SCOOP

SAR Altimetry Coastal and Open Ocean Performance

SAR Altimetry Scientific Review (TN-1)
D1.1

Sentinel 3 For Science – SAR Altimetry Studies

SEOM Study 2. Coastal Zone and Open Ocean Study

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1 Introduction

1.1 Rationale and scope of this document

This is the **SAR Altimetry Scientific Review** (TN-1) report for SCOOP and represents the deliverable D1.1 of the project.

Research and Development in techniques for exploitation of SAR altimetry over the ocean and the coastal zone have increased exponentially in the last few years, when data from CryoSat-2 confirmed the oceanographic capabilities of SAR altimetry. Projects such as SAMOSA and CP4O have contributed to develop and test processing algorithms over the marine domain and to lay the foundations for the Sentinel-3 Detailed Processing Model over the ocean. A very active international research community in SAR altimetry has formed as a result of these and other projects. This community had its dedicated gathering at the Ocean SAR Expert Group Meeting at NOC Southampton in June 2013 and continues to contribute highly specialized input to events such as OSTST and the Coastal Altimetry Workshops, most recently in October 2014 in Konstanz and in October 2015 in Reston, USA. With the recent launch of Sentinel-3 on 16 February 2016, whose SRAL altimeter will be operated in SAR mode over the entire ocean, research into ocean SAR altimetry is now developing at its fastest pace ever, and SCOOP is an important contribution sponsored by ESA to this research field. WP1 in SCOOP aims at capturing the state of the art in this research field and at identifying the baseline requirements to allow further development to be carried out in the following WPs. This document, D1.1, summarizes the state of the art at the time of the start of the SCOOP project; other deliverables from WP1 capture: the technical baseline along with product and data requirements (D1.2: Requirements Baseline or RB), the theoretical basis of the processing algorithms (D1.3: Algorithms Theoretical Basis Document or ATBD) and the configuration options of the processor(s) used to generate SCOOP test datasets (D1.4: Processing Options Configuration Control Document, or POCCD).

1.2 Starting Point: Gommenginger et al.’s 2013 Review

The starting point for the present review is the document *“Review of State of Knowledge for SAR altimetry over ocean”* (Gommenginger et al., 2013a) stemming from the Ocean SAR Expert Group Meeting at NOC Southampton. This document was drafted in preparation of that Meeting and for discussion at the meeting; then it was significantly amended with the meeting findings, so it fully captures the research reported between 2010 and June 2013 by a number of international groups.

The Gommenginger et al.’s review presented a summary of several improvements from the (then) newly available CryoSat-2 data in SAR mode when compared to LRM altimetry from conventional (i.e., non-SAR) altimeters, LRM altimetry from CryoSat-2 and PLRM altimetry from reduced CryoSat-2 data:

- the measurement noise is diminished in SAR mode both for sea surface height (SSH) and significant wave height (SWH);
- transitions at mode switch are smooth, with no apparent discontinuity;

- the spectral description of SSH at short ocean wavelengths is improved. In particular, CryoSat-2 SAR along-track spectra do not show the spectral 'bump' in power at the mesoscale (7-100 km) that is instead seen in spectra from Jason-2 LRM and CryoSat-2 PLRM;
- the quality and availability of data in the coastal regions is visually improved (to be confirmed by more quantitative assessments)

Gommenginger et al. also reviewed different classes of waveform and retracking models for SAR altimetry: empirical, numerical, semi-analytical and fully analytical. The latter class includes the SAMOSA3 model, extensively validated against real waveforms from CryoSat-2 and selected for the Sentinel-3 SRAL Detailed Processing Model (DPM). Some considerations regarding the different retrackers need to be pointed out:

- A general differentiation can be done between the physical-based retrackers (also referred to as theoretical-based retrackers) (like Brown (1977), Hayne (1980), Ray et al (2015a)) and empirical retrackers (like Wingham et al (1986)). The latter are statistically-oriented approaches, which basically search for the peak of the waveform to infer the sea surface height without considering any physical relation to the backscattering mechanisms being observed. On the other hand, the physical-like retrackers try to theoretically model the echo waveforms on the basis of the electromagnetic interaction between the transmitted pulse and the surface beneath the altimeter.

- Analytical retracking requires a detailed characterization and analysis of the echo waveform backscattered from the surface. The shape of the echo is mainly affected by: i) type of surface and so its intrinsic scattering properties, ii) instrument/acquisition characteristic (frequency, bandwidth, antenna pattern, on-board processing, mode of operation SAR or LRM, among others) and iii) the on-ground processing strategy being followed. This leads to the typical well-known three-convolutional modelling approach initiated by Brown model (Brown, 1977).

- Theoretical-based retrackers are more attractive since they have a physical foundation in their modelling, but at the expense of a higher computational load compared to the empirical ones. Within the theoretical-based category different subtypes can be found: the fully numerical solutions of the modelled waveforms; semi-analytical models, where a closed-form expression is obtained for each term of the three-convolutional model, but the convolutional is computed numerically; and the fully-analytical ones, where a closed form expression of the power waveform is obtained (Brown (1977), Hayne (1980), Ray et al (2015a)). On one hand the first subtype (fully-numerical) have the advantage of being able to realistically model the different contributions without any simplification or assumption at the expense of a much higher computational load. On the other hand, the fully-analytical retrackers with closed-form expressions are far more computationally efficient, providing an intuitive physical linkage between instrument/scenario and the resultant waveform being modelled, but at the expense of a less accurate modelling of the reality since some assumptions/simplifications (which in general can be assumed correct) have been made to obtain a closed-form expression.

Moreover, the review presented a full assessment of the various available options to 'reduce' SAR altimetry data to PLRM data, with a clear indication of the pros and cons of each technique.

A particularly important outcome of Gommenginger et al.'s review was the set of recommendations for Jason-CS (Sentinel-6), i.e., that it should be implemented with the interleaved SAR mode, as this is beneficial to many ocean applications and allows the generation of LRM data that are statistically equivalent to those from conventional LRM missions. It therefore allows a complete SAR/LRM inter-calibration and satisfies the need for seamless, long-term continuity of sea level monitoring. The SCOOP partners should discuss whether the technical improvement of the interleaved mode should still be recommended for the altimeters on the Sentinel-3 C/D satellite pairs, given the clear consensus that had already emerged in 2013 on the superiority of this solution[1].

Finally, Gommenginger et al.'s review also identified a number of issues that were undergoing (or required) further investigations:

- sensitivity of the SAR altimetry measurements to platform mispointing.
- the lack of a Sea State Bias (SSB) in SAR mode.
- the effects of swell and swell direction on SAR mode waveforms (and therefore potentially on the observables).

We note explicitly that these points are amongst those under investigation in SCOOP.

It should also be noted that Gommenginger et al.'s review did not dwell on some technical aspects of the processing to L1b (such as windowing in azimuth, zero-padding, 'peeling' of the stack prior to multi-looking and correctly accounting for the samples set to zero in the stack when forming the L1b waveform) but this is not surprising as the discussion on these and other low-level technical aspects had only barely started at the time of the report. Since then, research on these technical aspects has developed significantly, and they are now amongst the main issues under investigation in SCOOP.

1.3 Progress Reported in 2013-2015

In this section we list and briefly describe the sources of information used as input to this review to document the advancement of the field since the Gommenginger et al.'s review. We have considered meetings, papers and reports published or made available online up to the end of October 2015 (i.e., the month in which SCOOP has started, and in which the 9th Coastal Altimetry Workshop and OSTST2015 were held). Therefore, the present review aims to capture the state of the art and open issues in SAR altimetry over the ocean as of 31 October 2015.

[1] Within the scope of the present SCOOP project this can only take the form of a discussion and literature review of the potentialities of the interleaved mode rather than an "explicit" performance evaluation. An explicit evaluation currently cannot be made without specific simulated data emulating the interleaved mode, and would only be possible as a contract extension.

1.3.1 7th Coastal Altimetry Workshop and OSTST, Boulder (USA), October 2013

In virtue of the increasing recognition of the importance of SAR altimetry for oceanography, the 7th Coastal Altimetry Workshop (CAW-7) and OSTST organized a joint session on SAR altimetry (and SARin altimetry, which is out of the scope of SCOOP) in Boulder on 8 October 2013. [Note: at the ESA Living Planet Symposium 2013 in Edinburgh the previous month there had been several presentations on SAR altimetry, but the two meetings in Boulder allowed the presentation of an update on the work by the various groups, as well as the more dedicated discussion, so we take those two meetings as the first step for this review]. All the presentations from CAW-7 and from the joint SAR session are available online at http://www.coastalt.eu/boulderworkshop13. A number of remarkable new or recent ideas were presented in the SAR session. Amongst these, improvements in processing that were under consolidation in the ESA suite that would subsequently originate the SARvatore service on G-POD (Dinardo et al) and at the same time were being implemented in the Jason-CS Poseidon-4 Ground Prototype Processor (Roca et al). These improvements included: at L1b, a pre-FFT zero-padding in range, the Doppler beam weighting before multi-looking to compensate for echo shape differences due to different incidence angle, the application of a window in azimuth (recommended in the coastal zone), the stack thresholding; at L2, an improved version of the SAMOSA3 model fully adapted to any kind of L1 SAR mode processing (and also to the interleaved mode) that has then flowed into the SAR DPM for Sentinel-3. The adoption of zero-padding was supported by a study by Smith and Scharroo on waveform aliasing (subsequently published as Smith and Scharroo, 2014). Thibaut et al. proposed at CAW-7 a sub-waveform approach to L1b SAR waveform retracking, similarly to what CLS and other groups had developed for conventional altimetry, and which is particularly useful in the coastal zone where it helps rejecting off-nadir artefacts in the tail of the waveform. Also very important was some updated work by Dinardo et al on computing SAR altimetry measurements on a finer along-track step, for which ~80m (corresponding to a 80Hz posting rate) is a convenient choice. All these ideas have become part of the current understanding of SAR altimetry processing options and are discussed and/or exploited in SCOOP. Other notable presentations confirmed the excellent quality of the SAR altimetry observations of ocean dynamics (Labroue et al) and SWH (Fenoglio et al).

