# Algorithm Theoretical Basis Document (ATBD) of the CPP SAR numerical retracker for oceans

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# SOMMAIRE

# 1. INTRODUCTION

## 1.1. PURPOSE AND SCOPE

This document is the Algorithm Theoretical Basis Document (ATBD) for the method used to retrack CryoSat-2 SAR mode waveforms over Open Ocean, as defined within the Cryosat Processing Prototype (CPP) from CNES. This document provides the scientific background of the retracking algorithm.

## 1.2. DOCUMENT STRUCTURE

This document is structured into an introductory chapter followed by two chapters describing:

- the background of this work and its aims (section 2), and
- the CPP SAR-mode retracking algorithm (section 3) that is applied for retrieving the different geophysical parameters.

A short description of the proposed approach is done within the document. The capabilities and limitations of the algorithm are also discussed.

# 2. ACRONYMS LIST

| | |
|---|---|
| AIR | Azimuth Impulse Response |
| ATBD | Algorithm Theoretical Basis Document |
| BRF | Burst Repetition Frequency |
| CPP | Cryosat Processing Prototype |
| FBR | Full Bit Rate (un-calibrated, geo-located I and Q individual echoes in time domain) |
| FSSR | Flat Sea Surface Response |
| LRM | Low Resolution Mode |
| LSE | Least Squares Estimator |
| NA | Not Applicable |
| NRT | Near Real Time |
| POD | Precise Orbit Determination |
| PTR | Point Target Response |
| RD | Reference Document |
| RDSAR | Reduces Synthetic Aperture radar |
| RIR | Range Impulse Response |
| SAR | Synthetic Aperture radar |
| SIRAL | Synthetic Aperture Interferometric Radar Altimeter |
| SLA | Sea level Anomalies |
| SSB | Sea State Bias |

# 1. OVERVIEW

## 1.1. THE SAR-MODE ALTIMETER

The CryoSat-2 radar altimeter (SIRAL) has three operating modes: the Low Resolution Mode (LRM), the SAR mode and the SARIn mode. For the SAR mode, in contrast to the LRM, the altimeter is transmitting pulses in groups (bursts), of 64 pulses at high PRF (18.182 kHz), with a burst repetition frequency (BRF) of 85.7 Hz [Wingham et al., 2006]. The closed-burst timing is shown in Figure 2.1. The PRF is about 10 times higher than that of LRM, which inherently ensures a high level of phase coherence from pulse to pulse within the burst. The returning echoes are thus correlated making them suitable for azimuth processing (SAR). The 128, I and Q, time domain samples of each individual echo are directly telemetered to ground for SAR processing then geo-located to form the FBR data.

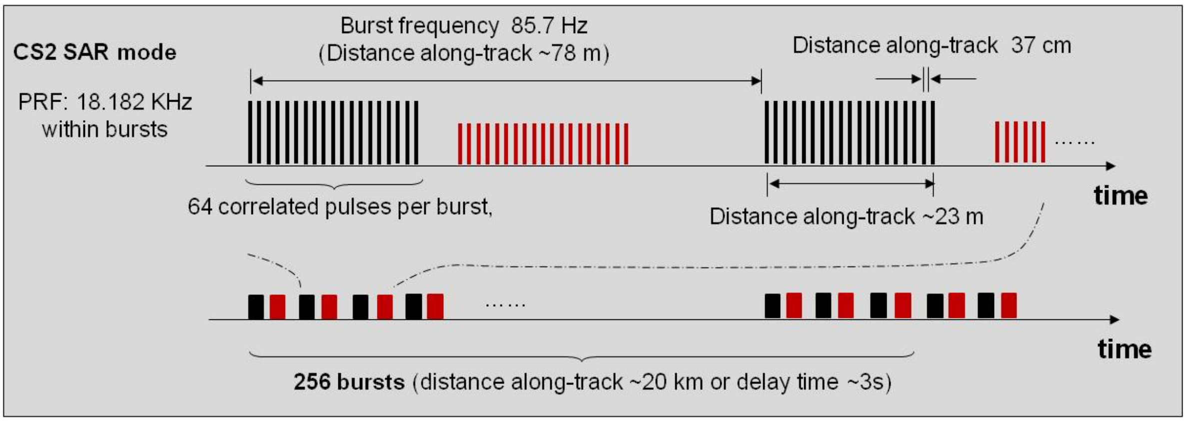


**Figure 2.1: SIRAL transmission and reception timing in SAR-mode.**

CryoSat-2 is the first satellite to operate in a SAR altimetry mode [Wingham et al., 2006]. But the use of the SAR technique in altimetry was first theoretically introduced by Raney in 1998 [Raney, 1998]. The key innovation of the proposed concept is the addition of an azimuth processing for increased spatial resolution in the along-track dimension, and an incoherent summation processing (a.k.a. multi-looking) that consists of accumulating several looks of a scattering area (average), leading to speckle reduction and improved altimetric performance. Due to this innovation the SAR altimetry technique provides higher precision and resolution capabilities than what is typically seen with conventional pulse limited altimeters.

