CP4O

Cryosat Plus for Oceans

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Abstract

This document is the Development and Validation Plan document resulting from the Preliminary Analysis of the State of the Art activity (Work Package 2000 1000) of the Cryosat Plus for Oceans (CP4O) project. The present document provides an initial overview of the activities planned under WP4000 (Product Development and Validation). These plans were initially described in the project proposal [RD.1], and have been updated as necessary following the analysis of user requirements [RD.2] and the analysis of the state of the art [RD.3], which is the other deliverable from WP2000.

The purpose of this document is to provide sufficient summary information to allow the reader to understand:

- What new products will be developed under each theme
- What input data will be used to generate each product
- The geographical location and time period covered by the product
- The key steps in the processing chain, what new processes and techniques will be applied
- What data will be used to validate these products, and what methodologies will be applied
- How the task will be organised, and who will be involved
- What risks there are

More information on the processing schemes and techniques is provided in [RD.3] and more detail on the data sets to be used (for product generation and validation is provided in the data set user manual **[RD .4]**.

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Abbreviations and Definitions

ATBD	Algorithm Theoretical Basis Document
AMR	Advanced Microwave Radiometer
CLS	Collecte Localisation Satellites
CNES	Centre National d'Etudes Spatiales
CODE	Centre for Orbit Determination in Europe (University of Bern)
COMAPI	Coastal Modelling for Altimetry Product Improvement
CP4O	Cryosat Plus 4 Oceans
CPP	Crysosat Processing Prototype
Dcomb	An objective analysis data combination methodology
DEM	Digital Elevation Model
DTU	Danmarks Tekniske Universitet
DUACS	Developing Use of Altimetry for Climate Studies – CLS altimeter Processing system
ECMWF	European Centre for Medium-Range Weather Forecast
Envisat	ESA Remote Sensing Satellite (2002-2012)
EO	Earth Observation
ERA	ECMWF ReAnalysis
ERS-1	ESA Remote Sensing Satellite (1991-2000)
ERS-2	ESA Remote Sensing Satellite (1995-2011)
ESA	European Space Agency
ESOC	European Space Operations Centre
FBR	Full Bit Rate data – Cryosat Product that contains (in SAR mode) individual complex echo waveforms
FES*YYYY*	Finite Element Solution Global Tide models
FDM	(Cryosat) Fast Delivery Marine Product
GDR	Geophysical Data Record
Geosat	US Altimetry Satellite Mission (1985-90)
GIM	Global Ionospheric Map
GNSS	Global Navigation Satellite System
GOCE	Gravity field and steady-state Ocean Circulation Explorer – ESA Satellite Gravity Mission
GOT (*X.Y*)	Global Ocean Tide model derived from satellite altimetry
GPS	Global Positioning System
IGDR	Interim Geophysical Data Record
IPF	Instrument Processing Facility
IRI95	International Reference Ionosphere, 1995
Jason	US/French Altimeter Satellite (2001-)
JPL	Jet Propulsion Laboratory
LRM	Low Resolution Mode
LUT	Look Up Table
L1B	Cryosat Product that contains (in SAR mode) multi-looked waveforms
L2	Cryosat Product that contains geophysical parameters
MDT	Mean Dynamic Topography
MLE (N)	Waveform re-tracking approach - Minimum Likelihood Estimate –

	providing N (3 or 4) output parameters
MOG2D	2 Dimensional gravity wave model used to model dynamic ocean response to atmospheric winf and pressure forcing
MSS	Mean Sea Surface
MWR	Micro-Wave Radiometer
NCEP	National Center for Environmental Predictions
NEA	North East Atlantic
NIC09	New Ionosphere Climatology generated by Scharroo and Smith
NOAA	National Oceanic and Atmospheric Administration
NRT	Near Real Time
OA	Objective Analysis
OCOG	Offset Centre Of Gravity
OGDR	Operational Geophysical Data Record
PTR	Point Target Response
PVR	Preliminary Validation Report
RADS	Radar Altimeter Database System (TU Delft) - http://rads.tudelft.nl/rads/rads.shtml
RB	Requirements Baseline
RDSAR	ReDuced SAR Mode
RIM	Regional Ionospheric Maps
RMS	Root Mean Square
SAMOSA	SAR Altimetry Mode Studies and Applications – ESA funded Project
SARIN	Synthetic Aperture Radar INterferometric mode
SAR	Synthetic Aperture Radar
SI-MWR	Scanning/Imaging MWR
SIRAL	Synthetic aperture Interferometric Radar ALtimeter
S/N	Signal to Noise Ratio
SLA	Sea Level Anomaly
SPECTRE	Service and Products for ionosphere Electronic Content and Tropospheric Refractivity over Europe from GPS data – Regional Ionosphere model
SSB	Sea State Bias
SSH	Sea Surface Height
SST	Sea Surface Temperature
STSE	Support To Science Element
SWH	Significant Wave Height
TEC	Total Electron Content
TOPEX	US / French Altimeter Satellite (1992-2006)
TU Delft	Technical University of Delft
UPC	Technical University of Catalonia
uTEC	Unit of TEC (10^{16} electrons/m^2).
WTC	Wet Tropospheric Corrections

1 Introduction

The "Cryosat Plus for Oceans" (CP4O) project is supported under the ESA Support To Science Element Programme (STSE) and brings together an expert consortium comprising, CLS, DTU Space, isardSAT, NOC, Noveltis, SatOC, Starlab, TU Delft, and the University of Porto. The main objectives of CP4O are:

- To build a sound scientific basis for new scientific and operational applications of Cryosat-2 data over four different areas, which are: open ocean, polar ocean, coastal seas and 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.

1.1 Purpose, Scope and Goals

This document is the Development and Validation Plan document resulting from the Preliminary Analysis of the State of the Art activity (Work Package 2000 1000) of the Cryosat Plus for Oceans (CP4O) project. The present document provides an initial overview of the activities planned under WP4000 (Product Development and Validation). These plans were initially described in the project proposal **[RD.1]**, and have been updated as necessary following the analysis of user requirements **[RD.2]** and the analysis of the state of the art **[RD.3]**, which is the other deliverable from WP2000.

The purpose of this document is to provide sufficient summary information to allow the reader to understand:

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- What risks there are

More information on the processing schemes and techniques is provided in **[RD.3]** and more detail on the data sets to be used (for product generation and validation is provided in the data set user manual **[RD .4]**.

1.2 Documents

[RD.1] Cryosat Plus for Oceans, Technical Proposal, SatOC, DTU Space, isardSAT, NOC, Noveltis, STARLAB, TU Delft, University of Porto and CLS, Response to ESA ITT AO/1-6827/11/I-NB, November 2011

[RD.2] Cryosat Plus for Oceans - Scientific Requirements Consolidation (D1.1), STARLAB, NOC, CLS, DTU Space, SatOC, ESA Project Report, March 2013.

[RD.3] Cryosat Plus for Oceans – Preliminary Analysis Review (D2.1), TU Delft, CLS, DTU Space, isardSAT, NOC, Noveltis, SatOC, STARLAB, University of Porto, ESA Project Report, May 2013.

[RD.4] Cryosat Plus for Oceans – Data Set User Manual (D3.2), isardSAT, SatOC, CLS, DTU Space, NOC, Noveltis, STARLAB, TU Delft, University of Porto, ESA Project Report, May 2013.

[RD.5] Cryosat Plus for Oceans, Project Plan v3.1, SatOC, May 2013

[RD.6] Cryosat Plus for Oceans, Financial, Administrative and Management Proposal, SatOC, DTU Space, isardSAT, NOC, Noveltis, STARLAB, TU Delft, University of Porto and CLS, Response to ESA ITT AO/1-6827/11/I-NB, November 2011

1.3 Conclusions from the state of the art analysis

In the PAR **[RD.3]** the number of known issues with the ESA CryoSat-2 Level-2 data products for application to oceanography were listed and assessed. These problems were sufficiently significant that it was concluded these data should not be directly used in the framework of this project. Although the new Fast Delivery Product offers some improvements, as some of the key anomalies have been put right, this still leaves the problem that the main backlog of already processed data retain these anomalies. The project team therefore came to the collective conclusion that within the time frame of the project LRM L2 and SAR L2 were not useful for oceanographic applications and also that SAR L1b was sub-optimal, and so the project analyses would use alternative data sets provided by CNES (CPP) and TU Delft (RADS).

It is important to recognize at the same time the exceptional performance of the SIRAL altimeter on CryoSat-2, and to note that the team was confident that high-quality state-of-the-art products will be available in due course from the ESA processing chain. The work of CP4O will help achieve this aim.

Chapter 4 of **[RD.3]** – the Preliminary Analysis Report - provides a comprehensive and detailed summary of the current state of the art by CP4O theme, and the reader is referred to that document for full details.

For the ***open ocean*** the ultimate objective is to develop and assess products in terms of their potential to contribute to mesoscale and sub-mesoscale oceanography, and to map fine scale features. Available LRM and SAR mode data products were reviewed, their accuracy analysed, and studies that had investigated continuity with respect to previous and concurrent missions were summarised. In addition, the document reviewed a number of approaches that have been developed to produce LRM-like products from SAR mode (RDSAR). The aim of these products is to ensure continuity from coastal zone to open ocean, and continuity from LRM to SAR mode. Finally a review was provided of new SAR retracking schemes that have been proposed, developed and investigated with a focus on mapping fine scale features in the sea surface height.

