CP4O

CryoSat Plus for Oceans

ESA/ESRIN Contract No. 4000106169/12/I-NB

D6.1 Scientific Road Map Version 1.0

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EUROPEAN SPACE AGENCY (ESA) REPORT

CONTRACT REPORT

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Glossary

AltiKa	Indian / French Ka band altimeter mission
ATBD	Algorithm Theoretical Basis Document
CCI	Climate Change Initiative – ESA programme for developing Essential Climate Variables with Earth Observation data
CCN	Contract Change Notice
CLS	Collecte Localisation Satellites
CNES	Centre National d'Etudes Spatiales
COMAPI	Coastal Modelling for Altimetry Product Improvement
Copernicus	Programme to establish a European capacity for Earth Observation
CP4O	CryoSat Plus 4 Oceans
CPP	Crysosat Processing Prototype
CryoSat	ESA altimeter mission to measure the Cryosphere
Dcomb	An objective analysis data combination methodology
DPM	Digital Processing Model
DTU	Danmarks Tekniske Universitet
DTU13	DTU Global Marine Gravity Field
DUACS	Developing Use of Altimetry for Climate Studies – CLS altimeter Processing system
ECMWF	European Centre for Medium-Range Weather Forecast
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FBR	Full Bit Rate data – CryoSat Product that contains (in SAR mode) individual complex echo waveforms
Globcurrent	ESA project to generate ocean current products
GMES	Global Monitoring for Environment and Security (now Copernicus)
GNSS	Global Navigation Satellite System
GOP	Geophysical Ocean Product (Delayed mode CryoSat product for oceans)
GOT (*X.Y*)	Global Ocean Tide model derived from satellite altimetry
GPD	GNSS-derived Path Delay
IR2007	International Reference Ionosphere, 2007
Jason	US/French Altimeter Satellite Programme
Jason CS	Continuation of JASON series , funded by Europe and US. Will carry a SAR mode altimeter
JPP	Jason CS Processing Prototype
Lotus	Framework 7 project to develop inland applications for Sentinel-3 altimeter data.
LRM	Low Resolution Mode, sometimes also called Low Rate Mode
L1B	CryoSat Product that contains (in SAR mode) multi-looked waveforms
L2	CryoSat Product that contains geophysical parameters
MyOcean	EU GMES Programme to provide ocean monitoring and forecasttng products
MWR	Micro-Wave Radiometer
NCEP	National Center for Environmental Predictions
NEA	North East Atlantic
NOAA	National Oceanic and Atmospheric Administration
NOC	National Oceanography Centre

NRT	Near Real Time
NWF	Numerical Weather Forecasting
PAR	Preliminary Analysis Review – CP4O Technical Note reviewing the state of the art of SAR altimetry at October 2012
PDF	Probability Density Function
PISTACH	CNES funded project to develop a Processing Prototype for coastal hydrological applications of altimeter data
PLRM	Pseudo-LRM
PSD	Power Spectral Density
PTR	Point Target Response
PVR	Preliminary Validation Report
RADS	Radar Altimeter Database System (TU Delft) - http://rads.tudelft.nl/rads/rads.shtml
RDSAR	ReDuced SAR
SAMOSA	SAR Altimetry Mode Studies and Applications – ESA funded Project
SARIN	Synthetic Aperture Radar INterferometric mode
SAR	Synthetic Aperture Radar
Sentinel-1	European C-Band SAR mission in the Copernicus Sentinel series, launched 2014
Sentinel-3	Planned European EO ocean mission in the Copernicus Sentinel series, will carry a SAR mode altimeter, ocean colour instrument and surface temperature radiometer
Sentinel-6	Planned follow on to Sentinel-3
Sigma0, σ0	Nadir, normal incidence surface backscatter, measured in dB
SIRAL	Synthetic aperture Interferometric Radar ALtimeter
SLA	Sea Level Anomaly
SPECTRE	Service and Products for ionosphere Electronic Content and Tropospheric Refractivity over Europe from GPS data – Regional Ionosphere maps
SSB	Sea State Bias
SSH	Sea Surface Height
SST	Sea Surface Temperature
STSE	Support To Science Element
SWH	Significant Wave Height
TU Delft	Technical University of Delft
TWLE	Total Water Level Envelope
U Porto	University of Porto
WTC	Wet Tropospheric Corrections

Reference Documents

RD 1 Naeije, M. and P. D. Cotton, 2014: "Preliminary Analysis Report", Technical Report for Cryosat Plus for Oceans (CP4O) Project. ESA Contract No. 4000106169/12/I-NB

RD 2 Scharroo. R., 2014, RADS RDSAR Algorithm Theoretical Basis Document, CP4O Technical Note, WP4000

RD 3 Naeije, M. and R. Scharroo. 2014, Product Validation Report of the RADS RDSAR processing for oceans, CP4O Technical Note, WP4000

RD 4. Boy F., and T. Moreau, 2013. "Algorithm Theoretical Basis Document (ATBD) of the CPP RDSAR numerical retracker for oceans", CNES report, S3A-NT-SRAL-00098-CNES

RD 5 Moreau T., F. Boy and M. Raynal, 2013. "Product Validation Report (PVR) of the CPP RDSAR numerical retracker for oceans", CLS-DOS-NT-13-155, WP4000 CP4O

RD 6 Boy F., and T. Moreau, 2013. "Algorithm Theoretical Basis Document (ATBD) of the CPP SAR numerical retracker for oceans", CNES report, S3A-NT-SRAL-00099-CNES

RD 7. Moreau T., F. Boy and M. Raynal, 2013. "Product Validation Report (PVR) of the CPP SAR numerical retracker for oceans", CLS-DOS-NT-13-156, WP4000 CP4O

RD 8 Egido, A, 2014, "Algorithm Theoretical Basis Document (ATBD) for Starlab SAR Ocean Data Product (SAMOSA)". CP4O Technical Note, WP4000

RD 9 Egido, A, 2014, "Product Validation Report (PVR) for Starlab SAR Ocean Data Product (SAMOSA). CP4O Technical Note, WP4000

RD 10 Cotton, P.D., S. Dinardo and B Lucas, 2014, "Algorithm Theoretical Basis Document (ATBD) for SAR Ocean Data Products Produced by ESA (ESRIN)". CP4O Technical Note, WP4000

RD 11 Gommenginger C., P. Cipollini and H Snaith, 2014, "Product Validation Report (PVR) for SAR Altimetry over the Open Ocean and Coastal Zone". CP4O Technical Note, WP4000

