FDR4ALT

Detailed Processing Model

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Object	Name
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CHRONOLOGY ISSUES

Issue	Date	Object
1.0	29/11/20	Creation
2.0	30/06/21	Updated with inputs from different partners
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6.0	24/05/2023	Final version for Final Review Meeting with RIDs implemented
6.1	05/07/2023	Minor Corrections

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1 Introduction

This document has been written in the frame of the FDR4ALT project, ESA contract N°4000128220/19/I-BG.

1.1 The FDR4ALT Project

In the framework of the European Long Term Data Preservation Program (LTDP+) which aims at generating innovative Earth system data records named Fundamental Data Records (basically level 1 altimeter and radiometer data) and Thematic Data Records (basically level 2+ geophysical products), ESA/ESRIN has launched a reprocessing activity of ERS-1, ERS-2 and ENVISAT altimeter and radiometer dataset, called the FDR4ALT project (Fundamental Data Records for Altimetry). A large consortium of thematic experts has been formed to perform these activities which are:
1) To define products including the long, harmonized record of uncertainty-quantified observations.
2) To define the most appropriate level 1 and level 2 processing for improving the data product performances.
3) To reprocess the whole times series according to the predefined processing.
4) To validate the different products and provide them to large communities of users focused on the observation of the atmosphere, ocean topography, ocean waves, coastal, hydrology, sea ice, ice sheet regions.

1.1. Purpose and scope of this document

The objective of this document is to provide a Detailed Processing Model (DPM) for each FDR (Fundamental Data Record) and TDP (Thematic Data Products) algorithms.
For the sake of consistency, here we do not describe algorithms that were already existing in the official products, or algorithms already fully described in others ESA projects. In those cases, the corresponding reference will be detailed.

1.2. Document structure and strategy

For a better comprehension of this document, algorithms used for this project have been grouped as follows:

- ✓ FDR altimetry algorithms (ALTFDR)
- ✓ FDR radiometry algorithms (MWRFDR)
- ✓ Level-2 algorithms (L2)
- ✓ TDP Atmosphere processing baseline
- ✓ TDP Land-Ice processing baseline
- ✓ TDP Sea-Ice processing baseline
- ✓ TDP Ocean & Coastal Topography processing baseline
- ✓ TDP Ocean Waves processing baseline
- ✓ TDP Inland processing baseline

Note that the outputs of the FDR4ALT project are Level-1 products (FDR) and Level-2P products. Several level-2 algorithms have been developed in the frame of this project, and their different outputs have been used by the different TDPs as inputs or direct outputs. Therefore, section 4 is dedicated to these algorithms that are not necessary linked to a single FDR4ALT product.

In this document, two different strategies are followed:

- o For the FDRs, algorithms that were not in the official products and that were developed in the frame of the project are detailed one by one. For the sake of clarity, each algorithm was given a dedicated name.
- o Each TDP is described as one big process with various steps. For each TDP, one logical flow is proposed, and the different steps are then detailed.

1.3. General rules

In the case where the algorithm is already existing in a current official product, the reference will be given and the processing steps will not be further detailed for the sake of clarity.
For all the other algorithms, the procedure will be the following:
Each algorithm is described, using the following items:

- Identifier and name of the algorithm

Algorithm specification:

- Input data
- Logical Flow
- Key principles of the Algorithm
- Output data

The following basic rules are applied to the specification of the algorithms:

- The specifications of an algorithm are always relevant to the processing of a single data point and not to a set of data points.
- The input and output data are always identified by a precise description, i.e [*parameter, variable name, unit and source*] for the inputs and *[parameter, variable name and unit*] for the ouputs. Please note that the “source” of the inputs are specified only if they are dynamics (i.e not a static parameter). It will be either:
    - The output of a FDR4ALT algorithm described in this document. In this case, the name of the algorithm will be explicitly mentioned (ex : ”ALTFDR_EN_ORBIT”)
    - A variable from previous processing baseline, i.e. ERS REAPER L2 and ENVISAT V3.0 reprocessing;
    - A variable from auxiliary dataset. In that case, the name and version of the data used will be explicit.

In this document, the TDPs are considered as one big algorithm, i.e., with a single set of inputs/outputs.

2 ALT Fundamental Data Records

2.1 Overview

In the frame of FDR4ALT project, the Altimetry Fundamental Data Records (ALT FDR) product inherits from previous official products which are:

- Baseline V3.0 for ENVISAT: https://earth.esa.int/eogateway/documents/20142/37627/Envisat-RA-2-Level-2-Product-Handbook.pdf
- REAPER reprocessing for ERS-1/2: https://earth.esa.int/eogateway/documents/20142/37627/reaper-product-handbook-for-ers-altimetry-reprocessed-products.pdf

This document aims at describing the additional added value algorithms included in the ALT FDR product.

One should note that Level-1 and Level-0 are directly coming from previous processing baselines (namely ERS REAPER and ENVISAT V3.0 reprocessing) with the same variables' name in most cases for the sake of simplicity. Therefore, one should refer to previous baseline documents [**RD-11**] and [**RD-15**] for more details about their corresponding algorithms ("half-power method" for internal path delay for instance). No Point Target Response (PTR) array is provided for ERS whereas the PTR have been recomputed for ENVISAT from I&Q data to perform the new Adaptive retracker that used the PTR as input. Low Pass Filter (LPF) in Ku-band from Level-0 are made available for both missions.

Note also that 1Hz original variables have been duplicated at 20Hz and no specific algorithm is detailed here. For each concerned fields the "Copied from 1hz" is mentioned in the attribute.

Therefore, we present only the improvements and evolutions brought by the project at Level 1 in the ALTFDR product (see [D-1-02]).

The following algorithms are described:

- The new orbits used
- The time jumps algorithm that edit the ERS time jumps identified as an issue in the REAPER project (**RD-11**)
- The correction of the ERS negative waveforms
- The ENVISAT waveform classification
- The ERS waveform classification
- The ENVISAT PTR averaging method
- The offset tracking flag
- The range burring correction
- The distance to coastline

Therefore, one can find the following variables in the ALTFDR product with respect to the previous baselines:

Algo. description	Output fields name	Type	ERS	EN
Distance to coastline (GSHHG)	*distance_to_coast* *surface_type*	scalar	✓	✓

Waveform Classification	*waveform_main_class* *waveform_main_class_score* *waveform_second_class* *waveform_second_class_score*	scalar scalar scalar scalar	✓	✓
Offset Tracking	*offset_tracking_flag*	scalar		✓
PTR	*ptr_ku* *ptr_s*	array	-	✓
Time jump	*time*	scalar	✓	-
Negative waveforms	*power_waveform*	array	✓	-
Flag waveform DFT	*Flag_waveform_dft*	array	-	✓

Figure 2-1 : Summary table of the variables whose algorithms are described in this section.

2.2 ALTFDR_EN_ORBIT

New orbit solutions have been developed in the last years for ENVISAT. The CNES POD team POE-F solution has been compared to the previous POE solution in the Round Robin Assessment Document [D-2-03] and was selected for this project to be used in all FDRs and TDPs.

2.2.1 Inputs

The inputs are the POE-F standard orbit files from CNES.

2.2.2 Outputs

Parameter	Variable name	unit
Latitude	*latitude*	degrees
Longitude	*longitude*	degrees
Altitude	*altitude*	meters

2.3 ALTFDR_ERS_ORBIT

As explained in the Round Robin Assessment Document [D-2-03], new orbit solutions have been developed in the last years for ERS-1 and ERS-2. In the POD dataset (REAPER v2) for the ERS-1 and ERS-2 missions, two different orbit solutions are provided together with a combined solution: those computed by DEOS (Delft Institute of Earth Observation and Space Systems), and those generated by ESOC (European Space Operations Centre) using different software (GeoDyn and NAPEOS respectively). Careful evaluation of the various solutions of REAPER v2 has shown that the DEOS solution for both ERS-1 and ERS-2 has the best performance and is recommended to be used as reference by the POD team. The FDR4ALT followed this recommendation and therefore the DEOS solution was selected for this project to be used in all FDRs and TDPs.

2.3.1 Inputs

The inputs are the orbit files from DEOS [**RD-12**].

2.3.2 Outputs

Parameter	Variable name	unit
Latitude	*latitude*	degrees
Longitude	*longitude*	degrees
Altitude	*altitude*	meters

2.4 ALTFDR_ERS_TIME: To edit the wrong time tags for ERS

2.4.1 Input parameters

- REAPER Level-2 NetCDF files, more specifically:
  - 1 Hz time tags of the REAPER Level-2 ERS data: field “time” in the NetCDF file
  - 20 Hz time tags of the REAPER Level-2 ERS data: field “time_20hz in the NetCDF file

- Threshold to edit 20Hz time jumps: set to 0.95. This value was the best trade-off based on the analysis performed in the frame of this project. This analysis is available in the Product Validation Report Document [D-4-02].

- Middle index of 1Hz packet: set to 10 (There are 20 measurements in a 1Hz packet)

Parameter	Source	Variable name	unit
Time 1Hz	L2 REAPER	*time*	s
Time 20Hz	L2 REAPER	*time_20hz*	s
Threshold to edit 20Hz time jumps	/	*thresh_20*	/
Middle index of 1Hz packet	/	*half_packet*	/

2.4.2 Logical Flow

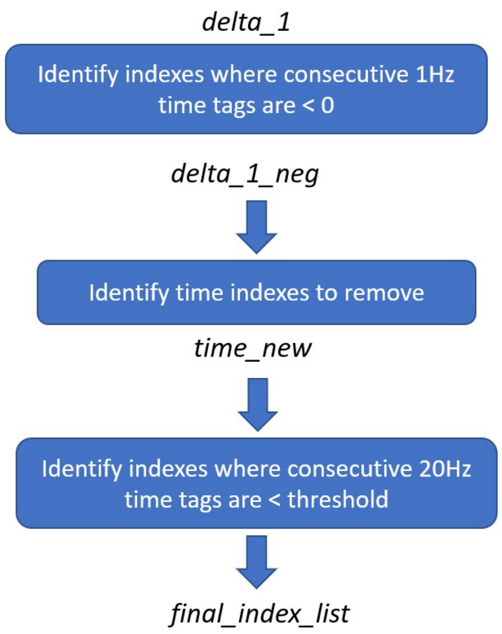


Figure 2-2 : Logical flow for the ALTFDR_ERS_TIME algorithm

2.4.3 Key principles of the algorithm

Identification of 1Hz indexes to remove

For each NetCDF file, the consecutive difference of the field “time” (1Hz time tag), delta_1, is computed.
Let delta_1_neg be the indexes where delta_1 <0.
Let index_1_to_remove be an empty list.

- For each j in delta_1_neg, we identify if there is a forward time jump or a backward time jump:
- *If abs(delta_1[j+1]>half_packet)*

  index_1_to_remove = index_1_to_remove + delta_1[j+1]

  Else

  index_1_to_remove = index_1_to_remove + delta_1[j]

Then, we define a new time array named new_time, corresponding to the original time fields where the indexes index_1_to_remove have been removed.

Identification of 20Hz indexes to remove

The consecutive difference of the array new_time, delta_20, is computed.
Let delta_20_th the indexes where delta_20 is below the threshold = thresh_20
Let index_20_to_remove be an empty list.

- *For j in delta_20_th:*

  index_20_to_remove = index_20_to_remove + delta_20[j]

Finally, we compute the 2-D array containing all indexes to delete, final_index_list.

- *Final_index_list = [index_**1_to_remove ; index_20_to_remove]***

2.4.4 Outputs

- Indexes identifying the incorrect time tags: **final_index_list**

The final output is the corrected time variable in all NetCDF groups.

Parameter	Variable name	unit
Time	*time*	s

2.5 ALTFDR_ERS_NEGWF: to correct the negative waveforms for ENVISAT

2.5.1 Input parameters

Parameter	Source	Variable name	unit
Ku-band waveform	REAPER L2	*power_waveform*	*ft p.u*

2.5.2 Logical flow

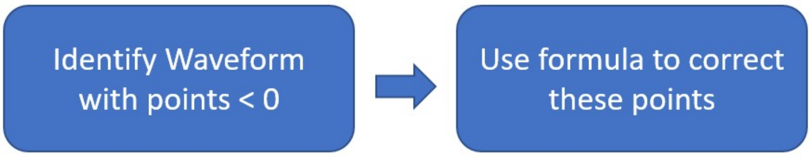


Figure 2-3 : Logical flow for the ALTFDR_ERS_NEGWF algorithm

2.5.3 Key principles of the algorithm

The principle is straightforward:

- Identification of the samples to be corrected: all waveform samples < 0
- Correction of the identified samples using the following formula:

$$WF[WF < 0] = -WF[WF < 0] + 2^{15} + 1$$

where WF is the *power_waveform*

2.5.4 Outputs

The output is the corrected Ku-band waveform.

Parameter	Variable name	unit
power waveform	*power_waveform*	-

2.6 ALTFDR_EN_CLASSIF: To compute the waveform classification for ENVISAT

2.6.1 Functional description

To determine the waveform's classification for the waveforms in Ku-band, using the waveform and a neural network algorithm (retracking estimates are needed as input).
For each elementary measurement, the determination of the waveform's classification is specified hereafter.

2.6.2 Inputs

Parameter	source	unit	dimension
Waveform samples	-	FFT P.U	128
Waveform abscissa	-	count	128
Waveform validity flag	ALT FDR	-	1
SWH MLE3	ENVISAT V3.0	m	1
Sigma0 MLE3	ENVISAT V3.0	dB	1
Epoch MLE3	ENVISAT V3.0	m	1

Distance to shoreline	ALTFDR_EN_DISTANCE_TO_COAST	m	1
Surface type flag	ALTFDR_EN_DISTANCE_TO_COAST	-	1
Neural Network (weights, bias, neurons, output classes) in SAD file	-	-	-

2.6.3 Logical Flow

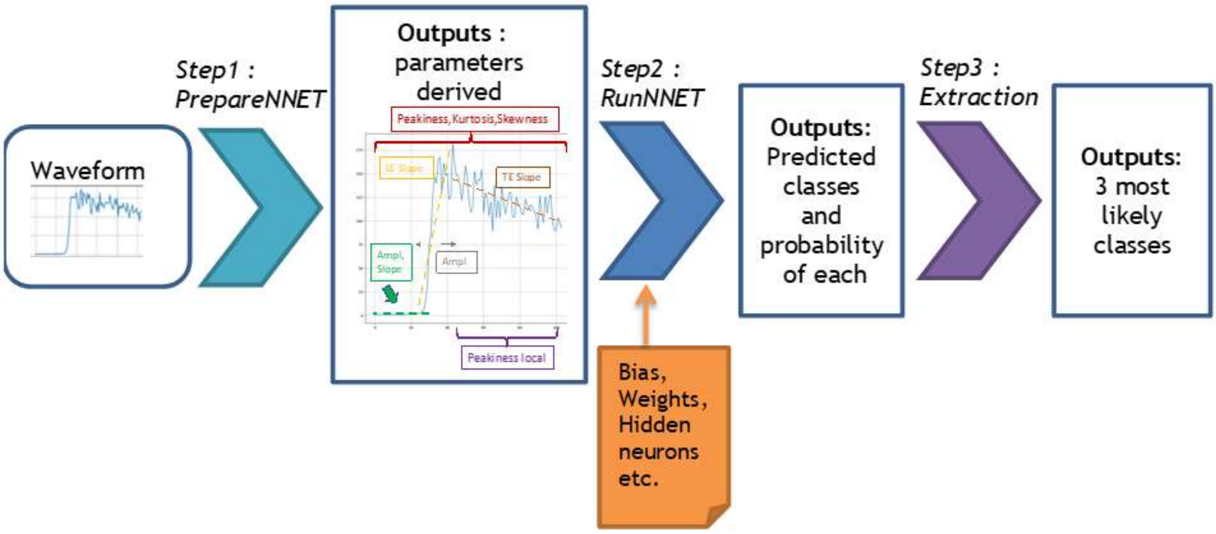


Figure 2-4 Schematic of the main steps of the classification algorithm

2.6.4 Key principles of the algorithm

For each 20Hz ENVISAT waveform, the determination of the class label is specified hereafter.

1. <u>Step1 PrepareNNET:</u>

   a. <u>Processing of invalid or null amplitude waveforms:</u>

Let V_Max be the maximum amplitude of the waveform samples WF(i) (iϵ[0: Nb_Samples-1]).

Let Sum_wf be the sum of all the waveform samples WF(i) (iϵ[0: Nb_Samples-1]).

Let WF_Val_Flag be the waveform validity flag as input.

Let WF_Main_Class, WF_Main_Class_Proba, WF_Second_Class and WF_Second_Class_Proba be the outputs of the algorithm.

- If { Sum_wf(i) = 0 } and {WF_Val_Flag(i) is set to “valid”}:
  - WF_Main_Class(i) and WF_Second_Class(i) are set to “null” i.e set to 0
  - WF_Main_Class_Proba(i) and WF_Second_Class_Proba(i) are set to 1.0 (maximum value)

- Then exit

In these two cases, the algorithm exits and returns label=0 for both outputs class labels as null value with 100% probability .

- If { Sum_wf != 0 } and {WF_Val_Flag is set to “valid”}:
  - If V_Max<0:
    - WF_Main_Class(i) and WF_Second_Class(i) are set to “unknown” i.e set to 9
    - WF_Main_Class_Proba(i) and WF_Second_Class_Proba(i) are set to 1.0
    - Then exit

In this case, the algorithm exits and returns label=9 for outputs class labels as default value with 100% probability.

b. Selection of the neural network (2 networks available)

- Else:
  - If {SWH = DV or Sigma0 = DV or Distance_to_coast = DV}:
    - NumNNet = 2 (so called “retracking_nnet”)
  - Else
    - NumNNet = 1 (so called “non-retracking_nnet")

With DV = Default Value.
Then, computation of the input parameters. The list of parameters depends on the chosen neural network.

- If NumNNet = 1, (9 parameters computed):
  - Epoch (from inputs)
  - SWH (from inputs)
  - Sigma0 (from inputs)
  - Flag surface type (from inputs)
  - Distance to coast (from inputs)
  - Mean Square Error (with respect to a fixed mean ocean waveform)
  - Slope of a detected leading edge
  - Slope of a detected trailing edge
  - Peak amplitude on the trailing edge
- If NumNet = 2, (7 parameters computed):
  - Global Peakiness
  - Amplitude of thermal noise on gate
  - Slope of a detected leading edge
  - Local slope between bins [35,55]
  - Slope of automatic-detected trailing edge
  - Peak amplitude on the trailing edge
  - Local peak amplitude between bins [50,60]

2. <u>Step2 RunNNET:</u>

Weights: Real values that are attached with each input. Convey the importance of that corresponding feature in predicting the final output.
Bias: Used for shifting the activation function towards left or right.
Summation function: The work of summation function is to bind the wrights and inputs together and calculate their sum.
Activation function: It is used to introduce non-linearity. Here Sigmoid function is used as best choice for classification.
Neurons: Basics units of a neural network where each neuron in a layer is connected to some or all of the neurons in the next layer. When inputs are transmitted between neurons, the weights are applied to the inputs along with the bias as following:

$$Y = \sum (weight * input) + bias$$

Let Weight_in, Bias_in, Weight_out and Bias_out be the input parameters for the two neural network models.

- For each h_th neuron of the single hidden layer (16 neurons in total):
  - Apply weight and bias to i_th parameters p (w.r.t NumNet):
    - X[h] = sum(Weight_in[h,i] * p[i]) + Bias_in[h]
  - Apply transfer function to the X:
    - Y[h] = 1 / (1 + exp(-X[h]))

- For each o_th neuron of the output layer (nb = nb of classes = 12):
  - Apply weights and bias of the layer to Y:
    - Z[o] = sum(Weight_out[o,h] * Y[h]) + Bias_out[o]
  - Conversion to probabilities:
    - tmp[o] = Exp(z[o]-max(z[o]); sum = Σ tmp[o]
    - **<u>Proba[o] = Val[o] / sum</u>**

3. <u>Step3 Extraction of the predictions:</u>

- Sort the probabilities in descending order.
- Write the results only for the first two most likely classes

2.6.5 Outputs

Please note that out of the 3 most likely classes, only the first 2 are considered as relevant and therefore provided in the final product.

Parameter	Variable name	unit
Most likely class [1]	*waveform_main_class*	-
Probability associated to the most likely class[2]	*waveform_main_class_score*	1

Second most likely class [1]	*waveform_second_class*	-
Probability associated to the second most likely class[2]	*waveform_second_class_score*	1

2.6.6 Comments

The first two most likely classes are provided in the ALT FDR as well as their associated probabilities that may be used to characterize the neural network models' performances for different applications.

[1] 12 possible classes: "brown ocean", "peaky", "noise", "strong peak", "brown + peak trailing edge", "brown + peak leading edge", "brown + flat trailing edge", "peak end", "unknown", "2 leading edge", "shifted brown + flat trailing edge ", "shited brown"

[2] Probability between 0 and 1

ENVISAT waveform classification algorithm has been developed in the frame of the CCI project and published in **[RD-1]** . For more information about neural network theory, one should refer to **[RD-3]** and **[RD-2].**

2.7 ALTFDR_ERS_CLASSIF: To compute the waveform classification for ERS-1/2

2.7.1 Functional description

To determine the waveform's classification for the waveforms in main band, using the waveform and a neural network algorithm (no retracking estimates are needed as input).
For each elementary measurement, the determination of the waveform's classification is specified hereafter.

2.7.2 Inputs

For this algorithm, there are no dynamic inputs, therefore there is no need to specify any sources for the input.

Parameter	unit	dimension
Waveform samples	FFT P.U	128
Waveform abscissa	count	128
Waveform validity flag	-	1
Bias and Weights files of hidden and output neurons' layers	-	-

2.7.3 Logical Flow

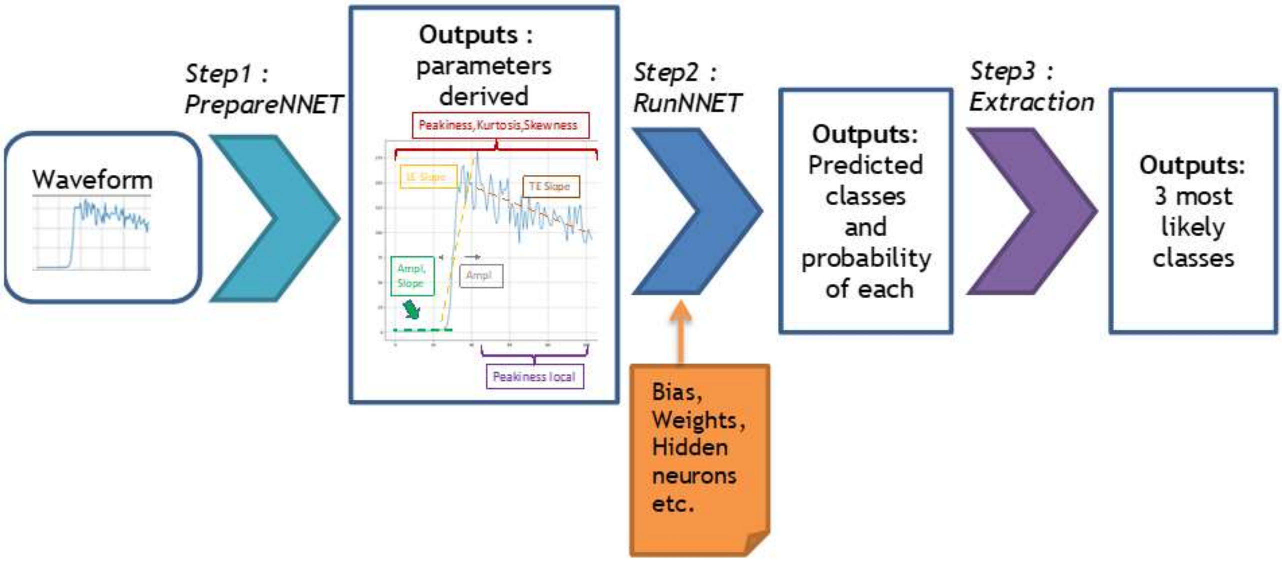


Figure 2-5 Schematic of the main steps of the classification algorithm

2.7.4 Key principles of the algorithm

For each 20Hz ERS waveform, the determination of the class label is specified hereafter.
<u>Processing of invalid or null amplitude waveforms:</u>

Let V_Max be the maximum amplitude of the waveform samples WF_Ampl(i) (iϵ[0: Nb_Samples-1]).

Let Sum_wf be the sum of all the waveform samples WF_Ampl(i) (iϵ[0: Nb_Samples-1]).

- If { Sum_wf(i) = 0 } and {WF_Val_Flag(i) is set to “invalid”}:
  - ➢ WF_Main_Class(i) and WF_Second_Class(i) are set to “null” i.e set to 0
  - ➢ WF_Main_Class_Proba(i) and WF_Second_Class_Proba(i) are set to 1.0

In these two cases, the classification determination processing is stopped and give main_class= second_class = 0 with probability of 100% for both meaning prediction aborted.

- If { Sum_wf != 0 } and {WF_Val_Flag is set to “valid”}:
  - o If V_Max<0:
  - ➢ WF_Main_Class(i) and WF_Second_Class(i) are set to “unknown” i.e set to 9
  - ➢ WF_Main_Class_Proba(i) and WF_Second_Class_Proba(i) are set to 1.0

In these two cases, the classification determination processing is stopped and give main_class= second_class = 9 with probability of 100% for both.

<u>Processing of valid waveforms:</u>

- Else:
  - o Waveform are normalized by the Max value and so reduced to [0,1].
  - o Call of PrepareNNET(computation of the 11 input parameters of the Neural Network)
    - o Global Peakiness
    - o Global Kurtosis

- Global Skewness
- Slope of the leading edge on [20:39]
- Slope of the trailing edge on [40:61]
- Slope on gates on [5:19]
- Amplitude on gates on [5:19]
- Amplitude of peak on trailing edge (adaptive search for interval)
- Breakage flag on leading edge
- Centre of Gravity of the waveform
- Mean Square Error w.r.t ERS mean ocean waveform

- Call of RunNNET (Application of neural network)
  - For each h_th neuron of the hidden layer (nb =25 neurons):
- Apply weight and bias to i_th parameters p (w.r.t NumNet):
  - X[h] = sum(Weight_in[h,i] * p[i]) + Bias_In[h]
- Apply transfer function to the X:
  - Y[h] = 1 / (1 + exp(-X[h]))

- For each o_th neuron of the output layer (nb = nb of classes = 15):
  - Apply weights and bias of the layer to Y:
    - Z[o] = sum(Weight_out[o,h] * Y[h]) + Bias_out[o]
  - Conversion to probabilities:
    - tmp[o] = Exp(z[o]-max(z[o]); sum = Σ tmp[o]
    - Proba[o] = Val[o] / sum

- Call of PredictClass:

Determination of the class of higher and second probability:

Sort the classes by descending order of their priorities

2.7.5 Outputs

Please note that out of the 3 most likely classes, only the first 2 are considered as relevant and therefore provided in the final product.

Parameter	Variable name	unit
Most likely class [1]	*waveform_main_class*	-
Probability associated to the most likely class[2]	*waveform_main_class_score*	1
Second most likely class [1]	*waveform_second_class*	-
Probability associated to the second most likely class[2]	*waveform_second_class_score*	1

2.7.6 Comments

This algorithm is applicable to ERS-1 and ERS-2
The first two most likely classes are provided in the ALT FDR as well as their associated probabilities that may be used to characterize the neural network models' performances for different applications.

[1] 15 possible classes: “brown ocean”, “peaky”, “noise”, “strong peak”, “brown + peak trailing edge”, “brown + peak leading edge”, “brown + flat trailing edge”, “unknown”, ”brown + thermal noise”, “2 leading edge”, “Brown + noisy leading edge”, “linear rise”, “linear rise”, “right-shifted brown”, “brown + broken leading edge”, ”linear decrease”

[2] Probability between 0 and 1

ERS waveform classification algorithm has been developed in the frame of this project. For more information about neural network theory, one should refer to [**RD-3**] and [**RD-2**].

2.8 ALTFDR_EN_PTR: To compute an averaged ENVISAT PTR for the Adaptive retracker

2.8.1 Functional description

In the frame of the FDR4ALT project, a new way of averaging the internal calibrations PTR (Point Target Response) was developed to be used as input of the Adaptive retracker [**RD-4**]. Although the Adaptive retracker is only performed on Ku-band echo, the same process has been applied to both Ku and S band. For the sake of clarity, only the Ku-band processing is described here, S-band processing being identical.

2.8.2 Inputs

The inputs are the calibrations from the Level 0 V2.1 documented in [**RD-5**]. Some details about the data:

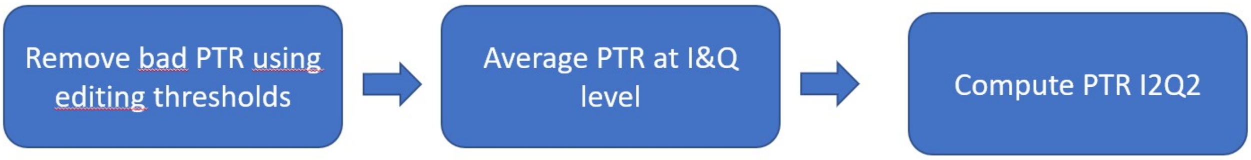
MPH (Main Product Header): p36

- SPH (Specific Product Header): p42
- Dataset: p48
- 50923 files in total
- 2.6 TB of data
- “RA2_ME___0P” files
- Format: I & Q times series (128 x 2 samples)
- 1 signed byte per sample

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Spare (6 bits)									AGC CAL				AGC CAL		
spare (8 bits)									Datation PTR (8 bits)						
Datation PTR															
Datation PTR															
PTR 1st I/Q sample															
....															
PTR 128 I/Q sample															
spare (1 byte)									Cal Band id						

Figure 2-6 : Description of the PTR in Level 0 V2.1 products

2.8.3 Logical Flow



2.8.4 Key principles of the algorithm

<u>To edit the bad PTR data</u>

To edit bad PTR waveforms that would lead to poor quality averaged PTR signals, different metrics and threshold have been defined to reject outliers:

1. Median value of the PTR must be superior to 1000 FFT.pu as the greater number of occurences in the figure is recorded for median values below 1000 FFT.pu.

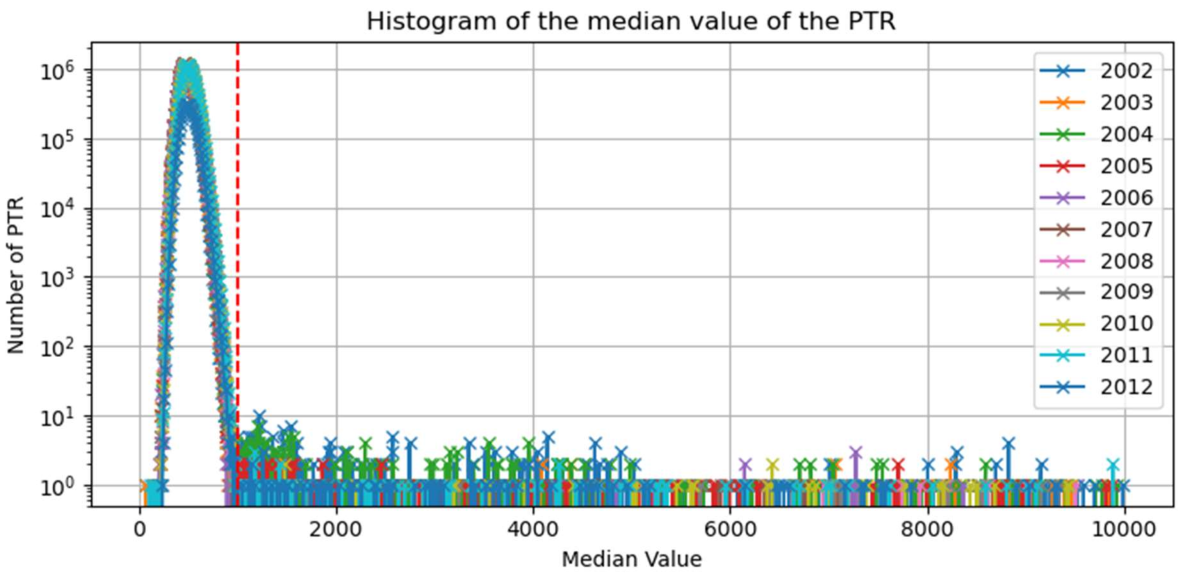


Figure 2-7 : Median value of the PTR for the whole ENVISAT lifetime

2. Maximum value of the PTR must be superior to 0.63e7 FFT p.u

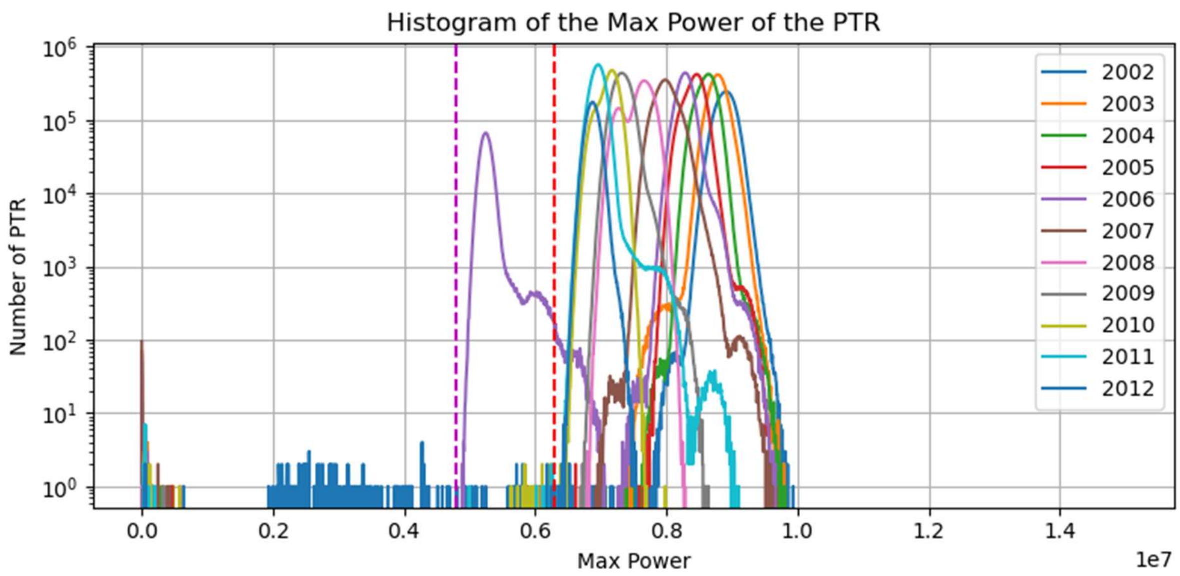


Figure 2-8 : Maximum power value of the PTR for the whole ENVISAT lifetime

3. Position of the maximum value of the PTR must be between [3717: 3723]

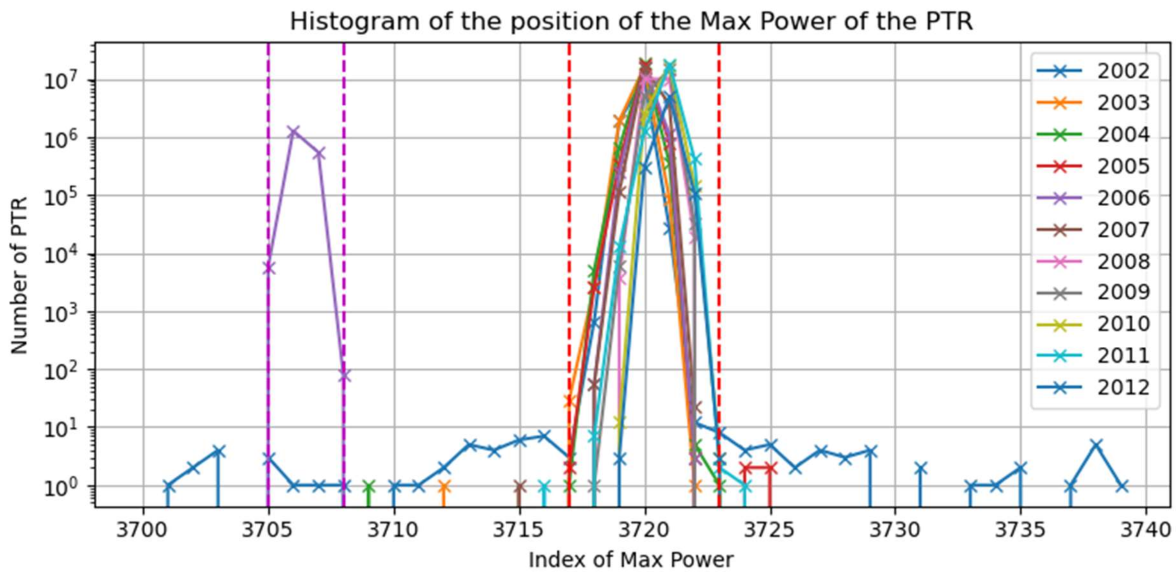


Figure 2-9 : Position of the maximum power of the PTR for the whole ENVISAT lifetime

A summary table of the editing intervals can be found in Table 1, for both Ku-band and S-band:

PARAMETER	KU BAND	S BAND
Max Power Index	3717 → 3723	3889 → 3893

Max Power	0.67e7 → inf	1.03e7 → inf
Median	0 → 1000	0 → 1000

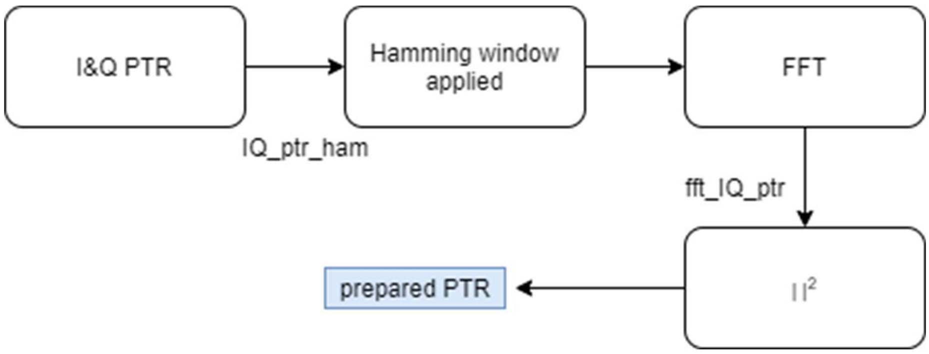
Table 1 : Summary of editing intervals to remove outliers PTR waveforms

To average the I and Q (complex)

For each pass (half-orbit and pole-to-pole), a single mean I&Q PTR is obtained by computing a 10-day averaging (located at the middle of the pass) of edited PTR waveforms.
To be valid, the process must be done over a minimum of **1000 valid PTR arrays.** If not valid, the closest valid averaged PTR (in the past) to the current pass is taken instead.

