SCOOP

SAR Altimetry Coastal and Open Ocean Performance

Scientific Roadmap D3.1

Sentinel 3 For Science – SAR Altimetry Studies

SEOM Study 2. Coastal Zone and Open Ocean Study

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1 Introduction

1.1 The SCOOP Project

SCOOP (SAR Altimetry Coastal & Open Ocean Performance) is a project funded under the ESA SEOM (Scientific Exploitation of Operational Missions) Programme Element, to characterise the expected performance of Sentinel-3 SRAL SAR mode altimeter products, and then to develop and evaluate enhancements to the baseline processing scheme in terms of improvements to ocean measurements. A further objective is to develop and evaluate an improved Wet Troposphere correction for Sentinel-3.

1.2 Rationale and scope of this document

This is the **Scientific Roadmap** (SR) report for SCOOP and represents the deliverable D3.1 of the project.
The aim of this document is to provide a scientific roadmap containing recommendations for further research, development and implementation, including algorithmic evolutions, especially in the coastal zone domain.

- Summary of key points from the State of the Art review
- Key findings from the Product Validation Reports
- Any new results from other studies that have come to light in the duration of the project
- Recommendations for implementation, or further investigation, of algorithms for processing in the open ocean and especially the coastal zone are provided

The reader is referred to SCOOP Technical Note 2 (Cotton et al, 2019b) and The SCOOP Product Validation Report (Cotton et al, 2019a) for more detail on the SCOOP Test Data sets and the validation results.

2 State of the Art Review Recommendations

2.1 Introduction

The first activity within the SCOOP project was to provide a Scientific Review to describe the "State of the Art" for SAR altimetry at the time of the beginning of the project. This document took Gommenginger et al (2013) as the starting point and then reviewed research presented at OSTST, Coastal Altimetry Workshops, and published literature from 2013 onwards. We summarise the main items and recommendations below, refer to Cipollini et al (2016) for full details.

2.2 Recommendations

The report noted the following approaches that were proposed / being investigated at the time of writing, and were of interest for further development:

- The Amplitude Compensation and Dilation Compensation (AC/DC) technique: Ray et al (2015). The application of this methodology would impact both the Delay Doppler Processing and the re-tracking model, by improving both the accuracy of retrieved SSH and SWH, particularly at low SWH, and also reducing the run-time.
- The effect of the partial correlation of the echoes in altimeters with high PRF. Egido and Smith (2018) found a faster decorrelation towards the trailing edge and not homogeneous Effective Number of Looks (ENL) in the waveforms, which could cause bias in the estimated parameters.
- Fully-focused SAR processing (as since published in Egido and Smith, 2017), a development which could yield data with the maximum achievable signal-to-noise ratio, and at a resolution up to 0.5m.
- Investigations into "Stack Weighting". How to determine the appropriate weights to apply to different Doppler bins prior to multi-looking.
- Exploitation of the power distribution information in the stack to derive platform attitude information (Moreau et al at. 2014, Scagliola et al., 2015)
- Re-tracking of individual Doppler echoes (N.B This was investigated and reported within SCOOP and reported in Moreau et al, 2019)
- Computation at a finer ground step (for instance at 84Hz – the Cryosat burst repetition frequency), to give higher along track sampling (Dinardo et al., 2013)

The following approaches to retracking the multi-looked echo were identified:

- geo-referencing of the stack,
- selection of range bins for re-tracking,
- development of the "ALES" approach – sub-waveform retracking applied to SAR echoes.

2.2.1 Sea State Bias Correction:

It was recommended that efforts must be put into the derivation of SSB models for SAR altimetry using the global Sentinel-3 data, and the issue of dependency on swell characteristics should be investigated further.

3 Product Validation Main Results

3.1 Introduction

The Product Validation Report (Cotton et al., 2019) summarises the findings of the validation of the SCOOP test data sets (RDSAR and SAR products), and identifies issues for further investigation and recommendations for processing. These were also reported in SCOOP Technical Note 2 "Scientific Outcomes", and are summarised in the next sub-section.

We first briefly recall that two test RDSAR and SAR altimeter data sets were generated, over 10 regions of interest.

Both test data sets were generated from CryoSat-2 FBR data. The first data set (TDS1) was processed with algorithms equivalent to the Sentinel-3 baseline, and the second (TDS2) with algorithms expected to provide an improved performance. The different processing schemes are detailed fully in two SCOOP Algorithm Theoretical Basis Documents (ATBD), available at:

http://www.satoc.eu/projects/SCOOP/docs/SCOOP_D1.3_ATBD_v17.pdf

and http://www.satoc.eu/projects/SCOOP/docs/SCOOP_D1.3_ATBD_L2_isardSAT_v1a.pdf

The products cover a 2 year period (2012-2013) for all regions of interest except ROI 10 (Harvest). The mode mask only switched to SAR mode for this region on 1st December 2015, so the time coverage for this region is 01/12/2015 to 31/12/2016.

3.2 Main RDSAR Product Validation Results

SCOOP RDSAR Phase 1 Test Data Set V Phase 2 test Data Set

- The RDSAR TDS1 and RDSAR TDS2 (MLE3 processing) give similar results in terms of SSH performance (accuracy and precision).
- The SSHA (anomaly) parameter in the RDSAR TDS1 shows an unexpected loss of data close to the coasts, which is corrected in RDSAR TDS2 in which a higher proportion of valid data is retrieved.