RD 12 Garcia, P., 2014, "Algorithm Theoretical Basis Document (ATBD): SARin for Coastal Ocean. CP4O Technical Note, WP4000

RD 13 Stenseng, L., 2014, "Algorithm Theoretical Basis Document (ATBD): SAR for Polar Ocean." CP4O Technical Note, WP4000

RD 14 Stenseng, L., 2014, "Product Validation Report (PVR): SAR for Polar Ocean. CP4O Technical Note, WP4000

RD 15 Andersen, O.B., 2014, "Algorithm Theoretical Basis Document (ATBD): SAR for Sea Floor Bathymetry." CP4O Technical Note, WP4000

RD 16 Andersen, O.B., 2014, "Product Validation Report (PVR): SAR for Sea Floor Bathymetry. CP4O Technical Note, WP4000

RD 17 Cancet, M., 2014, "Algorithm Theoretical Basis Document (ATBD): Ionospheric Correction." CP4O Technical Note, WP4000

RD 18 Cancet, M., 2014, "Product Validation Report (PVR): Ionospheric Correction. CP4O Technical Note, WP4000

RD 19 Cancet, M., 2014, "Algorithm Theoretical Basis Document (ATBD): Regional Tide Correction." CP4O Technical Note, WP4000

RD 20 Cancet, M., 2014, "Product Validation Report (PVR): Regional Tide Correction". CP4O Technical Note, WP4000

RD 21 Fernandes, M. J., C Lazaro, and A. L. Nunes, 2014, "Algorithm Theoretical Basis Document on the Improved Wet Tropospheric Correction for CryoSat-2." CP4O Technical Note, WP4000

RD 22 Fernandes, M. J., C Lazaro, and A. L. Nunes, 2014, "Product Validation Report on the Improved Wet Tropospheric Correction for CryoSat-2." CP4O Technical Note, WP4000

RD 23 Labroue S., M. Raynal, T. Moreau. 2014. "Validation Report: WP5000 Assessment of CPP PLRM Retracking", CLS-DOS-NT-13- 155. CP4O Technical Note

RD 24 Labroue S., M. Raynal, T. Moreau. 2014. "Validation Report: WP5000 Assessment of RADS RDSAR", CP4O Technical Note

RD 25 Labroue S., M. Raynal, T. Moreau. 2014. "Validation Report: WP5000 Assessment of CPP SAR retracking", CLS-DOS-NT-14- 113 CP4O Technical Note

RD 26 Raynal, M., T. Moreau.2014. "Validation Report: WP5000 Assessment of SAMOSA SAR Solution (ESRIN)", CLS-DOS-NT-14- 084 CP4O Technical Note

RD 27 Raynal, M., T. Moreau. 2014. "Validation Report: WP5000 Assessment of SAMOSA3 SAR retracker (S3 DPM 2.3.0)", CLS-DOS-NT-14- 085 CP4O Technical Note

RD 28 Raynal, M., T. Moreau. 2014. "Validation Report: WP5000 Global wet tropospheric correction (U Porto)", CLS-DOS-NT-14- 081 CP4O Technical Note

RD 29 Raynal, M., T. Moreau. 2014. "Validation Report: WP5000 Regional tidal correction (Noveltis)", CLS-DOS-NT-14- 083. CP4O Technical Note

RD 30 Raynal, M., T. Moreau. 2014. "Validation Report: WP5000 Ionospheric correction (Noveltis)", CLS-DOS-NT-14- 082. CP4O Technical Note

RD 31 Gommenginger, C., C. Martin-Puig, L Amarouche, R. K. Raney. 2013. Jason-CS SAR Mode Error Budget Study: Review Of State Of Knowledge For SAR Altimetry Over Ocean. Technical Report for EUMETSAT. EUM/RSP/REP/14/749304.

RD 32 Smith W.H.F, and R Scharoo. 2015. "Waveform Aliasing in Satellite Radar Altimetry". IEEE Transactions on Geoscience and Remote Sensing, Vol 52., No 4. April 2015.

RD 33 Dibarboure, G., P.Y. le Traon, and N. Galin. 2013. "Exploring the Benefits of Using CryoSat-2's Cross-Track Interferometry to Improve the Resolution of Multisatellite Mesoscale Fields". Journal of Atmospheric and Oceanic Technology, Vol 30, Issue 7, July 2013.

1. Introduction

This document provides a Scientific Roadmap for future developments 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 Scientific Roadmap includes 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.

In Chapter 2 we summarise the recommendations of priorities for further work that were identified in the Preliminary Analysis Report (RD.1), and in the subsequent review by the CP4O Expert Group. In Chapter 3 we provide a quick reminder of the CryoSat derived products that were developed, validated and assessed in CP4O, and in Chapter 4 we summarise the key findings of the validation and assessments of these products in terms of priorities for further developments. We also include in this chapter recommendations that came out of discussions at the final project meeting in ESRIN in June 2014. In Chapter 5 we report on the plans within the CP4O team for further development and exploitation of these products.

Finally, in Chapter 6 we provide a summary in the form of an overall Scientific Roadmap to build on the work of CP4O.

2. Key Issues from the Preliminary Analysis Review

2.1. Introduction

In this section we highlight key issues in SAR altimetry for which further investigation is recommended, as identified in compiling and reviewing the Preliminary Analysis Review (PAR), **RD.1.**

RD.1 was produced at the beginning of the CP4O project in order to provide a summary of the "State of the Art" of SAR Altimetry at a specified time (October 2012), as a basis for further developments within the project. The PAR was first produced in June 2013, and subsequently updated in June 2014 to incorporate expert reviewer input. Eight priority issues were identified and are listed with recommended further actions below.

2.1 Key Issues from PAR

2.1.1.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 planned 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.***

2.1.2.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, [RD 32]). 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 those received in Low Resolution Mode. The difficulty comes about because there are insufficient samples in the waveform to accurately recreate 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.***

2.1.3.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.

2.1.4.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.***

2.1.5.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.***

2.1.6.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.

2.1.7.Oceanographic Applications of SARin data

SARin mode data can be processed to retrieve across track slope and so provides the potential to extract 2d (along track and across track) information on ocean slopes. Some initial studies have looked into this possibility (e.g. Dibarboure et al., [RD 33]). ***Further work is recommended to compare the SAR/SARin performance and statistics by simply processing SARin as non-interferometric SAR data.***

2.1.8.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, both the CPP and RADS products (those evaluated in CP4O). Both the CPP and NOAA 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 is planned for Sentinel-3 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 [RD 31] 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. CryoSat SAR Altimeter Data Products Developed in CP4O

The CP4O project developed and assessed three types of products:

- **"RDSAR" products** - SAR mode data processed to be consistent with, and as equivalent as possible to Low Resolution Mode 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, at a spatial resolution compatible to that of the SAR altimeter data.