To compute the I2Q2 PTR (power)

Each averaged I&Q PTR is then converted into a I2Q2 PTR with 8192 samples.
Let *ptr* be the I&Q PTR, the following steps are:



Hamming window is defined in equation 31 from **RD-14**.

2.8.5 Outputs

The outputs are the averaged PTR arrays, one PTR per track used as an input of the Adaptive Retracker.

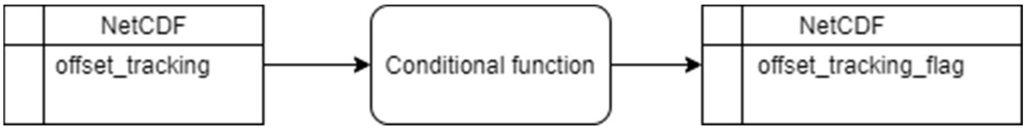
Parameter	Variable name	unit
PTR in Ku-band	*ptr_ku*	FFT.pu
PTR in S-band	*ptr_s*	FFT.pu

2.9 ALTFDR_EN_OFFSET_FLAG

2.9.1 Inputs

Parameter	Variable name	unit
Reference tracking point offset	*offset_tracking*	count

2.9.2 Logical Flow



2.9.3 Key Principles of the Algorithm

The goal of this conditional function algorithm is to provide a new flag indicating about the offset tracking gate scenario.

- If offset_tracking = - 4608:
  - Offset_tracking_flag=0
- Else:
  - Offset_tracking_flag=1

2.9.4 Outputs

Parameter	Variable name	dim	unit
Reference trackin point offset flag	*offset_tracking_flag*	1	-

2.9.5 Comments

Flag is set to “nominal” (equal to 0 by convention) for the nominal reference gate scenario. If not, the flag is set to “not nominal”, i.e equal to 1.

2.9.6 References

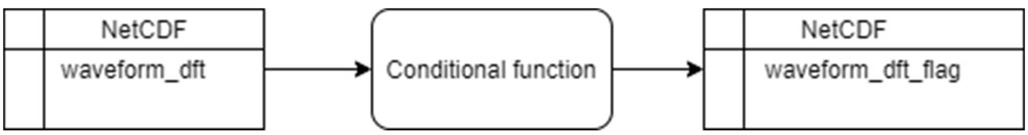
For more details about the algorithm and mathematical statements, please refer to [**RD-4**].

2.10 ALTFDR_EN_FLAG_DFT

2.10.1 Inputs

Parameter	Variable name	Source	dim	unit
Waveform DFT-points	*Waveform_dft*	ENVISAT V3.0	2	FFT.pu

2.10.2 Logical Flow



2.10.3 Key Principles of the Algorithm

The goal of this function is to compute a flag scenario indicating nominal DFT array values or not. Nominal scenario refers to bins 44.5 and 45.5.

- If waveform_dft[0] = 44.5 and wavefor_dft[1] = 45.5:
    - Flag_waveform_dft = 0
- Else:
    - flag_waveform_dft = 1

2.10.4 Outputs

Parameter	Variable name	dim	unit
Waveform DFT flag scenario	*flag_waveform_dft*	1	-

2.10.5

2.10.6 Comments

Flag is set to "nominal" (equal to 0 by convention) for the nominal reference DFT gates scenario. If not, the flag is set to "not nominal", i.e equal to 1.

2.10.7 References

For more details about the improvements brought by the FDR4ALT project, see [D-1-02].

2.11ALTFDR_EN_DISTANCE_TO_COAST

2.11.1 Inputs

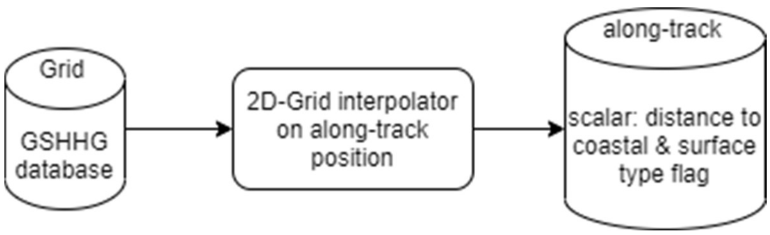
The coastline database used is the *GSHHG database <https://www.soest.hawaii.edu/pwessel/gshhg/>*.

More precisely the special NetCDF files for GMT.

Parameter	Source (grid name)	dim	Unit
Full (original) resolution GSHHG database	*Binned_GSSHS_f.nc*	Multi	deg

Derived from **RD-10** and processed by Paul Wessel and Walter H. F Smith, 1994-2017

2.11.2 Logical Flow



2.11.3 Key Principles of the algorithm

This algorithm is to compute coastal distance and land-water mask indicator. Given a list of points, it is used to compute the nearest points to the coast and the distance to it, along with the land-water mask.

For each point P (lon, lat) on earth, this module computes:

- the land-water mask of P (0=ocean, 1=land, 2=lake, 3=island in lake, 4=pond in island)
- the nearest point Q of P to the coast

Several pieces of information are available on the nearest point Q:

- its positions (lon, lat) in degrees
- its distance from P in km
- its angle in degrees to the local direction in P = angle of (PP', PQ) where P' is the successor of P

Grid interpolator is used to interpolate over a 2-D grid at the requested point.

2.11.4 Outputs

Parameter	variable name	dim	Unit
Coastal distance	*distance_to_coast*	1	m
Surface type flag	*surface_type*	1	-

Flag values: 0=ocean, 1=land, 2=lake, 3=island in lake, 4=pond in island

2.11.5 Comments

Angles in degrees has not been provided in the ALT_FDR products. The same algorithm is used for ERS missions.

2.11.6 References

For more details about the GSHHG database, please refer to [**RD-9**]

2.12 ALTFDR_ERS_DISTANCE_TO_COAST

Please refer to ALTFDR_EN_DISTANCE_TO_COAST.

2.13 Reference Documents

RD-1	J. Poisson, G. D. Quartly, A. A. Kurekin, P. Thibaut, D. Hoang and F. Nencioli, "Development of an ENVISAT Altimetry Processor Providing Sea Level Continuity Between Open Ocean and Arctic Leads," in IEEE Transactions on Geoscience and Remote Sensing, vol. 56, no. 9, pp. 5299-5319, Sept. 2018, doi: 10.1109/TGRS.2018.2813061.
RD-2	C. M. Bishop,Neural Networks for Pattern Recognition.NewYork,NY,USA: Oxford Univ. Press, 1995.
RD-3	G. Cybenko, "Approximation by superpositions of a sigmoidal function,"Math. Control, Signals, Syst., vol. 2, no. 2, pp. 303–314, 1989.
RD-4	C. Tourain, F. Piras, A. Ollivier, D. Hauser, J. C. Poisson, F. Boy; P. Thibaut; L. Hermozo; C. Tison, Benefits of the Adaptive algorithm for retracking altimeter nadir echoes: results from simulations and CFOSAT/SWIM observations, IEEE, 2021, 10.1109/TGRS.2021.3064236
RD-5	RA-2 ALGORITHMS SPECIFICATION FOR LEVEL 1B SOFTWARE PROTOTYPING, ISARD_ESA_L1B_ESL_DPM_022
RD-6	Davis C: "A robust threshold re-tracking algorithm for measuring ice-sheet surface elevation change from satellite radar altimeters", IEEE T. Geosci. Remote, 35, 974-979, doi :10.1109/36.602540, 1997.
RD-7	Helm, Veit & Humbert, A & Miller, H. (2014): "Elevation and elevation change of Greenland and Antarctica derived from CryoSat-2". The Cryosphere Discussions. 8. 10.5194/tcd-8-1673-2014.
RD-8	R Peacock, N. R., and S. W. Laxon (2004), Sea surface height determination in the Arctic Ocean from ERS altimetry, J. Geophys. Res., 109, C07001, doi:10.1029/2001JC001026
RD-9	Wessel, P., and W. H. F. Smith, A Global Self-consistent, Hierarchical, High-resolution Shoreline Database, *J. Geophys. Res., 101*, 8741-8743, 199
RD-10	World Vector Shoreline, CIA WDB-II, and Atlas of the Cryosphere
RD-11	D. J. Brockley, "REAPER—Product handbook for ERS Altimetry reprocessed products", Apr. 2014.
RD-12	PRARE Precise Orbit Product (ERS.ORB.POD) - Earth Online (esa.int), https://earth.esa.int/eogateway/catalog/prare-precise-orbit-product-ers-orb-pod-?text=deos
RD-13	Roemer, S., B. Legrésy, M. Horwath, and R. Dietrich (2007), Refined analysis of radar altimetry data applied to the region of the subglacial Lake Vostok/Antarctica, *Remote Sens. Environ.*, *106*(3), 269–284, doi:10.1016/j.rse.2006.02.026.
RD-14	M. Roca, S. Laxon and C. Zelli, "The EnviSat RA-2 Instrument Design and Tracking Performance," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 47, no. 10, pp. 3489-3506, Oct. 2009, doi: 10.1109/TGRS.2009.2020793.
RD-15	ENVISAT ALTIMETRY Level 2 Product Handbook : CLS-ESLF-18-0003, issue 2.0., 2018

3 MWR Fundamental Data Records

For FDR4ALT reprocessing, the specific prototypes for each mission were kept for the L0 and parts of L1 processing. Effort was focused on homogenizing the processing at L1.
The major updates brought on each ground prototype are listed here:

For ERS processing:

- ✓ Removal of 1Hz count averaging to keep radiometer 7Hz data rate [function A2: antenna temperature retrieval]
- ✓ Gain averaging [function A211 calibration smoothing and interpolation, antenna temperature calculation A212], detailed hereafter in section 2.2.4 of this document
- ✓ Interpolation of skyhorn transmission coefficient according to its physical temperature
- ✓ Radiometric model updates
- ✓ NetCDF outputs instead of binary (section 4 level1B formatting).

For ENVISAT processing:

- ✓ Removal of 1Hz TA averaging to keep radiometer 7Hz data rate [function A2: antenna temperature retrieval]
- ✓ NetCDF outputs instead of binary [section]
- ✓ Radiometric model updates

All the other processing steps and algorithm description can be found in REAPER Level 1B DPM **[RD-16]** for ERS and the ground processor specifications for ENVISAT **[RD-17].**

Figure 3-1 presents the general overview of MWR FDR processing. Each of the processing steps (blue boxes) is detailed in the following sections, where:

- MWRFDR_TL reads the instrument telemetry to extract instrument counts, physical temperatures and perform telemetry quality checks.
- MWRFDR_LOC compute the measurements coordinates using its time tag and the precise orbit files.
- MWRFDR_RAWCAL computes the raw calibration using the calibrations counts, physical temperatures and MWR radiometric model.
- MWRFDR_AVCAL average the raw calibrations around each antenna measurements.
- MWRFDR_TA computes the antenna temperatures using the antenna counts, physical temperatures and MWR radiometric model taking into account the calibration.
- MWRFDR_TA2 corrects for the gain drop (only for ERS-2 23.8GHz).
- MWRFDR_TB computes the brightness temperature by removing sidelobes effect off antenna temperature.
- MWRFDR_TBEN corrects for the drifts (only for EN 36.5GHz).
- MWRFDR_QUAL computes the quality flag associated to the brightness temperature.
- MWRFDR_UNC computes uncertainties of brightness temperatures.
- MWRFDR_BC to compute bias corrected brightness temperature.

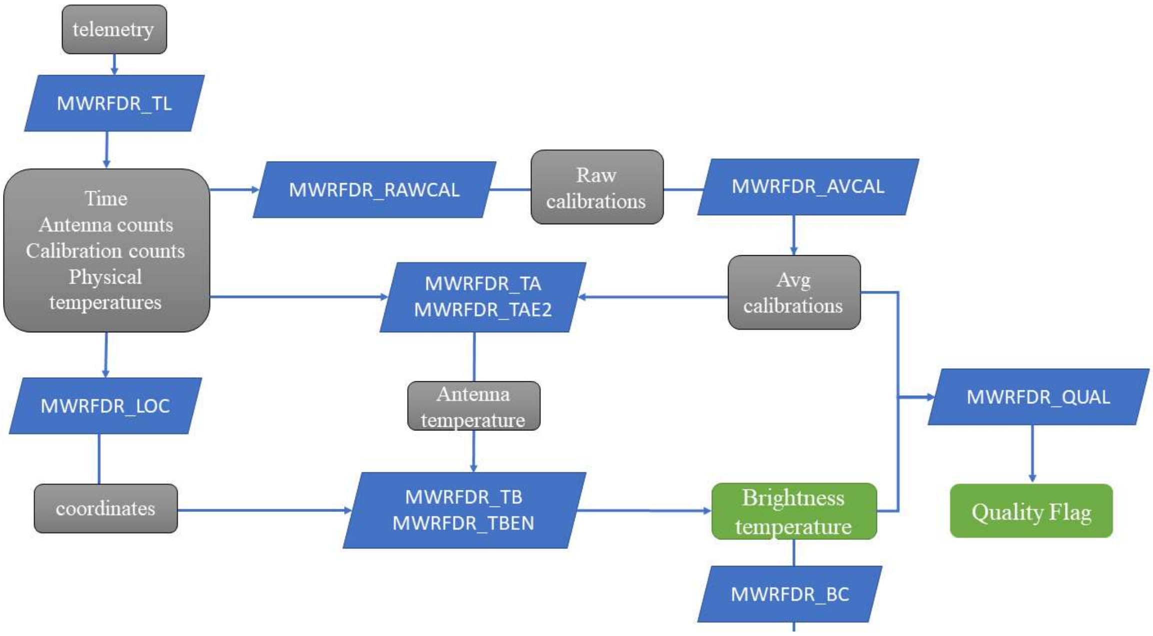


Figure 3-1 : General overview of MWR FDR processing

3.1 Radiometric model clarifications

The instrument design of ERS-1/2 and ENVISAT are very similar. Only one radiometric model is presented hereafter by Figure 3-2. Only the naming of some parameter can change between ERS and ENVISAT transfer model.
One radiometer channel can be modelled with an amplifier of gain G' function of its physical temperature Tg, a Dicke circulator at temperature Td, switching between the reference load Tref and the antenna input. The antenna channel is made of a calibration circulator switching between the main antenna and the calibration channels. Then, the h/c circulator switches the calibration input between the ambient load Tc and the sky horn.
Each circulator is characterized by four transmission factors, two for each way, and physical temperatures. Coefficients (a) stands for transmission and (b) for isolation. The mismatches introduce some coupling effects, and their contributions are included in the b coefficient.
In the main antenna circuit, the source transmission is named *afeed* and its temperature *Tfeed* and *ar*, Tr for the waveguide. Similarly, for sky horn circuit, *acc* and *Tcc* are related to the horn and *acw* and *Tcw* to the waveguide.

By computing the successive losses of a temperature in input of a given horn (sky or main antenna), and adding all the sources of contamination, one can write the radiometric equations along each measurement path (cold sky, hot reference, main antenna).
By inverting theses equations, on can write the radiometric model used to retrieve the measured instrument antenna temperature from measurements counts.

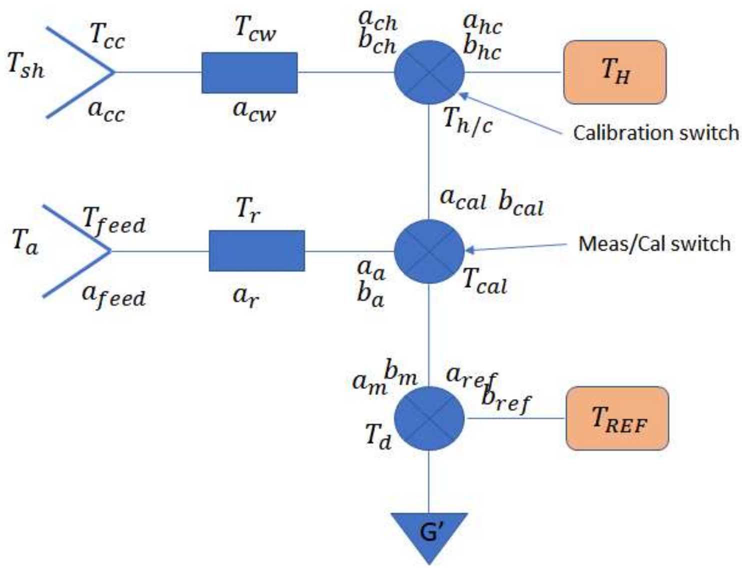


Figure 3-2: ENVISAT radiometric model

3.2 Intercalibration

Intercalibration of the brightness temperatures of the three missions has been achieved by analyses on measurement over natural targets on Earth, the so-called vicarious calibrations. These analyses allow to compare missions even without a tandem phase. Usually, two analyses are performed for lowest and highest brightness temperatures: coldest ocean points and Amazon Forest respectively. Results about the intercalibration can be found in the validation report [D-4-02], section 3.3.3.2 and section 3.3.3.4.
The reference selected for the intercalibration is Sentinel-3 MWR. The intercalibration of the brightness temperatures is achieved by the update of the characterisation parameters of the radiometric models, which will impact the lowest brightness temperatures, and the efficiencies of the sidelobe correction if required for the highest values.
The intercalibrated brightness temperatures are provided in the main group of the FDR products with the variables **tb_238** and **tb_365**. These brightness temperatures are used in input of the Artificial Neural Network (ANN) to compute the Wet Tropospheric Correction, the Atmospheric Attenuation and TCWV and CLWC, after an adjustment processing (linear relation).
Along with these variables, the user can also find in the expert group the bias-corrected brightness temperatures used by the 1DVAR processing, with the variables tb_238_bias_adjusted and tb_365_bias_adjusted**.** They are related to the intercalibrated BTs by a linear relationship similar to the adjustment used by the ANN.

3.3 Processing chains

3.3.1 ERS

The ERS processing chain is detailed in Figure 3-3.

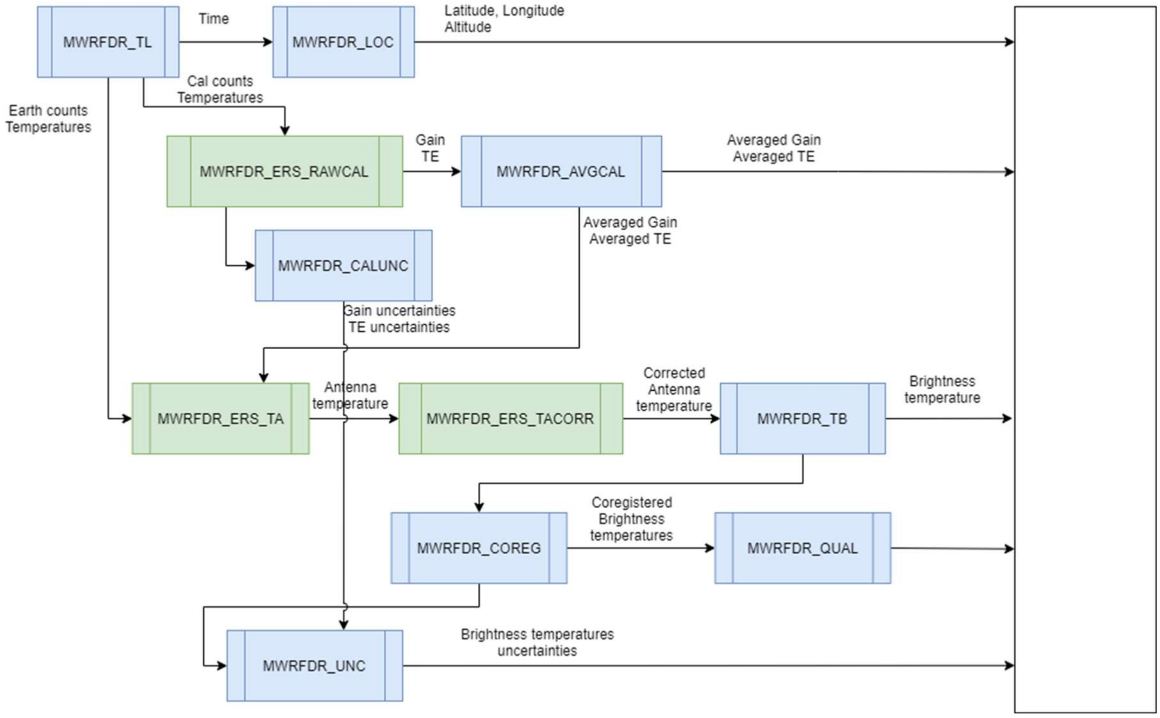


Figure 3-3: ERS processing chain

3.3.2 ENVISAT

The ENVISAT processing chain is detailed in Figure 3-4.

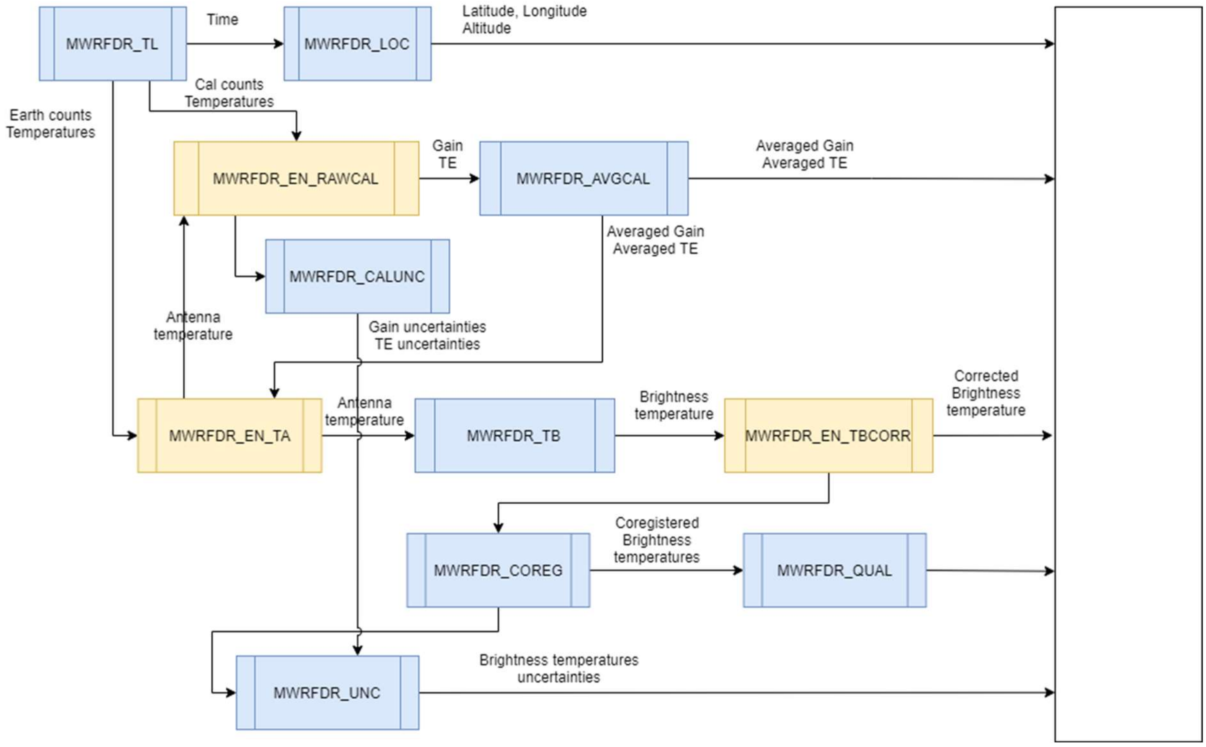


Figure 3-4: ENVISAT processing chain

ENVISAT processing is performed in two passes for every telemetry as illustrated with Figure 3-5.
The first step will be dedicated to fill the calibration window and compute averaged calibration parameters. Temperatures measurements are available once for every 32 source packets. Thus, temperature table shall be filled before any processing. Then, the processing moves forward in the telemetry processing only

calibration measurements, until the averaging calibration window is filled. During this step, the leakage temperature is a constant value provided as input parameter. Once, the window is full, the processing rewinds to the beginning of the product.
The second step starts from the beginning of the file. The averaged calibration parameters computed during the first step are used in this step to compute the antenna temperature, when an Earth count is found. In this step, the computed antenna temperature can be used as leakage temperature in the computation of calibration parameters.

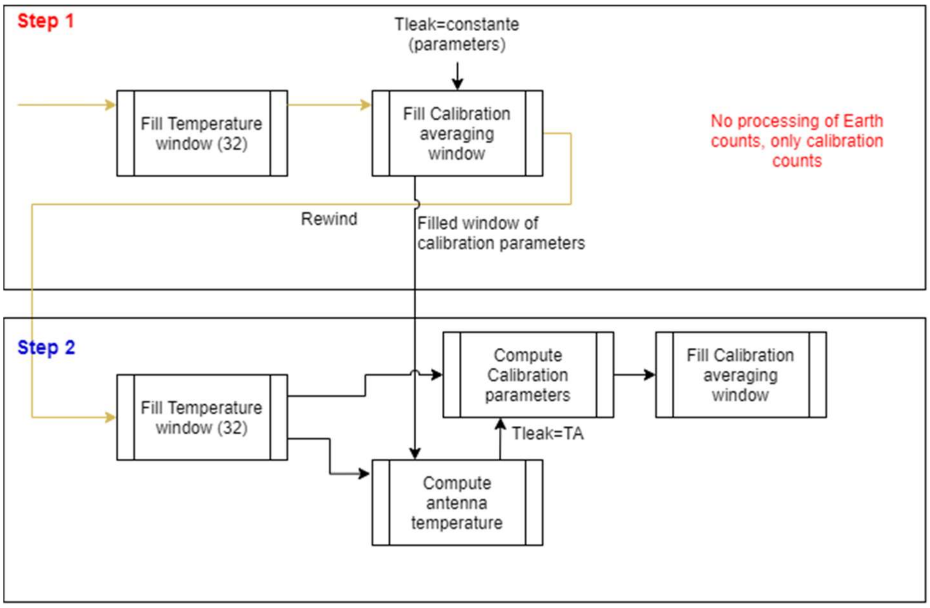


Figure 3-5: ENVISAT processing chain – Filling of temperature and calibration arrays

3.4 MWRFDR_TL: To read MWR telemetry

Some differences exist between the ERS and the ENVISAT designs:
- Different telemetry
- Different number of thermistances and validity checks
- Different localization in the instrument

Hence the specific prototypes for each mission (REAPER for ERS-1/2 and EN prototype for ENVISAT) were kept for the processing. The reading functions did not change, so will not be detailed here.

3.4.1 ERS telemetry description

Telemetry format and reading is partially described in REAPER Level 1B IODD **[**RD-18**]** for science packet only. The information is not complete because the whole file structure (headers, repeating records...) is not detailed and the bits counting is not always detailed in the same manner. Moreover, the reference document (ER-TN-CRP-AT-0042) was not found in any ESA servers. We decided to clarify as possible the whole telemetry structure when checking REAPER prototype for the sake of information preservation.
.
The following definition are used hereafter: one word is 16bits or 2bytes. One byte is 8bits. When counting bits in a word, we start at 1 and the first bit is MSB (Most Significant Bit).
One L0 telemetry is composed of N records. As illustrated by Figure 3-6, each record is divided in

1. A Main Product Header (MPH) of 176bytes
2. A Specific Product Header (SPH) of 316 bytes
3. A DataSet Record (DSR) of 900 bytes containing the DSR record number (4bytes) and the **Science Data Packet** (896 bytes).

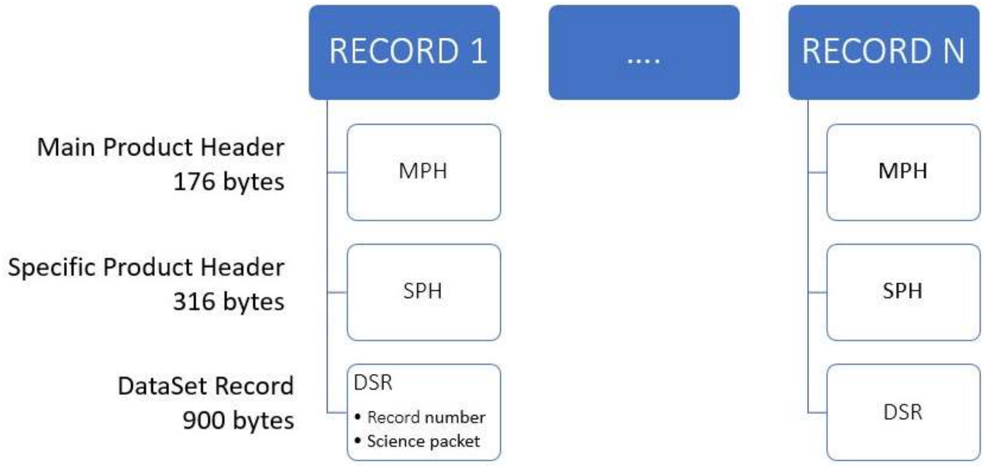


Figure 3-6: ERS telemetry records

Science Packet Description

The science packet is composed of 28 bytes repeated 32 times.

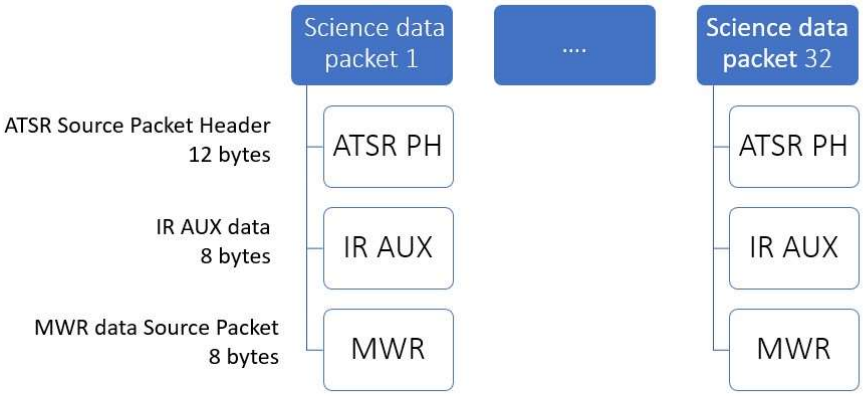


Figure 3-7: ERS telemetry Science Packets

One Science Packet will then be constituted of 32 radiometer counts per channel (C238 and C365), 32 resistances measurements (Ri) and 32 configuration status words. The sub commutation counter (ICDMW) gives an index from 0 to 31. Depending on ICDMW values, various housekeeping information (HK) are available, mostly related to configuration command.
For instance, it gives HK=IPM for ICDMW=25.
The IRR packet count CDIR allows to read the auxiliary Infra-red data, giving the radiometer status (MWR mode IDMW) when CDIR=5.

- ICU14 HK = IDMW for CDIR=5

The MWR data source packet words and bits composition are described in Table 3.

Table 2: ATSR source packet header (SPH) bits composition

words\bit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Word 1																
Word 2																
Word 3																
word 4	SP reference time (12 bytes)															

word 5																
word 6									CDIR (2bits)							

Table 3: ERS MWR data source packet (SP) bits composition

words\bit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
word 1	HK				CDMW											
word 1	HK													ICDMW		
word 2	IFONC	ICONF			C238											
word 3		ICU14 HK		IBP	C365											
word 4				IM	Ri											

Only the data from MWR in nominal mode are processed. It should have the following configuration:

Table 4 : ERS MWR nominal configuration

Configuration	parameter	value
Microwave radiometer ON	IDMW	3
Programmer mode nominal	IM	1
Microwave dicke range (T <TREF)	IPM	0
Normal calibration sequence	IFONC	0

3.4.2 EN telemetry description

Telemetry format and reading is partially described in ENVISAT Level 1B IODD [**RD-17**] for science packet only. The information is not complete because the whole file structure (headers, repeating records...) is not detailed.

According to **[RD-16],** the telemetry from the satellite is packetized in Level 0 product covering one orbit time (around 100 min) and composed of:

- A Main product Header:Table 5
- A Specific Product Header
- A series of Instrument Source Packet

However, after analysis of ENVISAT prototype, no Specific Product Header reading routine was identified.

The Instrument Source Packet is composed of

- Source Packet header (3 words): Table 6
- Packet Data field: header (6 words): Table 7
- Packet Data field: Source Data Field (640 words = 5 Science Data blocks of 128 words): Table 8
- Packet Error control
- Annotation (16 words)

Table 5: MWR MPH description

	Contents	Units	Length [bytes]
	ACQUISITION_STATION		20
	SENSING_START	UTC	27

	SENSING_STOP	Keyword	27
	PHASE		
	CYCLE		4
	REL_ORBIT		6
	ABS_ORBIT		6
	STATE_VECTOR_TIME	UTC	27
	DELTA_UT1		8
	X_POSITION	m	10
	Y_POSITION	m	10
	Z_POSITION	m	10
	X_VELOCITY	m	12
	Y_VELOCITY	m	12
	Z_VELOCITY	m	12
	VECTOR_SOURCE		2
	UTC_SBT_TIME	UTC	27
	SAT_BINARY_TIME	psec	11
	CLOCK_STEP	psec	11
	LEAP_UTC		27
	LEAP_SIGN		
	LEAP_ERR		

Table 6: MWR source packet header bits composition

words\bit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Word 1	Version number			Type	Header	Application process ID										
Word 2	Seg ID	Source sequence counter														
Word 3	Packet length															

Table 7: MWR Header Data Field words/bits composition

words\bit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Word 1	Data Header length															
Word 2	Instrument mode															
Word 3	Datation (On Board Time)															
Word 4	Datation (On Board Time)															
Word 5	Redundancy vector															
Word 6	Number of Science Data Blocks (set to 5)															

Table 8: MWR Source Data field words/bits composition

words\bit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Word 1	DHK0	CS			Line counter (for temperature)											
Word 2	CF				Channel 23.8GHz counts											
Word 3	EN_A	DHK1	DHK2	BPSP	Channel 36.5GHz counts											
Word 4	ST_PBP	ST_OLP	Spare	Prog mode	Temperature (subcommutated by											

Table 9: MWR Line Counter (from 0 to 31) definition

5	Dicke load ch1	

6	Dicke load ch2	
7	Skyhorn waveguide ch1	
8	Skyhorn waveguide ch2	
9	Circulator H/C ch1	
10	Feedhorn ch1	
11	Circulator Dicke ch1	
12	Circulator CAL ch1	
13	Circulator H/C ch2	
14	Feedhorn ch2	
15	Circulator Dicke ch2	
16	Circulator CAL ch2	
21	Skyhorn	
22	Reflector	
23	HotLoad ch1	
24	HotLoad ch2	
25	Feedhorn waveguide ch1	
28	Dicke load waveguide ch1	
29	Feedhorn waveguide ch2	
31	Dicke load waveguide ch2	

3.5 MWRFDR_EN_Time: To compute time

3.5.1 Inputs

Name	Source	units	dimension
OBDH time (Source Packet) SP_OBDH	MWRFDR_TL	s	N
OBT reference (MPH) MPH_OBT_ref	MWRFDR_TL		M
Start Sensing Time (sensing_time)	MWRFDR_TL		
UTC_SBT_TIME (MPH_UTC_ref)	MWRFDR_TL		
Clock Step (ClockStep)	MWRFDR_TL		
Packet_Telemetry_Counter (SPcounter)	MWRFDR_TL		

3.5.2 Key principles

The datation of science data is computed from a counter provided in the MPH (MPH_OBT_ref), which is synchronized with the reference time (**MPH_UTC_ref).** A similar counter provided in the Science Packet is compared to the counter provided in the MPH. The difference is multiplied by the ClockStep parameter. The reference time is expected to be prior to the sensing time. But, during the reprocessing, we found some cases where it was not the case. We implemented a patch to account for that case.

First step: Compute the delta parameter

Nominal case: sensing time is after the reference time (MPH_UTC_ref)

```
if (sensing_time >= MPH_UTC_ref )
        if (SP_OBDH >= MPH_OBT_ref)
                Delta = SP_OBDH - MPH_OBT_ref
        else
                Delta = SP_OBDH + (0xffffffful - MPH_OBT_ref + 1)
```

Degraded case : sensing time is after the reference time (MPH_UTC_ref)

```
else
        if (SP_OBDH >= MPH_OBT_ref )
```

```
            Delta = SP.OBDH_time - MPH_OBT_ref
      else
            Delta = MPH_OBT_ref - SP.OBDH_time
```

<u>Second step: compute the time of the science measurements</u>

```
if (sensing_time >= MPH_UTC_ref ){
      T0 = SPcounter * 0.15 + (Delta *ClockStep);
else
      if (SP_OBDH >= MPH_OBT_ref)
            T0 = SPcounter * 0.15 + (Delta * ClockStep);
      /* Case when the MPH counter is not covering the telemetry
      else
            T0 = SPcounter * 0.15 - (Delta * MPH.ClockStep)
```

3.5.3 Outputs

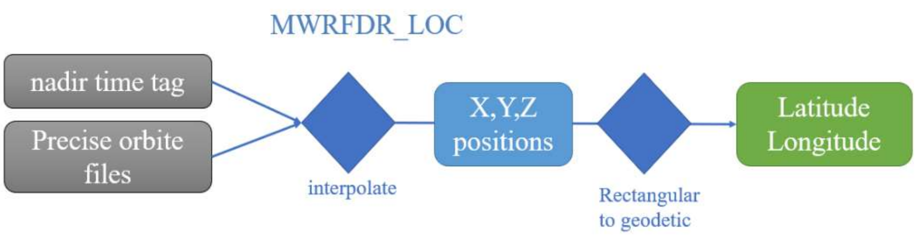
Name	units	dimension
sub-satellite time tag	UTC	N

3.6 MWRFDR_LOC: To compute location

3.6.1 Inputs

Name	source	units	dimension
sub-satellite time tag	MWRFDR_EN_Time MWRFDR_ERS_Time	s	N
Precise orbit files	ADF	/	M

3.6.2 Logical flow



3.6.3 Key principles

Search the orbit file corresponding to the time period. Load the selected orbit file and interpolate the rectangular coordinates to each time of the nadir time tag array.

Convert the rectangular coordinates to geodetic coordinates.