SCOOP RDSAR Phase 2 Test Data Set

- The RDSAR TDS2 demonstrated an improved noise performance (lower noise) in Sea Level Anomaly (SLA) when compared to the CNES CPP PLRM data set, but higher correlated errors, which degraded the SLA content at scales below 100km.
- The Significant Wave Height (SWH) in RDSAR TDS2 exhibited significant biases, particularly at low wave heights, This was believed to be a consequence of using a fixed PTR width in processing, rather lack than an SWH dependent value.
- Sigma0 shows a bias of 0.2 dB (with respect to the CNES CPP PLRM), the size of this bias was dependant on SWH, and possibly correlated with mis-pointing angle.
- Comparison of the RDSAR TDS2 and the CNES CPP PLRM showed differences below 2cm in Sea Level Anomaly.
- Residual errors were believed to be correlated to mispointing. The RDSAR processing uses attitude measurements from the products as inputs to the processing, but are estimated in the CNES CPP PLRM product through its MLE4 re-tracker

- The RDSAR TDS1 product showed a greater data loss at the coast than the TUDaBo RDSAR product[1]. This was attributed to the better performance of the coastal "TALES" re-tracker in the TUDaBo product compared to the MLE re-tracker applied to the SCOOP RDSAR product. Therefore, a coastal re-tracker, such as TALES, is recommended.
- The along-track noise of the RDSAR data is globally 50% higher than the noise of the SAR datasets.

SCOOP MLE4 RDSAR Phase 2 Test Data Set

- TU Delft produced a small test data set, processed in the same way as TDS2, except that an MLE4 re-tracker was used.
- U Bonn found that the phase 2 MLE4 RDSAR SSH retrievals were generally noisier than for the MLE3 dataset and a slight loss of data in the first 10 km offshore. However, the comparison with the in situ significant wave heights at Harvest carried out by Noveltis showed an improvement with the MLE4 dataset, compared to the MLE3 dataset.

3.3 RDSAR Issues and Recommendations

Resulting from these analyses a number of key issues and recommendations were identified:

- Further validation of RDSAR is recommended under a wider range of mis-pointing angles and radial velocities.
- A problem was identified with the CryoSat-2 attitude information, which was confirmed by colleagues working in the CryoSat-2 IPF and validation (Scagliola et al, 2018b). It is understood the new Baseline-D Cryosat-2 product will include corrected attitude information. It is recommended to investigate if this new product successfully addresses this problem.
- A (SWH dependent) correction for the PTR width should be included in the RDSAR processing.
- Further work is needed to better understand and correct the long wavelength errors in the RDSAR product. These issues need to be addressed to ensure better continuity with conventional altimetry missions, and ultimately make this processing of interest for the Sentinel-3 mission.
- Coastal re-trackers (e.g. ALES (Passaro et al., 2014), TALES (Fenoglio and Buchhaupt, 2017; Fenoglio et al., 2019), STAR (Roscher et al, 2017)) should be applied to coastal data sets as they have been clearly shown to improve performance.
- Further tests on the performance of an MLE4 re-tracker on the RDSAR product should be carried out.

3.4 Main SAR Product Validation Results

3.4.1 Open Ocean

Sea Surface Height / Sea Level Anomaly

- The global scale analysis over the two sets of regions shows consistency between the SSH in SAR TDS1 and SAR TDS 2.
- No dependency on the radial velocity was found on the SSH differences between SAR TDS1 and SAR TDS 2. SSH from initial versions of the product were found to exhibit such a dependency.

[1] Refers to an RDSAR product produced jointly by the Technical University of Darmstadt and University of Bonn

- Very similar noise performance is obtained for both SAR TDS1 and SAR TDS 2, with a slight improvement in SAR TDS2 at higher SWH that can be related to the intra-burst Hamming application.
- No improvement in the detection of small-scale oceanic structures was observed between SAR TDS1 and SAR TDS 2, since neither the sea level noise level nor the long ocean wave correlated errors have been reduced. In fact, the sea level spectrum has slightly more energy for scales from 2 to 10 km due to an overlap between consecutive measurements (resulting from the application of the Hamming function).
- The SAR altimeter Test Data Set 2 shows an improvement on the content of the LRM datasets for wavelengths below 100 km.

Significant Wave Height

- SAR TDS 2 provides a much-enhanced measurement precision of SWH on SAR TDS1, throughout the SWH dynamic range (1 to 8m) with a reduction > 35% at 2 m SWH. Part of this improvement is believed to be related to the combined setting of intra-burst Hamming and zero-padding, and part to the better stability of the re-tracker, associated to the way that the SWH initial seeding is implemented (based on a sliding window of previous estimates).
- However, a significant bias was seen in SAR TDS 2 SWH, especially at low SWH. This was thought to be related to the fact that SAR TDS1 used an variable PTR empirically tuned for the re-tracker implementation in GPOD (in which a Look Up Table is used to define the PTR width), while SAR TDS2 used the isardSAT in-house re-tracker with a fixed PTR setting. It is recommended that an SWH depended PTR width should be applied, using in-situ measurements for calibration.

Sigma0 (Nadir Surface Radar Backscatter):

- Global scale analysis shows consistency between the Sigma0 of SAR TDS1 and SAR TDS 2, where a small dependency (below 0.1 dB) as a function of radial velocity is observed on the Pacific regions. This can be linked specifically to a dependency on orbit height.
- Similar noise performance are obtained for both data sets SAR TDS1 and SAR TDS 2, with a slight improvement for SAR TDS 2.

Sea state impact on the SAR sea surface height estimates:

- The investigation of the SAR SSH absolute bias estimates against the in situ SWH measurements at Harvest shows the clear dependency of the bias variability with the significant wave heights.

3.4.2 Coastal Zone

Sea Surface Height / Sea Level Anomaly

- A general improvement was noticed from SAR TDS 1 to SAR TDS 2, with lower noise and variability in SAR TDS 2 (except in the first kilometre offshore) and more data retrieved whatever the distance to the coast.
- For Sea Level Anomaly, the SAR mode performs better than RDSAR, in terms of lower noise, and better agreement with reference data sets (models and tide gauge data).
- From the studies carried out by U Bonn, and through comparisons against a SAR product generated on GPOD by U Bonn using the SAMOSA+ re-tracker (Dinardo et al., 2018b), the SAMOSA+ re-tracker has been shown to provide better performance (in terms of lower noise in Sea Level Anomaly) at the coast than SAMOSA2.