In the ***coastal zone*** even finer scales are important, as key features vary on smaller temporal and spatial scales. The ability of the above products to produce useful additional in the coastal zone was discussed. The provision of accurate altimetric corrections become especially important in these areas. Also alternative SAR re-tracking schemes may be needed to minimise the effect of land contamination in the radar echo.

Specific issues for the ***polar ocean*** arise in the form of sea ice which require specialised re-trackers and processing schemes. Also we are confronted with the fact that no previous altimeter satellite has gone beyond 81.5° latitude. [RD.3] assessed the performance of the currently available processing techniques, for LRM, SAR and RDSAR products. The ultimate aim of the work in this theme is to develop new products that can make a significant contribution in terms of improving mean sea surface models, mean dynamic topography models, polar ocean circulation, and polar ocean tide models.

In the ***sea-floor mapping*** theme the potential ability of SAR altimetry data to resolve short-wavelength sea surface signals caused by marine gravity and sea-floor topography and the ability to map uncharted seamounts and trenches is addressed. Here it is necessary to use the CryoSat-2 SAR mode data to enable the highest along-track sampling resolution. However, to achieve sufficient cross-track sampling resolution at least 1 year of continuous data over a suitable region is needed. For this theme the SAR area (according to the latest mode mask) in the North Pacific was selected.

Finally, the need for improved geophysical corrections was investigated, including wet troposphere, ionosphere, sea state bias and regional tides.

The clear advantages of the CryoSat-2 SAR data over the conventional LRM data is that more independent looks (multi-look) leads to improved retrieval precision, and though the theoretical factor 2 has not yet been practically achieved, early results do show a factor of 1.5 improvement in sea surface height retrieval. 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 tracks that incident land at about 90° (perpendicular to coastline), and is also less sensitive to sea state. In the near future the Sentinel-3 surface topography mission will provide LRM over the open ocean and SAR globally over all coastal areas and over sea ice. The efforts in the CP4O project will not only benefit the exploitation of CryoSat-2 data but will also pave the way for proper exploitation of SAR data from Sentinel-3 (1st of 2 to be launched in 2014) and later from Jason-CS (to be launched in 2017).

Table 1-1 CP4O product development overview

		Initial Development and Validation	Large scale assessment
1	**LRM** for **Open Ocean**	Global (RADS & CLS)	
2	**RDSAR** for **Open Ocean**	NE Atlantic / Pacific	Global
3	**SAR** for **Open Ocean**	NE Atlantic / Pacific	Global
4	**SAR** for **Coastal Ocean**	South Coast UK	Global / regional Gulf of Cadiz, North-West Mediterranean & German Bight
5	**SARIn** for **Coastal Ocean**	Cuba, Chilean Coast	N/A
6	**SAR** for **Polar Ocean**	Arctic (initially Baffin Bay)	
7	**SAR** for **Sea Floor** Mapping	Pacific / North Pacific	
8	Improved **wet trop correction**	Global, full C2 mission	
9	Improved **iono correction**	Mediterranean Sea, European continental shelf	
10	Improved **regional tides**	North East Atlantic (coastal)	
11	**Other** improved **corrections**	Global (RADS)	

The core of the CP4O project is the next step: the development and validation of algorithms and processing schemes for new CryoSat-2 ocean products. In the WP4000 (Product Development and Validation) 7 new experimental altimeter data sets and 4 data sets with new geophysical corrections will be generated, Table 1-1 gives an overview.

After this stage WP5000 of CP4O will carry out an impact assessment by applying a “round robin” methodology to all data sets. The final aspects of the project are to plan for future exploitation by drawing up a scientific road map to ensure the fullest possible exploitation of CryoSat-2 data over the oceans, and to transfer of the results into scientific and operational activities.

The next sections in this document provide details on the plans for development and validation within WP4000.

2 Products - Development and Validation

2.1 Introduction

In this section an outline of the various planned product developments are presented. This description includes an overview of the products to be developed, including their geographical coverage and time period, together with the objectives for each development and the plans for validation and assessment.

2.2 Open Ocean Altimetry

The ultimate objectives for the products developed under the theme of Open Ocean altimetry are to support the following applications.

For products derived from LRM data:

- Find the best retracker to be applied to the L1b data (RADS/CPP).
- Generate Mean Sea Surface and Mean Dynamic Topography (through the use of the GOCE geoid model) and subsequent analysis of mesoscale and large-scale ocean features (e.g. boundary currents, eddy kinetic energy).
- Assess ocean wind speeds and wave heights, and their contribution to existing operational and research applications.
- Improve Cryosat-2 data by application of specifically modelled ionosphere and wet troposphere models to provide accurate estimates of radar path delay.

For products derived from SAR Mode data:

- Ability to detect short spatial scale 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 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.

2.2.1 LRM For Open Ocean (TU Delft)

<u>Overview, objectives</u>

This task will first select an appropriate algorithm to retrack the CryoSat-2 low rate mode (LRM) data over open oceans. Altimetrics and NOAA have already made significant progress with the production of GDR-type products (through RADS) using LRM fast-delivery and delay-time data. Particularly, the pros and cons of maximum likelihood estimators with four or three parameters (MLE4 and MLE3) need to be clarified. If off-nadir pointing is estimated during the retracking then performance can be boosted, but then star-tracker information needs to be included and checked for possible biases. The verification of the star-tracker information through MLE4 retracking of LRM data will also aid the SAR mode retracking.

The intent is to make a seamless connection between the LRM data and the SAR data.

With the adoption of new retracking algorithms for LRM data comes the additional need to create the corresponding sea state bias model, as that depends on the choice of the retracking algorithm. An appropriate non-parametric sea state bias model, as function of wave height and backscatter coefficient will be determined using the “direct method”.

Geographical coverage and time period,

Global ocean data will be used, from the period from February 2011 to current date (including both LRM and FDM where LRM is not yet available).

Data sources, processing steps, references

Data from the TU Delft RADS altimeter database will be used. The following processing steps are applied:

- Daily download FDM and LRM L1B data from ESA
- Retrack waveforms to compute wave height, backscatter, range (MLE3-type retracker)
- Merge data files (few to tens of minutes normally) into passes and sub-cycles of 29 days (à la GDR) in RADS
- Use additional geophysical corrections from L1B
- Overwrite and add common RADS geophysical corrections
    - SSB (in-house calculation)
    - Latest MSS models (DTU10, CNES-CLS11), geoid
    - Tides (FES2004, GOT4.8)
    - ECMWF and NCEP meteo, GPS and NIC09 iono, MOG2D IB
    - Off-line orbits from Delft, ESOC, CNES
- Compute wind speed from backscatter (Abdalla)
- Compute sea level anomalies from orbit - range - corrections

Plans for validation and assessment (tools, techniques, methodologies)

The resulting wave height, wind speed, and sea surface height measurements will be compared to all coincident altimeter missions (Envisat, Jason-1, Jason-2) through crossover analysis and global mean statistics. Biases and drifts in each of the measurements will be characterised and corrected for where desirable and possible. The cross-calibration of various altimeter missions will concentrate on the mesoscale (order 100 km and 10 days), but will also cover the global scale (reference frame offsets and geographically correlated errors) and longer time scales (relevant to sea level change). Both CNES/CLS (SSALTO/DUACS) and NOAA/TUDelft (RADS) have altimeter data base systems that carry all the altimeter data to date with up-to-date corrections, models and references, and these will be used in the global open ocean validation of the new CP4O products. In this also the RADS LRM product will be compared and validated against the CPP LRM product.

Organisation and schedule

This work has already started within the framework of RADS and all results will be fully provided to CP4O. Routine operational data processing (including both LRM and FDM) is already in place and these products will be made available to the project through RADS. Data coverage will be from February 2011 (sub-cycle 11) to June of this year (2013), more than 2 years worth of data.

A draft Algorithm Theoretical Basis Document (ATBD) is planned for August 2013, and a draft Product Validation Report (PVR) for September 2013.

Partners and responsibilities

TU Delft will carry out the work described utilizing RADS, with the direct support of Remko Scharroo (NOAA/Altimetrics LLC).

Risks (dependencies, potential bottlenecks, shortcomings).

No direct risks have been identified. Products to be used are already being generated and made available through RADS, which also guarantees the availability of the auxiliary data in form of altimetry from other satellite missions. Also the availability of all the necessary corrections and models is confirmed. The available resources (man-power) could be at risk due to the upcoming holiday season and the anticipated transfer of R. Scharroo from NOAA to EUMETSAT, but there is an agreed joint commitment to complete the work.

2.2.2 SAR For Open Ocean – RDSAR processing (RADS:NOAA/TUDelft)

Overview, objectives

In order to extend the CryoSat-2 data products to the coastal zone and fill other gaps in LRM coverage (SAR areas defined by the CryoSat mode maps), NOAA developed a process in which the level 1A SAR data (also referred to as FBR) are first combined into "Pseudo-LRM" (PLRM) or "reduced SAR" waveforms, which are similar to the conventional pulse-limited waveforms. Then these reduced SAR waveforms are retracked and combined with the LRM data to form the harmonised product, which can be found in RADS, and which provides a near global coverage of ocean LRM data.