3.6.4 Outputs

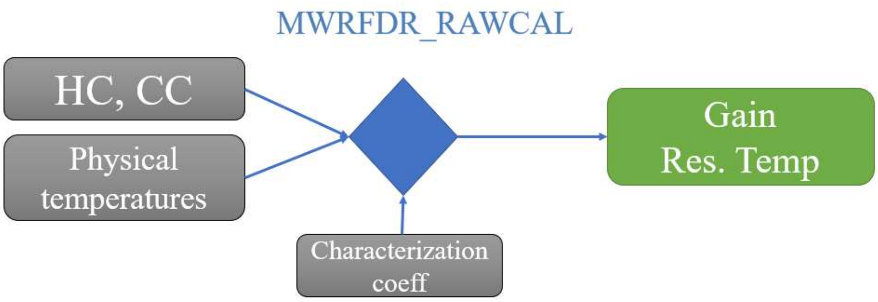
Name	unit	dimension
latitude of measurement	degree	
longitude of measurement	degree	

3.7 MWRFDR_ERS_RAWCAL: To compute raw calibration parameters

3.7.1 Inputs

Name	source	unit	dimension
hot count	MWRFDR_TL	mV	1
cold count	MWRFDR_TL	mV	1
offset counts	MWRFDR_TL	mV	1
characterization coefficients of MWR model	CCDB	Np	1
MWR physical temperatures	MWRFDR_TL	K	1

3.7.2 Logical flow



3.7.3 Key principles

Raw gain retrieval

G' is the gain between the calibration switch input and the numerical count output. It can be computed from hot and cold counts (CH and CC respectively) using cold sky temperature (Tsh2), hot reference temperature (TH), calibration switch temperature (Thc) and each element losses and leakage along the path.

$$G' = \frac{1}{(a_m - b_{re}) * a_a} * \frac{CH - CC}{c_h * TH + c_{hc} * T_{hc} + c_{fc} * T_{sh2} + (TE'_2 - TE'_3)}$$

$$G = G' * (a_m - b_{re}) * a_a$$

Residual temperature retrieval

The residual temperature represents the remaining signal not taken into account by the radiometric model. It can be computed using the hot calibration count and the gain.

$$TE = \frac{TE'}{(a_m - b_{re}) * a_a} = \frac{CH - offset}{G}$$
$$-a_{ref} * T_{ref} - a_d * T_d$$
$$+a_4 * TH + a_3 * T_{hc} + a_2 * T_{sh2} + a_6 * T_{cal} + a_{51} * T_{a2} + a_{50}$$

With

$$
\begin{aligned}
a_{ref} &= \frac{a_{re} - b_m}{(a_m - b_{re}) * a_a} \\
a_d &= \frac{1}{a_a} - a_{ref} = \frac{a_m + b_m - a_{re} - b_{re}}{(a_m - b_{re}) * a_a} \\
a_2 &= b_{hc} * \frac{a_{cal}}{a_a} \\
a_4 &= a_{hc} * \frac{a_{cal}}{a_a} \\
a_3 &= \frac{a_{cal}}{a_a} - a_2 - a_4 = \frac{a_{cal}}{a_a} * (1 - a_{hc} - b_{hc}) \\
a_6 &= \frac{1 - a_{cal} - b_{cal}}{a_a} \\
a_{51} &= \frac{b_{cal}}{a_a} \\
a_{50} &= \frac{\mathrm{TE2} - \mathrm{TE3}}{(a_m - b_{re}) * a_a}
\end{aligned}
$$

Note: TE1 and TE2 are respectively the bias of antenna and hot counts

3.7.4 Outputs

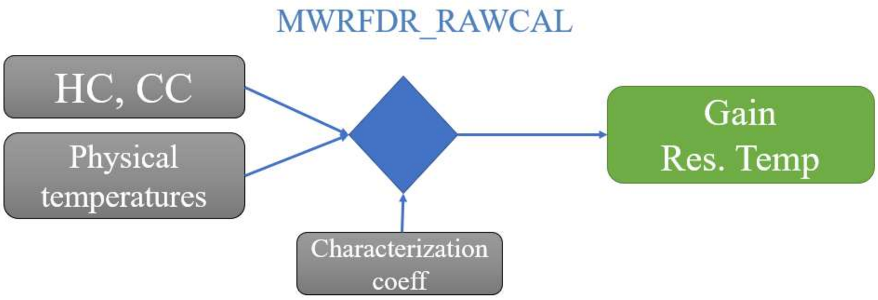
Name	unit	dimension
Gain	mV/K	1
residual temperature	K	1

3.8 MWRFDR_EN_RAWCAL: To compute raw calibration parameters

3.8.1 Inputs

Name	source	units	dimensions
hot count	MWRFDR_TL	mV	1
cold count	MWRFDR_TL	mV	1
offset counts	MWRFDR_TL	mV	1
characterization coefficients of MWR model	CCDB	1	1
MWR physical temperatures	MWRFDR_TL	K	1
Leak temperature	Parameter or MWRFDR_EN_TA	K	1

3.8.2 Logical flow



3.8.3 Key principles

Raw gain retrieval

G' is the gain between the calibration switch input and the numerical count output. It can be computed from hot and cold counts (CH and CC respectively) using cold sky temperature (Tsh2), hot reference temperature (TH), calibration switch temperature (Thc) and each element losses and leakage along the path.

$$G' = \frac{1}{(a_m - b_{re}) * a_a} * \frac{CH - CC}{c_h * TH + c_{hc} * T_{hc} + c_{fc} * T_{sh2}}$$

$$G = G' * (a_m - b_{re}) * a_a$$

Residual temperature retrieval

The residual temperature represents the remaining signal not taken into account by the radiometric model. It can be computed using the hot calibration count and the gain.

$$TE = \frac{TE'}{(a_m - b_{re}) * a_a} = \frac{CH - offset}{G} - a_{ref} * T_{ref} - a_d * T_d + a_4 * TH + a_3 * T_{hc} + a_2 * T_{sh2} + a_6 * T_{cal} + a_{50} * T_{a2}$$

With

$$a_{ref} = \frac{a_{re} - b_m}{(a_m - b_{re}) * a_a}$$

$$a_d = \frac{1}{a_a} - a_{ref} = \frac{a_m + b_m - a_{re} - b_{re}}{(a_m - b_{re}) * a_a}$$

$$a_2 = b_{hc} * \frac{a_{cal}}{a_a}$$

$$a_4 = a_{hc} * \frac{a_{cal}}{a_a}$$

$$a_3 = \frac{a_{cal}}{a_a} - a_2 - a_4 = \frac{a_{cal}}{a_a} * (1 - a_{hc} - b_{hc})$$

$$a_6 = \frac{1 - a_{cal} - b_{cal}}{a_a}$$

$$a_{50} = \frac{b_{cal}}{a_a}$$

Note: TE1 and TE2 are respectively the bias of antenna and hot counts

3.8.4 Outputs

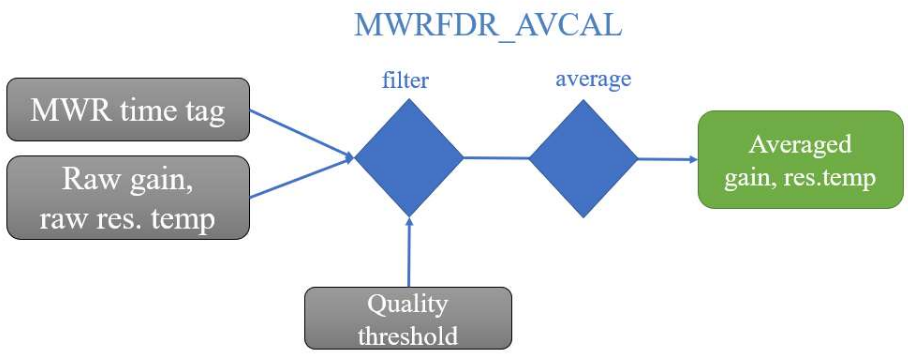
Name	unit	dimension
Gain	mV/K	1
residual temperature	K	1

3.9 MWRFDR_AVGCAL: To average raw calibrations around antenna measurement time

3.9.1 Inputs

Name	source	unit	dimension
timetag	MWRFDR_Time	K	1
averaging half window size	parameter	s	1
raw gain	MWRFDR_EN_RAWCAL	mV/K	ncal
raw residual temperature	MWRFDR_EN_RAWCAL	K	ncal
raw calibration timetag	MWRFDR_EN_RAWCAL	s	
gain quality threshold	parameter	mV/K	1

3.9.2 Logical flow



3.9.3 Key principles

First, a filtering of all raw gain spurious values is performed.
For each value G(i) of the ncal raw gain calibrations, compare it with its neighbours. The flag spurious is set to True in when the absolute difference is greater than the threshold, in the following cases:

- IF i == 0 AND ABS (G(i+1) – G(i)) >= threshold AND ABS (G(i+2) – G(i)) >= threshold
- IF the difference with its 2 surrounding neighbours is greater than the threshold:

  ABS (G(i-1) – G(i)) >= threshold AND ABS (G(i+1) – G(i)) >= threshold
- IF i == ncal-1 AND ABS(G(ncal-2) – G(i)) >= threshold AND ABS (G(ncal-3) – G(i)) >= threshold

Then, the valid index of calibrations within the averaging window centered on the measurement timetag are selected

IF timetag – cal_timetag(0) is inferior to half_window

- Find the indexes IDX of cal_timetag elements located within the window [timetag, timetag +2*avg_half_size] and having flag_spurious set to FALSE

ELSE IF cal_timetag(ncal-1)- timetag is inferior to half_window

- Find the indexes IDX of cal_timetag elements located within the window [timetag - 2*avg_half_size,timetag] and having flag_spurious set to FALSE

ELSE

- Find the indexes IDX of cal_timetag elements located within the window [timetag – avg_half_size, timetag +avg_half_size] and having flag_spurious set to FALSE

Compute the mean and standard deviation of gain for using G[IDX]
Compute the mean and standard deviation of the residual temperature using RES_TEMP[IDX]
Compute the number of data used for mean computation

3.9.4 Outputs

Name	unit	dimension
averaged gain	mV/K	1
averaged residual temperature	K	1
number of averaged raw values	/	1

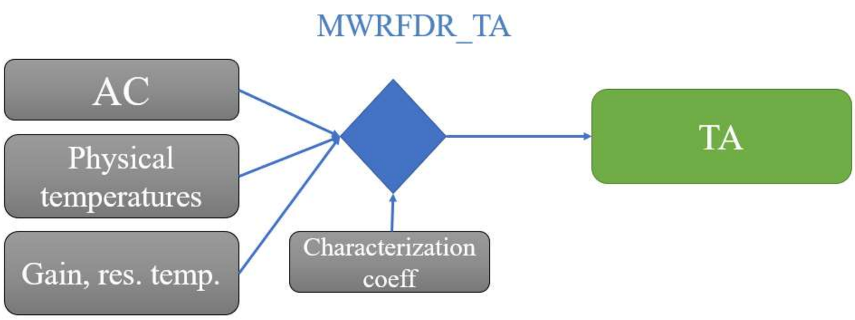
3.10MWRTDR_ERS_TA: To compute Antenna temperatures from antenna counts

3.10.1 Inputs

Name	source	unit	dimension
antenna counts	MWRFDR_TL	mV	1
averaged gain G	MWRFDR_AVGCAL	mV/K	1
averaged residual temperature TE	MWRFDR_AVGCAL	K	1
reflector temperature Tp	ADF	K	1
reflector efficiency nref	CCDB	/	1

For both ERS missions, the physical temperature of reflector Tp is not measured. It is provided as an input table in function of the latitude. The reflector loss correction is then applied by selecting the appropriate Tp corresponding to the measurement latitude.

3.10.2 Logical flow



3.10.3 Key principles

$$TA_p = \quad c1 * (-\frac{CA - offset}{G} + TE + b1 * T_{ref} + b2 * T_d - b_3 * T_{cal} - b'_4 * T_c - b_6 * T_{hc} - b_7 * T_{fc}) - c_2 * T_r$$

with

$$b'_4 \quad = \frac{b_{c1}}{a_{c1}} * a_{hc1}$$

$$b_6 \quad = \frac{b_{c1}}{a_{c1}} * (1 - a_{hc1} - b_{hc1})$$

$$b_7 \quad = \frac{b_{c1}}{a_{c1}} * b_{hc1}$$

$$TA = \frac{TA_p - (1 - n_{ref})\, T_p}{n_{ref}}$$

3.10.4 Outputs

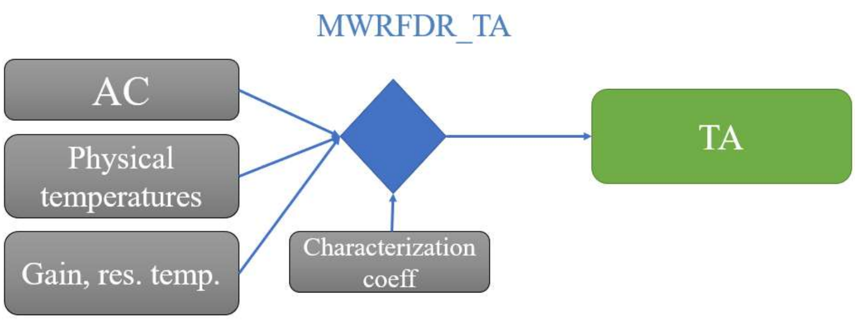
Name	units	dimension
Antenna temperature	K	1

3.11 MWRTDR_EN_TA: To compute Antenna temperatures from antenna counts

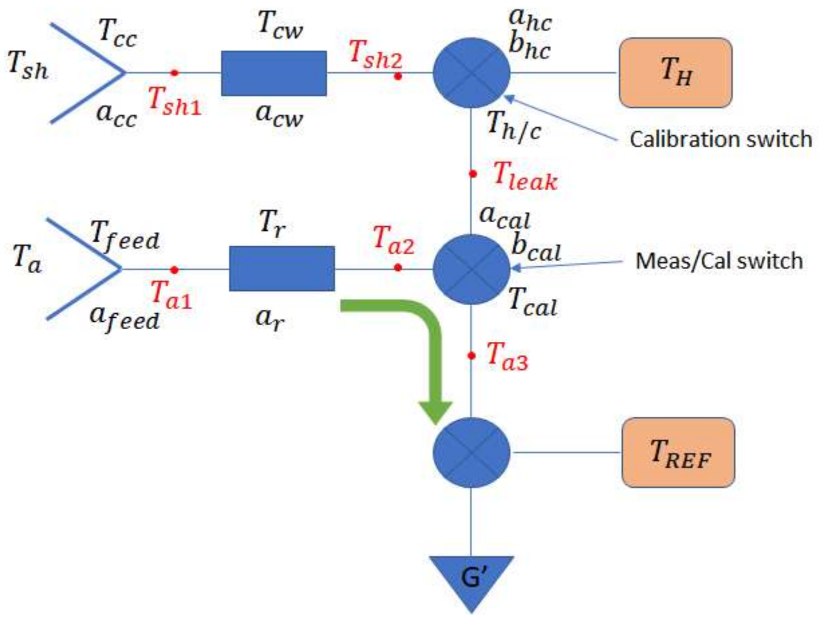
3.11.1 Inputs

Name	source	unit	dimension
antenna counts	MWRFDR_TL	mV	1
averaged gain G	MWRFDR_AVGCAL	mV/K	1
averaged residual temperature TE	MWRFDR_AVGCAL	K	1
Physical temperatures	MWRFDR_TL	K	1
reflector efficiency nref	CCDB	/	1

3.11.2 Logical flow



3.11.3 Key principles



$$TA_p = \quad c1 * \left(-\frac{CA - offset}{G} + TE + b1 * T_{ref} + b2 * T_d - c_2 * T_r - b_3 * T_{cal} - b_4 * T_{leak}\right) - c_3 * T_{feed}$$

With

$$c_1 = \frac{1}{a_r a_{feed}}$$

$$c_2 = 1 - c_1$$

$$c_3 = \frac{1}{a_{feed}} - 1$$

$$b_1 = \frac{a_{re} - b_m}{a_a(a_m - b_{re})}$$

$$b_{2} = \frac{1}{a_a} - b_1$$

$$b_3 = \frac{1}{a_a} - 1 - b_4$$

$$b_4 = \frac{b_a}{a_a}$$

The reflector contribution is corrected using the gain and the physical temperature:

$$TA = \frac{TA_p - \ (1 - n_{ref})\, T_{refl}}{n_{ref}}$$

3.11.4 Outputs

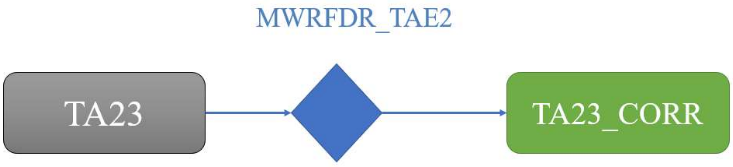
Name	units	dimension
Antenna temperature	K	1

3.12 MWRFDR_ERS2_TACORR: To correct ERS-2 Brightness Temperatures

3.12.1 Inputs

Name	source	units	dimension
Antenna temperature of channel 23.8GHz	MWRFDR_ERS_TA	K	1
Time	MWRFDR	UTC	1

3.12.2 Logical flow



3.12.3 Key principles

$$TA_{corr} = \begin{cases} TA + g(t) * \left(1 - \frac{TA}{280}\right), & TA < 280 \\ 0, & TA \geq 280 \end{cases}$$

$$g(t) = \begin{cases} 21 + 0.201 * \mathrm{t} - 0.688/(\mathrm{t} - 1.102), & before\ 1997, november\ the\ 25th \\ 21, & after \end{cases}$$

with t the decimal years since the beginning of the mission (1995-04-28)

$$t = (day - day0)/365.25$$

3.12.4 Outputs

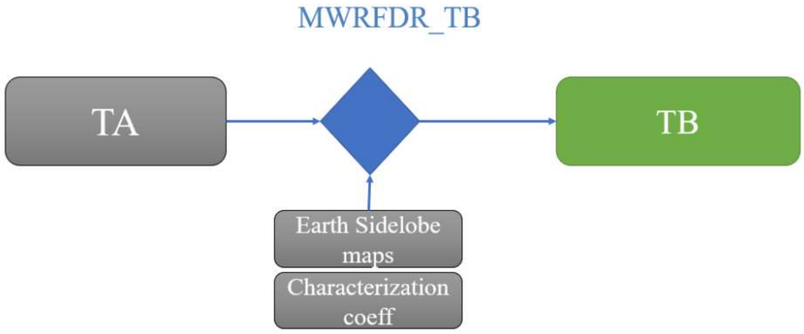
Name	units	dimension
Corrected Antenna temperature of channel 23.8GHz	K	1

3.13 MWRFDR_TB: To compute Brightness Temperatures from Antenna Temperatures

3.13.1 Inputs

Name	Source	unit	dimension
Co-registered Antenna temperatures	MWRFDR_E2_TACORR MWRFDR_EN_TA	K	1
main lobe efficiency (nml)	CCDB	/	1
sky sidelobe efficiency	CCDB	/	1
On-Earth sidelobe efficiency	CCDB	/	1
satellite sidelobe efficiency	CCDB	/	1
sar efficency	CCDB	/	1
coupling coefficient alpha	parameter	/	1
Sky temperature contribution Tsky	CCDB	K	1
On-Earth sidelobe temperature	ADF	K	4*Nlon*Nlat
Time tag	MWRFDR_TL	UTC	1

3.13.2 Logical flow



3.13.3 Key principles

The antenna temperature can be written as a combination of contributors emitting in the antenna field of view. A portion of the antenna measurement is contaminated by cold sky, satellite and sar antenna emission as well as earth emission in the side-lobes:

$$TA = n_{ml} T_{ml} + n_{earth} T_{ear} + n_{sat} T_{sat} + n_{sar} T_{sat} + n_{sky} T_{sky} + n_{sun} T_{sun}$$

The sun contamination is neglected and satellite and sar ones are estimated using Tearth through a coupling factor α. The sidelobe correction is now written as

$$T_{sl}(lat, lon, t) = n_{sky} T_{sky} + n_{earth} T_{eart} (lat, lon, t) + (n_{sat} + n_{sar})\, \alpha\, T_{eart} (lat, lon, t)$$

The sky temperature Tsky is set to 2.7 and Tearth comes from the spatial and temporal interpolation of seasonal sidelobe temperature maps.

Once the antenna temperature is computed, it is corrected of the sidelobe contamination to derive the brightness temperature:

$$TB = (TA - T_{sl})/n_{ml}$$

3.13.4 Outputs

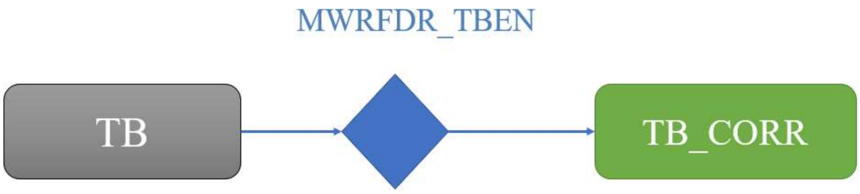
Name	unit	dimension
Brightness temperature	K	1

3.14 MWRFDR_EN_TBCORR: To correct ENVISAT Brightness Temperatures

3.14.1 Inputs

Name	source	unit	dimension
Brightness temperature of channel 36.5GHz	MWRFDR_TB	K	1
Time tag	MWRFDR	UTC	1

3.14.2 Logical flow



3.14.3 Key principles

The correction to apply on 36.5GHz brightness temperature is defined as a piece-wise function of the measurement's time t, expressed in in decimal years since 1950-01-01:

$$TB_{corr} = TB + f(t)$$

According to the value of t, the function is defined as:

$$f(t) = \begin{cases} 0.25, & t < 19443 \\ 0.25 - \frac{0.2}{(19496 - 19443)}(t - 19443), & t \geq 19443 \; and \; t < 19496 \\ -0.05 - \frac{0.2}{(19496 - 19443)}(t - 19443), & t \geq 19496 \; and \; t < 19504 \\ -0.65 - \frac{0.4}{(20202 - 19504)}(t - 19504), & t \geq 19504 \; and \; t < 20202.583 \\ -1.05, & t \geq 20202.583 \; and \; t < 21293 \\ -1.25 - \frac{0.6}{(22500 - 21293)}(t - 21293), & t \geq 21293 \end{cases}$$

3.14.4 Outputs

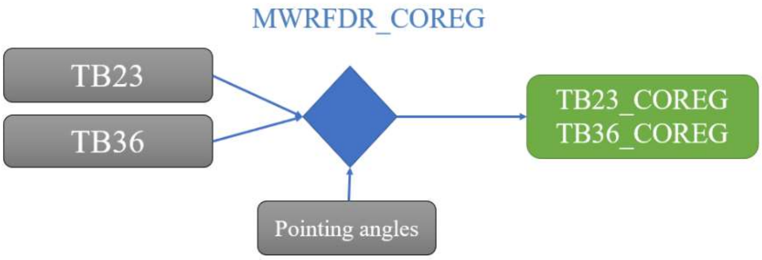
Name	unit	dimension
Corrected 36.5GHz Brightness temperature	K	1

3.15 MWRFDR_COREG: To co-registrate to nadir time

3.15.1 Inputs

Name	source	unit	dimension
MWR measurements timetag	MWRFDR_TL	s	N
Measurements of channel 23.8GHz	MWRFDR_TB	K	N
Measurements of channel 36.5GHz	MWRFDR_EN_TBCORR MWRFDR_TB	K	N
Pointing angle of the 23.8GHz channel (negative when pointing rear, positive when pointing front)	CCDB	°	1
Pointing angle of the 36.5GHz channel (negative when pointing rear, positive when pointing front)	CCDB	°	1
Satellite altitude	MWRFDR_LOC	Km	1
Earth mean radius	ADF	Km	1
Satellite velocity	ADF	Km/s	1

3.15.2 Logical flow



3.15.3 Key principles

Compute the timeshift Δt_i using pointing angle δ_i for each channel i

$$\Delta t_i = sign(\delta_i)\frac{R}{V}\sin^{-1}(H\tan\left(\frac{|\delta_i|}{R}\right))$$

Where R is the Earth mean radius, V the satellite velocity and H the satellite altitude.

Compute the subsatellite timetag (nadir) by shifting the time tag t2 of the reference channel (36.5GHz) of the corresponding timeshift Δt_2

$$t_{nadir} = t_2 + \Delta t_2$$

Shift the time tag of the remaing channel (23.8GHz)

$$t_x = t_1 + \Delta t_1$$

For each time tag t_x(k), find the index j of the nearest time in t_{nadir} array.
Reindex the measurement array m for channel to coregister

$$m_{1,coregistered}(k) = m_1(j)$$

The reference channel measurements are already coregistered:

$$m_{2,coregistered}(k) = m_2(k)$$

3.15.4 Outputs

Name	units	dimensions
Sub-satellite timetag	s	1
Measurements of channel 23.8GHz at sub-satellite timetag	K	1
Measurements of channel 36.5GHz at sub-satellite timetag	K	1

3.16MWRFDR_QUAL: to compute Brightness Temperature quality flag

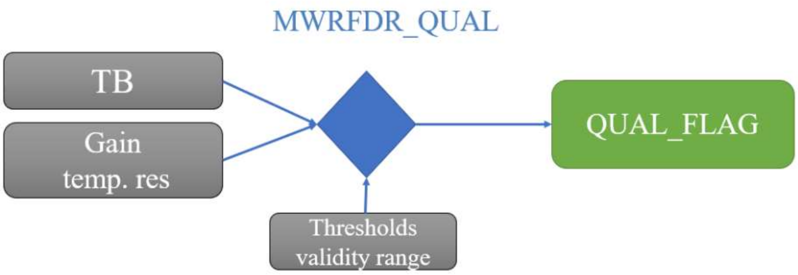
3.16.1 Inputs

Name		units	dimensions
Brightness temperature	MWRFDR_COREG	K	1
Averaged gain	MWRFDR_AVG_CAL	mV/K	1
Averaged Residual temperature	MWRFDR_AVG_CAL	K	1
Std threshold for averaged gain	parameters	K	1
Std threshold for averaged residual temperature	parameters	mV/K	1
Brightness temperature validity range [min,max]	parameters	K	2

Table 10: Std thresholds used to compute Brightness temperature quality flags

	ERS-1	ERS-2	EN
Std threshold for 23.8GHz averaged gain	0.07	before 1996-06-26T16:28: 0.07 after 1996-06-26T16:28: 0.014	0.2
Std threshold for 23.8GHz averaged residual temperature	0.8	before 1996-06-26T16:28: 1.0 after 1996-06-26T16:28: 2	3
Std threshold for 36.5GHz averaged gain	0.06	0.06	0.2
Std threshold for 36.5GHz averaged residual temperature	0.7	0.7	3
23.8GHz Brightness temperature validity range [min,max]	[120,320]	[120,320]	[120,320]
36.5GHz Brightness temperature validity range [min,max]	[120,320]	[120,320]	[120,320]

3.16.2 Logical flow



3.16.3 Key principles

For each brightness temperature of each frequency channel, a quality flag is defined.
The quality flag is set to “bad” if:

- The standard deviation of residual temperature is greater or equal to its std threshold
- The standard deviation of the gain is greater of equal to its std threshold
- The brightness temperature is outside the validity range
- The number of averaged calibrations is inferior or equal to 2

The quality flag is set to “degraded” if the orbit is coming from orbit state vector propagation instead of Precise Orbit files.
The quality flag is set to “good” in the other cases.

3.16.4 Outputs

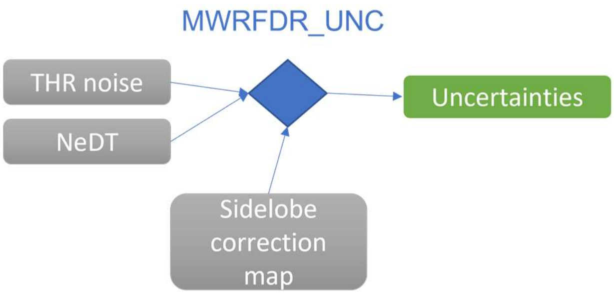
Name	unit	dimension
Brightness temperature quality flag	/	1

3.17 MWRFDR_CAL_UNC: To compute uncertainties of calibration parameters

3.17.1 Inputs

Name	source	unit	dimension
Noise for each thermistor		K	1
Noise equivalent delta temperature		K	1
Counts		mV	
Temperatures		K	
Characterisation coefficients	CCDB	Np	

3.17.2 Logical flow



3.17.3 Key principles

The uncertainty on the gain and residual temperatures are computed using the equations provided in the uncertainty definition document. For these parameters, the NeDT and the noise on the temperature sensors are required.

$$u^2(\mathrm{G}) = \left(\frac{u^2(C_\mathrm{H}) + u^2(C_\mathrm{C})}{\left(c_h.T_p^H + c_{hc}.T_p^{hc} + c_{fc}.T_p^{fc}\right)^2}\right) + G^2.\left(\frac{\left(c_h.u(T_p^H)\right)^2 + \left(c_{hc}.u(T_p^{hc})\right)^2 + \left(c_{fc}.u(T_p^{fc})\right)^2}{\left(c_h.T_p^H + c_{hc}.T_p^{hc} + c_{fc}.T_p^{fc}\right)^2}\right) \quad (3.1)$$

$$u^2(TE) = u^2(C_\mathrm{H}) + \left(\frac{CH - offset}{G}\right)^2 * \left(\frac{u(G)}{G}\right)^2 + \left(a_\mathrm{ref}.u(T_p^\mathrm{ref})\right)^2 + \left(a_\mathrm{d}.u(T_\mathrm{p}^\mathrm{d})\right)^2 + \left(a_4.(T_\mathrm{p}^\mathrm{H})\right)^2 + \left(a_3.u(T_\mathrm{p}^\mathrm{hc})\right)^2 + \left(a_2.u(T_{sh2})\right)^2 + \left(a_6.u(T_\mathrm{p}^\mathrm{cal})\right)^2 + \left(a_{50}.u(T_{a2})\right)^2 \quad (3.2)$$

The uncertainties for the averaged calibration parameters are computed.

$$u^2(G_{avg}) = \sum_{N=0}^{N_{cal}-1} \frac{u(G)^2}{N^2} \quad (3.3)$$

$$u^2(TE_{avg}) = \sum_{N=0}^{N_{cal}-1} \frac{u(TE)^2}{N^2} \quad (3.4)$$

3.17.4 Outputs

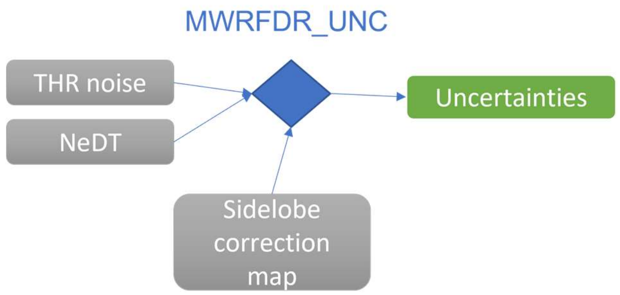
Name	unit	dimension
Gain uncertainty	mV/K	1
Residual temperature uncertainty	K	1

3.18 MWRFDR_TB_UNC: To compute uncertainties of Brightness Temperatures

3.18.1 Inputs

Name		unit	dimension
Noise for each thermistors		K	1
Noise equivalent delta temperature		K	1
On-Earth Sidelobe correction maps		K	4*Nlat*Nlon

3.18.2 Logical flow



3.18.3 Key principles

The uncertainties of the antenna temperatures are computed using the equations provided in the uncertainty definition document. The NeDT for the antenna count is computed from linear interpolation between the cold and hot calibration NeDT. The uncertainties for the averaged calibration parameters are used here.
The uncertainties of the brightness temperatures are computed by accounting for the on-earth sidelobe correction uncertainties. They are estimated by performing the difference between the antenna temperature and the on-earth sidelobe temperature.

$$u(TA)^2 = c_1{}^2 . u(A_0)^2 + c_3{}^2 . u^2(T_p^{feed}) \quad (3.5)$$

$$u^2(A_0) \quad = u(CA)^2 + \left(\frac{CA - offset}{G_{\text{avg}}}\right)^2 * \left(\frac{u(G_{\text{avg}})}{G_{\text{avg}}}\right)^2 + u^2(TE_{\text{avg}}) \quad + \left(b_1.u(T_p^{\text{ref}})\right)^2 + \left(b_2.u(T_p^d)\right)^2 + \left(c_2.u(T_p^r)\right)^2 + \left(b_3.u(T_p^{\text{cal}})\right)^2 + \left(b_4.u(T_{\text{leak}})\right)^2$$

(3.6)

$$u(Tsl_{earth}) = abs(Tsl_{earth} - TA)$$

(3.7)

$$u(TB)^2 = \left(\frac{1}{\eta_{ML}}u(TA)\right)^2 + \left(\frac{\eta_{earth}}{\eta_{ML}}u(Tsl_{earth})\right)^2$$

3.18.4 Outputs

Name	unit	dimension
Brightness temperature uncertainty	K	1

3.19 MWRFDR_BCTB: To compute Harmonized Brightness Temperatures from TB

3.19.1 Inputs

Name	source	unit	dimension
Brightness temperature	MWRFDR_EN_TB	K	1
ERA-5 profiles		various	various

3.19.2 Logical flow

Bias correction for ERS-1:

TB23_corrected = TB23_uncorrected – (14.5033 - 0.0548752 * TB23_uncorrected)

TB36_corrected = TB36_uncorrected – (17.1971 - 0.0726986 * TB36_uncorrected)

Bias correction for ERS-2:

TB23_corrected = TB23_uncorrected – (14.1783 - 0.0515457 * TB23_uncorrected)

TB36_corrected = TB36_uncorrected – (18.8452 - 0.0810627 * TB36_uncorrected)

Bias correction for ENVISAT:

TB23_corrected = TB23_uncorrected – (11.5401 - 0.0459759 * TB23_uncorrected)

TB36_corrected = TB36_uncorrected – (18.1554 - 0.0885029 * TB36_uncorrected)

3.19.3 Key principles

Harmonised brightness temperatures are obtained by correcting each MWR brightness temperature observation for the bias against a corresponding top-of-atmosphere simulation (Figure 12) based on collocated ERA-5 data.

Successful bias correction constitutes an intercalibration between the MWR observations from the ERS-1, ERS-2, and Envisat missions and is a pre-requisite for the generation of a harmonized, self-consistent, long-term time series.

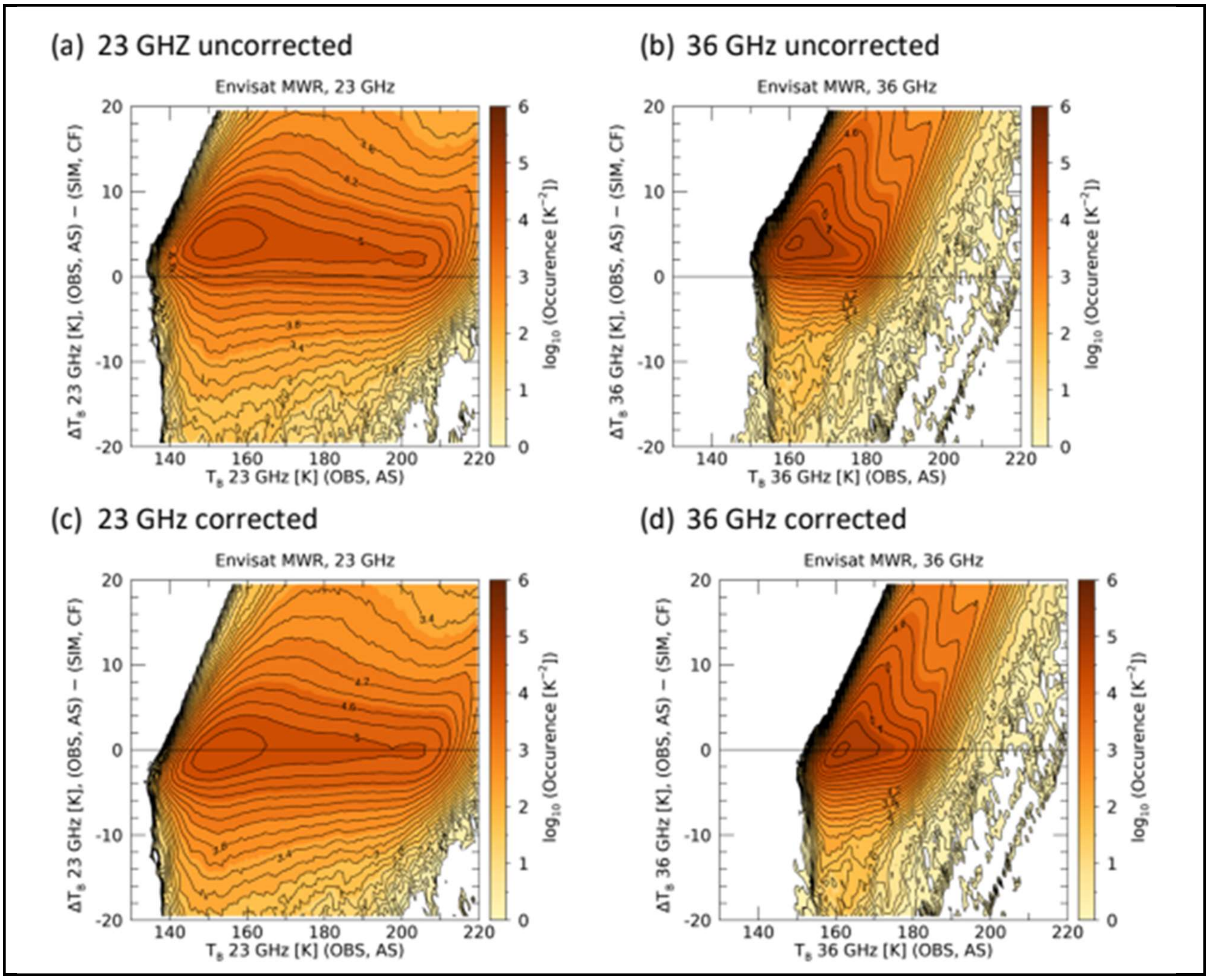


Figure 12: Data density plots of ENVISAT brightness temperature differences (observations-simulations) before and after applying the above-described bias correction.

3.19.4 Outputs

Name	unit	dimension
Harmonized Brightness temperature	K	1

3.20 Reference Documents

RD-16	REAPER Level 1B DPM **REA-DD-DPM-MWR-6001**
RD-17	MWR algorithms specifications for level 1B software prototyping **TNO/RAS/0010/ALS**
RD-18	REAPER MWR level 1B IODD **REA-DD-IODD-MWR-6002**

4 Level-2 algorithms

In the frame of the FDR4ALT, some algorithms have been applied and developed at Level-2, such as retracking algorithms. They are described in this section. Please note that all the outputs of these algorithms are **not** all available in the FDR4ALT products. Indeed, the FDR4ALT products are either FDR (Level-1) or TDP (Level-2P), meaning that the following outputs have been either used as input of the TDPs processing chains, or directly put into the TDP final variables.
In Table 11 below are described which TDPs benefited from this sections' algorithms.