Figure 2.2 illustrates the differences in footprint geometry between the conventional pulse limited altimeter and the SAR altimeter: the footprint of a conventional altimeter is pulse-limited whereas the SAR altimeter uses the Doppler principle to achieve a small along-track footprint. The resulting LRM and SAR power thus have an important distinction. Figure 2.2 shows the differences in the received echoes from a conventional altimeter and the SAR altimeter. The SAR altimeter waveform has now a peaky shape with a steep leading edge and fast decay trailing edge, which is different from the conventional altimetric echo. It may be interpreted as a change of illuminated geometry on sea surface from a “classical” surface-constant ring type to a fragment only of the ring area that is narrowed along the satellite track direction by the synthetic aperture processing (a few hundreds of meters in width in the along track direction). The pulse-limited classic altimetry model (i.e. Brown, 1977) is no longer valid for a “beam-limited” altimeter that needs the development of a new altimetric signal model to fit the observed Doppler return waveforms.

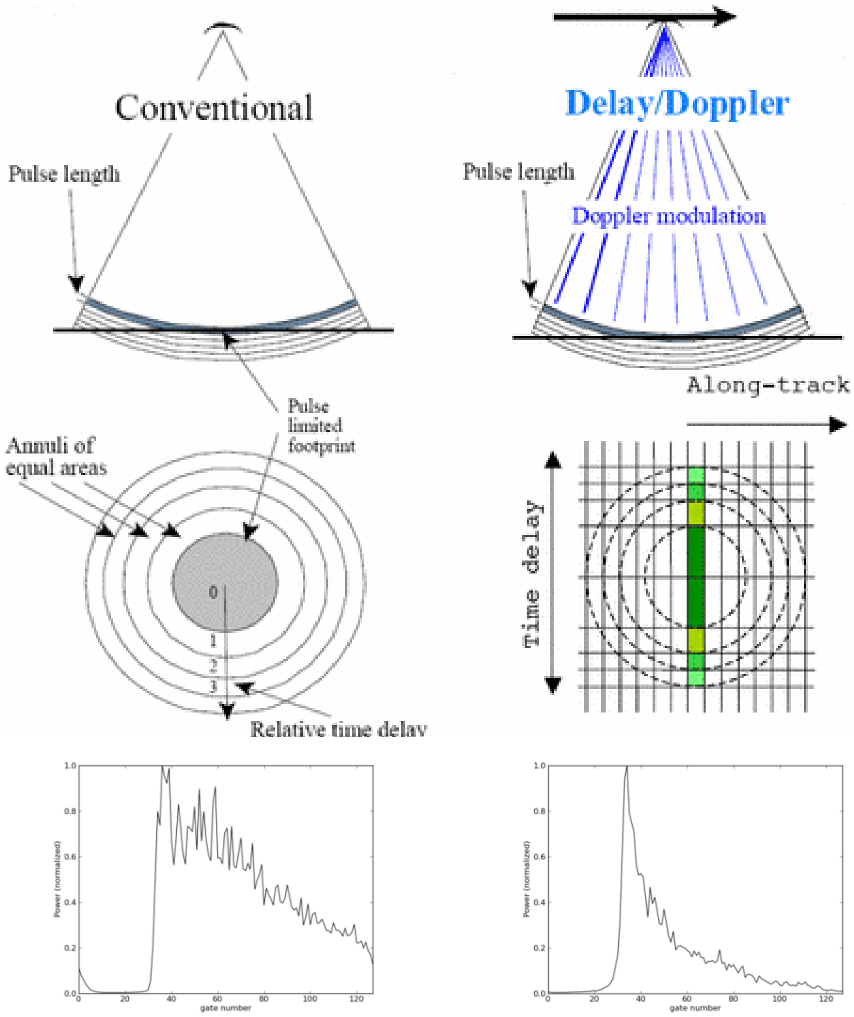


**Figure 2.2: Comparison of the footprint geometry between (left panels) LRM conventional radar altimeter and (right panels) Delay/Doppler SAR altimetry (Credits R.K. Raney, Johns Hopkins University, Applied Physics Laboratory) and example of LRM waveform and a multi-looked echo power from CPP (lower panel).**

Several studies have been initiated and are ongoing to develop and test the most suitable oceanic retracker algorithm, with the final objective to enhance the potential benefit of the SAR mode data in term of noise precision and ground resolution. But very few of them have analyzed in enough detail this new altimeter mode and its performances over the ocean surface (there is also several studies ongoing for other surfaces types like inland water, coastal, …), which is of high importance for the Sentinel-3 mission and the expected Jason-CS mission.
Though the along-track improvement in sampling resolution is straightforward (notably for near-shore altimetry applications as illustrated in Figure 2.3), it still remains some uncertainties in the SAR retrieved elevations as well as the other surface parameters accuracies. These uncertainties may be related to several effects, in particular the impact of the long-wavelength swell waves (close to the along-track SAR resolution), but also the sensitivity of the retrieval to varying orbital and instrumental parameters, such as the platform mispointing angles, the altitude, the spacecraft velocity. Another issue that remains unresolved is the lack of wind speed measurements and a corresponding Sea State Bias (SSB) correction due to the difficulty in retrieving the Sigma0 for peaky waveforms. Finally it is also of a major concern to ensure a good continuity of SAR mode data with respect to LRM mode data.

