CP4O

Cryosat Plus for Oceans: CP4O
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EXECUTIVE SUMMARY

Introduction

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 Oceanoography 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.

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.

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.

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.

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 along side concurrent data from other satellite missions.

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 (Coastal)	Jan 2011- Jan 2013

Table 1: *Products Developed and Evaluated within CP4O*

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.

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.

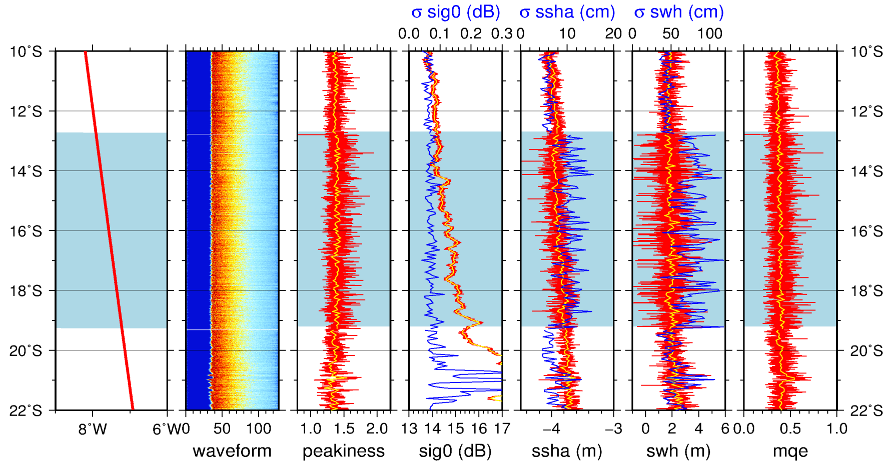

Figure 1: *Time series of LRM – RDSAR- LRM data near St Helena in the South Atlantic, demonstrating consistency across the products. The blue sector represents the RDSAR coverage, the white LRM. Credits TU Delft*

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.

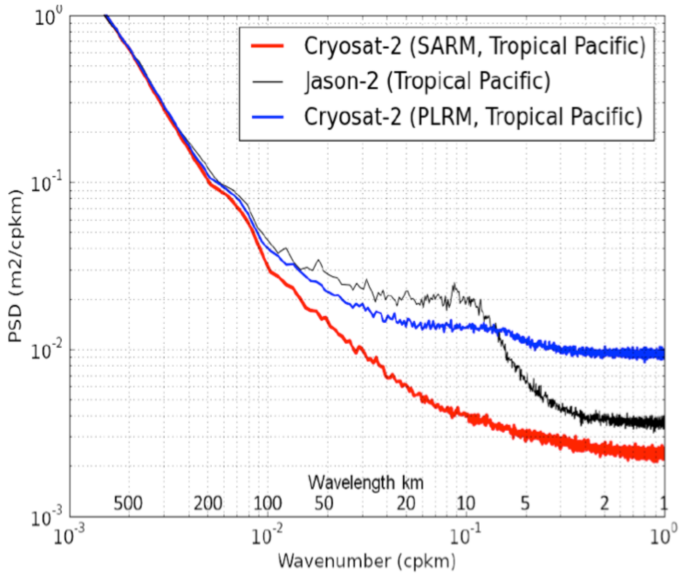

Figure 2: *SAR mode (red) can resolve scales from 10-100km, not observable by conventional altimetry (Jason-2: Black, Cryosat-2 "Pseudo" LRM: blue) Credits: CNES/CLS*

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.

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).

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.

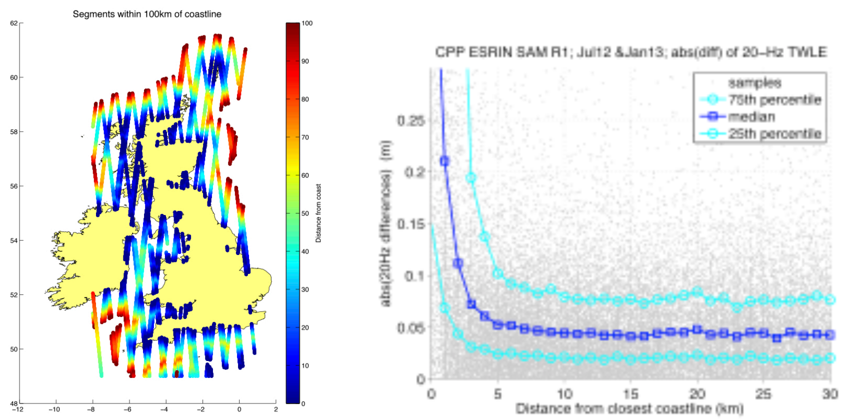

Figure 3: *Cryosat-2 data provides measurements close to the coast (left panel), and maintains accuracy to within 5km (right), a significant improvement on previous missions. Credits NOC*

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. 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.

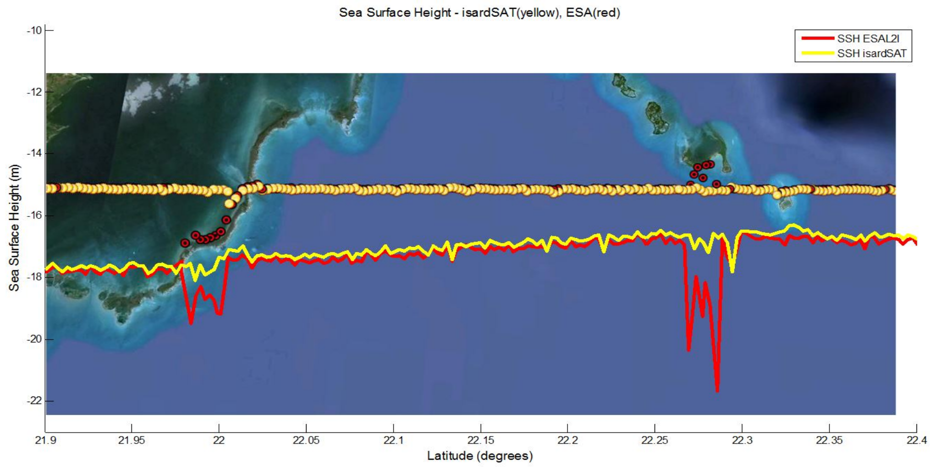

Figure 4: *Examples of SARIN data during coastal transitions. Reprocessing (yellow) can correct the initially processed data (red) which selects reflections from bright targets away from the sub-satellite track. Credits: isardSAT*

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 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.

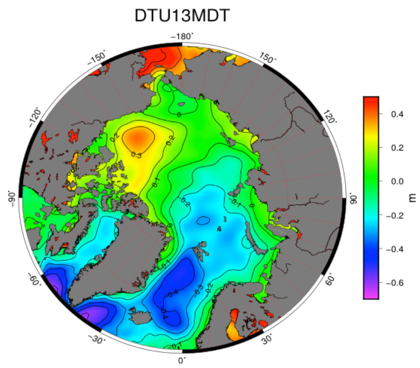

Figure 5: *Cryosat-2 data provide important improvements to maps of Mean Dynamic Topography for the Arctic Ocean, and so support analysis of key ocean circulation features. Credits DTU Space*

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.

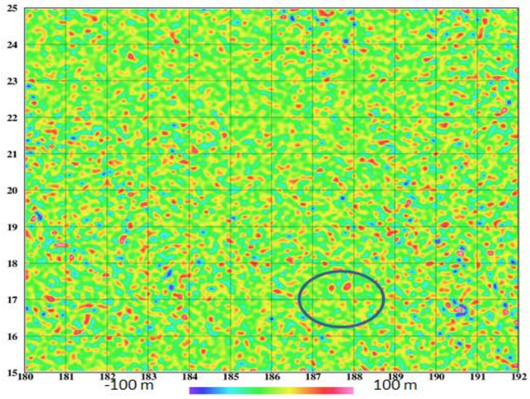

Figure 6: *The retrieved residual bathymetry signal relative to a "pre" Cryosat-2 era bathymetry (DTU10 Bathymetry). There are some clear indications in the marked circle of a bathymetric/tectonic feature that could be an improved mapping of an existing seamount or a mapping of an unknown sea mount.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

Geophysical Corrections

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

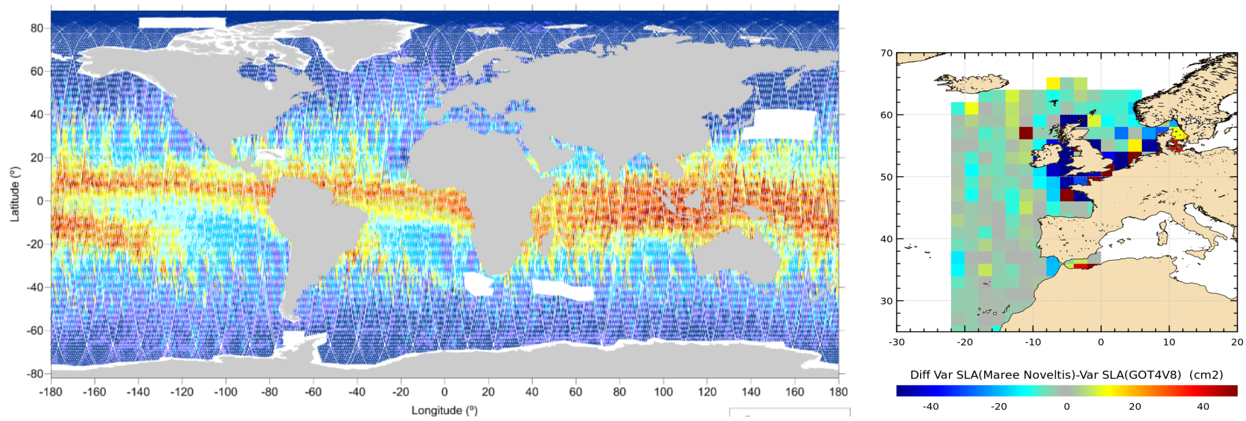

Figure 7 (Left) *Wet Troposphere Correction from Dcomb algorithm estmated for CryoSat-2 sub-cycle 35, using data from GNSS stations, MWR satellite data and the ERA interim model. Credits University of Porto. (Right) Regional Tide Model: Improvement in SLA variance (cm^2) between COMAPI (tide model used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

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.

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

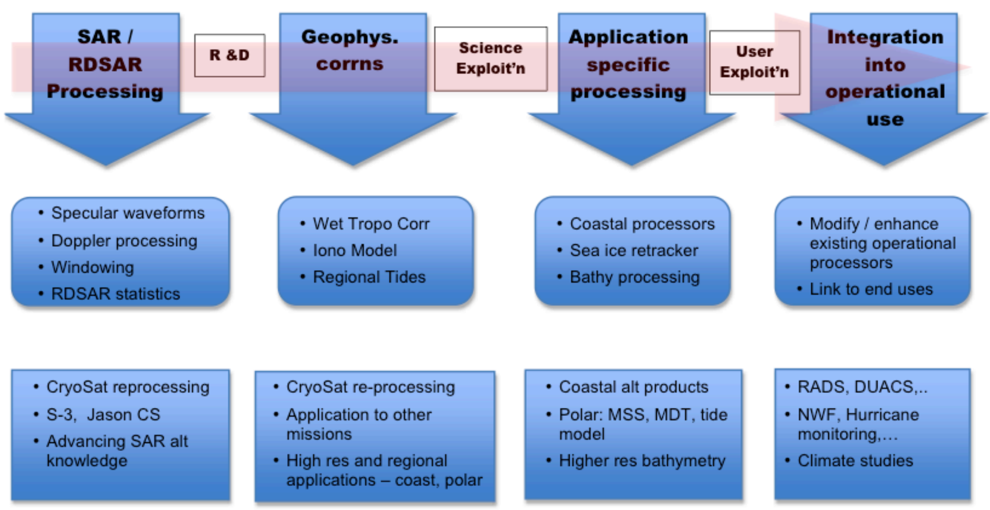

Figure 9: *CP4O Scientific Road Map, with four modes of development. Credits SatOC.*

Acronyms and Abbreviations

Abbreviation	Meaning
AGC	Automatic Gain Control
AMR	Advanced Microwave Radiometer (radiometer on Jason-2)
ATBD	Algorithm Theoretical Baseline Documents
CAL2	CryoSat SIRAL on board calibration sequence
CCI	Climate Change Initiative
CCN	Contract Change Notice
CLS	Collecte Localisation Satellites
CNES	Centre Nationale d'Etudes Spatiales
COASTALT	ESA Project on Coastal Altimetry
COMAPI	NE Atlantic / Mediterranean Tide Model – Coastal Modelling for Altimetry Product Improvement
CP4O	Cryosat Plus for Oceans
CPP	Cryosat Processing Prototype (CNES Processor for Cryosat)
CryoSat	ESA altimeter satellite for polar ice investigations
DComb	Data Combination
DTU Space	National Space Institute, Technical University of Denmark
DPM	Detailed Processing Model
ECMWF	European Centre for Medium Range Weather Forecasting
EOP-SER	Earth Observation – Exploitation, Research and Development
ESA	European Space Agency
ESRIN	ESA Space Research Institute (ESA Centre for Earth Observation)
eSurge	ESA project: Satellite data for the Storm Surge Community
FBR	Full Bit Rate
FFT	Fast Fourier Transform
GIM	Global Ionospheric Maps (http://iono.jpl.nasa.gov/gim.html)
GNSS	Global Navigation Satellite Systems
GOT	Global Tide Model provided with altimeter data
IceBridge	NASA airborne polar ice survey project.
IRI	International Reference Ionosphere
Jason-1, Jason-2	Radar Altimeter Satellites
LiDAR	Laser Radar
LRM	Low Rate Mode
LPF	Low Pass Filter
LSE	Least Squares Estimation
LUT	Look Up Table
MDT	Mean Dynamic Topography
MLE	Maximum Likelihood Estimation
MQE	Mean Quadratic Error
MSS	Mean Sea Surface
MWR	MicroWave Radiometer
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NOC	National Oceanography Centre
OA	Objective Analysis

Abbreviation	Meaning (continued)
OSTST	Ocean Surface Topography Science Team
PISTACH	CNES supported project to develop Coastal Altimetry Products
PAR	Preliminary Analysis Report
PLRM	Pseudo LRM – An LRM equivalent product generated from SAR data
Pu	Waveform power value in output of the re-tracking stage
PVR	Product Validation Report
PTR	Point Target Response
RADS	Radar Altimeter Data System maintained by TUDelft.
RDSAR	Reduced resolution SAR mode data to pseudo LRM
SAMOSA	SAR altimetry Mode Studies and Applications
SAR	Synthetic Aperture Radar
SARIN	SAR interferometric mode
SatOC	Satellite Oceanographic Consultants
SI-MWR	Scanning Imaging Microwave Radiometer
Sigma0 (σ^0)	Radar Backscatter at nadir
SIRAL	LRM / SAR / SARin mode radar altimeter on CryoSat
SLA	Sea Level Anomaly
SPECTRE	Service providing 2D maps of total electron content over Europe
SSB	Sea State Bias
SSH	Sea Surface Height
SSMI	Special Sensor Microwave / Imager
STSE	Support to Science Element
SWH	Significant Wave Height
S-3	Sentinel-3: ESA EO mission due for launch in 2015
TCWV	Total Column Water Vapour
TEC	Total Electron Content
TUDelft	Technical University of Delft
WTC	Wet Troposphere Correction

1 PROJECT OVERVIEW

1.1 SAR Altimetry and CryoSat

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.

1.2 Project Objectives

The general objectives of the “Cryosat Plus for Oceans” (CP4O) project were:

- to build a sound scientific basis for new scientific and operational applications of Cryosat-2 data over the open ocean, polar ocean, coastal seas and for sea-floor mapping.
- to generate and evaluate new methods and products that will enable the full exploitation of the capabilities of the Cryosat-2 SIRAL altimeter, and extend their application beyond the initial mission objectives.
- to ensure that the scientific return of the Cryosat-2 mission is maximised.

In addition there were specific objectives under each of the sub-themes as follows:

Open Ocean Altimetry

The application and evaluation of Cryosat-2 SAR Mode data:

- Ability to detect short spatial scale open ocean features.
- The improvement of CryoSat-2 Oceanographic products through the application of new SAR retracking schemes.
- The application of the RDSAR technique to convert SAR Full Bit Rate (FBR) data to LRM data and so to study the best method for ensuring continuity in Sentinel-3 ocean products from the coastal zone to the open ocean.
- The improvements to Cryosat-2 data offered by application of specifically modelled ionospheric and wet troposphere models to provide accurate estimates of radar path delay

Polar Ocean Altimetry:

To develop and evaluate processing schemes applicable to sea-ice affected regions, so that Cryosat-2 SAR Mode data can be used to study large scale polar ocean signals and so make a significant new contribution to in the following important applications:

- Generation of Mean Sea Surface and Mean Dynamic Topography and subsequent analysis of key polar ocean circulation features
- Improvements of polar tide models
- Investigations into the coupling between wind forcing and polar current patterns.
- Support investigations into critical Climate Change issues in the polar oceans such as ice-melting effects on circulation and sea-level rise

Coastal Zone Altimetry:

The exploitation of Cryosat-2 SAR Mode data in the Coastal Ocean to demonstrate their finer spatial resolution, improved retrieval accuracy and lower sensitivity to land contamination, and so deliver high-quality altimeter measurements closer to the shore, to improve the estimation of coastal sea level changes, the detection of coastal features (coastal current jets, coastal wave set up, coastal tides) and the characterisation of inshore wave conditions.

The demonstration of the potential of Cryosat-2 SARIn mode data to help discriminate and mitigate land contamination signals from off-nadir land targets (e.g. steep cliffs) in SAR and LRM waveforms over coastal regions.

Sea-Floor Altimetry:

The potential offered by the higher resolution and improved Signal to Noise Ratio of Cryosat-2 SAR mode data to resolve short-wavelength sea surface signals caused by sea-floor topography elements and to map uncharted sea- mounts/trenches.

1.3 Project Overview

Scientific Requirements Consolidation, State of the Art Analysis

The first Work Package (WP1000), led by Starlab, was the Scientific Requirements Consolidation – with the aim to consolidate the preliminary scientific requirements for the four sub-themes under analysis in this proposal (open ocean, high-resolution coastal zone, high-resolution polar ocean and high-resolution sea floor).

This activity was followed by the Preliminary Analysis of the State of the Art (WP2000), led by TU Delft, which provided a comprehensive review of the state-of-the-art, relevant current initiatives, algorithms, models and EO-based products and datasets that are relevant in the context of the Cryosat+ ocean theme.

Product Development and Validation, Independent Assessment

This aspect formed the main part of the project in which methods and algorithms needed to derive Cryosat-2 products fit for scientific exploitation analysis were analysed, developed and validated. For each of the four sub-themes (open ocean, coastal zone, polar ocean, sea floor), a Data Set of prototype Cryosat-2 products was produced and validated, followed by further refinement of the methods and algorithms as necessary. A “validation data set” was then produced by the final version of the algorithms for an independent assessment, with the aim of determining the potential impact of the algorithms and demonstration data products in operational use.

Scientific Roadmap

In the final activity, the results of the Impact Assessment were used, together with recommendations coming from other aspects of the project, to define an agreed Scientific Roadmap to support the fullest possible exploitation of Cryosat-2 data over the oceans, and to promote the transfer the results into scientific and operation activities to optimise the application of data flowing from the Sentinel-3 series of satellites.

2 SCIENTIFIC REQUIREMENTS & REVIEWING THE STATE OF THE ART

2.1 Scientific Requirements

A survey was carried out (Clarizia, et al., 2013) in order to establish baseline scientific requirements. The resulting document analysed the results from a user consultation undertaken with key institutions, merged these results with those derived from the COASTALT and PISTACH user surveys. It then used these results together with previous literature and main outcomes from recent workshops and meetings, to characterize the limitations and drawbacks of existing altimetric products, and defined a list of scientific and operational requirements under the four main scientific themes addressed by CP4O:Open Ocean; Coastal Zone; Polar Ocean and Sea Floor Bathymetry, and in terms of data format, delivery and latency.

Limitation of space precludes the inclusion of all the requirements in this document, though it is worthwhile to note some key general recommendations;

- **SAR Retracking methods:**
  - Optimal and computationally efficient SAR altimeter waveform retracking methods need to be defined, and the quality of SAR altimeter L1B multi-looked waveforms needs to be assessed.
  - Investigations on how to improve the capability of SAR altimeters (i.e. in low sea state conditions) are needed.
  - Studies on the impact of other factors like swell direction and mis-pointing need to be addressed.
  - The inter-calibration (or absolute calibration) of the different open ocean retrackers (i.e. conventional Brown retrackers, SAR retrackers, pseudo-LRM retrackers) should be addressed to guarantee continuity and consistency of results.
- **Surface Backscatter Coefficient and Sea State Bias:** A proper derivation of Sigma-0 (σ^0) and wind speed is necessary to derive a SSB correction, and there is a need for an increase of the amount of SAR mode data, currently insufficient to apply the standard methods to develop SSB models (e.g. non-parametric method).
- **Coastal Zone Processing:**
  - Further studies are needed to improve the wet tropospheric correction (WTC) in coastal areas.
  - Further development on retracking techniques in coastal areas is needed. Dedicated coastal retrackers might have to be developed for SAR altimetry data in the coastal zone (as for conventional coastal altimetry).
  - The impact of ground-track orientation with respect to the coast should be addressed.
  - Some new quality flags and auxiliary data specific to SAR/SARIn in coastal zone need to be developed (e.g. coastal proximity parameter for SAR mode, cross-track angle for SARIn, land fraction in SAR footprint, misfit etc.).
  - Identification of the most crucial and urgent atmospheric corrections for SAR altimetry to improve the performances in coastal areas. Development of atmospheric corrections for Cryosat-2 data in coastal areas (i.e. as a combination of existing radiometer data and models).
- **Improvements in data and data formats are needed**: Data need to be reliable, bug-free, and products need to be upgraded more often. Data formats need to be standardized and uniform, with practical structures.
- **Documentation of SAR data processing:** Public documentation for all stages of the SAR data processing should be provided for the benefit of the users. This should include clear information about how the SAR data are focused, stacked and retracked.

