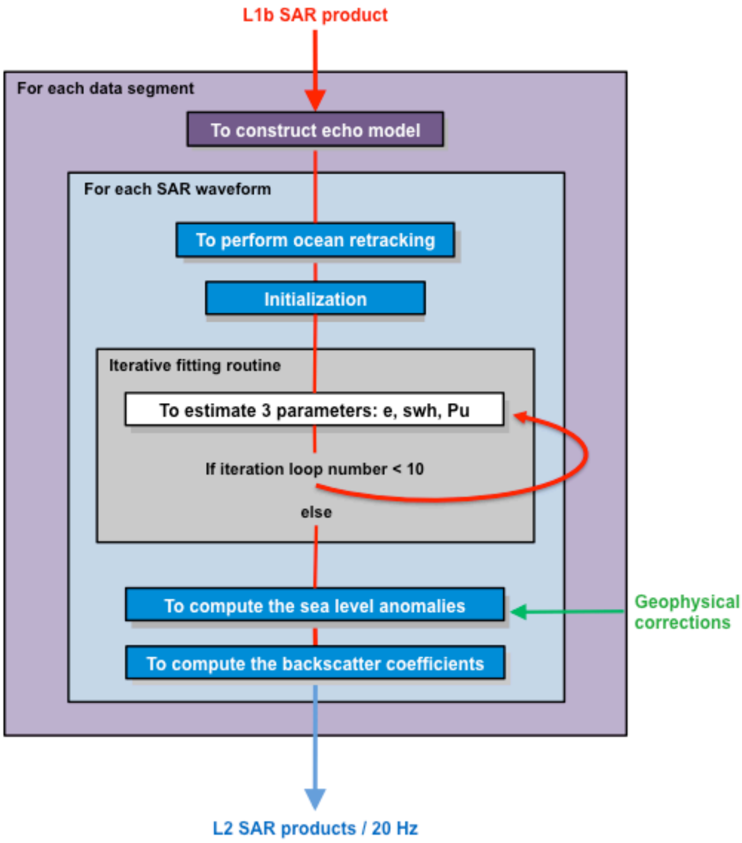

Figure 6 : Flowchart of the Level-2 SAR processing

RD-SAR Level -2

RDSAR echoes are retracked using a classical Maximum Likelihood Estimator fitting the classical Brown model .

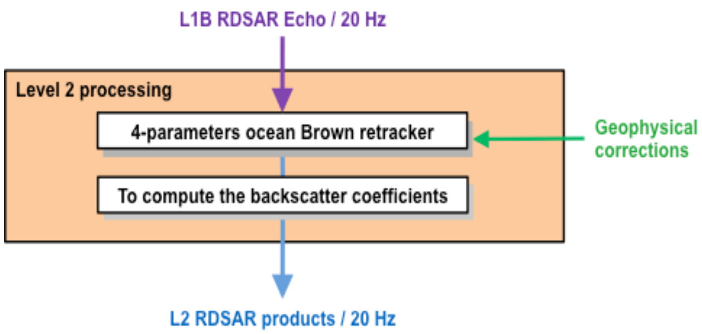

Figure 7 : Flowchart of the Level-2 RDSAR processing

Geophysical corrections

Concerning the geophysical corrections, the following figure presents the flowchart of the different corrections implemented :

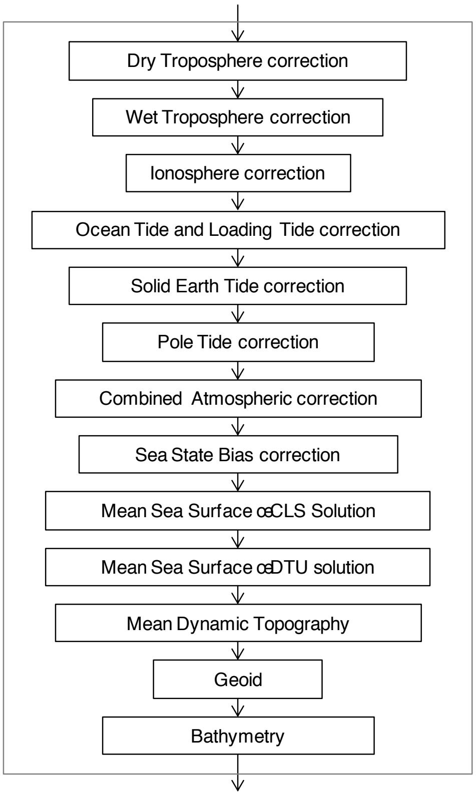

Figure 8 : Flowchart of the corrections implemented in the LOTUS processing chains.