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 3.1 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.

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. (RD.2 - RD. 22).

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 3.1 Table of products developed and assessed within CP4O. Data sets highlighted in bold are available for download on the CP4O ftp directory

4. Results from Product Validation Reports and Impact Assessment Summaries

4.1. Introduction

The products listed in Table 3.1 were validated as part of the product development process and then subjected to an independent assessment carried out by CLS. We summarise the key findings of the validations and independent assessments below, together with points that were raised during discussions at the final CP4O project meetings at ESA/ESRIN in June 2014.

4.2. RDSAR

4.2.1. CLS Impact Analysis – Open Ocean

Two RDSAR products were assessed: the CNES CPP product and the TU Delft RADS product. The major objective of RDSAR processing is to provide a "Pseudo" LRM (or RDSAR) product that is entirely consistent with the LRM product. A direct comparison between CryoSat LRM and RDSAR products is not possible as SAR mode and LRM data are not available at the same time. Instead overall statistics and the analysis of the products at the point of transition were used for the assessment.

CPP Product (RD.5 and RD.23):

- For SWH, analysis showed there was a seamless transition between RDSAR and LRM products, but a bias between both the RDSAR and LRM SWH when compared to Jason-2.
- Analysis of Sea Level Anomaly showed a seamless transition for some data, but a bias / step at transition in other data. Also some discrepancies between ascending and descending tracks was observed over the from the Pacific SAR region.
- Analysis of a longer period data set is recommended to provide improved statistics and to investigate if a drift evolving with time is present.

RADS Product (RD. 3 and RD. 24):

- Good agreement between the (RADS) RDSAR and LRM was seen at the mode transitions with no significant bias in SWH or SLA. The 1 Hz noise on the RDSAR is higher than for the LRM, though less than the theoretical √3 factor, because of the additional averaging applied along track (see Figure 4.1.
- 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. A later version of the CPP processor corrected a one-gate shifted waveform error, and comparisons then showed very similar performances between RADS and CPP in terms of SWH and no residual dependencies on SWH in the other measured parameters.

- However a time tag difference of -540 μs between the CCP 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.

4.2.2. Final Review Meeting Discussions / Recommendations for RDSAR

It was noted that for Sentinel-3, there will be a need to plan for validation of RDSAR against LRM, which will in turn require suitable mission planning during the validation phase (e.g. to provide LRM/SAR crossovers). Thus the recommendations for RDSAR data are:

a. 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.

b. Suitable planning should be made for the Sentinel-3 validation phase to support a validation of Sentinel RDSAR data

c. (also section 2.1.8) The RDSAR processing schemes should be further developed to improve the waveform statistics so they are more consistent with those of LRM data.

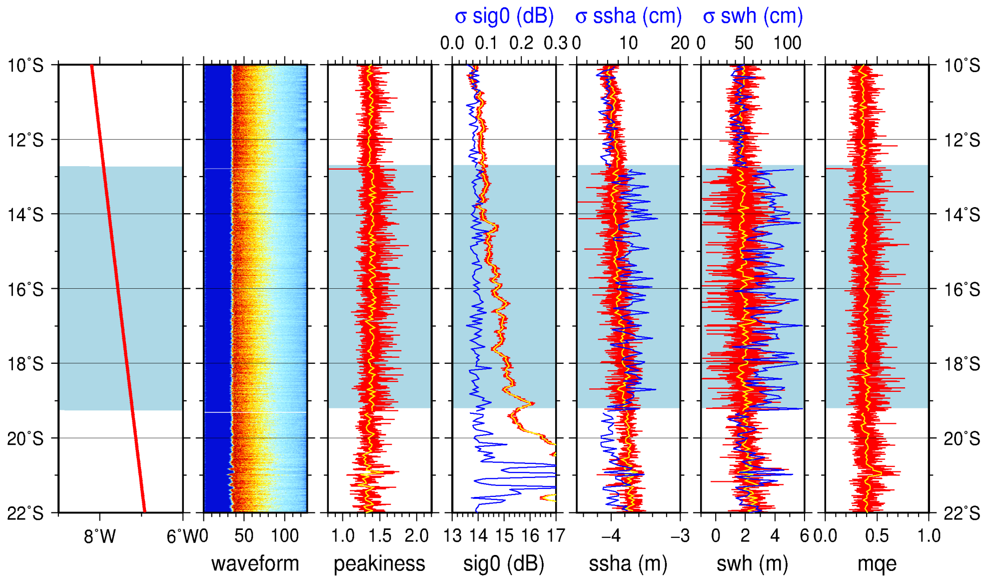

Figure 4.1 *Time series of LRM – RDSAR- LRM data near St Helena in the South Atlantic, demonstrating consistency across the products. The blue sector represents the RDSAR coverage, the white LRM. Credits TU Delft*

4.3. SAR for Coastal and Open Ocean

Three L2 SAR processing schemes were developed and validated for application in open and coastal ocean, and then products produced by these schemes subjected to an independent impact assessment by CLS. These three processing approaches are the CNES CPP SAR Numerical retracker (RD.6), the Starlab application of the SAMOSA retracker (RD 8), and the ESA application of the SAMOSA retracker (RD 10).

We summarise the key findings and recommendations from the validation and impact assessment reports below:

4.3.1. CLS Impact Analysis – Open Ocean

CPP Numerical SAR Retracker (RD.7, RD.25)

- Shows improved content for SLA, SWH and σ0 at scales below 100 km. The more continuous decay of the SLA power spectrum should yield better observations to capture oceanic structures below 100 km (Figure 4.2).
- Surface Backscatter (σ0) provides more short scale content and thus more accurate content due to the 300 m footprint in the along track direction.
- The SLA shows no residual errors correlated to mis-pointing or to radial velocity. Long wavelength error correlated with SWH has been found, suggesting either an error in the SAR re-tracking or a different Sea State Bias (SSB) behaviour between LRM and SAR modes. The impact is close to 0.4% SWH, providing a SAR SSB higher than the LRM SSB. *This effect on SSB should be further confirmed with other SAR re-tracking schemes.*
- The SWH exhibit residual error correlated with SWH close to 4% SWH.
- σ0 shows negligible bias of 0.2 dB m, possibly correlated with mispointing.
- The absolute biases on SAR parameters are close to 3 cm for range, 5 cm for SWH and 0.4 dB for sigma0.
- CNES plans further improvements to the CPP SAR processing scheme to improve SWH retrieval.