1.3.2 8th Coastal Altimetry Workshop and OSTST, Konstanz (Germany), October 2014

At the time of these meetings (October 2014) the interest in SAR altimetry for ocean applications had really taken off amongst potential users so the two meetings were preceded by a two-day SAR Altimetry Training course sponsored by ESA, with about 25 participants and lectures by some of the leading experts in the field. All the presentations and several posters from CAW-8 are at http://www.coastalt.eu/konstanzworkshop14 while those from OSTST2014 (plus a useful meeting summary) are on http://www.aviso.altimetry.fr/en/user-corner/science-teams/ostst-swt-science- team/ostst-2014-lake-constance.html .

K. Raney gave a keynote at CAW-8 reviewing past and recent milestones and indicating several promising evolutions of altimetry, amongst which focused SAR processing (i.e., a true SAR mode, as opposed to the unfocused one currently employed) that could yield an along-track resolution of 0.5 m, and the use of polarimetry and/or coherence to achieve across-track selectivity. Other notable contributions to CAW-8 were from Thibaut et al. on an update of the sub-waveform approach for SAR altimetry, the geo-referencing of the L1 stack with applications to coastal altimetry by Egido et al., integrated within the level-2 processing chain in the framework of the LOTUS project, and the rolling out of the DComb wet tropospheric correction for CryoSat-2 over open and coastal ocean by Fernandes et al. (a follow-on of correction is now called GPD+).

At OSTST, Cristina Martin-Puig et al presented comprehensive details on the revision of the SAMOSA retracker in the Jason-CS GPP processor at isardSAT. Improvements include different windowing along- and across-track, different clock frequency (sampling) and receiving bandwidth, a revisited noise floor in the multi-look waveform, stack masking with range cell migration compensation and Doppler ambiguity cancellation, and a non-equal range bin incoherent integration.

Chris Ray presented an improvement to SAR stacking by reshaping each look in the stack, the so- called ACross-track Dilation Compensation (AC/DC) technique. This results in both a potential noise reduction, by up to a factor 2.5 for SSH and 4.0 for SWH, and a simplified re-tracking. This approach has been recently published (Ray et al 2015) and should be taken into consideration in SCOOP or future extensions if resources allow.

Other important presentations at OSTST were an accurate evaluation by Michele Scagliola et al. of the antenna pattern compensation in L1b data which showed an improvement of the effective number of statistically independent looks up to 30% for CryoSat-2 data but requires further validation, and an analysis of the Power Distribution in the Stack (PDS) over ocean and other surfaces by T. Moreau, showing promising dependence on surface type and roughness and the possibility of estimating the pitch angle, in good agreement with the star-tracker-derived mispointing.

At both meetings there were presentations on results from the CP4O Project that was drawing its conclusions at the time; an account of those results is however included in the summary in section 1.3.3 below.

1.3.3 CP4O Scientific Road Map, February 2015

The “CryoSat Plus for Oceans” (CP4O) project, supported by the ESA Support to Science Element (STSE) Programme and by CNES, was dedicated to the exploitation of CryoSat-2 data over the open and coastal ocean. The general objectives of the CP4O project were: to build a sound scientific basis for new oceanographic applications of CryoSat-2 data; to generate and evaluate new methods and products that will enable the full exploitation of the capabilities of the CryoSat-2 SIRAL altimeter, and to ensure that the scientific return of the CryoSat-2 mission is maximised. The project started in May 2012 and ran until late 2014. The Project reviewed the existing knowledge in SAR altimetry, carried out a number of investigations and produced a final report (Cotton et al., 2015) and a detailed Scientific Road Map (Cotton, 2015). This latter document, released in final form in February 2015, is directly relevant to the present review and to the SCOOP Requirement Baseline document D1.2 as it identifies the main unresolved issues in SAR processing.

As far as L1a to L1b processing goes, one of the high priority issues in the CP4O Road Map is the optimization of the Doppler processing, selection and weighting: should the outer Doppler bins be given less weight, or more weight? Other issues concern the under-sampling of peaky waveforms and therefore the requirement for zero-padding prior to the FFT, and the purpose and optimization of any along-track windowing. Also, evidence of waveform blurring in SAR and SARin mode echoes in response to high spacecraft altitude rates was seen in CryoSat-2 data and should be properly checked in the new baseline C data. For processing to L2, there are still important issues on the specific implementation of SAMOSA (PTR, Thermal Noise). Moreover, a very high priority was assigned to the characterization of SWH dependencies and errors in SAR altimetry data and to the development and evaluation of SAR mode SSB models. This is also linked to the need for assessing impact of swell in SAR altimetry data.

A group of recommendations refers specifically to assessing what can be observed in SAR data: at L1a level this should require an investigation into the characteristics such as the data auto- covariance and correlation with the sea state; at L1b-S (stack) level this calls for exploiting stack statistics to observe ocean surface properties. [Other recommendations for SARin, polar oceans and sea floor bathymetry are not directly relevant to SCOOP.]

1.3.3.1 CP4O Extended Activities

ESA funded throughout 2015 an extension (CCN) to CP4O to look at some of the issues identified in the CP4O Road Map. Amongst those of relevance to SCOOP: an investigation into SARin data in the coastal zone that could potentially result into recommendations also for an application to SAR and LRM altimeter data; the development and evaluation of improvements to the SAMOSA SAR altimeter echo model and retracker; and a comprehensive evaluation of the performance of CryoSat-2 SAR mode in the coastal zone, which demonstrated better results from SAR mode when a specific coastal processing was applied (Cipollini and Calafat, 2016). A full summary of the findings is in Cotton (2016).

1.3.4 9th Coastal Altimetry Workshop and OSTST, Reston (USA), October 2015

The yearly meeting of the altimetric community for 2015 took place in Reston, Virginia, USA, on 18-23 October 2015. All the presentations and several posters from CAW-9 are at http://www.coastalt.eu/restonworkshop15, while material presented at OSTST2015 is available at http://meetings.aviso.altimetry.fr/programs/complete-program.html.

CAW-9 featured some new ideas on SAR retracking: Dinardo et al. suggested a strategy for coastal retracking of SAR echoes, which adds the mean square slope as free fitting parameter in case of high misfit[2]. Moreover, a new semi-analytical SAR retracker being developed at TU Darmstadt was presented by Buchhaupt et al. but is still in need of improvement. Cipollini et al. showed results from an assessment of SAR altimetry around the British Isles obtained within the CP4O contract extension described in 1.3.3.1, which show the excellent quality of the data and the possibility of retrieving good measurements up to 1-2 km from the coast (see Cipollini and Calafat, 2016). Gomez-Enri et al showed that it is possible to observe the signature of ships in SAR waveforms.

OSTST had many presentations and posters dealing with SAR altimetry: Bellingham et al. outlined the EUMETSAT SAR SSB study that will also provide as input to SCOOP. Aouf and

[2] It is fair to note that the adoption of the roughness as a fitting parameter to the SAMOSA analytical retracker was originally proposed by Jain et al (2014) at IGARSS2014: in that case they extended the exploitation of the ocean-like waveform model to account for more specular reflections from sea ice leads in the Arctic.

Phalippou provided another important paper for SCOOP, where the comparison of SWH from CryoSat-2 and a wave model revealed a bias induced by long swells, especially when propagating in a direction close to the ground track orientation.

Egido and Smith showed a very promising attempt to fully focused processing of L1a CryoSat-2 data. The measured along-track resolution is ~0.5 meters i.e. what expected theoretically, and the focused SAR geophysical parameters noise at 84 Hz is equivalent to the delay/Doppler noise at 20 Hz, so for SLA noise the theoretical limit of 0.5cm at 1 Hz is in sight. However, the coherent and incoherent scattering components could not be separated due to the presence of strong reflections from the ocean.

Dinardo, Scagliola et al assessed the performance improvement expected from the Along-track Antenna Pattern Compensation but found no conclusive results for SSH and SWH, and a slight improvement for sigma0 – so this issue needs further investigation.

Moreau et al suggested some improved SAR-mode ocean retrievals from new CryoSat-2 processing schemes: these include a weighted MLE3 retracking that assigns more importance to the outer looks in the stack and an individual Doppler beams retracker that allows a fine screening of the beams: this is being directly assessed in SCOOP.

Ray and Roca showed, as an application of the AC/DC approach, the direct algebraic computation of the antenna pointing from the AC/DC delay/Doppler map. Such technique allows the inversion of the antenna miss pointing directly from the data itself.

Fernandes et al. presented a new set of global wet tropospheric corrections for eight altimetry missions using the GPD+ algorithm (Fernandes et al. 2016). This latest version of the algorithm is an upgrade of the previously designated GPD (Fernandes et al. 2015), and DComb (Fernandes et al., 2013) algorithms, the first designed for missions such as Sentinel-3 and the second for CryoSat-2, which does not possess any on-board radiometer. In the GPD+ version, all the following data sets are combined: valid on-board microwave radiometer (MWR) measurements, if available, scanning imaging MWR data and GNSS-derived wet path delays. Moreover, the whole set of radiometers used in the GPD+ estimations have been calibrated using the SSM/I and SSM/IS set of radiometers as reference, due to their well-known stability and independent calibration.

1.3.5 New SAR Mode Literature up to October 2015

A number of important peer-reviewed papers have been issued in the area of SAR waveform modelling and retracking since 2013. The SAMOSA2 and SAMOSA3 formulations are described in Ray et al., 2015a. The Amplitude and Dilation Compensation of the SAR waveform is described in Ray et al., 2015b. The semi-analytical model by Halimi et al has also been published in 2014, with further inclusion of the antenna mispointing in Halimi et al. 2015.

For completeness, Garcia et al 2014 published their empirical SAR altimetry model. As detailed in the Gommenginger et al.'s review, this approximate model, first presented by Sandwell et al in 2011, has merits for gravity field recovery but is sub-optimal for other oceanographic applications.