3.2. Coastal Processing

3.2.1. CS_L2_Proc : Level 2 Coastal processing chain

The L2 processing for coastal products is based on a pre-processing selecting the range bins of the SAR waveforms that are not likely to be affected by land contamination. This is achieved by geo-locating the delay and Doppler pairs of the SAR Altimeter stack, i.e. the 2-dimensional array for the range cell migrated Doppler looks aligned with respect to the nadir position. The SAR waveform retracker is then fed with this information and neglects the range bins subjected to land contamination from the geophysical parameter estimation process. From the retracking results, we retrieve the relevant fields: SWH, SSH, and σ_0.

The coastal processing is described hereafter :

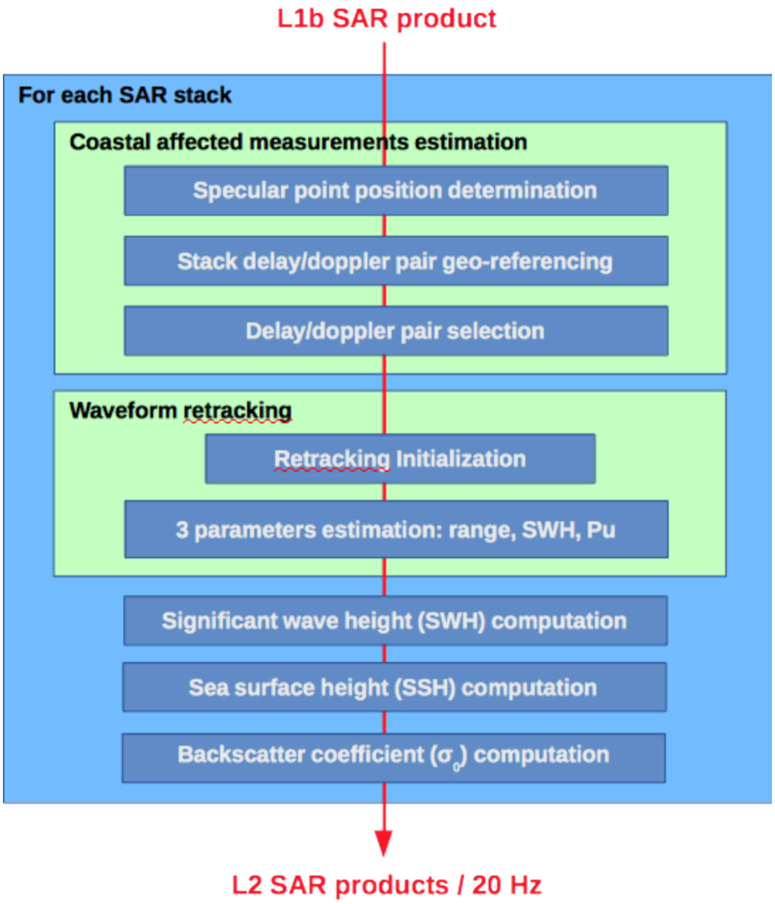

Figure 9 : Coastal SAR Level 2 processing

The coastal processing ATBD is given in LOTUS_D13 - SAR Ocean - ATBD - Final.pdf

3.3.Polar processing

3.3.1. PO_L2_Proc : Level 2 Polar Ocean processing chain

The Polar Ocean must be handled separately as the frequent presence of sea-ice and leads in the sea ice changes the waveform shape calling for a tailored retracking system using multiple retrackers.

In figure 10 the typical waveforms encountered in the Polar is seen. These are waveform corresponsind to open ocean, leads in the sea ice and sea ice (melange).