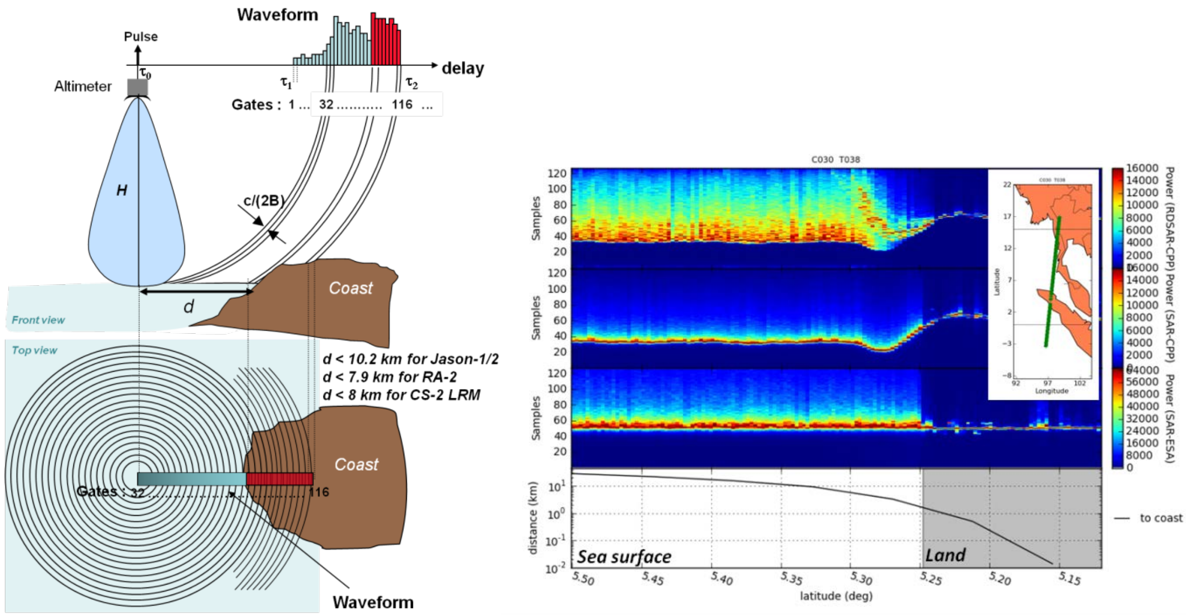


**Figure 2.3: (left) Footprint contaminated by land for a LRM conventional radar altimeter (right) Coastal waveforms plotted from CPP RDSAR and SAR and SAR ESA products (from Thibaut et al., 2012).**

## 1.2. THE CRYOSAT PROCESSING PROTOTYPE (CPP)

On its side, CNES has developed the CPP processing chain [Boy et al., 2012], for SAR mode data (and LRM data) that aims at contributing to expertise studies for the future Sentinel-3 mission. This investigation is also relevant for the specification of the SAR mode to be embarked on-board the Jason-CS mission.
The CPP chain consists of two-step functions: a L1 processing and a L2 retracker. First, the CCP generates L1b data from Full Bit Rate (FBR) data sent by ESA. For SAR mode data, SAR and reduced SAR (RDSAR) echoes, also called "Pseudo LRM", are generated simultaneously, but from different processors. The SAR processor is based on the use of the aperture synthesis technique while a "conventional" processing on high PRF echoes (equivalent to on-board LRM processing) is applied to derive RDSAR echoes. Secondly the CPP re-tracks the echoes using a dedicated model for SAR data and RDSAR data (Brown model).
The CNES has developed a SAR echo model based entirely on an amplitude numerical simulator [Desjonquères et al., 2012] that mimics the Cryosat-2 altimeter response in SAR mode (taking into account the real elliptical antenna pattern and a real point target response). The simulator is fully numerical. It is based on a point-by-point radar response simulation on a gridded surface without limitation of resolution (fully adaptive). The satellite altitude and altimeter characteristics can be modified depending of simulated missions (Jason-2, AltiKa, Sentinel-3, CryoSat, Jason-CS…). A theoretical or measured antenna pattern can be used taking into account mispointing angle in both axes. Theoretical or measured Impulse Responses can be used as well. In addition, the surface height can be modified using a Digital Elevation Model and atmospheric attenuation or ground "reflection anomalies" can be introduced for specifics investigations. The Figure 2.4 illustrates the different steps of the SAR echoes simulator. Major processes of the SAR simulator are in sequence:

1- The power return signals from each point of the gridded surface are computed then sorted by Doppler band and accumulated in the appropriate range gates of the waveforms.
2- The flat sea surface response is then convolved with the azimuth and range impulse response (AIR and RIR) of the radar (approximated by a sinc² function).
3- Prior averaging, the Doppler bands are corrected in range to compensate the slant range migration, i.e. to place all observations of a scatterer at the same radial distance from the satellite when the satellite moves along its orbit.
4- The Doppler beam waveforms (looks) from the same surface are summed (multilooking) to finally form the SAR echo model for a flat sea surface (the sea wave height is applied "on the fly" in the retracking process to provide an exact solution for the SAR waveform).

5- To finish, the simulator convolves the previous result with the PDF of the significant wave height.