The implementation of the SAMOSA models for Sentinel-3, including some proposed upgrades not yet included in the current processor, have been summarized in a paper for the 2015 IGARSS conference (Dinardo et al., 2015). At the same conference Scagliola et al have presented an extended analysis of the antenna pattern compensation issue (Scagliola et al., 2015b).

On the issue related to the estimation of the pitch from an analysis of stack data, which has been presented at OSTST meetings as reported above, a possible solution has been recently published by Scagliola et al (2015a).

Regarding DTC and WTC corrections, significant work has been published by Fernandes et al., 2015, where a set of improved wet tropospheric corrections (the GPD algorithm) for all ESA and reference missions were proposed, with particular impact in coastal and polar regions.

Finally, on the validation side, a peer-reviewed contribution has been published by Fenoglio-Marc et al., 2015.

2 Current Status of SAR Altimetry Processing

2.1 Level 1a to Level 1b processing (Doppler Stack Processing)

In the following sections, a review of the state-of-the-art of the Delay-Doppler or Doppler stack processing is carried out, based on the well-known experience of isardSAT in the implementation of such processing baselines.

2.1.1 Overview of Altimeter SAR L1a to L1b Processing

The first Delay-Doppler Processor for Altimeter data from a European Earth Observation satellite was a Ground Processor Prototype (GPP) developed by UCL for the CryoSat-2 mission. This GPP was used for validating both CryoSat-2 products and end-to-end chain performances (Wingham, et al., 2006). This GPP was later operationally adapted by Aresys becoming the SAR and SARin chains of the Instrument Processing Facility (IPF-1) of the CryoSat-2 mission (Cullen et al., 2007).

In CryoSat-2, new, intermediate, lower-level products such as Full Bit Rate (FBR) and calibrated FBR (C-FBR) products, equivalent to the so called L1A products in Sentinel-3 and Sentinel-6, were originated with the main purpose of testing, debugging and internally verifying the processor algorithms. FBR products and C-FBR products were not made publicly available, hence a limited number of studies were carried out. The main goal of the CryoSat-2 L1 SAR Delay-Doppler processor was producing L1B products to be injected into L2 processor chain.

In addition to that, some calibration and validation activities also needed some customized L1 algorithms different than the baseline ones provided in the L1B GPP. For instance, the calibration activities developed by isardSAT using a transponder led to the implementation of a new algorithm to steer the beam to the transponder precise position in order to improve the absolute range calibration method.

The Sentinel-3 mission inherited all lessons learned from CryoSat-2 and a new L0/L1 Delay Doppler Ground Processor Prototype (GPP) was defined and implemented. This GPP was developed, tested and validated by isardSAT, based on the algorithms defined by CLS (see CLS 2013). This definition, together with the lessons learned from the GPP implementation, was later used to implement the Sentinel-3 Instrument Processing Facility by ACRI ST and CLS companies (see ACRI and CLS 2014).

In 2013, ESA released an L1 & L2 processor prototype called SARvatore: SAR Versatile Altimetric Toolkit for Ocean Research & Exploitation (GPOD CryoSat-2 SARvatore Software Prototype, on-line user manual Dinardo 2014). This processor offered to the scientific user community L1 Delay Doppler ocean dedicated capabilities (we should note that CryoSat-2 is a cryosphere mission) to customize L1 Delay Doppler from L1A products (CS-2 FBR products).

These processing capabilities include the application of Hamming weighting window and the selection of the size of the radar receiving window.

The new Sentinel-6/Jason-CS mission will be the successor of previous conventional altimetry Jason's missions including a new SAR Altimeter (Poseidon-4) on-board. The main differences between the Sentinel-3 altimeter (SRAL) and the Sentinel-6 altimeter (Poseidon-4) are the following:

1. Poseidon-4 includes an improved **digital** and radio frequency **hardware**.
2. Poseidon-4 includes an open burst Ku-band pulse transmission mode (**interleaved** mode) performing a near continuous transmission of Ku-band pulses. It will allow the simultaneous processing of measurements to obtain High Resolution along-track (HR or SAR) and Low Resolution (LR or LRM) data.
3. As on previous instruments, such as RA-2 on Envisat, Poseidon-4 transmits some secondary pulses at a lower frequency band (**C-band, S-Band on Envisat),** interleaved with the main pulses in Ku-band, to retrieve the correction for the ionospheric path delay. However, permanent calibration pulses will also be integrated within the transmission pattern without the need of switching between working modes.
4. Poseidon-4 implements an on-board "Range Migration Correction" (**RMC**) processing in order to reduce the amount of data to download to ground.

The Ground Prototype Processor of the Sentinel-6 mission altimeter, Poseidon-4, is being developed by isardSAT under an ESTEC/ESA contract that started in 2011 and is lasting until the end of the satellite Commissioning phase. This processor includes new features partly thanks to the experience gained with the CryoSat-2 data and partly thanks to the many studies carried out during the development of the project. The Sentinel-6/Jason-CS GPP has an important configuration capability, precisely to be able to study the different possible solutions and how they perform under different circumstances. The different processing algorithms or stages included in the GPP have specific internal switches to activate different processing options based on a configuration file descriptor. Among these re-configuration capabilities the most relevant ones are: exact or approximate method for the beamforming processing (azimuth processing) depending on the variability of the surface being imaged; reference beam for the geometric corrections (nadir one, beam with maximum power, …); different along- (at burst level) and across-track (before range compression) weighting functions; specific weighting (antenna and/or surface dependent) at stack level; application of different types of stack masking before multi-looking (incoherent averaging).

This development has taken advantage of simulated instrument source packets (ISP) produced by the ESTEC Sentinel-6/Jason-CS mission performance simulator. Simulated data have proven to be extremely useful for understanding details of this Delay-Doppler Processing, which is still relatively new in the altimetry world. The fact that we had to face a new configuration has also brought us to review some of the theory, coming up with new methodologies in different aspects of the processing.

Another major improvement, which is a new and **revolutionary** concept for the stack building, is the Amplitude Compensation and Dilation Compensation (AC/DC) technique. As said in 1.3.2 and 1.3.5 this was presented at the OSTST 2014 (AC/DC, Ray et al., 2014) and later published (Ray et al., 2015b). The application of this methodology would impact both the DDP and the retracking model, not only in terms of performances, particularly at low SWH, but also reducing the run-time. It must be noted that this new algorithm is not being investigated in the baseline of the SCOOP project due to budget limitations.

2.1.2 Doppler Stack Processing

Figure 2-1 shows the generic L1A/L1B SAR processing chain algorithms and output products.

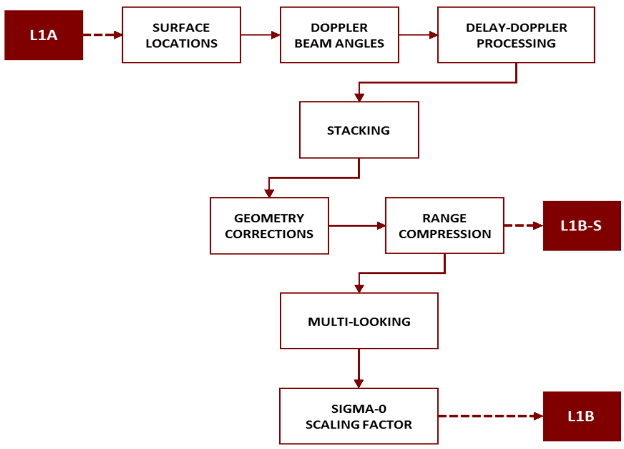

Figure 2-1 Level-1A/Level1-B SAR processing chain (credit: isardSAT).

The main algorithms of the Level-1 SAR-Ku chain are[3]:

2.1.2.1 Surface Locations

The L1B results are based on the surface sampling that has been performed. This algorithm is responsible for computing the spacing between the surface locations, considering the satellite Doppler resolution and the surface profile. This prevents the surface to be oversampled or with gaps.

The first step to compute the surface locations is to build an estimated surface. This is done using the satellite burst positions and the window delay (also called the tracker range).

Then, the first surface location is initialised with the values of the first burst. After that, an iterative process starts to compute the remaining surface locations, and is repeated until the end of the orbit is reached (see Figure 2-2). The iterative process proceeds to

- Compute the angular Doppler resolution, θ, through the Doppler frequency expression.
- Determine the intersection of this direction with the surface. This process is performed by iterating through the surface positions until the angle of sight α is bigger than the

[3] For a detailed description of the L1B processing and the different algorithms involved please refer to the ATBD described in the reference document [9].

angular Doppler resolution θ (see Figure 2-2).

- Once this is done, an interpolation of the surface is performed between the two last surface positions. In CryoSat-2, this is performed with a linear interpolation. On the other hand, in Sentinel-3 this interpolation is done with cubic splines. With this, a new surface location and its datation is found.
- After that, all the orbit parameters (satellite equivalent position, satellite velocity vector, satellite attitude) are computed with the new datation. These parameters are also obtained by interpolation (linear in CryoSat-2 and spline in Sentinel-3).

Then, the process starts again, taking as a reference this last surface location and its corresponding orbit parameters.

2.1.2.2 Doppler Beam Angles

To perform the Delay-Doppler processing, the angles between each satellite burst position and all the surface locations that have been illuminated have to be computed. This algorithm determines these directions and its geometry is shown in Figure 2-3. Each burst is composed of 64 pulses, and the Doppler spectrum is divided in 64 bins. Each bin is associated with a pulse, that with the azimuth processing, will be converted into a Doppler beam.