Heoai

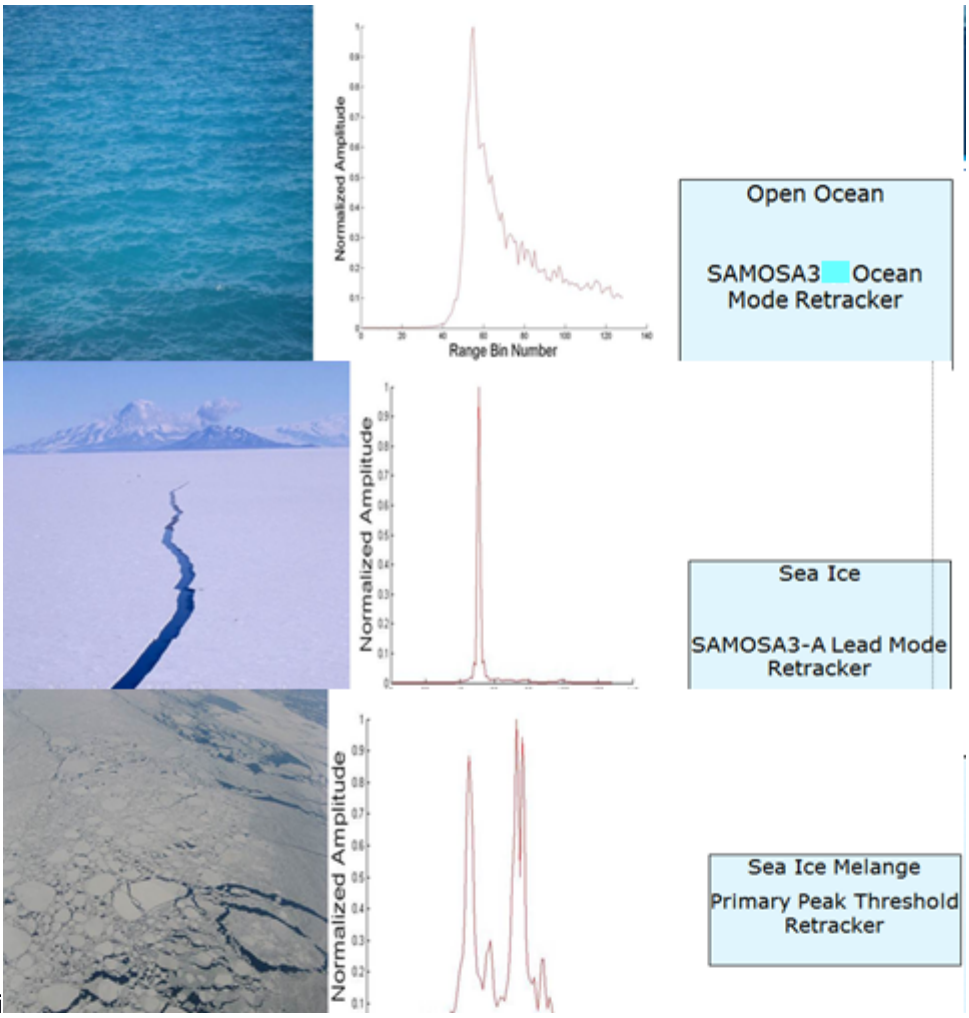

Figure 10. The three types of waveform typically encountered in the Arctic Ocean.

If only one retracker was used throughout in the Arctic sea surface height could not be recovered in large parts of the Arctic Ocean. Hence at DTU we developed a three step retracking system in order to enhance the recovery of sea level anomalies for SAR altimetry in the Arctic Ocean. This retracking system was developed using retrackers that was previously described in Deliverable 1..3 and 1.4 which are the ATBD for ocean and inland water respectively. Hence these will not be described in detail here.They are also described in the work by (Jain et al.,2015)

Once the retracking is completed as illustrated below the estimated range is corrected using the standard suite of range corrections as described in section 3.1 above using similar geophysical corrections except for the Mean sea surface correction which was changed to the DTU10MSS.

Algorithm flow chart

The algorithm flow charts are presented in Figure 11, which shows the way the ESA L1b waveforms are processed in order to derive the Polar ocean dataset. The choice of prioritizing physical retrackers comes from the fact that these shows higher precision in the Arctic Ocean (Jain et al., 2014) and because these enable retrieval of both sea surface height as well as significant wave-height and wind speed. The empirical threshold retracker that is used in case the physical retracker fails only enable retrieval of sea surface height.