Geographical coverage and time period

The geographical coverage is simply given by the definitions of the SAR areas in the CryoSat mode mask, which occasionally changes over time. We fill in these areas with PLRM data to arrive at a (near) global coverage. In RADS the pseudo-LRM data start on 1 April 2011 and end about one month before present day. These data will be provided to CP4O, in which we validate these data.

Data sources, processing steps, references

The process of reducing Level 1A SAR to PLRM and retracking PLRM to generate a level2 product that can be combined with the conventional LRM level2 product includes the following steps (to be carried out 20 times per second):

1. Gather 4 bursts of 64 echoes.
2. Align them to a common range by phase shifting the complex power for each of the bins for each echo by a phase shift equivalent to the change of range compared to the middle one. The change of range is based on the altitude rate rather than the on-board tracker information.
3. Apply a 1-dimensional FFT to the data in the frequency direction (128 bins). This creates 256 complex and very noisy “waveforms”.
4. Incoherently average (i.e. average the power) of each of the 128 bins across the 256 individual waveforms to form a single Pseudo-LRM waveform at 20-Hz.
5. Apply the low-pass filter correction.
6. Construct range, significant wave height and backscatter in a meaningful way, consistent with low-rate data.
7. Cross-calibrate the conventional and Pseudo-LRM data.

More details on these steps can be found in **[RD.3]**. These Pseudo-LRM data have been merged with LRM data and have been available via RADS since October 2012. Various newer developments are under implementation but have not been assessed yet.

After retracking, the RADS (Radar Altimeter Database System) is used to add or update all the commonly used geophysical corrections and then distributed to a multitude of users. Details about this work, including cross-calibration and validation can be found in **[Scharroo et al., 2013]**.

Plans for validation and assessment (tools, techniques, methodologies)

The plan for validating the RDSAR (or actually PLRM) data is the same as for the regular (conventional) LRM data (see previous section), which means that wave height, wind speed, and sea surface heights will be compared to the coincident altimeter missions, and that biases and drifts will be characterised and corrected for. Clearly also the consequences of the transition from LRM to SAR mode will be investigated further, both in the direction of bias and noise, all to ensure the smoothest transition possible. CNES/CLS (SSALTO/DUACS) and NOAA-TUDelft (RADS) have altimeter data base systems that carry all the altimeter data to date with up-to-date corrections, models and references, and these will be used in the global open ocean validation of these new CP4O products. In this also the RADS PLRM product will be compared and validated against the CPP PLRM product. For a smaller region, viz. the Northeast Atlantic, a smaller scale validation as part of the development will be undertaken using additional in situ measurements of sea level, wave height and wind speed.

Organization and schedule

As was the case for the LRM product this work has already started within the framework of RADS and all results will be fully provided to CP4O. Routine operational data processing is already in place and these products will be made available to the project through RADS. Data coverage will be from April 2011 (sub-cycle 11) to June of this year (2013), more than 2 years worth of data.

A draft Algorithm Theoretical Basis Document (ATBD) is planned for August 2013, and a draft Product Validation Report (PVR) for September 2013.

Partners and responsibilities

TU Delft will carry out the work described utilizing RADS, with the direct support of Remko Scharroo (NOAA/Altimetrics LLC).

Risks (dependencies, potential bottlenecks, and shortcomings)

The work involved is similar to the work concerning regular (conventional) LRM products and again no direct risks have been identified. Products to be used are already being generated and made available through RADS, which also guarantees the availability of the auxiliary data in form of altimetry from other satellite missions. Also the availability of all the necessary corrections and models is confirmed. The available resources (man-power) could be at risk due to the upcoming holiday season and the anticipated transfer of R. Scharroo from NOAA to EUMETSAT, but there is an agreed joint commitment to complete the work

2.2.3 SAR For Open Ocean – RDSAR Processing (Starlab)

Overview, objectives

Within the frame of the SAMOSA contracts, Starlab developed a methodology to derive Low Resolution Mode (LRM) waveforms from SAR Mode (SARM) data. Such techniques are known as ReDuced-SAR (RDSAR) techniques, and the resulting waveforms Pesudo-LRM (or PLRM) waveforms.

The objective of this activity is to validate the (RD-SAR) processing method developed by Starlab over the Open Ocean respect to other current existing RD-SAR methods, and with respect to other existing independent data sources in order to assess the performance of the processing over different ocean dynamics and Sea State condition.

Geographical coverage and time period,

This activity will be based on Cryosat-2 SAR data from the North-East Atlantic. The period for the analysis comprises a time span of two weeks from 4th January 2012 until 16th January 2012.

Data sources, processing steps, references

The data used for this analysis will be the CryoSat-2 FBR data to be provided by ESA. The FBR data will be processed in order to produced the Pseudo-Low Resolution Mode waveforms. An independent member of the CP4O consortium (to be agreed) will then apply the already available LRM retracking in order to extract the SSH, SLA, and SWH information out of the Pseudo-LRM waveforms. Starlab will perform the final validation of the RD-SAR method by means of a cross-comparison of the Level 2 products with independent data sources, such as in-situ ground truth data from buoys for the case of SWH, and SLA data from the AVISO website.

Plans for validation and assessment (tools, techniques, methodologies)

A direct comparison of pseudo-LRM waveforms derived with the Starlab RD-SAR processing tool will be done against the pseudo-LRM waveforms provided by CNES within the CPP data product and by NOAA/TUDelft within the RADS data product. This will allow evaluating the noise level in the LRM waveforms, as well as other waveform characteristics, such as the waveform power level, steepness, and waveform delay with respect to the observation window.

A preliminary statistical comparison will be done with the retracking outputs of the RD-SAR data provided by CNES within the CPP data product. This will allow the cross-validation for range and SWH provided in the CPP data. Note however that the CLS analysis of CPP data (see below) will be carried out on data from a different geographical region.

Further cross-validation will be performed against the L2 products produced by the retracking of L1B SAR waveforms. This will ensure the necessary continuity between SAR and pseudo-LRM data.

The geophysical parameters output will be validated against in-situ data and models. For the validation of SWH data ground truth data from buoys was acquired during the time of the analysis on the North-East Atlantic.

Sea Level Anomaly data will be acquired from the AVISO website in order to validate the obtained retracking results.

Organisation and schedule

A draft Algorithm Theoretical Basis Document (ATBD) is planned for June 2013 and a draft Product Validation Report (PVR) for November 2013.

Partners and responsibilities

- Isardsat to request FBR data to ESA
- ESA to distribute FBR data
- Starlab to produce RD-SAR data
- NOC/CLS/NOAA to apply LRM retracker to RD-SAR data (to be confirmed)
- Starlab to produce final analysis and validation of L2 products

Risks (dependencies, potential bottlenecks, shortcomings).

The provision time of FBR data has been extended, and therefore it has prevented the generation of RD-SAR data.

The processing of the RD-SAR data by a third party within the Consortium could delay the validation, as the retracking of several days of data will need to be performed for the full validation of the RD-SAR methodology.

It is not clearly stated which member of the CP4O consortium will perform the retracking of the Pseudo-LRM waveforms to derive the L2 products.

2.2.4 SAR For Open Ocean –RDSAR Processing (CLS)

Overview, objectives

To allow the assessment of the in-orbit performances of the SAR mode data and in the same manner the quality of the processing method, CNES has designed the Cryosat Processing Prototype (CPP) with the ability to generate the Reduced SAR (RDSAR) mode data, that provide a LRM reference over the same ground tracks during SAR mode (enabling direct comparisons of their retrievals performance).

Geographical coverage and time period,

A small set of tracks, crossing the large SAR area in the equatorial Pacific Ocean, in May 2012, will be selected for these analyses. Recalling that the Pacific Ocean SAR zone was defined based on the following criteria:

1. Low ocean variability, so easing the comparison with other missions like Jason-2
2. Few occurrences of rain and sigma0 blooms events (which could have different impacts on SAR and RDSAR)

3. Mean SWH around 2 meters and mean wind around 7 meters, so the sea state is close to the mean conditions

So this area is particularly adapted for SAR mode data validating purposes.

Objectives

The overall objective of this study is to ensure that the RDSAR data are fully consistent and valuable for maintaining the data quality continuity between SAR and LRM modes. This condition must be satisfied for enabling RDSAR data to be considered as a LRM reference during SAR mode.

Data sources, processing steps, references

The CPP RDSAR processing methodology has been already developed and presented by **[Boy et al. in 2012]**. This method is based on the use of a two-step algorithm, first reducing SAR mode raw data to RDSAR waveforms, and then applying a conventional Brown ocean retracker to the RDSAR waveforms for retrieving the different geophysical parameters. A 4-parameter estimator is considered for adequately fitting the measured waveforms with the return power model since the CryoSat-2 satellite exhibits unstable off-nadir mispointing angle in flight. These parameters are then corrected to account for the Gaussian approximation of the PTR in the retracking algorithm scheme, the ellipticity of the CryoSat-2 antenna, and its particular speckle pattern, through pre-computed Look-Up correction Tables (LUT).