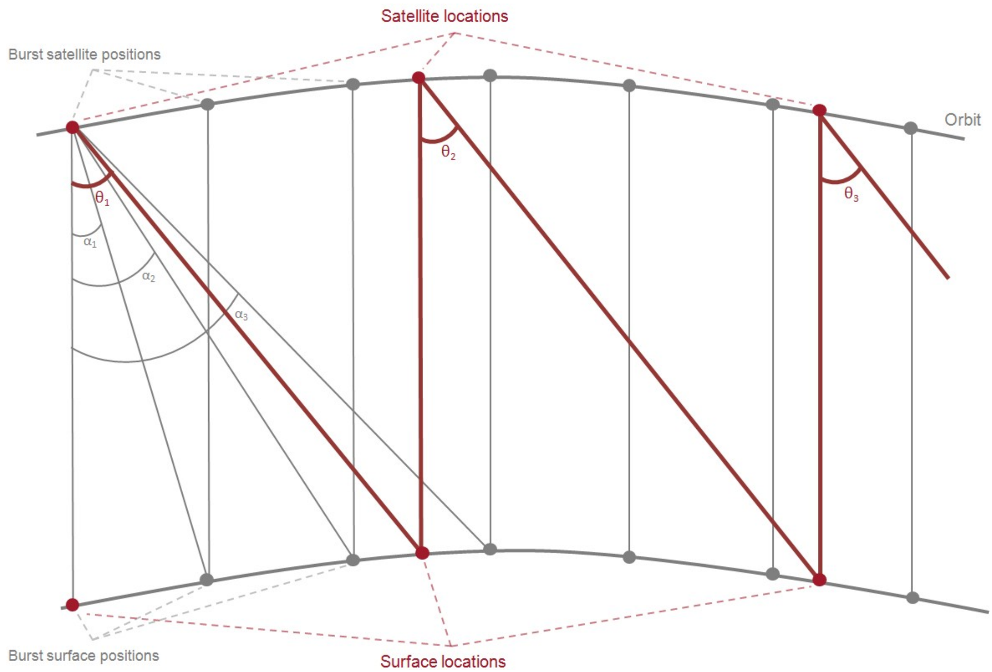

Figure 2-2 Compute surface locations (credit: isardSAT): α_i corresponds to the angle of sight (nadir direction and vector from satellite position to each ground location) and θ_j is the angular/beam Doppler resolution for the j-th surface.

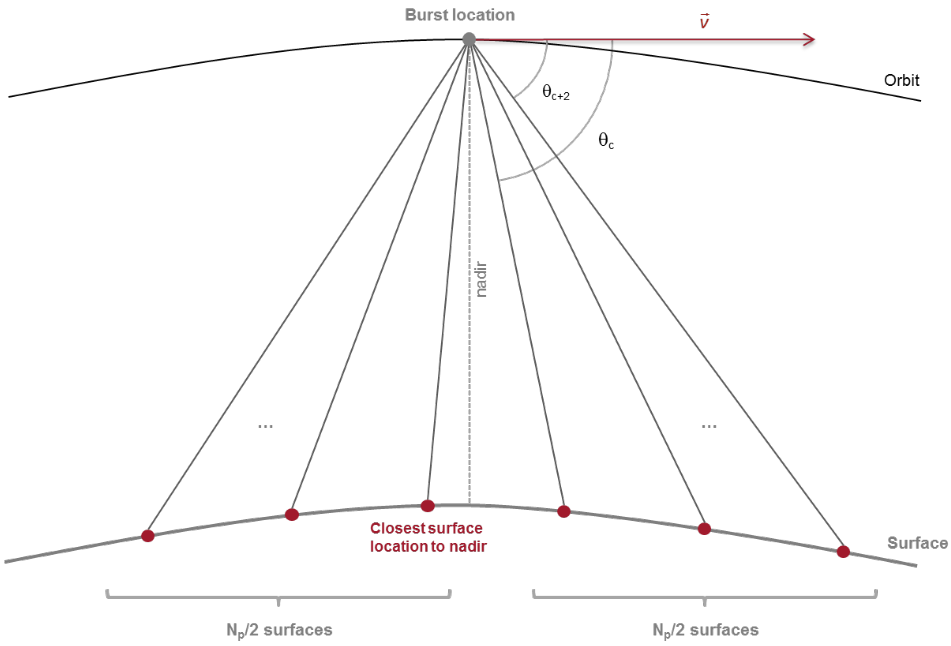

Figure 2-3 Determine Doppler beams directions (credit: isardSAT).

2.1.2.3 Delay-Doppler Processing

This algorithm creates the Delay-Doppler beams, each one steered to a different surface location. This is done by applying an FFT in the azimuth direction to all the pulses within a burst, which allows to divide the conventional altimeter footprint in a certain number of strips and thus to create the Delay- Doppler Map (DDM).

There are two ways of building the DDM: with a constant ground spacing, used only for low variability surfaces, or with a variable ground spacing, that is more precise and can be used for all kinds of surfaces (although it requires more computational time since it applies one FFT for each Doppler beam instead of one for the entire burst).

2.1.2.4 Stacking

From the DDM, all contributions coming from different strips can be identified and collected separately. When all the contributions from different bursts “q” are collected for a single surface location “l”, a stack is formed. Thus this process is called stacking (Figure 2-4 exemplifies this process).

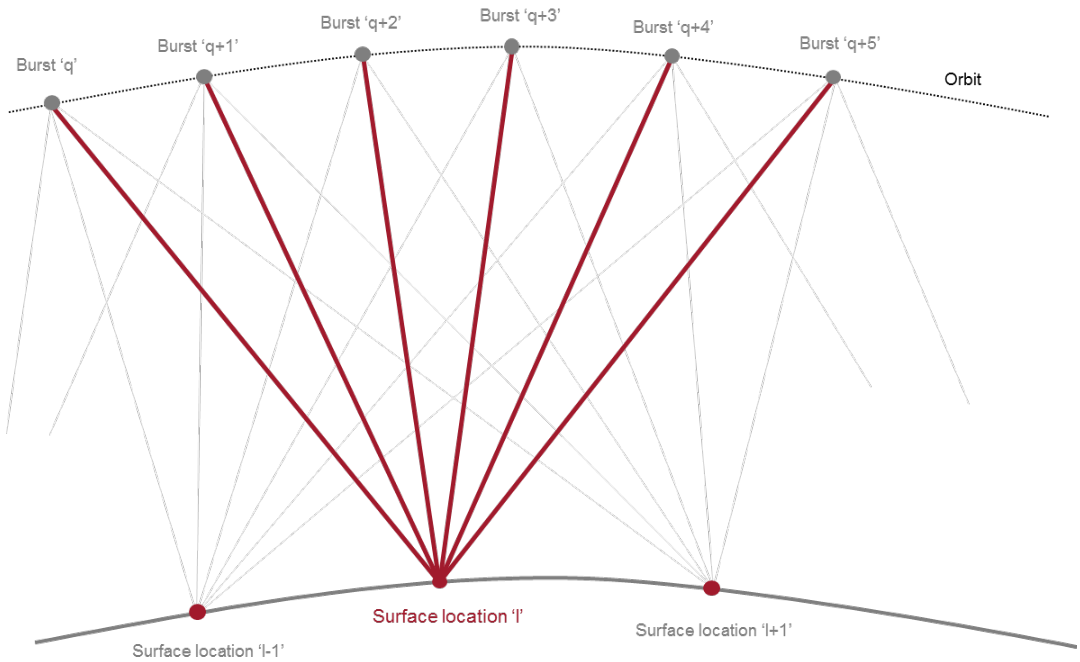

Figure 2-4 Stacking process for surface location 'l' (credit: isardSAT).

2.1.2.5 Geometry Corrections

This algorithm computes and applies all the corrections associated with the geometry of the scenario. These are the Doppler, slant range and window delay misalignments corrections.

- *Doppler correction*. Due to the movement of the satellite during transmission and reception with respect to the surface, unwanted Doppler frequencies are generated for each Doppler beam. Hence, a compensation to this phenomenon has to be applied. This is depicted in Figure 2-5.
- *Slant range correction*. Off-nadir beams suffer a range migration effect. This means these beams have greater round-trip distances than the nadir beam. The geometry of this scenario is shown in Figure 2-6.
- *Window delay misalignments*. Since all the beams that form a stack come from different bursts, they are associated with different window delays. This results into a misalignment of the different beams and has to be corrected

All these geometry-based effects are observed as a range misplacement within the receiving window. This can be seen when the range-compressed stack is plotted, as in Figure 2-7 (left panel). Once the corrections have been applied, the stack results range aligned (Figure 2-7 - right panel).

Although in CryoSat-2 and Sentinel-3 these corrections are applied separately and in different steps and domains (in the case of the slant range correction), it is intended to apply them all together and in the same domain, before the range compression is performed. Thus, all the corrections will be applied as a phase shift and with no need to be split into coarse and fine corrections.

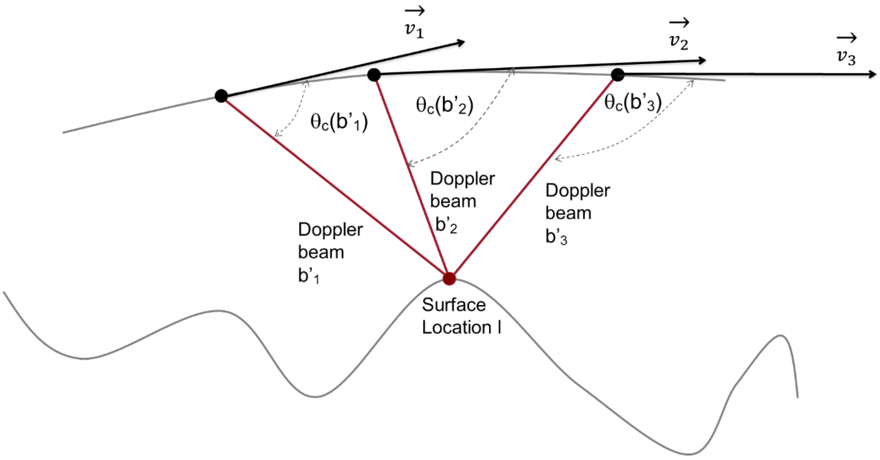

Figure 2-5 Doppler shift effect (credit: isardSAT)

