IMPROVED OCEANOGRAPHIC MEASUREMENTS FROM SAR ALTIMETRY: RESULTS AND SCIENTIFIC ROADMAP FROM THE ESA CRYOSAT PLUS FOR OCEANS PROJECT

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ABSTRACT

The ESA CryoSat mission is the first space mission to carry a radar altimeter that can operate in Synthetic Aperture Radar (SAR) mode. It thus provides the first opportunity to test and evaluate, using real data, the significant potential benefits of SAR altimetry for ocean applications.

The objective of the CryoSat Plus for Oceans (CP4O) project was to develop and evaluate new ocean products from CryoSat data and so maximize the scientific return of CryoSat over oceans. The main focus of CP4O has been on the additional measurement capabilities that are offered by the SAR mode of the SIRAL altimeter, with further work in developing improved geophysical corrections.

CP4O has developed SAR based ocean products for application in four themes: Open Oceans, Coastal Oceans, Polar Oceans and Sea Floor Topography. The team has developed a number of new processing schemes and compared and evaluated the resultant data products. This work has clearly demonstrated the improved ocean measuring capability offered by SAR mode altimetry and has also added significantly to our understanding of the issues around the processing and interpretation of SAR altimeter echoes.

This paper presents an overview of the major results and outlines a proposed roadmap for the further development and exploitation of these results in operational and scientific applications, with particular focus on their relevance for Sentinel-3.

1. CRYOSAT PRODUCTS DEVELOPMENT AND EVALUATION

The core activity of the CryoSat Plus for Oceans project was the development and validation of algorithms and processing schemes for new ocean products, based on CryoSat data. Seven new experimental altimeter data sets and three new geophysical correction data sets were created, as listed in Tab. 1.

The key findings under each theme are summarised below:

1.1. Reduced SAR mode product for Open Ocean Applications

The "RDSAR" product is a data set produced from SAR mode data, processed to be equivalent to the conventional "Low Rate Mode" altimeter data product conventionally produced from altimeters that do not operate in SAR mode. The objective is to provide a product that is as consistent as possible with the low rate mode product, although the processing necessarily then loses the higher along track resolution that is otherwise available in SAR mode.

Within CP4O two "RDSAR" products were assessed, the RADS RDSAR product produced by TUDelft/ NOAA/ EUMETSAT, and the CPP RDSAR product generated by CNES.

***Table 1:** Products Developed and Evaluated within CP4O*

Theme	Product	Partner	Area	Time Period
Open Ocean	RDSAR	TU Delft	Pacific and N Atlantic SAR boxes	July 2012, Jan 2013
	RDSAR	CNES/CLS	All SAR areas	Whole Mission
	SAR	Starlab	Pacific and N Atlantic SAR boxes	July 2012, Jan 2013
	SAR	ESA	Pacific SAR boxes	July 2012, Jan 2013
	SAR	CNES/CLS	All SAR areas	Whole Mission
Open and Coastal Ocean	SAR	ESA / NOC	N Atlantic SAR boxes	July 2012, Jan 2013
Polar Ocean	SAR	ESA / DTU	Lats > 60N	Mid July 2010 onwards
Sea Floor Mapping	SAR	ESA / DTU	Pacific SAR boxes	1 x 369 day cycle, starting 01/10/2012
Coastal Applications	SARIN	isardSAT	Cuba and Chile	Selected orbits
Corrections	Wet Tropo	U Porto	Global	July 2012, Jan 2013
	Ionosphere	Noveltis	Med / European Shelf	Jan 2011- Jan 2013
	Regional Tides	Noveltis	NE Atlantic	Jan 2011- Jan 2013