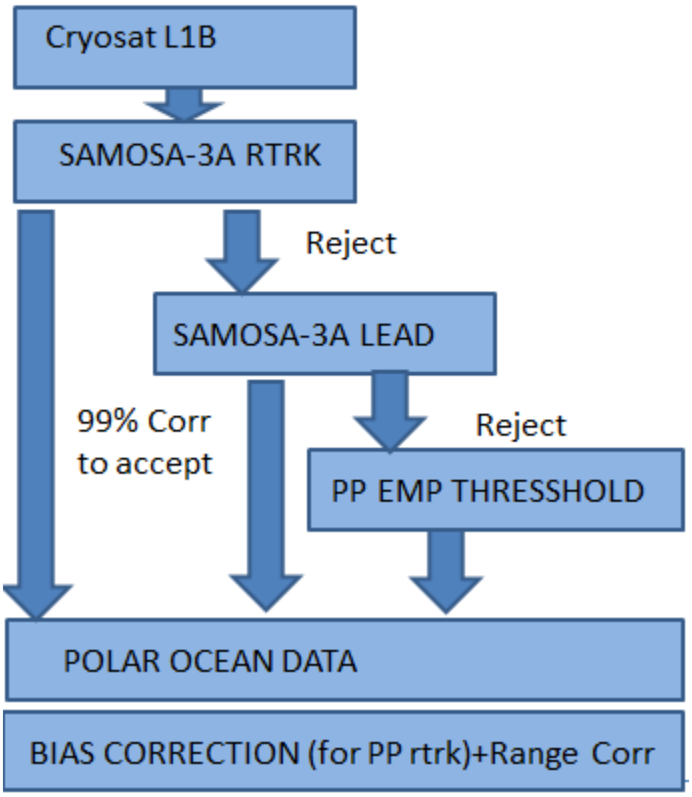

Figure 11. Flowchart of the retracking scheme for the Polar Ocean dataset.

As shown in Figure 11 then initially the fit of the SAMOSA-3A ocean retracker to the ESA L1B waveform is tested. If the fit has an R2 value greater than 0.99, the waveform is believed to be ocean type and accepted for the Polar Ocean dataset. If the waveform fit fails below this level, the waveform is retracked using the SAMOSA-3 Adapated Lead retracker . Again if the fit has an R2 value greater than 0.99 we accept this waveform as a lead waveform and the retracked height is believed to be from a lead in the ice and the height is put into the polar ocean dataset. If this fit fails the returned waveform is believed to be from a melange region with scattered ice. Here we use the most tolerant retracker which is the narrow primarily peak retraker. In very many cases the waveform can be retracked using this retracker and the height is then put into the Polar ocean dataset.

Once the retracking is completed and all retracked data have put into the polar ocean dataset the possible bias between the physical retrackers and the empirical retrackes should be estimated. There will be no bias between the various SAMOSA-3 retrackers. The Bias is calculated using the formula.
Bias = $\alpha + \beta * Hswh$
Here Bias is the bias between the SAMOSA3 SSHA and primary peak COG retracker's SSHA. α is the fixed component of the bias and β is the slope of the linear function which is multiplied to the significant wave height (Hswh). For lead type waveforms Hswh is almost zero and hence the bias should be just α.
For ocean type waveforms, Hswh is available as it is estimated through the fitting of the modelled waveform to the measured waveform. α is calculated using the mean bias of SAMOSA3 Lead mode SSHA and primary peak COG retracker's SSHA and is found to be 19.77 cm for the test region using in this study
As mentioned then the final range is finally corrected using the standard suite of range corrections as described in section 3.1.

References : Maulik Jain, Ole Baltazar Andersen, Jørgen Dall, Lars Stenseng, Sea surface height determination in the Arctic using Cryosat-2 SAR data from primary peak empirical retrackers, Advances in Space Research, Volume 55, Issue 1, 1 January 2015, Pages 40-50, ISSN 0273-1177, http://dx.doi.org/10.1016/j.asr.2014.09.006.

3.4.River and Lake Processing

3.4.1. RL_L2_Proc : Level 2 River and Lake processing chain

For each waveform a subwaveform is extracted based on start and stop thresholds. These thresholds are found from the standard deviation of the power differences in consecutive bins (Jain et al., 2015). Once the subwaveform is extracted, the retracking bin is found by applying a threshold retracker on the subwaveform. The retracker is referred to at the Narrow primary peak threshold retracker (NPPTR).

In a post-processing procedure the MODIS mask is used to identify measurements over a given in-land water body. For each track that contains more than 5 measurements a robust mean water level is estimated in addition to the retracked water levels. The algorithm flow charts are presented hereafter.

<u>References</u> : Maulik Jain, Ole Baltazar Andersen, Jørgen Dall, Lars Stenseng, Sea surface height determination in the Arctic using Cryosat-2 SAR data from primary peak empirical retrackers, Advances in Space Research, Volume 55, Issue 1, 1 January 2015, Pages 40-50, ISSN 0273-1177, http://dx.doi.org/10.1016/j.asr.2014.09.006.

Algorithm flow chart

The algorithm flow charts are presented in 12, where the left panel describes the initial processing and the right panel describes the post processing.