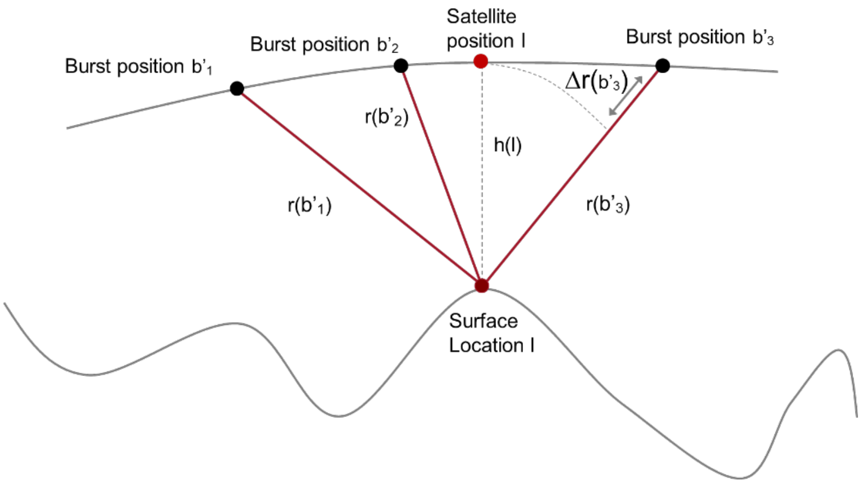

Figure 2-6 Slant range correction (credit: isardSAT)

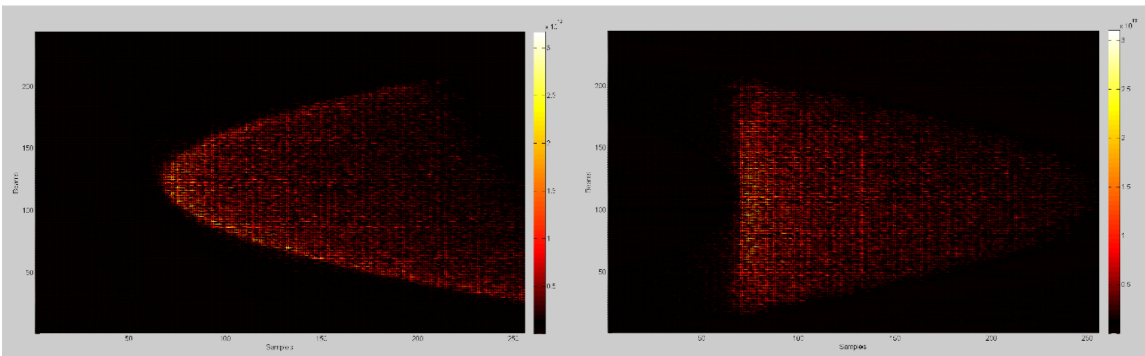

Figure 2-7 (left) Stack without geometry corrections, (right) stack with geometry corrections applied.

Although in CryoSat-2 and Sentinel-3 these corrections are applied separately and in different steps and domains (in the case of the slant range correction), it is intended to apply them all together and in the same domain, before the range compression is performed. Thus, all the corrections will be applied as a phase shift and with no need to be split into coarse and fine corrections.

2.1.2.6 Range Compression

This algorithm performs a range compression of the waveforms, that is, the conversion of each Doppler beam of a stack into the frequency domain. This is done with an FFT in the across-track direction.

Due to data rate volume limitations, the FFT is normally performed with a zero-padding factor of 1, or maximum 2. An FFT with a zero-padding factor is theoretically the best possible interpolation, because it uses the phase information, as it is performed with the video signals before the waveform power computation.

2.1.2.7 Multi-looking

This algorithm computes the non-coherent summation of all the power beams corresponding to each surface location. This means that, for each stack, the beams are squared (hence, phase information is lost) and, after that, averaged. The result of this operation is one L1B waveform per stack.

Apart from that, before averaging all the beams in the stack, another process is carried out. In order to compute the stack characterisation parameters for the L1B product, a smoothing is performed so as to have a better fitting of the stack with a Gaussian model as a function of the beams (look angle). This smoothing process is called sub-stacking. Note that this process is only applied for the characterisation of the stack and it is not applied to the waveforms. Such fitting allows the extraction of useful characterization parameters of the stack as a function of look angle, such as 3 dB width, centre of the stack, standard deviation and kurtosis.

2.1.2.8 Sigma-0 Scaling Factor

This algorithm computes the Sigma-0 scaling factor that is used at Level 2 to determine the backscatter coefficient of the surface from which the echoes have been reflected.

The Sigma-0 scaling factor is based on the radar equation, which indicates the power relationship between the transmitted and received echoes, considering a single beam.

2.2 Level 1b to Level 2 Processing

2.2.1 Waveform retracking

The model currently used for the retracking of Sentinel-3 SRAL L1b data is described in v 2.3.0 of the DPM documentation by Gommenginger et al. (2013b), and was originated from the efforts of the SAMOSA project. The evolution of the SAMOSA models over time is described in great detail in the CP4O final report (Cotton et al., 2015). Here we summarize the main stages of this evolution.

The fundamental theoretical model for the SAR altimeter backscattered waveform is described in the paper by Ray et al. (2015a). While the initial derivation of the mathematical model yielded a form only amenable to numerical retracking, Ray et al then applied some approximations to achieve a closed form. The rationale is that, as they explain in their own words “a closed-form formulation is advantageous compared with numerical solutions, in that the amplitude and shape of the waveform can be directly linked to geophysical parameters, and a simple inversion procedure can be then used to retrieve these parameters”.

The waveform model by Ray et al (2015a) in its most comprehensive closed form coincides to what is known as the SAMOSA2 model. Figure 2-8 shows a well-behaved CryoSat-2 waveform and its best fit with that model.

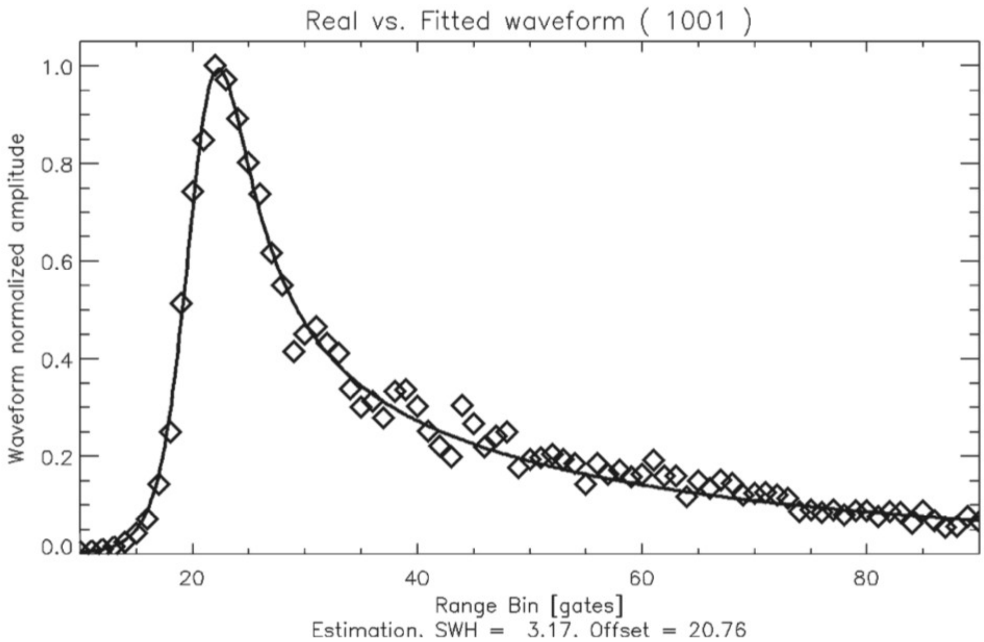

Figure 2-8 From Ray et al (2015a). A real SAR altimetry waveform from CryoSat-2 (diamonds), with its best fit with the SAMOSA2 model (solid line). The values of the estimated SWH and epoch (offset) are also given in the label.

SAMOSA2 is computationally intensive for an operational implementation, so a simplified version, SAMOSA3, was implemented for the earlier versions of the DPM by truncating SAMOSA2 to its zero-th order term (Gommenginger et al., 2013b).

During the CP4O project, Starlab had led a further evolution of the processing software (already documented in a Technical note by Egido, 2014a) resulting in a number of changes. One of these, namely:

- Thermal Noise is estimated from the waveform and fed as a priori input parameter in the retracker

has already been included in version 2.3.0 of the DPM (Gommenginger et al., 2013b), i.e. the one on which the current IPF is based (ACRI and CLS, 2014b).

CryoSat-2 data processed with this further improvement have been validated in the CP4O project against the output from the CryoSat-2 Product Prototype (CPP) processor provided by CNES (Boy and Moreau, 2013), and found to be fully consistent for range, for SWH above 2m and for waveform power (from which σ^0 is derived) retrievals with no bias between the two products (See Egido, 2014b for details). However, differences were found in the estimates of SWH (for SWH < 2m, see figure 11 in Cotton et al., 2015). Analysis and discussion within the CP4O partners ascribed this to a difficulty of the SAMOSA model in accurately catching the "toe" of the leading edge of the SAR echo waveform; it was suggested that this could be corrected by applying a dedicated correction to the SWH estimates.

Dinardo and Lucas (2015) have captured the suggestion above and other potential enhancements to the S3 DPM. The three changes made by Dinardo and Lucas (2015) are:

- Coding of the complete SAMOSA2 model (i.e. including the first-order term) and the introduction of a switch for its application instead of SAMOSA3. On the computational efficiency of such a solution, Dinardo and Lucas stated that "if the 1st order term is implemented as pre-calculated lookup table loaded into memory then the computational performance should be roughly the same".
- Stack masking, i.e. by resetting to zero (prior to stack summation) all the power bins in the DDM (Delay-Doppler Map) that get zero-padded in the delay/Doppler Stack data[4];
- Application of a Look-Up Table (LUT) for the selection of a variable width alpha_p of the Point Target Response (PTR) as a function of SWH.

These changes are also described in Dinardo et al. (2015) and have been included in the latest version (2.5.0) of the DPM (Gommenginger et al., 2015), which therefore contains the full SAMOSA2 model – but at the time of writing these changes have not yet been reflected in an IPF update. According to the information provided in the S3 Expert Group Meeting held at ESA/ESRIN on July 20th 2016, the SAMOSA 2.5.0 DPM is undergoing a validation phase for both Sentinel-3 and CryoSat-2.