- **Provision of full archive of SAR FBR and/or stack data in critical areas:** This should allow final scientific users to derive specially tailored applications especially in critical areas, such as coastal zones, and in-land waters.

2.2 State of the Art Review

The CP4O review of the State of the Art of SAR altimetry (Naeije and Cotton, 2014), or Preliminary Analysis Report (PAR) was produced at the beginning of the CP4O project, in June 2013, and was subsequently updated in June 2014 to incorporate expert reviewer input.

The PAR provides a comprehensive (164 page) review of the state-of-the-art, relevant current initiatives, algorithms, models and Earth-observation based products and datasets relevant in the context of innovative ocean applications for CryoSat-2 data. The review focussed on low and high-resolution open ocean altimetry, high-resolution polar ocean and coastal zone altimetry and high-resolution sea-floor altimetry. It included:

- A detailed review, assessment and cross-comparison of existing products, datasets, methods, models and algorithms, as well as related range of validity limitations, drawbacks and challenges;
- A detailed analysis of the suitable models and data integration approaches as well as their related limitations, drawbacks and challenges;
- A survey of all accessible data sets associated (space, airborne and in situ) that could be of use in helping ESA to perform an adequate development and validation activity. Investigation of problems such as the lack of sufficient data and identification of practical solutions;
- A survey of current and upcoming initiatives and projects related to CryoSat innovative ocean applications;
- An analysis and identification of the best candidate test areas to be used in the upcoming development and validation of products, including a complete analysis and description of the available data over those test areas.

Following an analysis of the known problems in the CryoSat data products published by ESA the project team came to the conclusion that in their current form at the time of the start of the project (June 2013), LRM L2 and SAR L2 were not useful for oceanographic applications, and that SAR L1b is sub-optimal. At the same time the CP4O team recognized the exceptional performance of the SIRAL altimeter on CryoSat, and was confident that in due course the high-quality state-of-the-art products possible would be available from the ESA processing chain. The team therefore decided that in order to be able to complete the CP4O activities on the agreed timescale it had to make use of alternative data sets come CNES CryoSat Processing Prototype and the TUDelft RADS altimeter data base.

The clear advantages of the CryoSat SAR data over the conventional LRM data is that more independent looks (multi-look) lead to improved retrieval precision, though the theoretical two-fold improvement has not yet been shown in analyses. In terms of height precision this is closer to a factor 1.5 improvement. SAR has finer spatial resolution along-track (about 300 metres), reaches a higher SNR (about 10 dB more), also provides a better performance close to land, especially for tracks that approach the coastline at close to normal incidence (90°), and is also less sensitive to sea state.

2.2.1 Outstanding Issues / Key Recommendations

SAR mode altimetry remains a relatively immature technology, in terms of its operation from a satellite platform, and exploitation for ocean applications. Naeije and Cotton (2014) identified a number of priority areas that merit further investigation but which could not be incorporated in the CP4O activities, due to limitation on time and resources. These are briefly summarised below, the order is not representative of any priority.

SAR Waveform Blurring at High Altitude Rates

Evidence of waveform blurring in SAR (and SARin) mode echoes in response to high spacecraft altitude rates was seen in CryoSat data. Subsequent analysis indentified two potential causes of this blurring effect: the misalignment of burst echoes that make up the waveform, and a shift effect on echoes within a single burst when there is a high altitude rate. Some solutions to reduce this effect have been proposed for the new processing baseline ("Baseline C"), and planned for implementation in late 2014. Once a sufficient volume of data has been generated from the new processor, the effectiveness of this solution to waveform blurring at high altitude rates should be assessed.

Under-sampling of Specular SAR Waveforms

A number of analyses have identified that current schemes have a difficulty in retracking the more specular SAR waveforms and so in retrieving reliable geophysical parameters (e.g. Smith and Scharroo, 2015). These types of waveforms occur over smooth water, at low wave heights, in sea ice leads, and the problem arises particularly for SAR waveforms because of the peakier nature of these waveforms compared to LRM echoes. The difficulty comes about because there are insufficient samples in the waveform to recreate accurately the full echo shape, in particular the leading edge.

Proposed solutions include over-sampling when the backscattering surface is near specular. Further work should clearly establish the impact of under-sampling of specular waveforms and develop / test some processing strategies to address it.

SAR Processing: Selection / weighting correction of Doppler Waveforms

The widely adopted process for processing the Doppler Waveforms is to include all 64 waveforms from each burst, and to give the contribution of each waveform equal weight. There is an argument that waveforms from the outer Doppler bins provide less useful information than those from the central bins and so should be given less weight in any processing approach.

Further work should continue to investigate ways to optimise SAR Doppler waveform processing that could guide the design of SAR altimeter data processors and SAR altimeter radar design.

SAR Processing: Hamming (or other) window functions

Some processing schemes apply windowing functions (e.g. Hamming) in order to reduce the sensitivity of waveforms to undesirable artefacts. It is recommended that a study be carried out, which would include a rigorous and carefully considered approach to consider the purpose of windowing functions in waveform processing, to review and test alternatives and provide recommendations.

The Impact of Swell on SAR altimeter data

The higher along track resolution provided by SAR altimetry (to ~400m) moves this resolution into the wavelength scales of ocean swell, with the potential consequence that the retrieved echoes and processing schemes may be sensitive to swell. A study should investigate the potential impact of swell on SAR altimetry and consider how to modify processing schemes to take this into account.

Investigations with Full Bit Rate Echoes and Stack data

The auto-covariance of FBR echoes (or stacks) can be expected to depend on different sea-states. Similarly it may be possible to derive further characterisation of the ocean surface from the stack data.

An investigation into the potential use of FBR echoes could yield interesting results for instance contributing to the development of robust schemes for RDSAR processing, and understanding the statistics of averaged waveforms.

Oceanographic Applications of SARin data

SARin mode data can be processed to retrieve across track slope and so provides the potential to extract along track *and* across track information on ocean slopes. Some initial studies have looked into this possibility (e.g. Dibarboure et al., 2013). Further work is recommended to compare the SAR/SARin performance and statistics by simply processing SARin as non-interferometric SAR data.

RDSAR Processing: The impact of the CryoSat Transmission pattern

In all RDSAR methodologies, SAR FBR echoes are combined coherently and/or incoherently to produce an LRM "equivalent" waveform. A key test of the effectiveness of the different schemes is to establish how closely the noise and speckle statistics of the "pseudo" LRM waveform generated from SAR waveforms match those of the "true" LRM waveform.

In the CryoSat implementation of SAR mode, the SIRAL altimeter transmits bursts of 64 pulses. Each burst lasts 3.5 ms, and there is a gap of 11.7 ms between bursts of emitted pulses whilst the return echoes are received. Thus whilst the Low Resolution Mode provides a regular sampling at 0.5 ms intervals, the SAR mode samples intensively for 3.5 ms and then has a 11.7 ms gap between successive bursts. This effectively makes it impossible to reconstitute an LRM like product with equivalent waveform statistics from SAR mode data.

The SAMOSA project developed a process that aimed to minimise summing of correlated echoes by sub-selection of waveforms. This process suppresses additive noise and achieved 9 averaged waveforms per burst, and 32 for every group of 4 bursts. However, the CPP (CNES/CLS) and RADS (TUDelft/NOAA/EUMETSAT) approaches involve incoherently summing correlated waveforms, and both note that (again) the true number of uncorrelated measurements is a 32, compared to 90 acquired in the LRM scheme. This summing of correlated waveforms means that the resulting pseudo-LRM waveform does not preserve the additive noise and speckle (measurement uncertainty) statistics expected of a true LRM waveform. As noted above, this is a direct consequence of the SAR mode transmission scheme implemented for CryoSat. Sentinel-3 will operate a similar "closed-burst" SAR mode scheme and so again it will not be possible to reconstitute a LRM product with (LRM) equivalent waveform statistics from the Sentinel-3 SAR mode. It is for this reason that Gommenginger et al (2013) recommended that JASON-CS implement an "interleaved" SAR mode.

Thus, further work is recommended in preparation for Sentinel-3 to develop an improved scheme for producing the best possible RDSAR product from S-3 SAR mode data, to provide consistency with LRM data sets in terms of bias and waveform statistics.

3 PRODUCT DEVELOPMENT, VALIDATION AND ASSESSMENT

3.1 Introduction

The central activity within CP4O was to develop and assess new products, derived from SAR altimeter data, for application in the four scientific themes. These products were of three types:

- **"RDSAR" products** - SAR mode data processed to be consistent with, and as equivalent as possible, to LRM data products.
- **SAR products** – products developed from SAR mode data which make full use of the higher spatial resolution and anticipated higher precision in range and wave height,
- **Improved Geophysical Corrections** - Products providing improved Geophysical Corrections (Wet Troposphere, Ionosphere and Regional Tides) for use with CryoSat data. In the first two cases these are needed for CryoSat data, as CryoSat does not have an on board Microwave radiometer, and only operates at a single frequency, and so dedicated synchronous measurements of the Wet Troposphere and Ionosphere Range Correction are not available. Regional tide corrections are important to provide accurate tidal corrections in shelf and coastal regions where SAR data are expected to be of particular interest, and where global tidal models are known to be less accurate.

In addition a small set of **SARin** data was processed to investigate issues for SAR data in complex coastal topography.

The products that were developed and assessed are summarised in Table 1 below. Data sets highlighted in bold are available for download on the CP4O ftp directory, according to instructions available on the Project Web Data page.

Figure 1 shows the CryoSat mode mask to show the areas where CryoSat operated in SAR (green) and SARin mode (purple) at the time the data analysed by CP4O were collected.

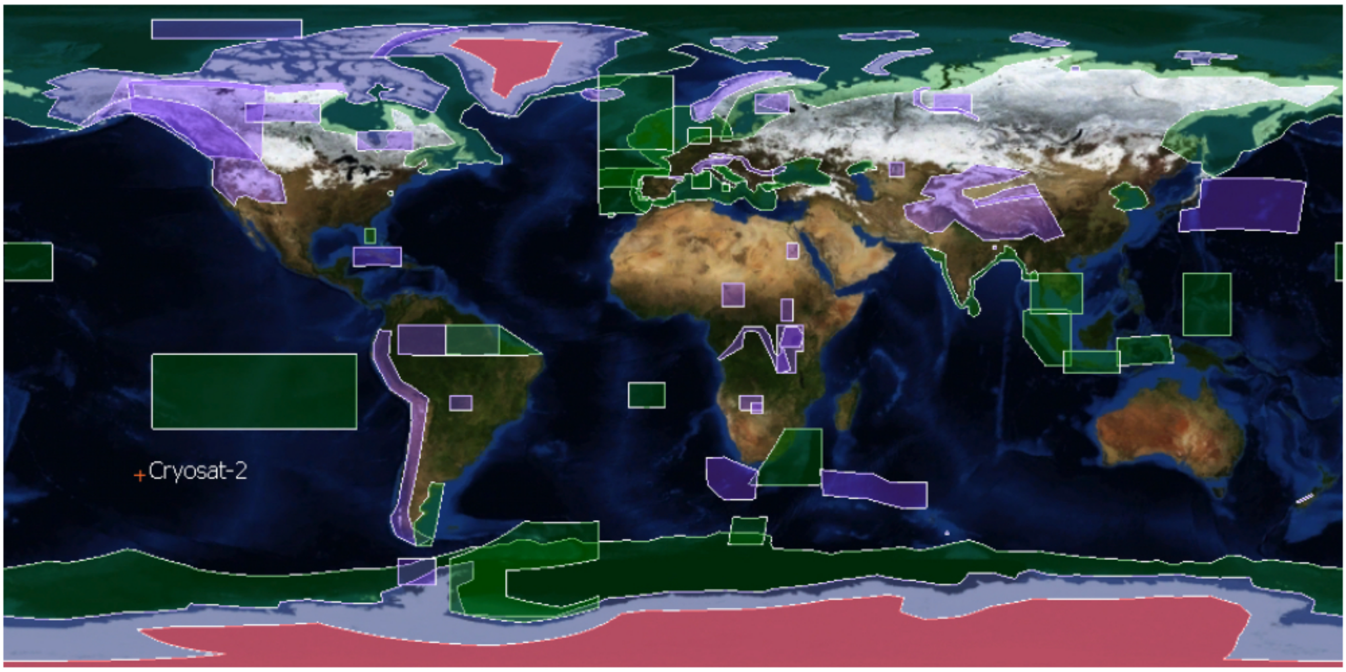

Figure 1: CryoSat Mode Mask v3.4. Operational from 01/10/2012 to 07/07/2014. Green is SAR mode, purple is SARin model, other areas are in LRM mode.

<table>
<tr><th>Theme</th><th>Product</th><th>Partner</th><th>Area</th><th>Time Period</th></tr>
<tr><td rowspan="5">Open Ocean</td><td>RDSAR</td><td>TU Delft</td><td>Pacific and N Atlantic SAR boxes</td><td>July 2012, Jan 2013</td></tr>
<tr><td>RDSAR</td><td>CNES/CLS</td><td>All SAR areas</td><td>Whole Mission</td></tr>
<tr><td>SAR</td><td>Starlab</td><td>Pacific and N Atlantic SAR boxes</td><td>July 2012, Jan 2013</td></tr>
<tr><td>SAR</td><td>ESA</td><td>Pacific SAR boxes</td><td>July 2012, Jan 2013</td></tr>
<tr><td>SAR</td><td>CNES/CLS</td><td>All SAR areas</td><td>Whole Mission</td></tr>
<tr><td>Open and Coastal Ocean</td><td>SAR</td><td>ESA / NOC</td><td>N Atlantic SAR boxes</td><td>July 2012, Jan 2013</td></tr>
<tr><td>Polar Ocean</td><td>SAR</td><td>ESA / DTU</td><td>Lats > 60N</td><td>Mid July 2010 onwards</td></tr>
<tr><td>Sea Floor Mapping</td><td>SAR</td><td>ESA / DTU</td><td>Pacific SAR boxes</td><td>1 x 369 day cycle, starting 01/10/2012</td></tr>
<tr><td>Coastal Applications</td><td>SARIN</td><td>isardSAT</td><td>Cuba and Chile</td><td>Selected orbits</td></tr>
<tr><td rowspan="3">Corrections</td><td>Wet Tropo</td><td>U Porto</td><td>Global</td><td>July 2012, Jan 2013</td></tr>
<tr><td>Ionosphere</td><td>Noveltis</td><td>Med / European Shelf</td><td>Jan 2011- Jan 2013</td></tr>
<tr><td>Regional Tides</td><td>Noveltis</td><td>NE Atlantic (Coastal)</td><td>Jan 2011- Jan 2013</td></tr>
</table>

Table 1: Products developed and assessed within CP4O. Data sets highlighted in bold are available for download on the CP4O ftp directory

Technical notes, “Algorithm Theoretical Basis Documents” (ATBDs), describe the processing schemes used to generate these products, and further reports, “Product Validation Reports” (PVRs) describe the validation activities and results carried out to validate these products. These documents are available on the Deliverables page of the project web site (www.satoc.eu/projects/CP4O)

A separate and independent assessment of the RDSAR and SAR products for the open ocean was carried out by CLS. In the sub-sections below we provide an overview description of the products and summarise the validation and assessment outcomes.

3.2 Open Ocean - RDSAR

Product Description

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. In fact a number of studies have shown (discussed in the PAR – Naeije and Cotton, 2014) that, because of the transmission and reception sequencing on CryoSat, (see **Figure 2**) there are regular gaps in the sampling of the sea surface, with the consequence that the range and wave height show higher 1 Hz standard deviations than the conventional Low Rate Product.

Two versions of the Open Ocean RDSAR product were developed, by TUDelft and CNES. Data for two separate monthly periods, July 2012 and January 2013, covering the CryoSat “SAR boxes” in the

N Atlantic and Pacific, were evaluated. The RDSAR processing schemes, to transform Level 1A "Full Bit Rate" (FBR) data into L1B 20-Hz waveforms, and the L1B to L2 processing to generate the final geophysical data product are described in Scharroo (2014) and Boy and Moreau (2013a). The two products were generated from the same source L1A FBR data.

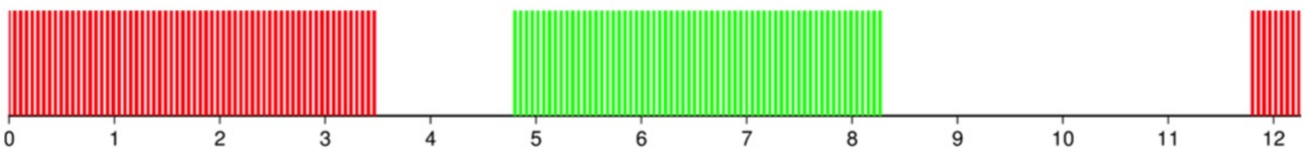

Figure 2: Illustration of one burst of pulses (red) and reception of their echoes (green). The total burst duration is 11.8 ms.

The major differences between the RADS and CPP RDSAR schemes are listed below:

- The RADS waveforms are oversampled by a factor of two (by zero-padding the complex echoes) producing power echoes of 256 bins. The CPP waveforms contain 128 samples.
- A 1-gate right shift correction has been applied to the RDSAR waveforms in RADS before the introduction of the Jensen's oversampling (e.g. Smith and Scharroo, 2015), which was not included in the original CPP RADS data (v13), considered in the assessment. (This correction has since been applied to v14 of the CPP product).
- The CAL2 (LPF) is already applied to the RADS and CPP waveforms. In RADS the LPF shape for the intermediate waveform samples is determined by linear interpolation between the 128 LPF values. The LPF shape is correctly aligned and does not need to be shifted to the right.
- In RADS, the pulse-to-pulse amplitude and phase corrections (from the IPF database) are applied to the echoes. This does affect the eventual shape of the PLRM waveforms. This is not done in CPP.
- Each echo is shifted in frequency to account for the radial velocity to align the echoes around the tracking point after FFT. The Doppler shift (in frequency) effect is taken into account within the RADS waveforms, but not considered in the CPP processing. However, this is not expected to have any consequence on the resulting waveform: after a 2-D FFT it only constitutes a vertical shift that disappears in the averaging (next step).
- The AGC is applied on CPP waveforms whereas it is not applied on RADS side. In RADS it is accounted for in the waveform scale factor.
- Both processing approaches have identified the presence of a time calibration bias resulting in altimeter altitude rate dependent measurement errors. For RADS, different timing biases are applied for different data. These timing biases are included in the time field on the RADS data and are accounted in the orbital altitude. For CPP (v13), a constant timing bias of +176 microseconds is determined and accounted in the precise orbit.
- The tracker range from RADS is counted from gate 34 in the range 0 to 127 window delay, whereas it starts from gate 0 in the CPP products. Thus a (negative) correction (of 15.92m) has to be applied to RADS tracker range values to subtract before range computation.

The Level 1B waveform data were then "retracked" to produce L2 geophysical data sets. RADS routinely applies an MLE3 re-tracker (using external information on mispointing) whereas CPP applies an MLE4 retracker (which generates an internal estimate of mispointing). These would provide different outputs from the same L1A data set, so for the sake of intercomparison, a second RADS L2 RDSAR data set was produced using the CPP MLE4 retracker.

Validation of RADS RDSAR / PRLM data

The TUDelft / NOOA/EUMETSAT internal validation of the RADS RDSAR product (Naeije and Scharroo, 2014) demonstrated that this product showed there was good continuity between RDSAR (or Pseudo LRM – PLRM) and LRM data (see Figure 3).