Plans for validation and assessment (tools, techniques, methodologies)

In the following, the validation of this algorithm is performed with:

- the current CPP LRM (assimilated in DUACS). Comparisons of the SLA, SWH, Sigma-0, mispointing estimates for areas where change in SAR/LRM modes occurs (time series, histograms)
- other satellite data. Comparisons of the SLA, SWH, sigma0 estimates using LRM data from the Jason-2 Poseidon-3 altimeter (histograms and geographical distribution)

Organisation and Schedule

The processing module of CPP has been already developed and tested. The error estimates (LUT) due to the use of the inaccurate model in the retracking algorithm must be computed for the retrieved quantities (range, swh, mispointing). The generation of the correction table and the validation of the RDSAR processing should be done by the end of June.

Partners and Responsibilities

CNES generates the L2 CPP RDSAR data and CLS analyses and validates the data it receives.

Risks (dependencies, potential bottlenecks, shortcomings).

As we are comparing LRM and RDSAR estimates, we should have a very good match (same retracking methods). However, due to the processing method implemented by CNES, a data gap of 2.5 seconds occurs at the transition between LRM and SAR mode, such impacting our analysis of the LRM/RDSAR continuity.

However the risk is considered low, as the ocean variability over the selected zone is minimum.

2.2.5 SAR For Open Ocean (Starlab)

Overview, objectives

This task concerns the selection of the best algorithm(s) to re-track Cryosat-2 SAR mode waveforms over the Open Ocean and to analyse the performance over different ocean dynamics and Sea State condition.

During the SAMOSA projects Starlab derived a fully analytical expression for the SAR waveforms of a delay-Doppler altimeter. Those were upgraded and implemented by means of a fast computation method by expanding the analytical waveform model in a set of basis functions, which could then be pre-stored in Look-up tables (LUT) for improved computational time.

A retracker was implemented based on a non-linear least square algorithm that relies on a Levenberg-Marquardt minimization method. The objective of this task is the validation of the analytical model, and the fast computation approach selected for the waveform-retracking algorithm.

Geographical coverage and time period,

This activity will be based on Cryosat-2 SAR data from the North-East Atlantic. The period for the analysis comprises a time span of two weeks from 4th January 2012 until 16th January 2012.

Data sources, processing steps, references

The analysis will be based on the CPP SAR products provided by CNES. The SAR waveforms will be retracked by the multi-look waveform model developed within the SAMOSA. The full analytical model, and the fast computational model (based on LUT) will be used for the retracking of the CPP data. A comparison between both retracking methods will be carried out to ensure the correct assumptions for the implementation of the fast computational retracking algorithm.

Plans for validation and assessment (tools, techniques, methodologies)

A preliminary statistical comparison will be done with the retracking outputs of the SAR numerical model developed by CNES, provided in the CPP SAR product. This will allow the cross-validation for range and SWH provided in the CPP data. The waveform goodness of fit will also be compared to the one provided by CNES in the CPP data.

The geophysical parameters output will be validated against in-situ data and models. For the validation of SWH data ground truth data from buoys was acquired during the time of the analysis on the North-East Atlantic.

Sea Level Anomaly data will be acquired from the AVISO website in order to validate the obtained retracking results.

Organisation and schedule

This work started on April 2013 and it is expected to be completed by the end of June 2013.

A draft Algorithm Theoretical Basis Document (ATBD) is planned for end of June 2013, and a draft Product Validation Report (PVR) for August 2013.

Partners and responsibilities

CNES generates the CPP SAR data and Starlab performs the retracking of the Doppler processed waveforms. IsardSat (WP3000) provides ancillary data and corrections in order to generate the final L2 SLA product for comparison with other independent sources.

Risks (dependencies, potential bottlenecks, shortcomings).

Sea State Bias estimates have not been developed yet for SAR/RDSAR data products. As a consequence, the validation of the SLA estimates might be partial.

2.2.6 SAR For Open Ocean (CLS)

Overview, objectives

The Delay Doppler/SAR radar altimeter is a new generation of instrument that has been embarked for the first time on the ESA CryoSat-2 satellite. Several studies have been initiated and are ongoing to develop and test processing algorithms – in term of retracking - for this new altimeter mode, with the final objective to enhance the potential benefit of the SAR mode data over the ocean surface (improved precision of the parameter estimates and increased along-track resolution with respect to conventional pulse width limited altimeters). On its side, CNES has developed a processing chain (CPP) for SAR data (and LRM data) that aims at contributing to expertise studies for the future Sentinel-3 mission. After more than two years of Cryosat-2 mission, it is now possible to assess the in orbit data quality of the SAR mode through the CPP chain.

Geographical coverage and time period,

A small set of tracks located in the large SAR area of the equatorial Pacific ocean, in May 2012, will be inspected for validating purposes.

Objectives

The overall objective of this activity is to demonstrate that the proposed processing algorithm allows obtaining the precision and resolution SAR-mode capabilities as they are theoretically expected, while maintaining consistency with LRM data (based on RDSAR data).

Data sources, processing steps, references

The CPP SAR-mode retracking algorithm is a standard least squares estimator consisting in fitting a Doppler waveform with a multi-looked echo model that is pre-computed off-line by a simulator. The main innovation of this approach resides in the generation of the echo model database in which the sensitive parameters (sea-state, satellite parameters) vary, one parameter at a time, in a range of values and with a step size, that have been chosen to ensure the accuracy and precision of the estimates. This numerical method is considered to be more robust than analytical ones, particularly when faced with atypical observations (e.g., elliptical antenna pattern, off-nadir mispointing angles, point target response) that are difficult to put into equations. This method has been developed and implemented in the CPP processing chain that is already operating [Boy et al., 2012] and currently able to generate and disseminate CPP SAR Level-2 products among the altimetry community.

Plans for validation and assessment (tools, techniques, methodologies)

The proposed approach consists in validating the SAR estimates with:

- The collocated and validated CPP RDSAR products. Comparisons of the SLA and SWH estimates will be done through time series and histograms.
- Other satellite data. Comparisons of the SLA, SWH estimates using LRM data from the Jason-2 Poseidon-3 altimeter (histograms and geographical distribution)

Organisation and schedule

The processing module of CPP including the SAR numerical retracking has been already developed and tested. The validation of the SAR algorithm should be done by the end of June.

Partners and responsibilities

CNES generates the L2 CPP SAR data and CLS analyses and validates the data it receives.

Risks (dependencies, potential bottlenecks, shortcomings).

No clear conclusion could be drawn from this validation exercise (e.g., discrepancies in SLA may be explained by the lack of SSB corrections in RDSAR and SAR data)

2.3 Coastal Ocean Altimetry

The ultimate objectives for the products developed under the theme of Coastal Ocean altimetry are

- 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.

2.3.1 SAR For Coastal Ocean (NOC)

Overview, objectives

The coastal zone represents a challenging environment for the validation of satellite altimeter data and it is important therefore to first establish the optimal methodologies for retracking SAR waveforms over the ocean. Thus, the development and validation plan proposed by NOC for Cryosat-2 SAR mode over the coastal ocean first comprises activities over the open ocean. Only then will it become possible to tackle some of the less tractable issues encountered closer to land.

The consolidated objectives of the proposed development and validation experiment over ocean and the coastal zone are:

- To define and validate the optimal SAR retracking methodology, considering different theoretical SAR waveform models and different L1B multi-looked waveform products and the effect of platform mispointing.
- To compare the performance of Cryosat-2 SAR mode SSH and SWH against data from other satellites (e.g. Jason-2) and from in situ measurements (e.g. offshore wave buoys).

These are followed by the specific objectives for validation over the coastal zone, which are:

- To ascertain the quality of C2 SAR mode waveforms within 10 kilometres of land compared to conventional pulse-limited altimeters.
- To validate and optimise the SAR retracking methodology defined for open ocean conditions to the case of SAR waveforms in coastal regions.
- To compare the performance of Cryosat-2 SAR mode SSH and SWH against data from other satellites (e.g. Jason-2) and from in situ measurements (e.g. inshore wave buoys and land-based tide gauges).

Geographical coverage and time period,

The validation experiment for the Coastal Ocean will take place over the North-West European Shelf Region – where CPP data are available and in situ measurements have been identified

Data sources, processing steps

Optimal SAR Re-tracking Methodology and Validation over Open Ocean

The large number of anomalies reported in the ESA IPF processing of Cryosat-2 SAR L1B products, compounded by the harmful effect for ocean applications of the Hamming window applied within Baseline B products, makes the ESA IPF Cryosat-2 SAR L1B waveforms sub-optimal to determine the true capabilities of Cryosat-2 SAR mode over water. The availability within the CP4O project of multi-looked waveforms processed by CNES from Cryosat-2 Level 0/FBR products provides a new source of Cryosat-2 SAR waveforms, which do not present these problems. The alternative products, known as CPP ("Cryosat Pilot Products") will offer a way to bring confidence to the development and validation of SAR retracking over water. The downside is that only limited amount of CPP data is currently available within CP4O.

As shown in WP2200, there exist a number of SAR waveform models to retrack SAR multi-looked waveforms, including numerical, analytical and empirical forms. So far, there has been no opportunity to compare these different SAR waveform models, nor any way to attribute observed discrepancies to either shortcomings of the models or processing artefacts in SAR L1B waveforms.

