IMPROVED OCEANOGRAPHIC MEASUREMENTS FOM SAR ALTIMETRY: RESULTS AND SCIENTIFIC ROADMAP FROM 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. Although the prime objective of the CryoSat mission is dedicated to monitoring land and marine ice, the SAR mode capability of the CryoSat SIRAL altimeter also presents significant potential benefits for ocean applications including improved range precision and finer along track spatial resolution.

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.

This task was addressed within four specific themes: Open Ocean Altimetry; High Resolution Coastal Zone Altimetry; High Resolution Polar Ocean Altimetry; High Resolution Sea-Floor Bathymetry, with further work in developing improved geophysical corrections.

The Cryosat Plus 4 Oceans (CP4O) consortium brought together a uniquely strong team of key European experts to develop and validate new algorithms and products to enable users to fully exploit the novel capabilities of the Cryosat-2 mission for observations over ocean. The consortium was led by SatOC (UK), and included CLS (France), Delft University of Technology (The Netherlands), DTU Space (Denmark), isardSat (Spain), National Oceanography Centre (UK), Noveltis (France), Starlab (Spain) and the University of Porto (Portugal).

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.

1. STATE OF THE ART REVIEW

The first task of CP4O was to establish the current state of the art for SAR altimetry over the oceans, and to identify major issues that required further investigation. This was achieved through a literature review and by bringing together international experts in a workshop that was held in Southampton in June 2013, and written up in a Preliminary Analysis Report (Naeije and Cotton, 2014).

2. USER SURVEY AND SCIENTIFIC REQUIREMENTS DEFINITION

Another early task was to carry out a survey of user needs and to establish a definition of scientific requirements for the project. This task was carried out by STARLAB, through a questionnaire exercise, and the results provided in the “Requirements Baseline” document (Clarizia et al., 2013).

3. PRODUCT DEVELOPMENT, EVALUATION AND ASSESSMENT

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-2 data. 7 new experimental altimeter data sets and 3 new geophysical correction data sets were created, as listed in Table 1.

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	Latitudes > 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 (Coastal)	Jan 2011- Jan 2013

The key findings under each theme are summarised below:

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. 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 data base used to monitor climate variability, and to be used operationally alongside 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.

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.

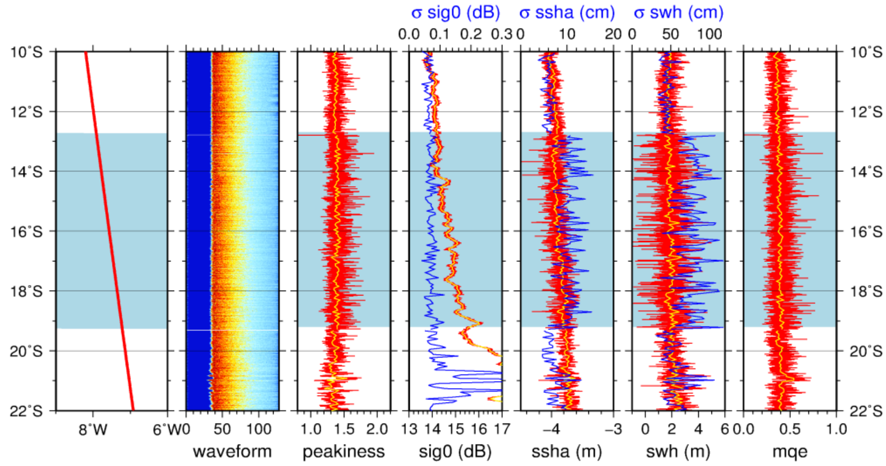

Figure 1. Time series of LRM – RDSAR- LRM data near St Helena in the South Atlantic, demonstrating consistency across the products. The blue sector represents the RDSAR coverage, the white LRM. Credits TU Delft

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.