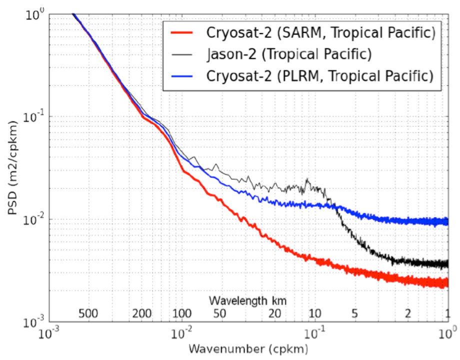

Figure 4.2: *SAR mode (red) can resolve scales from 10-100km, not observable by conventional altimetry (Jason-2: Black, Cryosat-2 "Pseudo" LRM: blue) Credits: CNES/CLS*

SAMOSA 3 SAR Retracker Starlab Implementation (RD.9, RD.25)

The Starlab implementation of the SAMOSA retracker is based on a modified version of the so-called "SAMOSA-3" model, which is a reduced version of the full analytical "SAMOSA-2" model, with some terms removed to improve computational efficiency. The modifications to SAMOSA-3 involve the re-inclusion of the SAMOSA-2 first order term, and an approximation for the effect of thermal noise on the waveform.

Key findings from the impact assessment and product validation are:

- In terms of range and σ0, the agreement between SAMOSA3 and CPP outputs products is near perfect with close behaviour and very similar performances. Differences of the order of few mms in range and one tenth of dB in σ0 are reported, and are found to be primarily dependent on SWH, but also on roll angle (as seen in the σ0 analysis), and at a lesser extent, on other parameters (such pitch angle and radial velocity). *Further analysis would be needed to more precisely evaluate these dependencies.*
- The SWH computed by the SAMOSA3 SAR retracker exhibits significant errors due to the Gaussian approximation of the Point Target Response (PTR) in the SAMOSA3 ocean model. *These errors might be corrected applying a dedicated correction Lookup Table to the SWH estimates.*

SAMOSA SAR Retracker - ESA Implementation (RD.11, RD.25)

ESA staff produced a number of data sets with different implementations of the SAMOSA retracker to allow an assessment by the CP4O team of the impact of different individual terms. These different implementations are described in RD.10. The data set used by CLS for the impact assessment (below) was a complete implementation of the full analytical SAMOSA model (SAMOSA-2). The key findings from this assessment were:

- Agreement for all parameters between ESRIN SAR solution retracker outputs and CPP products is near perfect. Differences of few mm in range, few cm in wave height and one tenth of dB in σ0 are reported, primarily dependent on SWH, but also on roll angle (as seen in the σ0 analysis). *Further analysis would be needed to more precisely evaluate these dependencies.*
- However, all the observed differences are relatively small, and may be even considered as negligible. Thus, these results demonstrate that both re-tracking algorithms (CPP and SAMOSA 2) have very close behaviour and very similar performances. *They are also well suited to derive very accurate and precise SAR altimeter measurements for the current CryoSat mission and for future missions (including Sentinel-3 and Jason-CS).*

4.3.2. NOC Evaluation – Open and Coastal Ocean

NOC assessed the performance of six different implementations of the SAMOSA echo model for open and coastal ocean (RD.11). Their conclusions are summarised below:

For Open Ocean

- There is excellent agreement between the results of various SAMOSA SAR retrackers and the CNES numerical retracker. The full SAMOSA analytical model (SAMOSA 2), and the modified versions of SAMOSA 3 perform particularly strongly. The un-modified version of SAMOSA 3 (consistent with the Sentinel 3 DPM baseline) showed the most marked difference from the CNES results.
- By focussing on open ocean buoys only and adopting very careful data editing, CryoSat SAR SWH shows no bias against buoys in the open ocean.
- Results for SAR SSH and SWH noise as a function of SWH confirm previous findings about the performance of SAR altimetry with regards to reduced noise in comparison with LRM.

The following issues were highlighted:

- The implementation of the SAMOSA echo model (SAMOSA-2) in the current version of the Sentinel-3 DPM does not perform as well as modified implementations, particularly in terms of significant wave height retrieval. *It is recommended that the DPM is updated to the best performing implementation as evaluated in CP4O.*
- Analyses of larger datasets are required in order to obtain more robust statistical results and estimates of the uncertainty.
- The use of misfit for data editing should be further explored.
- New and more robust methods to evaluate noise statistics could also be beneficial.

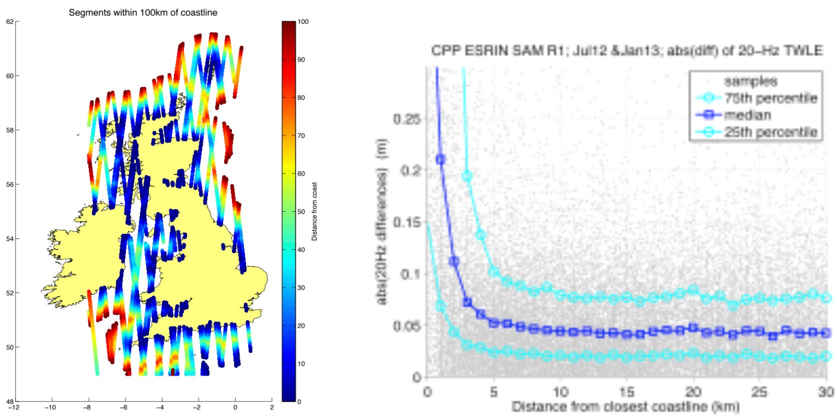

Figure 4.3: *Cryosat-2 data provides measurements close to the coast (left panel), and maintains accuracy to within 5km (right), a significant improvement on previous missions. Credits NOC*

For Coastal Ocean

- Only an initial analysis of data from the ESRIN implementation of the SAMOSA retracker was possible. Analysis was focussed on the measurement of the total water envelope and validation against tide gauge data, but there are a number of difficulties to be addressed in terms of adequately correcting for near-shore effects (e.g. tidal, wave field modification). Thus whilst some early results were encouraging, demonstrating that a 5cm precision in 20Hz range was maintained to within

2 km of the coastline (Figure 4.3), the main recommendation *is that a comprehensive evaluation of CryoSat SAR data in the coastal area is carried out.*

4.3.3. Final Review Meeting Discussions / Recommendations for coastal and open ocean SAR applications

The following priorities for further work regarding applications of SAR altimeter data in the coastal and open ocean are recommended:

a. 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. See also section 2.1.2.
b. Various processing options to optimise the generation of the Doppler Echo (e.g. selection / weighting of waveforms) should be investigated and evaluated. See also section 2.1.3 and 2.1.4.
c. The long wavelength error in CPP SLA and SWH correlated to SWH should be further investigated.
d. 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
e. CNES plans further improvements to the CPP SAR processing scheme to improve SWH retrieval
f. Investigation of the dependence on retrieved parameters by SAMOSA-3 on SWH, roll angle, pitch angle and radial velocity are recommended
g. The S-3 DPM should be updated to the best performing implementation found in CP4O.
h. 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.
i. A comprehensive evaluation of CryoSat SAR data in the coastal area should be carried out.