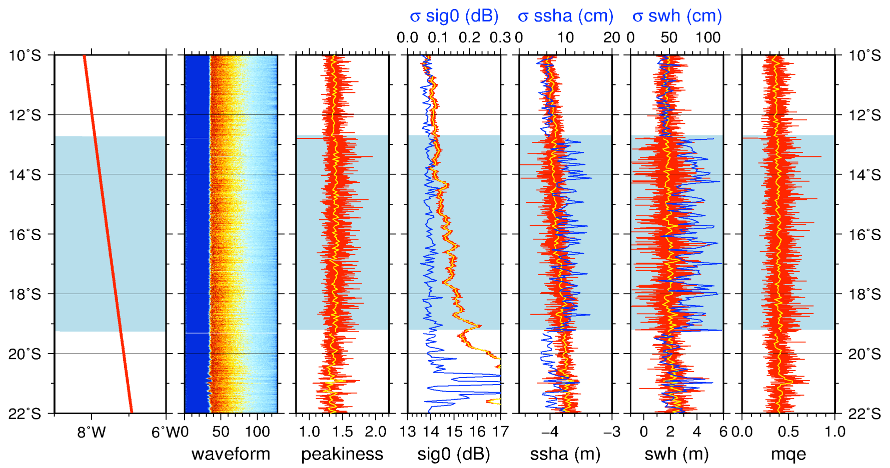

Figure 1: Time series of LRM – RDSAR- LRM data near St Helena in the South Atlantic, demonstrating consistency across the products. The blue sector represents the RDSAR coverage, the white LRM. Credits TU Delft

It has been demonstrated that both products provide continuity across the LRM / SAR mode sampling areas and so, when combined with LRM data are important in enabling a consistent global data "LRM" like data set spanning the CryoSat mission. This permits CryoSat data to be added to the existing long term satellite altimeter database used to monitor climate variability, and to be used operationally along side concurrent data from other satellite missions.

It is important to note that the CryoSat SIRAL transmission and reception sequencing in SAR mode results in sampling gaps. A consequence of this is that the along track standard deviation on retrieved oceanographic parameters is higher than for standard LRM data. This can be mitigated by applying averaging along track, as applied in the RADS RDSAR product, though this effectively reduces the along track resolution.

The comparative assessment of the two products showed a high level of consistency between the two, once a time tag difference had been understood and corrected for. There are differences in the processing schemes, which does result in some differences in the inter-dependencies between the retrieved parameters, particularly in dependencies on SWH.

Fig.1 shows an example of the TUDelft /NOAA/ EUMETSAT data set near St Helena in the South Atlantic, showing continuity across the SAR / LRM transitions, and the increased noise in the RDSAR data set.

This work and analysis provides important input to the preparation of the ground segment processing for generating and RDSAR product from the SRAL altimeter on the Sentinel-3 mission.
The following recommendations for RDSAR are highlighted:

- Analysis should be carried out on a larger data set to provide improved comparison statistics, and to investigate potential discrepancies between ascending /descending passes.
- Suitable planning should be made for the Sentinel-3 validation phase to support a validation of Sentinel RDSAR data.
- The RDSAR processing schemes should be further developed to improve the waveform statistics so they are more consistent with those of LRM data.

1.2. SAR mode product for Open Ocean Applications

The SAR product is a data set produced from SAR mode CryoSat data, processed to take full advantage of the higher along track resolution and precision offered by specialised SAR altimeter processing.
Two types of SAR L1B to L2 retracking processing schemes were used to generate products that were assessed within CP4O, the analytical SAMOSA echo model and re-tracker [1], and the CPP numerical model and retracker. A number of versions of the SAMOSA model were implemented to test the impact of various approximations and refinements.

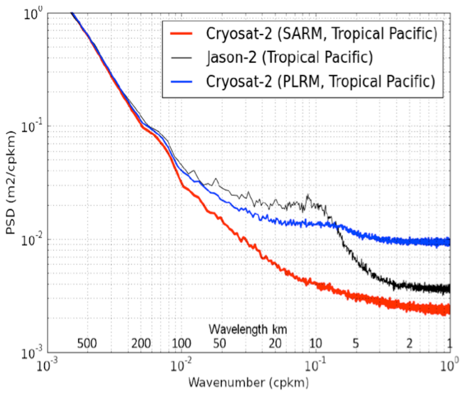

Figure 2: SLA spectra showing that SAR mode (red) can resolve scales from 10-100km, not observable by conventional altimetry (Jason-2: Black, CryoSat "Pseudo" LRM: blue) Credits: CNES/CLS