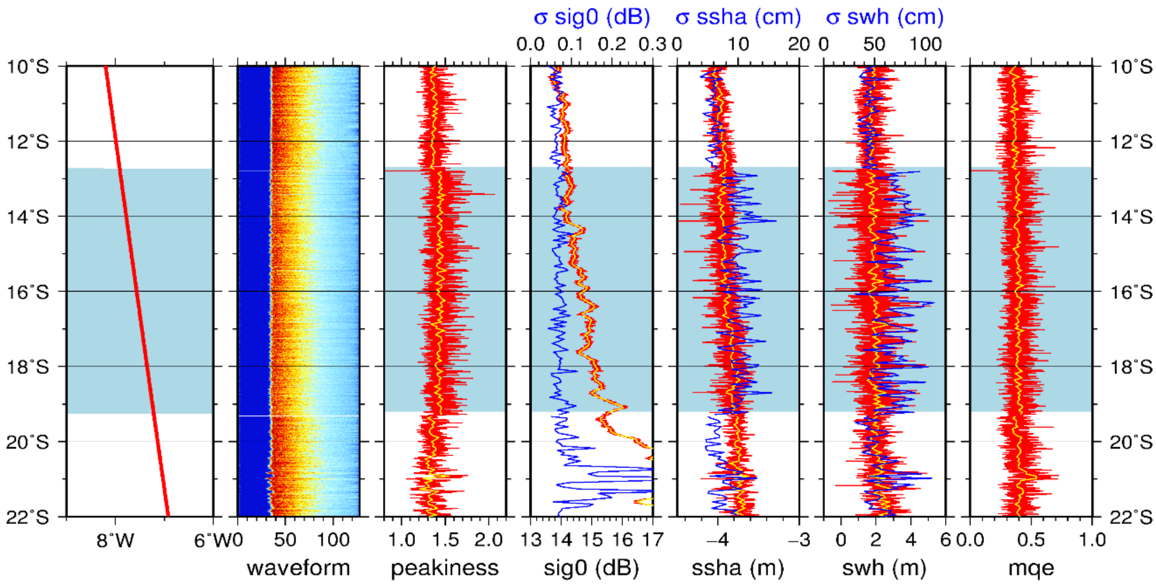

Figure 3: LRM (white area) and RDSAR (light blue area) data for a CryoSat track close to St Helena in the S. Atlantic. Panels are from left to right: track lat / long, waveform amplitude by gate, peakiness, naidr backscatter (σ^0), Sea Surface Height (SSH) Anomaly, Significant Wave Height (SWH), and waveform mean quadratic error (mqe).

For the global LRM plus PLRM dataset, RADS apply additional waveform averaging of ¼ (N-1) + 1//2 (N) + ¼ (N+1) to bring PLRM statistics (1 Hz standard deviations) into better agreement with LRM (see Figure 4).

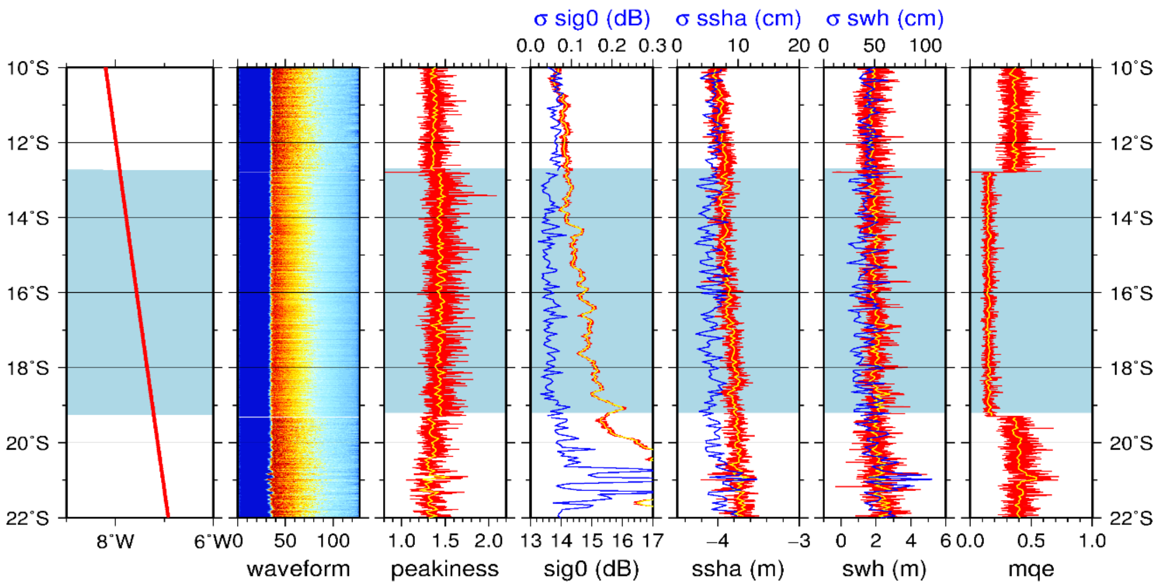

Figure 4: As for Figure 3, but with noise reduction in the P sector but ¼ + ½ + 1.4 waveform averaging. Panels as for Figure 3.

Figures mapping Sea Level Anomaly (SLA) (see Figure 5) show no discontinuity between PLRM data processed from SAR mode (processed to PLRM) and LRM data. Similarly analysis of maps for significant wave height and sigma-0 showed no apparent discontinuities. When a Cryosat reference frame offset was applied to the CryoSat SLA data (of -70.4 cm) the CryoSat data can be seen to fit well with the multi-year evolution of mean sea level as calculated from other satellite altimeter missions (Figure 6)

Analysis of cross-overs showed sea level variance slightly higher than is found for Jason-1 and Jason-2, but this is to be expected as the latter have the benefit of direct measurements of wet troposphere and ionosphere range corrections.

It was concluded that the RADS PLRM data is on a par with the quality of the LRM data, and that the RADS PLRM products are a good LRM-reference during CryoSat SAR mode operations, maintaining continuity with LRM mode data.

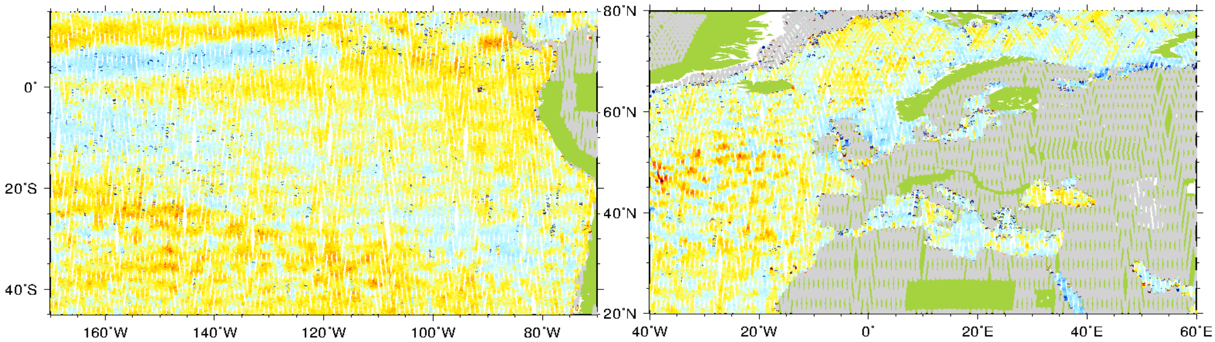

Figure 5: Maps of combined PLRM and LRM Sea Level Anomaly from RADS, zooming in over regions with LRM and SAR mode measurements (refer to Figure 1).

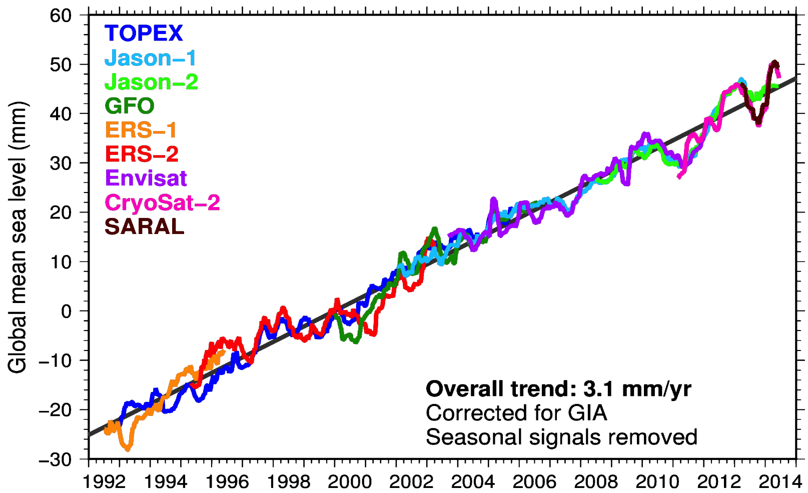

Figure 6: Evolution of global mean sea level including all historic altimeter data available in RADS. The CryoSat results can be seen to fit seamlessly with earlier and concurrent data.

Validation of CPP RDSAR / PRLM data

Moreau et al., (2013a) describes the approach taken to validate the CPP RDSAR data which includes analysis of RDSAR / LRM Sea Level Anomaly (SLA), Significant Wave Height (SWH) and Sigma-0 across the SAR / LRM transition, and comparisons of these same parameters to measurements from Jason-2 over the same area.

(Figure 7) demonstrates good continuity in averaged along track LRM and RDSAR CPP data as CryoSat switches from LRM to SAR mode, from a pass in the South Pacific. The jump in mispointing angle may be a consequence of the higher noise levels in the RDSAR data. A small discontinuity in σ^0 can also be seen. Some minor discrepancies between ascending and descending tracks were found over the Pacific Ocean

Along track precision (calculated as 1 Hz standard deviation) for SLA was found to be 6.6 cm from LRM, and 10.4 cm for RDSAR, at a SWH of 2m, confirming the expected higher noise on the RDSAR data (Figure 8).

The analysis concluded, as for the RADS RDSAR data, that the CPP reduced SAR L2 products are a good LRM-reference during SAR-mode maintaining the continuity with the LRM mode data and allowing the assessment of the in-orbit performances of the SAR mode data.

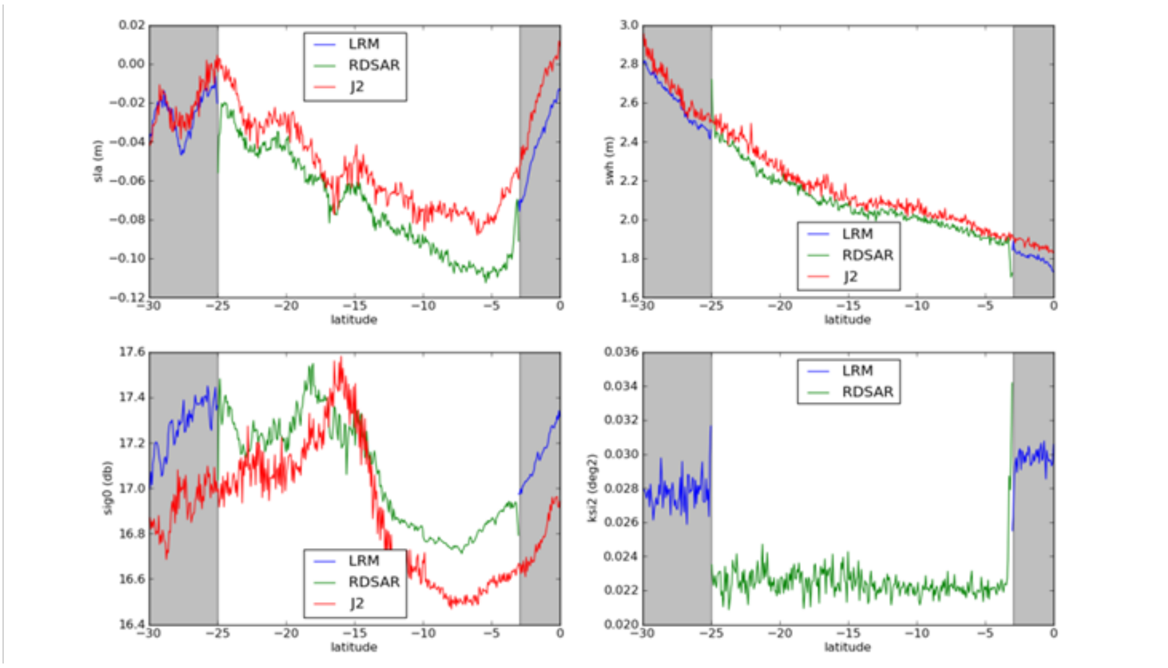

Figure 7: Mean of SLA (upper left), SWH (upper right), Sigma0 (lower left) and mispointing angle (lower right) by band of latitude for CryoSat LRM and RDSAR, and Jason-2 LRM– Cycle 30 – pass 82. The shaded area corresponds to the LRM zone.

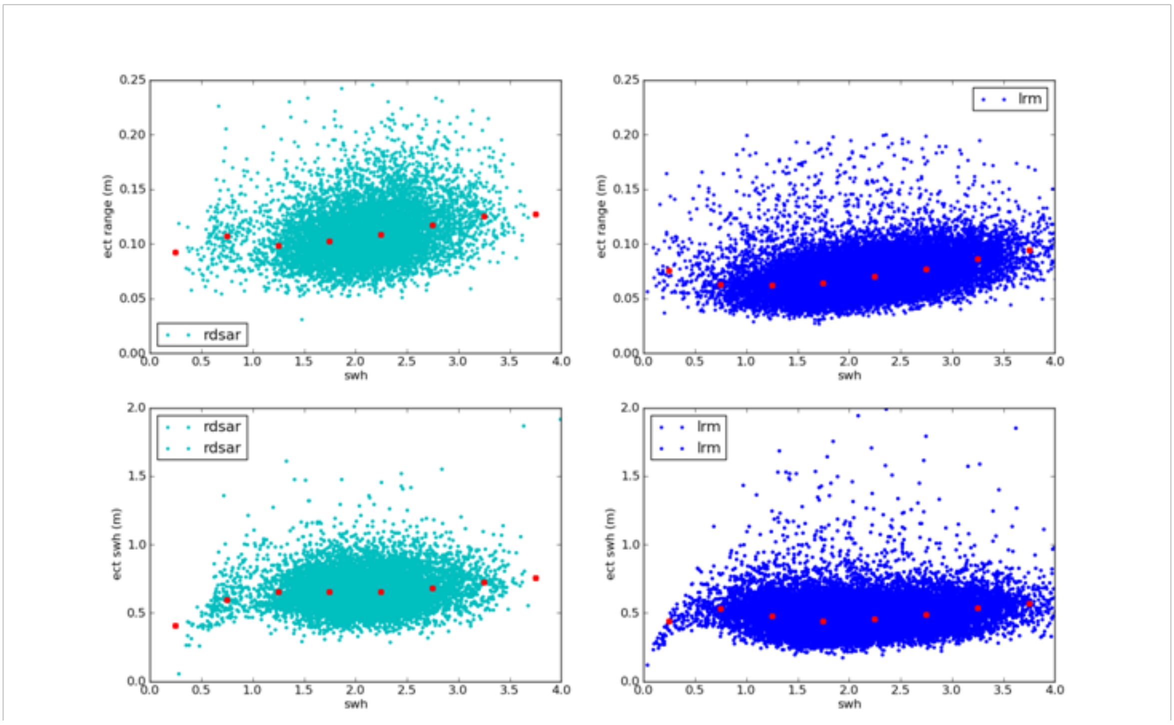

Figure 8: Precision of SLA (top) and SWH (bottom) in LRM mode (right) and SAR mode (left) from several passes of Cycle 30.

Assessment of CPP and RADS RDSAR / PRLM data

CLS carried out a comparison of CPP and RADS RDSAR data (Labroue et al., 2014a). To ensure a valid comparison, the same retracker (MLE4) was applied to the RADS and CPP L1B data, and the values were directly compared without applying any of the usual geophysical model corrections. Identical data editing criteria were applied. The assessment included:

- Waveform misfit analysis
- For range, SWH, σ^0 and mis-pointing angle
    - Comparison of estimates (spectral analysis, along track difference and histogram analysis)

- Inter-dependency of SLA on wave height and radial velocity
- Large scale mapping of SLA differences
- Performance in coastal zones
- Continuity across LRM to SAR mode transitions

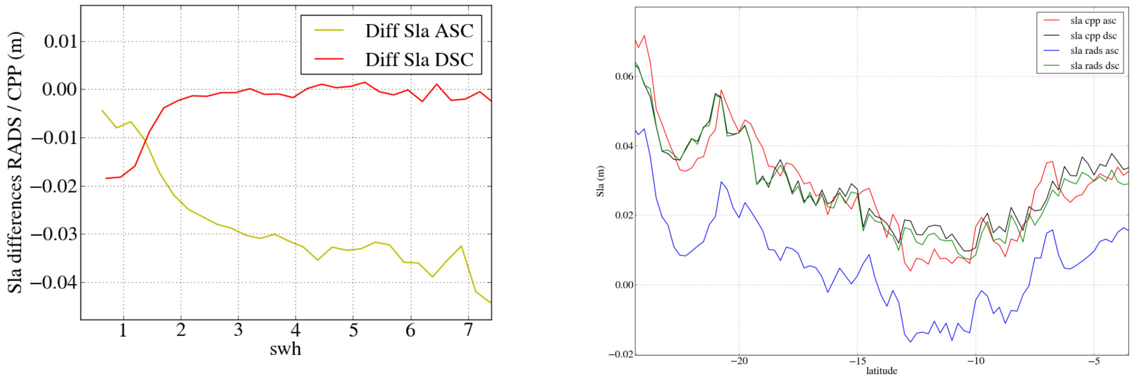

Figure 9: SLA of TUDelft and CPP V14 CPP datasets as function of filtered SWH (left panel), and their differences as a function of band of latitudes over two months (right panel).

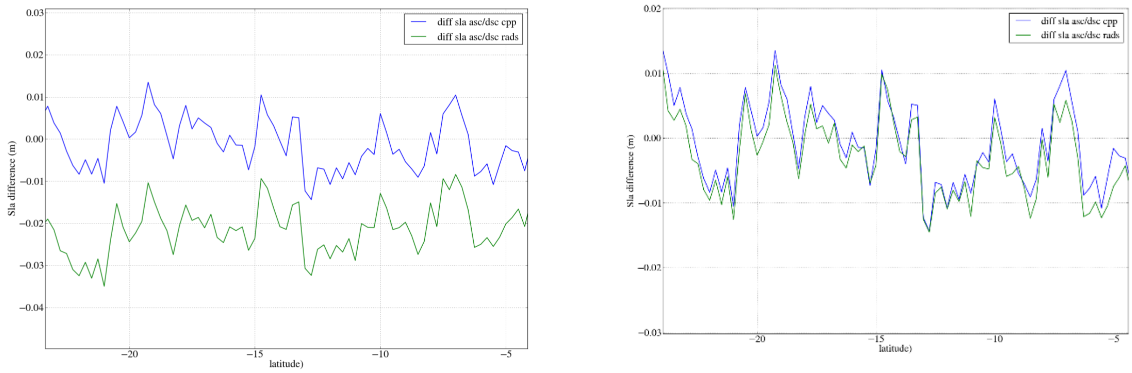

Figure 10: (left) Mean differences of SLA between ascending and descending passes as function of band of latitudes for the TUDelft solution (in green) and the V14 CPP dataset (in blue) over two months (July 2012 and January 2013). (right) Mean differences of SLA after timing bias correction of -541us applied on TUDelft data sets

Comparison between the RADS and CPP RDSAR products identified good general agreement, but small-scale residuals in all parameters that were the consequence of differences in the characteristics of the Significant Wave Height (SWH) in the two products. The later version (v14) of the CPP processor with the corrected one-gate shifted waveform error showed very similar performances between RADS and CPP in terms of SWH and no residual dependencies on SWH in the other measured parameters (Figure 9).

However a time tag difference of -540 µs between the CPP and RADS RDSAR data sets was found (the correction has to be subtracted from the RADS data). An incorrect adjustment of 400 µs previously applied to the RADS RDSAR data was identified and has since been removed, so now there is a residual difference of -140 µs in the time tags between the RADS and CPP RDSAR products (see Figure 10).

To allow a more comprehensive and authoritative assessment it is recommended to repeat this analysis with a larger (consistent) data set that spans a longer period (several years) and, if possible, larger area.

Conclusions for CPP and RADS RDSAR / PRLM data

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 along side concurrent data from other satellite missions.

There is one important respect to note in that the standard deviation (sometimes called “noise”) on retrieved oceanographic parameters (range, significant wave height, nadir surface backscatter) is higher than for standard LRM data, a consequence of the radar transmission and reception sequencing which results in sampling gaps along track. 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.

The RADS processing scheme includes a factor of two “over-sampling” of the L1A waveforms, which is applied with the aim of improving fitting (and hence retrieval of geophysical parameters) or the peakier waveforms returned at low wave heights. The analysis in CP4O has not been able to quantify any consequent improvement, but the supporting database is possibly too small for such an assessment. Readers are referred to Smith and Scharroo (2015).

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 statistics for comparison, 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.

3.3 Open Ocean - SAR

Products Description

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.

Three SAR mode data processors were used to generate SAR altimeter products that were evaluated within CP4O. These were the Starlab implementation of the SAMOSA3 re-tracker as specified in the Sentinel-3 DPM (Egido, 2014a), an ESRIN implementation of the SAMOSA re-tracker with some variations with respect to the S-3 DPM specification (Cotton et al., 2014), and the CNES CPP SAR numerical retracker (Boy and Moreau, 2013b).