Note that, the simulator can also generate LRM numerical model. In that case, the step 3 is not performed (no range migration). This simulation option has been very useful since it was possible to cross compare and validate the simulator with the Brown model.
The validation has consisted in generating a LRM numerical model with a real azimuth impulse response but with a Gaussian range impulse response to get the same assumptions than Brown. Then, this model has been retracked using a Brown model and the estimated parameters have been compared to the simulation parameters. The agreement is very good since differences are less than 1 mm for epoch and 1 cm for SWH.

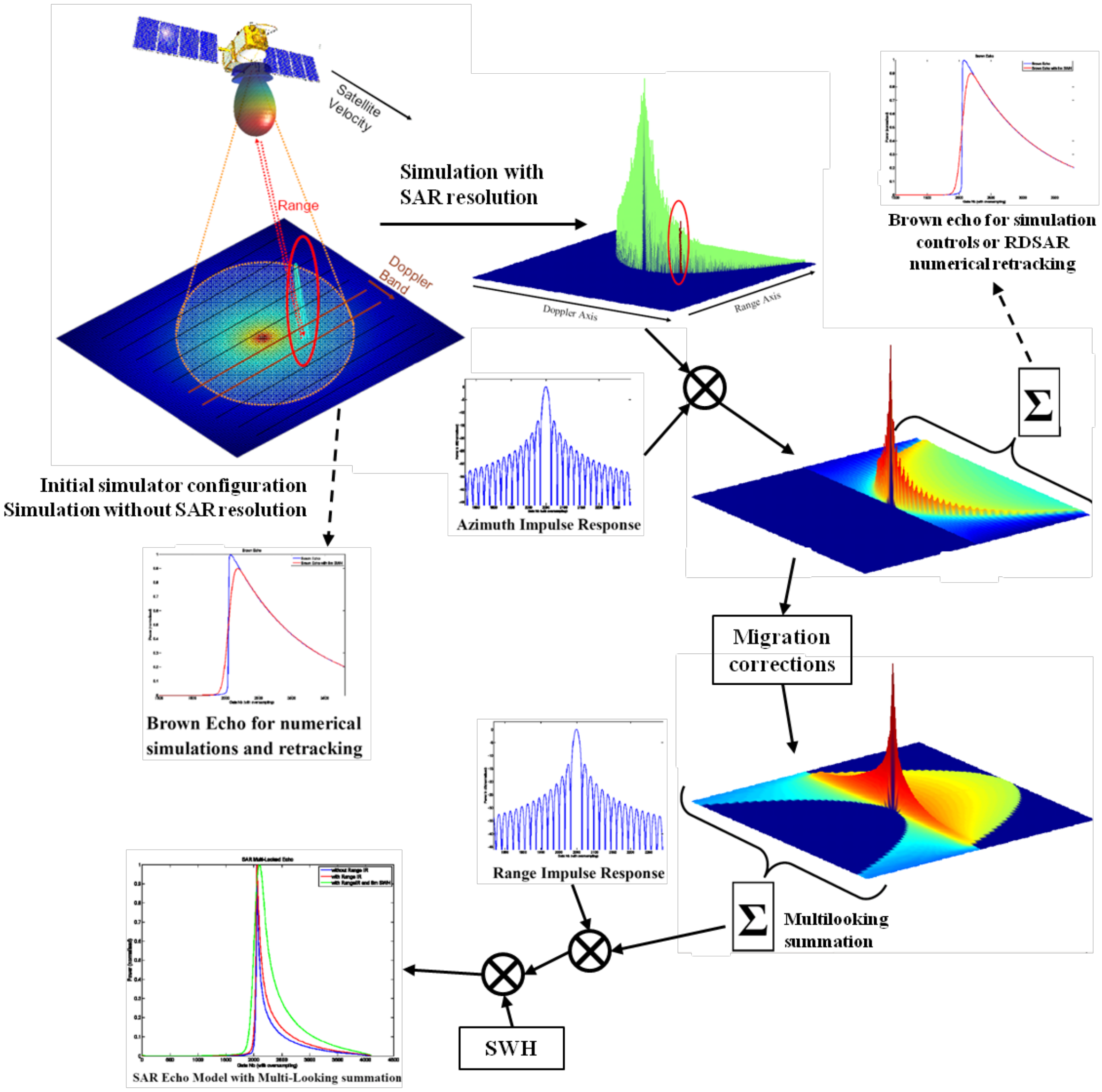


**Figure 2.4: SAR echoes simulator (from Desjonquères et al., 2012).**

The amplitude simulator model is currently implemented in the CPP SAR retracking. This approach is considered to be more robust than analytical ones, particularly when faced with atypical observations (e.g., elliptical antenna pattern, off-nadir mispointing angles, point target response) that are difficult to put into equations.
The CPP retracking algorithm is a standard least squares estimator (LSE) consisting in fitting a SAR waveform with an echo model, also called multi-looked echo, that is pre-computed off-line by the simulator. As for conventional altimetry, the ocean parameters estimated from the numerical SAR retracking are expressed as:

$$\theta_{n+1} = \theta_n - g(BB^T)^{-1}_{\theta_n}(BD)_{\theta_n}$$

where $\theta_{n+1}$ is the estimated parameter at iteration *n+1*; *B,D* are the partial derivatives and residuals matrix, and *g* is the loop gain (between 0 and 1).
As for unsolved analytical model, derivatives of the mean return power are computed numerically. The method consists in approximating the derivatives by a finite difference involving the echo model database in which the sensitive parameters (sea-state, satellite parameters) vary, one parameter at a time, in a range of values and with a step size that have been chosen to ensure the accuracy and precision of the estimates. At each iteration *n*, models using the current estimation vector $\theta_n$ are directly taken from the database. The performances of this method have been evaluated theoretically using simulated LRM waveforms and, have been statistically validated on real data by applying it on J2 raw measurements. The results are found to be consistent with those obtained from a classical MLE4 retracking.