Significant Wave Height

- A bias in the SWH measurements was observed between the SAR TDS1 and SAR TDS 2, for SWH less than 1.6 m.

Coastal Proximity

- In terms of the noise of Uncorrected Sea Surface Height (USSH) on approaching the coast, the performance of the SAR TDS1 and SAR TDS 2 was similar, with a median value of “noise” (measured as the differences between successive values of USSH) of less than 5cm to within 3km of the coast. A filter only allowing data with a waveform misfit value of greater than 3 was applied. No dependence of USSH performance on Significant Wave Height (SWH) was found.

Angle of Arrival

- An investigation into dependency on performance with the angle of arrival with respect to the coastline found no dependence of noise in SSH on angle of arrival, but did find a greater loss of data for measurements along tracks arriving at angles of 30° or less with respect to the coastline, i.e. for tracks more parallel to the coast. This indicated that the data filtering was removing noisy or contaminated waveforms. It is explained by the fact that the cross-section of the sea surface sampled by the SAR altimeter is highly asymmetric, 5-10km across track and 350m along track. Thus, for a flat coastline, tracks running parallel to the coast but within 5km may be contaminated by echoes originating from the land, whereas tracks approaching the coast at right angles will not be affected until ~350m.

Data Filtering

- The SKYMAT /SatOC study found that the application of the misfit < 3 filter significantly reduces the data available within 10km of the coast, but improved the noise performance, by excluding contaminated waveforms.
- Noveltis applied a filter on waveform misfit < 4, and a Pearson Correlation > 95%. The Pearson correlation parameter was only available in SAR TDS2. They found the selection based on misfit < 4 to be stricter, but suggested the optimum values of this threshold could vary dependent on region.

isardSAT Coastal Data Set

- isardSAT produced a small “experimental coastal data set, in which first window delay of the first full ocean return as the reference point for retracking, thus (in theory) waveforms are aligned with respect to the first burst or look in the stack marked as ocean and not lost.
- However, none of the studies found any improvement in the “experimental“ coastal data set when compared to the SAR TDS 2. In fact a degraded performance was found at Harvest. Some further investigation is recommended to understand this result.

3.4.3 SAR Product Issues and Recommendations

- On the basis of the assessment results, showing substantial reduction of SWH noise and almost matching SLA performance (with CNES CPP), the use of the innovative SARM processing (Zero padding factor 2 and Hamming window) for Sentinel-3 mission is recommended to improve ocean altimetry products for end-users.
- Application of the Hamming windowing appears to increase the bias in SWH at low wave heights
- In situ measurements should be used to fine tune and calibrate the PTR settings within the (isardSAT) SAR mode processing.

- Further analyses should be performed on a global scale (using Sentinel-3 data) to confirm results over a wider range of conditions. Such analyses should pay close attention to any sea level changes in the spectrum.
- The increase in the SSH bias variability for large wave conditions highlights the fact that an appropriate SSB correction dedicated to the SAR SSH is needed to compute accurate SSH.
- Further investigations are required to understand why performance degradations were observed in the “experimental coastal” data set prepared by isardSAT.
- Further studies should be carried out into the development of coastal re-trackers for SAR mode echoes.
- Vertical motion of wave particles (VMWP) in SAR mode is an important factor that should be further analysed, and retracking models that account for it should be developed (Buchhaupt et al., submitted). This will be very important for Fully Focused SAR, but also relevant for unfocused SAR
- Further studies by the SCOOP team are needed to support the ESA team in developing improved processing baselines and for the benefit of the Community. These should include
    - A larger (global) scale validation with Sentinel-3 data.
    - Develop and evaluate coastal re-trackers for SAR mode echoes.
    - Calibrate PTR settings for SAR mode processing.
    - Carry out further evaluations of the impact of implementing Hamming Windowing and Zero Padding
    - Carry out evaluations of new implementations of the SAMOSA retracker (e.g. SAMOSA+)
    - To investigate the issues with the isardSAT coastal data set.

- For the above, we note the availability of the SARVATORE SAR altimeter processing service on ESA GPOD, and also developments such as the TUDaBo processor (Fenoglio and Buchhaupt, 2017, 2019), which includes along-track zero padding and accounts for vertical motion of wave particles (VMWP) (Buchhaupt et al. 2018, Buchhaupt, 2019).

3.5 WTC Product Assessment Results

CLS and the University of Porto carried out an assessment of the GPD+ WTC (Fernandes and Lázaro, 2016) generated for CryoSat within the SCOOP project. Both CLS and U Porto noted the limited geographical coverage of the regions of interest and observed that a data set with global coverage would be preferred to give a comprehensive analysis.

- CLS found that the GPD+ approach leads to a significant improvement in the accuracy of the Cryosat-2 SSH and SLA.
- The GPD+ WTC reduces the sea level anomaly variance with respect to the ECMWF operational model correction from both along-track analysis and cross-overs by ~2 cm² (particularly effective in low latitude areas).
- Along track discontinuities of a few mm height were observed, without however adverse impact on the SLA accuracy. In case of occurrence of higher discontinuities, a strategy to better handle such discontinuities should be envisaged.

- U Porto’s analysis found that when compared to the ECMWF operational model, GPD+ leads to SLA variance reduction at crossovers and in particular near the coast for most of the SCOOP regions of interest.
- Other diagnostics such as WTC differences with respect to J2 and with respect to GNSS confirm that overall GPD+ is closer to these accurate WTC datasets and therefore offers an improved correction in comparison with the ECMWF model. The comparison with GNSS also shows no evidence of land contamination in the GPD+ WTC.