4.4. SAR Polar Ocean

A Polar Ocean sea surface height data set was produced by DTU Space from CryoSat SAR data, by using a re-tracking processing scheme (LARS) especially developed for polar oceans (RD. 13). This was applied to the ESA CryoSat L1B (Baseline B) product for 2012. The products developed were Polar Ocean Sea Surface Height, Polar Mean Sea Surface model (DTU13), and Polar Mean Dynamic Topography (Figure 4.4). The first two of these products were validated against the limited available reference data, and the findings reported in RD.14.

Conclusions are:

- The waveform classification scheme was validated against (limited) in-situ data.
- Comparison (of Mean Sea Surface) to previous models indicates significant improvements
- Trend and bias analysis indicates errors related to inaccuracies in open ocean areas.

Recommendations for further work regarding the application of SAR altimeter data in the polar ocean are:

a. 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.

b. 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

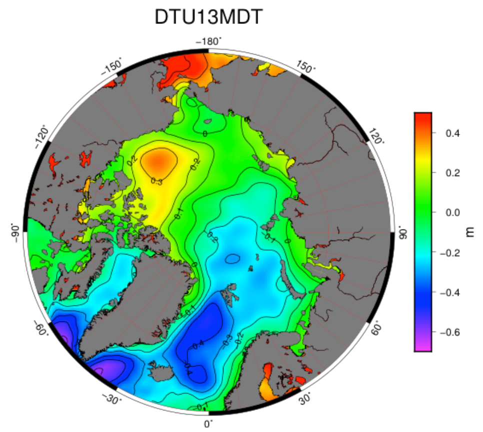

Figure 4.4: *Cryosat-2 data provide important improvements to maps of Mean Dynamic Topography for the Arctic Ocean, and so support analysis of key ocean circulation features. Credits DTU Space*

4.5. SAR for Sea Floor Bathymetry

A sea floor bathymetry product was developed and assessed by DTU Space from CryoSat SAR Baseline-B SAR FBR data provided by ESA (ESRIN). The data cover the period October 2012 to January 2014, and a region in the North Pacific in the area 15°-25°N, 178°E-167°W. Standard height corrections were applied, with an empirically derived Sea State Bias correction and the geoid correction updated with the EGM 2008 geoid. An ad-hoc retracker bias was added to bring the Mean Sea Surface Height into agreement with DTU10MSS.

Bathymetry was derived for the whole region at 1Hz, 2Hz and 4Hz, and compared to available bathymetry models and vessel measured profiles. Whilst there were significant differences in the long wavelength content (which cannot be captured by altimetry), there was clear evidence that the SAR derived bathymetry captured short wavelength features also seen in the ship sounding data, and identified potential features not seen in existing bathymetric models (Figure 4.5). Interestingly the analysis also demonstrated the need for a better long wavelength bathymetry to support such investigations.

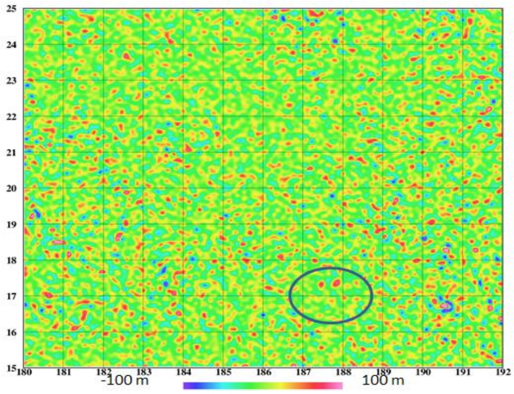

Figure 4.5: *The retrieved residual bathymetry signal relative to a "pre" Cryosat-2 era bathymetry (DTU10 Bathymetry). There are some clear indications in the marked circle of a bathymetric/tectonic feature that could be an improved mapping of an existing seamount or a mapping of an unknown seamount. Credits DTU Space*

Conclusions are:

- We were able to predict sea floor bathymetry better than one year data from both conventional LRM data and RDSAR data from the RADS database.
- We were also able to predict bathymetry in the central (shallow most) part of the region more accurate than with LRM and RD SAR data in this analysis. We were even able to predict bathymetry more accurate that with the DTU10 and Sandwell and Smith V17.1 (2014) bathymetry model.
- The validation performed here demonstrates that the potential of SAR altimetry derived within the ESA CP40 project to derive sea floor bathymetry and the ability to predict bathymetric features using Cryosat-2 SAR altimetry.
- We did not yet see the full potential of using Cryosat-2 for sea mapping. However we highlighted the potential of using 1,2 and even 4 Hz for sea floor mapping to resolve finer scale structures.

Recommendations are:

- The full potential of using SAR for sea floor bathymetry should be further investigated as bathymetry is a fundamental important parameter for i.e. climate and ship safety and Cryosat-2 SAR can provide very valuable new information which is to be investigated further.
- We recommend a revisit of the investigation area using multiple years of altimetry to retrieve the full potential at these medium water depth (3-5 km).
- We recommend a careful analysis is performed in more coastal / shallow water region to explore the limitations of the data as we expect that there is also a huge potential here with the very positive results obtained.
- The results also point toward performing a study with the use of a better prior bathymetry for the long wavelength signal which proved inadequate in our investigation. We used GEBCO-1 (version 2008) which does not include altimetry. However we have recently been alerted to a new 30 minutes NGDC

bathymetry (Becker et al., 2009) which should also use the bathymetric observations presented here and hence should give considerably better agreement.