The numerical SAR retracking is based currently on a 3-parameters model (range, significant wave height, amplitude) that accounts for varying off-nadir mispointing angles provided by the star tracker information (raw telemetry) $T_x$ and $T_y$ (roll and pitch angles). However this information is not directly usable and has to be first aligned on the altimeter electromagnetic axis using the mispointing angle $\xi^2$ estimated from the retracking of LRM data. To find the roll and pitch biases (*a,b*) we apply the least squares method that consists of minimizing the following squared residuals:

$$\xi^2 - [(Tx + a)^2 + (Ty + b)^2] = 0$$

This fitting method returns the duplet values a = -0.100° and b = -0.015°. The solution corresponds to the minimum mean squared error estimator as shown in Figure 2.5. Then, the biases are added to the star tracker information to get the mispointing angle of the antenna in both axes (in along-track and cross-track directions) to be injected as input to the retracker.

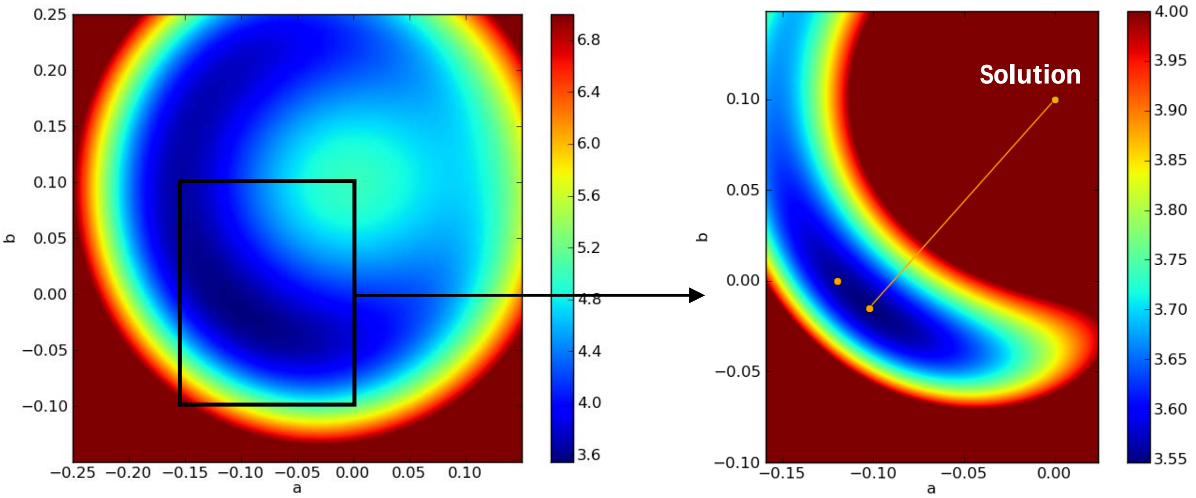


**Figure 2.5: Square errors calculated for different values of a and b.**

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# 2. ALGORITHM DESCRIPTION

## 2.1. ALGORITHM FLOW CHART

The description of the algorithm in the subsequent sections is facilitated by the flow chart shown in Figure 3.1, which outlines the overall structure of the algorithm.