- The small size of some of the selected ROI made difficult the assessment of the correction in some regions, e.g. in Harvest and Indonesia. Previous studies had shown that the WTC errors in the Indonesia region are particularly large, even exceeded by the ocean tide errors (Handoko et al, 2017, Legeais at al., 2018), and should be subject of a dedicated study.

U Porto also generated a GPD+ WTC for Sentinel-3 and analysed its performance. (Fernandes and Lázaro, 2018). Two versions of the corrections have been generated: GPD1, “a la Cryosat”, using only third party data; and GPD2, the “usual” GPD+ WTC, using all available data sources, including valid observations from S3A on-board MWR. Their main findings were:

- The comparisons of the S3A MWR with other MWR (GMI and J3) indicate good overall agreement between all sensors.
- A stable temporal evolution of the S3A MWR-derived WTC is observed. A strong periodic signal is found in the differences with respect to GMI due to the orbit configurations of the respective spacecrafts.
- Strong ice and land contaminations are observed in the S3A MWR observations, in line with the expected behaviour of a dual-frequency MWR. This makes the establishment of validation criteria for the MWR observations difficult, but unavoidable and indispensable, particularly at the high latitudes.
- Comparison with GNSS shows land contamination in the S3A MWR up to 20-25 km from the coast. The same is not observed in any of the analysed GPD+ WTC.
- The GPD2 WTC (includes S3A MWR) shows a small reduction in SLA variance at crossovers with respect to GPD1 (no S3A MWR), however this reduction in SLA variance is not observed when analysing along-track variance differences. The later result was not previously expected and has not been observed before for any of the analysed missions, thus indicating that the S3A MWR-derived WTC can still be improved.

3.6 WTC Recommendations

- The GPD+ correction clearly outperforms the ECMWF operational model-derived correction in both open ocean and coastal areas. This improved solution is of particular interest for altimetry missions which do not possess on-board microwave radiometer. For the Sentinel-3 mission embarking an MWR sensor, such a solution is of interest whenever MWR measurements are considered invalid, but could also be used as independent data for assessing the on-board MWR derived WTC (using a version of the correction solely based on third party data).
- Along track discontinuities of a few mm height were observed, without however adverse impact on the SLA accuracy. In case of occurrence of higher discontinuities, a strategy to better handle such discontinuities should be envisaged.
- The composite correction present in the products is not suitable for use. The average percentage of points with invalid Composite WTC is 23%.
- The GPD+ WTC would be an added value for Sentinel-3A products
- An assessment of the GPD+ performance over polar regions was not possible due to the limited geographical coverage of the test data set.
- Due to its unique characteristics, it is recommended that the Indonesia region should be the subject of a dedicated study, improving both the WTC and the ocean tide model in this region

4 CLS Level 1 and 2 Processing Study Main findings

CLS carried out a study aimed at assessing the potential benefits of exploiting the Cryosat-2 radar altimeter single look echoes instead of the SAR-mode multi-looked echoes, for ocean and coastal applications. (Moreau et al, 2019)

This study investigated the potential usefulness and relevance of the individual Doppler beam retracker in retrieving oceanic geophysical parameters from non-averaged Cryosat-2 SIRAL altimeter data. Contrary to traditional delay/Doppler processing approach that computes the altimetric parameters from averaged waveforms, the proposed methodology first makes estimates of the sea surface height and sea state for each look bin of a stack then sums them, giving thus equal weight in the noise level reduction and an expected improvement of the parameter precision. The results have been compared with the outputs of the CPP v14 products obtained with the CNES processing prototype developed by CNES.

The analysis of this method has shown a significant noise reduction in range and SWH, better than what is obtained in unfocused SAR altimetry. However this study did not permit to draw clear conclusion on its capability to make accurate estimates due to the use of inaccurate SAR backscattered waveform model (from the CPP prototype) for retracking individual Doppler beams. If approximations made in developing the SAR CPP echo models were of low importance for processing multi-looked power waveforms, they now appear critical to fit model with individual beam data. This effect mostly impacts the parameter estimation of the outer beams and at the end the accuracy of the mean parameters. It should be noted that the SAMOSA model also uses approximation (Gaussian PTR) that would prevent to converge to the exact solution. A more realistic SAR multilook altimeter model as the one developed in CNES Sentinel-3 processing prototype (S3PP) should lead to much better performance. Further work is needed for fully validating the method based on the use of the S3PP SAR altimeter model.

Secondly, due to the high computational burden required for estimating mean parameters of each 20-Hz sample, the number of study cases has been limited to few cases. A trade-off has to be found between the computational cost and the accuracy to make use the method with a larger amount of data.

The individual Doppler beam processing is of some interest for a wide range of applications (in ocean and coastal regions as well as sea ice and inland water areas). It may also be used to reveal potential inaccuracies in the multilook altimeter observation model to fit SAR altimeter data. Other sources of improvement in SAR processing (accounting for the range walk, including the vertical orbital wave velocity in the model) could also be assessed through this method to see whether their contribution may improve the consistency between data and backscattered waveform models, enhancing the accuracy of the estimates.

5 Swell and Sea State Bias Study Main Findings

5.1 Swell

Most studies agree that there is evidence of increased variability, and increased bias in retrieved SWH for larger wave heights, and longer wavelengths. Whether or not this is specifically swell dependent is a point for discussion. The evidence in terms of the effect of larger SWH and longer wavelength on range retrieval is inconsistent, though there is evidence that the SAR waveforms become noisier and hence more difficult to fit for larger SWH and longer wavelength. Hence it could be expected there would be more variability in the retrieved SSH.