4.6. SARin for Coastal Applications

The analysis of SARIn data on tracks crossing / or running parallel to, coastlines demonstrated how off-nadir echoes from bright targets (usually non ocean surfaces) create multi-peaked waveforms that cause errors in the retrieved range measurements (RD.12). A technique was developed that used information from the phase and coherence waveforms to identify the true location of the nadir echo which was then used to "seed" a modified retracker. This technique was shown to provide improved tracking in a number of demonstration tracks (Figure 4.6). However, this technique can only be applied to interferometric SAR mode data, from which coherence and phase information are available. Thus, whilst it can be used for CryoSat data, it would not be applicable to future missions where the SARin mode is not available.

a. Thus further work is recommended to use SARin data to develop and test approaches to improve retrieval of ocean parameters (especially sea surface height) from SAR altimeter data from tracks over complex coastal topography.

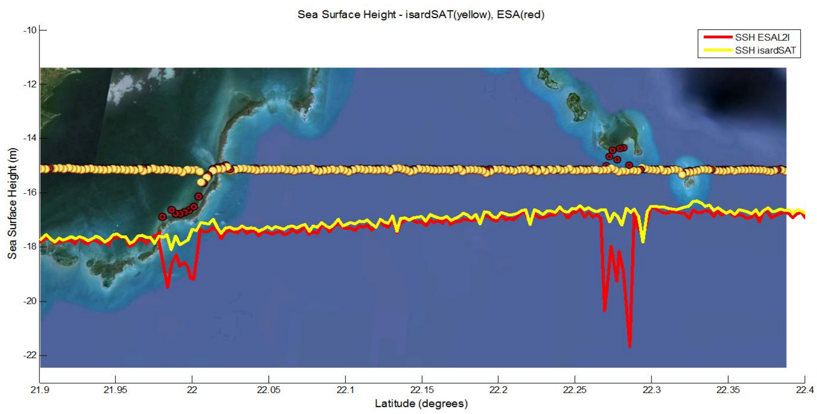

Figure 4.6: *Examples of SARIN data during coastal transitions. Reprocessing (yellow) can correct the initially processed data (red) which selects reflections from bright targets away from the sub-satellite track. Credits: isardSAT*

4.7. Geophysical Corrections

Products providing improved Geophysical Corrections (Wet Troposphere, Ionosphere and Regional Tides) for use with CryoSat data were generated and evaluated in CP4O. As noted above these corrections were required because CryoSat is a single frequency altimeter without an on-board Microwave

Radiometer. The ATBDs and PVRs for these three products are available in (RD.17-RD.22)

4.7.1. CLS Impact Analysis – Open Ocean

The impact assessment carried out by CLS came to the following conclusions.

Wet Troposphere – The assessment confirmed an appreciable improvement over the modelled WTC correction currently provided with the CryoSat data at latitudes < 50°, and in coastal regions. *However an analysis over a longer time period is recommended.*

Regional Tides – The assessment confirmed that the COMAPI model is consistent with existing tide model (GOT 4.8) in open ocean and provides good improvement on North-Western European shelf on scales of 50-200 km.

Ionosphere – The assessment found it difficult to evaluate this correction as the ionospheric signal is small in the region for which the product is available (Europe), and it is not an area where there is high ionospheric variability.

4.7.2. Final Review Meeting Discussions / Recommendations

Recommendations for further work in terms of Geophysical Corrections are:

a. 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.
b. A global gridded data set should be generated to provide a consistent Wet Troposphere Correction across all current satellite missions.
c. IRI 2007 should be used as a source for electron content above CryoSat orbit height.

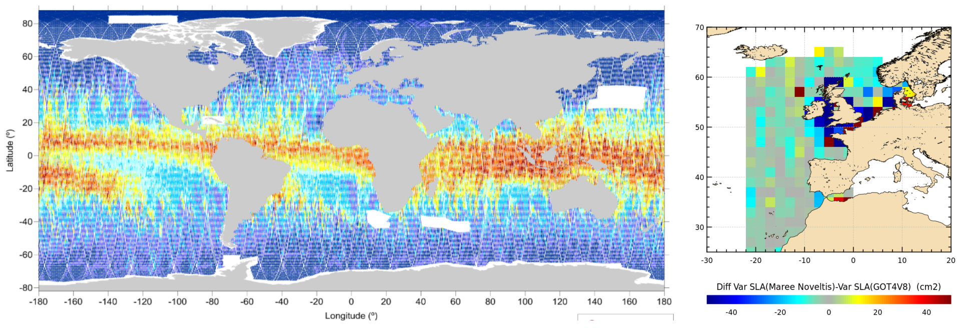

Figure 4.7*(Left) Wet Troposphere Correction from Dcomb algorithm. (Right) Regional Tide Model: Improvement in SLA variance (cm^2) between COMAPI (tide model used in CP4O) and GOT4.8 tidal model. Credits University of Porto and CLS*

5. Product Maturity Assessment, Priorities and Plans for Further Development

5.1. Product Maturity and Development Plans

All partners were asked to assess the maturity of the products developed and evaluated in CP4O, in terms of need for further development, and to outline plans for further development and eventual exploitation. Their responses are summarised in Table 5.1

5.2. Priority areas for Research

CP4O partners were also asked to identify priority areas for further work, and these are summarised below:

a. ***The unexpected high SAR SWH noise level is currently an issue.***
b. ***The sensitivity of the SAR-mode data to sea state conditions and various instrumental parameters should be investigated and characterized.***
c. ***Ensuring seamless transition between LRM and RDSAR data. While a lot has been accomplished all parties have shown some inconsistencies at the transition between modes.***
d. ***Develop a strategy to ensure consistency of long-term records of altimetric sea level when going from the LRM missions of the present to SAR mode altimetry of the future (Sentinel-3 and -6)***
e. ***Further establish the advantages of SAR mode data over LRM data. (The SAR-mode ability to capture oceanic structures of smaller scales needs to be clearly assessed.)***
f. ***In terms of corrections, a key issue is the sea state bias (SSB), in particular the SSB for the SAR mode, but also for LRM mode in the coastal regions.***