To support valid comparisons between the different approaches, it was essential that a consistent specification was applied to each of them. This specification is provided in Dinardo 2013, and a SAMOSA configuration control web page is maintained at:

http://www.satoc.eu/projects/samosa/samosa_config.html

A fuller description of three SAR processing schemes and their validations is given below:

SAMOSA3 SAR Model Development, Implementation and Validation by Starlab

SAMOSA is the name given to the implementation of a fully analytical model of the ocean SAR altimeter echo, developed within the ESA funded SAMOSA project (see Cotton and Martin-Puig, 2012, and Ray et al., 2014). SAMOSA2 is the most comprehensive version of the model and retracker, but is computationally intensive, and so for operational implementation in the Sentinel-3 Level-2 processing a simplified version, SAMOSA3, was developed. For CP4O, Starlab updated the Sentinel-3 baseline to provide improved handling of the energy distribution over the different echoes of the delay-Doppler stack, an application of a Look-Up Table (LUT) for the selection of a variable width Point Target Response (PTR) as a function of SWH, the complete implementation of the SAMOSA-2 model, and an improved estimation of the thermal noise from the SAR waveform. This updated model was integrated within a full waveform retracker, which performs the joint estimation of SSH, SWH, and σ^0, by means of an iterative Levenberg-Marquardt minimization algorithm. See Egido (2014a) for details.

This model was adjusted to process the Level-1 product from the Cryosat Product Prototype (CPP) provided by CNES, and to generate the NE Atlantic / Pacific two month validation data set as described in Table 1. Validation by along track comparison with the matching CPP SAR data set showed entirely consistent estimates of range, for Significant Wave Heights above 2m, and for Waveform Power (from which σ^0 is derived) with no bias between the two products (See Egido, 2014b for details). However differences were found in the estimates of SWH (for SWH < 2m) from the two products (Figure 11). This was ascribed to a difficulty the SAMOSA model has in accurately catching the "toe" of the leading edge of the SAR echo waveform.

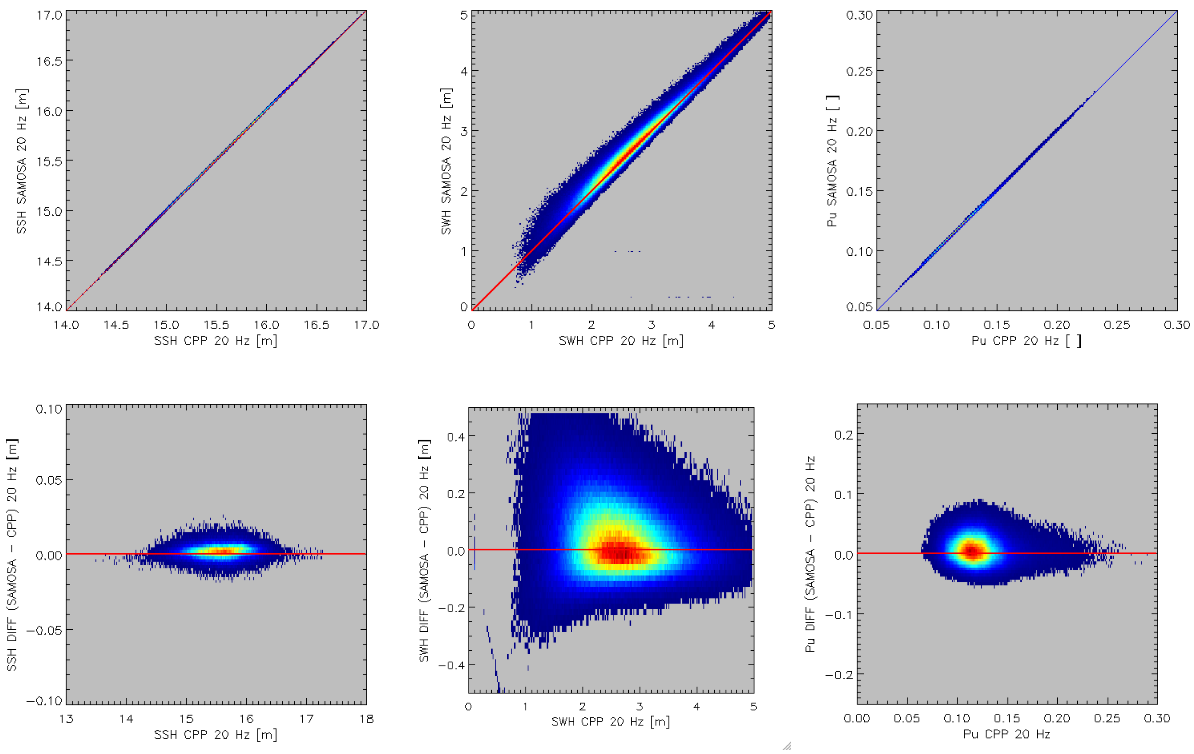

Figure 11: Scatter plot of SAMOSA and CPP SAR altimeter product for July 2012 in Pacific SAR box. Top row: SAMOSA v CPP SSH (left), SWH (centre) and Waveform Power (right). Bottom row, SAMOSA against CPP: SSH (left), SWH (centre) and Waveform Power (right)

SAMOSA SAR Model Development, Implementation and Validation by ESRIN / NOC

ESRIN implemented a number of versions of the SAMOSA retracker for validation in CP4O, as described in Table 2. The motivation for implementing the different versions was to enable direct comparison between the most complete implementation of the full analytical SAMOSA model (R1); a simplification of that model (R3), the currently implemented Sentinel-3 baseline (R6), the effect of two different improvements to that model (R2 – improved thermal noise estimation, and R4, inclusion of a look up table for alpha-p), and finally R5, which is the same as R1, but using ESA FBR SAR data as the L0 source, rather than CPP. The same set up configuration, as defined in Dinardo, 2014, was used for all processing schemes, so only the differences are in the processing algorithms, and not in the input parameters.

Run Reference	C2 L1B Product	L2 SAR retracker model	Alpha-p LUT	Peel Effect applied	Motivation
ESRIN R1	CPP	ESRIN SAM2	Yes	Yes	Full SAMOSA analytical model (Gaussian waves statistics
NOC R2	CPP	NOC SAM3	No	No	Consistent with Sentinel 3 DPM except for treatment of Thermal Noise. Only small data set available for benchmarking
ESRIN R3	CPP	ESRIN SAM3	Yes	Yes	To quantify impact on retrieval of omitting f1 term in SAMOSA3
ESRIN R4	CPP	ESRIN SAM3	Yes	No	Consistent with Sentinel 3 DPM but with inclusion of alpha_p LUT
ESRIN R5	ESRIN FBR	ESRIN SAM2	Yes	Yes	Possible impact of L0 – > L1B processing
ESRIN R6	CPP	ESRIN SAM3	No	No	Consistent with Sentinel 3 DPM baseline

Table 2: Summary of versions of SAMOSA SAR L2 Data sets produced by ESRIN

NOC carried out the validation and comparison between the different models (Gommenginger et al, 2014), and they also compared the ESRIN SAR output against the equivalent CNES CPP data set. We summarise their findings and conclusions below.

The comparison between R1 and CPP is essentially a comparison between the implementation of an analytical waveform model (R1) and a numerical model (CPP). In Figure 12 along track outputs from ESRIN R1 and CPP are compared for a track in the NE Atlantic. In this example, which is typical of many other tracks analysed, the agreement between the two data sets is extremely good, with average differences less than 0.5 cm for SSH and around 5 cm for SWH. The difference in Pu (waveform power) is also very stable across the data segment. However, the plots reveal noticeable spikes in all parameters showing some specific differences in a number of locations. In an analysis of waveform misfit, plotted against significant wave height (Figure 13), the two processing schemes showed very similar behaviour, both showing an increasing trend in misfit with wave height.

Further analysis compared the significant wave height estimates from each product against co-located buoy data, and analysed the precision offered by the different processing schemes through estimates of 20Hz and 1Hz “noise” (standard deviation) calculated along a 50km segment of track in the NE Atlantic. These results were compared against equivalent measurements from Jason-2, and the results are presented in Table 3.

From Table 3 we can see that:

- All the SAR processing schemes outperform Jason-2 in terms of 1 Hz noise on SSH (~1.2 cm compared to ~1.5 cm), and SWH (8-5-9.0 cm compared to 11 cm).
- There is in general excellent agreement between the SAMOSA SAR retrackers and the CPP numerical retracker, with R1, R3 and R5 performing the best (these are the more complete implementations of the SAMOSA model).
- CPP, R1, R3, and R5 estimates of SWH show little bias and ~20cm standard deviation when compared against open ocean buoy estimates.
- The implementations of the SAMOSA in R6 and R4, the implementation of the current DPM for Sentinel-3, plus a modification, show the largest difference from the CPP results, particularly for SWH estimates. *This highlights the need for L2 SAR retracking to take account of all aspects of the processing applied to the L1B waveforms, and indicates a need to modify the Sentinel-3 DPM.*

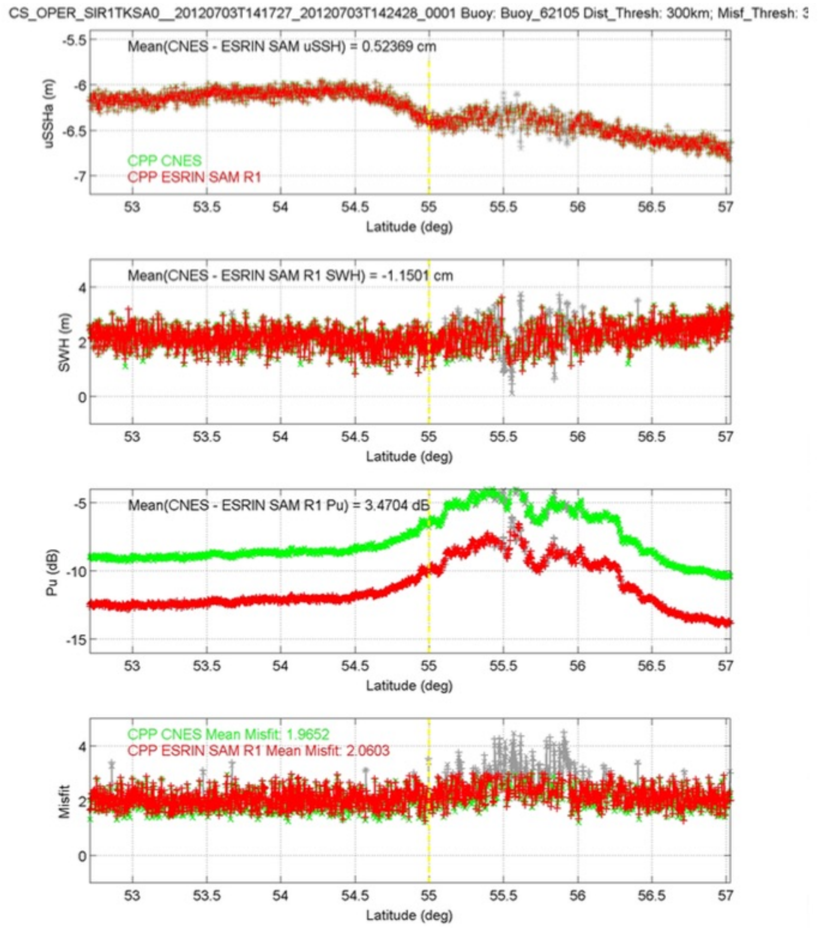

Figure 12: Extracted parameters from ESRIN R1 (red) and CPP (green) processing of SAR data from a track in the NE Atlantic on 3rd July 2012.

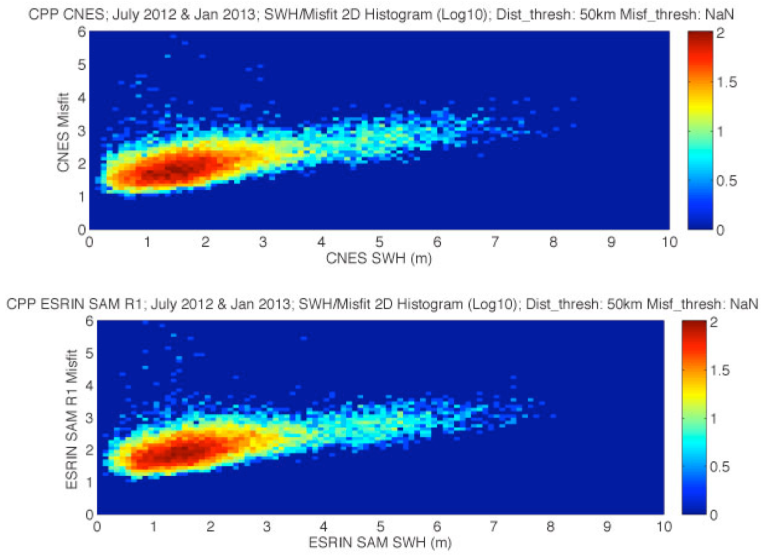

Figure 13: Waveform misfit calculated for CNES CPP SAR (top) and ESRIN RA (bottom) processing of SAR data for the NE Atlantic for July 2102 and January 2013.

In a further analysis not presented here SAR 1Hz noise on SSH and SWH was seen to increase as a function of wave period (i.e. more noise for longer period waves). Also it was noted that care had to be taken in data selection to ensure exact matching of outlier removal and collocations, which resulted in only a small data set being available for analysis. It is recommended that (a) the use of waveform misfit for data editing be further explored and (b) a larger data set is analysed to confirm and refine these findings.

Run Reference	**1 Hz noise @ 2m**		**SAR SWH v buoy SWH**		**CNES –ESRIN difference**		
	SSH (cm)	SWH (cm)	Bias (cm)	Std (cm)	SSH (cm)	SWH (cm)	Pu
CNES	1.254	8.74	6.3	22.8	-	-	-
ESRIN R1	1.223	8.62	5.1	22.5	0.0	1.2	3.42
ESRIN R3	1.246	8.58	5.0	22.5	1.7	1.2	-14.1
ESRIN R4	1.246	8.52	-15.8	22.2	-0.3	22.4	-13.9
ESRIN R6	1.250	9.25	-10.9	25.4	-0.3	17.4	-13.9
ESRIN R5	1.218	8.42	5.2	22.7	N/A	N/A	N/A
Jason-2	1.566	11.09	7.9	32.1	N/A	N/A	N/A

Table 3: Results from the NOC analysis of SAR products from different implementations of the SAMOSA model.

Validation of CPP SAR data

Moreau et al., (2013b) describes the approach taken to validate the CPP SAR data product, based on two data sets: along track measurements from a pass across the SAR region in the Pacific (sub-cycle 30, pass 82, 7th May 2012); data from a 30 day sub-cycle (May 2012) again within the S Pacific SAR zone. SAR products are compared to their RDSAR equivalents, and some statistical analyses were carried out.

Assessment of along-track SAR and RDSAR data, and of scatter plots between the two, showed consistency between the two data sets, with the SAR data showing lower noise levels as expected. Histograms of distribution functions (e.g. Figure 14) showed a bias of ~10cm in SWH and 3 cm in range. In fact this bias was found to be SWH dependent, and it is assumed to be largely due to the need for an accurate Sea State Bias (SSB) correction for SAR retracking. No residual error dependency was found for either roll angle or radial velocity. Spectral analysis (Figure 14) showed lower noise and improved signal content at scales below 100km for SLA and SWH.

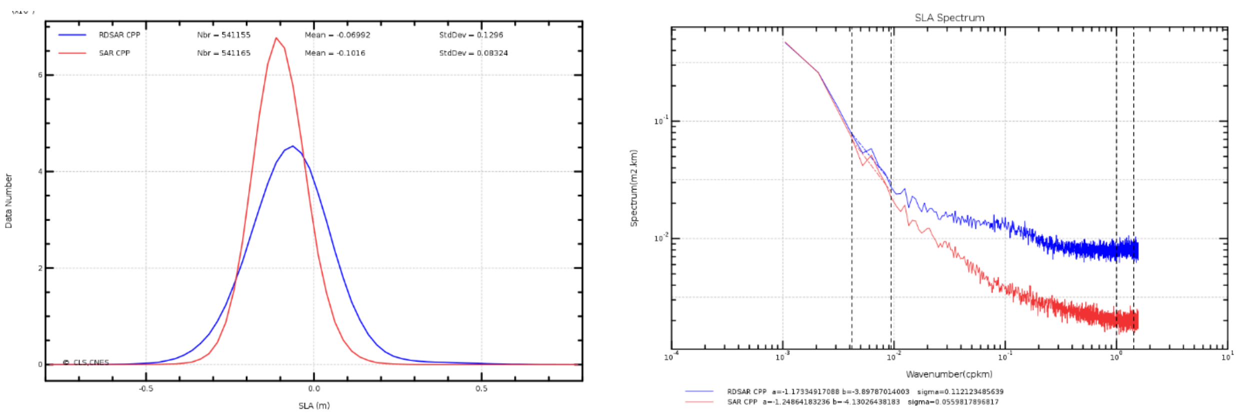

Figure 14: (Left) Histogram of SLA for CPP RDSAR (blue) and SAR (red), for sub-cycle 30, ascending tracks. (Right) SLA spectrum for CPP RDSAR and SAR), for sub-cycle 30, ascending tracks.

Some fine scale analysis of σ^0 data indicates that SAR σ^0 can detect small scale structures in sea surface roughness not seen in RDSAR data.

It was concluded that

- CPP SAR data show improved signal content for SLA, SWH and σ^0 at scales below 100km,
- The CPP SAR SLA data show no residual errors correlated to mispointing or radial velocity.

- A long wavelength error in SLA is correlated to SWH, which may be due to an inadequate SSB model, or to errors in SAR retracking.
- There is a residual error in SWH, correlated to SWH, of ~4% SWH.
- There is a small residual error in σ^0 of 0.2 dB, perhaps correlated to mispointing.
- There are small absolute biases of ~3cm for range, ~5cm for SWH, and 0.4 dB for σ^0.

A later version of the CPP has significantly reduced the dependencies of the SAR-PLRM differences (in SLA and SWH) to SWH. These results have been found very recently but have not been communicated in the frame of CP4O meetings or reports (except in the RADS/CPP study reporting the improvement of the new CPP version on PLRM CPP data).

However we still observe inconsistencies between SAR and PLRM estimates at low wave height in both SLA and SWH that are not explained yet and for which further investigations are required.

Independent Assessment of SAR Open Ocean Products

CLS carried out an independent assessment of three SAR open ocean validation data sets for the Pacific and NE Atlantic SAR regions, for July 2012 and January 2013 (Raynal and Moreau, 2014a and 2014d) using similar metrics and approach as for their evaluation of RDSAR products (Section 3.2). They considered SAR products produced by the ESRIN implementation of the SAMOSA re-tracker (R1 in Table 2), the ESRIN implementation of the Sentinel-3 DPM, configured for application to CryoSat (R6 in Table 2), and the CPP implementation of a numerical retracker. Where required, the same atmospheric and instrumental corrections were applied to ensure consistency.

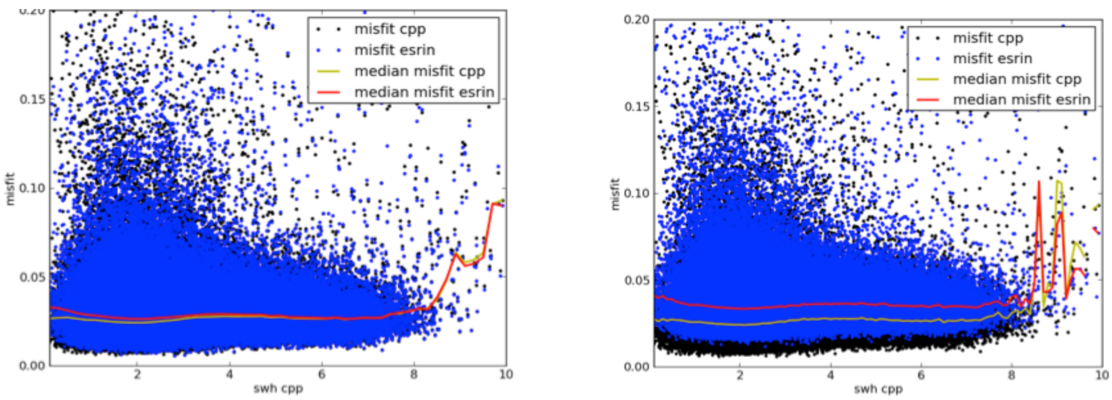

Figure 15: Waveform Misfit for ESRIN R1 (left) and R6 (right) implementation of the SAMOSA SAR retracker, against the CPP numerical retracker.

Analysis of the waveform misfit parameter Figure 15, showed better agreement between the R1 solution (full analytical solution) and CPP than between the R6 (Sentinel-3 DPM) solution and CPP, indicating there is scope for improving the waveform modelling in R6. The CPP shows lower misfit than both SAMOSA solutions at low wave heights (< 2m). Very little difference could be found between the three products in spectral analyses (of SLA, SWH and σ^0), though the R6 SWH PSD was slightly higher in amplitude. Analyses of SLA and σ^0 profiles and distributions showed very little difference between the three products. However, whilst the R1 and CPP distributions of SWH agreed well, a bias of ~ 20cm was found between R6 and CPP (and R1), this agrees with the findings from the NOC analysis presented in Table 3.