It is also well established that there remain problems in accurately retrieving SWH in SAR mode for low wave heights, due to steepness of leading edge in SAR echo. This will have an impact on the nature of the error in retrieving SWH, as SWH increases.

While there is an obvious attraction to use modelled wave data, we believe that the observational data will provide more accurate evidence. A “climatology” of how frequently and where parallel swell of high SWH occur would be beneficial to infer if the problem arises frequently. This would allow future studies to identify and focus on regions where SAR altimetry would be most likely to experience a bias due to parallel swell. Further studies could make use of SAR data from the Sentinel-1 mission, or indeed other SAR missions.

5.2 Sea State Bias

As noted above there is general agreement that for larger and longer wave heights both variability (noise) and bias increase for SAR altimetry inferred SWH, though there is not full agreement that this is directly due to the presence of (increased) swell. In theory there should be a dependency, and research is ongoing to quantify this dependency both for swell magnitude, period and direction. If SAR waveforms are noisier (for larger SWH, and for longer wave period) then this not only poses a problem for SWH retrieval, but also increases the noise in the SSH retrieval. In addition, problems with SWH will enter the sea level estimate through the use of an SSB model. All studies also agree that greater global spatial coverage is needed for analyses (for CryoSat we have only a few SAR patches scattered around the globe) together with a much longer time series. A good way forward would be to work on an SSB_swell correction or an SSB correction with swell incorporated, based on studies comparing Sentinel-1 imaging SAR and Sentinel-3 SAR altimeter data. A comparison with real wave data (as opposed to simulated model data) is recommended. It is also well established that there remain problems in accurately retrieving SWH in SAR mode for low wave heights, due to steepness of leading edge in SAR echo. This will have an impact on the nature of the error in retrieving SWH, as SWH increases.

Based on the observed limitations in the SAR-altimeter processing to cope with measurements of long ocean waves, concerns are raised about the ocean wave sensitivity of other innovative measure techniques like the upcoming Surface Water and Ocean Topography (SWOT) mission carrying a high-resolution altimeter (KaRin) or other innovative processing methodologies capable of providing higher spatial resolution. This indicates an urgent need for more detailed studies. A constructive approach would be to compute a SSB correction accounting for not only the wave height but also the mean wave period, as already developed by Tran et al. (2010) for LRM missions.

Some researchers recommend an empirical approach to develop the SSB model using wave period information from a wave model, whereas others are concerned that the use of information from models could propagate possible errors from models into the satellite products, and prefer to develop an SSB model based only on altimeter derived information. This remains a point for discussion.

5.3 Recommendations

We propose/recommend two types of future investigations:

- A focussed case study on some individual examples of clearly defined long wavelength swell in selected orientations to the altimeter track. This could investigate in detail the impact on altimeter SAR waveform shapes, and the impact on the parameters retrieved from re-tracking

- A larger scale study using a data base of co-located SAR and SAR altimeter data. This could make use of Sentinel-1 SAR wave mode data. Otherwise some form of routine processing of other SAR missions' data to extract swell characteristics is needed

The final answer will come when sufficient Sentinel-6/Jason-CS data have been gathered. This will provide the first opportunity to directly compare LRM, PLRM, and SAR at the same time and at the same locations (approximately). This mission is currently scheduled for launch in November 2020.

6 Other work: Presentations and Published Literature

6.1 Introduction

In this section we briefly summarise relevant new developments by researchers outside the SCOOP project team and have been presented at meetings such as OSTST, Coastal Altimetry workshops and in the published literature.

6.2 11th Coastal Altimetry Workshop Report

The following points were taken from the summary of the 11th Coastal Altimetry Workshop, held at ESRIN on 13-15 June 2018.

- Beneficial effects have been identified from adaptive re-tracking on SWH and from the open-loop tracking mode (OLTC) in SAR mode (Dinardo et al, 2018a)
- First results on Fully Focussed-SAR (achieving resolutions of 65 cm) have been reported. (Thibaut et al, 2018)
- Optimized coastal processing including Hamming window, Zero Padding, extended receiving window size and advanced retrackers (e.g. SAMOSA+) improves results for Sentinel-3 (Dinardo et al, 2018a, 2018b, Fenoglio et al., 2018)
- Comparable quality of CryoSat-2 and Sentinel-3A coastal G-POD/SARvatore SAMOSA+ sea level, with standard deviation of instantaneous in-situ differences smaller than 2 cm (Fenoglio et al., 2018)
- A new version for the proximity to coast parameter was suggested to replace the one available in Sentinel-3 products. Nencioli et al (2018)
- Coastal tide models that include ALES data perform better. Improvements have no clear dependence on sea state (Piccioni et al, 2018)
- Bathymetry plays a key role on tidal dynamics especially in coastal waters and estuaries. (Cancet et al, 2018)
- Evaluating the accuracy of the different altimetry corrections when approaching the coast is of cardinal importance. Areas presenting different coastal dynamics should be considered. Birol et al, 2018)
- Tropospheric Corrections (DTC & WTC) in current altimetry products (including Sentinel-3A) are inadequate. They shall be computed at 20-Hz (not just interpolated). (Fernandes et al 2018)
- In the coastal zone, the SAMOSA+ retracker clearly performs better than the SAMOSA2 retracker adopted to produce official Sentinel-3 products. (Dinardo et al, 2018b, Fenoglio et al., 2018). With SAMOSA+ data are usable starting from 3 km from coast.
- The need to have an SSB correction at 20Hz and a specific SSB for each retracker was emphasised. The SSB could be split into a re-tracker correction (to be applied at 20Hz) and geophysical one that is smoother (Fernandes et al 2018)

6.3 OSTST 2018 Ponta Delgada

Key points taken from the section summaries of the 25 Years of Satellite Altimetry and OSTST meeting in 2018 at Ponta Delgada in September 2018.