Product	Partner	Maturity	Development Plans	Exploitation Plans
LRM, RDSAR: RADS 1Hz data	TU Delft	Fully mature, operationally produced for > 2 years	Possible refinements to LRM, RDSAR processing Planned extension to include SAR mode provided either CryoSat data becomes mature (Baseline C, GOP data), or SAR retracker implementation by TU Delft.	Planned to CryoSat and Sentinel-3. If/ when extended to other missions, readers and corrections will be developed and supplied. The RADS database has been used extensively as reference for ESA CCI for Sea Level. Regarded as the de facto standard for a Climate Data Record.
RDSAR RADS 20Hz data and waveforms	TU Delft	Developed for CP4O Full independent evaluation needed	Could be pilot for general distribution of 20-Hz data through RADS. The same RDSAR techniques can be used for the processing of “individual echoes” of Envisat and SARAL, which should be fully equivalent to LRM waveforms.	Applicable to CryoSat and Sentinel-3. Not (yet) an operational product so no established links with other programmes
RDSAR, SAR -CPP	CNES/CLS	Mature Operationally produced Fully validated	Further investigations on SAR mode performance (SWH noise, ability to map short scale structure) on a longer time series. Upgrade echo modelling for S3 and Jason CS.	Sentinel-3, Jason CS: DUACS, PISTACH, Globcurrent, AltiRegional, Lotus, Glyder, postdoctoral research, S3PP (Sentinel-3 Processing Prototype), JPP (Jason-CS Processing Prototype)
SAR - SAMOSA	Starlab	SAMOSA adopted for the Sentinel-3 DPM, but further improvements are recommended	Improvements to implementation of the SAMOSA model are ***proposed as part of a CCN***	For implementation in Sentinel-3 and future SAR altimetry missions
SAR - SAMOSA	ESA	Needs further limited development to enhance SAMOSA3 implementation. A fully operational and configurable	Initial analysis confirmed potential for providing much improved coastal zone measurements. ***Further evaluation for coastal application is needed and is proposed as part of a CCN***	

		implementation of both SAMOSA2 and SAMOSA3 is available online at https://gpod.eo.esa.int/services/CRYOSAT_SAR/		
SAR – Polar Ocean	ESA / DTU	Needs limited further development. Some issues need to be improved (ready < 1 year)	Test possible improvement from additional FFT interpolation (beyond the Baseline-B ESA L1b). Additional testing in ocean around Antarctica. ***Development of Polar Regional tide model proposed for CP4O CCN***	The CP4O developed Polar Ocean classification and retracking methods will be used to produce sea surface heights to be assimilated into the tide model. 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. Can be applied to all future SAR altimeter missions with polar coverage, with appropriate adaptations.
SAR – Sea Floor Bathymetry	ESA/DTU	Needs further research and development (~ 1 year) before implementation / exploitation	Initial results are encouraging. Recommendations are to revisit the same area of the Pacific using a longer data set and to carry out a careful analysis in shallower / coastal regions. Also a better prior bathymetry should be used as input	The aim will be to generate a higher resolution altimetry based bathymetry. Bathymetry is a fundamentally important parameter for a range of applications including climate, ocean circulation models and ship safety.
SARin – Coastal Ocean Applications	isardSAT	No plans for developing SARin data product	Although there are no plans for developing SARin data product, analysis of SARin data can help to develop processes and approaches to improve SAR data products for coastal oceans, and ***this is the subject of a proposal for a CCN.***	
Wet Tropo	U Porto	Needs limited further development. Some issues need to be improved (ready	The correction is ready and proved to be an improvement with respect to the WTC from the ECMWF operational model, but some	The correction is applicable to any altimeter mission, present or future, but of particular interest to SARAL/AltiKa, Sentinel-1,

		< 1 year)	issues should be further investigated. Also a gridded correction would be of benefit to other missions and other applications.	Sentinel-3, Jason-3 and Jason-CS. Funding needed to implement the global WTC grids and the GPD/DComb WTC for Sentinel-3 and other future altimeter missions. In the scope of ESA Sea Level CCI the University of Porto is carrying on with the computation of the DComb WTC for CryoSat and the GNSS-derived path delay (GPD) WTC for other missions.
Spectre Ionosphere Correction	Noveltis	For non-NRT altimeter products, the SPECTRE correction is mature (the correction is available after a 3-day delay). For NRT altimetric products, a development is necessary to reach near real-time capacity.	Development plans include the production of global SPECTRE maps and/or regional maps on regions of interest (e.g. the Arctic Ocean). A prototype of the service is already operating for the North Pole area, and the production of Near Real Time ionospheric corrections for altimetry missions.	The correction is applicable to any current or future altimetry mission (in particular Sentinel-3, Jason-3 and Jason-CS).
COMAPI Regional Tide Model	Noveltis	Fully Mature and validated (ready for operational or scientific use now)	Plans for further development include - Implementation of a regional tidal atlas over the Arctic Ocean. ***(included as a proposed CCN work package***) - Update of the COMAPI NEA tidal atlas (better modelling, better bathymetry, longer altimetry time series). - Implementation of regional tidal atlases over the main shelves, where the global tidal models still have large errors.	The correction is applicable to any past, current or future altimetry mission (in particular Sentinel-3, Jason-3 and Jason-CS).

Table 5.1 Maturity assessments and development / exploitation plans for products developed within CP4O

6. Summary – Priority Areas for Research, Plans for Product Development and Exploitation

6.1. Introduction

In this final section we pull together the recommendations and plans for further work identified in the previous chapters and present them within in an overall strategy for priority developments in SAR Altimetry. 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 6.1 provides a diagram of the various aspects and objectives of the different strands of activity.

We have assigned priority rankings (High, Medium, Low) to the recommended activities. These could be seen as somewhat subjective, but are based on expert judgement, and allocated on the basis of what activities are thought most likely to have the most significant impact on the validity / usefulness of the end product.

6.2. 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, with appropriate section references.

- SAR Processing Issues
  - SAR Waveform
  - Under-sampling peaky waveforms: 2.1.2, 4.3.3a: *Medium Priority*
  - Optimising Doppler processing /selection / weighting: 2.1.3, 4.3.3b: *High Priority*

- Purpose /optimisation of Windowing: 2.1.4: *Medium Priority*
- SAMOSA implementation (PTR, Thermal noise): 4.3.3g,h: *High Priority*
- SAR waveform blurring at high alt rates: 2.1.1: *Low Priority*