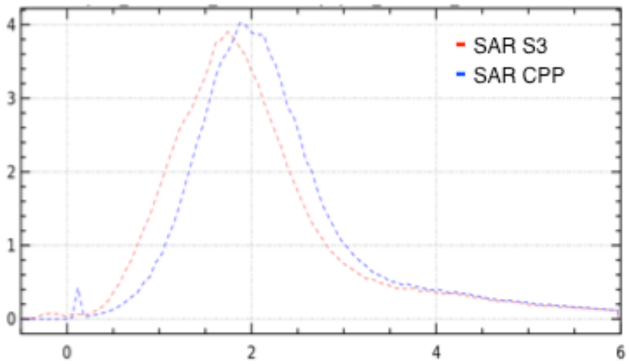

Figure 16: Histogram of Significant Wave Height from SAMOSA R6 solution and CPP.

It was concluded that all three solutions showed good agreement and equivalent performance in terms of range and σ^0, with differences of ~mm in range and 0.1 dB in σ^0 (the latter correlated to roll angle). However, whilst SAMOSA R1 and CPP solutions also agree well for SWH to within a few cm, SAMOSA R6 does show a significant SWH dependent bias and also an increased noise in SWH at low wave heights. It is recommended that this analysis is extended with data covering a much larger time period to allow firmer conclusions to be made.

Conclusions for SAR Open Ocean Data

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. (Table 3)
- Improved precision in SWH with respect to LRM data. In terms of 1Hz noise, improvement from 11.09 cm to ~ 8.5 cm. (Table 3)
- Improved along track resolution, shown in SLA and SWH spectra, so that scales of less than 100km can be resolved (Figure 14)
- 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 (e.g. “zero-padding” / “Jensen Sampling”). CNES and TU Delft /NOAA have applied versions of this technique and found different results.

- CLS proposes to add: After applying LUT to RADS PLRM data, correcting timing biases to RADS PLRM data and applying 1-gate right shift correction to the CPP waveforms, the study (comparison RADS/CPP PLRM) has on the contrary shown very similar estimates and performances between both approaches. It was difficult to identify any differences due to the "zero-padding" method (even at very low wave height). Differences of 2cm only have been found in SWH RADS/CPP comparison (that may be related to other aspects of the processing). And very consistent SLA are observed.
- Various processing options to optimise the generation of the Doppler Echo (e.g. selection / weighting of waveforms) should be investigated and evaluated.
- The long wavelength error in CPP SLA and SWH correlated to SWH should be further investigated.
- The Sea State Bias model for SAR altimetry needs to be further developed and assessed. Differences in behaviours between LRM and SAR (with regard to SSB) should be investigated
- CNES plans further improvements to the CPP SAR processing scheme to improve SWH retrieval
- 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). These could include an improved estimate of the thermal noise, and a more accurate representation of the Point Target Response.
- As a general comment, we may also recommend to perform new spectral studies to consolidate the last results (interpretation of the PSD at small scales)

3.4 Coastal Ocean - SAR

Evaluation of CryoSat SAR Data in the Coastal Zone

In addition to the evaluation of SAR altimeter data in the open ocean, NOC carried out an assessment of capabilities of SAR altimetry in the coastal ocean (Gommenginger et al, 2014). This validation study was carried out on the ESRIN R1 data set (the full implementation of the SAMOSA 2 model: Table 2), at locations close to the sites of UK coastal tide gauges. The data set available was limited in time and was not long enough to include any repeat visits to any of the locations, and an initial attempt at match ups showed large offsets which varied from pass to pass. The analysis was therefore limited to assessing the availability of valid data, and of the noise levels on these data. An analysis of a longer times series will be needed to allow a comparison between tide gauge and SAR data measurements (e.g. of Total Water level Envelope - a parameter relevant to tidal surge studies).

Segments of the R1 CryoSat SAR validation data set that lay within 100km of the UK coast were extracted, and values for the Total Water Level Envelope (TWLE) calculated at 20 Hz intervals (TWLE is calculated as the SHH, with all relevant atmospheric corrections applied, and inclusive of ocean tides and atmospheric forcing). The noise level on the TWLE estimates was calculated as the absolute difference between consecutive measurements. This is believed to provide a good proxy for measurement noise, as the spatial separation between consecutive measurements will be ~300m, so the sea level should only be different by an order of mm. Figure 18 shows the results, for all data, and for data selected according to waveform misfit < 3.

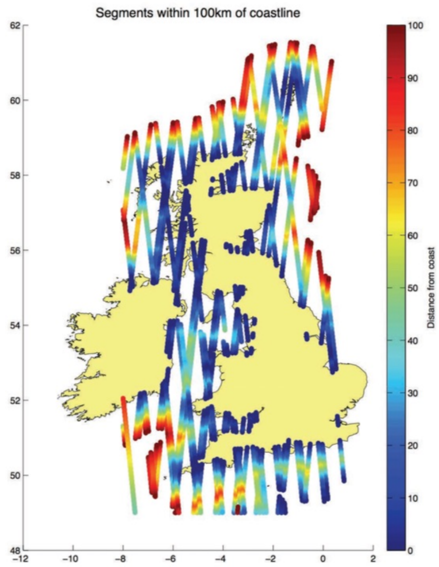

Figure 17: Segments of along track CryoSat SAR data within 100km of UK tide gauge locations.

In the left panel of Figure 18, it can be seen that the median of the absolute differences remains at 5 cm to within 5 km of the coast. Assuming that the noise is Gaussian, with variance of $2\sigma^2$, then the difference between adjacent samples will have a variance of $2\sigma^2$. Thus a median absolute difference of 5cm is equivalent to a noise level of 3.5cm for 20Hz data, or 0.8 cm for 1Hz data. This remarkable low noise level can be achieved to within 1km of the coast if the data are more carefully filtered according to waveform misfit < 3 (right panel of Figure 18), though of course the number of data being included in the calculation becomes significantly less (under 25% at 3km from the coast – see bottom right panel of Figure 18).

Raynal et al (2014a and 2014b) also looked briefly at the performance of the different SAR products close to the coast, and found very little difference between R1, and R6 SAMOSA products and the CPP product, in terms of the mean calculated Sea Level Anomaly, the number of valid points (per km), and the standard deviation (Figure 19).

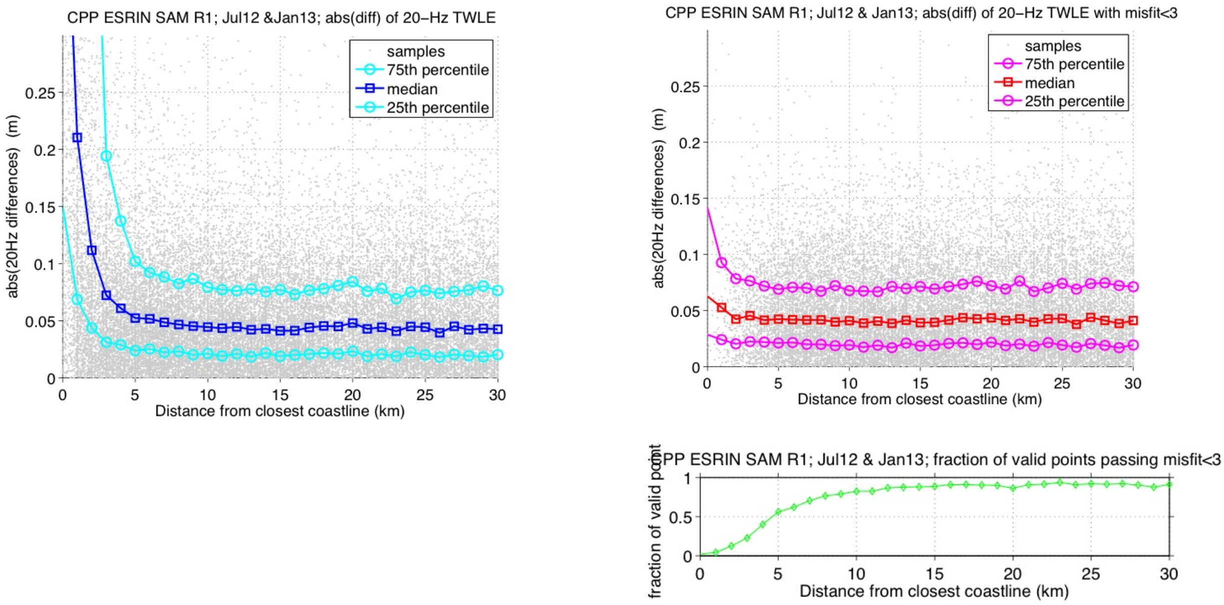

Figure 18: 20Hz “Noise” on TWLE (see text) against distance from the coastline. (left) all data passing normal data flags, (top right) As left but further selected for misfit < 3, (bottom right) no of data points in top left panel

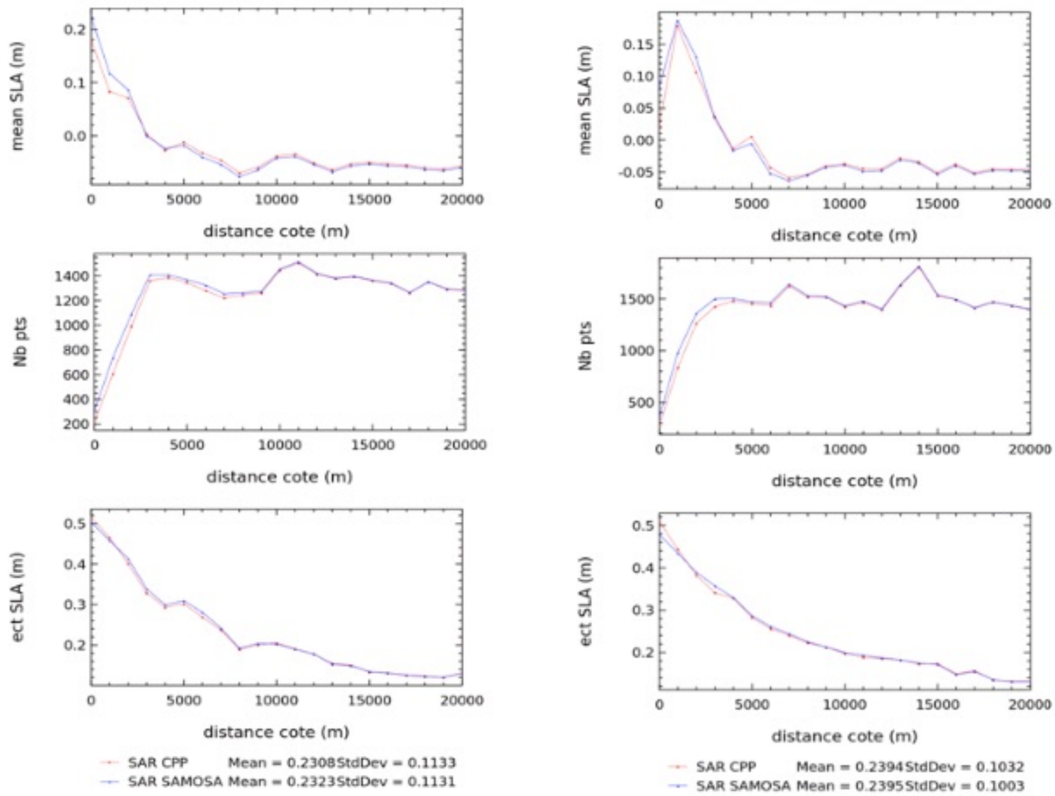

Figure 19: Sea Level Anomaly (top), number of points (middle), and standard deviation of SLA (bottom), for CPP SAR (red) and SAMOSA R1 SAR (blue) data with distance from the coast. For ascending (left) and descending (right) passes on tracks close to the UK.

Note that Dinardo et al., (2014) also assessed the capability of CryoSat SAR mode data in the German Bight, using data processed with the SAMOSA retracker. This work was carried out outside the CP4O project, but was reported to CP4O. The study found that CryoSat SSH, SWH and wind speed measurements were consistent with those in the RDSAR products, and the SWH and wind speed measurements were also consistent with buoy and model data.

Conclusions for CryoSAT SAR Coastal Zone Data

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.

3.5 Coastal Ocean – SARin

Garcia et al. (2014) describes the short scientific study that was carried out into the use of SARin data from CryoSat to provide insight into the potential for SAR altimetry in the coastal zone. This study made use of data from the SAR Interferometric Mode of CryoSat (SARin), whereby a second altimeter mounted side by side (in terms of the direction of flight) is used to receive the reflected signals, in addition to the main active antenna, and so across track information is provided. The relative phase information from the two antennas allows the angle of arrival (AoA) of off-nadir across track echoes to be derived. In the example of Figure 20 the SIRAL has received a direct nadir echo from the ocean surface and an off nadir echo from a reflector on land. Because of the elevation and brightness of the reflecting facet on the land, the land echo arrives earlier, and has a similar power, to that of the nadir ocean echo.

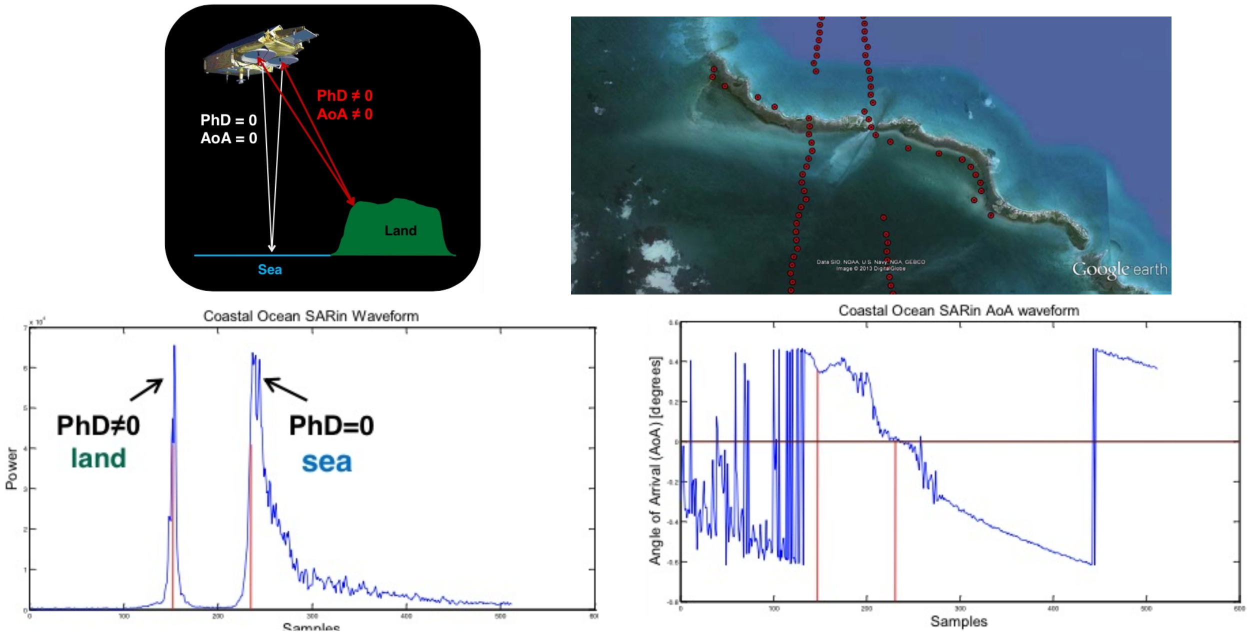

Figure 20: Off nadir returns in SARin mode. (Top left) Schematic of the geometry of a nadir ocean and off nadir land echo. (Top Right), Examples of non-nadir echoes received on pass close to Cuba, with true echoing locations identified. (Bottom Left) Power waveform, showing land echo received before ocean echo, and (Bottom right) phase waveform. The two red lines identify the position of the first echoes from the land and ocean reflectors.

Figure 21: The two SARin regions considered, (left) the Cuban archipelago, (right) the Chilean coastal strip.

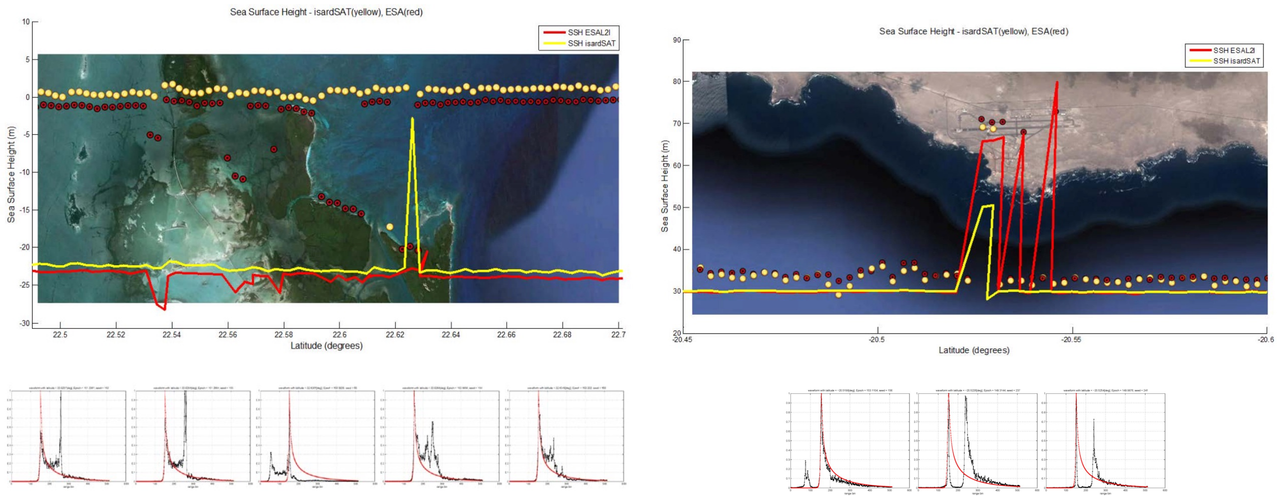

Figure 22: Reprocessed SARin data from passes over (left) Cuba, and (right) Chile. The top panels show the locations of the originally processed echo points in red dots, and the echo points identified by the isardSAT processor in yellow dots. The solid lines give the retrieved Sea Surface Height in m (scale on the left) with the same code colour. The bottom panels show a selection of the power waveforms (in black). The retracking fitted waveform is shown in red.

The purpose of the study described in Garcia et al., (2014) is to build an approach that can be used for processing SAR mode data which will distinguish and minimise the effect of the contaminating land echo. SARIN for two areas was requested, one region covering the Cuban Archipelago, which includes coastal cliffs and offshore cays, in general lying roughly perpendicular to the CryoSat sub-satellite track, and a second region close to the Chilean coast, where the coastline (predominantly cliffs) lies closer to parallel to the CryoSat sub-satellite track (Figure 21).

The existing L2 processing often selects and retracks the off-nadir land echo, which can arrive earlier and be of similar of higher power, and so returns an erroneous range. Thus a modified L2 processing scheme was developed that took as input L1 power, phase difference and coherence waveforms and through an iterative process identified the true nadir echoing point. The processor then used this true echoing point to provide a "seed" to a purpose built re-tracker which returns the true range of the nadir echo, together with the latitude and longitude of the nadir echoing point.

Figure 22 shows the result of using this modified processor on two sections of SARin data, the first across the Cuban Coast and the second close to the Chilean coast. In both cases the original processing wrongly tracked off nadir echoing points and so returned SSH values that could be ~10m in error (red). The new scheme provided much improved tracking (yellow), though not with a 100% success rate. The algorithm was tuned by running it across a large number of tracks, selecting processing tolerances that provide the best results in most circumstances. As some trade offs were necessary, it was not possible to design a general scheme that worked for all cases.

This activity therefore demonstrated that the existing 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. 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.

3.6 Polar Ocean – SAR

Processing CryoSat SAR data in the Polar Ocean

The objective of work under the Polar Oceans theme was to support improved information and knowledge on polar ocean process and dynamics, through the development and evaluation of oceanographic polar ocean SAR products. Because of its high orbit inclination, CryoSat offers previously unavailable high latitude coverage of the Arctic Ocean, but there are many challenges in retrieving an oceanographic signal from an ocean often covered in sea-ice.

The first challenge therefore was to develop a processing scheme to classify and re-track SAR waveforms received over the polar oceans in the presence of sea-ice. Echoes from a sea-ice affected region can show a different character, depending on the nature of reflecting surface (Figure 23)

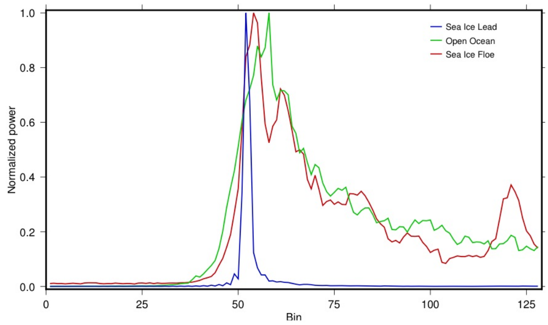

Figure 23: Typical Arctic Ocean Waveforms. Green – open ocean, blue – sea ice lead, red – sea ice floe.

Thus the processing scheme must be able to establish what sort of surface the echo has been returned from, select useful echo waveforms, and then process the echo accordingly. The approach developed by DTU Space is described in detail in Stenseng (2014a) and is illustrated in Figure 24.