The key finding is that the improved performance of SAR mode over the open ocean was confirmed in terms of:

- Improved precision in range (and derived parameters: SSH, SLA, etc.) with respect to LRM data. In terms of 1Hz noise, improvement from 1.57 cm to 1.22 cm.
- Improved precision in SWH with respect to LRM data. In terms of 1Hz noise, improvement from 11.09 cm to ~ 8.5 cm.
- Improved along track resolution, shown in SLA and SWH spectra, so that scales of less than 100km can be resolved (see Fig. 2)
- In general the SAR products are consistent with LRM products, or have known biases that can be corrected for.

In terms of the differences between the processing approaches, the following conclusions are identified:

- The products from the full implementation of the SAR SAMOSA model (SAMOSA2), and the CPP numerical model are very consistent in terms of performance and error characteristics. Analysis of a larger data set is necessary to fully identify and characterise potential small differences.
- The version of the SAMOSA processing scheme currently implemented for the Sentinel-3 SRAL DPM (SAMOSA3) provides range measurements that are consistent with the full implementation of SAMOSA, and with the CPP product, but the SWH estimates are not consistent at low wave heights. It is strongly recommended that the Sentinel-3 DPM is modified with an improved implementation of the SAMOSA model.

The following recommendations for SAR (open ocean) are highlighted:

- Techniques to address the under-sampling of more specular waveforms should be carried out.
- Various processing options to optimise the generation of the Doppler Echo should be investigated and evaluated.
- The Sea State Bias model for SAR altimetry needs to be further developed and assessed.
- Investigation of the dependence on retrieved parameters by SAMOSA-3 on SWH, roll angle, pitch angle and radial velocity are recommended
- The S-3 DPM should be updated to the best performing implementation found in CP4O.
- Further improvements to the Starlab implementation of SAMOSA-3 should be applied and evaluated (using a larger data set).

1.3. SAR mode product for Coastal Ocean Applications

Analyses of the CP4O SAR products demonstrated that the product provided low noise estimates of Sea Surface Height, and parameters derived from SSH (SLA, TWLE) to within 1 km of the coast, if the data are filtered appropriately (Fig. 3). It has not been possible to investigate the relative performance of different processing schemes in this aspect.

It was concluded that whilst early results were encouraging, a more comprehensive evaluation of CryoSat SAR data in the coastal area was required.

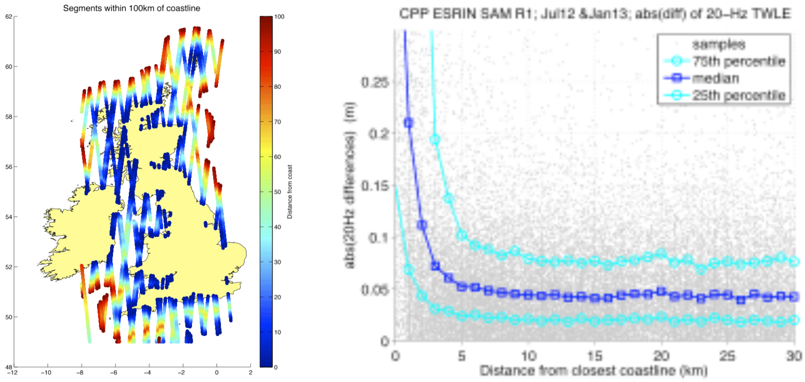

Figure 3: CryoSat data provides measurements close to the coast (left panel), and maintains accuracy to within 5km (right), a significant improvement on previous missions. Credits NOC