2.2.1.1 Specific Coastal Issues in retracking

The performance of SAR altimetry in the coastal zone has been assessed by two groups within the CP4O project.

First, Raynal et al. (2014a and 2014b) looked briefly at the performance of the different SAR products close to the coast, and found very little difference among the Full SAMOSA analytical model (with Gaussian wave statistics), a product from the earlier implementation of the Sentinel 3 DPM and the CPP numerical product, in terms of the mean calculated Sea Level Anomaly, the number of valid points (per km), and the standard deviation (see Figure 2-9, from Cotton et al., 2015).

The coastal performance has been analysed in detail in the extended CP4O phase by Cipollini and Calafat, (2016). Their analysis compared one year of CryoSat-2 data around the coast of the UK from two different processors, in the configurations detailed below:

- CNES CPP (Boy and Moreau, 2013): this is a good example of a very efficient numerical retracker, very efficient, but not optimized for coastal performance, so it is perfect to act as a reference for the improvements expected from a coastal-specific processing scheme;

[4] We note explicitly that this improvement relates to L1A to L1B processing

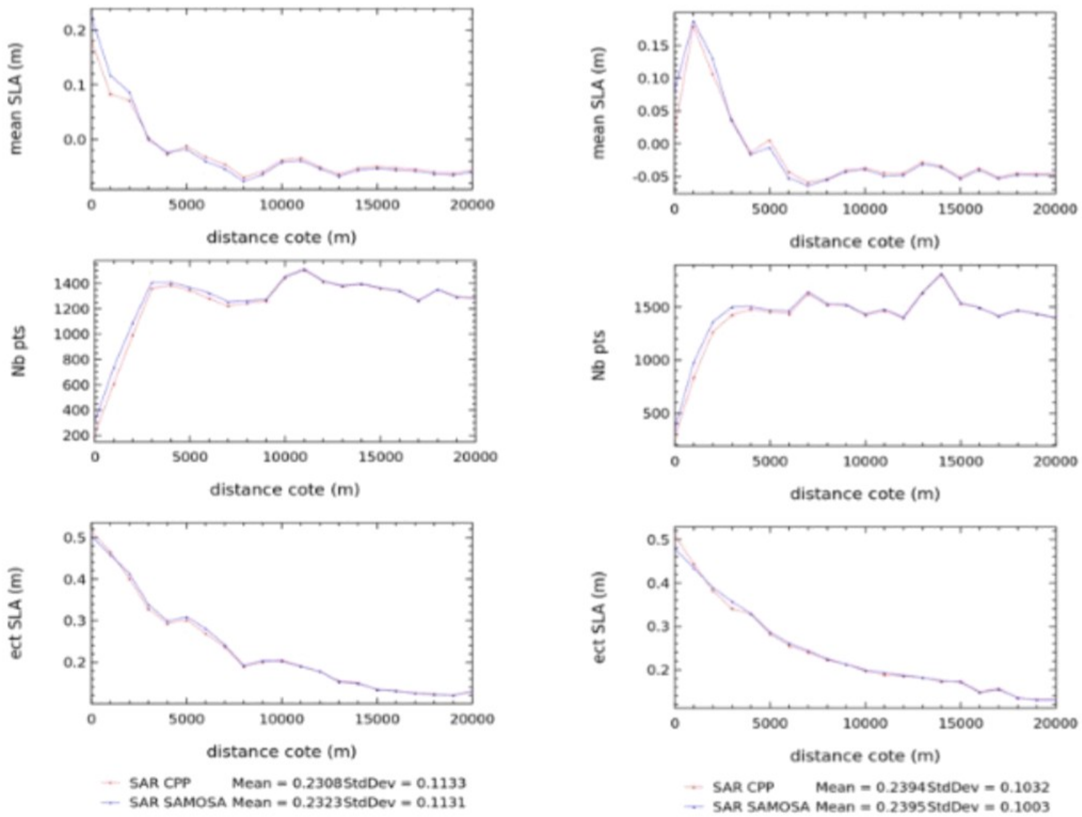

Figure 2-9 From Cotton et al., 2015. Sea Level Anomaly (top), number of points (middle), and standard deviation of SLA (bottom), for CPP SAR (red) and SAMOSA R1 SAR (blue) data with distance from the coast. For ascending (left) and descending (right) passes on tracks close to the UK

ESRIN GPOD SAR altimetry processor (based on SARvatore, see Dinardo, 2014), which was used to explore the effects of a coastal-specific processing. This processor has been run in a configuration similar to the SAMOSA DPM 2.5.0, using the SAMOSA2 model with the improvements first proposed at CAW-7 by Martin-Puig et al. and Dinardo (see 1.3.1); at L1A to L1B these are the application of a Hamming weighting in azimuth, the pre-FFT zero padding and extended range window, and the masking of the delay/Doppler map; at L1b to L2 the LUT for the PTR has also been applied.

Results of the coastal assessment by Cipollini and Calafat (2016) show clearly both the intrinsic good quality of the CryoSat-2 data from both processors, and the improvements achievable when the coastal-specific processing is adopted. Figure 2-10 illustrates these improvements in the measurement noise: for the coastal-specific processing, 20-Hz noise values are 2–8 mm lower than the CPP reference at distances greater than 5 km from the coast, but the gain is larger in the coastal strip (7.3 cm versus 8.8 cm at 3 km). This gain comes from the combination of pre-FFT zero padding, extended range window and azimuth weighting at L1. Note that azimuth weighting also reduces the effective along-track resolution of the data and therefore some reduction (in absolute value) of adjacent differences is to be expected. More experiments should be carried out to quantify the impact of the single processing configuration choices.

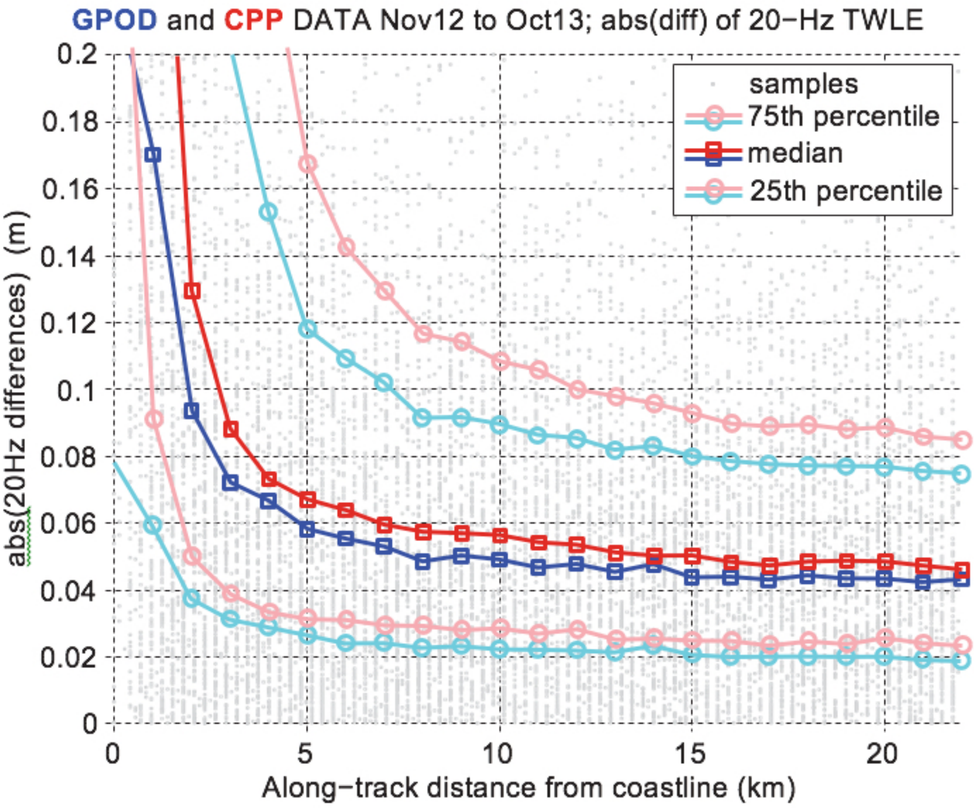

Figure 2-10 Scatterplot of the absolute value difference between consecutive total water level envelope (TWLE) measurements, a proxy for measurement noise**, against along-track distance from coast, and the statistics of its distribution in 1-km distance bins, for the GPOD-processed dataset (in blue and cyan) and for the CPP-processed dataset (in red and pink).**

Cipollini and Calafat (2016) also clearly demonstrated the impact of ground-track orientation with respect to the coast. However, defining an unambiguous 'angle to coast' direction in areas of complex coastal morphology is not possible. Given the elongated across-track shape of the narrow SAR altimetry footprint the noise statistics can be studied as a function of across-track distance to coast; when the noise statistics are plotted against this quantity they are very similar to those of Envisat, increasing from about 5 km from the coast, confirming the pulse-limited nature of the SAR footprint in the across-track direction. Conversely, in a selected case study around Brighton in the South coast of the UK where the altimeter tracks are approximately orthogonal to a simple E–W coastline, the noise stays at values similar to those over the open ocean, up to 1-2 km from the coast.

An alternative retracking strategy that has been proposed in recent years for pulse-limited altimetry is the retracking of 'sub-waveforms', i.e., a portion of the waveform unaffected (or less affected) by coastal artefacts (as proposed in Yang et al., 2012). In the pulse limited case this has led for instance to the ALES (Adaptive Leading-Edge Subwaveform) retracker (Passaro et al., 2014), which has been validated for sea level and SWH and used for different altimeters in number of case studies. ALES is a two-pass retracking algorithm, where the second-pass sub-waveform window is 'adapted' based on the first-pass estimates of SWH. The same approach is in principle usable also in the case of SAR altimetry – even in this case in fact, bright off-nadir targets in the coastal environment (for instance specular reflectors at the coast such as a small, very calm harbour) will originate artefacts in the tail portion of the waveform, and the accuracy of the fitting may improve if that portion is left out altogether. As said in section 1.3, Thibaut et al. have proposed that approach at CAW-7, and refined it at CAW-8 (Thibaut et al., 2014); they used sub-waveform windows of fixed width. One improvement that would be worth exploring is the adoption of a sub-waveform window size which varies gradually in dependence of a first-pass SWH estimate, as it is done in ALES.