Algorithm Name	Name of the TDP using algorithm outputs
L2_EN_RTK_ADAPTIVE	Ocean & Coastal Topography TDP Ocean Waves TDP
L2_EN_RTK_TFMRA	Land-Ice TDP Inland Waters TDP Sea-Ice TDP
L2_ERS_RTK_TFMRA	Land-Ice TDP Inland Waters TDP Sea-Ice TDP
L2_ERS_RANGE_SIGMA0	Ocean & Coastal Topography TDP Ocean Waves TDP Inland Waters TDP Atmosphere TDP
L2_ENVISAT_RANGE_SIGMA0	Ocean & Coastal Topography TDP Ocean Waves TDP Inland Waters TDP Atmosphere TDP
L2_EN_RELOC	Land-Ice TDP
L2_EN_RELOC	Land-Ice TDP
L2_ERS_ELEV	Land-Ice TDP
L2_ERS_ELEV	Land-Ice TDP
L2_ERS_BLURRING	Sea-Ice TDP
L2_SURFACE_MULTI_CLASSIF	Sea-Ice TDP

Table 11 : List of FDR4ALT level-2 algorithms and link to TDPs

4.1 L2_EN_RTK_ADAPTIVE: To perform the Adaptive numerical retracking

For each L1B waveform, this algorithm estimates the following (20Hz) altimetric parameters:
Epoch, Significant Wave Height, Amplitude, shape parameter

4.1.1 Inputs

Parameter	Name	Unit
Orbit altitude	Sat_Alt	m
Off-nadir angle derived from platform data	Square_Mis_Platf	degree2
Waveform		
Number of samples	Nb_Sample	-
Number of initial samples	Nb_Sample_Init	-
Abscissa of samples in the analysis window	Wf_Abs [0 :Nb_Sample-1]	-
Samples amplitude	Wf_Ampl [0 :Nb_Sample-1]	count
Waveform quality flag (“valid” or “invalid”)	Flag_Wf	-
Waveform features		
Sampling interval of the analysis window (1)	FFT_Step	s
Antenna beamwidth in along-track direction	Ant_Beam_along_track	degree
Antenna beamwidth in across-track direction	Ant_Beam_across_track	degree
Abscissa of the reference sample for tracking (1)	Abs_Ref_Track	-
Ratio PTR width /FFT Step	Ratio_PTR_FFT	-
Number of pulses composing one waveform	Nb_Imp	-
Waveform classification id (from ALTFDR_EN_CLASSIF)	Wf_class	-
Altimeter instrumental characterization data		
Number of PTR samples	Nb_PTR_Samples	-
Internal Path Delay from V3.0	Int_Path	m
Real part of the FFT of the PTR	FFT_PTR_I [0:Nb_PTR_Samples]	-
Imaginary part of the FFT of the PTR	FFT_PTR_Q [0 :Nb_PTR_Samples]	-
Total power of the PTR	PTR_Tot_Power	FFT Power Units
Correction due to the round of the internal path delay	PTR_Round_Value	s
ADAPTIVE tuning parameters		
Processing flag for the ADAPTTIVE retracking (“valid” or “invalid”)	ADAPT_Proc_Flag	-
Skewness coefficient	Skew_Coef	-
Default value of the epoch	Epoch_Def	s
Default value of SigmaS	SigmaS_Def	s
Default value of the amplitude	Ampl_Def	count
Threshold for the detection of low amplitudes	Ampl_Thresh	count
Abscissa of the first sample for noise estimation	Tn_First	-
Abscissa of the last sample for the noise estimation	Tn_Last	-

Maximum number of iterations in the estimation process	Max_Iter	-
Minimum SWH value in the estimation process	SWH_Min	m
Maximum SWH value in the estimation process	SWH_Max	m
Abscissa of the first sample for estimation	Ew_First	-
Abscissa of the last sample for estimation	Ew_Last	-
Minimum Gamma value in the estimation process	Gamma_Min	-
Maximum Gamma value in the estimation process	Gamma_Max	-
Threshold for the MQE ratio testing	Th_Ratio	-
Limit argument for the erf function (absolute value)	Erf_Limit	-
Offset to apply to waveform and model in the likelihood criterion	Offset	-
Terminating limit for variance of function values	Var_Min	-
Universal constants		
Earth radius	Earth_Rad	m
Light velocity	Light_Vel	m/s

4.1.2 Logical Flow

Here we explained through a logical flow the different steps of the Adaptive retracking algorithm.

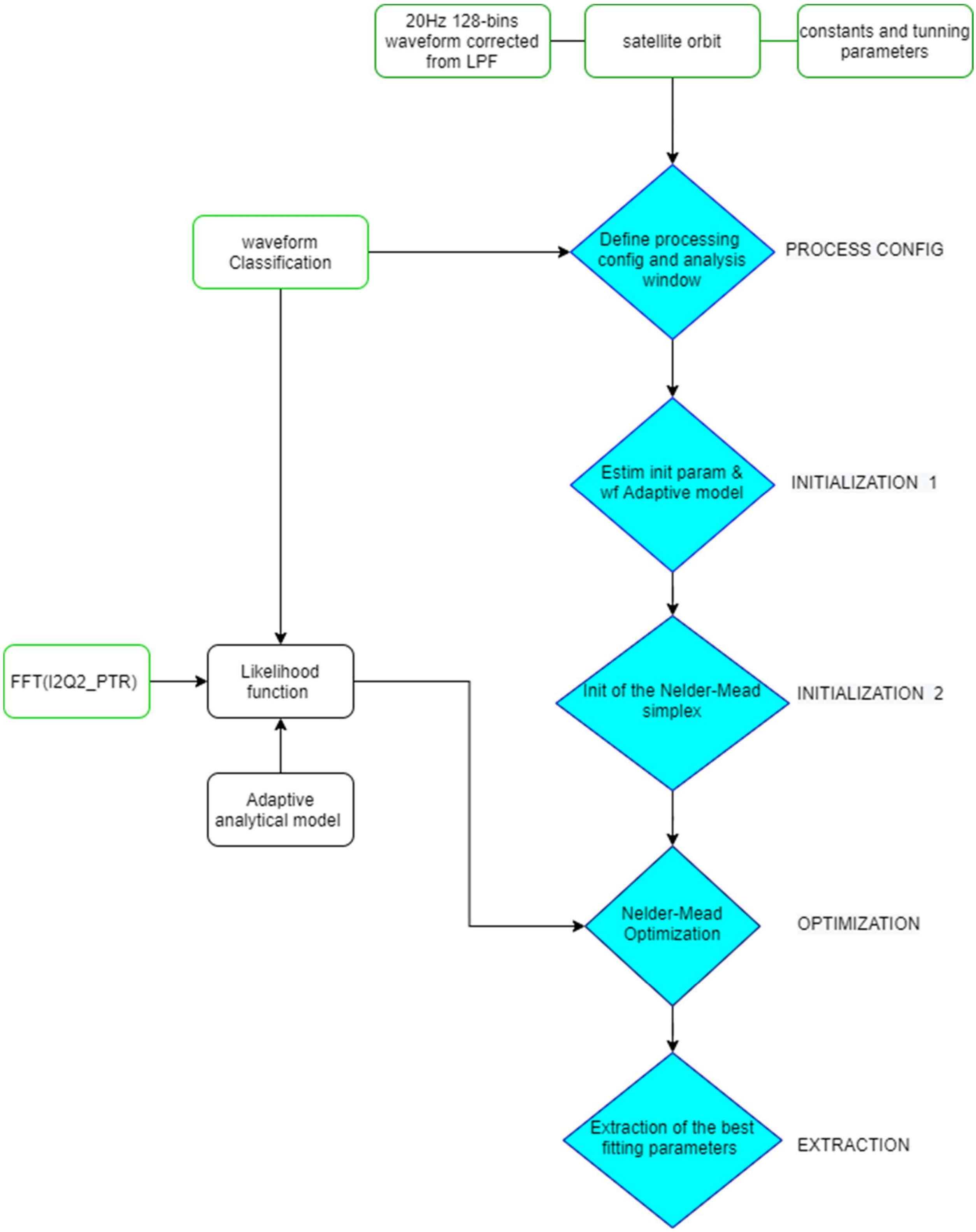


Figure 4-1 : Logical flow of the Adaptive retracker

4.1.3 Key Principles of the Algorithm

1. <u>PROCESSING CONFIGURATION</u>

This first step consists in selecting the appropriate retracking window. It depends on the waveform classification number coming from ALTFDR_EN_CLASSIF.
According to the list of classes for ENVISAT, the following configurations has been set up:

Processing options	Classes	Likelihood criterion	Analysis window
Ocean	1, 6, 10	MLE	Full waveform
Ocean-like	5, 7	MLE	Static Reduced waveform
Peaky	2 ,4	Least square	Dynamic reduced waveform
Tricky	others	Least square	case-by-case

This allows to adapt the analysis windows to each waveform and the fitting procedure focuses only on the "useful" parts of the waveform. This improves performances on non-oceanic waveforms that may be encountered over all surfaces (for instance peaky echoes on sea-ice, rivers and blooms or echoes with a disturbed trailing-edge on coastal areas).

2. <u>INITIALIZATION</u>

Before performing Nelder-Mead optimization, the second crucial step is to initialize the 4 estimates (epoch, SWH, amplitude and Gamma). The values are taken from MLE4 estimates or if not available by performing the so-called "Sea Ice" retracker (fast and empirical). This allows to initiate the Nelder-Mead simplex with these first guess by computing the Likelihood function.

The likelihood estimation procedure depends on the processing configuration:

- Function is a True MLE for *Ocean* and *Ocean-like*
- Function is a Least Square for *Peaky* and *Tricky*

The estimation is done over the Adaptive numerical model (convoluted with the PTR waveform coming from ALTFDR_EN_PTR) and performed on the corresponding window. The output is a simplex of initial vertices that enable to initialize the Nelder-Mead optimization.

3. <u>OPTIMIZATION PROCEDURE</u>

The retracking is performed according to the flowchart presented in Figure 4-2 that explains in more details the Nelder-Mead method, also known as downhill simplex method.

4. <u>EXTRACTION OF THE FINAL BEST ESTIMATES</u>

The fitting procedure stops after reaching the maximum number of iteration or the Rtol value. Then low amplitude threshold detection as well as Mean Quadratic Error computation are performed to provide the final estimates, associated with a quality flag.

The quality flag is set to "not valid" if:

- Max_Iter is reached
- Estim_Amplitude is < Ampl_Thresh,
- Estim_SigmaS or Estim_Gamma are out of limit values (see inputs)

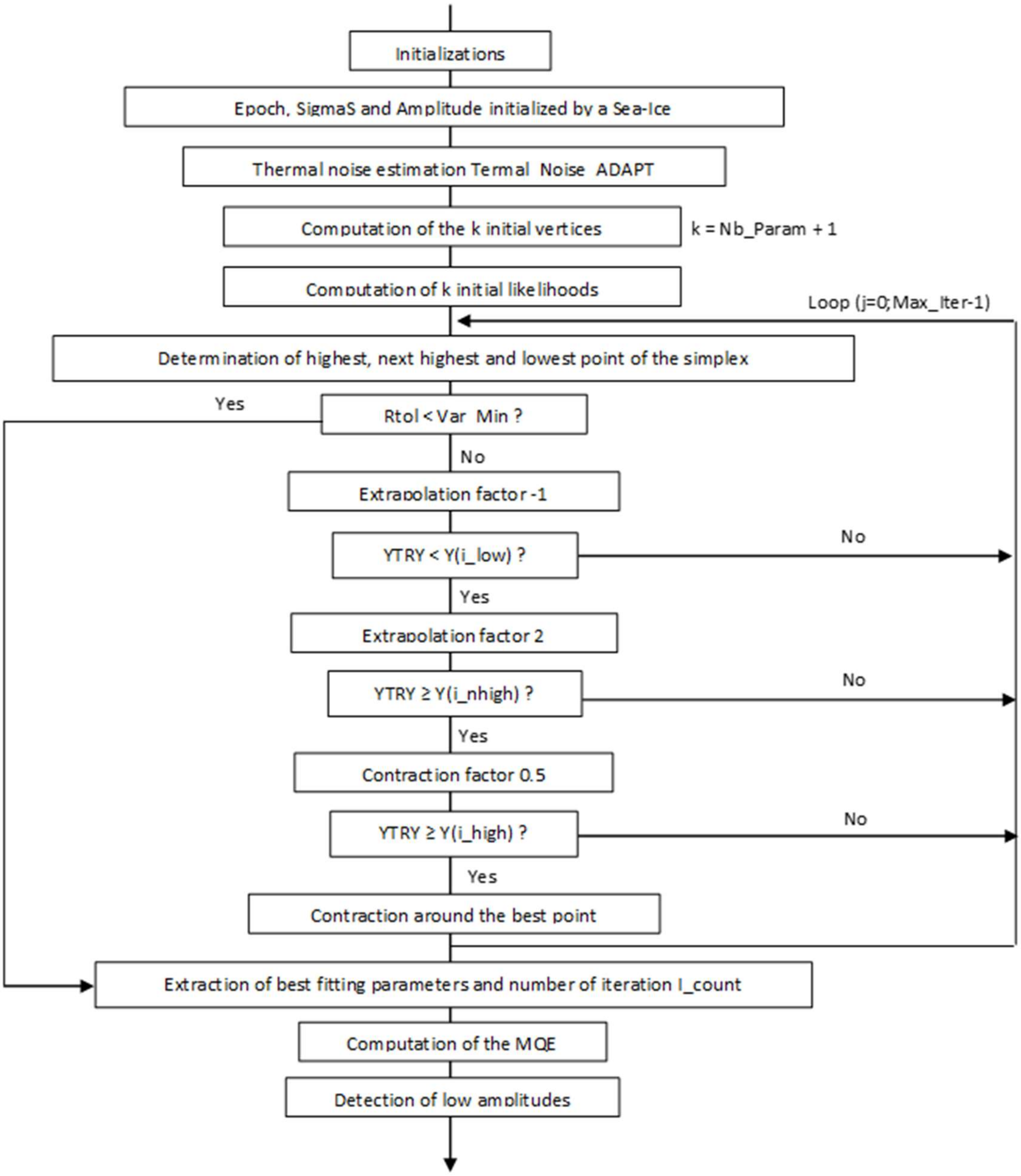


Figure 4-2 Flow chart about the Nelder-Mead minimization procedure

4.1.4 Outputs

Parameter	Name	Unit
Retracking estimates		
Epoch	*epoch_adaptive*	s
Significant Wave Height	*swh_adaptive*	m
Amplitude	*amplitude_adaptive*	count

Thermal noise level	*thermal_noise_adaptive*	count
Gamma (related to shape parameter MSS)	*gamma_adaptive*	-
Execution of the retracking algorithm (“valid” or “invalid”)	*flag_qual_adaptive*	-
Low amplitude (“valid” or “invalid”)	*flag_low_amp_adaptive*	-
Mean quadratic error in the estimation window	*mqe_adaptive*	-
Number of iterations	*nb_iter_adaptive*	-

4.1.5 Comments

The Adaptive numerical retracking algorithm is only applied on ENVISAT 20Hz 128-bins waveforms. Not applicable to ERS in the frame of this project.

4.1.6 References

For more details about the algorithm and mathematical statements, please refer to [**RD-4**].

4.2 L2_EN_RTK_TFMRA

The TFMRA algorithm has been developed by [**RD-7**] to retrack Cryosat-2 data in LRM and SAR/SARIn mode. The aim of the TFMRA retracking algorithm is to determine the tracking offset (or epoch) and the amplitude corresponding to the waveform first energy peak. The outputs of this algorithm have been used for the Round Robin Exercice for the Land-Ice TDP, the Sea-Ice TDP and the Inland Waters TDP.
It was not selected as main algorithm for the Land-Ice TDP and Inland Waters TDP but has been selected as the chosen retracker for the Sea-Ice TDP.

4.2.1 Inputs

Parameter	Variable Name
Processing flag for the TFMRA retracking	*TFMRA_Proc_Flag (“valid” or “invalid”)*
Samples amplitude	*Wf_Ampl [0 -Nb_Sample-1] (FFT power unit)*
First bin used in the retracking calculation	*First_Bin (/)*
Last bin used in the retracking calculation	*Last_Bin (/)*
First bin used in the TN calculation	*Tn_First (/)*
Last bin used in the TN calculation	*Tn_Last (/)*
Thermal noise threshold	*Tn_Thresh (FFT power unit)*
Oversampling factor	*N_Over (/)*
Boxcar averaging width	*Width_Boxcar (/)*
Linear regression LSM width	*Width_LSM (/)*
Number of consecutive decreasing samples for peak detection	*N_Dec (/)*
Thermal noise level for peak detection	*Thresh_Tn_Peak (FFT power unit)*
Power threshold	*Thresh_Power (FFT power unit)*

4.2.2 Logical Flow

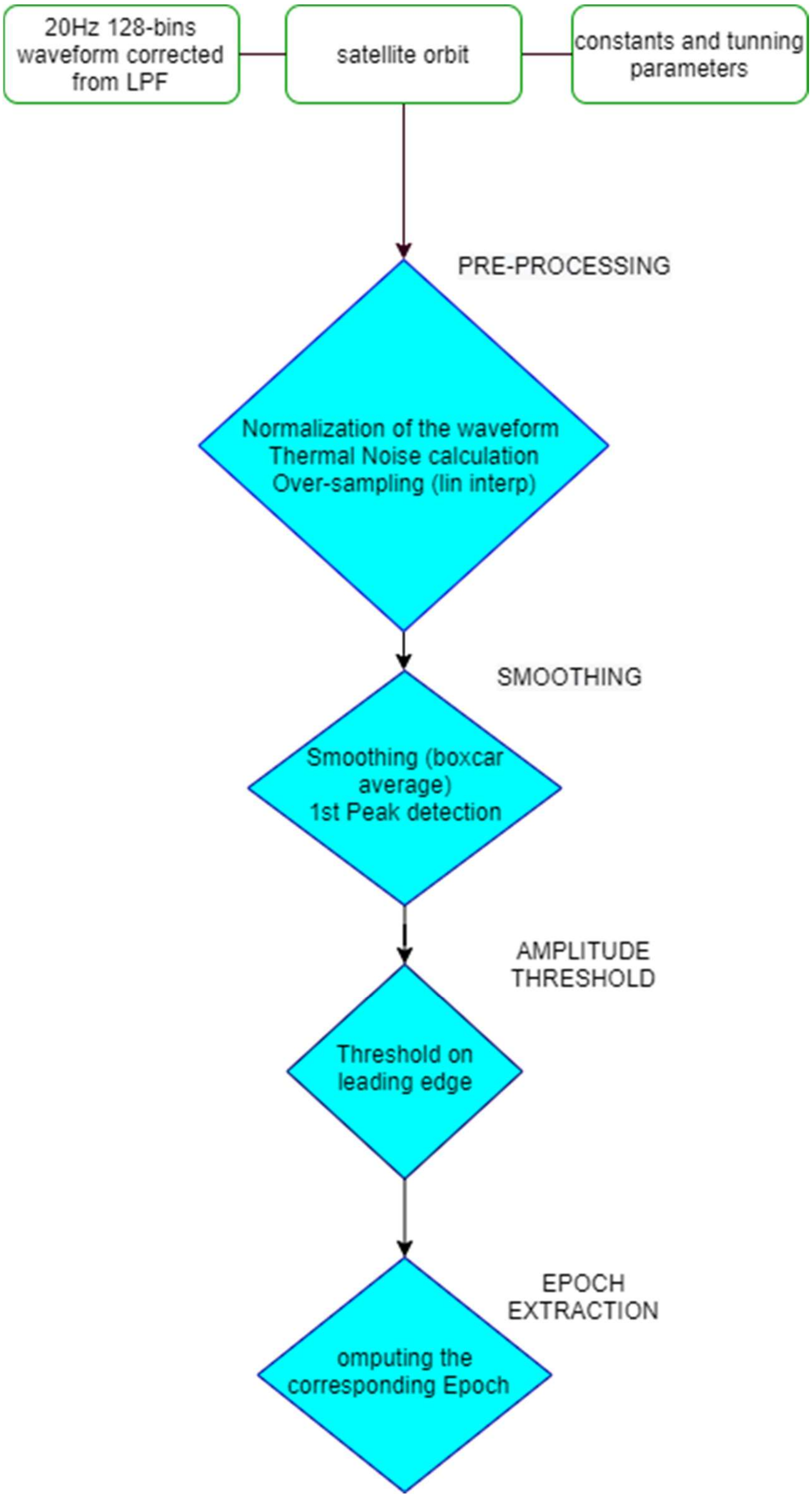


Figure 4-3 : Logical flow of the TFMRA retracker

4.2.3 Key Principles of the Algorithm

The basic principle and the main steps of the processing are defined hereafter.

- Normalization of the waveform to its maximum
- Calculation of the thermal noise using the first n range bins
- Rise quality flag for null or NaN waveform and return epoch=power=Nan.
- Over-sample waveform by a factor N_Over using linear interpolation
- Calculate the smoothed waveform (P) with a boxcar average
- Detect the first energy peak by computing polynomial fits on the oversampled waveform
- Compute the amplitude (Pmax) of the first energy peak
- Determine the location of the first gate exceeding the threshold level TL at the leading edge of the first local maxima, where P>Pmax*TL
- Determine the leading-edge position nret by interpolation between adjacent oversampled bins to the threshold crossing

4.2.4 Outputs

Parameter	Variable name	unit
Epoch	*epoch_tfmra*	m
Amplitude	*amplitude_tfmra*	FFT.pu
Quality Flag	*flag_qual_tfmra*	-

4.3 L2_ERS_RTK_TFMRA

Please refer to ALTFDR_EN_RTK_TFMRA.

4.4 L2_ERS_RANGE_SIGMA0

Note that for ERS, the selected retracker was the MLE3 from REAPER. The Atmospheric TDP needs a Sigma0 not corrected from the atmospheric attenuation. This information was not directly available in the REAPER L2 products at 20Hz, but we were able to recover it using different REAPER variables. Indeed, the only amplitude available was the ICE-1 amplitude, allowing us to use to deconstruct the Sigma0 ICE1 to recover the atmospheric attenuation.

4.4.1 Inputs

Parameter	Source	Variable name	unit
Epoch	L2_ERS_RTK_TFMRA	*epoch_tfmra*	m
Relative tracker	ALT FDR	*relative_tracker*	m
Doppler correction	ALT FDR	*range_cor_doppler*	m
Amplitude	L2_ERS_RTK_TFMRA	*amplitude_tfmra*	fft p.u
Sigma0 ICE1	REAPER L2	*Sigma0_ice1*	dB
Amplitude ICE1	REAPER L2	*amplitude_ice1*	fft p.u

Scaling factor	ALT FDR	*scaling_factor*	dB
Sigma0 bias ERS-1	*REAPER handbook*	*bias_ers1*	dB
Sigma0 bias ERS-2	*REAPER handbook*	*bias_ers2*	dB

4.4.2 Key principles of the algorithm

$$\text{range\_tfmra} = \text{epoch\_tfmra} + \text{relative\_tracker}$$

$$\text{sigma0\_tfmra} = 10 * \log_{10}(\text{amplitude\_tfmra}) + \text{scaling\_factor}$$

$$\text{atmospheric\_attenuation} = \text{sigma0 ice1} - (10 * \log_{10}(\text{amplitude}_{\text{ice1}}) + \text{scaling}_{\text{factor}} + \text{bias})$$

**where bias is either bias_ers1 or bias_ers2 depending on the mission*

$$\text{sigma0\_mle3\_nocorr} = \text{sigma0\_mle3} - \text{atmospheric\_attenutation}$$

4.4.3 Outputs

Parameter	Variable name	unit
Range TFMRA	*range_tfmra*	m
Sigma0 TFMRA	*sigma0_tfmra*	dB
Sigma0 MLE3 not corrected	*sigma0_mle3_nocorr*	dB

4.5 L2_ENVISAT_RANGE_SIGMA0

In this section are described the formulas to compute the ranges and Sigma0 from the two retrackers Adaptive and TFRMA described respectively in 4.1 and 4.2. Please note that the SWH is a direct output of the Adaptive retracker.

4.5.1 Inputs

Parameter	Source	Variable name	unit
Epoch Adaptive	L2_EN_RTK_ADAPTIVE	*epoch_adaptive*	m
Epoch TFMRA	L2_EN_RTK_TFMRA	*epoch_tfmra*	m
Relative tracker	ALT FDR	*relative_tracker*	m
Doppler correction	ALT FDR	*range_cor_doppler*	m
Amplitude Adaptive	L2_EN_RTK_ADAPTIVE	*amplitude_adaptive*	fft p.u
Amplitude TFMRA	L2_EN_RTK_TFMRA	*amplitude_tfmra*	fft p.u
Scaling factor	ALT FDR	*scaling_factor*	dB

4.5.2 Key principles of the algorithm

$$\text{range\_tfmra} = \text{epoch\_tfmra} + \text{relative\_tracker} + \text{range\_cor\_doppler}$$

$$\text{range\_adaptive} = \text{epoch\_adaptive} + \text{relative\_tracker} + \text{range\_cor\_doppler}$$

$$\text{sigma0\_adaptive} = 10 * \log_{10}(\text{amplitude\_adaptive}) + \text{scaling\_factor}$$

$$\text{sigma0\_tfmra} = 10 * \log_{10}(\text{amplitude\_tfmra}) + \text{scaling\_factor}$$

4.5.3 Outputs

Parameter	Variable name	unit
Range Adaptive	*range_adaptive*	m
Range TFMRA	*range_tfmra*	m
Sigma0 Adaptive	*sigma0_adaptive*	dB
Sigma0 TFMRA	*sigma0_tfmra*	dB

4.6 L2_EN_RELOC

4.6.1 Inputs

Parameter	Source	Variable name	unit
Latitude	ALTFDR_EN_ORBIT	*latitude*	degrees
Longitude	ALTFDR_EN_ORBIT	*longitude*	degrees
Altitude	ALTFDR_EN_ORBIT	*altitude*	meters

4.6.2 Logical Flow

This algorithm follow the Roemer location described in [**RD-13**]

4.6.3 Key principles of the Algorithm

This algorithm follow the Roemer location described in [**RD-13**]

4.6.4 Outputs

Parameter	Variable name	unit
POCA latitude	*ice_sheet_lon_poca*	degrees
POCA longitude	*ice_sheet_lat_poca*	degrees
Relocation processing flag	*Ice_sheet_qual_relocation*	/
Surface type flag	*Ice_sheet_surface_flag*	/
Ice sheet range correction	*Ice_sheet_range_correction*	meters

4.7 L2_ERS_RELOC

Please refer to ALTFDR_EN_RELOC

4.8 L2_EN_ELEV

4.8.1 Inputs

Parameters	Source	Variable name	unit
Latitude	ALTFDR_EN_ORBIT	*latitude*	degrees
Longitude	ALTFDR_EN_ORBIT	*longitude*	degrees
Altitude	ALTFDR_EN_ORBIT	*altitude*	meters
Surface type flag	ALTFDR_EN_RELOC	*Ice_sheet_surface_flag*	/
Relocation processing flag	L2_EN_RELOC	*Ice_sheet_qual_relocation*	/

Ice sheet range correction	ALTFDR_EN_RELOC	*Ice_sheet_range_correction*	meters
Range Ice-1	ENVISAT V3.0	*range*	meters
Dry tropospheric correction	ECMWF	*mod_dry_tropo_cor*	meters
Wet tropospheric correction	ECMWF	*mod_wet_tropo_cor*	meters
Pole Tide correction	Wahr 85	*pole_tide*	meters
Ocean tide correction	Got 4V10	*ocean_tide*	meters
Load Tide correction	GOT4V10	*load_tide*	meters
Ionospheric correction	GIM	*iono_cor_gim*	meters
Inverted barometer height correction	ECMWF	*Inv_bar_cor*	meters
Solid Earth tide correction	Cartwright	*solid_earth_tide*	meters
Doppler Correction	ENVISAT V3.0 / REAPER	*doppler_cor*	meters
Doppler Correction with slope correction	ENVISAT V3.0 / REAPER	*doppler_slope_corr*	meters

4.8.2 Key principles of the Algorithm

First are computed the geophysical corrections on ice sheet and ice shelves :

$$\text{corr\_geophy\_ice\_sheet} = \text{mod\_dry\_tropo\_cor} + \text{mod\_wet\_tropo\_cor} + \text{pole\_tide} + \text{solid\_earth\_tide} + \text{iono\_cor} + \text{load\_tide}$$

$$\text{corr\_geophy\_ice\_shelves} = \text{mod\_dry\_tropo\_cor} + \text{mod\_wet\_tropo\_cor} + \text{pole\_tide} + \text{solid\_earth\_tide} + \text{iono\_cor} + \text{ocean\_tide} + \text{inv\_bar\_cor}$$

Then, the following is applied only if the latitude is higher than 58° or lower than -58°:

if (*Ice_sheet_surface_flag* =2 or *Ice_sheet_surface_flag* =4) and (*Ice_sheet_qual_relocation* =0 or *Ice_sheet_qual_relocation* =2) :

ice_sheet_elevation_ice1_roemer

=

altitude – range – corr_geophy_ice_sheet + Ice_sheet_range_correction

Else if (ice_sheet_surface_flag=3 or) and (*Ice_sheet_qual_relocation* =0 or *Ice_sheet_qual_relocation* =2)

ice_sheet_elevation_ice1_roemer

=

altitude – range – corr_geophy_ice_shelves + Ice_sheet_range_correction

Finally, the following formula is applied to take into account the proper Doppler correction (that includes the slope correction):

ice_sheet_elevation_ice1_roemer_corrected

=

ice_sheet_elevation_ice1_roemer - doppler_slope_cor + doppler_cor

4.8.3 Outputs

Parameter	Variable name	unit
Ice sheet elevation at POCA	*Ice_sheet_elevation_ice1_roemer_corrected*	meters

4.9 L2_ERS_ELEV

4.9.1 Inputs

Parameters	Source	Variable name	unit
Latitude	ALTFDR_ERS_ORBIT	*latitude*	degrees
Longitude	ALTFDR_ERS_ORBIT	*longitude*	degrees
Altitude	ALTFDR_ERS_ORBIT	*altitude*	meters
Surface type flag	ALTFDR_ERS_RELOC	*Ice_sheet_surface_flag*	/
Ice sheet range correction	ALTFDR_ERS_RELOC	*Ice_sheet_range_correction*	meters
Range Ice-1	REAPER	*range_ice1_20_ku*	meters
Dry tropospheric correction	ECMWF	*mod_dry_tropo_cor*	meters
Wet tropospheric correction	ECMWF	*mod_wet_tropo_cor*	meters
Pole Tide correction (	Wahr 85	*pole_tide_01*	meters
Load Tide correction	GOT4V10	*load_tide_got4v10*	meters
Ionospheric correction	GIM	*iono_cor_gim*	meters
Inverted barometer height correction	ECMWF	*Inv_bar_cor*	meters
Solid Earth tide correction	Cartwright	*solid_earth_tide*	meters

4.9.2 Logical Flow

Please refer to ALTFDR_EN_ELEV

4.9.3 Outputs

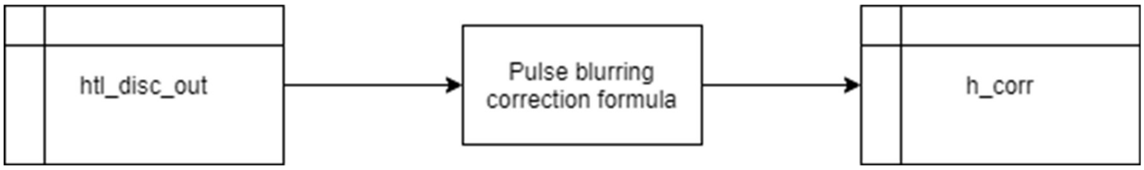
Please refer to ALTFDR_EN_ELEV

4.10 L2_ERS_BLURRING

4.10.1 Inputs

Parameter	Variable name	Source	dim	unit
Height Tracking loop command	*htl_disc_out*	REAPER	1	m

4.10.2 Logical Flow



4.10.3 Key Principles of the Algorithm

According to [**RD-8**] a corrected height h_{corr} can be calculated from the retracked height h_{rtk} as follows:

$$h_{corr} = h_{rtk} - \frac{\epsilon}{m} \quad (\epsilon > 0)$$

Where m is taken to be -3.5 for ERS-1 and -5.0 for ERS-2, ∈ refers to *htl_disc_out* variable in the product in meter. h_{corr} was used to the computed a corrected SLA in the Sea-Ice TDP (see 6). This corrected range is not provided in the ALT FDR product since user can easily apply it according to the above formula.

4.10.4 Outputs

Parameter	Variable name	dim	unit
Pulse blurring correction on range	*range_cor_blurring*	1	m

4.10.5 Comments

This range correction has been used in Sea Ice TDP's processing only.

4.10.6 References

For more details about the improvements brought by the FDR4ALT project, see [D-1-02].

L2_SURFACE_MULTI_CLASSIF

4.10.7 Inputs

Parameter	Variable name	Source	unit
Altimeter time-tag (1 Hz)	*time*	ALT FDR	s
Latitude of the altimeter measurement (1 Hz)	*latitude*	ALTFDR_ERS_ORBIT	degrees
Longitude of the altimeter measurement (1 Hz)	*longitude*	ALTFDR_ERS_ORBIT	degrees
Surface type classification (1-Hz)	*surface_type_globcover*	GlobCover[1]	-
Ku-band sigma0 corrected for atmospheric attenuation (1 Hz)	*sigma0*	Atmosphere TDP	dB
23.8 GHz brightness temperature (1 Hz)	*tb_238*	MWRFDR_TB	K
36.5 GHz brightness temperature (1 Hz)	*tb_365*	MWRFDR_TB	K

[1] 7-state surface flag ("open_ocean", "land", "continental_water", "aquatic_vegetation", "continental_ice_snow", "floating_ice", "salted_basin") computed by combining data from different sources: the GMT mask of surface (30x30 arc sec) used for the generation of the Jason-2 MNT + Globcover land cover v2.0 data (10x10 arc sec) from Medias France + Modis Mosaic of Antarctica (30x30 arc sec) from NSIDC + Water body outlines from LEGOS (providing historic river/lakes outlines for undried bodies) and used for ENVISAT, Sentinel-3 and Sentinel-6 missions.

4.10.8 Key principles of the Algorithm

The basic principle and the main steps of the processing are defined hereafter:

- Initialization of the outputs and testing of the input data: computation performed only if Ku-band sigma0 and brightness temperatures are available with valid values; otherwise, the ocean/sea-ice flag is set to "not evaluated"
- Determination of the rough situation of the data point (geographical: north or south hemisphere and temporal: day in year) to select the appropriate geographical mask to apply.
- Application of the specific mask to determine if the classification algorithm will be used or not (i.e., data inside or outside the area delimited by the selected mask)
- If the data are inside the area:
  - computation of the classes' memberships.
  - then determination of the ocean/sea ice flag state based on the memberships values.
  - followed by the application of a few post-classification correction for some known cases of bad classification by the algorithm.
- Otherwise, the ocean/sea-ice flag is set to "ocean".

4.10.9 Outputs

The flag is based and computed from 1-Hz data. In the FDR4ALT products, it is distributed at 20-Hz by duplicating the 1-Hz value.

Parameter	Variable name	unit
Ocean/Sea-ice flag[1]	*flag_ice.multi*	-
Membership value associated to the open water[2]	*open_water_fraction.multi*	1
Membership value associated to the first-year ice[2]	*first_year_ice_fraction.multi*	1
Membership value associated to the multi-year ice[2]	*multi_year_ice_fraction.multi*	1
Membership value associated to the wet ice[2]	*wet_ice_fraction.multi*	1

[1] 6-state flag : “0: ocean”, “1: first-year sea-ice”, “2: wet sea-ice”, “3: multi-year sea-ice”, “4: ambiguous / mixture of type” or “5: not evaluated”

[2] Values between 0 and 1

4.11 L2_MWR_INTERP_TO_ALT

4.11.1 Inputs

Name	source	unit	dimension
ENVISAT Brightness temperatures 23.8GHz 7Hz	MWRFDR_EN_TBCORR	K	N_Rad
ENVISAT Brightness temperatures 36.5GHz 7Hz	MWRFDR_EN_TBCORR	K	N_Rad
ERS Brightness temperatures 23.8GHz 7Hz	MWRFDR_TB	K	N_Rad
ERS Brightness temperatures 36.5GHz 7Hz	MWRFDR_TB	K	N_Rad
Validity flag	MWRFDR_QUAL	/	N_Rad
Altimeter Surface type			N_Alt
MWR time tag	MWRFDR_EN_TIME MWRFDR_ERS_TIME	UTC	N_Rad
ALT time tag		UTC	N_Alt
Land/Sea mask	ADF		
Half_Width_Av	parameter	s	1
	parameter	s	1

4.11.2 Logical flow

4.11.3 Key principles

The algorithm used for FDR4ALT reprocessing is the algorithm used for Sentinel-3 operational processing.

<u>**First the MWR surface type is computed for each measurement, :**</u>
For each point imwr of MWR timeseries,

- Found All points of the Land Sea Mask within a radius of 25km.
- Count the number of points with a LSM set to “ocean.”
- The land fraction is computed with the ratio: LF=100*Nb_Pts_Grid_Land/Nb_Pts_Grid
- Set the MWR Surface Type flag:

- If LF >0, then MWR_Surface_Type[imwr]=0 (ocean);
- else MWR_Surface_Type[imwr]=1 (land)

- Find the M radiometer antenna measurements (m index) such as:

  Time_Alt- Half_Width_Av £ Time_Rad(m) £ Time_Alt+ Half_Width_Av

  And MWR_Flag_Valid = VALID

  And MWR_Flag_Valid = VALIDIf M = 0 (no radiometer antenna measurement is found), then:

– Interpolation quality flag is set to 3 ("Failed")

– The processing is stopped.

– Default values are provided in output.

- Else:

–

– If the altimeter surface type is set to "open ocean or semi-enclosed seas", or "enclosed seas or lakes":

  – **Within the interpolation window,**

    - found the radiometer measurement with a land fraction <= 0 and **a validity flag set to Valid**:
    - average the selected measurement TB_int[j] = sum(TB[IndSel[0:M-1]] [j])/M
    - Interpolation quality flag is set to 0 (good)

  – **else** if No such measurement are found within the interpolation window look inside the extrapolation window for radiometer measurement with a land fraction <= 0 and the same surface type as the altimeter **then**:.