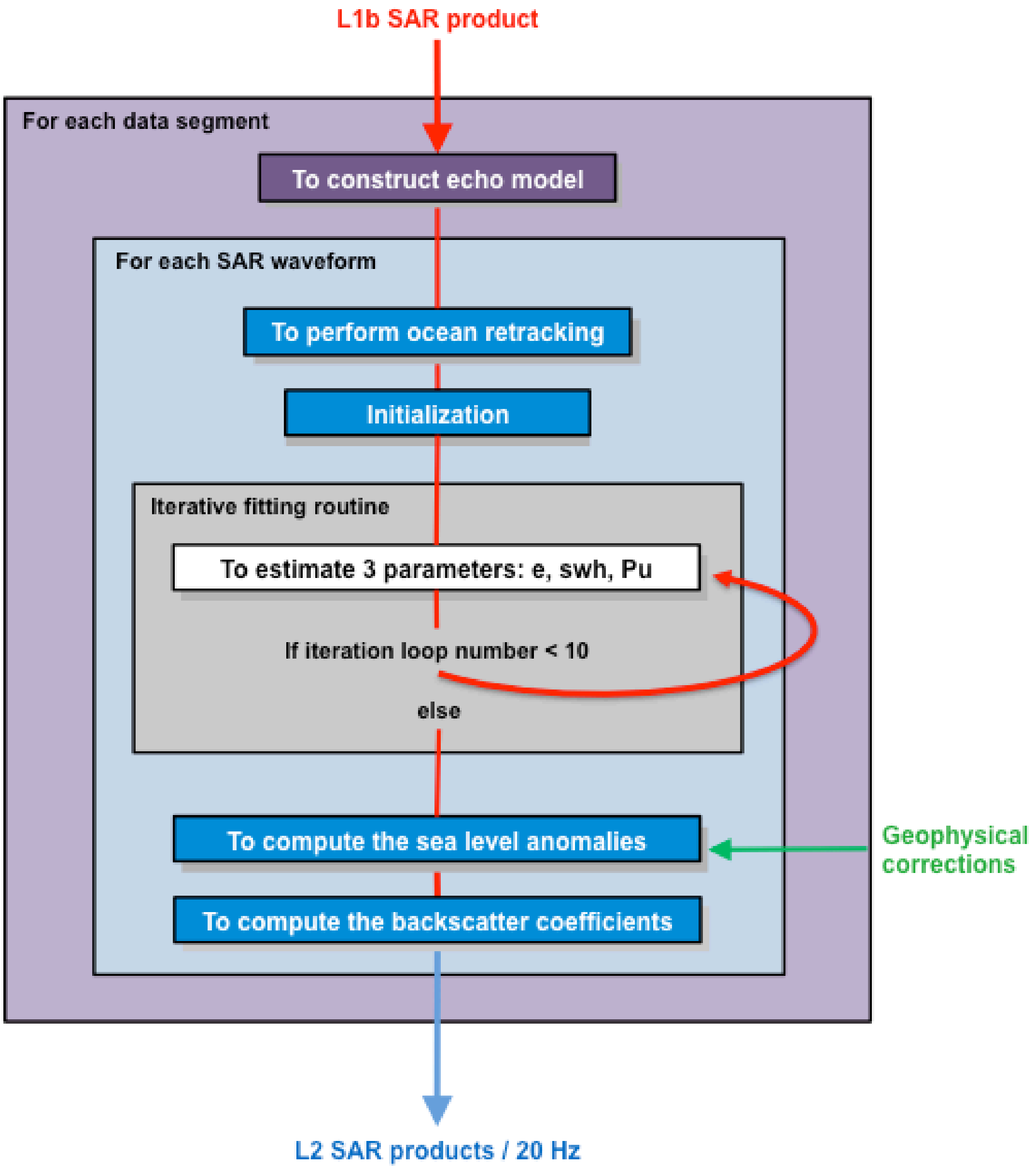


**Figure 3.1: Flowchart showing the sequence of operations performed by the SAR numerical ocean retracker**

## 2.2. ALGORITHM DEFINITION

In this section, a definition of the different block algorithms is given. They are listed in an order that follows the retracking scheme.

### 2.1.1. TO LOAD THE SAR ECHO MODELS

Prior processing the SAR echo waveforms, a set of 63 synthetized Doppler beams model is loaded into memory to be used as input to the retracker (see Figure 2.1). The selected beams correspond to a simulated model using configuration parameters that match the orbital and instrumental information for this series of data (notably the star tracker information). These sharpened beams (also called looks) are equally spaced in angle (through the plane defined by the satellite velocity and the Doppler axis). They are sampled in a range window of 256 bins that are oversampled by a factor of 64. Impulse responses in range and azimuth are used for generating the models.

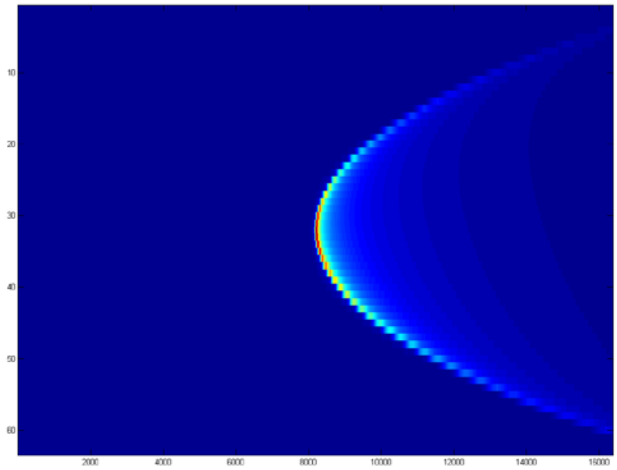

**Figure 3.2: The simulated Doppler beams with 63x16384 samples. The apex of the hyperbola is placed at the centre of the range window.**

### 2.1.2. TO CONSTRUCT THE MULTILOOKED WAVEFORM MODEL

For each data segment (up to 6mn of maximum length), there are four main steps in the process, following the sequence below:

- First, the centre of the echoes, $E_{centre}$, is evaluated based on the median of the estimated epoch from the reduced SAR echo.
- Secondly, the Doppler beams are truncated for those samples that are considered out of the altimeter range window, with respect to the $E_{centre}$ value (see Figure 3.3).