2.2.2 Corrections

2.2.2.1 Not SAR-specific

Most altimetric corrections (for range and for the removal of unwanted geophysical contributions to the measured height, such as tides and the dynamic forcing of the atmosphere) are not specific to the SAR case, so SAR altimetry can take advantage of the improvements in this field driven for instance by research in coastal altimetry or support of the reference altimetric missions. For completeness we briefly mention in this section the main progress in this area in recent years, and the main solutions available for the corrections.

Ionospheric path delay: the accuracy of the Global Ionospheric Maps (GIM) is 2 to 8 Total Electron Content Unit (TECU) in vertical (Rovira-Garcia et al., 2015) and as 1 TECU induces a path delay of 2.18 mm in Ku band (13.6 GHz) (Fernandes et al., 2014) the accuracy is between 4 and 17 mm. This means in practice that this correction is not the major contributor to the error budget, also for single-frequency altimeters, as shown experimentally by CryoSat-2 SIRAL. Sentinel-3 SRAL is dual frequency (bursts of 64 Ku-band pulses surrounded by two C-band pulses) so a full dual-frequency correction can be developed.

Wet Tropospheric delay: as amply demonstrated within the ESA Sea Level CCI Initiative, the best correction is the new set of global wet tropospheric corrections for eight altimetry missions designated as GPD+ (Fernandes et al., 2016). It is an upgrade of the previous GPD (Fernandes et al. 2015), and DComb (Fernandes et al., 2013) algorithms, the first designed for missions such as Sentinel-3 and the second for CryoSat-2, which does not possess any on-board radiometer. In the GPD+ version, all the following data sets are combined: valid on-board microwave radiometer (MWR) data, if available (which is the case for Sentinel-3 but not for Cryosat-2), scanning imaging MWR data, and GNSS-derived wet path delays. Moreover, the whole set of radiometers used in the GPD+ estimates have been calibrated using the SSM/I and SSM/IS set of radiometers as reference, due to their well-known stability and independent calibration. This correction represents an improvement against the traditional MWR-based, model-based corrections or the AVISO Composite correction (a combination of MWR and model values), especially in coastal zones and polar areas.

Dry Tropospheric delay: models of surface atmospheric pressure are used to generate this correction with an accuracy of a few mm (Fernandes et al., 2014). The ECMWF ERA Interim (Dee et al., 2011), provided at 0.75° × 0.75° resolution on a regular grid (or about 80-km on a Gaussian grid) is recommended for its homogeneity (Fernandes et al., 2014) and positive impact on long- term trends (Carrère et al., 2016).

Tides: the accuracy of the tidal models continues to improve steadily, both over the open ocean and in shelf and coastal areas (Ray et al., 2011). For the latest models we refer to the comprehensive review and inter-comparison by Stammer et al. (2014).

Dynamic Atmospheric Correction (DAC): the DAC includes both the inverse barometer response and the dynamic response to atmospheric forcing at high frequencies (Carrère and

Lyard, 2003), which is well modelled using the MOG2D hydrodynamic finite element model. The latest development is the computation of this correction forcing the MOG2D barotropic ocean model with the corrected ERA Interim meteorological data (Carrère et al., 2016).

2.2.2.2 SAR-specific: Sea State Bias and Swell Effects

It is well known that the Sea State Bias (SSB) is linked to retracking. There is a consensus in the scientific community that SAR altimetry requires a specific SSB solution, and this need had been already explicitly underlined in the Gommenginger et al. (2013a) review. The review highlighted that no solution was yet available for SAR mode SSB. The need for a solution had then been reiterated as a high priority in the CP4O Scientific Road Map (Cotton et al., 2015). This need is even more pressing now that Sentinel-3 is providing global observations in SAR mode.

The 300-m along-track dimension of the SAR resolution cell also suggests that swell with comparable (or longer) wavelength may induce a bias (or more precisely what is known as ‘range spreading’) on the measured height, particularly when it propagates approximately parallel to the satellite track, as observed by Gommenginger et al. (2013a). Effects of this kind have been reported by Aouf and Phalippou (2015) in their paper at OSTST 2015 (see 1.3.4), where the comparison of SWH from CryoSat-2 and from a wave model revealed a bias induced by long swells, especially when propagating in a direction close to the ground track orientation as expected. Now these effects must be quantified. Numerical simulations (Moreau et al., 2013) and analyses of Cryosat-2 SAR mode waveforms in swell conditions (reported in Gommenginger et al., 2013a) also point to a distortion of SAR altimeter waveforms caused by the swell.

In 2015 EUMETSAT commissioned a study (in preparation for Jason-CS) on SAR Mode Sea State Bias, including also an investigation of the effect of swell and swell direction in SAR mode altimetry. This study is on-going, and has already resulted in a full review of the various issues (Srokosz et al., 2015). Srokosz et al’s review concluded that “the empirical methods developed for LRM are equally applicable to SAR mode altimetry and this must be the way forward in the first instance, for correcting for SSB in SAR-enabled missions […] since they (the methods) can be tailored to a particular instrument and therefore also account for instrument and processing effects”. This is certainly the case for Sentinel-3, launched in February 2016, which is gathering global altimeter data in SAR mode (although at the time of writing in June 2016 only a very limited test dataset is openly available to the community of expert users). The investigation on the effects of swell is still being carried out at the time of writing of this report.

The EUMETSAT ITT stipulates that the outcome of the study and its deliverables will be shared with ESA and CNES. The results will therefore be reported into SCOOP, where they will be reviewed and used to generate recommendations for the application to Sentinel-3.

2.3 Key Progress Points and Remaining Challenges

In this section we list some “key points” including both key achievements from the last few years, and unresolved challenges considered crucial for future development.

2.3.1 Stack Weighting

The issue is how to weight the stack prior to multi-looking, and in particular how to weight the outer Doppler bins. Moreau et al. (2015) at OSTST have tackled this issue by following a study of SAR mode speckle noise presented by L. Amarouche at the SAR Altimetry Expert Group Meeting in Southampton, June 2013. They first reason is the Maximum-likelihood estimator algorithm (MLE) used in conventional pulse-limited retracking. This algorithm gives more importance to portions of the waveform with low power, see Figure 2-11. In the same fashion, on a stack of Doppler beams the amplitude of those beams that are attenuated because of the viewing geometry must be weighted-up for optimal speckle rejection when averaging all the beams. This approach is being investigated further by CLS in SCOOP. It is worth noting that the concept of a "weighting-up" of the outer Doppler beams is also present in the AC/DC approach, see later.

2.3.2 Exploiting Power Distribution in the Stack (L1)

The distribution of power in the stack can in principle be exploited to derive some platform attitude information, like mispointing (as suggested by Moreau et al at. OSTST2014), and for pitch estimation (Scagliola et al., 2015). Also the AC/DC approach allows the derivation of mispointing directly from the stack.

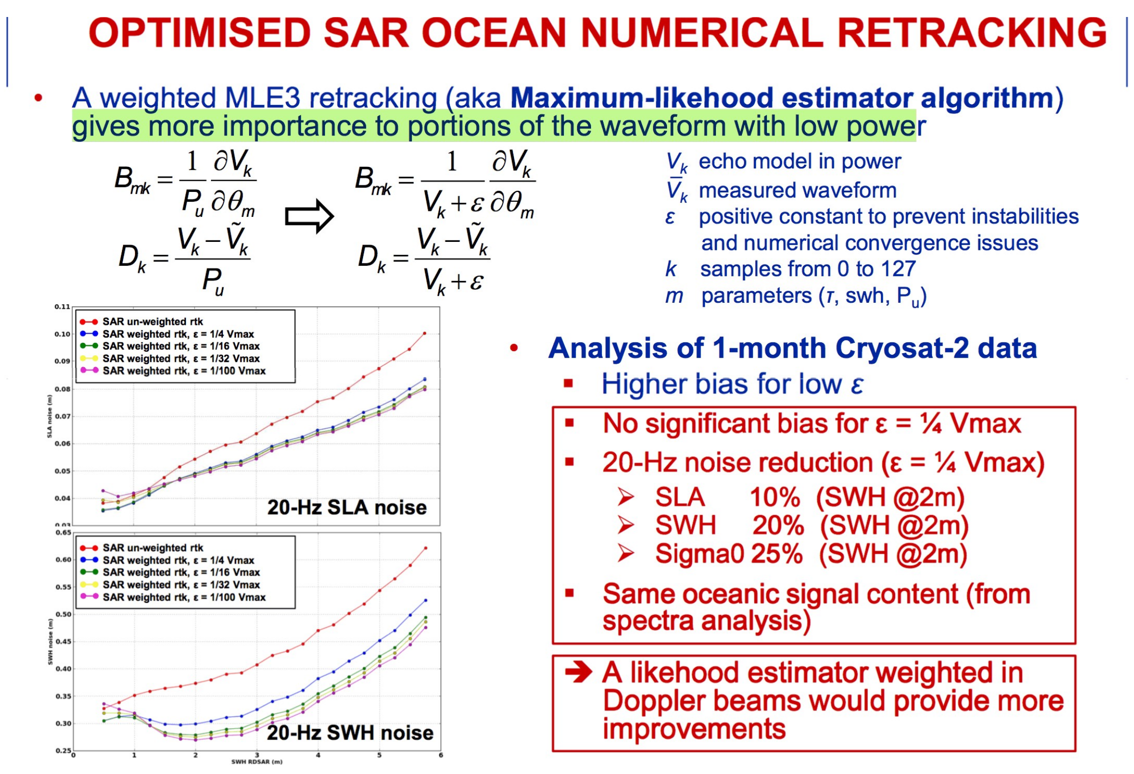

Figure 2-11 From Moreau et al., 2015 – Derivation of the concept of a likelihood estimator weighted in Doppler beams from the conventional MLE3 retracker approach.