The RADS RDSAR processing scheme is described in Scharroo (2014), and the performance assessed in Naeije and Scharroo (2014) and Raynal and Moreau (2014a).

The CNES CPP RDSAR Processing scheme is described in Boy and Moreau (2013a) and the performance assessed in Moreau et al., (2013a) and Labroue et al. (2014a)

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, 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.

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
- In general the SAR products are consistent with LRM products, or have known biases that can be corrected for.

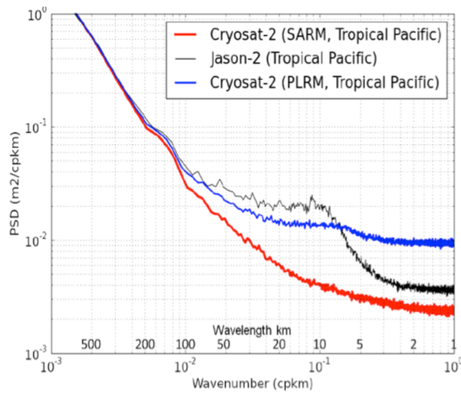

Figure 2. SAR mode (red) can resolve scales from 10-100km, not observable by conventional altimetry (Jason-2: Black, Cryosat-2 "Pseudo" LRM: blue) Credits: CNES/CLS

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 SAMOSA SAR retracker is described in Egido (2014), and the performance assessed in Egido et al (2014), Raynal and Moreau (2014b), and Raynal and Moreau (2014c)

The CPP SAR Retracker is described in Boy and Moreau (2013b) and the performance assessed in Moreau et al., (2013b) and Labroue et al. (2014b)

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).

SAR mode product for Coastal Ocean Applications

Although further work on a larger data set is necessary, it can be concluded from the CP4O analyses that the SAR product can provide 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. It has not been possible to investigate the relative performance of different processing schemes in this aspect.

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

- A comprehensive evaluation of CryoSat SAR data in the coastal area should be carried out.

The performance of the different SAR mode retrackers in the open and coastal ocean is described in Gommenginger et al (2014).

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.

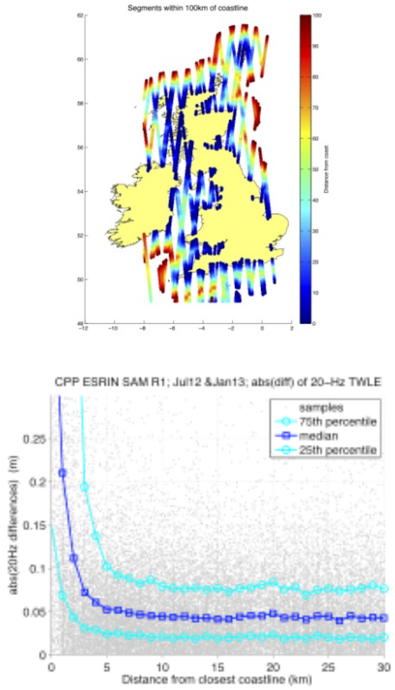

Figure 3. Cryosat-2 data provides measurements close to the coast (left panel), and maintains accuracy to within 5km (right), a significant improvement on previous missions. Credits NOC.

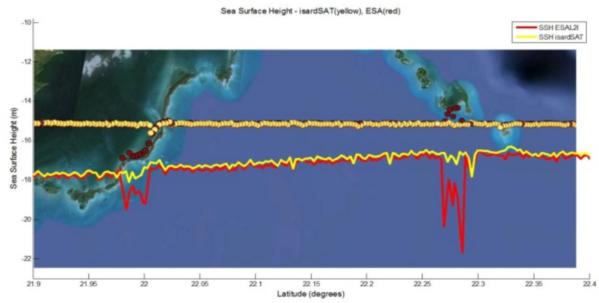

Figure 4. Examples of SARIN data during coastal transitions. Reprocessing (yellow) can correct the initially processed data (red) which selects reflections from bright targets away from the sub-satellite track. Credits: isardSAT

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.