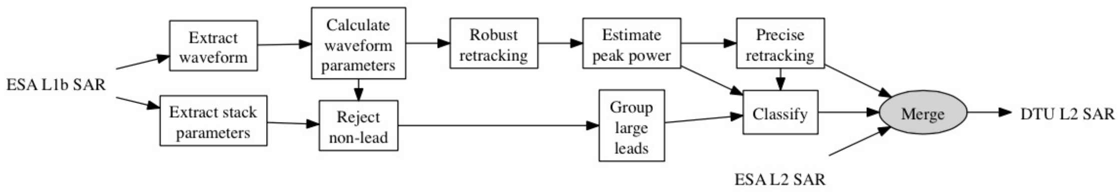

Figure 24 DTU Space Sea-ice processing algorithm flow

The processing scheme operates on SAR L1B data and includes the following steps:

- Determine a power benchmark for the retracker – by identifying the bin of maximum power, and fitting a model distribution (Gaussian) to get an estimate of the true maximum echo return power.
- Retrack using a simple leading edge retracker
- Identify if leads are present based on the parameters returned by the retracker, reject if not.
- Identify and select individual lead return from waveform, carry out precise retracking.
- Output to DTU L2 sea-ice product

This scheme was used to process all Cryosat-2 SAR data available for the period since July 2010, for latitudes greater than 60°N.

Validation of CryoSat SAR Polar Ocean Data

Validation was carried out through comparison against DTU13 Mean Sea Surface and against data from the NASA IceBridge mission (Stenseng 2014b).

For validation against the DTU13 Mean Surface, ESA CryoSat L1B Baseline-B data from April 2013 were processed to obtain SSH values. Observations for latitudes greater than 70° were extracted, outliers removed and profiles with more than 100 valid observations selected. The offset of individual values from the DTU13 MSS was then calculated, as was the standard deviation (Figure 25). The overall mean offset with respect to DTU13 MSS was found to be -1.435m. Taking into account an offset of -0.710 in the chart datums for DTU13 MSS and Cryosat-2, and a further known range bias of -0.673m in the CryoSat Baseline B product (Scagliola and Fornari, 2013), the resulting final bias is a remarkably low -5.2 cm, with a standard deviation on the mean of 7.4 cm, indicating good agreement,

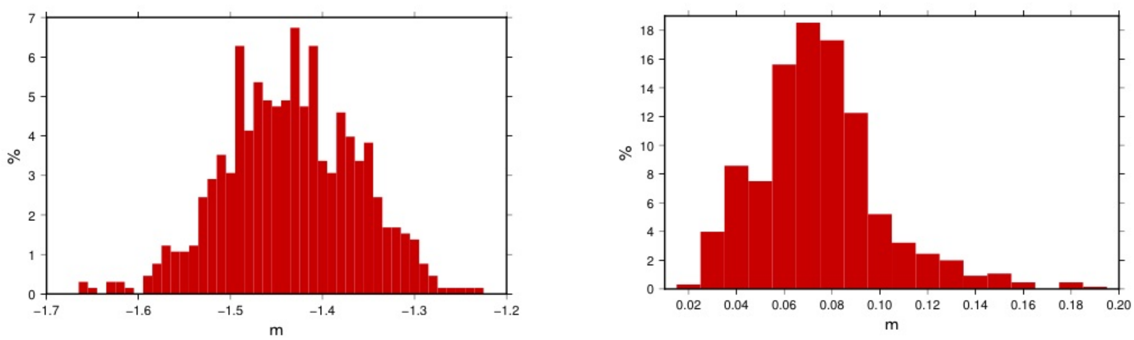

Figure 25: Validation of Polar Ocean CryoSat SAR Sea Surface Height against DTU13. (Left) Histogram (Percent occurrence of profiles) of mean height difference with respect to DTU13 MSS, (right) histogram of standard deviation of mean height difference with DTU13 MSS.

For validation against IceBridge airborne LiDAR data, it was first necessary to identify leads from imagery in transects that were made to underfly CryoSat passes, and to establish that these leads were co-located with leads identified in the processed CryoSat data. Suitable data from three dates were identified, and the difference between the CryoSat polar product Sea Surface Heights (with tidal corrections and barometric effects removed) and the IceBridge data sets calculated (Table 4). Once the known range correction was applied, their mean offset across the three dates was 0.0cm, with a standard deviation between 5 and 10cm. Whilst the volume of data available to support this validation was clearly not optimal, this general agreement is encouraging.

Date	No. Points	Mean	Corrected Mean	Std Dev
20130424	11	-0.602m	0.071 m	4.5 cm
20130402	21	-0.709m	-0.036 m	10.9 cm
20130321	2	-0.777m	-0.104 m	0.6 cm

Table 4: Mean differences and standard deviation between CryoSat and Icebridge SSH measurements.

Higher Level SAR Polar Ocean Products – Mean Sea Surface and Mean Dynamic Topography

With input from the Polar Ocean SAR data set generated within CP4O, and DTU Space has produced updated versions of its Arctic Mean Sea Surface and Mean Dynamic Topography, labelled DTU13 (Figure 26. These models show improved representation of known features, and are already providing new insights into polar ocean dynamics. The release of the entire CryoSat dataset in a consistent L1b processing (Baseline-B) will allow for an improvement of the Mean Sea Surface over the DTU13 model.

Conclusions for SAR Polar Ocean Data

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 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.

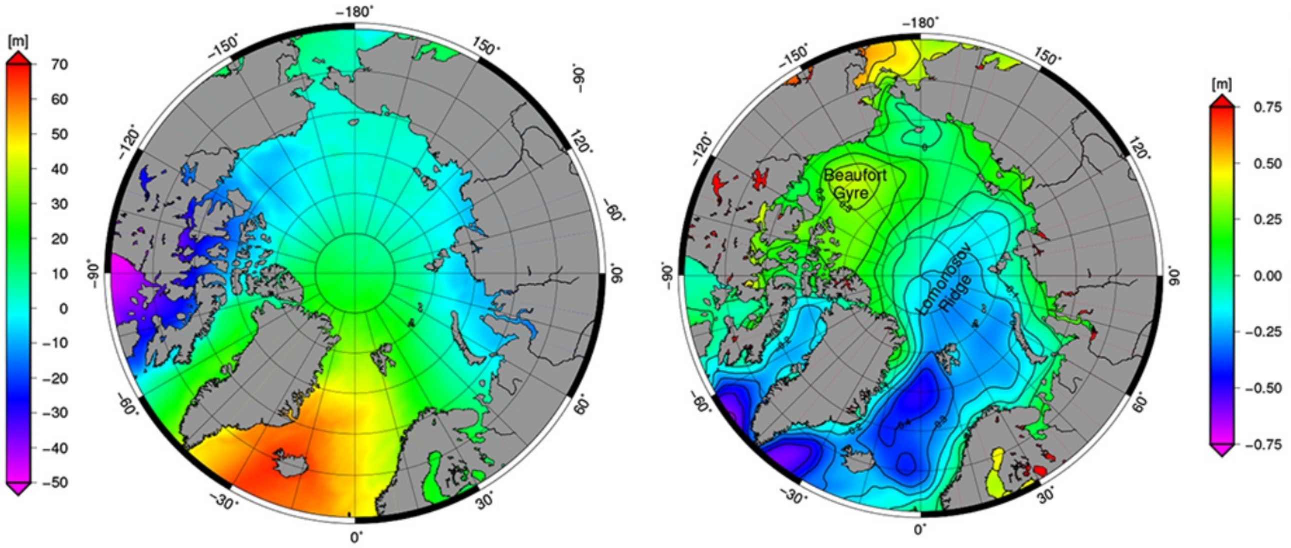

Figure 26: DTU13 Mean Sea Surface (left) and Mean Dynamic Topography, built using retracked CryoSat data, processed using the scheme developed and validated in CP4O.

The following recommendations for further work with regard to SAR altimetry in the polar oceans are highlighted:

- The release of the entire CryoSat dataset in a consistent L1b processing (Baseline-B) is recommended to support an improvement of the Mean Sea Surface over the DTU13 model, which only includes 2012 data.
- The generation of an improved Polar Tide model based on the above developments is a priority development, as current tidal models are known to be inaccurate in polar regions

3.7 Seafloor Topography – SAR

Processing CryoSat SAR data for Sea Floor Topography Applications

The objective of work under the Sea Floor Topography Theme was to investigate the potential offered by the higher resolution and improved signal to noise ratio of CryoSat SAR mode data to resolve short-wavelength sea surface signals caused by sea floor topography elements, and so to map previously uncharted sea mounts and sea trenches.

To support this work, a request was made to implement a new SAR mode mask over a region of the Pacific Ocean for a least a whole 369-day cycle, to allow sufficient across track resolution. The criteria for this area were that it should be at least 200 x 200 km, there should be no sea ice present, it should not be so deep such that any gravity signals would still be detectable, it should contain strong geophysical signals, and that in situ marine gravity data should be available for ground truth. The area selected is shown in Figure 27, together with the known underlying bathymetry. The mask covers the region 15°-25°N and 180°-203°E, and was part of the CryoSat Mode Mask 3.4 that was in place from 01/01/2012 to 07/07/2014. The northern part of the region is relatively deep (4-5km), but with prominent sea-mounts, whereas the southern area is shallower (2-3km)

CryoSat FBR data for 10/10/2012 to 01/01/2014 from 472 tracks were processed by the ESA EOP-SER altimetry team with the SAMOSA2 analytical retracker. SSH anomalies at 1Hz and 20Hz from this data set were used in this study. All the usual range corrections (where available) were added, as indicated in the CryoSat Product Handbook. In the absence of an accepted SAR mode sea state bias solution, an SSB equal to 0.045*SWH was used, and the height reference was adjusted to be consistent with that for DTU10 MSS. Data were edited to remove outliers and those with bad range corrections, and further processed to compute 1 Hz, 2 Hz and 4 Hz data.

These data were then further processed by DTU Space into residual altimetric geoid height, and hence gravity field. The long and short wavelength gravity anomalies were then separated, providing the inversion parameters used to predict the bathymetry. Further details are provided in Andersen (2014a and 2014b).

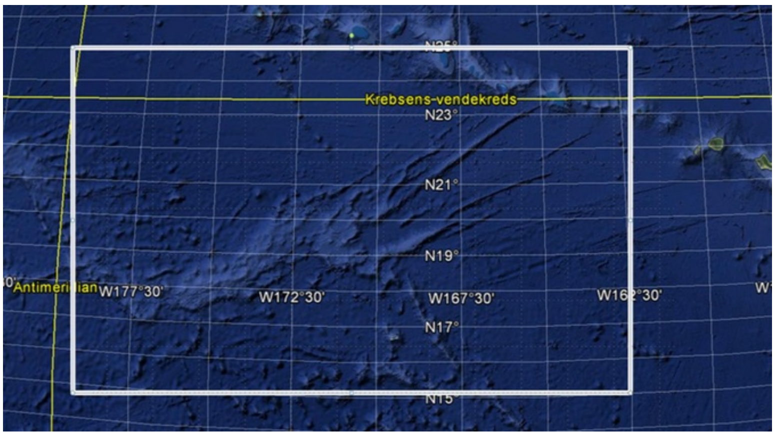

Figure 27: The known bathymetry in the SAR area in CryoSat Mode Mask 3.4 requested to support the Sea Floor Topography study in CP4O.

Validation of Sea Floor Topography parameters derived from Cryosat SAR data

The gravity and bathymetry derived from CryoSat SAR data were validated against marine gravity and bathymetry observations acquired from the US National Geospatial Agency, which were measured during the 1990s.

For the purposes of validation three different regions in the larger area were identified: The northern region, which contains a number of very large seamounts, has a good number of marine observations, and which has an average depth of close to 5km; the southern region which also has a large number of seamounts, but which is less well surveyed and so offers the potential for identification of new seafloor topography features; the central region, which is a shallower plateau area (average depth 2800m) potentially offering easier identification of features. Marine survey profiles for these different regions were identified and processed. Table 5 provides the standard deviation between the bathymetry estimated from CryoSat SAR data at various resolutions, against the measured bathymetry from the marine surveys. Note that these results are suitable for assessing the relative performance of the different CryoSat derived data sets, but not for performance against the general reference bathymetry model - as that is derived from multi-year and multi-satellite data. Accuracy is partly determined by the number of data points used to define the residual geoid heights, and the results of the validation reflect this.

	Entire Region	**Northern**	**Southern**	**Central**
1 Hz SAR (provided)	484 m	398 m	410 m	523 m
1 Hz LRM	482 m	397 m	411 m	521 m
1 Hz RDSAR	486 m	401 m	411 m	522 m
1Hz SAR (computed)	467 m	372 m	411 m	489 m
2 Hz SAR (1Hz setting)	467 m	372 m	412 m	489 m
2 Hz SAR (optimised)	465 m	371 m	410 m	487 m
4 Hz SAR (1Hz setting)	467 m	367 m	409 m	488 m

Table 5: Standard deviation between estimated and interpolated bathymetry from 5 CryoSat derived data sets, against the measured bathymetry from marine vessels.

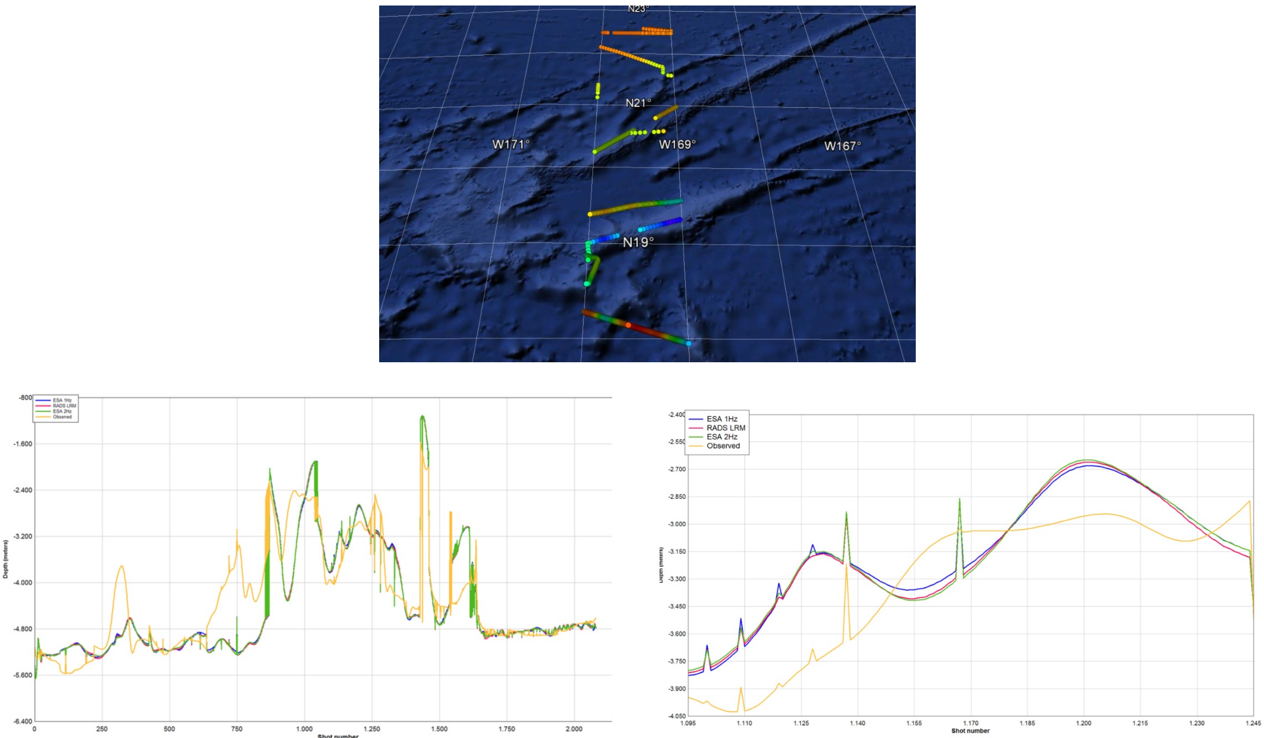

Figure 28 Marine bathymetry profiles in the Central and Southern part of the Pacific SAR region, (top) – Map showing the location of the marine survey lines, depth is colour coded, (bottom) Depth along these compiled profiles, the yellow line is the marine survey, blue is SAR 1 Hz, red is RADS LRM, Green is SAR 2Hz. Bottom right is all the profiles, bottom left zooms in on the profile just north of 20°N.

Andersen 2014b gives more detail on the different CryoSat derived data sets. The conclusions to draw from Table 5 are that the DTU reprocessed SAR data improve the standard deviation for all regions, and by the most in the central region. The performance of the 2 Hz optimised product, and the 4 Hz product seem roughly similar.

Inspection of bathymetry profiles from marine survey compared to the predicted bathymetry from CryoSat SAR data (Figure 28, bottom right – look at the green line – SAR derived bathymetry, compared to the yellow line – marine survey bathymetry) shows that there are long wavelength differences in the measured and predicted bathymetry, which is largely due to inaccuracies in the GEBCO-1 model used to provide the long wavelength in the altimeter derived data. However, a more careful look (bottom right) at an individual profile shows how the altimeter derived bathymetry (red, blue, green) sees a larger bathymetric variation than seen by the marine survey (yellow), whilst also capturing the misplaced profile points. The 2 Hz CryoSat data give the best comparison with the observed bathymetry.

Finally a map comparing the retrieved residual bathymetry signal to an existing bathymetry (DTU10) (Figure 29) does seem to indicate the existence of a feature which could be an improved mapping of an existing seamount or a mapping of a previously unknown feature.

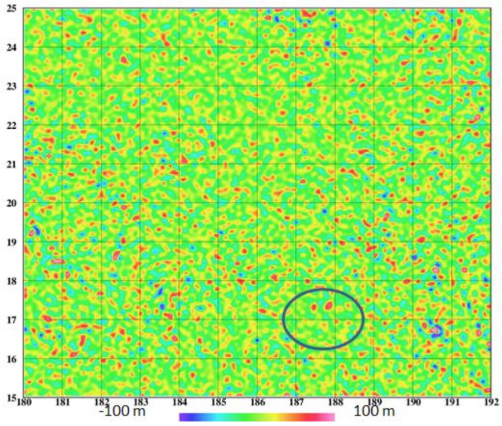

Figure 29 The retrieved residual bathymetry signal relative to the DTU10 bathymetry. The circled area highlights a feature not present in the earlier bathymetry

Conclusions and Recommendations for SAR Altimeter Derived Sea Floor Topography

This analysis 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 has 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.

3.8 Geophysical Corrections

CP4O included three activities to develop and evaluate improved geophysical range corrections. This aspect is especially important for applications of CryoSat data, because

- CryoSat does not carry an on-board Microwave Radiometer to provide coincident along track measurements of atmospheric water content and hence wet troposphere delay on the altimeter signal. Instead corrections from a global model are used, which is limited in time and space resolution and so does not offer the Wet Troposphere Correction (WTC) to the same accuracy.
- CryoSat only operates at a single frequency and so cannot provide coincident along track estimates of ionospheric delay on the altimeter signal. Again corrections from a global model are used, which again is limited in time and space resolution and so does not offer the ionospheric correction to the same accuracy as an on board measurement
- CryoSat SAR mode is offering the potential of altimeter data at a higher resolution, and closer to the coastline, than was previously possible. Range corrections are now one of the larger sources of error on the altimeter measurement and it is important to test and validate the performance of these corrections at smaller scales, and close to coastlines where variability (specifically in wet troposphere and tides) is expected to be higher.

Therefore CP4O carried out activities to develop and evaluate new corrections for wet troposphere, ionosphere, and regional tides.

3.8.1 Wet Troposphere Correction (WTC)

The WTC provided by ESA for use with CryoSat data is a model-based correction provided by ECMWF. Within CP4O, U Porto has developed and validated an improved WTC for use with CryoSat (Fernandes et al., 2014a, and 2014b). This work has also been written up as a peer reviewed paper (Fernandes et al., 2013) As part of their overall independent evaluation of CP4O products, CLS also carried out an evaluation of this correction (Raynal and Moreau, 2014b).

Fernandes et al., (2014a) describes how the improved Wet Troposphere Correction was generated, through the development of a Data Combination Algorithm (DComb), which estimates the WTC using objective analysis (OA) of a number of available sources, including satellite radiometer data, GNSS data, and model output. The Dcomb OA method updates a first guess WTC value for each location and epoch, and provides a quantification of the mapping error associated with each estimated WTC value.

The Dcomb algorithm was implemented globally and applied to generate along track values of WTC for Jason-2 and CryoSat data for January 2012 to January 2013. For this data set the RADS altimeter data base was used. A second data set was generated for the independent analysis by CLS, this data set was created for July 2012 and January 2013, and in this case the CryoSat SAR data set generated by the ESA EOP-SER altimeter team was used.

The WTC data sets generated included data from 11 operational satellite missions providing scanning MWR images of Total Column Water Vapour (TCWV), data from 400 GNSS stations, and model data from the ECMWF operational model. The operational ECMWF model was chosen in preference to the ERA-interim model primarily because it has a finer resolution. ERA interim is a better solution for long-term studies as it has been especially developed to provide a continuous consistent data set.

The relative contribution from each source varied in time and space according to the proximity with the CryoSat or Jason-2 orbit. Known biases and corrections were applied, the contribution of each source weighted according to the distance and time different from the point of estimation, and finally all contributions summed together. A maximum of 25 GNSS and SI-MWR measurements were used to generate each value, selected by those with the greatest weights. ECMWF model data were always included to reduce potential discontinuities in the transition zones between the availability of data from different satellites.