2.3.3 Individual Doppler Retracking (L1)

Moreau et al (2015) have also proposed an innovative approach to SAR mode retracking, which does not require neither Doppler beam weighting nor antenna pattern compensation: to retrack each look in the stack separately, and then average their estimates. In this way every look gives the same contribution to the noise reduction, irrespective of its viewing geometry. As explained in detail by Moreau et al. (2015), tracker range alignment is not applied (only the distance migration correction is) mitigating possible errors. Inconsistent looks still contaminated by land / calm waters can be edited out. This approach needs a full demonstration and assessment, which is being carried out in SCOOP.

2.3.4 Computation on a Finer Ground Step (L1)

As shown by Dinardo et al. at CAW-7 in 2013 and then upgraded at OSTST2015, it is possible to compute the stack at a finer ground step, with 84 Hz (the burst repetition frequency) being a natural choice. This has the advantage of allowing a finer resolution which is particularly beneficial for observations of inland waters, but it has also the advantage that the datation time and geo-location information are provided at each burst centre in the FBR products so they do not require interpolation, thus removing one possible source of inaccuracy.

2.3.5 Full SAR Focusing (L1)

The fully-focused processing of SAR altimetry echoes, suggested by Raney (2014) in his review at CAW-8, has been developed by Egido and Smith who have presented the first results at OSTST2015. The achieved along-track resolution, as demonstrated by overflights over transponders, is ~0.5 meters i.e., what expected theoretically, and the focused SAR geophysical parameters noise at 84 Hz is equivalent to the delay/Doppler noise at 20 Hz, so for SLA noise the theoretical limit of 0.5cm at 1 Hz is in sight. However, the coherent and incoherent scattering components could not yet be separated due to the presence of strong reflections from the ocean. This is a development at the cutting edge of SAR altimetry, which can potentially yield data with the maximum achievable signal-to-noise ratio, and should be investigated in future extensions of SCOOP if resources allow.

2.3.6 Amplitude Compensation / Dilation Compensation (L1)

As said in 1.3.2, this is an improvement to SAR stacking involving the reshaping of each look in the stack. It is known as Amplitude Compensation and Dilation Compensation (AC/DC) technique and results in both a potential noise reduction, by up to a factor 2.5 for SSH and 4.0 for SWH, and a simplified re- tracking. This approach has been recently published (Ray et al 2015) and should be taken into consideration in future extensions of SCOOP, if resources allow.

2.3.7 Improvements in SAMOSA Models (L1 to L2)

Comprehensive details on the latest improvements have been presented by Roca et al. at CAW/OSTST2013, Martin-Puig et al at OSTST2014, and in a technical note by Egido (2014a) as discussed in 2.2. The DPM for Sentinel-3 in its version 2.5.0 is now adapted to any kind of SAR mode processing (Gommenginger et al., 2015).

2.3.8 Coastal Specific Retracking (L1 to L2)

Solutions that have been proposed to improve the retracking in the coastal zone and exploit the intrinsically superior performance of SAR altimetry in this domain are the geo-referencing of the stack, the selection of range bins for retracking (Egido, 2014) and the reduction of the fitting window (i.e. the sub-waveform approach, as discussed in 2.2.1.1). Both these solutions should be explored in SCOOP or future projects.

2.3.9 Improved Wet Tropospheric Correction (L2)

The University of Porto has led in recent years a significant improvement in the evaluation of wet tropospheric corrections, motivated initially by coastal altimetry but also bringing advantages over the open ocean. The latest correction, GPD+, is derived by merging data from altimeter MWRs, ~700 GNSS stations, imaging MWRs and is available globally for 8 missions. See 2.2.2.1 for details.

2.3.10 Challenge: Sea State Bias and Swell Effects (L2)

See 2.2.2.2.

3 Summary and Recommendations

This document has reviewed the state of the art in SAR altimetry and the progress made in the field since 2013, when a previous review of the discipline had been carried out by Gommenginger et al (2013a).

The key progress points have been identified both for the Level 1a to Level 1b processing (Doppler Stack Processing) in section 2.1 and for the Level 1b to Level 2 processing in section 2.2 which also includes a description of the improvements in corrections. Those points are clearly summarized in section 2.3. and should all be tackled in SCOOP if possible, or in future extensions to the Project.

The remaining challenge which is absolutely crucial towards proper exploitation of SAR altimetry is the quantification of the SSB correction and the effect of swell, as discussed in 2.2.2.2. **We recommend that efforts are put into the derivation of SSB models for SAR altimetry using the global Sentinel-3 data, and that the issue of dependency on swell characteristics is investigated further**.

We conclude by stressing that further possible ameliorations have emerged, that if accomplished would enable major steps forward in processing efficiency and achievable accuracy: the first is the set of new processing algorithms at L1B identified in section 2.1 and in particular the AC/DC approach (see 2.3.6). The other is the fully-focused SAR processing of L1 data proposed by Egido and Smith at OSTST2015, (see 2.3.5) a development which can potentially yield the data with the maximum achievable signal-to-noise ratio. **We recommend that these aspects at the cutting edge of SAR altimetry should be investigated in future extensions of SCOOP, if resources will allow it** (CCN proposals for these aspects have been submitted).

4 References

4.1 Reference Documents

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5 List of Acronyms

AC/DC	Amplitude Compensation and Dilation Compensation
ALES	Adaptive Leading-Edge Subwaveform (a retracking algorithm)
ATBD	Algorithm Theoretical Baseline Documents
AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic data
CAW	Coastal Altimetry Workshop
CCI	Climate Change Initiative
CCN	Contract Change Notice
C-FBR	Calibrated Full Bit Rate
CLS	Collecte Localisation Satellites
CNES	Centre Nationale d'Etudes Spatiales
COASTALT	ESA Project on Coastal Altimetry
CP4O	CryoSat Plus for Oceans
CPP	CryoSat Processing Prototype (CNES Processor for CryoSat)
CryoSat	ESA altimeter mission for polar ice investigations
CryoSat-2	ESA research satellite for the CryoSat mission, launched on 8 April 2010
DAC	Dynamic Atmospheric Correction
DComb	Data Combination
DDM	Delay-Doppler Map
DDP	Delay-Doppler Processor
DPM	Detailed Processing Model
EGU	European Geophysical Union
ECMWF	European Centre for Medium Range Weather Forecasting EO Earth Observation
Envisat	ESA Environmental Satellite
ERA	ECMWF Reanalysis
ERS-1, ERS-2	ESA Remote Sensing satellites ESA European Space Agency
ESRIN	ESA's European Space Research Institute
ESTEC	ESA's European Space Research and Technology Centre
eSurge	ESA project: Satellite data for the Storm Surge Community
EUMETSAT	EUropean Organisation for the Exploitation of METeorological SATellites
FBR	Full Bit Rate
FFT	Fast Fourier Transform
GIM	Global Ionosphere Maps
Globwave	ESA Project to produce and disseminate satellite wave data
GNSS	Global Navigation Satellite Systems
GPD	GNSS-derived Path Delay
G-POD	Grid-Processing On Demand (ESA on-demand processing service)
GPP	Ground Processor Prototype

HR	High Resolution
IGARSS	International Geoscience and Remote Sensing Symposium
IODD	Input Output Definition Document
ITT	Invitation to Tender
Jason-1, Jason-2	Radar Altimeter Satellites
Jason-CS, Sentinel-6	Joint US / European Radar Altimeter Satellite mission. CS stands for Continuity of Service.
L1, L1a, L1b	(data) Level 1/1a/1b
L2	(data) Level 2
LOTUS	Preparing Land and Ocean Take Up from Sentinel-3 (EU Project)
LR	Low Resolution
LRM	Low Resolution Mode
LSE	Least Squares Estimation
LUT	Look Up Table
MDT	Mean Dynamic Topography
MLE	Maximum Likelihood Estimation
MOG2D	Modèle 2D d'Ondes de Gravité, a barotropic oceanic model
MSE	Mean Square Error
MSS	Mean Sea Surface
MWR	MicroWave Radiometer
MyOcean	GMES project to provide operational ocean products
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NOC	National Oceanography Centre
OA	Objective Analysis
OSTST	Ocean Surface Topography Science Team
PDS	Power Distribution in the Stack
PI	Principal Investigator
PISTACH	CNES supported project to develop Coastal Altimetry Products
PLRM	Pseudo-LRM mode
POCCD	Processing Options Configuration Control Document
PSD	Product Specification Document
PTR	Point Target Response
PVP	Product Validation Plan
PVR	Product Validation Report
RADS	Radar Altimeter Data System maintained by TU Delft.
RA-2	ENVISAT Radar Altimeter System
RB	Requirements Baseline
RDSAR	Reduced resolution SAR mode data to pseudo LRM
REAPER	ESA Project to Reprocess ERS-1 and ERS-2 data
SAMOSA	SAR Altimetry MOde Studies and Applications
SAR	Synthetic Aperture Radar

SARIN	SAR interferometric mode
SARM	SAR Mode
SARvatore	SAR Versatile Altimetric Toolkit for Ocean Research & Exploitation
SCOOP	SAR Altimetry Coastal and Open Ocean Performance
SEOM	Scientific Exploitation of Operational Missions
SatOC	Satellite Oceanographic Consultants
Sentinel-3	ESA Remote sensing mission in the Copernicus programme
Sigma0	Radar Backscatter at nadir
SIRAL	SAR interferometric Radar Altimeter on CryoSat-2
SLA	Sea Level Anomaly
SRAL	Synthetic Aperture Radar Altimeter on Sentinel-3
SSB	Sea State Bias
SSH	Sea Surface Height
SSM/I	Special Sensor Microwave / Imager
SSMIS	Special Sensor Microwave Imager / Sounder
STSE	Support to Science Element
SVD	Single Value Decomposition
SWH	Significant Wave Height
TCWV	Total Column Water Vapour
TDS	Test Data Set
TECU	Total Electron Content Unit
TN	Technical Note
TOPEX	French / US Radar Altimeter Satellite
TUDelft	Delft University of Technology
TWLE	Total Water Level Envelope
UCL	University College London
WP	Work Package
WTC	Wet Troposphere Correction

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