- A number of papers looked at Fully Focused SAR processing: Rieu et al, (2018), Ray and Egido (2018), Makhoul et al (2018), Scagliola and Guccione (2018), Feng et al (2018)
- Faugere et al (2018) presented analyses of results from the LR-RMC processing approach (Low Resolution – with Range Migration Correction), which demonstrated a reduction in noise in SWH and range, and a reduction in dependency on swell. Buchhaupt et al. (2018b) and Moreau et al. (2018) also discussed about an effective method to correct LR-RMC data from high along-track sea surface slope and curvature.
- Another possible improvement to Delay Doppler processing was presented by Egido and Ray (2018). They showed that the decorrelation distance of adjacent DD waveforms is, in fact, much shorter than the actual along-track resolution of ~300 meters. Therefore, increasing the posting rate from the typical 20 Hz to 80 Hz can lead to a significant improvement in the final effective number of looks, which can in turn lead to a noise reduction in the estimation of geophysical parameters.
- An additional feature that must be considered in FFS is surface motion as discussed by Ray and Egido 2018) and by Buchhaupt et. al. (2018a). Because the integration time for FFS is so long (about 2-3 sec) it is obvious that the ocean will move significantly, which affects both the range and Doppler used in the reference function and/or WF model. One must consider both the surface height and velocity caused by waves as the resolution cells are comparable to long wavelength waves violating the usual Gaussian random surface assumption in scattering models. Ray and Egido's presentation focused on finding the proper trade-off between the finest resolution possible (Doppler resolution is tens of meters depending on the surface acceleration) and the effects above. FFS processing can lead to up to a factor of two improvement in the variance of SSH and SWH with respect to DD based on the effective number of looks (ENL). Buchhaupt et al. (2018a) introduced the vertical motion of wave particle (VMWP) in a SAR stack model showing an improvement of the consistency of SWH estimations with respect to RDSAR.
- Scagliola et al (2018a) demonstrated a processing approach allowing the fast computation of the "range walk compensation", while ensuring the expected results to be achieved (a reduction in the SWH bias with respect to LRM).
- Raynal et al (2018) presented the latest results in investigations of SAR mode products dependency on swell, based on a global analysis with Sentinel 3A data. They showed an increase in noise in SWH measurements with SWH and wave period, and also an increase in range noise with SWH. There is also some indication of dependency in wave direction with respect to the satellite track. They also presented evidence that a red noise slope was seen more strongly in the SWH and SLA spectra in swell dominated regions.
- Dinardo et al (2018c) reported on the improvements in performance from applying Hamming windowing, zero-padding, an extended vertical swath window (in order to mitigate tracker errors), and the new dedicated SAMOSA-based coastal retracker – SAMOSA++, which exploits the Range Integrated Power (RIP) which is an extra information provided by SAR altimeters (see also Dinardo (2019)).

6.4 Additional Items

We list some additional work to note not covered in the previous two sub-sections:

- The effect of vertical wave velocity and acceleration in the estimation of the geophysical parameters in SAR and Fully-focused SAR. It was recognized that the precision in SAR depends on both SWH and mean zero crossing period, which is related to particle velocity. In Buchhaupt

(2019) the two parameters have been included in the SAR retracker model, whereas in Buchhaupt et. al. (submitted) an extension of the model for Fully-Focused SAR is presented.

6.5 Published Literature

In this section we list relevant papers published during the project.

- Buchhaupt C., L. Fenoglio and M. Becker (2018): “A Fast Convolution Based Waveform Model for Conventional and Unfocused SAR Altimetry”, Advances in Space Research, Volume 62, Issue 6, p. 1445-1463. https://doi.org/10.1016/j.asr.2017.11.039
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- Vieira, T., Fernandes, M. J., Lázaro, C. (2019). Independent assessment of on-board Microwave Radiometer measurements in coastal zones using tropospheric delays from GNSS. IEEE Trans. on Geoscience and Remote Sensing. 57(3), 1804-1816. doi:10.1109/TGRS.2018.2869258.
- Vieira, T., Fernandes, M. J., Lázaro, C. (2018). Analysis and retrieval of tropospheric corrections for CryoSat-2 over inland waters. Advances in Space Research, Volume 62, Issue 6, p1479-1496. doi:10.1016/j.asr.2017.09.002

7 Roadmap Recommendations

7.1 RDSAR Processing

Re-tracking

- The MLE4 RDSAR processing shows some improvement regarding the SWH, compared to MLE3. However, the MLE4 SSH retrievals are noisier, with an additional slight loss of data at the coast, which needs further analyses. (See Section 7.6 below).
- Coastal re-trackers (e.g. ALES, TALES, STAR) should be applied for coastal data sets as they have been clearly shown to improve performance (See Section 7.6 below).
- An unbiased estimator should be considered using the exact maximum likelihood criteria to improve the accuracy of the estimates
- The PLRM waveform retracking should also address the effects of the pulse-to-pulse correlation within bursts, that leads to varying statistical properties over the waveform bins and furtherly estimate biases.
- The STAR retracker (Fenoglio et al., 2019) has been shown to be superior to the other RDSAR retrackers with results comparable to SAR. Further analysis of results and possible implementation in GPOD could be of interest.

SWH errors

- A (SWH dependent) correction for the PTR width should be included in the RDSAR processing.
- Some method should be considered to account for the real PTR in the waveform model computation to eliminate the need to correct for the Gaussian approximation through the use of LUT. The TUDaBo processor uses a numerical method for RDSAR/TALES and for unfocused SAR and therefore already implements this recommendation. Results are promising (Fenoglio et al., 2019), TUDaBo has been implemented in GPOD and so can be tested through that route.