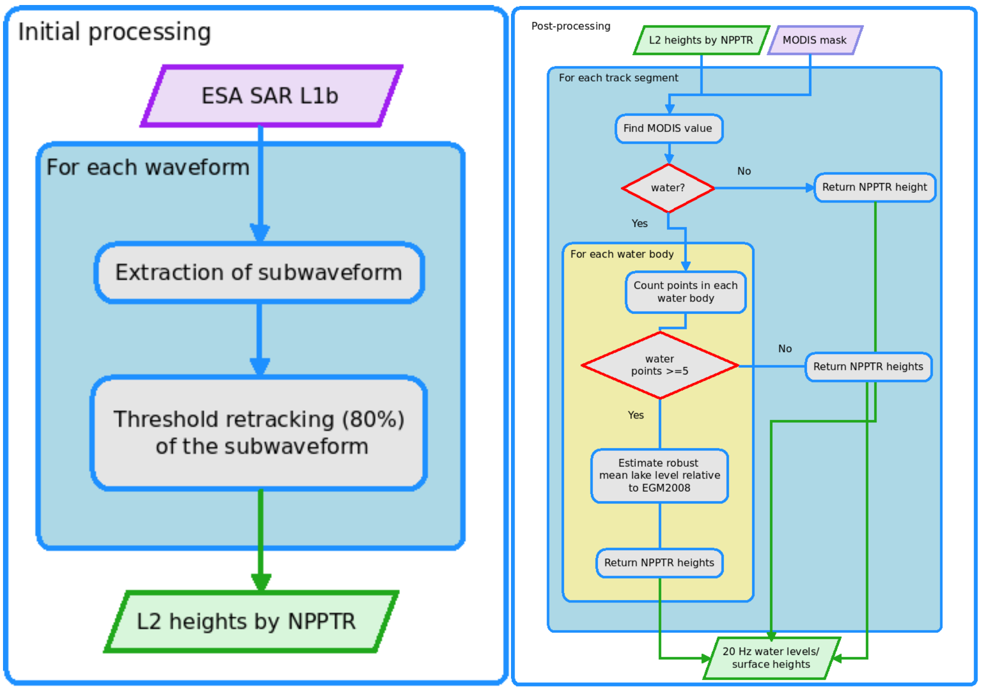

Figure 12 : (Left) Flow chart describing the steps in SAR retracking procedure. (Right) Flow chart describing the steps in the post-processing

3.5.Snow Water Equivalent processing

3.5.1. SW_L2_Proc : Level 2 Snow Water Equivalent processing chain

From the L1B SAR products, we apply a retracker on waveforms for land applications. The outputs fed a model developed [Papa et al. 2002] to estimate the snow depths over areas.

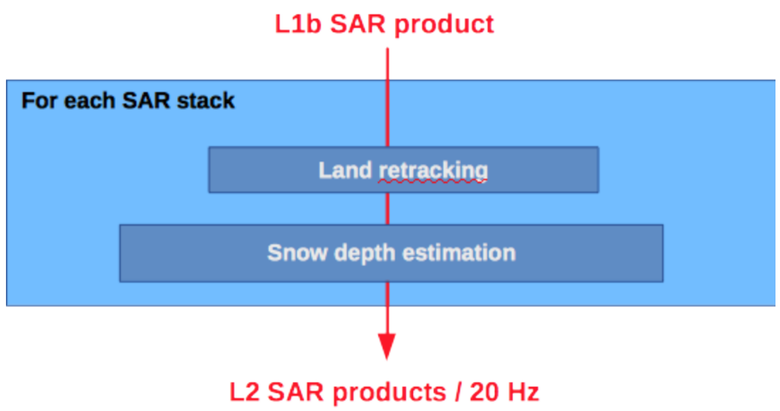

Figure 10 : Flowchart of the SAR Snow Water Equivalent processing

References :

- LOTUS_D25_Snow_Depth_Theoretical_Basis_Document.pdf
- [Papa et al. 2002]: Papa, F., Legresy, B., Mognard, N. M., Josberger, E. G., & Remy, F. (2002).Estimating terrestrial snow depth with the Topex-Poseidon altimeter and radiometer. *Geoscience and Remote Sensing, IEEE Transactions on*, 40(10), 2162-2169.

3.5.2. SW_L3_Proc : Level 3 Snow Water Equivalent processing chain

The level 3 processing chain has not been developed considering the results obtained at level -2

3.6. Soil Moisture processing

3.6.1. Processing Overview

Key parameters used in this processing chain are summarised in Table 1.