    Select the closest radiometer measurement : TB_surf[ichan] = TB[Ind_Sel_N[i0]]

    Interpolation quality flag is set to 1 (extrapolated)

  – **else** perform a classical interpolation with no consideration of the surface type :

    TB_surf[0:M-1][ichan] = TB[Ind_Sel[0:M-1]][ichan]

    Interpolation quality flag is set to 2 (degraded)

4.11.4 Outputs

Name	unit	dimension
Averaged brightness temperatures 23.8GHz	K	1
Averaged brightness temperatures 36.5GHz	K	1

5 Land-Ice Thematic Data Products

5.1 Overview

The Land Ice TDP processing chain takes ERS-1, ERS-2 and ENVISAT Level-2 parameters as input, and generates consistent, geolocated elevation measurements at fixed nodes along the reference ground track, together with associated uncertainty, plus several auxiliary fields related to waveform characteristics and surface classification. The core methodology and workflow of the TDP has an established basis in the literature (e.g.,[**RD-24**],[**RD-25**],[**RD-22**],[**RD-23**],[**RD-26**]), which we have built upon to meet the objectives of the FDR4ALT Land Ice TDP. In essence, the approach splits the data into small along-track segments and associates each segment with a node on a reference ground track. It then migrates data from all cycles within each segment onto a common node of the reference ground track, thereby mitigating the impact that orbit drift has on the variance of elevation measurements at any given location and making it easier for the user to isolate temporal changes in ice sheet elevation. As such, the processing chain delivers a more consistent along-track dataset that maintains the native 20 Hz sampling of a Level-2 product but improves its ease-of-use for the end user. It should be noted that no correction is applied to account for any biases in elevation between missions, because any bias will be spatially variable, and the origin of the signal remains unknown. Hence the applicability and form of any inter-mission bias correction should be decided by the end user, depending upon the specific needs of their application.

5.2 Inputs

The Land Ice Thematic Data Product processor ingests the following Level-2 input parameters:

Input variable	Variable name	Source	Unit
Time	"*time*" from	FDR ALT	days
Nadir Latitude	"*latitude*" from	ALTFDR_EN_ORBIT	deg
Nadir Longitude	"*longitude*"	ALTFDR_EN_ORBIT	deg
POCA Latitude	"*ice_sheet_lat_poca*"	L2_EN_RELOC; L2_ERS_RELOC	deg
POCA Longitude	"*ice_sheet_lon_poca*"	L2_EN_RELOC; L2_ERS_RELOC	deg
POCA Elevation	"*ice_sheet_elevation_ice1_roemer*"	L2_EN_ELEV ; L2_ERS_ELEV	meters
Surface Type Flag	"*ice_sheet_surface_type*"	L2_EN_RELOC; L2_ERS_RELOC	/
Waveform Classification	"waveform_main_class"	ALTFDR_EN_CLASSIF; ALTFDR_ERS_CLASSIF	/
Retracking Quality Flag	*"Retracking_ice1_qual_20_ku"*	*V3.0 reprocessing ; REAPER*	/
Relocation Distance Flag	"*ice_sheet_qual_relocation*"	L2_EN_RELOC; L2_ERS_RELOC	/
Sigma-0	*"sig0_ice1_20_ku"*	*V3.0 reprocessing ; REAPER*	*dB*
Ice sheet waveform quality flag	"*ice_sheet_waveform_qual*"	*V3.0 reprocessing ; REAPER*	/
Ice sheet echo relocation flag	"*ice_sheet_qual_relocation*"	ALTFDR_EN_RELOC; ALTFDR_ERS_RELOC	/
Doppler Corrections	"*dop_cor_20_ku*": ENVISAT "*dop_slope_cor_20_ku*": ENVISAT *"delta_doppler_corr_20h"*: ERS-1/2	*V3.0 reprocessing ; REAPER*	meters

Multiple additional parameters are also ingested from the Level-2 product and passed through to the 'expert' group within the TDP. These parameters do not undergo any additional processing within the Land Ice Thematic Data Product processor before they are outputted Land Ice TDP product (see full list and description in the corresponding Products Requirements & Format Specifications Document).

5.3 Logical Flow

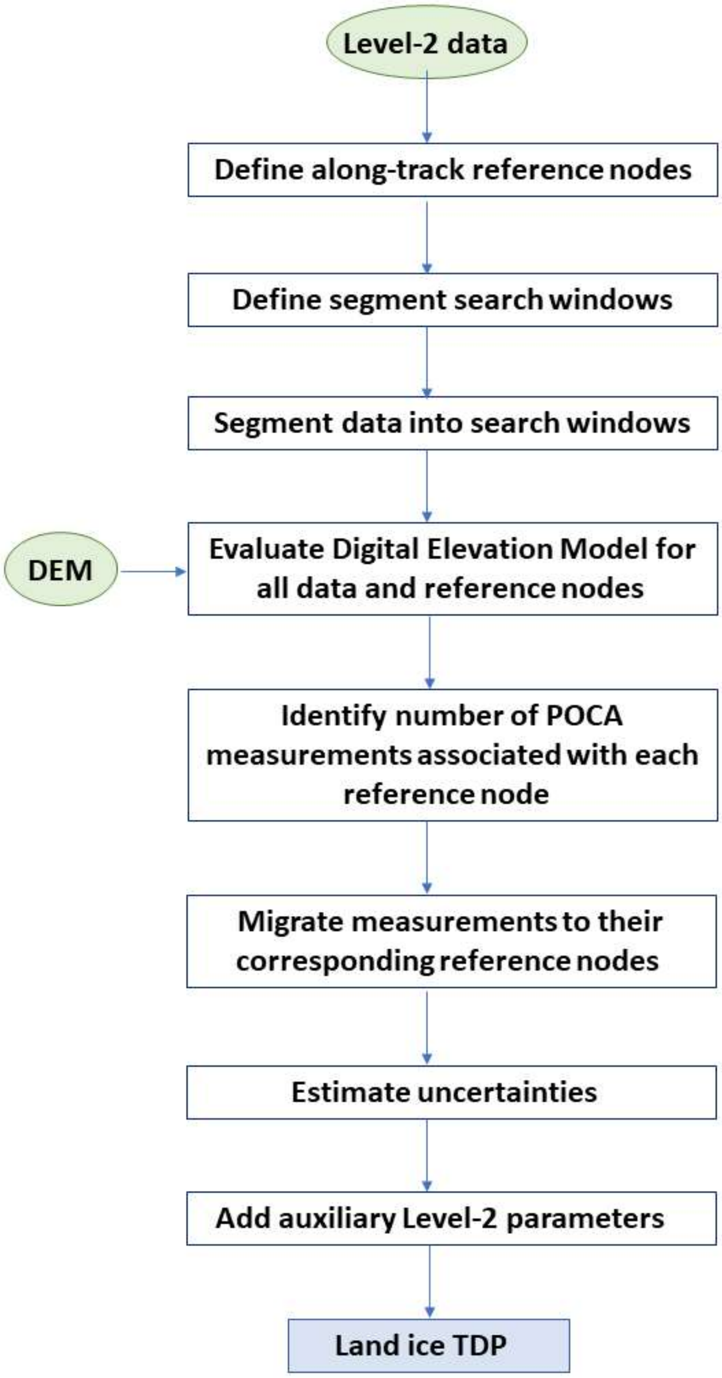


Figure 5-1 : Land Ice TDP Processing Workflow

5.4 Description of Processing Steps

Outlined below are the principal processing steps that are depicted in Figure 5-1 for the Land Ice Thematic Processor. The steps describe the process for an individual satellite pass. Greenland and Antarctic ice sheets are processed separately and result in ice sheet specific products.

Read Level 2 input parameters.
For each cycle, all relevant Level 2 input parameters are read. The data are then masked to the ice sheet domain, and waveform quality flags and echo relocation flags are applied to remove poor quality records. An additional filter is applied to the Level-2 ice sheet elevation parameter to remove elevations that differ by more than 100 m from a reference DEM (ArcticDEM for Greenland; REMA for Antarctica). Typically, this filter removes <2 % of the data.

Define along-track reference nodes.
For each pass, the latitude and longitude vectors for the nadir ground track are converted into polar-stereographic coordinates. For each pass, a reference track (for all cycles) is then defined based upon the cycle which has a start point that is closest to the median of all start points of that pass. This reference track is then sampled at ~ 380 m intervals to create the reference nodes that will form the common basis of the TDP product.

Define segment search windows.
For each reference track, a rectangular search window around each node is calculated, which has an along-track dimension equivalent to the reference node spacing (~380 m) and an across-track dimension chosen to cover the maximum Level 2 relocation distance (20 km) plus a buffer to account for the across-track orbit drift. This ensures that the search window will cover all Point Of Closest Approach (POCA) measurements, irrespective of how far they have been migrated in the Level-2 echo relocation step.

Segment data in to search windows.
For each rectangular search window along the satellite track, data from all cycles that fall within that search window are identified and associated with the respective reference node corresponding to that search window.

Evaluate Digital Elevation Model for all data and reference nodes.
For each rectangular search window along the satellite track, an auxiliary Digital Elevation Model (DEM) is used to compute the surface elevation at the locations of all the POCA data identified within the previous step. For Greenland, ArcticDEM is used (https://www.pgc.umn.edu/data/arcticdem/). For Antarctica, the Reference Elevation Model of Antarctica (REMA; https://www.pgc.umn.edu/data/rema/) is used. In each case, we use a relatively coarse resolution version of the DEM product (200 m – 500 m), to ensure consistency with the size of the pulse limited footprint. Elevations are given as heights above the WGS84 ellipsoid. The same Digital Elevation Model is also used to evaluate the surface elevation at the associated reference node.

Identify number of POCA measurements associated with each reference node.
In areas of high topographic relief, more than one POCA measurement per cycle can be segmented in a single search window. In this instance, the POCA measurement with the smallest topographical correction (difference between DEM elevation at POCA location and DEM elevation at reference node) is chosen to be migrated onto the reference node (next processing step). In these high relief areas, it is also sometimes the case that more than one nadir measurement has been migrated to the same POCA location during echo

relocation in the Level-2 product. Thus, when this occurs, for a single POCA location, Level-2 parameters are averaged as follows:

- Median elevation determined.
- Median backscattered power determined.
- Mode of surface type determined.
- Mode of waveform class determined.
- Median time determined.

As a results of this processing step, each TDP reference node has a single data point associated with it per cycle.

Migrate measurements to their corresponding reference nodes.

POCA points for all cycles within the current search window are then migrated onto the associated reference node. In essence, this step corrects for the topographic difference in elevation between each POCA measurement location and the reference node location. The topographic difference in elevation is computed based upon the Digital Elevation Model information extracted in the previous step.

More specifically, let *z(i,j)* be the altimeter elevation at POCA location *i,j*. For each POCA measurement, *z(i,j)*, within the segment, then the migrated elevation *z(i',j')* at the associated reference node *i',j'* is given by:

$$z(i',j') = z(i,j) + \Delta z_{topo}(i,j)$$

where

$$\Delta z_{topo}(i,j) = z_{DEM}(i',j') - z_{DEM}(i,j)$$

and $z_{DEM}(i,j)$ and $z_{DEM}(i',j')$ are the DEM elevations at the POCA location and the reference node, respectively.

Around the very margin of the ice sheet, occasionally this topographic correction becomes unreliable (for example, if the POCA is located on a mountain ridge rather than on ice). Therefore, if the magnitude of the topographic correction exceeds 200 meters, then the correction is deemed unreliable and the corresponding elevation at the reference node is set to the fill value. Less than 1 % of the topographic corrections exceed 200m ice sheet wide, for both ice sheets, and for all cycles. Once all cycles have been migrated onto their respective reference nodes, a final quality control step is applied to the TDP elevations to remove occasional tracks that exhibit a residual systematic elevation bias. This step is required to remove data where there is a systematic error in the L2 range measurement that has not been captured by previous filtering steps. Specifically, an elevation difference is calculated between the new, topographically corrected, elevation measurement and the reference DEM at each node. For any given cycle and track, if more than half of the reference nodes along the track have a DEM difference of more than 5 m, all the data within that cycle is removed. Ice sheet wide, this filtering step typically affects 1 cycle per mission, for approximately 10% of the reference tracks over Greenland and Antarctica.

Estimate uncertainties.

Uncertainties on the elevation measurements are estimated using an empirical parameterisation, based upon the per-mission differences between co-located (within 500 meters), coincident (within 30 days) satellite and airborne measurements. Full details of the methodology and implementation of this approach are provided within the Land Ice section of the Uncertainty Characterisation Report.

Add auxiliary Level-2 parameters.

Prior to writing the TDP output files, several auxiliary parameters from the FDR4ALT Level-2 product are added to the 'main' TDP group, namely the waveform classification, the surface type, and the sigma-0 backscatter coefficient. The 'expert' user parameters that have been ingested directly from the Level-2 data are also outputted into the TDP product 'expert' group, without applying additional processing steps other than formatting changes required to conform with the TDP product specification requirements.

5.5 Outputs

The Land Ice Thematic Data Product consists of the following parameters in the 'main' user group:

Time
Latitude
Longitude
Elevation
Elevation Uncertainty
Reference Node Elevation
Surface Type
Waveform Classification
Sigma-0

41 additional parameters are written to the 'expert' user group. Further details of all parameters are provided in the Product Requirements and Format Specification document [D-2-02].

5.6 Reference Documents

RD-19	Blankenship, D. D., Kempf, S. D., Young, D. A., Roberts, J. L., Ommen, T. van, Forsberg, R., et al.: IceBridge Riegl Laser Altimeter L2 Geolocated Surface Elevation Triplets, Version 1. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/https://doi.org/10.5067/JV9DENETK13E, 2013.
RD-20	Krabill, W. & Thomas, R. & Martin, C. & Swift, R. & Frederick, E. (1995). Accuracy of Airborne Laser Altimetry Over the Greenland Ice Sheet. International Journal of Remote Sensing - INT J REMOTE SENS. 16. 1211-1222. 10.1080/01431169508954472.
RD-21	Martin, C. F., Krabill, W. B., Manizade, S. S., Russell, R. L., Sonntag, J. G., Swift, R. N., & Yungel, J. K.: Airborne Topographic Mapper Calibration Procedures and Accuracy Assessment. NASA Technical Report NASA/TM\u20132012-215891, Goddard Space Flight Center, Greenbelt, Maryland 20771. Available Online at: Http://Ntrs.Nasa.Gov/Archive/Nasa/Casi.Ntrs.Nasa.Gov/20120008479.Pdf, 2012.
RD-22	McMillan, M., Muir, A., Shepherd, A., Escolà, R., Roca, M., Aublanc, J., Thibaut, P., Restano, M., Ambrozio, A. and Benveniste, J.: Sentinel-3 Delay-Doppler altimetry over Antarctica, Cryosphere, 13(2), 709–722, doi:10.5194/tc-13-709-2019, 2019.
RD-23	L. S. Sørensen, S. B. Simonsen et al, Mass balance of the Greenland ice sheet (2003–2008) from ICESat data – the impact of interpolation, sampling and firn density, The Cryosphere, 5, 173–186, 2011 www.the-cryosphere.net/5/173/2011/ doi:10.5194/tc-5-173-2011
RD-24	Malcolm McMillan, Andrew Shepherd, Aud Sundal, Kate Briggs, Alan Muir, Andrew Ridout, Anna Hogg, Duncan Wingham, Increased ice losses from Antarctica detected by CryoSat-2. (2014) **https://doi.org/10.1002/2014GL060111**

RD-25	Malcolm McMillan et al., A high-resolution record of Greenland mass balance, Geophysical Research Letters Volume 43, Issue 13. **https://doi.org/10.1002/2016GL069666**
RD-26	Flament, T., & Rémy, F. (2012). Dynamic thinning of Antarctic glaciers from along-track repeat radar altimetry. *Journal of Glaciology, 58*(211), 830-840. doi:10.3189/2012JoG11J118

6 Sea-Ice Thematic Data Products

6.1 Input data and corrections

Please note that the Sea-Ice TDP **does not** uses as input the ALT FDR but directly the ENVISAT V3.0 reprocessing and the ERS Level-2 Reaper products.

Input variable	Source	Unit
Altimetry data		
Time	ENVISAT V3.0 and ERS REAPER	days
Orbit	ENVISAT V3.0 and ERS REAPER	m
Range	Range from TFMRA	m
Waveform	ENVISAT V3.0 and ERS REAPER	p.u
Geophysical corrections		
DTC (Dry Tropospheric Correction)	ECMWF	m
WTC (Wet Tropospheric Correction)	ECMWF	m
IB: Inverse Barometric Correction	LEGOS/CNES/CLS MOG2D 2.1.0 model	m
IC: Ionospheric Correction	GIM	m
Tides	Ocean tide FES2014 from LEGOS, long period ocean tide, ocean loading tide, solid Earth tide from Cartwright and Edden [1973], pole tide from Wahr [1985]	m
Auxiliary data		
Sea-Ice Concentration	NSIDC	%
Sea-Ice Type	NSIDC 0644 (for first-year and multiyear ice distinction)	/
Mean Sea Surface	DTU15	m
Snow Depth Estimate	Warren 1999	m
Others		
Multi open sea-ice flag	ENVISAT 3.0 and L2_SURFACE_MULTI_CLASSIF	/

6.2 Key principles of the algorithm

The retrieval of sea ice information from altimetry is based on differences in the return echoes from the surface. A distinction is firstly made between different types of echoes – specular and diffuse. Specular echoes originate from smooth, mirror-like surfaces, that in the sea ice domain would correspond to leads or very thin ice. Diffuse echoes occur when the reflection is coming from a rougher surface, like an ice floe or open ocean. Next distinction is made within the diffuse waveforms, to differentiate between ice and ocean returns. In this step, an external sea ice concentration product (NSIDS 0051) is used to identify areas where sea ice concentration is higher than a certain threshold, these are classified as sea ice, and similarly areas where sea ice concentration is lower than another certain threshold are classified as ocean.

After surface type identification, retracking is applied to find the exact point of the observed surface within the returned waveform. Once the retracking points are estimated, elevations over the reference mea sea surface (MSS DTU15) are calculated for both leads and floes. Once these elevation estimates are ready, **radar freeboard** is calculated by subtracting the ocean elevation from the floe elevation. In ice-covered areas, the ocean elevation is interpolated from lead elevations within a threshold distance from each other. **Sea ice freeboard** is then calculated from this by applying a correction for the reduced propagation speed of light through the snow cover. Sea ice freeboard is converted to **sea ice thickness** by assuming the hydrostatic equilibrium, and some fixed estimates for sea ice, snow and sea water densities, along with snow depth estimates.

6.3 Logical flow

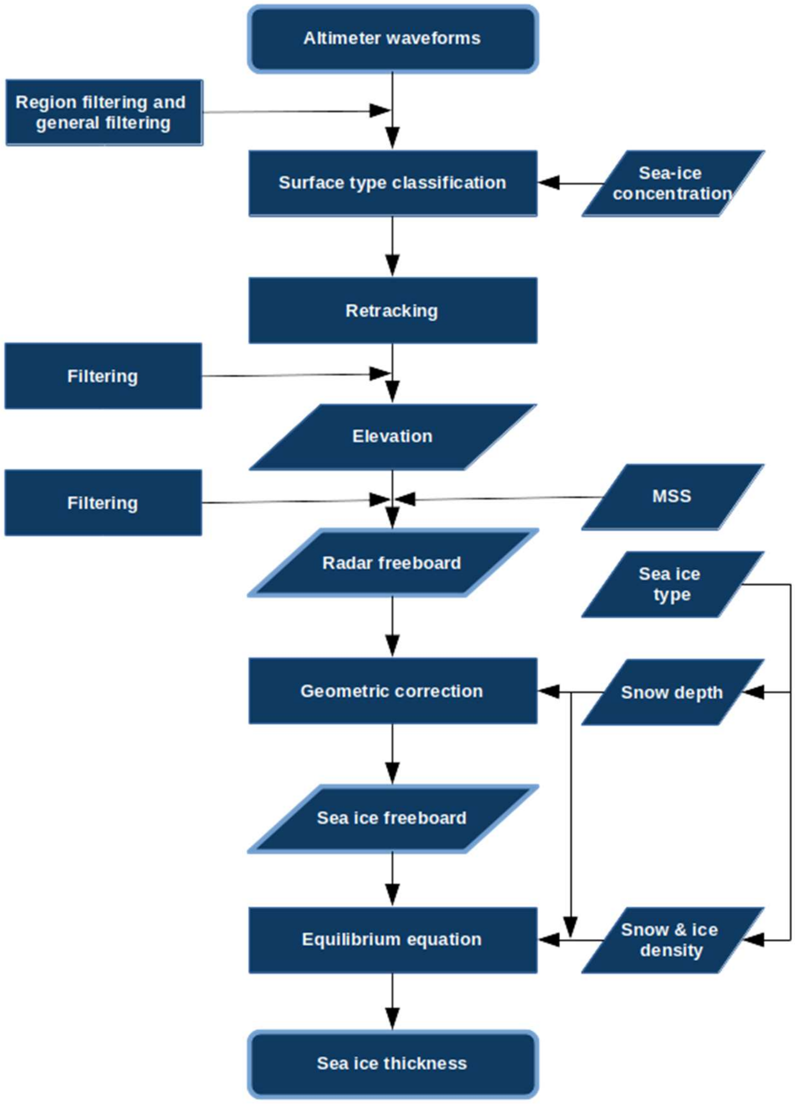


Figure 6-1 : Sea Ice – Logical Flow. Higlighted are the FDR4ALT products.

Above (Figure 6-1) is the logical flow of The Sea Ice TDP processing. These steps are shortly described below.

The Sea Ice TDP algorithm takes the ERS-1&2 RA and ENVISAT RA2 as input data and outputs radar freeboard, sea ice freeboard, and further thickness. There are several external datasets that are needed:

atmospheric and tidal corrections, sea ice concentration, snow depth and density, sea ice type, sea ice and water densities. The processing steps for the Sea Ice TDP are as follows:

- **Read input RA/RA-2 files.**

  The first step is reading the product files into the processor.

- **Region selection**

  The second step filters the in-read data to be processed based on the region, here Arctic.

- **General filtering**

  Removing invalid data/waveforms based on flags (e.g., qual_wf_not_tracking) and unrealistic/inexistent values. This cleaning step includes pulse deblurring procedure for the ERS satellites as described in [**RD-27**]

- **Lead/floe/ocean discrimination**

  This step includes the classification of surface type. The discrimination between leads and floes is done following the preliminary work of Laxon et al. [**RD-28**] and Peacock and Laxon [**RD-29**]. Here, the peakiness of the radar waveform a.k.a pulse peakiness, is used to distinguish between specular and diffuse surfaces. In order to ensure the continuity between the missions, the proportion of leads and floes is kept the same for overlapping satellite mission periods. This step is detailed in [**RD-27**].

  Note: Auxiliary estimate on SIC is traditionally used to distinguish open ocean from ice floes – both yielding diffuse waveforms.

- **Retracking**

  The retracking step aims to find the location of the actual surface in the nadir of the measurement. For the Sea Ice TDP, an empirical retracker, Threshold First Maximum Retracker Algorithm with a 50% threshold, has been used. This step is detailed in [**RD-27**].

- **Filtering**

  This step quality checks the retracking results and discards the waveforms that do not fit certain conditions.

- **Computing elevations**

  After filtering of retracked waveforms, elevations are computed. First, distance from satellite to retracked surface is computed, which requires the satellite altitude as additional input. Next, geophysical and atmospheric corrections are applied. The corrections are listed in Section 6.1. Finally lead and floe elevations are tied to an ellipsoid surface, here WGS84.

- **Mean sea surface removal.**

  Input is taken from the previous step, and an auxiliary mean sea surface (DTU15, **RD-31**) product is used.

- **Radar freeboard and sea ice freeboard computation**

  Local sea surface is interpolated from the lead elevations, and difference between the floe elevation and local sea surface is calculated, resulting into radar freeboard. Here, a threshold is used for maximum distance between two leads, from which the sea surface can be interpolated. Sea ice freeboard is derived from the radar freeboard by correcting for the lower wave-propagation speed in the snow layer [**RD-30**, **RD-32**].

- **Sea ice thickness computation**

  Sea ice thickness is then calculated with the assumption of hydrostatic equilibrium, as described in [**RD-27**]. This step requires additional input of snow depths and densities, sea ice densities, sea ice type and water density. See the Product Requirements and Format Specification [D-1-01][D-2-02] and Section 6.1 for snow depth and density, and sea ice type specifications, [**RD-33**] for sea ice and water densities.

- **Uncertainty estimation**

This step is documented in the Uncertainty Characterization Definition [D-5-02] and Uncertainty Characterisation Report [D-5-02].

- **Writing the output products**

  This step takes the computed sea ice freeboard and thickness, their uncertainties, as well other relevant variables detailed in the Product Requirements and Format Specification [D-1-01] [D-2-02], and writes them in product files, following the FDR4ALT common style.

6.4 Outputs

The output for the Sea Ice TDP consists of a set of NetCDF files with the following variables:

TDP_main
time
longitude
latitude
radar_freeboard
sea_ice_freeboard
sea_ice_thickness
radar_freeboard_uncertainty
sea_ice_freeboard_uncertainty
sea_ice_thickness_uncertainty
surface_height
sea_level_anomaly
sea_level_anomaly_uncertainty
snow_depth
sea_ice_type
surface_type
measurement_status
mean_sea_surface
sea_ice_concentration
TDP_expert
dry_tropospheric_correction_model
wet_tropospheric_correction_model
inverse_barometric_total_correction
ionospheric_correction_model
ocean_tide_correction
ocean_tide_long_period_correction_model
ocean_load_tide_correction

solid_earth_tide_correction
pole_tide_correction
open_sea_ice_flag_rad_alti

6.5 Reference Documents

RD-27	M. Bocquet, S.Fleury, F.Piras, E.Rinne, H.Sallila, F.Garnier, and F.Rémy : Arctic sea ice radar freeboard retrieval from ERS-2 using altimetry: Toward sea ice thickness observation from 1995 to 2021, submitted in The Cryosphere (under review), 2022
RD-28	Laxon, S., Peacock, H., and Smith, D. (2003). High interannual variability of sea ice thickness in the Arctic region, Nature, 425, 947–950, https://doi.org/10.1038/nature02050.
RD-29	Peacock, N. R. & Laxon, S. W. (2004). Sea surface height determination in the Arctic Ocean from ERS altimetry. Journal of Geophysical Research, Vol. 109, No. C7, C07001 10.1029/2001JC001026.
RD-30	Kwok, R. (2014). Simulated effects of a snow layer on retrieval of CryoSat-2 sea ice freeboard. Geophysical Research Letters, 41, 5014-5020, https://doi.org/10.1002/2014GL060993.
RD-31	Andersen, O., Stenseng, L., Piccioni, G., and Knudsen, P. (2016). The DTU15 MSS (Mean Sea Surface) and DTU15LAT (Lowest Astronomical Tide) reference Surface, http://lps16.esa.int/, ESA Living Planet Symposium 2016; Conference date: 09-05-2016 through 13-05-2016.
RD-32	Ulaby, F. T., R. K. Moore, and A. K. Fung, (1986). Microwave Remote Sensing, Vol. 3, From Theory to Applications, Artech House.
RD-33	Alexandrov, V., Sandven, S., Wahlin, J., and Johannessen, O. M. (2010). The relation between sea ice thickness and freeboard in the Arctic. The Cryosphere, 4, 373-380, https://doi.org/10.5194/tc-4-373-2010.

7 Ocean & Coastal Thematic Data Products

7.1 Overview

Within the framework of the FDR4ALT project, the Ocean and Coastal Thematic Data Product (OCO TDP) inherits from previous official products which are:

- Baseline V3.0 for ENVISAT: https://earth.esa.int/eogateway/documents/20142/37627/Envisat-RA-2-Level-2-Product-Handbook.pdf
- REAPER reprocessing for ERS-1/2: https://earth.esa.int/eogateway/documents/20142/37627/reaper-product-handbook-for-ers-altimetry-reprocessed-products.pdf

This document aims at describing the additional added value algorithms included in the OCO TDP. Given the complexity of the Ocean & Coastal TDP processing baseline, here we do not present the TDP as one big algorithm but divided it into several algorithms corresponding to the main steps of the processing baseline.

The following algorithms are used and described in detail in the following parts:

Algorithm	inputs	outputs
OCOTDP_SSHA **see 7.2.1**	All ssha components	sea level anomaly
OCOTDP_OCEAN_VALIDATION_FLAG_01HZ **see 7.2.5**	All ssha components Anciliary : - Oceanic variability - surface type (land / ocean) - ice / sea ice flag	validation_flag
OCOTDP_OCEAN_VALIDATION_FLAG_20HZ **see 7.2.6**	All ssha components Anciliary : - Oceanic variability - surface type (land / ocean) - ice / sea ice flag - peakiness - sigma0 - sea surface temperature	validation_flag
OCOTDP_COMPRESSION_20HZ_1HZ **see 7.2.7**	Retracker outputs (resp. range, swh, sigma0) retracker output quality flags	Resp “range,” “swh”, “sigma0”, and associated number and rms of 20Hz elementary measurements
OCOTDP_COMPRESSION_07HZ_1HZ **see 7.2.8**	Wet Tropospheric Correction	Wet Tropospheric Correction
OCOTDP_DECOMPRESSION_01HZ_20HZ **see 7.2.9**	Atmospheric attenuation	Atmospheric attenuation
OCOTDP_WIND_SPEED **see 7.2.2**	swh, sigma0 and atmospheric attenuation	“wind_speed” values

OCOTDP_EN_SSB_BM4 **see 7.2.3**	All ssh components wind speed significant wave heigh	"sea_state_bias_bm4" coefficients
OCOTDP_EN_SSB_3D **see 7.2.4**	All ssh components wind speed significant wave heigh wave period	"sea_state_bias" tables
OCOTDP_GEOPHYSICAL_CORRECTIONS **see 7.2.11**	Models inputs	ionospheric_correction, dry_tropospheric_correction, dynamic_atmospheric_correction, ocean_tide_height, internal_tide, pole_tide, solid_earth_tide
OCOTDP_MSS_MDT **see 7.2.12**	MSS and MDT grids	mean_dynamic_topography and mean_sea_surface
OCOTDP_ANCILIARY **see 7.2.10**	wave_period_ERA5 oceanic variability CLS grids	Wave_period_t02_era5 oceanic_variability

Table 12 : List of all Ocean & Coastal Topography TDP algorithms detailed in this section.

7.2 OCOTDP algorithms

7.2.1 OCOTDP_SSHA

Input variable	Source	Unit
Time	"*time*" from FDR ALT	days
Latitude	*"latitude" from* ALTFDR_EN_ORBIT or ALTFDR_ERS_ORBIT	degrees
Longitude	*"longitude" from* ALTFDR_EN_ORBIT or ALTFDR_ERS_ORBIT	degrees
orbit	"*orbit*" from ALTFDR_EN_ORBIT or ALTFDR_ERS_ORBIT	m
range	*Depend on the mission, run step and data time resolution* *Detailed for each case in 7.5*	m
Sea State Bias	*Depend on the mission, run step and data time resolution* *Detailed for each case in 7.5*	m
High Frequency Correction	*Depend on the mission, run step and data time resolution* *Detailed for each case in 7.5*	m
Ionospheric correction	*From OCOTDP_GEOPHYSICAL_CORRECTIONS*	m
Wet tropospheric Correction	*Depend on the mission, run step and data time resolution* *Detailed for each case in 7.5*	m
Dry Tropospheric Correction	*From OCOTDP_GEOPHYSICAL_CORRECTIONS*	m
Dynamical Atmospheric Correction	*From OCOTDP_GEOPHYSICAL_CORRECTIONS*	m
Ocean Tide	*From OCOTDP_GEOPHYSICAL_CORRECTIONS*	m
Internal Tide	*From OCOTDP_GEOPHYSICAL_CORRECTIONS*	m
Pole Tide	*From OCOTDP_GEOPHYSICAL_CORRECTIONS*	m
Solid Earth Tide	*From OCOTDP_GEOPHYSICAL_CORRECTIONS*	m
Mean Sea Surface	*From OCOTDP_MSS_MDT*	m

For ENVISAT, the SSHA is computed as:

altitude - range_ssb_hfa - ionospheric_correction - wet_tropospheric_correction - dry_tropospheric_correction - dynamic_atmospheric_correction - ocean_tide - internal_tide - pole_tide - solid_earth_tide - mean_sea_surface

with range_*ssb_hfa* =

- at 20Hz:

  (range + sea_state_bias + high_frequency_adjustment)

- at 1Hz before HFA computation:

  (range + sea_state_bias)

with :

  - *range* = OCOTDP_COMPRESSION_20HZ_01Hz output of 20Hz range_adaptive
  - *sea_state_bias* = OCOTDP_EN_SSB_3D or OCOTDP_EN_SSB_BM4 update at 1Hz, depending on the processing step

- at 1Hz after HFA computation:

  (range + sea_state_bias + high_frequency_adjustment)

  - *range_ssb_hfa* = OCOTDP_COMPRESSION_20HZ_01Hz output of 20Hz

For ERS, SSHA is computed both at 1Hz and 20Hz as:

altitude – range – sea_state_bias - ionospheric_correction - wet_tropospheric_correction - dry_tropospheric_correction - dynamic_atmospheric_correction - ocean_tide - internal_tide - pole_tide - solid_earth_tide - mean_sea_surface

7.2.2 OCOTDP_WIND_SPEED

This algorithm is performed only during ENVISAT OCEAN TDP processing.
Wind speed value is computed with Collard's 2D-algorithm [**RD-46**] as for the Jason and Sentinel-6 missions after biasing ENVISAT sigma0.

Input variable	Source	Unit
Time	"*time*" from FDR ALT	days
Latitude	*"latitude" from* ALTFDR_EN_ORBIT	degrees
Longitude	*"longitude" from* ALTFDR_EN_ORBIT	degrees
swh	*From L2_EN_RTK_ADAPTIVE applied to 20Hz data point then OCOTDP_COMPRESSION_20HZ_1HZ for 1Hz dataset*	m
sigma0	*From L2_EN_RANGE_SIGMA0 applied to 20Hz data point then OCOTDP_COMPRESSION_20HZ_1HZ for 1Hz dataset*	dB
atmospheric attenuation applied to sigma0	*From ATMTDP intermediate 1Hz data*	dB

7.2.3 OCOTDP_EN_SSB_BM4

This algorithm is performed only during ENVISAT OCEAN TDP processing.

Input variable	Source	Unit
Altimetry data		
Time	*"time"* from FDR ALT	days
Latitude	*"latitude" from* ALTFDR_EN_ORBIT	degrees
Longitude	*"longitude" from* ALTFDR_EN_ORBIT	degrees
ssh	*From OCOTDP_SSHA*	m
Validation flag	*From* OCOTDP_OCEAN_VALIDATION_FLAG_01HZ	/
swh	*From L2_EN_RTK_ADAPTIVE applied to 20Hz data point then OCOTDP_COMPRESSION_20HZ_1HZ*	m
Wind_speed	*From OCOTDP_WIND_SPEED*	m/s

SSH differences are computed at crossover points. A regression between these differences with respect to swh and wind_speed values is done in order to deduced BM4 coefficients as described by Gaspard et al. in [**RD-37**].

7.2.4 OCOTDP_EN_SSB_3D

This algorithm is performed only during ENVISAT OCEAN TDP processing.

Input variable	Source	Unit
Time	*"time"* from FDR ALT	days
Latitude	*"latitude" from* ALTFDR_EN_ORBIT	degrees
Longitude	*"longitude" from* ALTFDR_EN_ORBIT	degrees
ssh	*From OCOTDP_SSHA*	m
validation flag	*From OCOTDP_OCEAN_VALIDATION_FLAG_01HZ*	/
swh	*From L2_EN_RTK_ADAPTIVE applied to 20Hz data point then OCOTDP_COMPRESSION_20HZ_1HZ*	m
Wind_speed	*From OCOTDP_WIND_SPEED*	m/s
Wave_period	*From ERA5 T02 model*	s

Sea state bias corrections are developed as regular three-dimensional look-up table against SWH, WS and ERA5 mean wave period (T02) with a non-parametric estimation technique based on kernel smoothing. The table values are estimated from differences at crossovers of 1Hz SSH data without SSB correction applied and measured over a 1-year period. SWH and sigma0 come from adaptive retracking algorithm. WS value is computed with Collard's 2D-algorithm [**RD-46**] as for the Jason and Sentinel-6 missions after biasing ENVISAT sigma0. The SSB computation method is detailed in [**RD-47**]. Sea state bias correction is then computed at each 20Hz location through a trilinear interpolation, for each (SWH, WS, T02) triplet. A high-frequency adjustment (HFA) term is then also applied on 20-Hz SSH data [**RD-45**]. HFA is an additional correction that reduces the high-frequency noise in SSH correlated to the high-frequency noise in SWH following the approach developed by Zaron and Decarvalho [**RD-47**]. It is computed from 20Hz SWH data and is based on the following formulae:

HFA_for_SSH = F(filtered_SWH)(SWH – filtered_SWH)*

Where filtered_SWH is low-pass filtered SWH value computed with a Lanczos filter. F is a polynomial function of the form : $y=a+b*x^{-3}+c*x^{-2}+d*x^{-1}+e*x^{-0.5}+f*x^{0.5}+g*x+h*x^{2}+i*x^{3}$; and its parameters are determined by polynomial regression. The approach consists in the following steps:

- Compute the filtered_SWH with a Lanczos filter
- Compute the HFA_for_SSH by applying the polynomial model

Note, HFA_for_SSH is not applied everywhere but only when the 2 following conditions are satisfied (SWH in [1, 13] m and abs(HFA_for_SSH) < 20 cm) otherwise it sets to 0.

7.2.5 OCOTDP_OCEAN_VALIDATION_FLAG_01HZ : Validation flag at 1Hz

See section 7.8.2.1

7.2.6 OCOTDP_OCEAN_VALIDATION_FLAG_20HZ : Validation flag at 20Hz

See section 7.8.2.2

7.2.7 OCOTDP_COMPRESSION_20HZ_01HZ

20 Hz values of Adaptive retracker outputs are used for ENVISAT SSH estimations (see part 4.1). 1Hz range estimations are deduced from 20Hz range values compressed to 1Hz following the same compression method as the one used for ENVISAT v3.0. An additional variable is available in the TDP product, taking advantage of the noise reduction at 20Hz thanks to the use of the hfa correction: the *range_ssb_hfa* variable (1Hz data_01 group only) is computed by directly compress the $(\text{range} + \text{ssb} + \text{hfa})_{\text{at\_20Hz}}$ values.

7.2.8 OCOTDP_COMPRESSION_07HZ_01HZ

This algorithm is used to deduce 1Hz Wet Tropospheric Correction values from 7Hz native radiometer resolution. As a first step, brightness temperatures are interpolated to 1Hz data points following L2_MWR_INTERP_TO_ALT (note that a dedicated to coastal zone area process is implemented during this step).

7.2.9 OCOTDP_DECOMPRESSION_01HZ_20HZ

This algorithm is run for atmospheric attenuation (given at 1Hz) and Wet Tropospheric Correction (WTC). Atmospheric attenuation valued to apply to sigma0, and WTC values are interpolated from 1Hz timestamps to 20Hz records.