Validation / Error Analysis

- Further validation of RDSAR is recommended under a wider range of mis-pointing angles and radial velocities. This should include an analysis of CryoSat Baseline-D data.
- Further work is needed to better understand and correct the long wavelength errors in the RDSAR product. These issues need to be addressed to ensure better continuity with conventional altimetry missions, and ultimately make this processing of interest for the Sentinel-3 mission's ground segment.
- It is recommended to make use of the ESA G-POD facility for testing different processing options and re-tracker implementations.

7.2 SAR Processing

Processing Implementation

- On the basis of the assessment results, showing substantial reduction of SWH noise and almost matching SLA performance (with CNES CPP), the use of the innovative SARM processing (Zero padding factor 2 and Hamming window) for Sentinel-3 mission is recommended to improve ocean altimetry products for end-users.

Processing Developments

- In situ measurements should be used to fine tune and calibrate the PTR settings within the (isardSAT) SAR mode processing.
- Improvements of the unfocused SAR altimeter data processing are needed to correct the observed SWH bias. Some of this bias is already explained by the range walk which must be compensated for in operational ground segment, other part of the bias is likely due to the surface wave motion (as discussed at the OSTST meeting 2018) and in Buchhaupt (2019) and Buchhaupt et al. (2019 submitted). More investigations are needed to design an appropriate SAR altimeter waveform model accounting for this motion.
- The variability in the stack and along-track should be investigated for different sea states to examine different effects of sea state at short spatial scales.
- ACDC techniques are encouraged, as they show an even more reduction in the SSH and SWH estimate noise, by a factor of 2. This is again improved when a full Maximum Likelihood estimator is used as fitting routine.
- The effect of Vertical Motion of Wave Particles (VMWP) should be investigated and the standard deviations of vertical wave particle velocities and accelerations shall be considered in retrackers for both unfocused and focused SAR data.

Validation /Error Analysis

- Further analyses should be performed on a global scale (using Sentinel-3 data) to confirm results over a wider range of conditions. Such analyses should pay close attention to any sea level changes in the spectrum.
- SAR Processing for open ocean has been implemented in TUDaBo (Fenoglio and Buchhaupt, 2018). Comparison with SAR GPOD should be investigated in open ocean.

Sea State Bias

- An appropriate SSB correction dedicated to the SAR SSH is needed in the products to compute accurate SSH. (See Section 7.4 below).

7.3 Wet Troposphere

- The GPD+ WTC: i) outperforms the ECMWF model, the Composite WTC and the baseline MWR-derived WTC (in regions where the last WTC is invalid), ii) iis continuous, consistent and valid over all surface types, it is therefore recommended that this correction should be implemented on Sentinel-3.
- For validation purposes, the version of the GPD+ WTC solely based on third party data would also be of interest for Sentinel-3
- The effective impact of small discontinuities present in the correction associated e.g. with transitions between points with available observations and points for which only the model-derived WTC is available shall be assessed and strategies for minimising these effects shall be developed.

7.4 Swell / SSB

A set of investigations and developments have been recommended by SCOOP partners:

Recommendations for research:

- The sensitivity of SAR mode data to swell and high sea state should be further examined using directional wave spectra from observations and not just numerical models. These should include:

    - To make a statistical analysis of swell occurrences impacting SAR data (done locally and in global) in terms of accuracy and precision
    - To fully characterize the SWH estimate errors in SAR mode as function of the wave period and the relative azimuth angle. The same analysis should be carried out for SSH in order to test for any impact (preliminary results showed no impact on the range estimates but non-negligible effect on SSH via the SSB).
    - To study possible synergy of the collocated PLRM/SAR (or LR-RMC/SAR) data to set up a flag of swell occurrences.
    - Too make further analysis on the "red noise" spectral component found in the SAR SLA PSD and determine whether links to swell events exist
- To make use of the Sentinel-3a&b satellites in tandem phase to improve our understanding of the long ocean wave effects
- To study new SAR processing approaches that mitigate sensitivity to swell, whilst offering same high performances already achieved (as for the LR-RMC processing shown by Boy et al., 2017).

Recommendation for SAR products

- A recommendation from one partner is to add wave model parameters (wave period, wave direction, Hs) in the products to allow users make their own analysis of the SAR altimeter sensitivity to long ocean waves. The relative azimuth angle between the mean wave field propagation and the satellite flight direction is to be computed for use in this parameter sensitivity analysis.

Recommendations for Sea State Bias models:

- An appropriate SSB correction dedicated to the SAR SSH is needed in the products to compute accurate SSH.
- One approach would be to develop a SSB solution in SAR mode based on new wave parameters (the wave period and the relative azimuth angle between the swell direction and the satellite track) to mitigate the SSB impact on SSH estimates
- We note that some researchers recommend an empirical approach to develop the SSB model using wave period information from a wave model, whereas others are concerned that the use of information from models could propagate possible errors from models into the satellite products, and prefer to develop an SSB model based only on altimeter derived information. This remains a point for discussion.

7.5 Open Ocean Issues / Recommendations

From SCOOP results, and issues highlighted at scientific meetings during the running of the SCOOP project

- A high priority is to address SAR SWH issues (SWH discontinuity between LRM and SAR mode, and sea state effects) for the Copernicus Marine Environment Monitoring Service to provide wave products with better quality (also used for assimilation into real-time global wave models and for operational wave forecasts)
- There is concern about potential SAR SWH impact on the sea level time- series when data from the different Sentinel-3 missions but also from the forthcoming Sentinel-6 mission, which all have SAR-mode radar altimeter, will be incorporated. Particular analysis should be undertaken to assess whether or not long ocean wave effects on SAR mode estimates cause spurious trends in the altimeter climate record.
  Differences between RDSAR and SAR estimates of SWH should be better understood and the impact of Vertical Motion of Wave Particles on wave parameter retrieval investigated.
- The impact of Vertical Motion of Wave Particles on the estimation of the SAR SWH need to be clarified, and, in general, the differences between RDSAR and SAR SWH better understood for different sea states.