Symbol	Descriptive Name	I/O	Origin
σ_{0CRY}	Sigma0 value recalculated from waveform amplitude using scaling factors	Internal	Calculated in processing
Sig_A	Scaling parameter for backscatter calculation	Input	From IPF2 configuration file
Sig_B	Scaling parameter	Input	From IPF2 configuration file
P_i	Waveform power in bin i	Input	Input from Cryosat2 L1B datafile and rescaled to microwatts
i	Bin number	Input	Assigned at Cryosat2 L1B data read-in
A	Waveform Amplitude	Internal	Calculated in processing
W	Waveform Width	Internal	Calculated in processing
σ_{0CRY_ADJ}	σ_{0CRY} scaled for DREAM comparison	Internal	
σ_{0diff}	Sigma0 difference from DREAM	Internal	Calculated in processing
σ_{0DREAM}	Sigma0 value from DREAM pixel	Internal	Input from DREAM
σ_{mean}	Mean Sigma0	Internal	
σ_{rms}	RMS of mean Sigma0	Internal	May be output to inform error estimates
Soil_Moisture	Percentage soil moisture estimate	Output	Calculated in processing

Tableau 2 : Key Parameters for soil moisture processing

References

- R1: Cryosat Product Handbook, 2012: CryoSat-PHB-17apr2012.pdf.
- R2: D2.4 Cryosat2 Soil Surface Moisture Algorithm Theoretical Basis Document v.1.1. LOTUS_D2_4_NEWC.pdf, June 2014.
- R3: Berry, P.A.M., Dowson, M., Smith, R.G., Benveniste, J., 2012. Soil Moisture From Satellite Radar Altimetry (SMALT). Proceedings of the ESA Living Planet Symposium 2012.

Each level of processing is briefly summarised in the following sections. A detailed description may be found in R2.

3.6.2. SM_L2_Proc : Level 2 Soil Moisture processing chain

The processing chain for the internal soil moisture product SM_L2_Proc from Cryosat2 L1B input data is shown in Figure 11. Note that this processing chain is designed to work for each desert region separately: thus the Internal Product output by this processing chain contains data only over one DREAM file. However, the external datafiles, both the DREAM file and the CSME Datafile, may contain parameters for all desert regions: in this event, separate internal products SM_L2_Proc datafiles must be produced for each DREAM region.

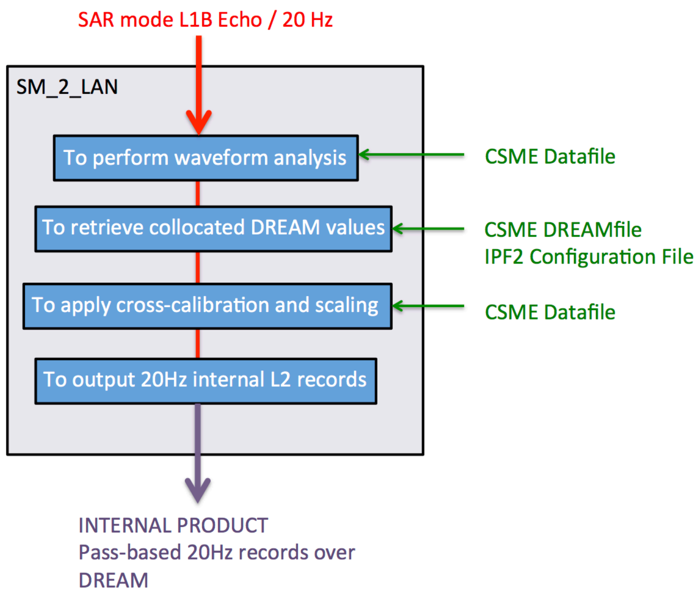

Figure 11 : Processing chain for SM_L2_Proc from input SAR data file

Datafiles

Several input files are required for this processing chain. The sigma0 calibration parameters from the IPF2 calibration file (R1) are required to calculate sigma0 from the OCOG derived parameter 'amplitude' (R2). The CSME DREAM file contains DREAM model values for the relevant desert (R2). The CSME datafile supplies cross-calibration and scaling parameters to this processing chain. A summary of essential input variables from the CSME datafile is given in Tableau 3.

Name	Units	Comment
A_L	Microwatts	Empirically determined amplitude lower limit
A_U	Microwatts	Empirically determined amplitude upper limit
W_L	Bins	Empirically determined width lower limit
W_U	Bins	Empirically determined width upper limit
Masked	dB	Exotic unit set to exclusion value in DREAM
Offset	dB	Exotic unit set for each DREAM
Limit1	dB	Exotic unit set for each DREAM
Limit2	dB	Exotic unit set for each DREAM
M1	None	Scaling factor 1
M2	None	Scaling factor 2
N_points	None	Number of points used to create σ_{mean}

Tableau 3 : CSME External Datafile Essential Parameters

Algorithm

The SM_L2_Proc algorithm chain is summarised here for each stage shown in Figure 11.