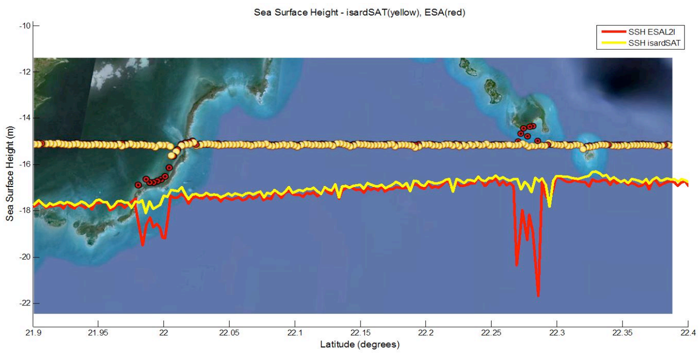

Figure 4: Example of SARin coastal transition data. Reprocessing (yellow) can correct the initially processed data (red) that selects reflections from bright targets away from the sub-satellite track. Credits: isardSAT

1.4. Study of SARin data in the Coastal Zone

A study of SARin data in the coastal zone demonstrated that the existing CryoSat SARin processing scheme was returning incorrect SSH values, by retracking on non-nadir echoes, in a significant number of cases in the coastal zone, and has developed an improved scheme to minimise the contamination from non-nadir echoes. Fig. 4 demonstrates the improved results achieved with this scheme.

Further work is recommended to:

- Further improve the modified SARin processing scheme to fine tune the retracker seed production and the retracking solution itself.
- Produce a test data set for coastal zones to support the development of an improved SAR coastal zone retracking solution.
- Adapt the SARin processing approach for application to SAR data to improve retrieval of ocean parameters (especially sea surface height) from tracks over complex coastal topography.

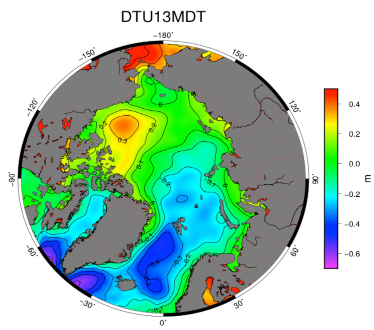

Figure 5: A new Mean Dynamic Topography for the Arctic Ocean produced by DTU using CryoSat data. Credits DTU Space

1.5. *SAR mode product for Polar Ocean Applications*

A scheme for processing CryoSat SAR L1B data in sea-ice affected oceans has been developed and validated within CP4O. The validation demonstrated good agreement with available sources, though only limited suitable reference data were available. Using these

processing schemes DTU Space has processed CryoSat SAR Polar Ocean data which have supported an improvement to previously available Arctic mean sea surface and mean dynamic topography models (Fig. 5). Further enhancements are planned, making use of the entire CryoSat SAR data set.
Plans for future work include further enhancements to the sea-Ice processing algorithms, and to test / apply this also in the oceans around Antarctica.

1.6. *SAR mode product for Improvements to Sea Floor Topography*

Analysis in CP4O has validated the process applied by DTU Space to generate predictions of sea floor topography from altimeter SSH provided at 1 Hz and 20 Hz, and shown that the SAR altimeter derived bathymetry is more accurate than that derived from conventional LRM, RDSAR data, and offers an improvement on the DTU10 and Sandwell and Smith V17.1 (2014) bathymetry model.

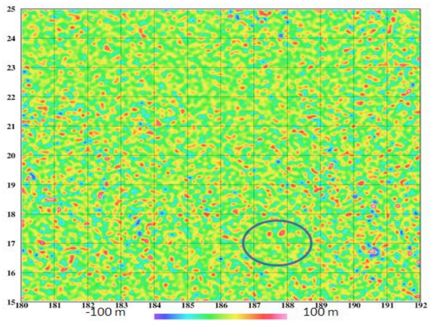

Figure 6: The retrieved residual bathymetry signal relative to a "pre" CryoSat bathymetry (DTU10). The marked circle indicates a possible improved mapping of an existing bathymetric/tectonic feature or a new, previously unmapped, feature. Credits DTU Space

Whilst it has not been possible to establish the full potential of using CryoSat SAR altimeter data for sea floor topography mapping, it has been shown that the potential exists as possible new features have been identified. A initial comparison of the relative capabilities of data sampled at 1 Hz, 2Hz and 4 Hz for sea floor mapping to resolve finer scale structures has been completed (See Fig. 6), and indicates that the 2 Hz data can identify features better than 1 Hz.