7.2.10 OCOTDP_ANCILIARY

Input variable	Source	Unit
Altimetry data		
Time	"*time*" from FDR ALT	days
Latitude	*"latitude" from* ALTFDR_EN_ORBIT or ALTFDR_ERS_ORBIT	degrees
Longitude	*"longitude" from* ALTFDR_EN_ORBIT or ALTFDR_ERS_ORBIT	degrees
Auxiliary data		
Surface Type Flag	"surface_type" from ALTFDR_EN_DISTANCE_TO_COAST or ALTFDR_ERS_DISTANCE_TO_COAST	/
Coastal Distance	"*distance_to_coast*" from ALTFDR_EN_DISTANCE_TO_COAST or ALTFDR_ERS_DISTANCE_TO_COAST	m
Sea surface temperature		K
Sea ice fraction	From OSISAF	/
Oceanic variability	CLS oceanic variability grids	m

7.2.11 OCOTDP_GEOPHYSICAL_CORRECTIONS

Input variable	Source	Unit
Time	"*time*" from FDR ALT	days
Orbit	"*orbit*" from ALTFDR_EN_ORBIT or ALTFDR_ERS_ORBIT	m
Latitude	*"latitude" from* ALTFDR_EN_ORBIT or ALTFDR_ERS_ORBIT	degrees
Longitude	*"longitude" from* ALTFDR_EN_ORBIT or ALTFDR_ERS_ORBIT	degrees
Geophysical corrections		
IC (Ionospheric Correction)	GIM for EN1 and ER2. GIM from cycle 106 included onwards & NIC before cycle 106 for ER1	m
DTC (Dry Tropospheric Correction)	From ECMWF ERA5 pressures	m
DAC (Dynamical Atmospheric Correction)	From ECMWF ERA5 + TUGO model for EN1 and ER2. From ECMWF ERA5 + TUGO model from cycle 64 included onwards & copied from REAPER before cycle 64 for ER1	m
OT (Ocean Tide)	From FES14B (load tide included), 34 waves included	m
IT (Internal Tide)	From ZARON2019 / HRET 8.1 model	m
PT (Pole Tide)	From DESAI2015 algorithm setting Mean Pole Location from IERS2017 recommendation	m
SET (Solid Earth Tide)	From Cartwright and Edden [1973] tables	m
Auxiliary data		
Surface Type Flag	"surface_type" from ALTFDR_EN_DISTANCE_TO_COAST or ALTFDR_ERS_DISTANCE_TO_COAST	/

Geophysical corrections of each 1Hz and 20Hz datasets are applied respectively to 1Hz or 20Hz time/latitude/longitude points.

7.2.12 OCOTDP_MSS_MDT

Input variable	Source	Unit
Time	"*time*" from FDR ALT	days
Latitude	*"latitude" from* ALTFDR_EN_ORBIT or ALTFDR_ERS_ORBIT	degrees
Longitude	*"longitude" from* ALTFDR_EN_ORBIT or ALTFDR_ERS_ORBIT	degrees
Mean_sea_surface	MSS model grids (Combined SIO/CNES_CLS15/DTU15)	m
Mean_dynamic_topography	MDT model grids (CNES CLS 201)	m

Mean Sea Surface and Mean Dynamic Topography values of each 1Hz and 20Hz datasets are deduced from grids interpolation and applied respectively to 1Hz or 20Hz time/latitude/longitude points.

7.2.13 OCOTDP_WTC_EDITED

Input variable	Source	Unit
Time	"*time*" from FDR ALT	days
Latitude	*"latitude" from* ALTFDR_EN_ORBIT or ALTFDR_ERS_ORBIT	degrees
Longitude	*"longitude" from* ALTFDR_EN_ORBIT or ALTFDR_ERS_ORBIT	degrees
Radiometer_WTC	Radiometer-derived Wet Tropospheric Corrrection from Neural Network Solution (ATM TDP)	m
Distance to Coast	GSHHG global shoreline dataset (https://www.soest.hawaii.edu/pwessel/gshhg)	m
GPD+ WTC	Fernandez et al. 2015 dataset for ENVISAT/ERS-1/ERS-2	m

In spite of the good quality of the new radiometric processing made in this project, the behavior of the radiometer in the approach to the coast is always problematic. The presence of land induces a shift in brightness temperatures and the WTC calculation from these altered values give rise to unrealistic data near the coasts. The GPD+ method of Fernandes et al. [RD-36] uses additional data to compensate the deviation of radiometry near the coast; namely, the reference SSM/I mission and Global Navigation Satellite System (GNSS) data. Nevertheless, the GPD+ algorithm only improves the basis of the raw radiometry WTC calculation. Because of the use of the radiometer WTC calculation in the ocean part of the OCO TDP, we cannot simply use an old GPD+ correction for consistency reasons and the GPD+ should be completely recalculated. Unfortunately, the scheduling of the project made this impossible and we must settle for an edited WTC correction.

The algorithm for editing the radiometry WTC is relatively simple and is based on the divergence of this WTC with respect to the well-behaved GPD+ solution.

First, an example of the raw radiometer WTC and the old GPD+ correction, on map view over the Mediterranean Sea. As seen on the figure below, very near the coast (distance < 20km there is an unrealistic shift in WTC values for the radiometer solution (upper panel), but the GPD+ solution preserves continuity (lower panel).

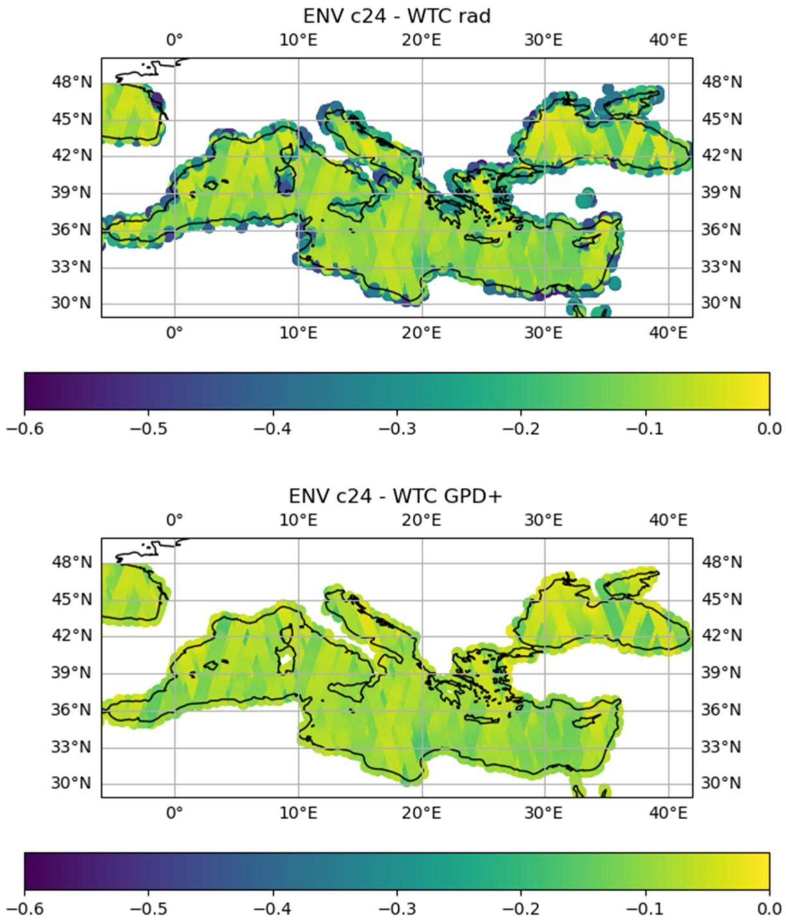


Figure xx – WTC correction over the Mediterranean Sea. Above, the radiometric WTC. Below, the GPD+ correction (old dataset, not consistent with radiometric WTC). The darker points along the coast of the WTC rad correction are unrealistic, and not present on the GPD+ solution.

Unfortunately, we cannot easily reproduce the GPD+ results and must simply remove the worst values near the coast. This edition works as follows and is applied only to points at a distance less than 50 km from the coast:

- ✓ We calculate the standard deviation of the GPD+ signal within a moving window.
- ✓ We calculated the absolute difference between the radiometer WTC and the (old) GPD+ correction. Differences are expected, but the local trends should be similar; otherwise, the correction is wrong.
- ✓ If the difference exceeds 3 times the GPD+ variability (the std dev calculated above), we flag the radiometer WTC as bad.

The condition is:

std = minstd + 3*stdev(gpd, moving window)
Edit if abs(wtc – gpd) > std & (dist_to_coast < 50 km)

Where minstd is a minimum standard deviation to ensure good behavior (with value = 0.03). An example of this is given below for pass number 100 in its full length, and then in a zoom when crossing the Mediterranean region.

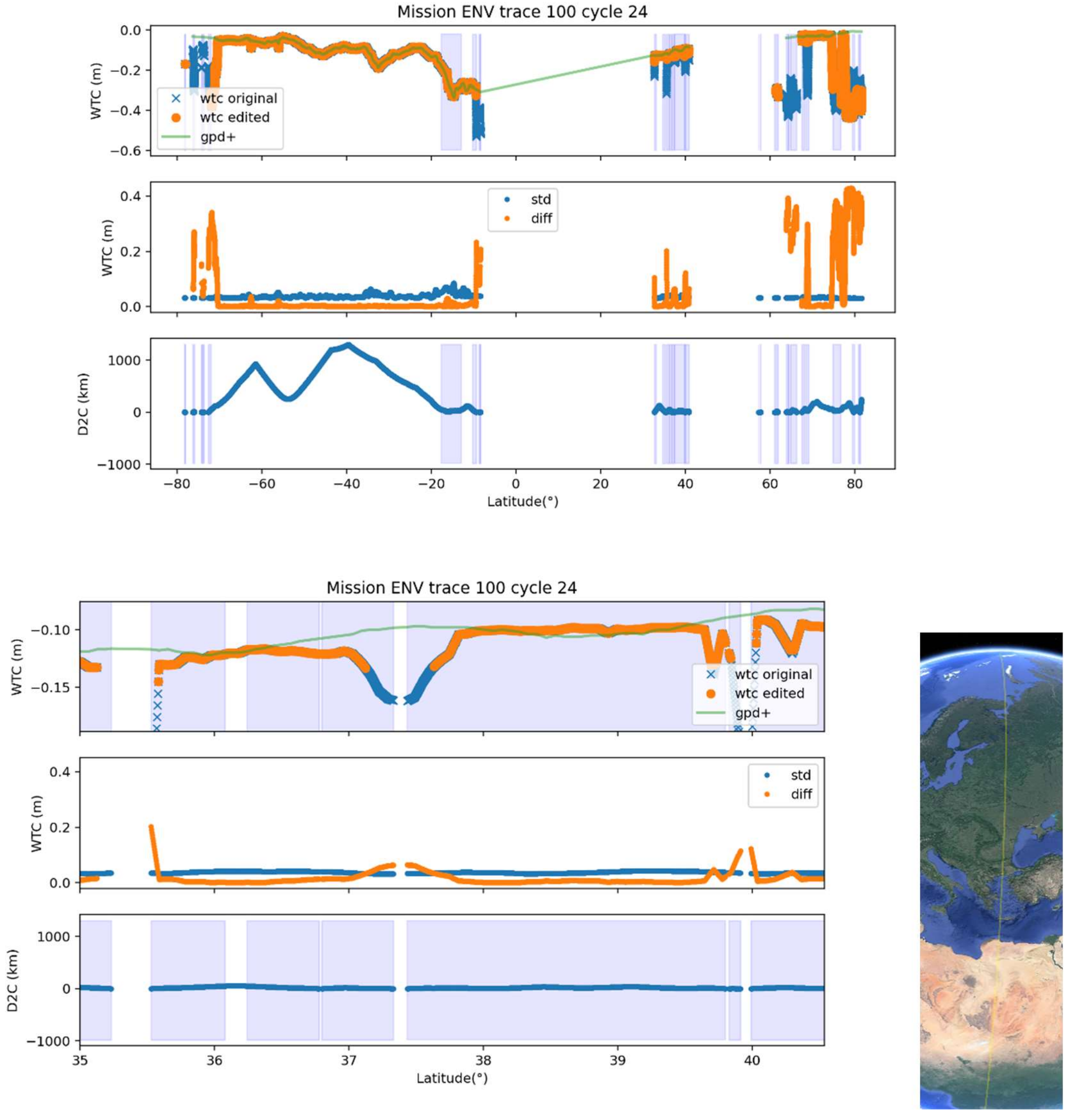


Figure – Above panel, the full length of pass 100 of ENVISAT in cycle 34. In blue the original radiometer WTC and green the old GPD+ correction (not used in this project because of consistency) and in orange the final edited WTC. A zoom is provided below, near the mediterranean region with a map of its footprint in the zone. Near the 37.5° latitude we see the strong dip in the radiometer WTC, not seen in the GPD+ correction in green. The editing algorithms gets rid of the points whose difference with GPD+ exceeds the std value shown in the middle panel. D2C is the distance to coast.

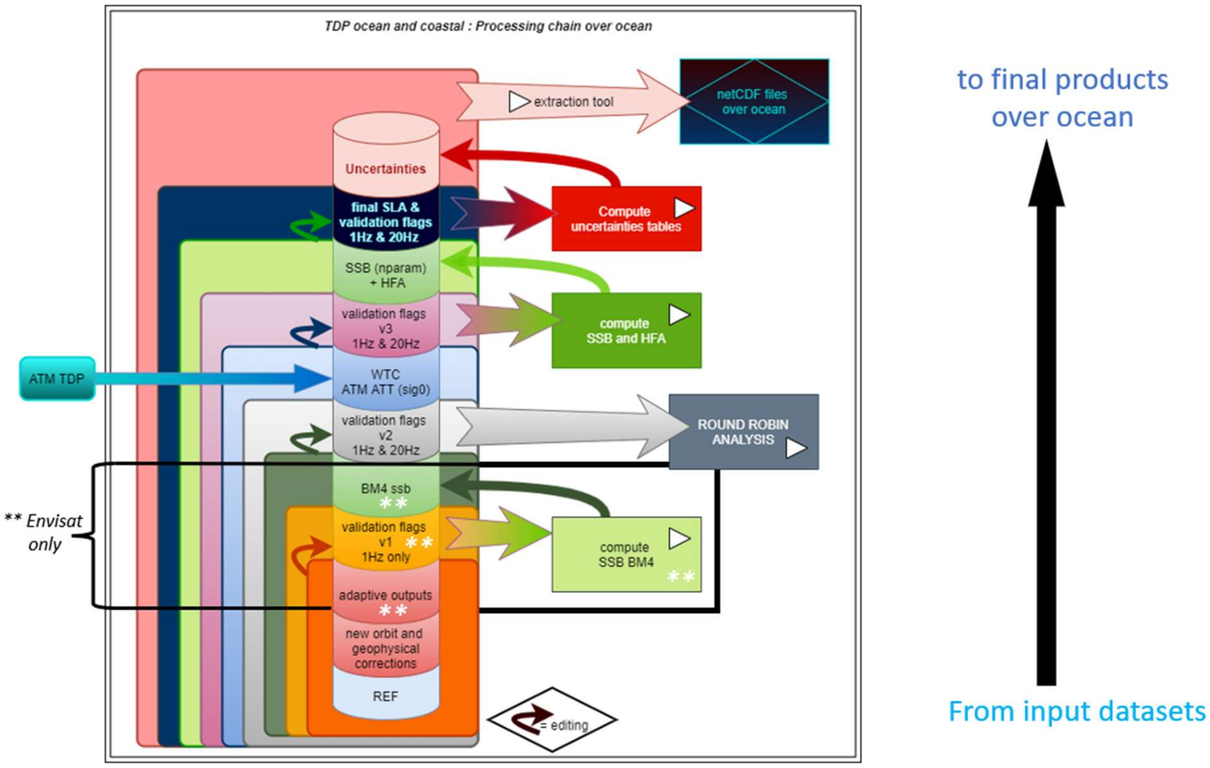
7.3 Inputs

Input variable	Source	Unit
Altimetry data		
Time	"*time*" from FDR ALT	days
Orbit	"*orbit*" from ALTFDR_EN_ORBIT or ALTFDR_ERS_ORBIT	m
Latitude	*"latitude" from* ALTFDR_EN_ORBIT or ALTFDR_ERS_ORBIT	degrees
Longitude	*"longitude" from* ALTFDR_EN_ORBIT or ALTFDR_ERS_ORBIT	degrees
range EN **range_ssb_hfa EN**	*"range_adaptive"* from L2_ENVISAT_RANGE_SIGMA0 at 20Hz *"range_adaptive"* from OCOTDP_COMPRESSION_20HZ_01Hz at	m

	1Hz *"range_ssb_hfa"* from OCOTDP_COMPRESSION_20HZ_01Hz at 1Hz	
range ERS	*"range_mle3"* from REAPER at both 20Hz and 1Hz	m
Sigma0 EN (not corrected from atmospheric attenuation)	*"sigma0_adaptive"* from L2_ENVISAT_RANGE_SIGMA0 at both 20Hz and 1Hz	db
Sigma0 ERS (not corrected from atmospheric attenuation)	*"sigma0_mle3_nocorr"* from L2_ERS_RANGE_SIGMA0 at both 20Hz and 1Hz	db
Atmospheric attenuation EN	*"atm_att"* with Neural Network solution from ATMTDP at 1Hz from OCOTDP_DECOMPRESSION_01HZ_20Hz at 20Hz	db
Atmospheric attenuation ERS	*"atm_att"* with Neural Network solution from ATMTDP at 1Hz from OCOTDP_DECOMPRESSION_01HZ_20Hz at 20Hz	db
Geophysical corrections		
SSB ERS (Sea State Bias)	From REAPER at 1Hz	m
SSB EN (Sea State Bias)	From OCOTDP_EN_SSB_3D	
IC (Ionospheric Correction)	GIM for EN1 and ER2. GIM from 1994 onwards & NIC before 1994 for ER1	m
WTC (Wet Tropospheric Correction)	WTC with Neural Network solution from ATMTDP	m
DTC (Dry Tropospheric Correction)	From ECMWF ERA5 pressures	m
DAC (Dynamical Atmospheric Correction)	From ECMWF ERA5 + TUGO model	m
OT (Ocean Tide)	From global FES14B over ocean Dedicated Regional solution when available	m
IT (Internal Tide)	From ZARON2019 / HRet 8.1 model	m
PT (Pole Tide)	From DESAI2015 algorithm setting Mean Pole Location from IERS2017 recommendation	m
SET (Solid Earth Tide)	From Cartwright and Edden [1973] tables	m
Auxiliary data		
MDT (Mean Dynamic Topography)	CNES CLS 2018	m
MSS (Mean Sea Surface)	Combined SIO/CNES_CLS15/DTU15	m
Surface Type Flag	"surface_type" from ALTFDR_EN_DISTANCE_TO_COAST or ALTFDR_ERS_DISTANCE_TO_COAST	/
Coastal Distance	"*distance_to_coast*" from ALTFDR_EN_DISTANCE_TO_COAST or ALTFDR_ERS_DISTANCE_TO_COAST	m

7.4 Key principles and logical flow (global ocean)

As no new retracking has been computed for ERS missions, some steps are only applied to ENVISAT processing.



3 (ERS) or 4 (EnviSat) iterations of editing steps

Figure 7-1: global ocean OCOTDP processing flow

7.5 Description of the processing steps (global ocean)

For ENVISAT:

1) ENVISAT V3.0 acquisition at 1Hz and 20Hz

2) Database enrichment at 1Hz and 20Hz

- altitude, latitude and longitude from ALTFDR_EN_ORBIT applied respectively to 1Hz and 20Hz data points
- distance_to_coast and surface_type from ALTFDR_EN_DISTANCE_TO_COAST
- ionospheric_correction, dry_tropospheric_correction, dynamic_atmospheric_correction, ocean_tide_height, internal_tide, pole_tide, solid_earth_tide from OCOTDP_GEOPHYSICAL_CORRECTIONS
- mean_sea_surface from OCOTDP_MSS_MDT
- wave_period, oceanic_variability and ice_flag from OCOTDP_ANCILIARY

3) Adaptive retracker from FDRALT work package at 20Hz

- range_adaptive, sigma0_adaptive from L2_ENVISAT_RANGE_SIGMA0 applied to 20Hz data points,
- swh_adaptive from L2_EN_RTK_ADAPTIVE applied to 20Hz data points,

4) Adaptive retracker outputs of step3 compression from 20Hz to 1Hz [OCOTDP_COMPRESSION_20HZ_01HZ]

5) **ATMTDP work / Neural Network Solution**

   a) sigma0_adaptive_nocorr compression from 20Hz to 7Hz (part of ATMTDP work / Neural Network Solution)
   b) atmospheric attenuation computed at 1Hz (part of ATMTDP work / Neural Network Solution)
   c) wet tropospheric correction computed at 7Hz, compressed to 1Hz (part of ATMTDP work / Neural Network Solution) see [OCOTDP_COMPRESSION_07HZ_01HZ]

6) **Sea state bias (more details in 7.7.2)**
   a) Compute a preliminary validation flag at 1Hz (validation_flag_01hz_prelim1) following [OCOTDP_OCEAN_VALIDATION_FLAG_01HZ]. For this first step, sea_state_bias from ENVISAT V3.0 is used.
   b) This step consist in computing a dedicated to adaptive retracking wind_speed following [OCOTDP_WIND_SPEED].
   c) This step consist in computing a dedicated to adaptive retracking sea_state_bias_adaptive_bm4 following [OCOTDP_EN_SSB_BM4].
   d) Then a second preliminary validation flag (validation_flag_01hz_prelim2) is computed at 1Hz following [OCOTDP_OCEAN_VALIDATION_FLAG_01HZ], using the same input information than for step 8 except for sea_state bias. For this first step, sea_state_bias_adaptive_bm4 from step 10 is used.
   e) Finally, sea_state_bias_adaptive_3d table is computed and applied to 1Hz and 20Hz data following [OCOTDP_EN_SSB_3D].

7) **Compute of a third preliminary validation flag** (validation_flag_01hz_prelim3) flag at 1Hz following [OCOTDP_OCEAN_VALIDATION_FLAG_01HZ], using the same input information than for step 8 and 10 except for sea_state bias (sea_state_bias_adaptive_3d from step 11 is used). At 20Hz [OCOTDP_OCEAN_VALIDATION_FLAG_20HZ] is used, without hfa information.

8) **High Frequency Adjustment computation**, following [OCOTDP_SSB_HFA]

9) **Compression** of range_ssb_hfa, following [OCOTDP_COMPRESSION_20HZ_1HZ]

10) **Compute of the final validation flags** at 1Hz following [OCOTDP_OCEAN_VALIDATION_FLAG_01HZ], using the same input information than for step 6a and 6d except for range and sea_state bias (range_ssb_hfa from step 9 is used). At 20Hz [OCOTDP_OCEAN_VALIDATION_FLAG_20HZ] is used, considering hfa information.

For ERS:

1) **ERS REAPER acquisition at 1Hz and 20Hz**

2) **Database enrichment at 1Hz and 20Hz**
   - altitude, latitude and longitude from ALTFDR_ERS_ORBIT applied respectively to 1Hz and 20Hz data points
   - distance_to_coast and surface_type from ALTFDR_EN_DISTANCE_TO_COAST
   - ionospheric_correction, dry_tropospheric_correction, dynamic_atmospheric_correction, ocean_tide_height, internal_tide, pole_tide, solid_earth_tide from OCOTDP_GEOPHYSICAL_CORRECTIONS
   - mean_sea_surface from OCOTDP_MSS_MDT
   - oceanic_variability and ice_flag from OCOTDP_ANCILIARY

3) **No new retracking available for ERS data**
   - sigma0_mle3_nocorr from L2_ERS_RANGE_SIGMA0,
   - range_mle3, swh_mle3 from REAPER data acquisition,

4) **ATMTDP work / Neural Network Solution**

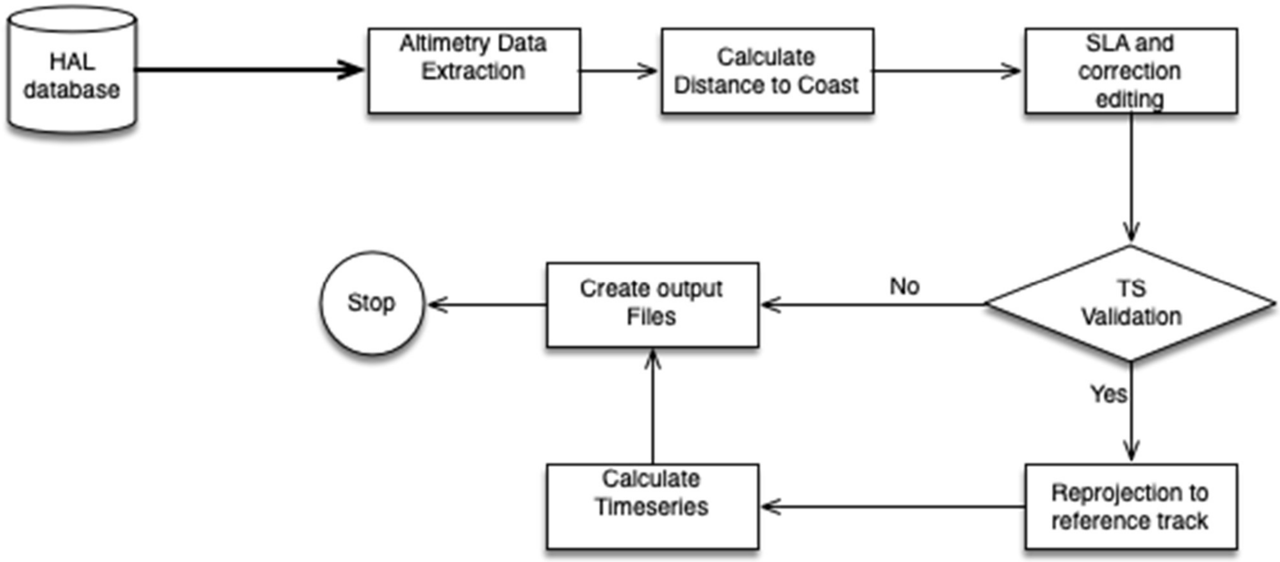
   a) sigma0_mle3_nocorr compression from 20Hz to 7Hz (part of ATMTDP work / Neural Network Solution)
   b) atmospheric attenuation computed at 1Hz (part of ATMTDP work / Neural Network Solution)
   c) wet tropospheric correction computed at 7Hz, compressed to 1Hz (part of ATMTDP work / Neural Network Solution), using a specific algorithm near coastal areas. see [OCOTDP_COMPRESSION_07HZ_01HZ]
   d) This wet_tropospheric_correction solution is then decompressed from 1Hz to 20Hz database [OCOTDP_DECOMPRESSION_01HZ_20HZ].

5) **Sea state bias and hfa** : as no new retracking outputs are available, REAPER mle3 sea state bias is used at 1Hz. Decompression values from REAPER 1z to 20Hz are used for 20Hz dataset (OCOTDP_DECOMPRESSION_01HZ_20Hz). No High Frequency Adjustment available for ERS data, and so no compression of range_ssb_hfa at 1Hz.

6) **Compute of the final validation flags at** 1Hz following [OCOTDP_OCEAN_VALIDATION_FLAG_01HZ], and at 20Hz [OCOTDP_OCEAN_VALIDATION_FLAG_20HZ].

7.6 Key principles and logical flow (coastal only)

The Coastal TDP uses the Level-2 parameters which are output from the FDR processing chain, by reading OCTANT tables on the cluster. The output of the processing chain are new parameters in additional tables which are specific to the Coastal TDP. The following high-level view of the processing follows the exposition made of it in Birol et al. 2017 and updated to take into account the particularities of the FDR4ALT project. When referenced, the X-TRACK processor used is X-TRACK 2021.



It starts with the selection of the altimetry measurements located in the region of interest, defined as on of the regional polygons defining the X-TRACK coastal zones (http://ctoh.legos.obs-mip.fr/data/coastal-products/sla-1hz). After calculating the important missing information of distance to coast for every altimetry data point, a two-step editing strategy is then used to recover the maximum of meaningful sea level observations. The first step consists in rejecting potential outliers through the analysis of the different corrective terms. Abrupt changes in geophysical corrections are assumed to be associated with errors. First, threshold values are used (see Table 9.1 in [**RD-42**]) and then a 3σ or 4σ (depending on the coastal area) threshold filter is applied along the satellite track (σ is the standard deviation of the along track record). In addition to outliers in corrections, their adjoining neighbours, which often contain erroneous values, are also eliminated. This strategy rejects much more SSH data than the standard procedure used by operational centers (c.f. editing criteria in the Aviso User Handbooks). Thus, in a second step, all the correction values are interpolated from a Bezier curve built from the edited data. One should note that only the corrections are interpolated in X-TRACK, not the altimeter measurements. Examples of this procedure are illustrated in Fig. 2 of [**RD-44**] and Fig. 9.1 of [**RD-42**]. The efficiency of this approach was shown in different studies ([**RD-44**]; [**RD-35**],[**RD-31**],[**RD-33**]).

The L2 product is output at this step, with the additional final filtering based on a 3-sigma filtering of the regional SLA values (values outside this range are edited out of the final dataset).

For validation purposes, additional steps are done so as to obtain timeseries coastal data and compare with tide gauge data. This “Reprojection to reference track” is done as follows: once the corrected SSHs are derived using Eq. (1), a mean sea surface height (MSSH) is computed along the nominal ground track, at equally sampled reference points (i.e., every 6–7 km for 1-Hz data). This is done using an inverse method, which accounts for the cross-track gradient of the SSH values ([**RD-41**]). The data are then resampled at the reference points along the nominal track: the SLA time series are obtained by subtracting to the corrected SSH data both the MSSH at the closest reference point and the MSSH difference between the closest reference point and the actual location of the altimeter observation. This procedure is important since it was found that in coastal areas, where the surface topography gradients are large, inaccurate MSSH leads to significant errors in SLAs ([**RD-44**]).

$$\text{Corrected SSH} = \text{altitude} - \text{range} - \sum \text{propagation corrections} - \sum \text{geophysical corrections}$$

Equation 1 – Corrected SSH

R. The SLA precision is further enhanced by combining the SSH time series of different missions that share the same orbit (e.g. Topex/Poseidon, Jason1&2) in order to obtain homogeneous time series from several altimetry missions over long time periods (**RD-32**).

Each corrective term is now edited in a different way in order to take into account its individual characteristics (i.e. the corresponding geophysical variations along the track). The processing of the ionospheric, wet tropospheric and sea state bias corrections are presented below. In the other altimeter corrections, usually derived from models, very few values are discarded by the editing process. Flagged corrections are simply replaced by their nearest valid neighbours.

7.7 Description of the processing steps (coastal only)

7.7.1 Wet tropospheric correction

The WTC is a major issue in coastal products, and the quality of the coastal product and particularly the availability of the coastal solution depends on the quality of the WTC. We use the OCOTDP_WTC_EDITED algorithm described above.

7.7.2 Sea state bias correction

7.7.2.1 Input data

- Datation: 1-Hz and 20-Hz altimeter time tag
- Location:
    - Latitude of the measurement (1 Hz and 20 Hz) from ALTFDR_EN_ORBIT; ALTFDR_EN_ORBIT
    - Longitude of the measurement (1 Hz and 20Hz) from ALTFDR_EN_ORBIT; ALTFDR_EN_ORBIT
- 1-Hz sea state bias correction (as chosen by round robin)

7.7.2.2 Output data

Edited sea-state bias correction at 20-Hz edited and filtered in the along-track direction by the X-TRACK algorithm.

7.7.2.3 Processing steps

The sea-state bias (SSB) correction is the sum of three components: an electromagnetic bias which accounts for stronger reflection of wave troughs relative to wave crests, the skewness bias related to the difference between the mean and the median of the height of specular facets, and the tracker bias which is the error in the tracker determination of the Significant Wave Height (SWH) ([**RD-37**] ; [**RD-43**]). The determination of accurate sea state bias corrections is another challenging issue for coastal altimetry because of the rapidly changing characteristics of the waves and the wind, and because of noisy waveforms. The SSB correction provided in GDRs products is generally computed from parametric (BM4;[**RD-37**]) or non-parametric models ([**RD-38**]). In X-TRACK, the SSB correction is filtered in the along-track direction by using a Loess low-pass filter, and missing values are replaced by the nearest interpolated data.

7.8 Description of the processing steps for validation_flag (SLA editing)

7.8.1 Coastal areas

Within X-TRACK, the 1-Hz SLA time series computed (see Section 2.1), were finally edited using a 3σ threshold filter (4 s in the Tropical Pacific). In the X- TRACK strategy, we consider that the difference in SLA that can be explained by the ocean dynamics between consecutive 1-Hz measurements should be limited in amplitude.

Considering the geostrophic approximation and a maximum geostrophic current speed of 2 m/s at mid latitudes, the SLA difference (DSLA) over 7 km should not be higher than 14 cm (using the geostrophic equation with a value of 1.e-4 s^{-1} for the Coriolis parameter). After computation of the corrected SSH (Equation 1), temporary filtered SLA values SLA_L are calculated relative to the mean sea surface provided in the GDR products, using a low-pass local regression (Loess). SLA values outside the interval 1⁄2 SLA_L DSLA are flagged as invalid and the corresponding sea level measurements are not further used in X-TRACK processing (including the computation of the MSSH and the final SLA data).

7.8.2 Global ocean

Data editing is necessary to remove altimeter measurements having lower accuracy. A recommended in altimetry missions user handbooks is used at 1Hz (see 7.8.2.1). Such a process is not applicable to 20Hz data. A dedicated point to point validation method is developed, using first surface classification grid to remove land data and OSISAF data records combined with retracker related parameters to allow ice detection, and then an iterative process on SLA at 20Hz values, using oceanic variability and swh information (see 7.8.2.2).

7.8.2.1 OCOTDP_OCEAN_VALIDATION_FLAG_01HZ: Validation flag at 1Hz

At 1Hz, it consists in:
- First: removing land data and data corrupted by sea ice. The aim of this first step is to select the points where the editing thresholds will be applied.
In order to detect sea ice, a dedicated flag (not provided in the final products) is use. A record is flagged as ice if |latitude| > 45° and if one of these criteria is met:

- |Radiometer_Wet_Tropospheric_Correction – model_Wet_Tropospheric_Correction | > 10cm
- Range_number (number of 20Hz elementary measurement used to compu the 1Hz record) < 17
- Peakiness > 2

After this step, only the following measurements are kept:

• the ice flag is 0 (=notice),
• and the surface classification is ocean and lakes). Detection of data over land is done thanks to a surface classification deduce from GSHHG: via the selection of values 0 or 2, corresponding to ocean and lake measurements).

- Then, removing measurements out of thresholds tuned for several parameters. The editing criteria are defined as minimum and maximum thresholds for altimeter, radiometer, and geophysical parameters (in particular, 1Hz values of altimeter outputs rms deduced from HR data):

Parameter	Min thresholds	Max thresholds
Sea surface height (m)	−130	100
Variability relative to MSS (m)	−2	2
Number of 18Hz valid points	10	−
Std deviation of 18Hz range (m)	0	0.25
Off nadir angle from waveform (deg2)	−0.200	0.160
Dry troposphere correction (m)	−2.500	−1.900
Inverted barometer correction (m)	−2.000	2.000
MWR wet troposphere correction (m)	−0.500	0.001
Dual Ionosphere correction (m)	−0.200	−0.001
Significant waveheight (m)	0.0	11.0
Sea State Bias (m)	−0.5	0
Backscatter coefficient (dB)	7	30
Ocean tide height (m)	−5	5
Long period tide height (m)	−0.500	0.500
Earth tide (m)	−1.000	1.000
Pole tide (m)	−5.000	5.000
RA2 wind speed (m/s)	0.000	30.000

Figure 7-2: Thresholds criteria for SLA editing over ocean at 1Hz

- Finally, spurious bad data are edited thanks to pass statistics analysis of SLA.

7.8.2.2 OCOTDP_OCEAN_VALIDATION_FLAG_20HZ: Validation flag at 20Hz

A validation flag has been set up to remove inconsistent measures and select the open ocean (remove land and sea ice).

7.8.2.2.1 First step: Ice flag

Ocean validation flag need first to remove all ice data. No ice flag is provided in 20Hz ENVISAT product so one had to be implemented.

PRINCIPLE

Interpolation or duplication of a 1Hz ice flag is not as efficient as a 20Hz one, that is why we propose to use a solution with a multi-criteria selection. First OSISAF model for sea ice fraction is used, all data with more than 50% of sea ice fraction is considered as ice. If OSISAF is not defined or if its sea ice fraction is 0%, the measurement can still be considered as ice if three condition are respected: first the sea surface temperature must be under 278 K. Then, a threshold on the peakiness and the backscatter coefficient are applied. These thresholds are very high because the OSISAF model will be ignored (the measurement will be considered as ice) if both thresholds are exceeded. If OSISAF sea ice fraction is between 0 and 50 %, the measurement is considered as ice if another (more restricted) threshold over the peakiness is exceeded.

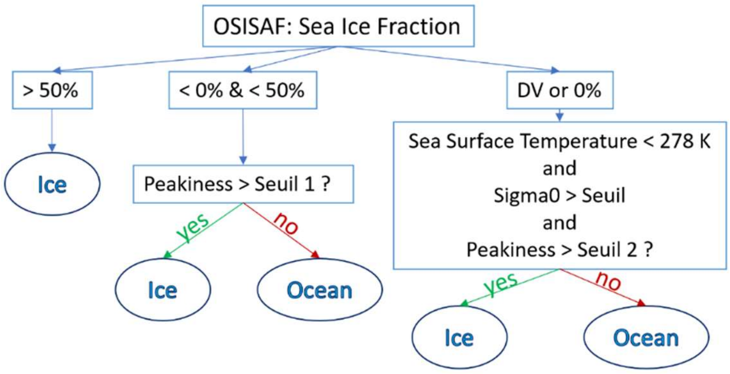


Figure 7-3: Scheme of ice detection process at 20Hz for TDP coastal & ocean SLA validation flag over ocean purpose

CHOICE OF THRESHOLDS

Figure 7-4 shows repartition histograms of backscatter coefficient over ocean and ice. Both histograms are different but the threshold of 20dB is coherent for both MLE3 and adaptive retracking to insured not to select ocean data: a threshold of 20dB on backscatter coefficient is used for both retrackers.