Retrieve the 20Hz L1B SAR data over one DREAM region. For each record, perform the following steps.

Perform Waveform Analysis

Input record from the Cryosat2 L1B product; check waveform for significant power present and to exclude waveforms where the leading edge is missing. Check all error flags and exclude flagged records from further analysis.
Analyse Cryosat2 waveform using the OCOG parameterisation:
Calculate waveform width (W) and corrected amplitude (A).

$$Amplitude = \sqrt{\frac{\sum_{i=1+n_l}^{n_u-1} P_i^4}{\sum_{i=1+n_l}^{n_u-1} P_i^2}}$$

$$Width = \frac{\left(\sum_{i=1+n_l}^{n_u-1} P_i^2\right)^2}{\sum_{i=1+n_l}^{n_u-1} P_i^4}$$

Where

- i is bin number
- P_i is waveform power in bin i
- n_l and n_u are the lower and upper aliasing exclusion limits

Note that waveform power is assumed transformed to microwatts prior to calculation.

This approach is noise-tolerant and gives an adequate representation of backscatter for this purpose for waveforms from diffusely reflecting desert surfaces. When wet, these surfaces become brighter and again, OCOG gives an adequate corrected amplitude estimate for this purpose as the filtering excludes very bright returns, although this algorithm is not generally recommended for land height retracking.

Compare with empirically determined lower and upper thresholds for amplitude A (A_L and A_U) and width W (W_L and W_U) and exclude waveforms outside these ranges. The purpose of this filter is to exclude echoes returned from bright targets, either salar or surface water, very low power returns, and, as far as possible, echoes from rough/sloping surfaces remaining within the masked DREAMs.

Retrieve collocated DREAM value

For each valid record, calculate σ_{0_CRY} using equation of form:

$$\sigma_{0\_CRY} = 10\ \mathrm{LOG}_{10}(\mathrm{Amplitude/Sig\_A}) + \mathrm{Sig\_B}$$

where Sig_A and Sig_B are constants defined in the IPF2 configuration file (REF 1).

Using latitude and longitude, retrieve collocated DREAM value from external file DREAM model and determine if DREAM value is valid or corresponds to one of the exclusion codes. If exclusion, reject record.

Apply cross-calibration and scaling

Apply pre-determined cross-calibration scaling factors from auxiliary datafile to re-reference σ_{0_CRY} to the DREAM backscatter range (DREAMS are created with an offset to all values to keep the DREAM backscatter always positive). An auxiliary datafile is therefore utilised to adjust the mission recalculated backscatter to the correct range for each DREAM.

$$\sigma_{0CRY\_ADJ} = \sigma_{0CRY} + \mathrm{Offset}$$

Calculate difference for each altimeter point from corresponding DREAM pixel.

$$\sigma_{0diff} = \sigma_{0CRY\_ADJ} - \sigma_{0DREAM}$$

Error trap. Where σ_{diff} >LIMIT2, exclude point from further analysis. This test is required to allow for the contingency that the full variation in surface characteristics may not be successfully captured by the model.

Output internal SM_L2_Proc record

For each record, output record with collocated DREAM value as the SM_L2_Proc product. This product is generated for internal use only. The CSME processing chain does not product individual soil moisture estimates at 20Hz, as analysis has shown that the presence of high frequency noise on Cryosat2 land sigma0 values critically impairs product utility.

3.7. SM_L3_Proc : Level 3 Soil Moisture processing chain

The algorithm chain for the SM_L3_Proc is briefly described here.

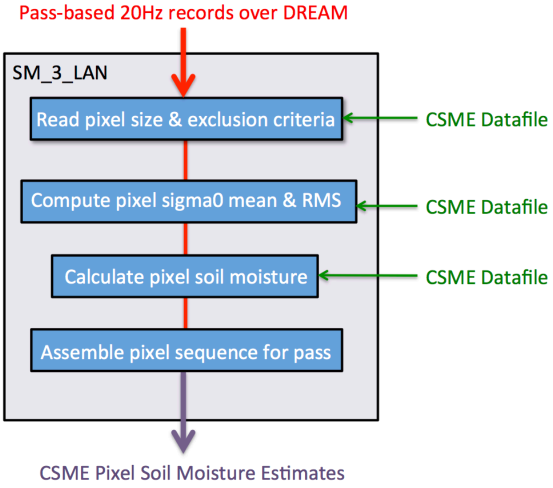

Figure 12 : SM_L3_Proc

Algorithm Summary

This processing chain takes the internal product 'Pass-based 20Hz records over a DREAM and processes to generate soil moisture estimates for 'pixels' along the satellite track.