The SARin processing applied is described in Garcia (2013).

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 (Stenseng, 2014a and 2014b). The validation demonstrated good agreement with available sources, though only limited suitable reference data were limited. 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. 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.

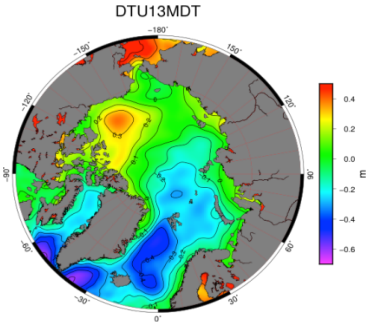

Figure 5. Cryosat-2 data provide important improvements to maps of Mean Dynamic Topography for the Arctic Ocean, and so support analysis of key ocean circulation features. Credits DTU Space

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.

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, 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-2 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.

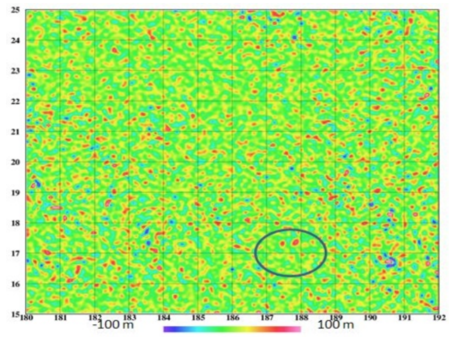

Figure 6. The retrieved residual bathymetry signal relative to a "pre" Cryosat-2 era bathymetry (DTU10 Bathymetry). There are some clear indications in the marked circle of a bathymetric/tectonic feature that could be an improved mapping of an existing seamount or a mapping of an unknown sea mount. Credits DTU Space

Geophysical Corrections

UPorto developed and implemented a data combination algorithm to provide an improved Wet Troposphere Correction (Fernandes et al, 2014a), which was assessed internally at U Porto (Fernandes et al, 2014b) and independently by CLS (Raynal and Moreau, 2014d).

Noveltis developed and implemented a regional tide model (Cancet et al., 2010) which was assessed internally at Noveltis and independently by CLS (Raynal and Moreau, 2014e). Finally Noveltis also implemented a regional ionosphere model (Crespon et al., 2007) which was assessed internally at Noveltis and independently by CLS (Raynal and Moreau, 2014f)

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).

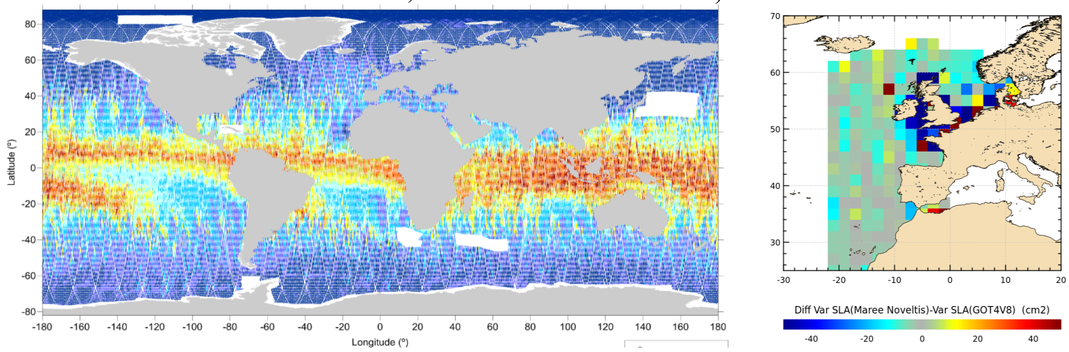

Figure 7. (Left) Wet Troposphere Correction from Dcomb algorithm estimated for CryoSat-2 sub-cycle 35, using data from GNSS stations, MWR satellite data and the ERA interim model. Credits University of Porto. (Right) Regional Tide Model: Improvement in SLA variance (cm^2) between COMAPI (tide model used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

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

4. SCIENTIFIC ROAD MAP

The final activity of CP4O was to propose a Scientific Roadmap outlining activities ranging from further research 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.