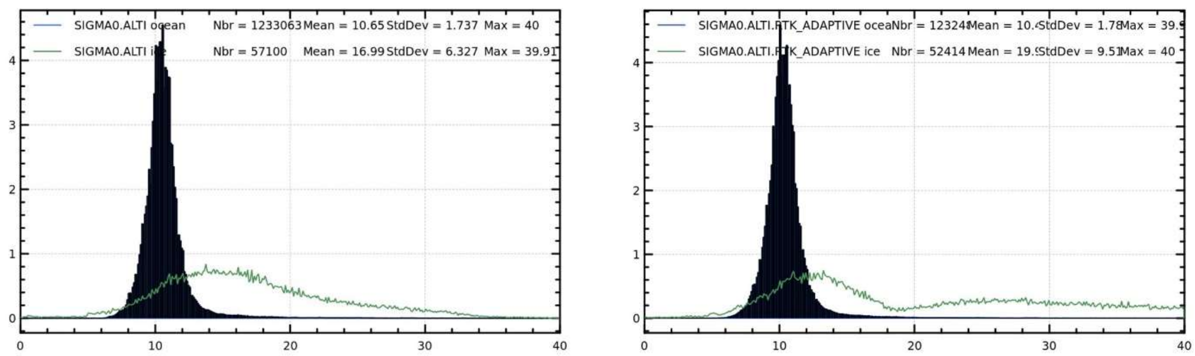


Figure 7-4: Histogram of backscatter coefficient for ocean (plain blue) and ice only (green curve) for MLE3 [left] and adaptive [right]

As presented in Figure 7-3, two different thresholds are needed for peakiness whereas sea ice fraction is in]0,50%], or set to zero / undefined. The first threshold ("seuil1" in Figure 7-3) is applied if the OSISAF sea ice fraction is between 0 and 50% and aim at excluding most of the ocean data: it has been fixed to 2.2 for ENVISAT (blue bars of Figure 7-5). The second one ("seuil2" in Figure 7-3) needs to strictly exclude all ocean data in case of unusable statement of sea ice fraction: it has been fixed to 22 for ENVISAT (green curve of Figure 7-5).

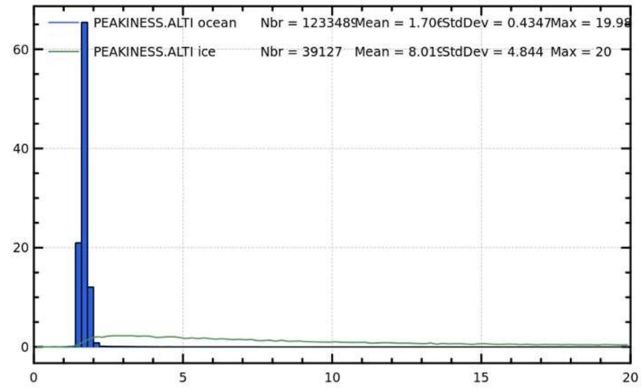


Figure 7-5: Histogram of peakiness over ocean (plain blue) and ice (green curve)

RESULTS

These two ice flags (one for MLE3 and one for adaptive retracking) has been computed and compared with the 1Hz flag ice. The two new ice flag show very good consistency with less than 250 measurements (over 35 days of 20Hz data) considered as ice for one retracking and not for the other. On the other hand, these new ice flags show some differences with the 1Hz ice flag. Figure 7-6 shows MLE3 new ice flag and the 1Hz one (duplicate at 20Hz) on top and the difference between both on the bottom. In red the newly rejected measurements that seems concentrated on iced area. In green the measurements that are no longer considered as ice that seem to be mostly on open ocean area.

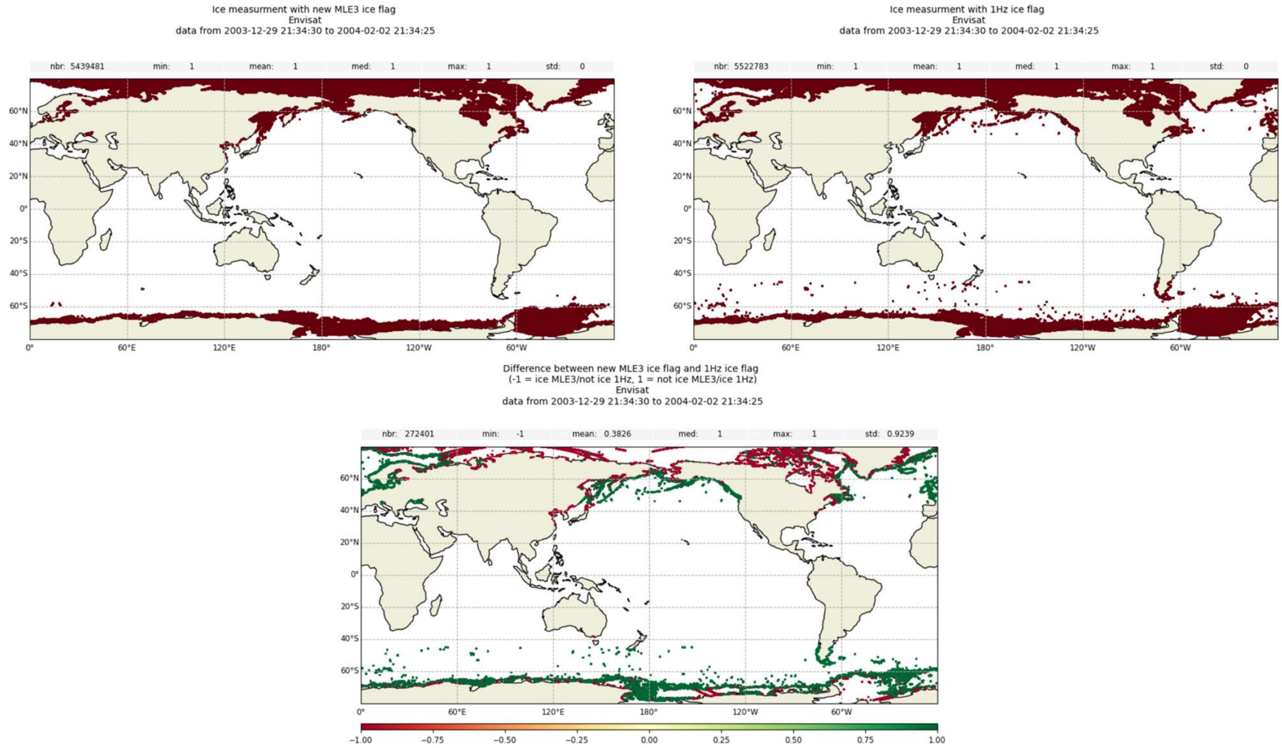


Figure 7-6: New ice flag [left], 1Hz ice flag [right] and differences between both [bottom]

7.8.2.2.2 Second step: Validation flag

REMOVAL OF DEFAULT VALUE

If one of the required fields is not defined, the measurement is invalidated, the validity flag is set to 1. The required fields are:

- Coastal distance (model GSHHG)
- Sea Level Anomaly (Orbit – Range - Geophysical corrections – Mean Sea Level)
- Ice flag
- Longitude
- Latitude
- Oceanic variability
- Filtered wave

Threshold validation

The second check, corresponding to the validation flag set to 2 is a threshold validation step. These thresholds are:

- Coastal distance < 0km (land measurements)
- |Sea Level Anomaly| > 2m
- Ice flag > 0 (ice measurements)

Robust std/mean validation

The third verification is the removal of outliers on the Sea Level Anomaly, which set the validity flag to 3. The condition of selection of outliers is:

$$|value - mean| > 5 + OceanicVariability * 10 * std$$

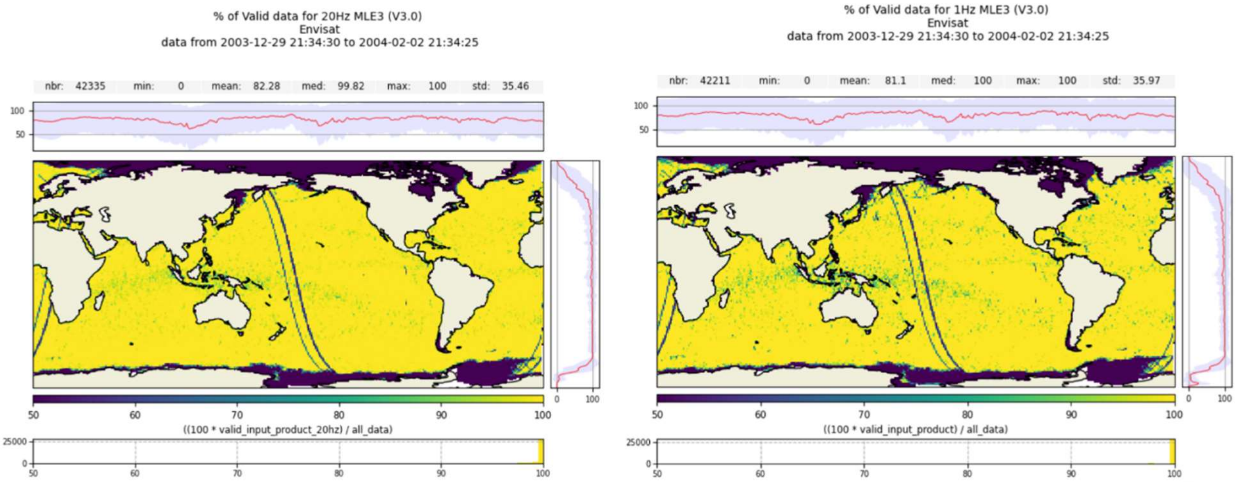
Iterative filter

The last step, associated to value 4 of the validity flag is an iterative composite filter on the Sea Level Anomaly. Maximal number of iterations is 5. The filter is composed of a median filter with a half window size of 1 and a Lanczos filter with a half windows size of 4.5. Threshold of this filter is swh dependant:

$$2.3 * (1 + (\,if\ (SWH.ALTI.FILTR\ >\ 2)\ then\ 0.3 * SWH.ALTI.FILTR, else\ 0.6))$$

Results

Validation flag has been computed for MLE3 retracking with V3.0 standards. Figure 7-7 shows the rate of valid points at 20Hz and 1Hz and their differences over thirty-five days of data. Both validation flags (at 20Hz and 1Hz) are coherent.



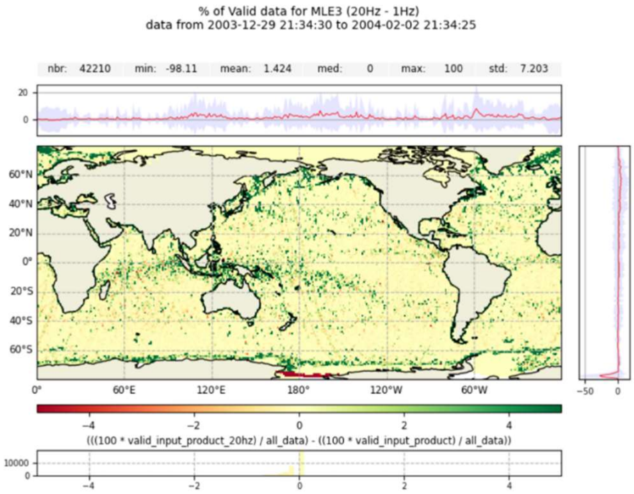


Figure 7-7: Validation flag for MLE3 retracking with V3.0 standards at 20Hz [left] and 1Hz [right] and their differences (percentage per box).

7.8.3 Merge into one single validation flag

Global ocean and coastal ocean processing is done independently. At this stage, before merging each processing (global or coastal) will have a flag indicating if a particular data point is rejected (value 0) or valid (value 1). At the merging step, we apply Boolean logic to give the final meaning to the validation flag:

- 0 means the data has been rejected by both global and coastal processing.
- 1 means data is valid over the open ocean.
- 2 means data is valid over the coastal ocean.

If a user wants to know if the data is to be used, regardless of the application, he can simply test if the values is different from 0. For more specific applications, he can test if values is 1 (for the open ocean) or 2 (if interested in coastal areas).

7.9 Outputs

The output for the ocean and coastal TDP consists of a set of NetCDF files with 4 groups and the following variables (please note that variables in data_01_main and data_20_main are the same):

group data_01_main

- ✓ time
- ✓ latitude
- ✓ longitude
- ✓ sea_level_anomaly
- ✓ inter_mission_bias
- ✓ validation_flag
- ✓ distance_to_coast
- ✓ meso_scale_uncertainty
- ✓ short_scale_uncertainty

group data_01_expert

- ✓ time
- ✓ latitude
- ✓ longitude
- ✓ sea_level_anomaly
- ✓ inter_mission_bias
- ✓ validation_flag

- distance_to_coast
- meso_scale_uncertainty
- short_scale_uncertainty
- surface_classification_flag
- altitude
- range
- sea_state_bias
- ionospheric_correction
- range_ssb_hfa
- wet_tropospheric_correction
- dry_tropospheric_correction_model
- dynamic_atmospheric_correction
- ocean_tide_height
- ocean_tide_height_model_type
- internal_tide
- pole_tide
- solid_earth_tide
- mean_sea_surface

group data_20_main

- time
- latitude
- longitude
- sea_level_anomaly
- inter_mission_bias
- validation_flag
- distance_to_coast
- meso_scale_uncertainty
- short_scale_uncertainty

group data_20_expert

- time
- latitude
- longitude
- sea_level_anomaly
- inter_mission_bias
- validation_flag
- distance_to_coast
- meso_scale_uncertainty
- short_scale_uncertainty
- surface_classification_flag
- altitude
- range
- sea_state_bias
- ionospheric_correction
- high_frequency_adjustment
- wet_tropospheric_correction
- dry_tropospheric_correction_model
- dynamic_atmospheric_correction

- ✓ ocean_tide_height
- ✓ ocean_tide_height_model_type
- ✓ internal_tide
- ✓ pole_tide
- ✓ solid_earth_tide
- ✓ mean_dynamic_topography
- ✓ mean_sea_surface

7.10 Reference Documents

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8 Ocean Waves Thematic Data Products

8.1 Inputs

For this dataset SWH and range outputs from the Adaptive retracker is necessary (ALTFDR_EN_RTK_ADAPTIVE). By construction no Look-Up tables (LUT) are needed.

Parameter	Variable name	source	unit
SWH	*swh_adaptive*	ALTFDR_EN_RTK_ADAPTIVE	meters
sea ice concentration	*sea_ice_fraction*	*OSI-SAF*	%
Distance to closest shoreline GSHHG	*distance_to_coast*	ALTFDR_EN_DISTANCE_TO_COAST	/
Altitude	*altitude*	ALTFDR_EN_ORBIT	meters
Range	*range*	ALTFDR_EN_RTK_ADAPTIVE	meters
Mean Sea Surface	mean_sea_surface	CNES/CLS15	meters

8.2 Logical Flow

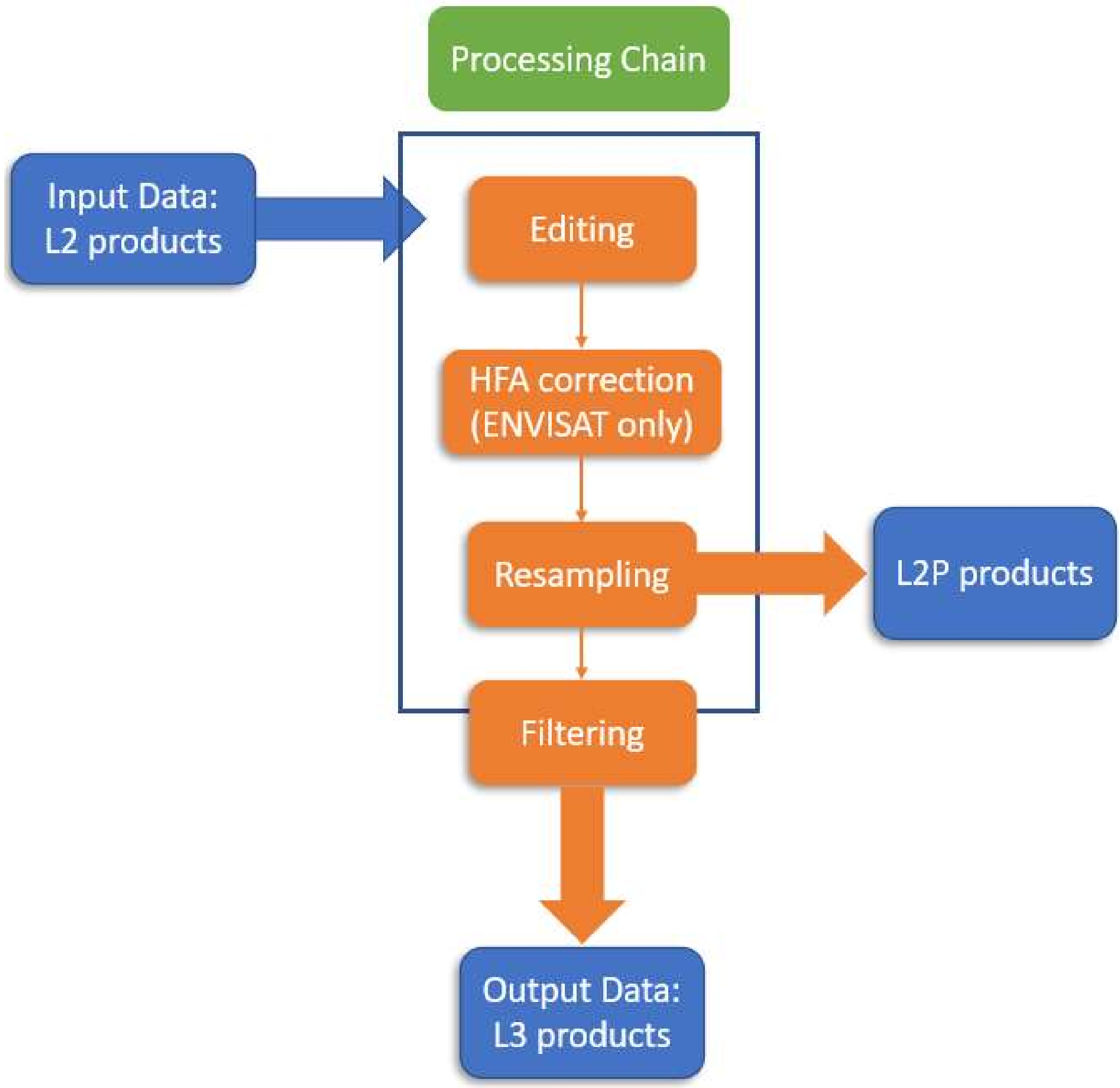


Figure 8-1 : Ocean Waves TDP. Compression process applied to post process 20Hz Adaptive retracking outputs

8.3 Key principles of the algorithms

8.3.1 Data selection (editing) method at 20Hz

The data selection has two main steps/objectives:

- ✓ Making the best data selection to keep as many "good" data as possible, notably near coasts.
- ✓ Removing the noise by a new compression method based on this data selection.

To determine if a SWH value is considered valid, the processing follows the two following steps:

Removing large outliers

The removal of large outliers is based on three criteria:

- ✓ Values of SWH below 0 m and above 20 m are considered as invalid data.
- ✓ All measures on land are removed using *distance_to_coast*
- All measures on points polluted by sea ice are removed. Every measure with a strictly positive sea_ice_fraction value (from OSI SAF data) is considered as invalid.

Iterative statistical removal of closer outliers

The second step is an iterative statistical one:

- ✓ The SWH signal is filtered by a Median filter (half size window = 0.4 s) and a Lanczos filter (half size window = 12 s)
- ✓ All points out of the interval [filter_signal – thresh*STD; filter_signal + thresh*STD] (STD is the standard deviation of the difference between the signal and the filtered signal) are removed.

The parameter *thresh* depends on the mission. During this step, it is important to consider the fact that the high frequency content of waves, (speckle noise, correlation effects and signal not captured by ERA5 model) is higher for high waves. Thus, this parameter *thresh* should depends on SWH values if one does not want to remove valid high SWH data.

The value of this parameter is computed with the following processing: the standard deviation of the difference between SWH measures and ERA5 data is computed per bins of SWH values (the size of each bin being 0.05 m). The data selection made for this computation is removing every data on land (distance to the coast below zero), all SWH values out of the interval [0m, 20m] and data above latitude of 60°.
This gives a different curve for each mission and each retracking algorithm. From this curve, a linear regression between two and six meters is computed to evaluate the slope of the evolution of the variability under 300 km in SWH measured data as a function of SWH values.

To compute the threshold parameter mentioned above, it is computed with this function:
If SWH < 2:
    Thresh = 3
Else:
    Thresh = (3 – 2*slope) + slope*SWH

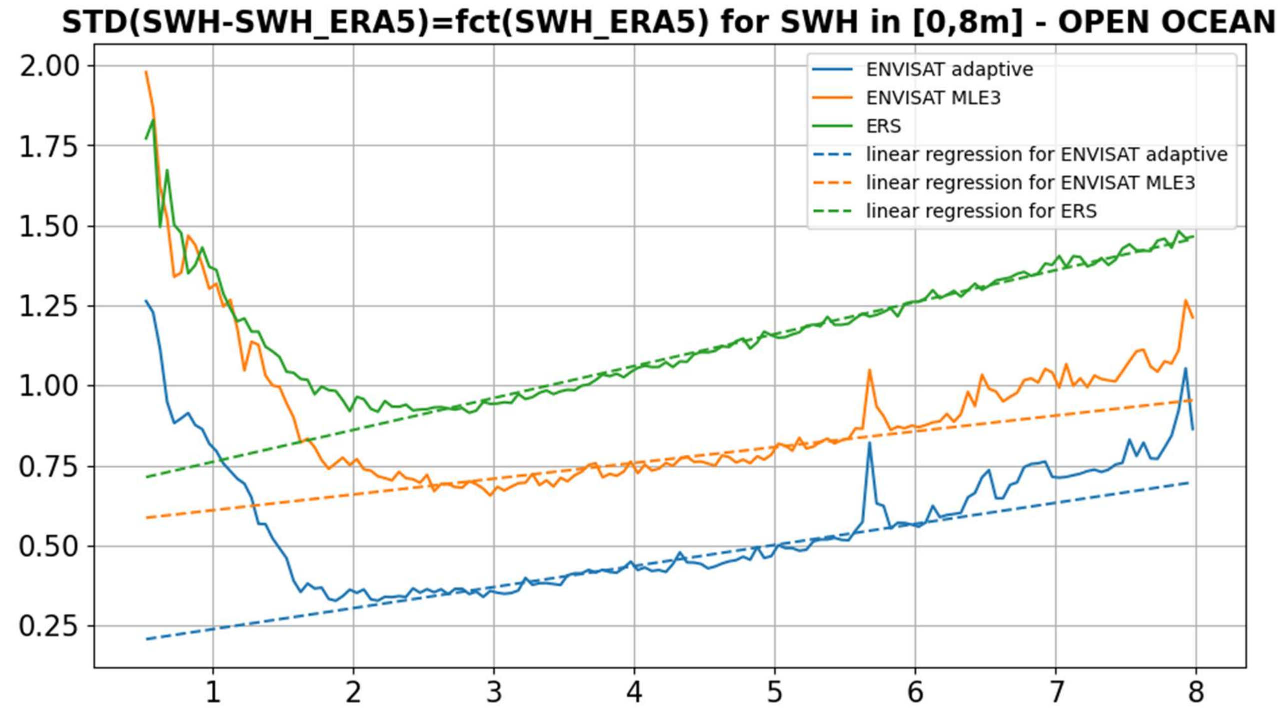


Figure 8-2 : Ocean Waves TDP. The data selection is tuned to free the natural variability of high waves. Dependency of STD(SWH) to SWH value, linear between 2m and 6m for ENVISAT (with MLE3 and Adaptive retracking) and ERS

8.3.2 HFA for SWH computation method

Similarly to the HFA application that reduces the high-frequency noise in 20Hz SSH for the TDP Ocean and Coastal, it is possible to apply a HFA correction for 20Hz SWH to reduces its high-frequency noise. In this case, it is the SWH noise correlated to the range noise that is removed by following the approach described in **[RD-44]**. The HFA correction for SWH is computed from 20Hz data and is based on the following formulae:

HFA_for_SWH = F(filtered_SLA_REDUCED) * (SLA_REDUCED – filtered_SLA_REDUCED)

where SLA_REDUCED = (orbit – range – MSS), filtered_SLA_REDUCED is the low-pass filtered SLA_REDUCED, MSS is the 2015 CNES/CLS mean sea surface [**RD-**] and F is a polynomial function of the form : y=a+b*(x^{-1})+c*($x^{0.5}$)+d*(x), and its parameters are determined by polynomial regression. The approach consists in the following steps:

- Compute the SLA_REDUCED values.
- Compute the filtered_SLA_REDUCED with a Lanczos filter.
- Compute the HFA_for_SWH by applying the polynomial model.

Note that the HFA_for_SWH term is not applied on some 20-Hz SWH value when the associated SLA_REDUCED value is larger than a threshold and it is therefore considered as anormal value.

8.3.3 Compression method

The resampling step consists in processing high-resolution data (20 Hz) to obtain the final 5 Hz resolution which is the final resolution of the Ocean Waves TDP.
It is not a brutal mean by group of 4 or 8 values that would damage the spectral content of final data.

The method chosen here is designed to preserve this spectral content and is divided into four steps applied on each group of four or eight values (depending on the initial data frequency):

- ✓ Computing the SWH mean value using an arithmetic mean (a linear regression using least square method or least absolute deviation is also possible): SWH_mean
- ✓ Compute the standard deviation with Bessel's correction (degrees of freedom n-1): SWH_std
- ✓ If the standard deviation is below a given threshold, stop the process
- ✓ Restrict the set of SWH values to compress: Remove all SWH values such as $|SWH - SWH\_mean| \geq 3 * SWH\_std$.

The validation flag taken for 5 Hz times is the one computed at 20 Hz at the same date.

8.3.4 Filtering of 5 Hz data with Empirical Mode Decomposition method (EMD)

The method to filter the Level-2P data is the Empirical Mode Decomposition (EMD) described in [**RD-48**]. The method was adapted to be functional with 5 Hz data instead of 1 Hz and applied to L2P data to remove the spectral bump at 10 km and obtain a smooth along track SWH signal.
The choices made for the computation of the Empirical mode decomposition was:

- ✓ To fill small gaps (less than 15 points in a row) of missing or invalid data.
- ✓ To compute the EMD filtering on each pass: the processing of one pass is independent of the previous one.
- ✓ The number of denoised IMF (Intrinsic Mode Function) is set to 2.
- ✓ The method used is the Iterative Interval Thresholding (see [**RD-48**])

8.3.5 Computation of uncertainties

The method used to compute uncertainties is based on the residual between the raw signal and the filtered signal (with EMD method). The spectral analysis of both signal show that the two spectra (with and without EMD filtering) split below 50 km.
Therefore, it has been decided to compute the uncertainty on the filtered data as the standard deviation of this residual between the filtered and the un-filtered SWH along track signal on a moving window of 50 km.

8.3.6 Calibration of ERS data

8.3.6.1 Goal of the calibration step

The calibration step between missions (ERS-2 and ENVISAT; ERS-1 and ERS-2) aims at obtaining a consistent time series of significant wave height (SWH) data over the whole studied time period.

8.3.6.2 ERS-2 compared with ENVISAT

ENVISAT and ERS-2 missions did not have a tandem phase where both satellites can measure the same place at approximately the same time.
However, over one year from 2002 June to 2003 May, ERS-2 and ENVISAT orbits have a lot of cross over points with a time delta inferior to 3 hours. Those points can then be used to compute a correction of ERS-2 data depending on the significant wave height, as illustrated in Figure 8-3:

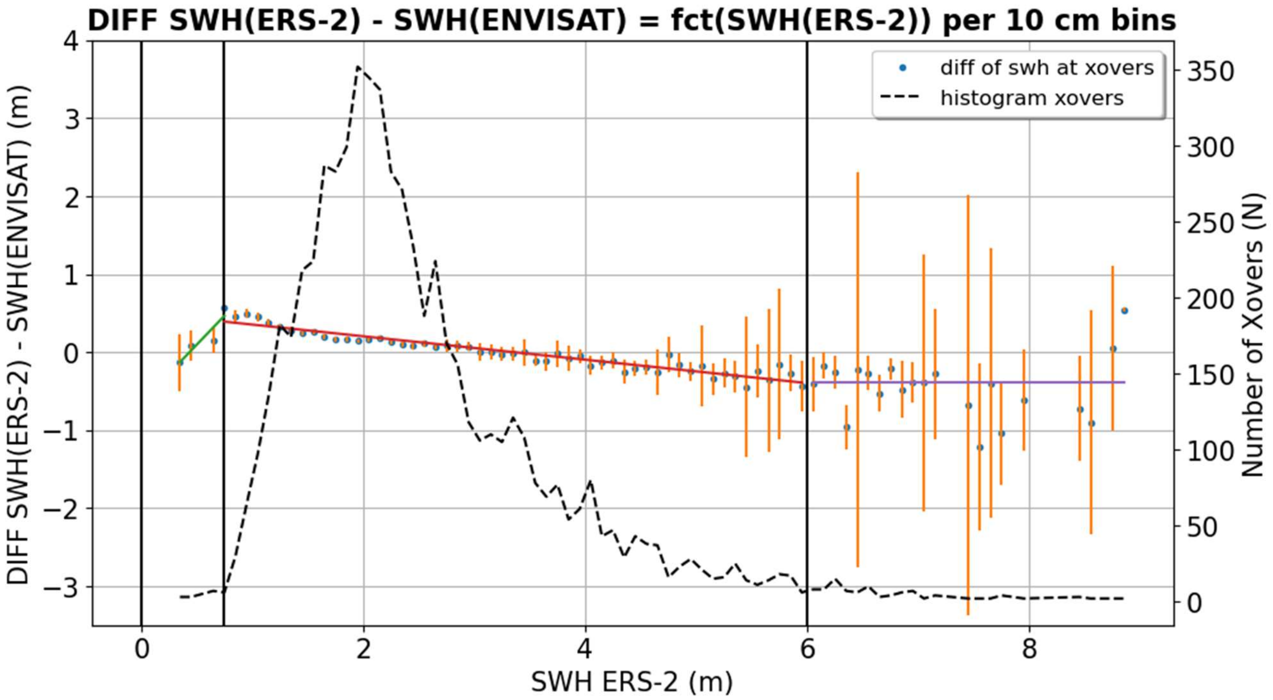


Figure 8-3 : Differences between ERS-2 and ENVISAT SWH data with respect to SWH

A linear regression on different intervals is computed to interpolate the correction to be applied to ERS-2 data.

8.3.6.3 ERS-1 compared with ERS-2

The same method cannot be applied between ERS-1 and ERS-2 data because there are no cross over points between ERS-1 and ERS-2 orbits with a 3 hours delta time constraint.
It was necessary to find another method to perform a calibration between ERS-1 and ERS-2 data (as ERS-1 and ERS-2 missions did not have a tandem phase either).
The idea is to use the ERA5 model SWH data as a common reference to compare ERS-1 and ERS-2 data and to substract the piecewise linear calibration. The goal is not to perform a calibration between ERS-1/2 and the model, but to use the model as an externalreference to reduce the geophysical variability.
The difference between ERS-2 and ERA5 SWH data is computed with respect to ERA5 SWH. The same diagnosis is performed on ERS-1 data. Results from this step are presented in the following Figure 8-4:

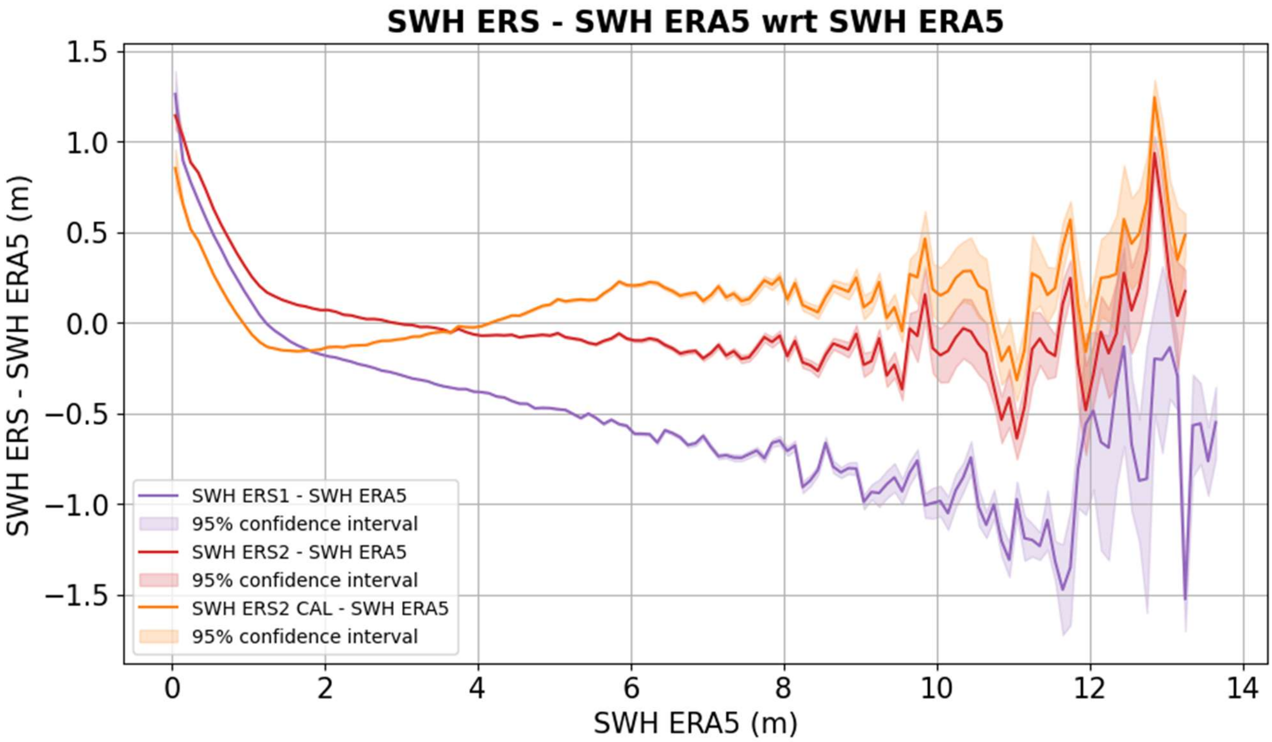


Figure 8-4 : Differences between ERS-1 ; ERS-2 data and ERA5 model SWH data

Then, the difference between the purple and the orange curve is computed to obtain a difference between ERS-1 and ERS-2 with respect to ERA5 SWH data. The result is presented In the following Figure 8-5:

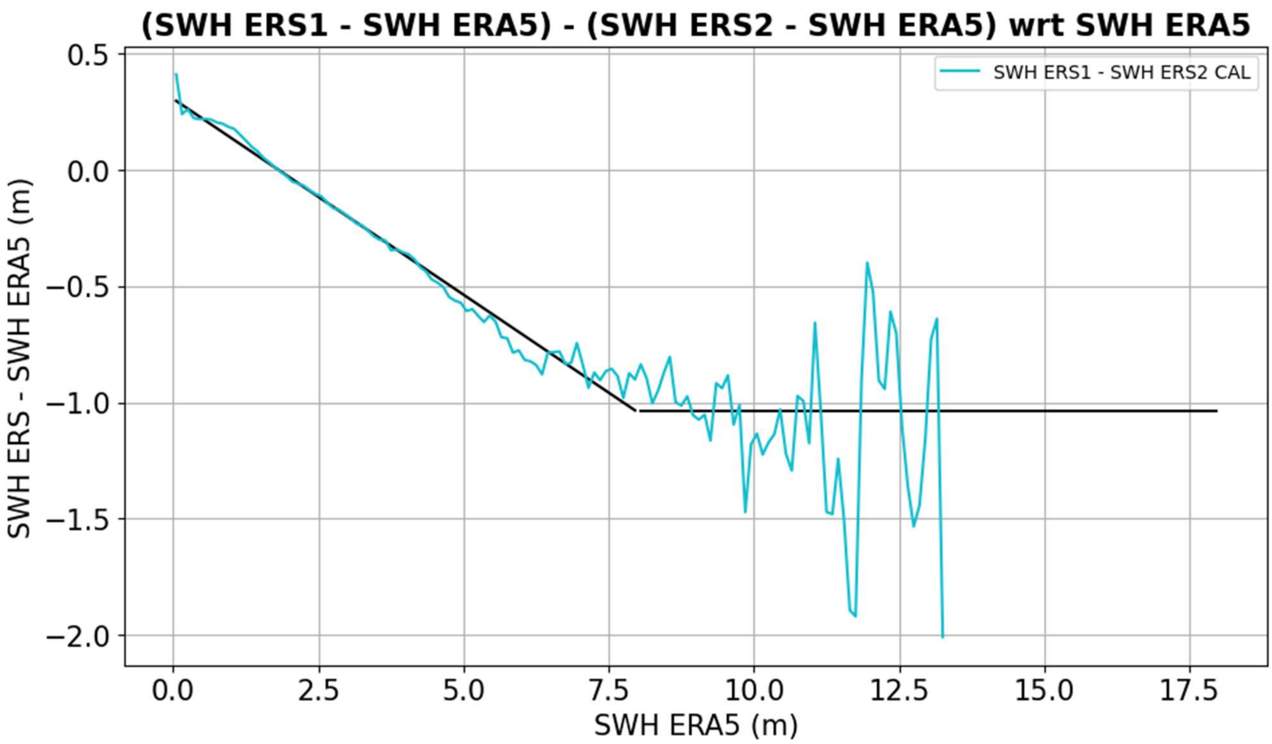


Figure 8-5 : Differences between ERS-1 and ERS-2 data with respect to ERA5 data

As for the calibration between ERS-2 and ENVISAT data, a linear regression is computed per interval to interpolate the correction to be applied.

However, below a value of 0.35 m, nothing is done because removing the value suggested by the correction for SWH values below 35 cm would lead to a negative resulting value for SWH.

Results from this calibration step are presented in the Ocean Wave TDP chapter of the FDR4ALT Validation Report [D-4-02].