Read Pixel Size and Exclusion Criteria

Because the short-wavelength spatial fluctuations in desert sigma0 differe for different surface conditions, optimal retrieval of soil surface moisture may require different levels of averaging prior to soil surface moisture estimation. Similarly, the exclusion thresholds are surface dependent and thus are uniquely defined for each DREAM. Ths algorithm retrieves the required parameters for the DREAM from the CSME datafile (Tableau 3) and sets the averaging spatial extent.

Compute Pixel Sigma0 Statistics

This algorithm calculates the mean sigma0 difference from DREAM for each pixel, and associated statistics, retrieving required parameters from the CSME external datafile (Tableau 3). The pixel positions are defined such that, for each repeat pass, pixel mean locations will be similar and thus time series can subsequently be constructed.

Where σ_{diff} < LIMIT1, pass values to the averaging algorithm.

Read parameter file for number of points to be averaged along-track. Create mean value σ_{mean} and RMS σ_{rms}.

Initial settings for this average will be for the whole pass over a DREAM, yielding a track_average soil moisture estimate from the processing chain. However, it may be possible to increase the spatial resolution; this will be determined after the processing scheme has been confronted with multiple passes of Cryosat2 data over each desert. Thus the configuration allows for multiple soil moisture estimates to be created along one pass. It is also noted that the necessary extent of averaging may vary between DREAMS. The Simpson DREAM with previous altimeter missions allowed the highest product spatial resolution (R3), and the Kalahari desert the lowest (ibid).

Calculate Pixel Soil Moisture

Reading parameters from the CSME datafile, the soil moisture is calculated for each valid pixel using the defined equation (R2).

Reading parameter values from parameter file, transform to first soil surface moisture estimate using equation of form:

$$Soil\_Moisture = M1*\sigma_{diff} + M2$$

This equation is appropriate for soil moisture less than approximately 5% (saturated surface soil moisture is approximately 8%).. This equation may be replaced by a more sophisticated equation after testing over a range of soil surface moisture conditions. The reason for taking this approach is that to utilize the more complicated equation and have it perform satisfactorily requires sampling the Cryosat-2 backscatter over the DREAMS through a range of surface soil moisture conditions. Because the terrain is arid or semi-arid, multiple years of data may need to be amassed before the equation empirically determined constants can be sufficiently well determined.

Assemble Pixel Sequence for Pass

This algorithm assembles the individual pixel soil surface moisture values for the pass being processed. These data are then output as the pass-based CSME Pixel Soil Moisture Estimates and form the L3 external product.

3.8. SM_L4_Proc : Level 4 Soil Moisture processing chain

This algorithm chain creates time series from the individual pass-based products in SM_L3_Proc.

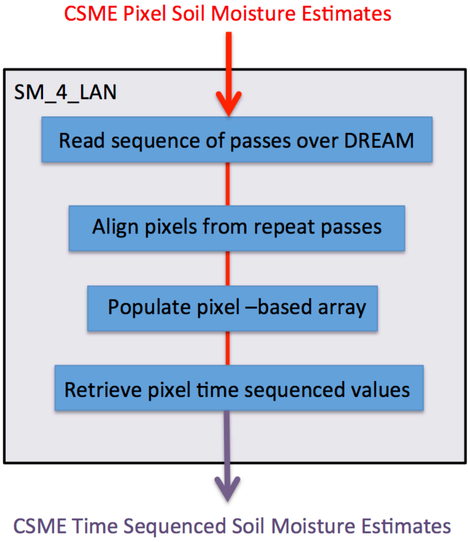

Figure 13 SM_L4_Proc processing chain

The SM_L4_Proc processing chain assembles repeat arcs of SM_L3_Proc products and aligns them to produce pixel-based time series of soil surface moisture over one desert DREAM.

Read sequence of Passes

This algorithm inputs the series of products from SM_L3_Proc and sorts the products into repeat passes, identifying a repeat arc sequence for processing.

Align Pixels

This algorithm reads in one repeat arc sequence and aligns the pixels, ensuring that 'excluded pixel' values are generated for any missing pixels in the sequence.

Populate Array

This algorithm inputs the aligned pixel sequences and re-orders them by time, populating a two-dimensional array for each arc.

Retrieve Pixel Time Series

This algorithm reads the populated array and constructs a time series for each pixel, produing soil surface moisture value and associated statistics for each pass and outputting individual time series for each pixel as the Level 4 product.

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