- The impact of sea state on SAR SSH, SWH and Sigma0 respectively need to be clarified, and recommendations need to be put forward about the optimal way to mitigate these effects (e.g. dedicated two-parameter SAR SSB correction; calibration of SAR using LRM SSB correction and LRM SWH and Sigma0; dedicated three-parameter correction; etc.)
- To meet the evolving ocean community needs, future SAR-mode data processing should enhance altimeter capabilities in monitoring ocean circulation (below the actual limit of observability achieved in unfocused SAR mode) and measuring short oceanic scales (for MSS/seafloor geodesy). Theoretical studies suggest that greater improvements can be achieved in this area.

7.6 Coastal Zone Issues / Recommendations

7.6.1 RDSAR Processing

- Further analyses are needed to determine the applicability and benefits of MLE4 in coastal regions compared to MLE3 ALES-type adaptive retracking methods and to other coastal retracking, e.g. statistical retracking.
- Coastal re-trackers (e.g. ALES, TALES, STAR) should be applied for coastal data sets as they have been clearly shown to improve performance. The impact of the choice of SSB computation on performance in the coastal zone should be better quantified. Specifically, it should be investigated how improved performance of ALES-type methods for SSH can be achieved without reducing the reliability of SWH and Sigma0 data in the coastal zone.
- The STAR retracker (Fenoglio et al., 2019) has been shown to be superior to the other RDSAR retrackers with results comparable to SAR in coastal zone. Further analysis of results and possible implementation in GPOD could be of interest.
- As for the open ocean it is recommended to make use of the ESA G-POD facility for testing different processing options and re-tracker implementations.

7.6.2 SAR Processing

- The exploitation of SAR mode altimetry in the coastal zone calls for improved characterisation of the orientation, proximity and nature of nearby coasts. Further efforts should be directed towards developing improved parameters to summarise the likelihood of contamination of the SAR altimeter echoes.
- The limits of SAR in coastal regions in comparison with FF SAR need to be investigated, as well as the real resolution of FF SAR.
- Further investigations are required regarding the “SAR coastal” processing proposed by IsardSAT, given the degradation observed in the data at Harvest. A second approach, building from work in a CCN to CP4O, which used the mean surface from the product (DTU15) as reference for window delay demonstrated promising results for Cuba. It is recommended that this approach be further developed and investigated.
- SAR Processing for open ocean has been implemented in TUDaBo (Fenoglio and Buchhaupt, 2019). Tests and extension to coast should be investigated. The impact of VMWS on the estimation of the SAR SWH need to be clarified, and, in general, the differences between RDSAR and SAR SWH better understood for different sea states and distance to coast.
- Noting that because of more complex topography and bathymetry at small spatial scales close to the coast, it is possible that measured ”noise” could in fact be a representation of genuine physical variability (in SSH, SWH and Sigma0). The challenge then is to devise techniques to provide an independent verification of this variability, with models, in situ data, and other remote sensing data.

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9 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, which was launched on 8 April 2010
DAC	Dynamic Atmospheric Correction
DComb	Data Combination
DDM	Delay-Doppler Map
DDP	Delay-Doppler Processor
DPM	Detailed Processing Model
ECV	Essential Climate Variable
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
GSHHS	Global Self-consistent, Hierarchical, High-resolution Geography Database; a high-resolution shoreline data set in the public domain.
HF	High Frequency
HR	High Resolution
IGARSS	International Geoscience and Remote Sensing Symposium
IODD	Input Output Definition Document
isardSAT	SCOOP project partner (company based in Spain, UK and Poland)
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
MLE3	Altimeter waveform MLE retracker with 3 free parameters that are estimated (Range, significant wave height, and radar backscatter)
MLE4	Altimeter waveform MLE retracker with 4 free parameters that are estimated (Range, significant wave height, radar backscatter, and altimeter attitude)
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
NOVELTIS	SCOOP Partner (Company based in France)
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.
RB	Requirements Baseline
RDSAR	Reduced resolution SAR mode data to pseudo LRM
REAPER	ESA Project to Reprocess ERS-1 and ERS-2 data
ROI	Region of Interest
SAMOSA	SAR Altimetry MOde Studies and Applications
SAMOSA2	A model for the SAR mode altimeter waveform derived in the SAMOSA project, which includes non_Guassian ocean wave statistics, the effects of earth curvature.
SAMOSA+	An implementation of the SAMOSA2 re-tracker modified for coastal application
SAR	Synthetic Aperture Radar
SARAL / AltiKa	Joint Indian / French Satellite Ka frequency altimeter mission and instrument
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
SLCCI	Sea Level Climate Change Initiative
SOW	Statement of Work

SPMT	Software Programme Management Tool
SPS	(Sentinel-3) System Performance Simulator
SRAL	Synthetic Aperture Radar Altimeter on Sentinel-3
SSB	Sea State Bias
SSH	Sea Surface Height
SSHA	Sea Surface Height Anomaly
SSM/I	Special Sensor Microwave / Imager
SSMIS	Special Sensor Microwave Imager / Sounder
STARLAB	SCOOP partner (company based in UK and Spain)
STSE	Support to Science Element
SVD	Single Value Decomposition
SWH	Significant Wave Height
TALES	TU Darmstadt Adaptive Leading Edge Sub-waveform retracker
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
UBonn	University of Bonn (SCOOP partner)
UCL	University College London
VMWP	Vertical Motion of Wave Particles
WP	Work Package
WTC	Wet Troposphere Correction

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