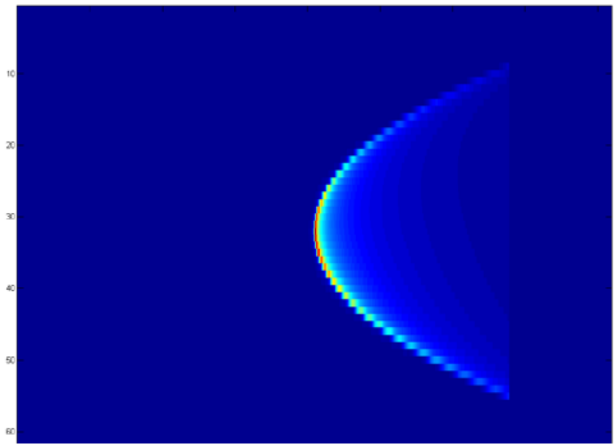

**Figure 3.3: The Doppler beams have been shortened in range.**

- The next stage consists of correcting in range the Doppler beams to align all looks viewing the same surface scatterer. Shifts in range are performed by a convolution operation with a Dirac delta function.

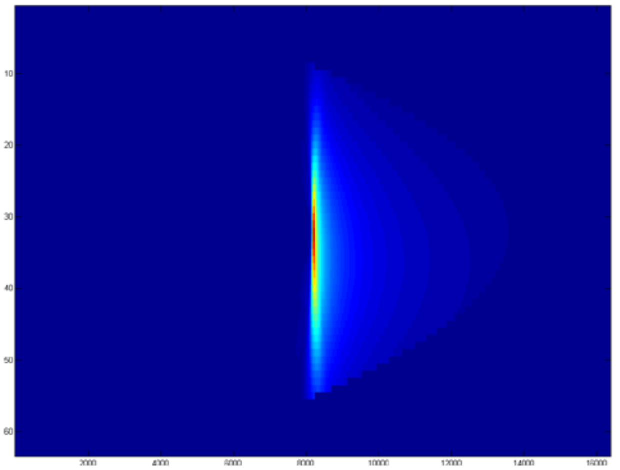

**Figure 3.4: The Doppler beams have been aligned in range.**

- Finally all squared Doppler beam waveforms of the stack are summed. The constructed multilooked echo is the numerical model that will be used to process the data segment.

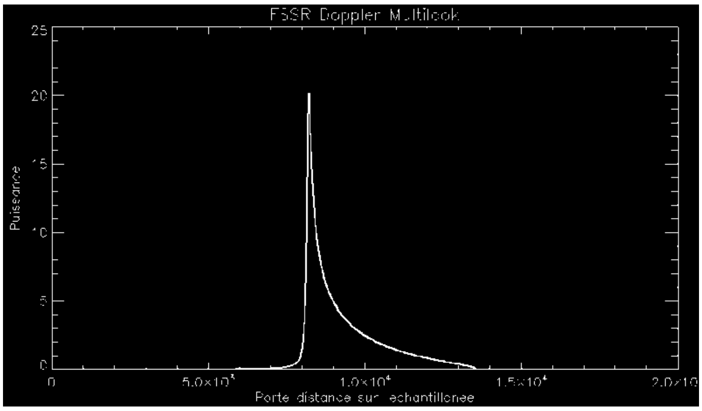


**Figure 3.5: The multilooked echo model.**

### 2.1.3. TO PERFORM OCEAN RETRACKING

This function fits the numerical multilooked waveform model to one 20 Hz Level 1B SAR waveform using the LSE method and retrieve geophysical variables and fitting quality information.
For each SAR echo waveform, a 3-parameter ocean retracker based on unweighted least square estimations (also known as MLE) that are traditionally used with LRM echoes [Amarouche et al., 2004], is applied for retrieving the different geophysical parameters (range, significant wave height, backscattering coefficient). This method exploits the multilooked echo model as computed previously, for which different sea state parameters *E*, *SWH*, *Pu* are considered on each iteration step of the retracking process.

#### 2.2.1.1. To compute the echo model for a given sea state

The echo model with the parameters *E*, *SWH*, *Pu* is calculated as follows:

1- the echo model is convolved with a Dirac delta function at the epoch *E*,
2- the shifted echo model is then convolved with a Gaussian sea surface height distribution (defined by a standard deviation equal to ¼ of the significant wave height),
3- *Pu* gain is applied,

4- The echo model is sub-sampled by factor 128 (keeping every 128-th sample) to provide a waveform with a resolution of 128 ranges gates.

#### 2.2.1.2. Basic principle

The problem to solve is the estimation of a set of $N_\theta$=3 parameters $\theta = \{\theta_1 = e, \theta_2 = swh, \theta_3 = Pu\}$. The system to solve results from the maximization of the logarithm of the likelihood function $\Lambda(\theta)$, i.e. from the system:

$$C(\theta) = \nabla[-Ln(\Lambda)] = 0$$

where *C* is the total cost function and ∇ is the gradient function.
This system is reduced to weighted Least Square Estimators, and is equivalent to set the Least Square function $\nabla\chi^2$ to 0, where the merit function $\chi^2$ is defined by:

$$\chi^2 = \sum_i \left(\frac{V_i - Vm_i}{\sigma_i}\right)^2$$

where *V* represents the measured waveform, *Vm* the echo model, and where the weighting function is $\{\sigma_i\}$ = $\{Vm_i\}$.
This system may also be represented by the following set of $N_\sigma$ equations:

$$\sum_i \left(\frac{V_i - Vm_i}{{\sigma_i}^2}\right)^2 \cdot \frac{\partial Vm_i}{\partial \sigma_k} = 0$$