As an example Figure 30 shows the WTC along track for an individual Jason-2 pass, and compares the ECMWF mode (blue) against the on board measurement (red) and the UPorto Dcomb (black) correction. The striking feature of this figure is how well the DComb WTC captures the signal present in AMR at latitude 40ºN, which is not present in the ECMWF model. Figure 31 and Figure 32 illustrate the global Dcomb WTC and the formal error for CryoSat sub-cycle 35. The signature of satellite tracks is clearly visible on the plot of formal error, showing the impact on the error of the WTC estimate of the (un)availability of data from individual instruments.

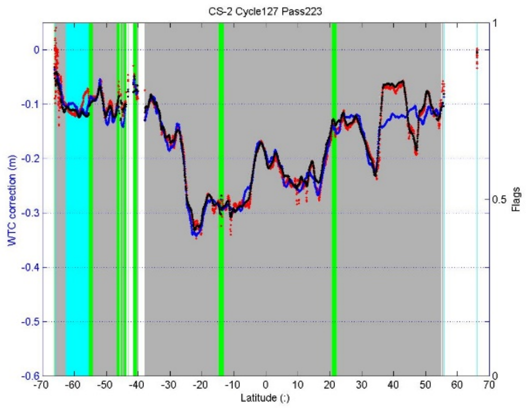

Figure 30: Comparison of Wet Troposphere Corrections for Jason-2 cycle 127, pass 223: (blue) ECMWF model, (red) AMR on board Jason-2, (black) UPorto DComb. The shaded areas represent regions for with Si-MWR observations (grey), GNSS (green) or model only (blue) are available as inputs.

U Porto validated the DComb WTC that they generated through along track analysis of SLA(variance analysis, mean cycle values, and analysis of collocated data), and analysis of Sea Level Anomalies at cross-overs. Global data sets had been produced for Jason-2 and CryoSat. Figure 33 shows the reduction in variance on Jason-2 SLA from applying the on board AMR WTC rather than from the ECMWF model (green), and the Dcomb WTC rather than the ECMWF model (blue), calculated along track. It can be seen that the AMR WTC performs best, as expected, but that use of the Dcomb WTC also provide a significant improvement on the ECMWF correction. Figure 34 shows the reduction in SLA variance at cross overs for CryoSat SLA – showing the difference when SI-MWR or GNSS observations are available (orange). Again we can see that use of the DComb WTC results in a significant reduction in SLA variance (~1 cm^2). The improvement does not appear to have any geographically coherent pattern (Figure 35).

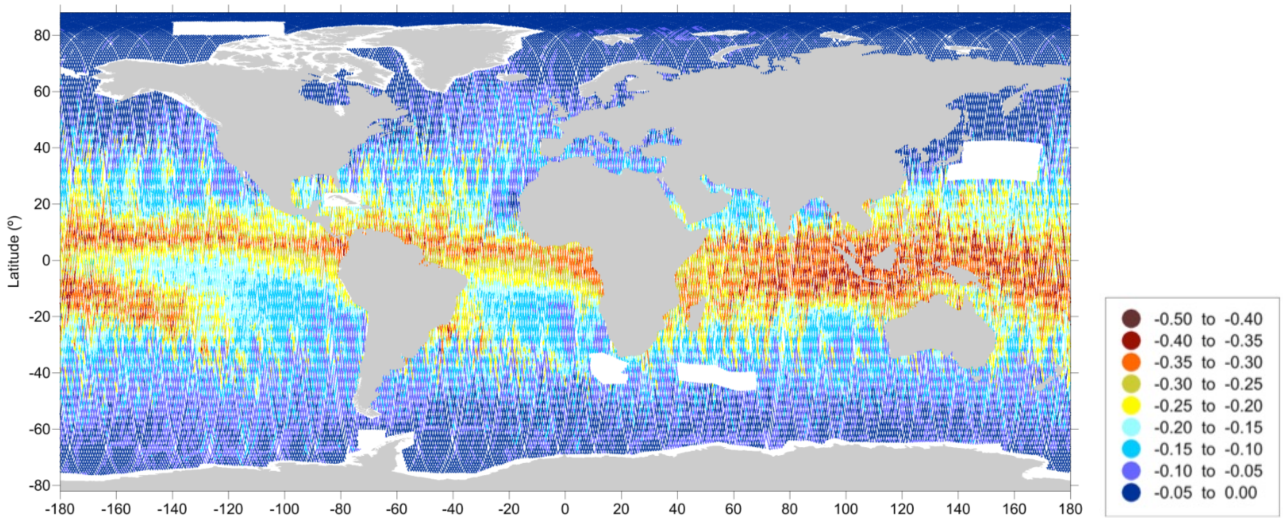

Figure 31: Dcomb WTC (in m) for CryoSat sub-cycle 35

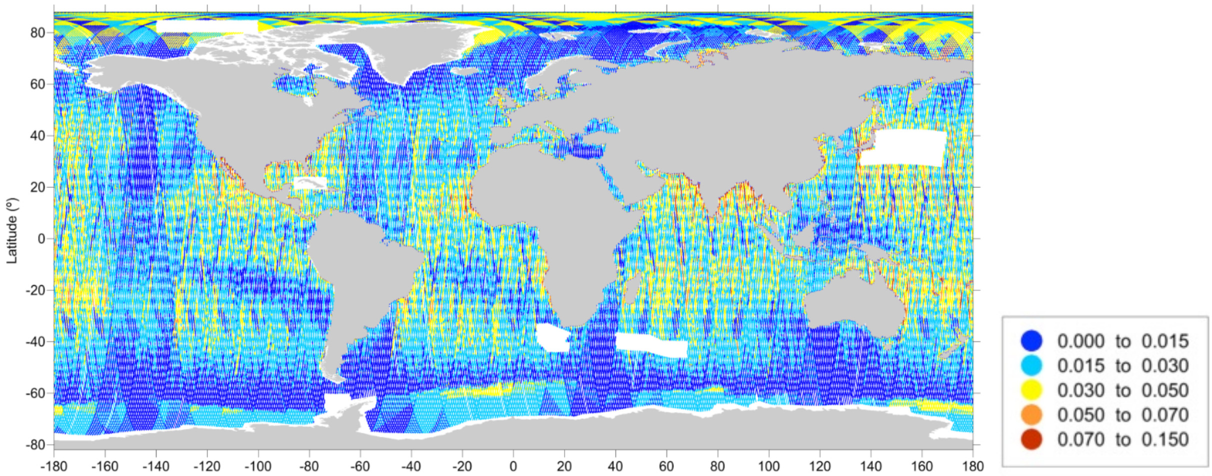

Figure 32: Formal error (in m) for CryoSat sub-cycle 35

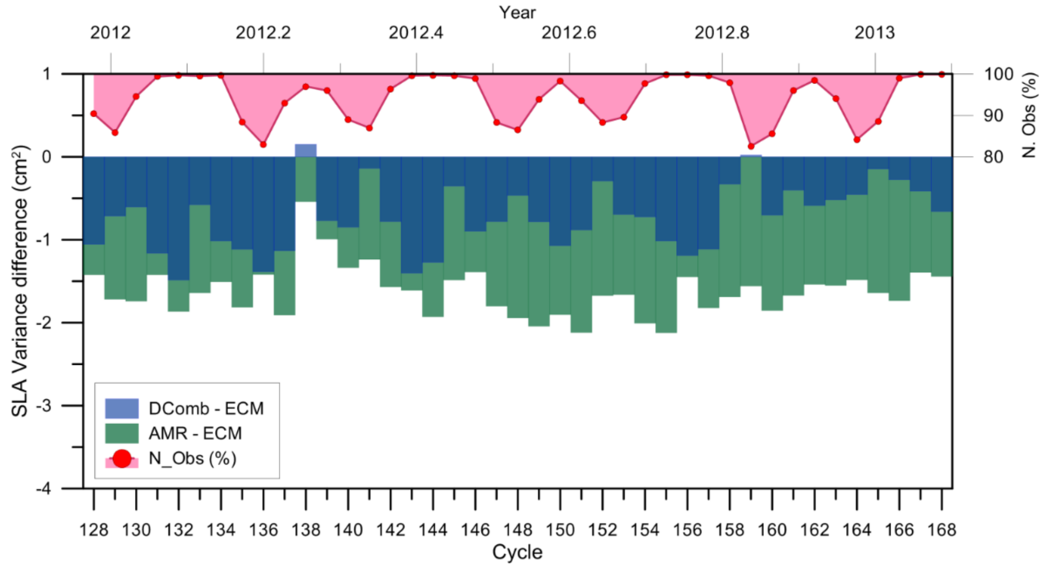

Figure 33: SLA variance differences (cm^2) for each J2 cycle and different WTC computations: between Dcomb and ECMWF operational (blue) and between AMR and ECMWF operational (green) using all points. The top panel shows the percentage of measurements with observations of any type (GNSS or SI-MWR).

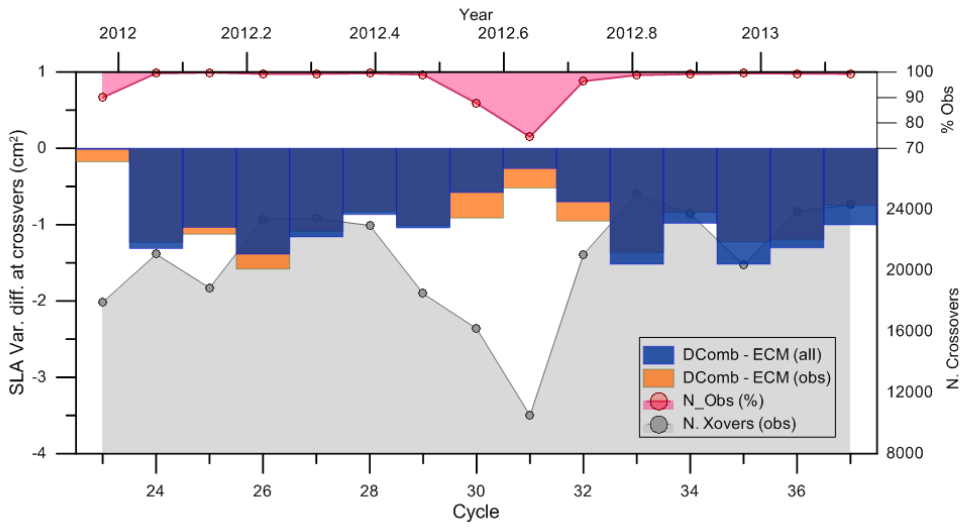

Figure 34: SLA variance difference at crossovers (cm2), for each CS-2 cycle and for different WTC computations: Between DComb and ECMWF Operational model, using all points (blue); only points for which either GNSS or SI-MWR observations were available (orange). Top plot shows the percentage of measurements with GNSS or SI-MWR observations. The grey dots represent the number of crossovers.

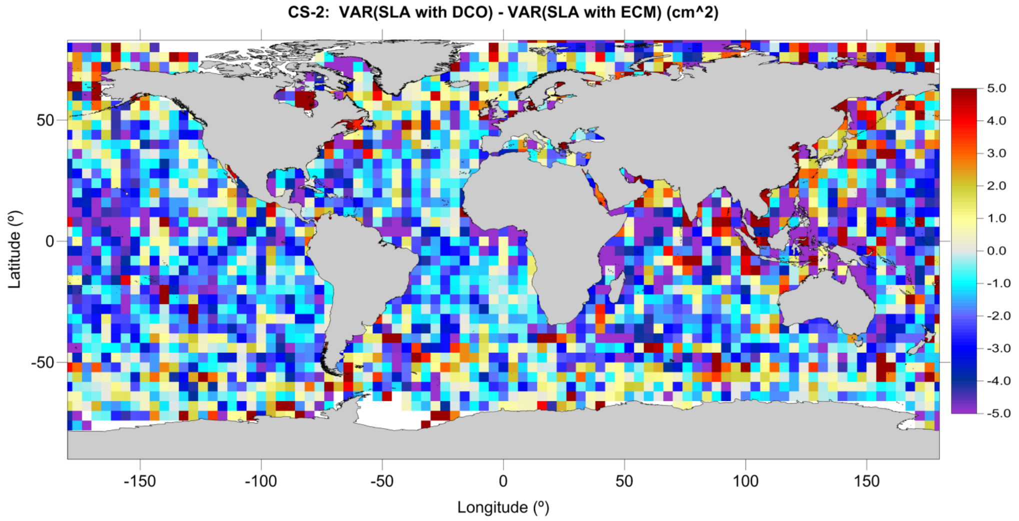

Figure 35: SLA variance differences at crossovers (cm2), between DComb and ECMWF Operational model WTC computations, for the period covered by CS-2 cycles 23-37.

The CLS assessment of the impact of the DComb WTC (Raynal and Moreau, 2014b) was based on along track and cross over analysis of 2 months of data, July 2012 and January 2103. It was concluded that use of the DComb WTC improved the Cryosat-2 SSH accuracy between 50°N and 50°S, with a mean reduction in variance at crossovers of ~2 cm^2 compared to application of WTC from the EMCWF operational model (**Figure 36**). This improvement was up to 4 cm^2 locally. However, the DComb correction appeared to degrade the performance at higher latitudes (through along-track SLA gain of variance diagnosis though this degradation needs to be confirmed over a longer time series (a full year of data). The DComb correction also improves the performance near the coast, by reducing the SLA variance by 2.4 cm^2 for distance less than 100 km (**Figure 37**).

The improvement of this correction is achieved notably where the sensor observations are available, while the quality of the DComb WTC is slightly degraded where the ECMWF model is applied. The quality of the DComb WTC could be enhanced with better handling of the along track discontinuities.

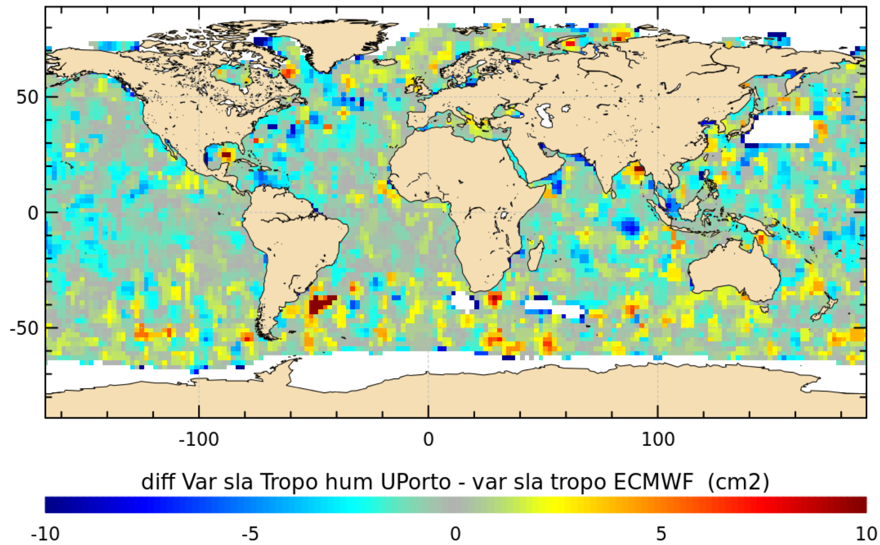

Figure 36: Difference in SLA variance between SLA calculated with DComb WTC, and ECMWF model WTC, calculated along track and averaged in 2° x 2° bins (July 2012)

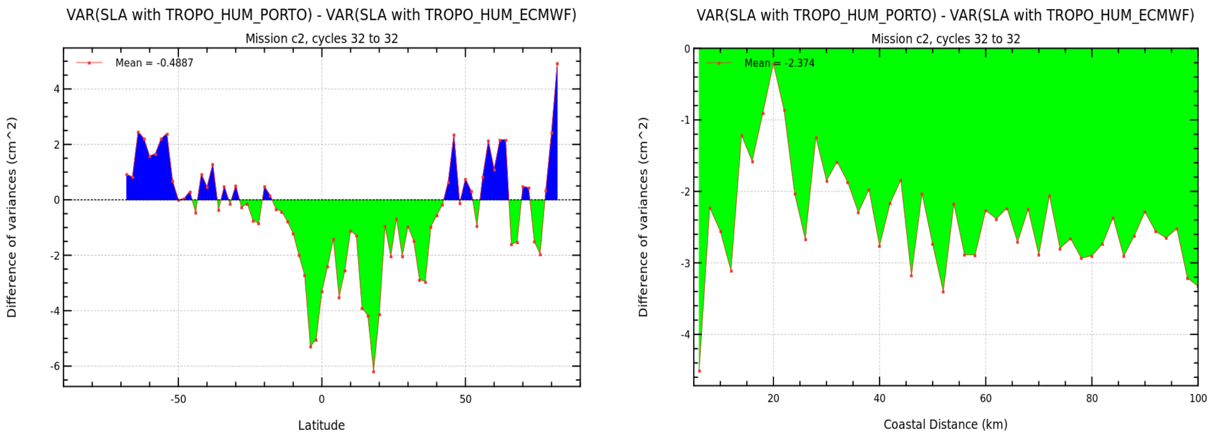

Figure 37: Difference in SLA variance between SLA calculated with DCOMb WTC, and ECMWF model WTC, (left) as a function of latitude, and (right) as a function of distance from the coast (July 2012)

Conclusions on the U Porto DComb Wet Troposphere Correction for CryoSat Data

The U Porto DComb Wet Troposphere Correction (WTC) is recommended for application to Cryosat range data as it has shown to provide better performance than the currently provided WTC from the ECMWF operational model. There is some indication that this improvement in performance is even greater close to the coast, but not so good at higher latitudes (> 50°). Some improvements could be made in handling along track discontinuities at points where observations become unavailable.

3.8.2 Regional Ionosphere Correction

As CryoSat SIRAL is a single frequency Ku band altimeter, no direct instantaneous measurement on ionospheric delay is available. Therefore the GIM product is used to provide the ionospheric range correction. An alternative regional ionospheric correction is offered by the SPECTRE service, through Total Electron Content (TEC) maps generated over Europe, calculated from delays on GNSS signals (Crespon et al., 2007, Cancet 2014a). The SPECTRE service provides a mapping of Vertical Total Electron Content over Europe, sampled at 30 seconds, with a spatial resolution of 2.5° x 2.5° (Figure 38). In contrast GIM provides maps updated every 2 hours, at a spatial resolution of 5° x 2.5°.

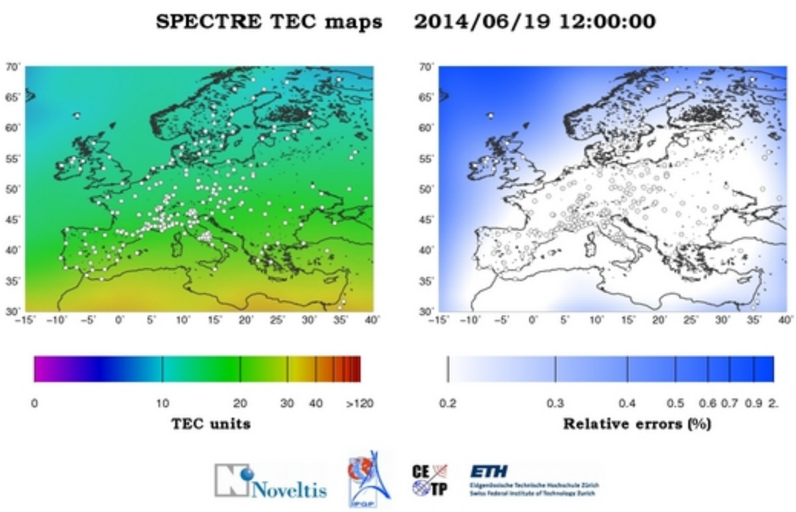

Figure 38: Example SPECTRE maps of Total Electron Content and the calculated error for 19 June 2014

For CP4O the SPECTRE corrections were provided for the European area for the months of January 2011 to January 2013, interpolated onto the CryoSat tracks for the time of the pass. CLS carried out a validation through an along track comparison, analysis of difference in variance, and along track spectral analysis (Raynal and Moreau, 2014d), from May 2012 to January 2013. In direct comparisons between the two corrections large scale patterns of difference were seen, though these were not consistent between ascending and descending passes. Differences were also seen to vary with time. The variance of the differences between the corrections showed negligible difference between the two corrections for descending passes (at local night) but higher variability for ascending passes (during local daylight) - Figure 39.

It was concluded that although local differences could be seen in the two ionospheric corrections, it was not possible to identify any significant differences that result in an improvement in the range data. A problem was the limited amount of altimeter data available which precluded the use of other methods of assessment (e.g. crossover analyses). Also it should be noted that the NE Atlantic is not a particularly favourable area for this study, as the ionosphere is not especially dynamic over this region. A higher resolution ionosphere correction may be of greater utility at higher magnetic latitudes, or in regions of higher magnetic field variability such as the South Atlantic Magnetic Anomaly.

It was noted in discussions that IRI 2007 is the best currently available source of electron content above the CryoSat Orbit height.