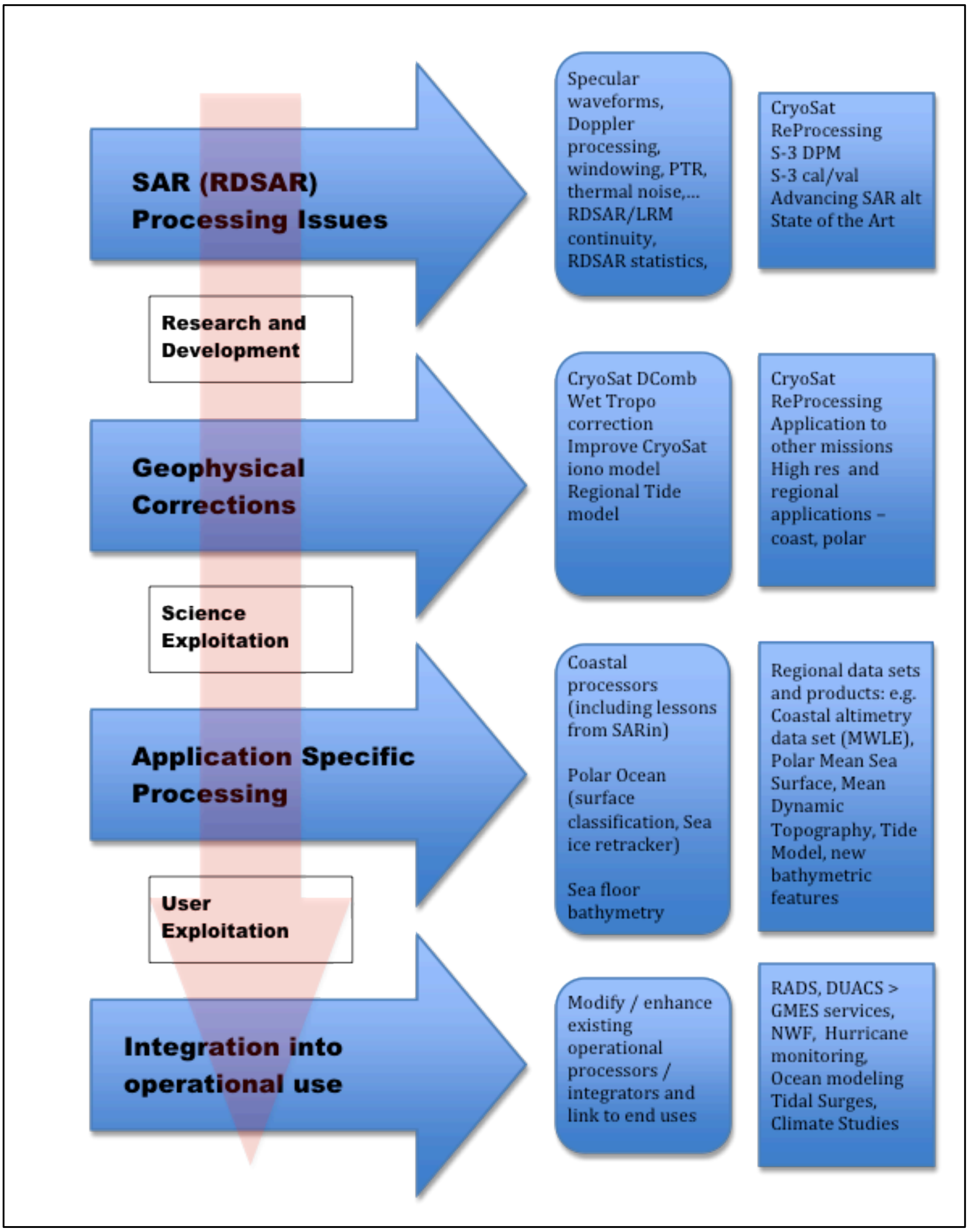

Figure 6.1 Strategy for Continuing / Exploiting CP4O Results

- RDSAR Processing
  - Effect of SAR transmission pattern on waveform statistics: 2.1.8, 4.2.2c: *Medium Priority*
  - How to improve waveform statistics / minimize use of correlated echoes: 2.1.8, 4.2.2c, 5.2c, d, e: *Medium Priority*

- Investigations into SAR Altimetry Characteristics
  - SWH dependencies / errors: 4.3.3c,e,h, 5.2a: *High Priority*
  - Impact of swell: 2.1.5, 4.3.3c: *Medium Priority*
  - Development and evaluation of SAR mode SSB models: 4.3.3d, 5.2f: *High Priority*
  - Dependence of retrieved parameters on roll angle, pitch angle, radial velocity: 4.3.3f, 5.2b: *Medium Priority*
  - Characteristics of Full Bit Rate echoes, stack data: 2.1.6: *High Priority*

- Validation activities
  - Comprehensive evaluation of CryoSat SAR data for coastal application: 4.3.3i: *High Priority*
  - Larger data sets for SAR and RDSAR validation: 4.2.2a, 4.3.3i, 5.2e: *Medium Priority*
  - Sentinel-3 validation planning (mode selection and possible extension of validation period beyond 2 months): 4.2.2b: *Low Priority*

6.3. Geophysical Corrections

It is essential that geophysical corrections are provided that will ensure 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, with section references.

- Geophysical Corrections
  - WTC data set for whole CryoSat mission, global along-track and gridded data sets: 4.7.2a,b: *High Priority*
  - Change ionosphere model used to estimate electron content above CryoSat orbit: 4.7.2c: *Medium Priority*

6.4. Application Specific Processor and Product Development

Some applications of SAR data require specific processing developments, we list below recommendations by theme (also refer to Table 5.1.)

- Open Ocean
  - Sentinel-3 DPM updated to include best performing implementation of SAMOSA3:4.3.3g: *High Priority*
  - Further improvements to CPP SAR mode processing scheme: CPP: 4.3.3e: *Medium Priority*

        - SARin processing for oceanography (e.g. across track slope): 2.1.7: *Medium Priority*
        - Exploitation of the Sentinel-3 (S-3 SPS) simulated test data set: *Low Priority*
- Coastal Ocean
    - SARin investigations, Develop schemes to improve processing of SAR data at coast: 4.6a: *High Priority*
    - Exploitation of the Sentinel-3 (S-3 SPS) simulated test data set: *Low Priority*
- Polar Oceans
    - Cryosat reprocessing (all polar data with consistent Baseline):4.4a: *High Priority*
    - Develop and publish improved Polar tide model: 4.4b: *Low Priority*
- Sea Floor Bathymetry
    - Processing of a longer period of SAR mode altimeter data for the Pacific SAR region, using an improved prior bathymetry: *Medium Priority*
    - Investigations in shallow / coastal regions to investigate potential capabilities of data in this environment.: *Medium Priority*

6.5. Integration into Operational Use

Table 5.1 provides details of the maturity of products assessed within CP4O and the 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. We provide an overview of these plans below:

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 < 1year)

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 so that a fully optimised version can be implemented in an operational processing chain. 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.