In this task, we propose to apply the SAMOSA SAR waveform model(s) to CPP products to compare with previous results obtained with IPF SAR L1B waveforms. The CPP waveforms have been retracked by CNES with the numerical SAR retracker by **[Boy et al., 2012]** and these retracked ocean parameters contained in the CPP products will enable for the first time a direct comparison of the performance of different theoretical models applied to the same data. However, in order for these analyses to be conclusive, it will be important to ensure that the same instrument and configuration parameters are used in both SAR retrackers.

It was shown previously **[Gommenginger et al., 2011]** that platform mispointing is an important parameter in SAR altimetry because of its effect on the shape and magnitude of the waveforms. The analyses in this task will include an assessment of the impact of mispointing on model misfit and on the quality of the retracked parameters as assessed against validation data.

The SAR retracking methodology will be developed and optimized using internal consistency tests and comparisons against independent data from other satellites (e.g. Jason-2) and in situ measurements (e.g. offshore wave buoys).

Optimal SAR Re-tracking Methodology and Validation over Coastal Ocean

The development and validation activities specific to the coastal region comprise two elements:

First, we examine the quality of the Cryosat-2 SAR waveforms and of retracked geophysical values within 10 kilometres of land, to determine the degree of contamination by land for different track/coastline orientations compared to conventional satellite altimeters. Both IPF SAR L1B (baseline A) and CPP products retracked with the SAMOSA and the CNES model will be examined. Based on this, we determine what could be undertaken to further improve the SAR mode data close to land.

Second, we take advantage of the extensive in situ measurements of waves and sea level from inshore buoys and tide gauges along the south coast of the UK to perform a more in depth validation of the Cryosat-2 SAR data. Retracked SSH will be corrected for geophysical effects (e.g. wet tropospheric delay) using the corrections in the ESA products and new corrections developed within CP4O. The proximity of in situ wave and sea level measurements will afford a first look at the performance of C2 SAR against tide gauges in different sea states. Particular attention will be give to finding occurrences of swell from different directions to try to distinguish any possible impact on SAR waveforms and retrieved range.

2.3.2 SARIN for Coastal Ocean (isardSAT)

Overview, objectives

This task consists of a small scientific study of the capability of Cryosat-2 SARIN products to assist the mitigation of land contamination echoes in the coastal zone.

This activity will differ from others in WP4000 in that the aim is not to develop and test a new product but rather to help to characterise the origin and nature of land contamination for different track/coast configurations and draw up recommendations to design strategies to mitigate land echo contaminations in the coastal zone.

The use of SAR mode represents a notable improvement in spatial resolution along track with respect to LRM. SARin mode is another big step forward, enhancing the resolution across track, due to the use in reception of the two antennas onboard CryoSat-2, collocated perpendicular to the satellite track. Having the echoes information in module and phase of the two antennas, it is possible to derive the phase difference between the two antennas, and from it the across track angle of arrival. This means that we are able to discriminate across track the different facets of a SARin mode waveform, therefore working with the phase information we could geo-locate every particular facets or re-tracked points of a waveform and also compute the elevation of that point.

Then, in a second stage, with the starting point of the geo-location and elevation results, and the waveform itself, we could analyse some aspects that could help to mitigate the land contamination in coastal areas.

Geographical coverage and time period,

The SARin activity will focus on two areas:

- The coast of Chile, where Cryosat-2 tracks run almost parallel to the coast line.
- The coast of Cuba, where Cryosat-2 tracks are perpendicular to the coast.

Moreover, other SARin areas around the world will be also checked in order to find interesting tracks cases, taking into account not only the geometry of the coast with respect to the satellite track but also the coastal land topography.

The time period considered is not restricted. The whole CryoSat-2 mission is considered.

Data sources, processing steps, references

The study will consider the information provided in Cryosat-2 SARIN L1b and L2I products to derive the angle of arrival of the echoes (that can be extracted from the phase difference), which combined with a DEM, should make it possible to build the actual reflection point and geo-locate it.

A geo-location and elevation of a particular reflection point can be computed, and then validated against a DEM.

Plans for validation and assessment (tools, techniques, methodologies)

No validation against in-situ data or other EO missions is considered in this small scientific study.

Organisation and schedule

This work started on December 2012 and is expected to be completed by October 2013.

Partners and responsibilities

This work will be carried out by isardSAT.

2.4 Polar Ocean Altimetry

The objectives under the theme of Polar Ocean altimetry are to develop and evaluate processing schemes applicable to sea-ice covered regions, so that Cryosat-2 SAR Mode data can be used to study large scale polar ocean signals and thereby 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 current polar ocean 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.

2.4.1 SAR For Polar Ocean (DTU Space)

Overview, objectives

In this activity the need for improvements of the estimation of SSH in Polar Ocean regions will be addressed through the use of robust retrackers and echo type classification specifically targeted towards the specular echoes encountered in sea ice covered areas.

The SSH is extracted from echoes identified as sea ice leads or ocean using appropriate retrackers. The SSH observations are filtered for outliers and gridded to form the basis for an updated MSS. The updated MSS will then be combined with a gravity field to obtain a MDT. Furthermore the SSH observations will be used to improve tide models and estimate annual variability.

Geographical coverage and time period,

The region initially selected for the Polar Ocean validation experiment was the Baffin Bay, in the Davis Strait, west of Greenland, where Cryosat-2 operates in SAR mode and where independent data are available for validation. Later the region has been extended to cover the entire Arctic Ocean, defined as above 65° Latitude, where CryoSat-2 operates in SAR mode for almost the entire region.

This region has been chosen for another important reason: the Baffin Bay and the ocean north of Russia and Alaska are sea-ice covered for only part of the year, and this makes it possible to obtain SAR estimates of SSH over water in summer and over ice in winter. Assuming the seasonally variability allows, this offers the unique possibility of comparing the SSH for the same region in winter conditions (with extensive sea ice coverage) and in summer conditions, when high precision SSH can be retrieved using the SAMOSA retracker.

Initial studies that the general quality of the CryoSat-2 Baseline A processing is degraded compared to the Baseline B product and therefore will only Baseline B products be used. This currently limits the period to February 2012 and later, but with the on-going reprocessing of older data the period might be extended.

Data sources, processing steps, references

The performance of three existing retrackers that have already been applied to Cryosat-2 SAR data over sea ice will be investigated. These include a number of threshold retrackers, an OCOG retracker and a 5-parameter beta-retracker. In addition, DTU Space will implement a new leading-edge retracker, which has already produced very good preliminary results for Cryosat-2 SAR waveforms

(**[Idris and Deng, 2011]**, Coastal Altimetry Workshop, San Diego). This analysis could form the basis for possible reprocessed L1B products by ESA using more robust retrackers in the Polar Ocean.

Plans for validation and assessment (tools, techniques, methodologies)

Comparisons with sea surface height retrieved from the ERS-1, Geosat Geodetic Mission, and ENVISAT altimetry will be performed in the region to investigate the presence of all spatial signals in the datasets.

Individual profiles of Cryosat-2 SAR data will be compared with airborne CryoVEx and IceBridge data as well as collocated satellite data such as ENVISAT to evaluate the along-track signal to noise.

Throughout the region the Cryosat-2 SAR data will be compared with ENVISAT data for detailed evaluation of the sea surface height retrieval.

Organisation and schedule

This work started on October 2012 and is expected to be completed by late 2013.

The reason for extending the deadline as long as possible is to wait for the ESA reprocessing of the 2011 with the baseline B of the CS-2 processor. This is to obtain two years of CS-2 SAR data processed using the same processor for the study of annual to inter-annual sea level variations in the Arctic Ocean. Without more than one year of data study of the important annual and inter-annual variations in the Arctic Ocean is not possible. This reprocessing by ESA was foreseen to be completed by spring 2013, but is so far delayed to summer/autumn 2013.

A draft Algorithm Theoretical Basis Document (ATBD) is planned for 1 December 2013 and a draft Product Validation Report (PVR) for 31 December 2013.

Partners and responsibilities

DTU Space will carry out this work.

Risks (dependencies, potential bottlenecks, shortcomings).

The Cryosat-2 SAR waveforms display extreme peakiness compared to conventional altimeter waveforms, particularly over Polar Regions where highly specular echoes are very frequent. These are very difficult and noisy to retrack, and might explain the bad performance of existing L2 SAR data in the Arctic Ocean (**[Stenseng and Andersen, 2012]**).

This is a problem that is recognized by ESA, who upgraded the operational Cryosat-2 L1B SAR processor to produce SAR waveforms with finer gate resolution (still 128 gates, but with half the current resolution; Duncan Wingham, pers. comm.) that should be better able to capture the leading edge of these very sharp echoes. Analyses will be performed with Cryosat-2 SAR data obtained to date with the original gate resolution, and for Cryosat-2 SAR products with finer resolution waveforms that become available from early 2012 onwards.

Due to the presence of sea ice a high number of echoes have to be discarded leaving a significant reduced number of observations available for generation of a MSS, see Figure 2-1. Furthermore, along-track averaging is will not be possible as the open water leads only will be visible in one or a few adjacent observations.

Finally, leads observed at cross-track off-nadir will induce a negative bias in the generated MSS and careful investigation of this will be needed.