8.4 Outputs

The outputs consist of 4 fields:

- ✓ the raw significant wave height averaged and compressed at 5Hz.
- ✓ the EMD filtered field, calibrated on ENVISAT data (for ERS-1 and ERS-2 missions)
- ✓ The bias applied to uncalibrated data is also in final products.
- ✓ The uncertainty associated.

swh_adjusted
swh_adjusted_filtered
swh_bias_adjusted
swh_uncertainty

Flagged data are set to default value in order to be compliant with L3 CMEMS format (see [**RD-49**] [**RD-50**])

8.5 Reference Documents

RD-48	Ocean Surface Wave-Current Signatures From Satellite Altimeter Measurements Y. Quilfen, B. Chapron, GRL, 2018
RD-	Pujol, M.-I., Schaeffer, P., Faugère, Y., Raynal, M., Dibarboure, G., & Picot, N. (2018). Gauging the improvement of recent mean sea surface models: A new approach for identifying and quantifying their errors. Journal of Geophysical Research: Oceans, 123, doi: 10.1029/2017JC013503.
RD-49	https://catalogue.marine.copernicus.eu/documents/PUM/CMEMS-WAV-PUM-014-001-002-003-004.pdf
RD-50	https://catalogue.marine.copernicus.eu/documents/QUID/CMEMS-WAV-QUID-014-001.pdf

9 Inland Water Thematic Data Products

9.1 Input data and corrections

Input variable	Source	Unit
Altimetry data		
Orbit	ALTFDREN_ORBIT and ALTFDR_ERS_ORBIT	m
Range MLE3	ENVISAT V3.0 and ERS REAPER	m
Range Adaptive	L2_ENVISAT_RANGE_SIGMA0 (ENVISAT only)	m
Range ICE-1	ENVISAT V3.0 and ERS REAPER	m
Range TFMRA	L2_ENVISAT_RANGE_SIGMA0 and L2_ERS_RANGE_SIGMA0	m
Geophysical corrections		
DTC (Dry Tropospheric Correction)	ERA Interim model from ECMWF	m
WTC (Wet Tropospheric Correction)	ERA Interim model from ECMWF	m
IC (Ionospheric Correction)	GIM (Global Ionosphere Map) is provided for ENVISAT and ERS2 missions while NIC09 (NOAA Ionosphere Climatology) is provided for ERS1 mission	m
Tides		
Pole tide correction	Desai, Wahr, and Beckley [2015], Revisiting the pole tide for and from satellite altimetry	
Solid earth tide correction	Cartwright and Edden [1973] Corrected tables of tidal harmonics - J. Geophys	
Ancilliary data		
Land water occurrence	Statistical water occurrence from Global Surface Water Explorer (1984-2015).	
Surface type	Global Lakes and Wetlands Database classification	

Altimetry data:

- **Orbit from ALTFDR_EN_ORBIT; ALTFDR_ERS_ORBIT** : The orbit of the satellite is calculated by the ground segment of each mission: ERS1, ERS2, ENVISAT. It corresponds to the altitude of the satellite above the reference ellipsoid (WGS84)

  Range: Over continental waters, the radar echo which is assembled into waveforms usually does not fit with the Brown model (waveform class 1), for which the on-board tracking algorithm was adapted. Hence, alternate algorithms are run during post-processing, the so-called retracking algorithms to calculate the range:
    - MLE3 from V3.0 (ENVISAT) and REAPER (ERS)
    - ICE-1 from V3.0 (ENVISAT) and REAPER (ERS)
    - TFMRA from ALTFDR_EN_RTK_TFMRA and ALTFDR_EN_RTK_TFMRA
    - Adaptive from ALTFDR_EN_RTK_ADAPTIVE (ENVISAT only)

Geophysical corrections:

- **DTC**: Dry Tropospheric Correction is directly proportional to the atmospheric pressure and is provided in the expert group of the Inland Water TDP. The altitude of the water body is taken into account.

WTC: Wet Tropospheric Correction is related to the water vapor contained in the air column that the electromagnetic wave intersects. It can be estimated in two ways: either with an onboard bi- or tri-frequency radiometer or from a global meteorological model. For Inland Waters is most appropriate to use data from model.

IC: The Ionospheric correction is related to the interaction of the electromagnetic wave with free electrons in the upper atmosphere

Tides: The Earth tide (ET) and Pole tide (PT) are estimated using models and are included in the FDR.

Ancillary data:

- **GSWE**: The Global Surface Water Explorer dataset, developed by European Commission's Joint Research Centre in the framework of the Copernicus Programme, maps the location of water surfaces at global scale providing statistics on the occurrence of water.

  GLWD3: Global Lakes and Wetlands database contains information of lakes, reservoirs, rivers, and different wetland types in the form of a global raster map at 30-second resolution.

9.2 Key principles of the algorithm

Radar altimeters send an electromagnetic pulse to the satellite nadir and record the propagation time to and from the emitted wave and its echo from the surface (Figure 9-1)

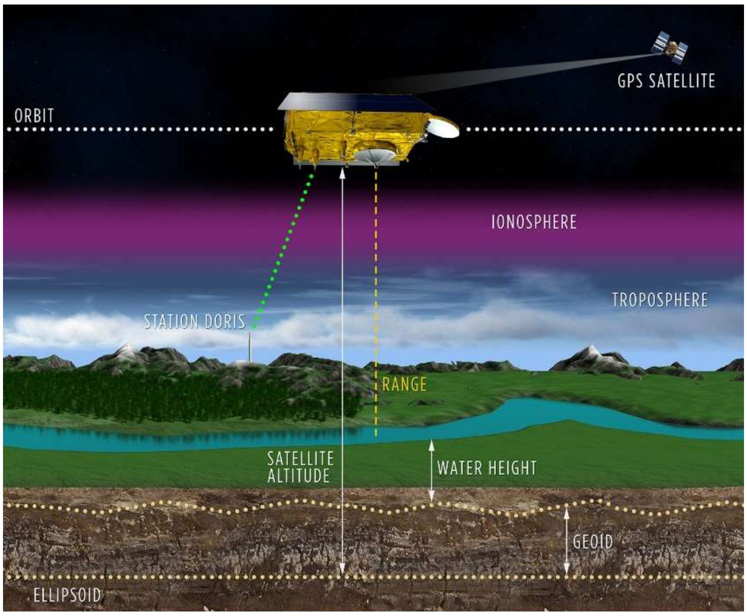


Figure 9-1. Key principles for Inland Water estimation (Credits Cnes/Mira Production/Aviso)

The height *H* of the reflective surface is given by the following equation (**RD-51**, **RD-52**):

$$H = -a - (R + \Sigma C_p + \Sigma C_g)$$

Equation 2

where *a* is the orbital altitude of the satellite with respect to the ellipsoid and R (range) is the distance between the satellite and the reflective surface Corrections must be made for propagation in the atmosphere (C_p) and also vertical movements of the Earth's crust (C_g).

9.3 Logical Flow

The logical flow for the processing of the water surface height is show in Figure 9-2

Figure 9-2. Inland Water – Logical Flow

9.3.1 Measurement selection

The first step consists in selecting only the measurements over land. Furthermore, only measurements with water occurrence values above 0 are selected. This occurrence is based on the Global Surface Water Explorer dataset which contains the frequency of occurrence of water on the land surface over the period 1984-2015, expressed as percentage of time. The spatial resolution of this dataset is 30m.

9.3.2 Edition of values based on backscatter coefficient values

Measurements with a backscatter coefficient below a retracking-dependent threshold are edited. The value of the threshold was defined empirically based on the distribution of sigma0 over different hydrological targets (lakes and reservoirs, rivers, floodplains, and wetlands) with land water occurrence of 100 percent based on Global Surface Water Explorer. Figure 9-3 shows the distributions for ICE1 and Table 13 contains the thresholds for the different retrackers.

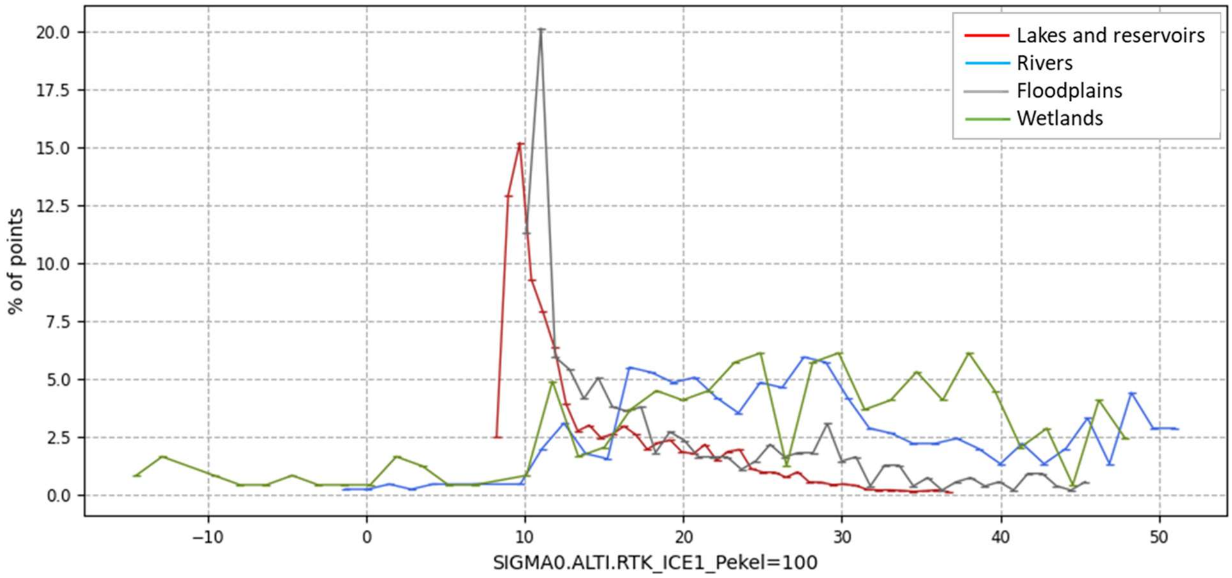


Figure 9-3. Distribution of the backscatter coefficient over different hydrological targets with occurrence values of 100

Retracker	MLE4	ICE1	ICE3	TFMRA	ADAPTIVE
Threshold	7 dB	5 dB	40 dB	8 dB	10 dB

Table 13. Backscatter coefficient thresholds in the inland water TDP

9.3.3 Edition of values based on geophysical corrections

An editing based on geophysical corrections is also applied. Since for inland waters these corrections are model based, very few data measurements should be edited in this step. The values of those thresholds are indicated in *Table 14*.

Correction	Thresholds	
	Minimum	Maximum
Dry Tropospheric Correction	-2.5	-1.2
Wet Tropospheric Correction	-0.8	0.01
Ionospheric Correction	-0.4	0.04

Table 14. Geophysical correction thresholds in the inland water TDP

9.3.4 Estimation of the water surface height

As described in section 9.2, the water surface height below geoid is estimated by Equation 2

9.3.5 Quality flag

The quality flag is defined as a function of the waveform classification **[RD-53].** The different classes are shown in Figure 9-4. These classes are common to the three missions (ENVISAT, ERS1 and ERS2) For the waveforms 1, 2, 4 and 6 the target of the measure is a water body implying there is a good quality estimation. The measures with waveforms classes 5, 12 and 16 cannot be totally reliable to be on water bodies and they are considered as medium quality estimations. For measurements where the water surface height could not be estimated, the quality flag is considered as unknown (or 'no_data'). This is also the case for the measurements with the remaining waveforms classes, poorly presented in the datasets.

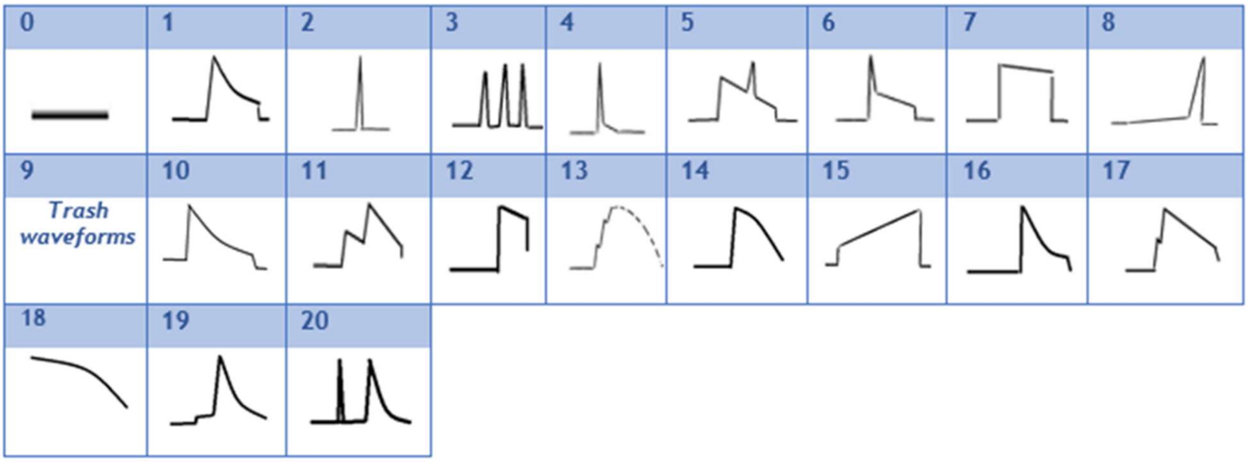


Figure 9-4. List of waveform classes (common to ENVISAT and ERS missions)

Other mission-dependent factors also have an impact on the quality of the measurement. Indeed, for ENVISAT mission, adaptive height resolution operation was implemented by selecting the transmitted bandwidth (320, 80 and 20 MHz). Over land, degraded measurements (with a bandwidth lower than 320 MHz), may result in lower quality of the estimations. For this reason, the quality flag was set to a bad quality for these measurements.

Concerning ERS-2 and ERS-1, the flag definition is similar for the waveform classification. Nevertheless, as the reference mode for land surfaces is ice (82.5 MHz), this information is not considered for the quality flag.

9.3.6 Uncertainty

The uncertainty provided for each measurement is, as explained in "Uncertainty characterization document", based on an error budget approach, summing all uncertainties form each component of WSH (Equation 2). These uncertainties use a combined empirical and theorical approach.

9.3.7 Ancillary data

Information on the type of surface, based on GLWD3, as well as information on the occurrence of water, based on GSWE, is added to the final product, providing useful information to end-users.

9.4 Outputs

The output for the Inland Water TDP consists of a set of NetCDF files with the variables separate in two groups:

Main group: adequate to most of the users:

time
longitude
latitude
wsh_above_ellipsoid: the water surface height above the ellipsoid WGS84 estimated with the most appropriate retracker for inland waters. The ICE1 retracker was selected after a round robin analysis of data from multiple retrackers as MLE4, TFMRA, ICE3 and Adaptive (available for ENVISAT data) that includes comparison to external datasets (Level 3) as well as the estimation by retracker of the (orbit-range) uncertainty and the percent of measurements edited due to the threshold of the backscatter coefficient (Level 2)
wsh_quality_flag
wsh_uncertainty
geoide_correction_model
land_water_occurrence: based on Global Surface Water Explorer
surface_type: based on GLWD3

Expert group: with additional data useful for specific targets or allowing the estimation of the water surface heigh with different retrackers or the use of different geophysical corrections.

waveform_class: the most probable waveform class
sigma0: backscatter coefficient in main altimeter frequency (one variable per retracker: mle4, ice1, ice3, tfmra, adaptive)
range_[rtk]: range estimated in main altimeter frequency (one variable per retracker: mle4, ice1, ice3, tfmra, adaptive)
altitude: the altitude of the satellite above the geoid
wet_tropospheric_correction_model
dry_tropospheric_correction_model
ionospheric_correction_model
pole_tide_correction_model

solid_earth_tide_correction_model

9.5 Reference Documents

RD-51	Birkett CM, Beckley B (2010) Investigating the performance of the JASON-2/OSTM radar altimeter over lakes and reservoirs. Mar Geodesy 33(1):204–238
RD-52	Calmant S, Seyler F, Cretaux JF (2008) Monitoring continental surface waters by satellite altimetry, survey in geophysics, special issue on 'Hydrology from Space' 29(4–5):247–269. https://doi.org/10.1007/s10712-008-9051-1
RD-53	Poisson, Jean-Christophe & Quartly, Graham & Kurekin, Andrey & Thibaut, Pierre & Hoang, Duc & Nencioli, Francesco. (2018). Development of an ENVISAT Altimetry Processor Providing Sea Level Continuity Between Open Ocean and Arctic Leads. IEEE Transactions on Geoscience and Remote Sensing. PP. 1-21. 10.1109/TGRS.2018.2813061

10 Atmosphere Thematic Data Products

10.1 Intercalibration

The intercalibration between the three missions is achieved in the FDR products within the radiometric model through the characterisation parameters. Details about the processing can be found in section 3.2 of this report and in the Validation Report [D-4-02]. The intercalibrated brightness temperatures and the bias-adjusted brightness temperatures from the FDR are used for the generation of the Atmospheric TDP parameters.

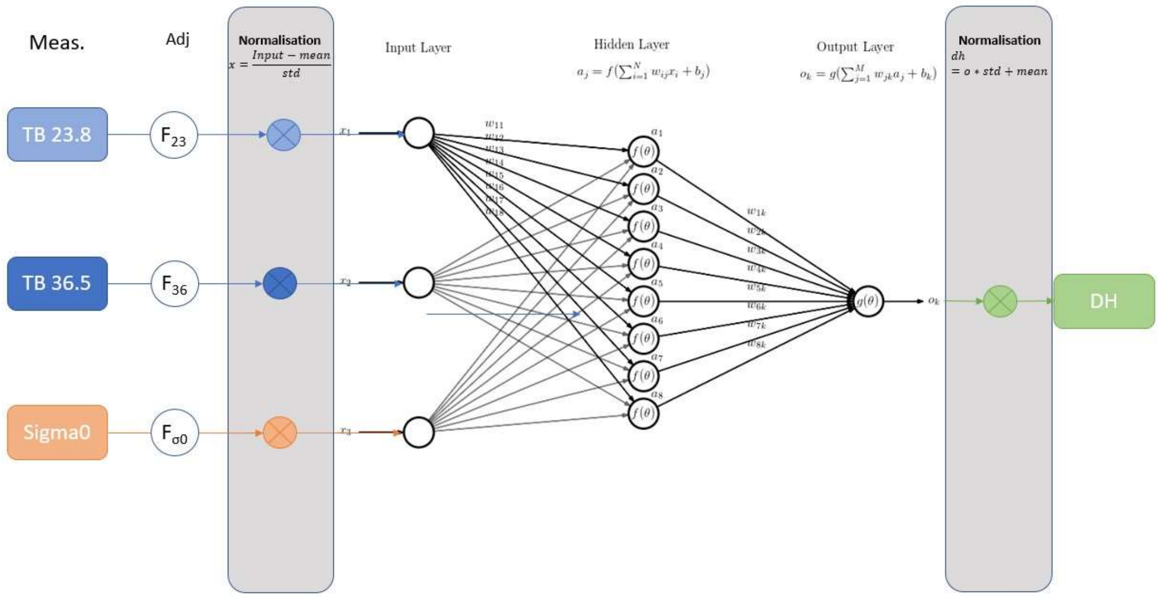
10.2 WTC, TCWV and LWP with Neural Network solution

10.2.1 Inputs

Name	source	unit	dimension
Calibrated and geolocated TB for 23.8GHz channel	MWRFDR_EN_TBCORR MWRFDR_TB	K	1
Calibrated and geolocated TB for 36.5GHz channel	MWRFDR_EN_TBCORR MWRFDR_TB	K	1
Sigma0 uncorrected of atmospheric attenuation (ERS)	*sigma0_mle3_nocorr* from L2_ERS_RANGE_SIGMA0	dB	1
Sigma0 uncorrected of atmospheric attenuation (ENVISAT)	*sigma0_adaptive* from L2_ENVISAT_RANGE_SIGMA0	dB	1
Sea surface temperature	ERA5	K	1
Atmospheric temperature lapse rate	ADF	K/km	1
Windspeed	ERA5	m/s	1

The main inputs to the retrieval are the calibrated and geolocated observations of the MWR brightness temperatures (TBs) at 23.8 GHz and 36.5 GHz, as well as the information on the surface roughness sigma_0 from concomitant radar altimeter observations.
It requires additionally the sea surface temperature (SST), and atmospheric temperature lapse rate values. These are taken from climatological data records.

10.2.2 Logical Flow



10.2.3 Key principle of the algorithm

The logical flow is identical for each output. The inputs are first adjusted using linear function coefficient to match the learning database dynamics. After that, it is normalised by subtracting its mean and dividing by standard deviation to provide inputs with the same scale. Inputs are propagated to layers of neurons and weighted by the weights resulting from the prior learning process. The output is computed using the sum of each weighted inputs of each neuron and finally un-scaled.
Two different kind of architecture is used for the FDR4ALT reprocessing. For the wet tropospheric correction and the total column water vapor, an algorithm by windspeed class defined. For the cloud liquid water content and the atmospheric attenuation, the classical architecture using one global class is used.

10.2.4 Outputs

The output of neural network algorithm will be the wet tropospheric correction, total water vapor content, liquid water path. The associated uncertainties will be provided for each parameter according to the Uncertainty Characterization Definition Document [D-5-01]

Name	unit	dimension
Wet tropospheric correction	m	1
Total column water content	kg/m2	1
Liquid water path	kg/m2	1
Atmospheric Attenuation of altimeter Ku-band sigma0	dB	1

10.3 TCWV, WTC, and LWP with 1D-VAR solution

10.3.1 Functional description

The FDR4ALT joint total column water vapour (TCWV) and cloud liquid water path (LWP) retrieval is based on a 1D-VAR scheme initially developed at ECMWF by Phalippou, 1996 **[RD-58]** with a focus on microwave observations from SSMIS and AMSU. It was later extended by Deblonde and English, 2001 **[RD-56]** towards a stand-alone scheme applicable to SSM/I, SSMIS, and AMSU. Subsequently, the TCWV retrieval scheme has been adapted to the CMSAF SSM/I Fundamental Data Record (FDR), and later on by Bennartz et al., 2017

[RD-55] to observations taken by the Microwave Radiometer (MWR) instruments onboard the ERS-1, ERS-2, and ENVISAT platforms.
The best estimate of the atmospheric state, characterised through atmospheric temperature and moisture profiles as well as surface temperature and wind speed, is determined by an iterative procedure to match simulated satellite radiances with the corresponding measurements within their respective uncertainties. The scheme follows optimal estimation theory considering the uncertainties in the required meteorological background information, forward modelling (radiative transfer simulations), and satellite observations. This methodology enables the provision of retrieval uncertainties that are mathematically consistent with the uncertainties of the input brightness temperatures and background fields and consistent among the retrieved variables.
The retrieved TCWV is used in a follow-on step to derive the wet tropospheric correction (WTC), using ancillary information on the atmospheric vertical structure from ERA-5 reanalysis.
The proposed method is applicable to the global ice-free open ocean. Close to the coast (i.e., less than ca. 50 km offshore), the retrieval accuracy is reduced.

10.3.2 Measurement function and processing/uncertainty diagram

The underlying retrieval follows an optimal estimation 1D-VAR retrieval strategy as described in Rodgers, 2000 **[RD-61]** and Deblonde, 2001 **[RD-60]**. The 1D-VAR retrieval used herein combines an iterative approach to calculate the optimal estimate of TCWV and LWP, given the observed brightness temperatures and other information, as specified and discussed below. Speaking in general terms, 1D-VAR finds an optimal solution for a vector of variables, ***x***, termed ”state vector”, given the observations, ***y***, and a set of other parameters that describe (among other things) the prior knowledge of the state of the parameters before the observations are incorporated. This prior knowledge is broadly termed “background knowledge”, or “*a priori”* knowledge [Rodgers, 2000] **[RD-61]**.
One of the advantages of the 1D-VAR approach is that it explicitly distinguishes different types of other input data, depending on their role in the retrieval process. This sets 1D-VAR approaches apart from other methods such as statistical inversion and provides better control over how input is handled, and more insights into the behaviour of the system and its uncertainty characteristics. In this context, four different types of input can be distinguished as outlined in *Table 15*.

Type of variable	Symbol	Principal function	1D-VAR realisation	Remarks
Observations and observation error covariance matrix	***y***, (***E***+***F***)	Observations ***y*** and their error characteristics (***E***+***F***). ***E***: instrumental error ***F***: representativeness error	MWR brightness temperatures (TBs)	The importance of the observations versus the background is determined by the magnitude of the observation error covariance matrix compared to the magnitude of the background error covariance matrix.
Parameter vector	***b***	Provide additional parameters, needed in the forward model, but not retrieved.	Sea surface temperature (SST), surface wind speed (U10M), water-vapour averaged mean inverse atmospheric temperature TM, atmospheric surface pressure (PSFC)	The 1D-VAR retrieval will depend on those parameters.
Background profiles and background error covariance matrix	$\boldsymbol{x}_b$, ***B***	Describes the best estimate of the state to be retrieved, before observations are included ($\boldsymbol{x}_b$) and its error covariance (***B***).	Parameterized as a function of an initial guess for TCWV	The degree to which the result of the 1D-VAR depends on the background information, depends on the information content of the observations.

First guess	x_0	Gives the starting point of the iterative 1D-VAR process.	Parameterized as a function of an initial guess for TCWV	In a well-posed 1D-VAR, the result is independent of the first guess.

Table 15: The different types of variables used in 1D-VAR and their realization within this project.

The various input parameters are discussed in full in the AMTROC ATBD [**RD-59**]. Here, we specify those parameters relevant to uncertainty estimation. The real-world relations between observations and the state of the observed system be characterized as follows:

$$\mathbf{y} = h^*(\mathbf{x}^*) + \mathbf{e}_\mathbf{y} \qquad (1)$$

- $\mathbf{y}$: Observations
- $\mathbf{x}^*$: Full, true state of the observed system in real world
- $h^*(\mathbf{x}^*)$: True relation between observations and system in real world
- $\mathbf{e}_\mathbf{y}$: Sensor noise

Note that the true state of the observed system (atmosphere and ocean) cannot be known. Only ***y*** is observed and known. Also, the sensor noise can be arbitrarily complicated, correlated between different observation frequencies and/or consecutive observations, and it might depend on various parameters, such as e.g., the temperature of the observing instrument or the magnitude of the signal received (i.e., on $h^*(x^*)$), amongst others. For any retrieval, the above Equation(1) must be approximated by:

$$\mathbf{y} = h(\mathbf{x},\mathbf{b}) \qquad (2)$$

- $\mathbf{y}$: Observations
- $\mathbf{x}$: State vector (variables to be retrieved from $\mathbf{y}$)
- $\mathbf{b}$: Variables not retrieved, but influencing forward model
- $h(\mathbf{x},\mathbf{b})$: Forward model

Note, that such an approximation is always necessary, either explicitly as in case of 1D-VAR retrievals where the forward model is explicitly specified, or implicitly as e.g., in case of empirical retrievals. For example, if an empirical retrieval is created by training a neural network using collocated observations ***y*** and components of the state vector ***x*** (e.g., wet tropospheric correction WTC), the forward model is implicitly inherent in the choice of combinations of ***y*** with WTC used for training the neural network.

10.3.3 The 1DVAR retrieval process

At the most fundamental level, a 1D-VAR retrieval thus works by inverting Equation(2) under appropriate constraints:

$$\hat{\mathbf{x}} = h^{-1}(\mathbf{y},\mathbf{b}) \qquad (3)$$

- $\hat{\mathbf{x}}$: Estimate of $\mathbf{x}$, given $\mathbf{y}$ and $\mathbf{b}$

The vector ***b*** is of crucial importance. It contains components of the observed system that affect ***y*** but are not directly retrieved. For example, in the context of WTC retrievals the vector ***b*** could include sea surface temperature and wind speed, among others.

The estimates of ***b*** must come from some source other than the observations and will inevitably also be associated with uncertainties. For example, a certain estimate of surface wind speed e.g., from altimeter or from a numerical weather prediction model will not be perfectly accurate. Rather it will have its own associated uncertainty. We therefore define another uncertainty matrix ***F*** that encompasses all uncertainties associated with ***b*** together with their covariances, expressed in kelvin. The term ***F*** can be arbitrarily complicated and often entails significant cross-correlations between different variables.

10.3.4 Calculation of a-posteriori errors

Defining the matrix ***E*** = *diag* (***e_y***), where ***e_y*** represents sensor noise and other sensor related error sources such as calibration uncertainty or temporal stability, the derivation of Equation (3) and Gaussian error propagation yields straight forward estimates of the *a-posteriori* error for the retrieved state:

$$\mathbf{E}_p = \left(\mathbf{K}(\mathbf{E}+\mathbf{F})^{-1}\mathbf{K}^T\right)^{-1} . \qquad (4)$$

$$K_{i,j} \; : \; \frac{\partial h_i(\mathbf{x},\mathbf{b})}{\partial x_j}$$

Here, the ***K***-matrix is the Jacobian of *h*, holding the derivates of *h* with respect to ***x***, while ***E*** and ***F*** represent instrumental errors and representativeness errors, respectively (see Table 15). The diagonal elements of the *a posteriori error* covariance matrix $\boldsymbol{E_p}$ hold the uncertainty of the retrieved variables $\hat{\boldsymbol{x}}$. We note here that the *a posteriori* error can be reduced by properly including background knowledge and associated background error covariances, if optimal estimation methods such as 1D-VAR are used. See [Rodgers, 2000] for more details on this. This, however, comes at the cost of including background information in the retrieval, which is not desirable in all instances. In any case WTC retrievals are heavily constrained by the observations alone and therefore, the inclusion of background data affects the retrieval only very weakly [Bennartz et al., 2017] [**RD-55**].
The above formulation however highlights the important point that beyond sensor noise, other parameters also affect the retrieval.

10.3.5 Input

The main input to the retrieval is the calibrated and geolocated observations of the MWR brightness temperatures (TBs) at 23.8 GHz and 36.5 GHz, as well as information on the surface roughness (sigma_0) from concomitant radar altimeter observations.
The 1D-VAR retrieval scheme additionally requires collocated TCWV, sea surface temperature (SST), and surface wind speed fields as *a priori* (background) values. These are taken from reanalysis (ERA-5).
Calculating WTC from TCWV additionally requires atmospheric profiles of pressure, temperature, and the water vapour mixing ratio. These profiles are also taken from the ERA-5 reanalysis.

Variable	Units	Description
TB at 23.8 GHz	K	From MWR FDR
TB at 36.5 GHz	K	From MWR FDR
Surface roughness sigma_0	dB	From concomitant altimeter observations
TCWV	km/m²	*A priori* value used in retrieval, from ERA-5
SST	K	*A priori* value used in retrieval, from ERA-5
Surface wind speed	m/s	*A priori* value used in retrieval, from ERA-5
Atmospheric pressure profile	Pa	Used to retrieve WTC from TCWV, from ERA-5
Atmospheric temperature profile	K	Used to retrieve WTC from TCWV, from ERA-5
Atmospheric water vapour mixing ratio profile	ppmv	Used to retrieve WTC from TCWV, from ERA-5

Table 16 : Input parameters for the different stages of the 1D-VAR retrieval scheme.

10.3.6 Inter-mission calibration

The inter-mission calibration of the Atmospheric TDPs is done at Level-1B by applying a bias correction to the top-of-atmosphere brightness temperatures TB which is described in more detail in Section 3.19. Applying the such inter-calibrated brightness temperatures as input to Level-2 product generation intrinsically produces inter-mission calibrated Atmospheric TDPs, i.e., TCWV, LWP, WTC, and ATT_KU.

10.3.7 Output

The FDR4ALT 1D-VAR retrieval output dataset is summarized in Table 16. The individual data files are provided in NetCDF 4 format and contain TCWV, WTC and LWP retrievals together with their associated *a posteriori* uncertainties, as well as various pieces of auxiliary information. Details on the result file contents are provided in the FDR4ALT Product Requirements and Format Specification document (see Table 18).

Variable	Units	Description
Total column water vapour	kg/m^2	Instantaneous retrieved value
Uncertainty of TCWV	kg/m^2	*A posteriori* uncertainty of instantaneous retrieved value
Liquid water path	kg/m^2	Instantaneous retrieved value
Uncertainty of LWP	kg/m^2	*A posteriori* uncertainty of instantaneous retrieved value
Wet tropospheric correction	m	Instantaneous retrieved value
Uncertainty of WTC	m	*A posteriori* uncertainty of instantaneous retrieved value
Attenuation at Ku-band	dB	Ku-band attenuation calculated from retrieved TCWV using *Lillibridge et al.*, 2014 **[RD-57]**
Cost function	unitless	1D-VAR retrieval cost function
Retrieval quality flag	unitless	0: Retrieval successfully performed 98: Out of range 99: No retrieval See detailed explanation below.

Table 17 : Output of the FDR4ALT 1DVAR retrieval scheme for atmospheric parameters.

The retrieval quality flag values are to be interpreted as follows:

- **Flag = 0**: A valid retrieval has been performed.
- **Flag = 98**: A retrieval has been attempted but failed. For example, this situation can occur when the observations are precipitation contaminated.
- **Flag = 99**: A retrieval has not been attempted, for example when parts of the orbit are known to be over land or sea ice and the user wishes to exclude those from being processed.

10.3.8 Processing steps

Figure 10-1 shows a simplified sketch of the FDR4ALT 1D-VAR processing flow to generate the atmospheric TDPs.

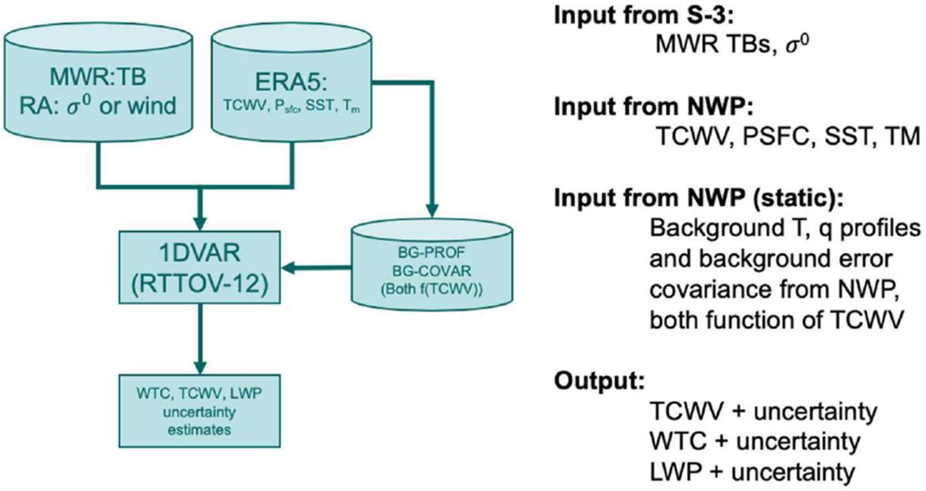


Figure 10-1 : Flow chart of the FDR4ALT processor to generate the atmospheric TDPs.

10.3.9 Uncertainty considerations

The 1D-VAR retrieval provides *a posteriori* uncertainties for all retrieved parameters at pixel level, including contributions from all individual sources of uncertainty in the retrieval process, including instrument noise, forward model error, and representativeness errors.
The availability of such uncertainty estimates taking all potential error sources explicitly into account allows for the identification of retrievals meeting application-specific quality requirements.

10.4 Reference Documents

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RD-55	Deblonde, G., and S. J. English, 2001: Evaluation of the FASTEM-2 fast microwave oceanic surface emissivity model. Tech. Proc. ITSC-XI Budapest, 20-26 Sept 2000, 67-78.
RD-56	Lillibridge, J., R. Scharroo, S. Abdalla, and D. Vandemark (2014), One- and Two-Dimensional Wind Speed Models for Ka-Band Altimetry, Journal of Atmospheric and Oceanic Technology, 31(3), 630-63810.1175/jtech-d-13-00167.1.
RD-57	Phalippou, L., 1996: Variational retrieval of humidity profile, wind speed and cloud liquid-water path with the SSM/I: Potential for numerical weather prediction. Q. J. R. Meteor. Soc., 122, 327-355
RD-58	Altimeter 1D-VAR Tropospheric Correction (AMTROC): Algorithm Theoretical Basis Document for AMTROC Products, V1.1, 30 pages, 31. March 2020, available at https://www-cdn.eumetsat.int/files/2020-06/pdf_ss_amtroc_atbd.pdf.
RD-59	Deblonde, G., 2001: NWP SAF user's guide: Standalone 1D-VAR scheme for the SSM/I, SSMIS and AMSU, NWPSAF-MO-UD-001 Version 1.0, 22 August 2001.
RD-60	Rodgers, C. D.: Inverse Methods for Atmospheric Sounding: Theory and Practice, World Scientific, Singapore [River Edge, N.J.], 2000.

Appendix A - FDR4ALT deliverables

The table below lists all FDR4ALT deliverables with their respective ID number and confidentiality level.

Document	ID	Confidentiality Level
Products Requirements & Format Specifications Document	[D-1-01] [D-2-02]	Public
Roadmap & Product Summary Document	[D-1-02]	Project Internal
Data Requirements Document	[D-1-03]	Project Internal
System Maturity Matrix	[D-1-04]	Project Internal
Examples of products	[D-1-05]	Project Internal
Review Procedure Document	[D-1-06]	Project Internal
Review Data Package	[D-1-07]	Project Internal
Phase 1 Review Report Document	[D-1-08]	Project Internal
Detailed Processing Model Document	[D-2-01]	Public
Round Robin Assessment Report Document	[D-2-03]	Public
Data Production Status Report	[D-3-01]	Project Internal
Final Output Dataset	[D-3-01]	Public
Product Validation Plan	[D-4-01]	Project Internal
Product Validation Report : FDR	[D-4-02a]	Public
Product Validation Report : Sea-Ice TDP	[D-4-02b]	Public
Product Validation Report: Land-Ice TDP	[D-4-02c]	Public
Product Validation Report : Ocean Waves TDP	[D-4-02d]	Public
Product Validation Report : Ocean & Coastal TDP	[D-4-02e]	Public
Product Validation Report: Inland Waters TDP	[D-4-02f]	Public
Product Validation Report: Atmosphere TDP	[D-4-02g]	Public
Uncertainty Characterization Definition Document	[D-5-01]	Project Internal
Uncertainty Characterization Report	[D-5-02]	Public
Product User Guide	[D-5-03]	Public
Completeness Report ALT	[D-7-01]	Public
Completeness Report MWR	[D-7-02]	Public

Table 18 : List of FDR4ALT deliverables

Appendix B - Acronyms

CAL	Calibration
CCI	Climate Change Initiative
CLS	Collecte Localisation Satellite
CNES	Centre National des Etudes Spatiales
DV	Default Value
ECMWF	European Centre for Medium-Range Weather Forecasts
ESA	European Space Agency
FDR	Fundamental Data Records
FFT PU	Fast Fourier Transform Power Unit
GMSL	Global Mean Sea Level
HFA	High-Frequency Adjustment
IMB	Ice Mass Balance
IRPI	Istituto di Ricerca per la Protezione Idrogeologia
LEGOS	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales
MLE	Maximum Likelihood Estimator
MPH	Main Product Header
MSSH	Mean Sea Surface Height
OIB	Operation Ice Bridge
PTR	Point Target Response
RMS	Root Mean Square
REAPER	REprocessing of Altimeter Products for ERS
SLA	Sea Level Anomaly
SSB	Sea State Bias
SPH	Specific Product Header
SSH	Sea Surface Height
SWH	Significant Wave Height
TDP	Thematic Data Products
WTC	Wet Tropospheric Correction
DFT	Discrete Fourier Transform