An iterative solution is obtained by developing the total cost function in a Taylor series at the first order about an initial set $\theta_0 = \{\theta_{01} = e_0, \theta_{02} = swh_0, \theta_{03} = Pu_0\}$ of estimates:

$$\theta_{n+1} = \theta_n - g.\varepsilon_\theta$$

with: $\varepsilon_\theta = (BB^T)^{-1}BD$ (valued to the current values $\theta_n$)
*B*,*D* are the partial derivatives and residuals matrix:

$$B_{ki} = \frac{1}{\sigma_i}.\frac{\partial Vm_i}{\partial \sigma_k},\ \ D_{i1} = \frac{1}{\sigma_i}.(Vm_i - V_i),$$

and where *g* is a loop gain (positive value, unique to the parameter being estimated).
Using $\{\sigma_i\}$ = $\{Vm_i\}$, the Least Square Estimators method described above would put the most weight on the regions with the least power, i.e. on the regions with the least information regarding the parameters to be estimated. For this reason, the weighting function is superseded by a factor constant over a waveform ($\{\sigma_i\} = \sigma$). In order to normalize the residuals ($\{Vm_i - V_i\}$), this factor $\sigma$ is set to the current estimate of the amplitude.

The derivatives of the mean return power *B* are computed numerically as following:

$$\frac{\partial Vm(swh_i, e_i, pu_i)}{\partial SWH} = \frac{Vm(swh_i + \delta swh, e_i, pu_i) - Vm(swh_i - \delta swh, e_i, pu_i)}{2\delta swh}$$

$$\frac{\partial Vm(swh_i, e_i, pu_i)}{\partial e} = \frac{Vm(swh_i, e_i + \delta e, pu_i) - Vm(swh_i, e_i - \delta e, pu_i)}{2\delta e}$$

$$\frac{\partial Vm(swh_i, e_i, pu_i)}{\partial pu} = \frac{Vm(swh_i, e_i, pu_i + \delta pu) - Vm(swh_i, e_i, pu_i - \delta pu)}{2\delta pu}$$

where models *Vm* using the current estimation vector $\theta_n$ are directly taken from the database.

#### 2.2.1.3. Estimation (unweighted Least Square fit)

The fine estimates of the epoch (e), the significant wave height (swh), the amplitude (Pu) are derived from the iterative process defined previously, which is initialized from default values e□ $swh_0$ and $Pu_0$ for each waveform.
This estimation process is stopped when 10 iterations is reached.

### 2.1.4. TO COMPUTE THE SEA LEVEL ANOMALIES

Some additional altimeter components are needed to be used in the Sea Level Anomalies (SLA) calculation as defined by this formula:

$$SLA = Orbit - Range - \sum_{i=0}^{N} C_i - MSS$$

where *Orbit* corresponds to the distance between the satellite and the ellipsoid, *Range* is the distance measured by the altimeter between the satellite and the sea surface, *MSS* is the Mean Sea Surface of the ocean over a long period and $\sum_{i=0}^{N} C_i$ is the sum of all the corrections needed to take into account the atmospherically effects (wet and dry troposphere, ionosphere, inverse barometer) and the geophysical phenomena (ocean tides, high frequency atmospheric effects on ocean).
Note that the sea-surface state (electromagnetic sea-surface bias) is not considered in the equation since no SSB solution has been calculated yet.

#### 2.1.5. TO COMPUTE THE BACKSCATTER COEFFICIENTS

For each averaged measurement, the 20 Hz Sigma0 is computed by combining the retracked amplitude of the waveforms with the scaling factors, as follows:

$$\sigma_0 = 30 * log_{10}(Orbit\_Alt) + 10 * log_{10}(Earth\_Rad + Orbit\_Alt) + 10 * log_{10}(Pu) + constant$$

## 2.3. KNOWN LIMITATIONS AND THEIR IMPLICATIONS

Known limitations and shortcomings of this algorithm to retrack CryoSat-2 SAR-mode waveforms over Open Ocean:

- The retrieval of the Sigma0 has been lately activated within the CPP chain after major update (implemented in version 13) in the way we compute this parameter. First analyses of this parameter have shown very good, promising and unprecedented results. Upcoming feedback from the science users of CryoSat-2 CPP products (that are currently distributed) will contribute to provide other analyses (like wind speed studies) on the quality of the data that will permit to consolidate the CNES implementation of SAR mode processing. Since SAR Sigma0 is now available, a SSB correction, which mainly depends on the SWH and wind speed, may be envisaged to be estimated.
- The accuracy of the resulting retracked parameters is also a function of the ability of the star tracker to give accurate information and the way we proceed to align the star tracker information on the altimeter electromagnetic axis. This is still under investigation.
- The inconsistent behaviour of SAR retracker at low wave heights (below 1m) where numerical singularities occur is observed by all the teams involved in SAR processing.
- This method may require huge data storage and, inevitably, long processing times to generate an echo model database with varying sets of sensitive parameter values (sea-state, satellite parameters) and with small sampling intervals. In implementing this strategy, the goal is to build a database in a way that ensures the accuracy and precision of the estimates. However, this may highlight some difficulties that should be considered in future or related work.

The mentioned limitations will be addresses and improved in future versions of the CPP products.

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# DIFFUSION

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