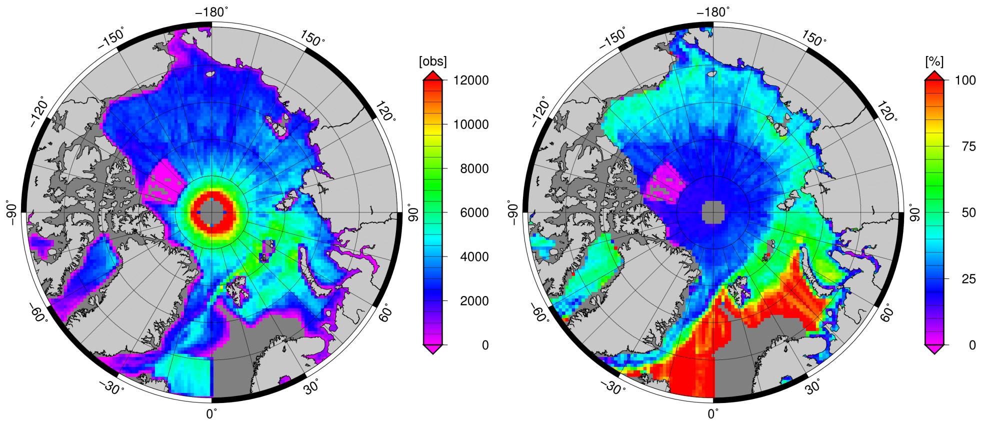

Figure 2-1 Number of observations, per 50 by 50 km square in 2012, that potentially can be included in a MSS (left). Percentage of potential useful observations of all available SAR echoes (right).

2.5 Sea Floor Altimetry

The main objective of this theme is to investigate the potential offered by the higher resolution and improved Signal to Noise Ratio (SNR) of Cryosat-2 SAR Mode data to resolve short-wavelength sea surface signals caused by sea-floor topography elements and to map uncharted seamounts/trenches.

2.5.1 SAR For Sea Floor Altimetry (DTU Space)

Overview, objectives

This task deals with the use of Cryosat-2 SAR data to detect ocean bathymetry features, in particular the mapping of seamounts. The detection particularly should benefit from the finer along-track resolution of SAR altimeters and the closely spaced tracks of the Cryosat-2 mission compared with retrieval from conventional geodetic altimetry from ERS-1 and GEOSAT.

As for the Coastal Ocean, the SAR re-tracking needed for mapping seamounts will be the same as for Open Ocean. The only addition to the processing is the need for further along-track processing and filtering to achieve the S/N needed to retrieve small gravity signals associated with bathymetry.

Geographical coverage and time period,

The work will be carried out on one complete (369 day) cycle of SAR mode data, in the region of the North Pacific first implemented in Mask 3-4 on 1st October 2012. Thus it will not be possible to complete this activity until the whole cycle of data is available and has been processed (i.e. late 2013).

Data sources, processing steps, references

The retracked SAR data will be evaluated for the test region with respect to signal to noise determination of possible residual geophysical signal. This will be done for one repeat of the Cryosat-2 SAR retracked data.

Part of the installed Mask was installed prior to October 2012, so for part of the region data from more than one year will be studied to evaluate the impact on oceanographic noise on gravity field determination to evaluate the signal to noise of the data. This analysis is essential in order to determine if the test region is at all suited for further validation of the sea floor bathymetry mapping application.

Plans for validation and assessment (tools, techniques, methodologies)

Comparisons with ERS-1 and GEOSAT Geodetic Mission altimetry will be performed in the region to verify and inspect the presence of all spatial signals in the datasets and determine the possible spatial resolution that can be obtained using Cryosat-2 SAR data. So far we only have results from “simulation of Cryosat-2 data in the SAMOSA project” which indicate that the best results wrt gravity and bathymetry prediction can be obtained using 4 Hz (1.5 km along track data spacing) Cryosat-2 SAR data.

However, we need to investigate the best possible along and across track filtering and averaging strategies of the Cryosat-2 SAR output to achieve suitable noise reduction that enables small sea mounds to be detected. In particular, studies of Cryosat-2 SAR data will be performed to identify the signal to noise of the data compared to geodetic studies.

If enough reprocessed data are available, the study will consider separately the results for single-pass vs repeated pass analyses for part of the investigated region, when Cryosat-2 enters its second cycle of SAR acquisitions over this region.

Organisation and schedule

This work cannot be started until a full cycle of data over the selected region is available. Thus the task will not be completed until the full cycle of data is completed in October 2013 and processed using the SAMOSA retracker to obtain geophysical parameters. Consequently completion is foreseen in early 2014.

Partners and responsibilities

This work will be carried out by DTU space with support from Starlab for the re-tracking of SAR mode data.

Risks (dependencies, potential bottlenecks, shortcomings).

The main risks to this activity are:

- That the mode mask is changed before a cycle is completed and so insufficient data are collected.
- That the region covered by SAR mode does not have sufficiently strong geophysical signal to allow new sea floor features to be identified.

There are not co-located marine gravity data available to validate and new features provisionally identified.

2.6 Improved Geophysical Corrections

The provision and assessment of improved geophysical corrections is an essential aspect of the CP4O project, for two key reasons:

- The Cryosat-2 mission is single frequency, and does not carry a Microwave Radiometer, therefore the production of accurate measurements for range, backscatter and wave height are dependent on auxiliary data to provide the ionosphere and wet troposphere corrections.
- The objective to provide accurate altimeter derived measurements at high resolution over coastlines and in polar regions means that corrections conventionally used to date may not have sufficient resolution and accuracy, and so new products are needed.

2.6.1 Wet Troposphere Correction (U Porto)

Overview, objectives

Unlike most altimetric missions, CryoSat-2 is not equipped with an on-board microwave radiometer (MWR) to provide the wet tropospheric correction (WTC) to the radar altimeter measurements, thus relying on a model-based one provided by the European Centre for Medium-range Weather Forecasts (ECMWF). In the ambit of CP4O, an improved WTC for CryoSat-2 data over ocean is under development, based on a data combination algorithm (DComb) through objective analysis of WTC values derived from all existing global-scale data types: GNSS-derived wet path delays, scanning/imaging MWR (SI-MWR) water vapour products and numerical weather model derived WTC (selected model is ERA

Interim, the ECMWF Re-Analysis model). Within WP2000 all selected data sets for the computation of the WTC were collected and pre-processed. Furthermore, methods were identified that shall be used to process these data and incorporate them in the DComb algorithm. The main topics regarding the development and validation of the improved WTC product for CS-2 are briefly summarised below.

Geographical coverage and time period,

As the computation will be performed globally, WTC datasets shall be available also for all of the selected validation regions. The temporal coverage corresponds to the period of the CS-2 mission ranging from January 2011 (CS-2 sub-cycle 11) to the end of 2012 (CS-2 sub-cycle 35).

Objectives

The objective is the computation of a more accurate WTC for CS-2 over ocean, when compared to the one provided by ECMWF.

Data sources, processing steps, references

In order to compute the improved WTC for CS-2, water vapour datasets of several (all available for the desired temporal coverage) scanning/imaging microwave radiometers (SI-MWR) on board various remote sensing missions shall be used.
Through an objective analysis data combination methodology (DComb), the above-mentioned SI-MWR datasets will be combined with GNSS- and ERA Interim-derived WTC. Details on the specific data sources used and access to them were detailed in D2.1 - Preliminary Analysis Report and will be further provided in D3.2 – Experimental Data Set User Manual. The analyses and inter-calibration of the SI-MWR data sets was described in **[Fernandes et al., 2013]**.

The main steps of the algorithm under development, detailed in D2.1, are:
(1) The inter-calibration of all SI-MWR using the Advanced Microwave Radiometer (AMR) on board Jason-2 and the ERA Interim model.
(2) Implementation of the DComb algorithm by Objective Analysis (OA) of all existing data types.
(3) Global computation of WTC for along-track data (1Hz, interpolated to 20Hz) -- positions as in RADS and in orbit files provided by ESA.

Coastal Ocean areas shall greatly benefit from the use of GNSS-derived WTC (computed at land-based, coastal or island, GNSS stations), due to the general unavailability of valid MWR measurements at short distances from the coast. For Open Ocean areas, the main data source shall be SI-MWR-derived WTC and also ERA Interim for epochs/locations with low SI-MWR data coverage. For Polar Ocean regions, generally with sparse GNSS coverage and some SI-MWR data flagged as invalid due to sea-ice contamination, improvements to present ECMWF WTC are expected to be more modest.

Plans for validation and assessment (tools, techniques, methodologies)

Considering the availability of independent data for the validation of the derived DComb WTC, the proposed validation methodologies shall consist of:

Open Ocean: as the main data source here will be the SI-MWR-derived WTC, and no absolute standard is yet available for spaceborne MWR, the validation shall be performed by comparing DComb-derived WTC with WTC from a chosen reference MWR (e.g. AMR on board Jason-2).

Coastal Ocean: comparison with GNSS-derived WTC not used in the computations.

Globally: analysis of sea level anomaly (SLA) variance at crossovers, also as function of latitude and distance from coast.