The following recommendations for further work with regard to application of SAR altimetry in improving mapping of sea floor topography are highlighted:

- The full potential of using SAR for sea floor bathymetry should be further investigated, as bathymetry is a fundamental and important marine parameter, which is very sparsely sampled. CryoSat SAR data can provide a very valuable contribution to new knowledge in this area.
- A revisit of the investigation area using multiple years of altimetry is recommended, to allow a more complete mapping at this medium water depth (3-5 km).
- A careful analysis should be performed in more coastal / shallow water regions to explore the potential contribution of SAR altimeter data in these regimes.
- A study should be carried out with the use of a better prior bathymetry for the long wavelength signal.

1.7. *Geophysical Corrections*

CP4O developed new models for Wet Troposphere [2] and ionosphere corrections, and also an improved regional tide model for NW Europe, so supporting/CNES improved measurements near the European coastline (Fig. 7). These products were developed with coverage to coincide with that of the SAR products generated in CP4O, and then analysed by CLS in terms of the impact on SSH and SLA measurements.
The general conclusions were that the UPorto Dcomb Wet Troposphere Correction and Noveltis COMAPI Regional Tide correction offer clear improvements to the equivalent corrections currently supplied for use with CryoSat data, but that there was no similar evidence to support the use of the regional ionosphere correction derived from the SPECTRE service, at least in the region where the analysis was performed (North East Atlantic).
The following recommendations for further work in terms of geophysical corrections are highlighted:

- A whole mission CryoSat Wet Troposphere product should be generated and made available. This is critical for the use of CryoSat data in ocean applications requiring accurate sea level information.
- A global gridded data set should be generated to provide a consistent Wet Troposphere Correction across all current satellite missions.
- IRI 2007 should be used as a source for electron content above CryoSat orbit height.

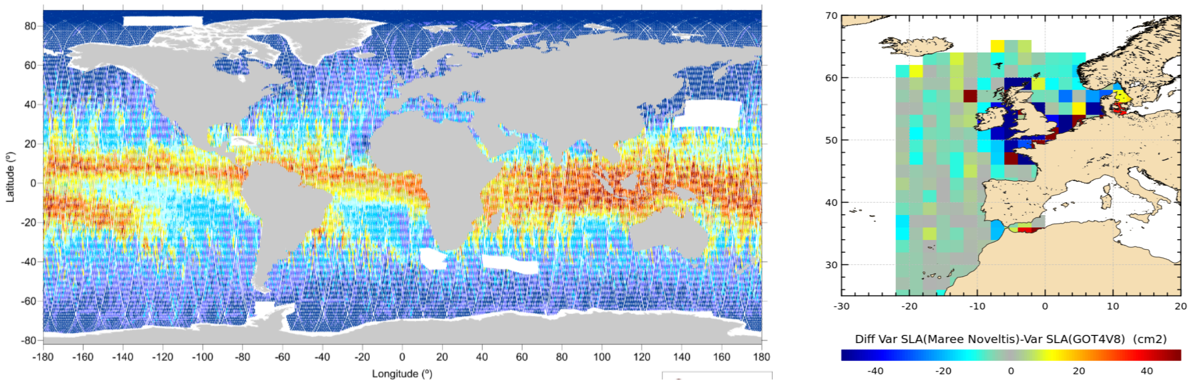

Figure 7 (Left) Wet Troposphere Correction from Dcomb algorithm estimated for CryoSat sub-cycle 35, using data from GNSS stations, MWR satellite data and the ERA interim model. Credits University of Porto. (Right) Regional Tide Model: Improvement in SLA variance (cm^2) between COMAPI (tide model used in CP4O) and GOT4.8 tidal model. Credits CLS.

2. SCIENTIFIC ROADMAP

The final activity of CP4O was to propose a Scientific Roadmap outlining activities needed to support improvement of SAR altimeter processing to the further development and exploitation of higher level products derived from SAR altimeter data.