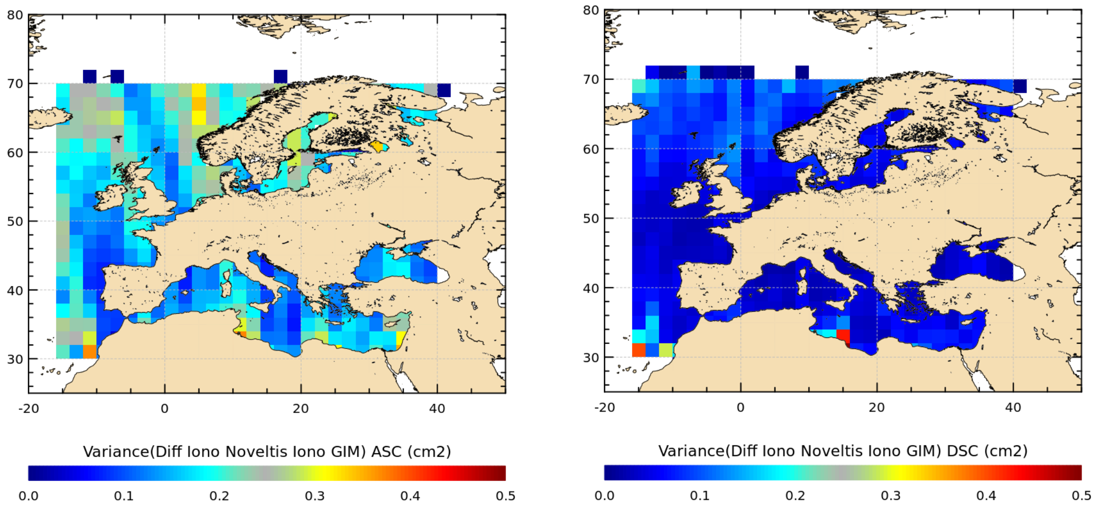

Figure 39: Variance in difference of Noveltis (SPECTRE) ionosphere correction and GIM ionosphere correction: (left) For ascending, daytime, passes; (right) for descending, nighttime, passes.

3.8.3 Regional Tide Correction

A number of tidal corrections are provided with the CryoSat products, offering the user a choice to select which best meets their requirements. However these are all global corrections, so although they provide global spatial consistency, with relatively low errors in the open ocean (1-2 cm), the errors of these models in coastal zones can be greater (~10cms). Regional tidal models can provide higher spatial resolution, incorporate better known local bathymetry, and allow better representation of local hydrodynamics. Thus, for evaluation of the potential benefits of the use of regional tidal models in CP4O, Noveltis used the COMAPI tidal model to compute regional tidal corrections for the North East Atlantic region for application to CryoSat data, for January 2011 to January 2013 (Cancet 2014c).

A comparison between the corrections (as the difference in variance) from the COMAPI tide model and GOT 4.8 (Raynal and Moreau, 2014c), shows significant differences in the correction in coastal regions and semi-enclosed seas (in the Channel, the Irish Sea, the Southern North Sea and the Skaggerak/ Kattegat (Figure 40 left). When the correction is applied to CryoSat SSH data, a significant improvement of more than 25 cm^2 (in terms of reduction of SLA variance) is seen in these areas (Figure 40 centre). The 1Hz SLA spectrum for this region, calculated with the COMAPI and GOT 4.8 tidal corrections, shows that SLA scales of 50-200km are better estimates using the COMAPI model (Figure 40 right).

Thus it was concluded that the use of the COMAPI model provides a correction consistent with other models in all areas where it is applied, and a significant improvement in NE European coastal regions, and semi-enclosed seas.

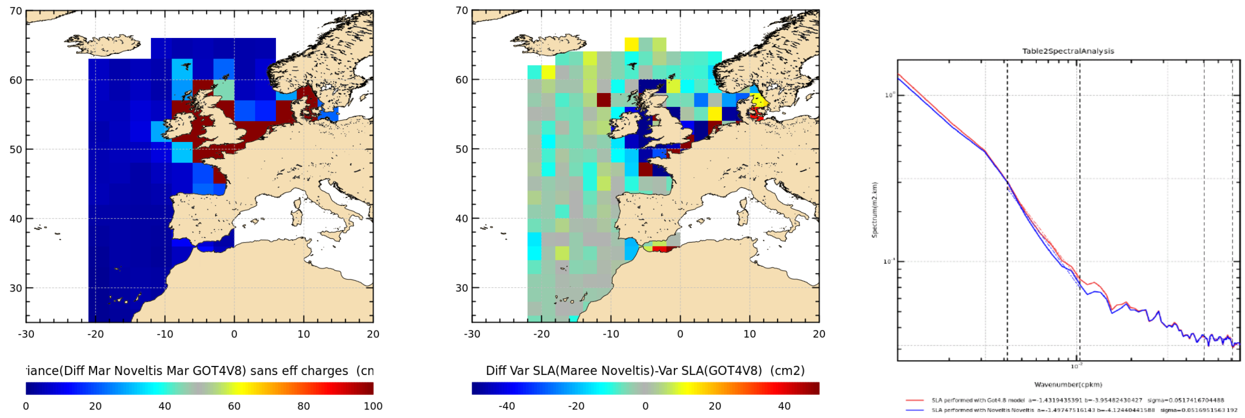

Figure 40: Comparison between COMAPI regional tide model and GOT 4.8 global tide model. (Left) difference in variances of the tidal correction, (centre) difference in variance between the SLA from CryoSat after the tidal correction has been applied, (right) SLA spectra for NE European Shelf (blue) using COMAPI, (red) – using GOT 4.8.

3.8.4 Conclusions from Geophysical Correction

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 for the regional ionosphere correction derived from the SPECTRE service, at least in the North East Atlantic, where the analysis was performed.

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.

3.9 Outreach and Access to Project Outputs

A key aspect of the CP4O project was to communicate the project findings to the wider community and to invite comment and involvement. To this end all project partners were encouraged to present their finding and results at relevant scientific meetings, and the table below lists the meetings at which CP4O results were presented. Of course the major event in this regard was the First SAR Altimetry Expert Group Meeting, held at the National Oceanography Centre, Southampton, on the 26-27 June 2013. Presentations from this meeting are available at:

http://www.satoc.eu/projects/CP4O/meetings.html

All project results, deliverables etc are available through the CP4O web pages (http://www.satoc.eu/projects/CP4O/index.html). In particular the data products produced by CP4O area available, and users are invited to download, test these products and to provide feedback to the CP4O team. Mostly access is via ftp, because of file size, instructions on how to access these data are available on the project data page: http://www.satoc.eu/projects/CP4O/data.html.

Meeting	Venue	Date
6th Coastal Altimetry Workshop	Riva del Garda, Italy	20-21 September, 2012
OSTST	Venice-Lido, Italy	27-28 September, 2012
AGU Fall meeting	San Francisco, USA	3-7 December 2012
Cryosat Third User Workshop	Dresden, Germany	12-14 March 2013
EGU General Assembly	Vienna, Austria	07-12 April 2013
1st SAR Altimetry Expert Group Meeting	Southampton, UK	3.9.1.1.1.1 26-27 June 2013
ESA Living Planet Symposium	Edinburgh, UK	9-13 September 2013
OSTST	Boulder, USA	8-11 October 2013
AGU Fall meeting	San Francisco, USA	9-13 December 2013
40th COSPAR Scientific Assembly	Moscow, Russia	2-10 August 2014
OSTST	Lake Constance, Germany	28-31 October 2014
AGU Fall meeting	San Francisco, USA	15-19 December 2014
IGARSS 2015	Milan, Italy	26-31 July, 2015
EGU General Assembly	Vienna, Austria	12-17 April 2015
Sentinel-3 for Science Workshop	Venice, Italy	2-5 June 2015
EUMETSAT Meteorological Satellite Conference	Toulouse, France	21-25 September 2015

Table 6: Table of meetings at which CP4O results have been presented

4 SCIENTIFIC ROADMAP

4.1 Introduction

Cotton (2014) provides a Scientific Roadmap which outlines proposed and planned 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.

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

Figure 41 provides a diagram of the various aspects and objectives of the different strands of activity

4.2 SAR and RDSAR processing - Advancing the State of the Art of SAR altimetry

In general activities under this heading would be categorised as Research and Development. As well as moving forward the state of the art for SAR altimetry, these developments will directly support improvements to the SAR altimeter processing chains, including those implemented for CryoSat reprocessing, and Sentinel-3 operational processing. They will also contribute to preparation for later SAR altimeter missions, in terms of instrument design, mission planning and processing chain design.

The recommended priorities are listed below.

SAR Processing Issues

- SAR Waveform
    - Under-sampling peaky waveforms
    - Optimising Doppler processing /selection / weighting
    - Purpose /optimisation of Windowing
    - SAMOSA implementation (PTR, Thermal noise
    - SAR waveform blurring at high alt rates

- RDSAR Processing
    - Effect of SAR transmission pattern on waveform statistics
    - How to improve waveform statistics / minimize use of correlated echoes

Investigations into SAR Altimetry Characteristics

- SWH dependencies / errors
- Impact of swell
- Development and evaluation of SAR mode SSB models
- Dependence of retrieved parameters on roll angle, pitch angle, radial velocity
- Characteristics of Full Bit Rate echoes, stack data

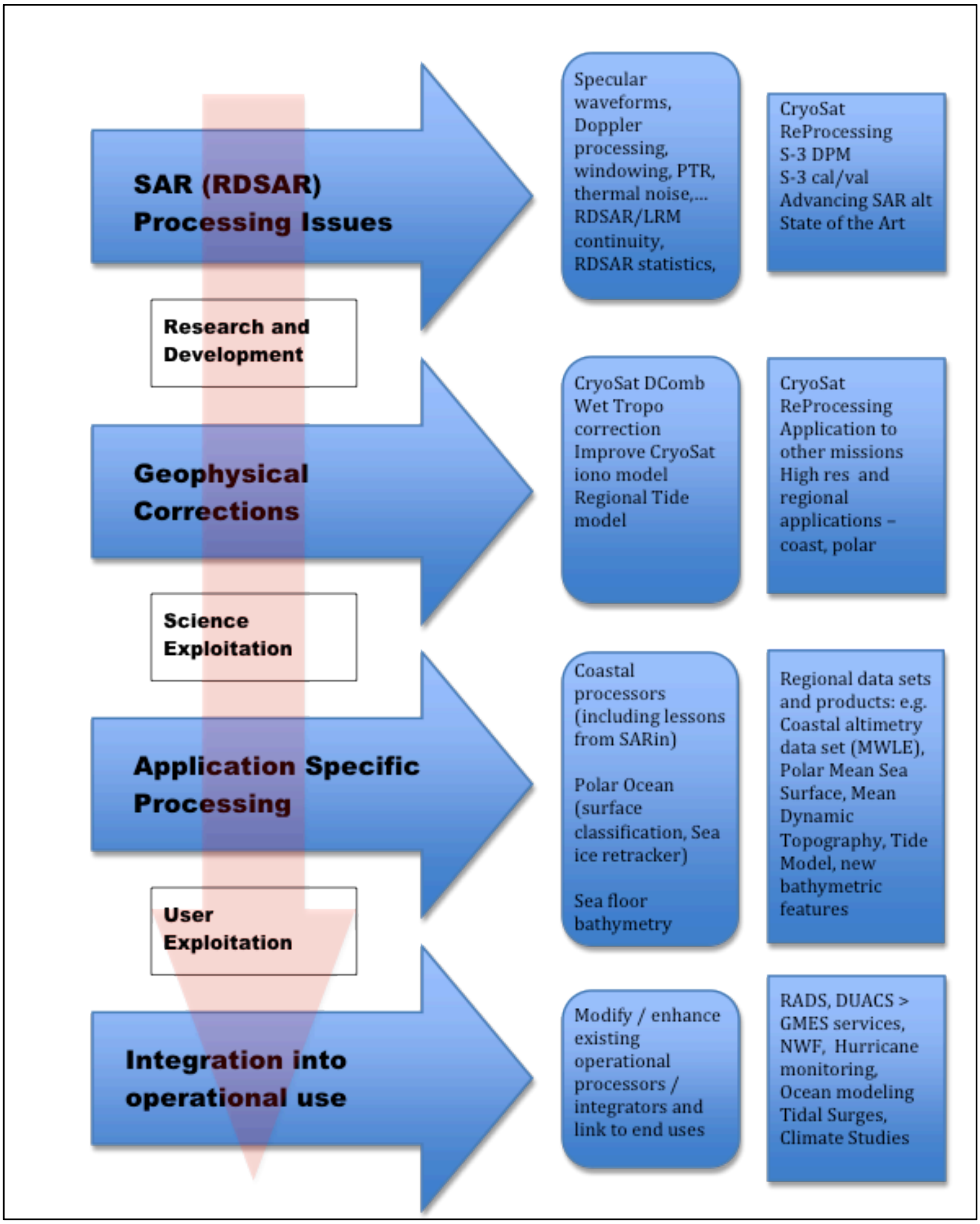

Figure 41: Strategy for Continuing/Exploiting CP4O Results

Validation activities

- Comprehensive evaluation of CryoSat SAR data for coastal application
- Larger data sets for SAR and RDSAR validation
- Sentinel-3 validation planning (mode selection)

4.3 Geophysical Corrections

It is essential that geophysical corrections are provided to ensure that the gains in measurement precision are not lost because of uncertainties in environmental corrections. Thus there must be parallel developments and improvements in these products. Recommended developments are listed below.

- Generate a WTC data set for whole CryoSat mission, global along-track and gridded data sets
- Change ionosphere model used to estimate electron content above CryoSat orbit

4.4 Application Specific Processor and Product Development

Some applications of SAR data require specific processing developments, we list below recommendations by theme.

Open Ocean

- Sentinel-3 DPM should be updated to include best performing implementation of SAMOSA3.
- Further improvements to CPP SAR mode processing scheme should be developed and implemented.
- Apply SARin processing for oceanography (e.g. across track slope)

Coastal Ocean

- Continue SARin investigations, and develop schemes to improve processing of SAR data at coast.

Polar Oceans

- Carry out a whole mission reprocessing of Cryosat data so that all polar data are available with a consistent baseline.
- Develop and publish improved Polar tide model.

Sea Floor Bathymetry

- Process a longer period of SAR mode altimeter data for the Pacific SAR region, and apply an improved prior bathymetry.
- Investigations in shallow / coastal regions to investigate potential capabilities of data in this environment.

4.5 Integration into Operational Use

In this section we categorise the products assessed within CP4O according to their maturity (or readiness for operational implementation) and outline any plans for eventual end-user exploitation, including integration into operational use by national /international agencies and within large scale initiatives. Clearly, a product has to reach a recognised level of maturity before it is appropriate for routine use in this way.

Mature Products

The following products have been identified as fully mature and ready for immediate integration into operational use:

- The RADS CryoSat RDSAR product is already operationally available and is used operationally, as part of the multi-mission RADS database by a range of users including NOAA. RADS has been used extensively as a reference during the ESA CCI for Sea Level project and is often regarded as the de facto standard for a climate data record.

- The CPP Cryosat RDSAR and SAR products are operationally produced and available through the SSALTO/DUACS multimission product set for potential incorporation in a wide range of applications.

- The Noveltis SPECTRE Ionosphere correction is mature and available (after a 3 day delay) for non Near Real Time applications. It could be made available for distribution alongside the altimeter products themselves. Further development would be required to achieve a Near Real Time capacity.

- The Noveltis COMAPI Regional Tide Model is fully mature and validated, ready for operational use. Again, it could be made available for distribution alongside the altimeter products themselves. Plans for further development include other regional implementations (including a polar tide model proposed for a CCN), and incorporation of an extended time series of altimeter data.

Almost Mature Products (Ready in < 1 year)

The following products were identified as almost mature, which are expected to be ready for integration into operational use in under a year, after limited further development:

- The STARLAB and ESA implementation of the SAMOSA echo model requires limited further development to improve representation of some waveform characteristics. Note that a fully operational and configurable online implementation of SAMOSA2 and SAMOSA3 processing to generate L2 products from Cryosat SAR FBR data is available through ESRIN at:

  https://gpod.eo.esa.int/services/CRYOSAT_SAR/

- The DTU SAR Polar Ocean products require limited further development to bring the SAR based Polar Ocean products (Mean Sea Level, Mean Dynamic Topography, Polar Tide Model) to full maturity. This includes testing and implementation of further improvements to the SAR processing algorithms, plus processing the whole CryoSat mission SAR data set with a stable, consistent L1B processing chain. This can then be applied to all future SAR missions with polar coverage. The polar ocean products would support a wide range of scientific studies and operational applications, include climate studies.

- The U Porto Wet Troposphere Correction is ready for operational implementation and has been demonstrated to provide an improvement with respect to the ECMWF operational model. However, there are some issues which should be further investigated before a final version of the product is generated and made available. An along track data set would provide a correction for use with CryoSat data, a fully global gridded product would be applicable and useful for other altimeter missions. This WTC is being developed in the scope of the ESA Sea Level CCI.

5 CONCLUSIONS

5.1 Summary

The CP4O project has carried out a wide-ranging study aiming 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.

5.2 Significance of the Projects

The significance of CP4O has been recognized by the External Review team requested to comment on the deliverables, as indicated by the following comments:

- "The CP4O Project is ambitious, timely, and important. It is abundantly clear from the results presented at this mid-term benchmark that the SAR mode of ocean-viewing radar altimetry offers numerous advantages over conventional altimetry. The investigators who have been contributing to this endeavour are to be congratulated for their respective efforts, and are encouraged to continue working towards a major contribution."
- "The team is extremely competent to analyse the existing data and propose algorithms and products."
- "efforts of the CP4O will directly contribute to near future satellite altimetry missions such as Sentinel-3 and Jason-CS"
- "This (project) is a crucial step for the team to successfully extend the CryoSat-2 to its complete data coverage over the whole earth surface"

5.3 Acknowledgements

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Katharine Giles – UCL, UK*
Keith Raney - 2kR-LLC, USA
Laurent Phalippou –Thales Alenia Space, France
Rob Cullen – ESA
Xiaoli Deng -Newcastle Univ, AUS

*One of the review team, Katherine Giles, suffered a tragic accident and died during the timescale of the project. This loss in 2013, together with that of another friend and colleague, Professor Seymour Laxon, has meant that the time of CP4O has been a very sad period for the satellite altimetry community.

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IMPORTANT WEB LINKS

CP4O Project: http://www.satoc.eu/projects/CP4O/
SAMOSA Project: http://www.satoc.eu/projects/samosa/
SAMOSA Configuration Control: http://www.satoc.eu/projects/samosa/samosa_config.html
ESA: http://esa.int
ESA Earth Observation: http://earth.esa.int
STSE: http://due.esrin.esa.int/stse/
ESA GPOD (Grid Processing on Demand: https://gpod.eo.esa.int/services/CRYOSAT_SAR/
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6 ANNEX 1 - ABSTRACT

Improved Oceanographic Measurements from SAR Altimetry: Key Results and Recommendations from the ESA CryoSat Plus For Oceans Project

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Introduction

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 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; and High Resolution Sea-Floor Bathymetry, A further activity developed and evaluated improved geophysical corrections for use with CryoSat data.

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.

The results are of course also highly relevant to support the planning for future missions, including Sentinel-3 and Jason-CS/Sentinel-6.

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.

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, the coverage and extent of which are listed in the following table:

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 CryoSat 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 CryoSat mission
Open & 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 (Coastal)	Jan 2011- Jan 2013

Table 1: List of CryoSat products developed and evaluated in CP4O

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. The objective is to provide a product consistent with the low rate mode product, although the processing necessarily then loses the higher along track resolution that is otherwise available in SAR mode.

Two “RDSAR” products were assessed, the RADS product produced by TUDelft/NOAA/EUMETSAT, and the CPP product generated by CNES. It was found 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 along side concurrent data from other satellite missions.

It is important to note that the SAR mode CryoSat SIRAL transmission and reception sequencing results in sampling gaps along track. A consequence is that the 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.

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.

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.

Products from two types of SAR L1B to L2 retracking processing schemes 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.

Improved performance of SAR mode over the open ocean was confirmed in terms of:

- Improved precision in range and SWH with respect to LRM data.
- Improved along track resolution in SLA and SWH, scales of less than 100km can be resolved
- The SAR products are consistent with LRM products, or have known biases.

In terms of the different 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 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.

Study of SAR and SARin data in the Coastal Zone

Although further work on a larger data set is necessary, analysis of a Total Water Level Envelope product derived from CryoSat SAR mode has shown that the SAR product can provide low noise estimates of Sea Surface Height to within 1 km of the coast.

A study of SARin data in the coastal zone has developed and evaluated an improved scheme to minimise the contamination from non-nadir echoes. Further work is recommended to:

- Develop further improve the modified SARin processing scheme
- Produce a test data set to support 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.

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. DTU Space has processed CryoSat SAR Polar Ocean data which have then 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.

SAR mode product for improvements to Sea Floor Topography

Analysis has validated the process applied by DTU Space to generate predictions of sea floor topography from altimeter SSH, and has shown that the SAR altimeter derived bathymetry is more accurate than that derived from conventional LRM, RDSAR data, also offering an improvement on the existing bathymetry models.

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.

Geophysical Corrections

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 over the NE Atlantic of the regional ionosphere correction derived from the SPECTRE service.

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

Scientific Road Map

A Scientific Roadmap has been produced which proposes 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.

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