Organisation and schedule

WP4100: Implementation of the DComb algorithm.
WP4200: Validation of the implemented algorithm against independent data sources and report the error analysis and cross-comparisons in the Product Validation Report (PVR).
WP4300: Creation of a detailed description of the final DComb algorithm, as contribution to the Algorithm Theoretical Basis Document (ATBD).
WP4400: Production of the WTC for Cryosat-2 (globally and for the Validation Data Set needed in WP5000 for the public round-robin exercise) and contribution to the Validation Data Set User Manual.

Partners and responsibilities

All work shall be performed at U.Porto, resulting from the joint effort of the team members.

Risks (dependencies, potential bottlenecks, shortcomings).

Validation through analysis of SLA at crossovers depends on the availability of experimental data set produced within CP4O. Alternatively, data from RADS can be used. Effective ice flagging and MWR land contamination to avoid the use of contaminated SI-MWR derived WTC for Polar Ocean and Coastal Ocean regions respectively, is a foreseen difficulty. A variable (in time and space) accuracy of derived WTC shall result from variable auxiliary data coverage (especially concerning SI-MWR data).

2.6.2 Ionospheric Correction (Noveltis)

In the frame of this project we propose to use Regional Ionosphere Maps (RIM) produced by NOVELTIS. The SPECTRE service is an operational service providing **TEC maps over Europe** from GPS network **with an accuracy of 2-3 uTEC**. This accuracy estimate is not the RMS estimated conjointly with the TEC maps by inverse theory (which is significantly lower) but the errors assessed by multiple comparisons with GIMs (JPL, CODE, UPC), altimeter satellites (TOPEX, Jason-1, Envisat) and ionosondes (Crespon et al., 2007). **These TEC maps have been archived since April 2004**.

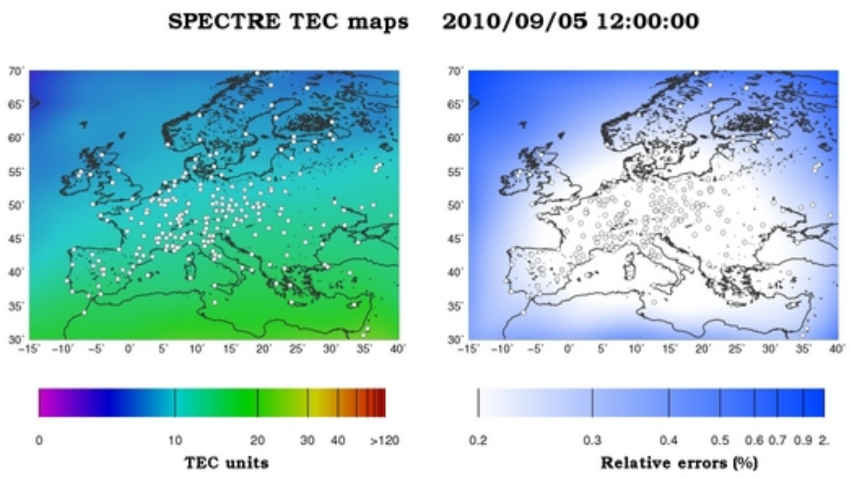

Figure 2-2: TEC and RMS (in percent) maps estimated by the SPECTRE service from the GPS receivers (white dots) of the European network.

The TEC maps extent from -15°E to 40°E and from 30°N to 70°N. The space resolution of the SPECTRE-TEC maps is 2.5° x 2.5° which provides a longitudinal resolution twice better than GIM products. However the best improvement concerns the time resolution, which is 30 seconds for SPECTRE products while it is 2 hours for GIM products. Increase of space and time resolutions allows estimating the ionospheric perturbations at smaller space and time scales. The European map product covers the Mediterranean Sea and the North East Atlantic area.

The reliable **TEC maps produced by NOVELTIS** will be used to generate a new Cryosat ionospheric correction. However, the TEC maps have to be processed in order to generate ionospheric correction products. Indeed, TEC maps are the estimation of the integral of the electron density from ground/ocean level to GPS satellites altitude (20,200km). Therefore ionosphere correction for satellite altimeters is computed by applying a **scale factor** to assess the integral of the electron density from ground/ocean level to the satellite altimeter. The scale factor is estimated by using the **IRI95 ionosphere model**.

Table 2-1 Summary of the coastal ionospheric correction for Cryosat.

	Content	Comments
Overview	Generation of ionosphere correction for Cryosat	
Geographical coverage	Mediterranean sea and North East Atlantic	Long: -15°E to 40°E Lat: 30°N to 70°N
Objectives	Provide time series of ionosphere correction for Cryosat tracks	
Data sources, processing steps, references	- CP4O products (at least satellite time and position) - TEC maps from SPECTRE database (NOVELTIS) - Ionosphere model IRI95	Crespon at al., 2007 Bilitza et al., 1997
Plans for validation and assessment (tools, techniques, methodologies)	CP4O products will be validated by partners in charge of their generation SPECTRE database and IRI95 are already validated	Crespon at al., 2007 Bilitza et al., 1997
Organisation and schedule	Activity will start when CP4O products are provided to NOVELTIS. Activity duration is ~2 weeks	
Partners and responsibilities	NOVELTIS is in charge of the provision of the ionosphere correction	No other partners directly involved
Risks (dependencies, potential bottlenecks, shortcomings).	If CP4O products (at least satellite time and position) are not available we won't be able to generate the ionosphere correction No other risk is foreseen	

2.6.3 Regional Tide Correction (Noveltis)

The COMAPI (Coastal Modelling for Altimetry Product Improvement) regional tide atlas in the North East Atlantic (NEA) was developed in the framework of a CNES project in 2009. It is based on the same methodology as the FES2004 and FES2012 models, using the same hydrodynamic model and assimilation scheme (Cancet et al., 2010).

The grid resolution was refined and the bathymetry closely quality-checked in order to be able to accurately model the non-linear tidal structures on the shelves. Once on a regular grid, the resolution of the NEA COMAPI regional model is 1/60° (~2 km), to be compared with the classical grid resolutions of the global models, from 1/2° to 1/16°. In addition, the physical parameters of the regional model were specially tuned for the area in order to give a realistic picture of the local tidal energy dissipation.

Concerning the data assimilation process, the NEA COMAPI regional atlas benefited from all the TOPEX/Jason-1 along-track data, with a point every 20 km (Figure 2-3, right panel). It should be noticed that in 2009, when the COMAPI NEA regional atlas was implemented, the TOPEX/Jason-1 time series on the interleaved orbit was not long enough to compute accurate tidal constituents. Today, with three additional years of measurements, i.e. a 6-year long time series, it is possible to add this mission in the assimilated dataset, as it was recently done for the FES2012 model (Figure 2-3, left panel).

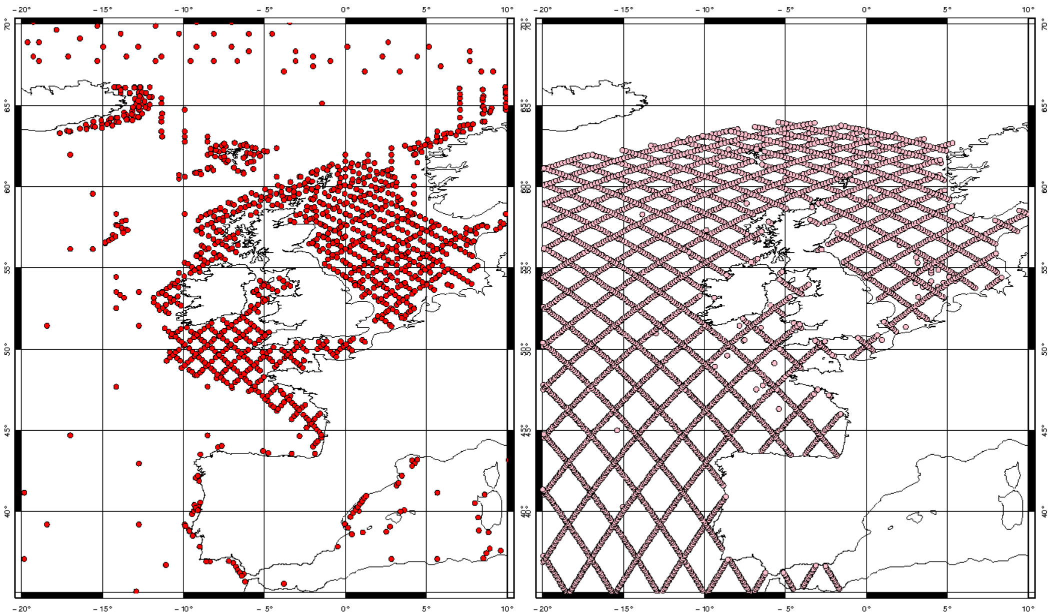

Figure 2-3: Altimetry data assimilated in FES2012 (left) and in the COMAPI NEA regional model (right), from Cancet et al., 2012.

The COMAPI regional tidal atlas was validated using two different methods. First, the harmonic components (amplitude and phase) of each tidal wave were compared to the tidal harmonic components extracted from tide gauge data time series. Then, the regional model was compared to global models (FES2004 and GOT4.7), using a criterion of altimetry SLA variability reduction (**[Cancet et al., 2010]**) .

In order to provide a regional tide correction for the CP4O products in the NEA, the tidal elevations will be predicted from the COMAPI model at the position and time of the CryoSat measurements in the area.