The common objective of the proposed activities is to transfer the outcomes of CP4O into future scientific and operational activities and to maximise the exploitation of SAR altimeter data, which began with CryoSat and will be sustained by the Sentinel-3 series of satellites.

The Outline Road Map is given in Fig. 8 and the following aspects are highlighted:

- Scientific Priority Areas to further improve SAR altimeter data processing, support exploitation of CryoSat data and prepare for Sentinel-3
- A Scientific Development Strategy for improving development methods and products
- An outline plan for fostering a transition from research to operation activities.
- Strategies for integrating the methods and models developed into existing large scientific initiatives and operational institutions.

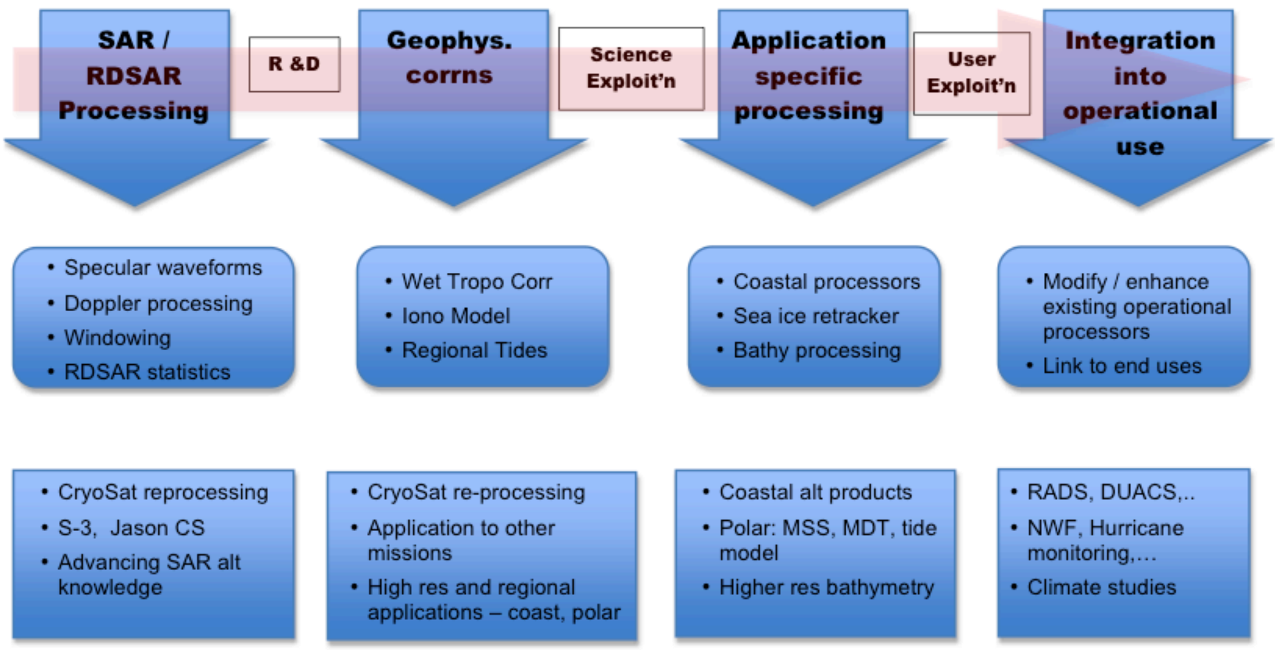

Figure 8. CP4O Scientific Road Map, with four modes of development. Credits SatOC.

3. CONCLUSIONS

The CP4O project has carried out a wide-ranging study to build a sound scientific basis for new applications of CryoSat SAR altimeter data under the four themes of Open Ocean, Coastal Ocean, Polar Ocean and Sea Floor Topography. Following an in-depth "State of the Art" review of SAR altimetry new products were developed and evaluated, demonstrating the extensive potential of SAR altimetry to provide improved measurements and further scientific understanding.

A number of recommendations for further work have been provided, these range from further basic research needed to build a more complete scientific and technical understanding of SAR altimetry over the oceans, to steps needed to support integration of CryoSat derived products in operational data streams.

4. REFERENCES

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