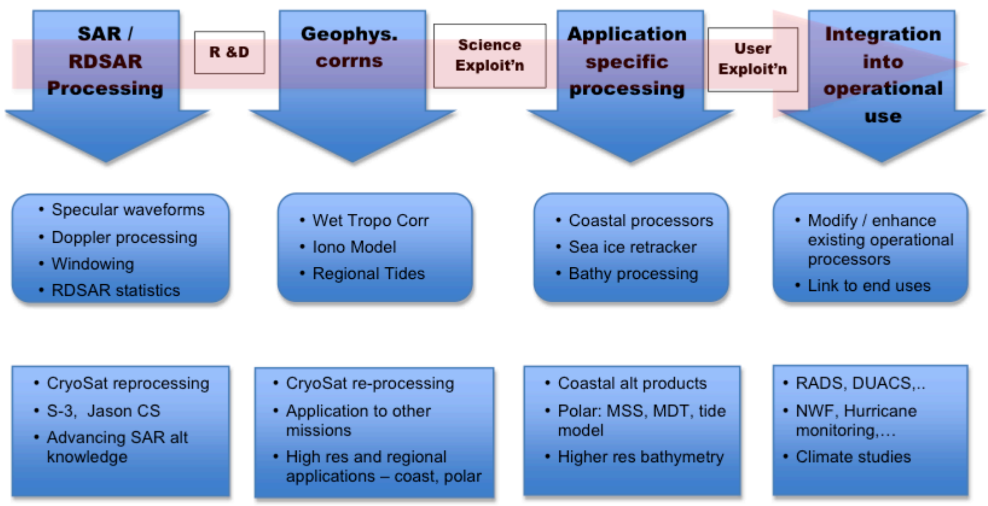

Figure 9. CP4O Scientific Road Map, with four modes of development. Credits SatOC

The following aspects are identified:

- Scientific Priority Areas to be addressed to further improve SAR altimeter data processing, to support the exploitation of CryoSat data and to prepare for Sentinel-3
- A Scientific Development Strategy for improving the 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

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REFERENCES

Andersen, O. (2014a) CryoSat Plus for Oceans Algorithm Theoretical Basis Document – Sea Floor Bathymetry, ESA CP4O Project Report, August 2014. Available at:
http://www.satoc.eu/projects/CP4O/docs/Sea%20Floor%20Bathymetry_ATBD.pdf

Andersen, O. (2014a) CryoSat Plus for Oceans Product Validation Report – Sea Floor Bathymetry, ESA CP4O Project Report, December 2014. Available at:
http://www.satoc.eu/projects/CP4O/docs/Sea%20Floor%20Bathymetry_PVR_V10.pdf

Boy, F, and T. Moreau. (2013a) CryoSat Plus for Oceans Algorithm Theoretical Basis Document of the CPP RDSAR processing for oceans, ESA CP4O Project Report, June 2013. Available at:
http://www.satoc.eu/projects/CP4O/docs/S3A-NT-SRAL-00098-CNES_RDSAR_ATBD.pdf

Boy, F, and T. Moreau. (2013b) CryoSat Plus for Oceans Algorithm Theoretical Basis Document of the CPP SAR Numerical Retracker for oceans, ESA CP4O Project Report, June 2013. Available at:
http://www.satoc.eu/projects/CP4O/docs/S3A-NT-SRAL-00099-CNES_SAR_ATBD.pdf

Cancet, M., Lux, M., Pénard, C., et al. (2010). COMAPI: New regional tide atlases and high frequency dynamical atmospheric correction, presented at the Ocean Surface Topography Science Team meeting, Lisbon, Portugal