Table 2-2: Summary of the regional tide correction for Cryosat

	Content	Comments
Overview	Generation of regional tide	

	correction for Cryosat	
Geographical coverage	North East Atlantic	Long: -20°E to 13°E Lat: 22.5°N to 64°N
Time period	Cryosat period (2008 - …)	
Objectives	Provide time series of tide correction for Cryosat tracks	
Data sources, processing steps, references	- CP4O products (at least satellite time and position) - COMAPI tide atlas (NOVELTIS/CNES)	Cancet et al., 2010
Plans for validation and assessment (tools, techniques, methodologies)	CP4O products will be validated by partners in charge of their generation The COMAPI tidal atlas is already validated	Cancet et al., 2010
Organisation and schedule	Activity will start when CP4O products are provided to NOVELTIS. Activity duration is ~2 weeks	
Partners and responsibilities	NOVELTIS is in charge of the provision of the tide correction	No partners directly involved in this activity
Risks (dependencies, potential bottlenecks, shortcomings).	If CP4O products (at least satellite time and position) are not available, we won't be able to generate the tide correction No other risk is foreseen	

2.6.4 Other Corrections (TU Delft)

Overview, objectives

Concerning all the corrections we obviously seek the best and most up-to-date geophysical corrections and models. Striving for the best quality data not only depends choosing the best re-tracker and by that get the best values for range, wave and backscatter, but also on the choice of corrections. These include:

- Altimeter instrumental corrections, i.e. monitored biases and drifts of the altimeter range and timing (ultra-stable oscillator and other instrumental variations), wave height (related to aging of the altimeter) and backscatter (due to variations in instrumental gain settings);
- Altimeter- and region specific algorithms and models like the sea state bias correction, as well as the wet troposphere path delay and ionosphere path delay for which no direct (platform) measurements are available;
- Orbital ephemerides, i.e. position of the satellite, the altitude in particular, which includes the selection of an appropriate gravity field model and

reference frame, also to align CryoSat-2 with other missions like Jason and Envisat;

- Tidal corrections, *i.e.* displacement of the land and ocean as a result of solar and lunar attraction, including second-order effects, like ocean loading, and complex tides;
- Dynamic atmospheric correction, i.e. the effect of atmospheric pressure on the sea level, taking into account the different responses of the sea surface to various frequencies in the atmospheric forcing.

[RD.3] provides the review of available CryoSat-2 altimeter corrections and also the proposal for alternative improved corrections w.r.t. the corrections provided on the ESA products. Both LRM and PLRM are developed in RADS and with these developments also all these measurements are at the same time provided with the most up-to-date corrections and models: e.g. FES2004, GOT4.7 and GOT4.9 ocean tide models, consistent pole and solid Earth tides, EGM2008 geoid, EGM2008, CLS11, and DTU10 mean sea surfaces, DTU10 bathymetry, wind/waves from WaveWatch3 model, high resolution MOG2D dynamic atmosphere correction, NCEP/ECMWF full resolution atmospheric path delays, and smoothed dual-frequency and JPL GIM and NIC09 ionosphere corrections. RADS takes care of both delayed precision products, near real-time (NRT) and interim products, so that you always will find the best data available for your purpose at the time you access the RADS servers.

Geographical coverage and time period

Both region and time period same as RADS LRM and RADS PLRM: global covering February 2011 until current date (June 2013).

Objectives

Concerning all the corrections we obviously seek the best and most up-to-date geophysical corrections and models. Striving for the best quality data not only depends choosing the best re-tracker and by that get the best values for range, wave and backscatter, but also on the choice of corrections.

Data sources, processing steps, references

Standard corrections for both LRM and RDSAR, but also applicable to SAR/SARIN data will be made available through RADS. All the needed models, correction subroutines and auxiliary data input are dealt with within the RADS processor and RADS service. Because of the retracking process SWH and backscatter have been improved and they are tailor-made to fit with the retraced product. Based on this improved combination of SWH and backscatter we produce a RADS (in-house) hybrid sea state bias model based on a 4 parameter model in which smoothed residuals have been blended back in; a procedure that has been investigated thoroughly and gives promising results. Details of this procedure can be found in **[RD.3]** and **[Scharroo and Lillibridge, 2004]**.

When improved corrections become available from the other CP4O partners like the wet troposphere product from uPorto, and ocean tides and ionosphere from Noveltis they will be incorporated in RADS so they can be chosen and applied to all regional and/or coastal CryoSat-2 data when needed. The same applies for improved polar ocean tide models.

<u>Plans for validation and assessment (tools, techniques, methodologies)</u>

Most geophysical corrections and models already have been assessed as being the best available up to current date (see **[RD.3]**). The CP4O partners responsible for the improved wet troposphere, ionosphere and ocean tide corrections will validate these. Additionally, we plan updates of the SSB model and comparison with SSB solutions from the CPP processor (SSALTO/DUACS solution) over the course of the project.

<u>Organisation and schedule</u>

This work is an already started activity in the framework of RADS and will be fully provided to CP4O. Data delivery will be actual along with the to be delivered LRM and PLRM data, which means that the corrections will be available from 1 February 2011 up to current date (June 2013), which provides more than 2 years worth of correction data.

A draft Algorithm Theoretical Basis Document (ATBD) is planned for September 2013, and a draft Product Validation Report (PVR) for October 2013.

<u>Partners and responsibilities</u>

TU Delft will carry out the work described utilizing RADS, with the direct support of Remko Scharroo (NOAA/Altimetrics LLC).

<u>Risks (dependencies, potential bottlenecks, and shortcomings)</u>

The work involved is already done for the generation of LRM and PLRM data. No direct risks have been identified. Products are available through RADS, which also guarantees the availability of the auxiliary sources in form of methods, subroutines, models and (meteo) input data. The available resources (man-power) could be at risk but is estimated to be controllable as discussed before for the RADS LRM and PLRM processing.

3 Development and Validation Cycle

3.1 Management

NOC is responsible for the management of WP4000 under which all of the activities described above lie, with support from SatOC as overall project managers.

Each partner is responsible for managing the product development and validation and generating the deliverables (ATBD and PVR) for each sub-theme. They must advise NOC and SatOC in case of expected delays or problems

3.2 Development and Validation Phases

The process of product development and validation will vary for each activity. In many cases the process will involve iteration as different approaches are tested, validated, revised and re-applied.

The steps to be carried out are as follows:

- Analyse, develop and validate the methods and algorithms needed to derive CryoSat-2 products fit for scientific exploitation in the Open Ocean, Coastal Ocean, Sea Floor Mapping and Polar Ocean sub-themes.
- Validate the methods and algorithms against independent data sources and report the error analysis and cross-comparisons in the Product Validation Report (PVR).
- Document the selected methods and algorithms for each sub-theme in the form of Algorithm Theoretical Basis Documents (ATBDs).
- Produce Cryosat-2 products for the Experimental Data Set needed in WP5000 for the public round-robin exercise.

Table 3-1 summarises the planned dates for the provision of the Draft Algorithm Theoretical Basis Document and Product Validation Reports under each sub-theme.

As described in the Project Plan **[RD.5]** the draft outputs will be compiled by NOC and circulated to the CP4O project team for review before submission to ESA.

Table 3-1 Planned dates for provision of draft deliverables for each sub-theme

WP4000 Product	Where	Who	Date Draft ATBD	Date Draft PVR
LRM for Open Ocean (RADS)	Global	TUDelft	Aug 2013	Sept 2013
LRM for Open Ocean (CPP)	Global	CLS	June 2013	June 2013
SAR for Open Ocean / SAMOSA retracker	NE Atlantic	Starlab/NOC	June 2013	Aug 2013
SAR for Open Ocean / CLS,CNES re-tracker	NE Atlantic	CLS	June 2013	Aug 2013
RDSAR for Open Ocean CNES/CLS SAR reduction algorithm	NE Atlantic	CLS	June 2013	Aug 2013
RDSAR for Open Ocean /SAMOSA RDSAR	NE Atlantic	Starlab	June 2013	Nov 2013
RDSAR for Opean Oceans / RADS RDSAR	Global (SAR mode mask)	TUDelft	Aug 2013	Sept 2013
SAR for Coastal Ocean	South Coast UK	NOC	June 2013	June 2013
SAR for Sea Floor Mapping	N Pacific	DTU Space	Early 2014	Early 2014
SAR for Polar Ocean	Arctic (Baffin Bay)	DTU Space	December 2013	December 2013
SARIN for Coastal Ocean	Cuba / Chile	isardSAT	Not applicable	Not Applicable
Wet troposphere corrections	Global	U Porto	October 2013	November 2013
Ionosphere Corrections	Europe	Noveltis	July 2013	June 2013
Regional Tides	NE Atlantic	Noveltis	June 2013	June 2013
Other Geophysical corrections	Global	TUDelft	Sept 2013	Oct 2013

4 Administration and Plan Approval

4.1 Management and Control Procedures

The management and control procedures are all described in the Project Plan [RD.5] and the original Management Proposal [RD.6] and are not repeated here.

4.2 Plan Approval

This Development and Validation Plan is provided to ESA for approval, and through ESA to the Expert Advisory Group for comment and guidance. Note that some of the activities described here are already underway.

5 References

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