Clarizia, M.P, P. D. Cotton, E Gil-Roldàn, S. Labroue, P. Thibaut, T. Moreau, C. Gommenginger, P. Cipollini, O. Andersen. (2013) CryoSat Plus for Oceans Scientific Requirements Consolidation, ESA CP4O Project Report, March 2013. Available at:
http://www.satoc.eu/projects/CP4O/docs/CP4O-WP1000-D11RB-FINALv1.pdf

Crespon, F., Jeansou E., Helbert J., Moreaux G., Lognonné P., Godet P.E., Garcia R., (2007) "SPECTRE (www.noveltis.fr/spectre): a web Service for Ionospheric Products", in
Proceedings of 1st Colloquium Scientific and Fundamental Aspects of the Galileo Programme, Toulouse, France, October, 2007.

Egido, A., (2014) CryoSat Plus for Oceans Algorithm Theoretical Basis Document of the SAMOSA Retracker, ESA CP4O Project Report, July 2014. Available at:
http://www.satoc.eu/projects/CP4O/docs/CP4O_WP4000_Starlab_ATBD_v1.0.pdf

Egido, A., D. Cotton, T. Moreau, S. Dinardo (2014) CryoSat Plus for Oceans Product Validation Report of the SAMOSA Retracker, ESA CP4O Project Report, July 2014. Available at:
http://www.satoc.eu/projects/CP4O/docs/CP4O_WP4000_Starlab_PVR_v1.0.pdf

Fernandes, M., J., C. Lazaro, and A.L. Nunes. (2014a) CryoSat Plus for Oceans Algorithm Theoretical Basos Document on the Improved Wet Troposphere Correction for CryoSat-2, ESA CP4O Project Report, June 2014. Available at:
http://www.satoc.eu/projects/CP4O/docs/D4.1%20-%20Improved%20WTC%20ATBD%20-%20U.Porto_V1.0_Reviewed.pdf

Fernandes, M., J., C. Lazaro, and A.L. Nunes. (2014b) CryoSat Plus for Oceans Product Validation Report on the Improved Wet Troposphere Correction for CryoSat-2, ESA CP4O Project Report, June 2014. Available at:
http://www.satoc.eu/projects/CP4O/docs/D4.2%20-%20Improved%20WTC%20PVR%20-%20U.Porto_V1.0_Reviewed.pdf

Garcia, P. (2013) CryoSat Plus for Oceans SARin for Coastal Ocean, ESA CP4O Project Report, December 2013. Available at:
http://www.satoc.eu/projects/CP4O/docs/WP4000_SARin_Coastal_ATBD.pdf

Gommenginger, C., P. Cipollini, and H. Snaith (2014).
CryoSat Plus for Oceans Product Validation Report of SAR altimetry over the open ocean and coastal zone, ESA CP4O Project Report, June 2014. Available at:
http://www.satoc.eu/projects/CP4O/docs/CP4O_WP4_SAR_OceanCoastal_PVR_v1.0.pdf

Labroue, S., M. Raynal, T. Moreau (2014a) CryoSat Plus for Oceans, Validation Report, Assessment of CPP PLRM Retracking, ESA CP4O Project Report, June 2014. Available at:
http://www.satoc.eu/projects/CP4O/docs/CP4O-WP5000-RDSARCPP-1-0.pdf

Labroue, S., M. Raynal, T. Moreau (2014b) CryoSat Plus for Oceans, Validation Report, Assessment of CPP SAR Retracking, ESA CP4O Project Report, June 2014. Available at:
http://www.satoc.eu/projects/CP4O/docs/CP4O-WP5000-SARCPP-1-0.pdf

Moreau, T., F. Boy, M. Raynal. (2013a) CryoSat Plus for Oceans Product Validation Report of the CPP

RDSAR processing for oceans, ESA CP4O Project Report, June 2013. Available at: http://www.satoc.eu/projects/CP4O/docs/CP4O-WP4200-RDSAROcean-PVR-XXX-1-0-1.pdf

Moreau, T., F. Boy, M. Raynal. (2013b) CryoSat Plus for Oceans Product Validation Report of the CPP SAR Numerical retracker for oceans, ESA CP4O Project Report, June 2013. Available at: http://www.satoc.eu/projects/CP4O/docs/CP4O_WP4000_Starlab_PVR_v1.0.pdf

Naeije, M. and P. D. Cotton (2014) CryoSat Plus for Oceans Preliminary Analysis Report, ESA CP4O Project Report, June 2014. Available at: http://www.satoc.eu/projects/CP4O/docs/CP4O-D21-PAR-V5c.pdf

Naeije, M. and R. Scharroo (2014b) CryoSat Plus for Oceans Product Validation Report of the RADS RDSAR Processing for Oceans, ESA CP4O Project Report, July 2014. Available at: http://www.satoc.eu/projects/CP4O/docs/CP4O-WP4000-RADS-RDSAR-PVR-1.0.pdf

Raynal, M., and T. Moreau (2014a) CryoSat Plus for Oceans, Validation Report, Assessment of RDSAR solution (RADS) for Open Ocean, ESA CP4O Project Report, October 2014. Available at: http://www.satoc.eu/projects/CP4O/docs/CP4O-WP5000-RDSAR_RADS_TUDelft-2-0.pdf

Raynal, M., and T. Moreau (2014b) CryoSat Plus for Oceans, Validation Report, Assessment of SAMOSA SAR Solution (ESRIN), ESA CP4O Project Report, October 2014. Available at: http://www.satoc.eu/projects/CP4O/docs/CP4O-WP5000-SAR_ESRIN-1-0.pdf

Raynal, M., and T. Moreau (2014c) CryoSat Plus for Oceans, Validation Report, Assessment of SAMOSA3 SAR SAR retracker (S3 DPM 2.3.0), ESA CP4O Project Report, October 2014. Available at: http://www.satoc.eu/projects/CP4O/docs/CP4O-WP5000-SAR_SAMOSA_S3_DPM-1-0.pdf

Raynal, M., and T. Moreau (2014d) CryoSat Plus for Oceans, Validation Report, Global Wet Troposphere Correction ESA CP4O Project Report, May 2014. Available at: http://www.satoc.eu/projects/CP4O/docs/CP4O-WP5000-TropWet_Porto-1-0.pdf

Raynal, M., and T. Moreau (2014e) CryoSat Plus for Oceans, Validation Report, Regional Tide Correction ESA CP4O Project Report, May 2014. Available at: http://www.satoc.eu/projects/CP4O/docs/CP4O-WP5000-TidalModel_Noveltis-2-0.pdf

Raynal, M., and T. Moreau (2014f) CryoSat Plus for Oceans, Validation Report, Ionospheric Correction ESA CP4O Project Report, June 2014. Available at: http://www.satoc.eu/projects/CP4O/docs/CP4O-WP5000-IonoModel_Noveltis-2-0.pdf

Scharroo, R. (2014) CryoSat Plus for Oceans RADS RDSAR Algorithm Theoretical Basis Document, ESA CP4O Project Report, August 2014. Available at: http://www.satoc.eu/projects/CP4O/docs/tud_rdsar_atbd.pdf

Stenseng (2014a) CryoSat Plus for Oceans, Algorithm Theoretical Basis Document – Polar Ocean, ESA CP4O Project Report, May 2014. Available at: http://www.satoc.eu/projects/CP4O/docs/ATBD-Polar_Ocean.pdf

Stenseng (2014b) CryoSat Plus for Oceans, Product Validation Report– Polar Ocean, ESA CP4O Project Report, July 2014. Available at: http://www.satoc.eu/projects/CP4O/docs/ATBD-Polar_Ocean.pdf