CP4O CCN1

CryoSat Plus for Oceans: CP4O CCN1
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EXECUTIVE SUMMARY

Introduction

The ESA CryoSat-2 mission is the first space mission to carry a radar altimeter that can operate in Synthetic Aperture Radar (SAR) mode. Although the prime objective of the CryoSat-2 mission is dedicated to monitoring land and marine ice, the SAR mode capability of the CryoSat-2 SIRAL altimeter also presents significant potential benefits for ocean applications including improved range precision and finer along track spatial resolution.

The “CryoSat Plus for Oceans” (CP4O) project, supported by the ESA Support to Science Element (STSE) Programme and by CNES, was dedicated to the exploitation of CryoSat-2 data over the open and coastal ocean. The general objectives of the CP4O project were: To build a sound scientific basis for new oceanographic applications of CryoSat-2 data; to generate and evaluate new methods and products that will enable the full exploitation of the capabilities of the CryoSat-2 SIRAL altimeter, and to ensure that the scientific return of the CryoSat-2 mission is maximised. Cotton et al, (2015) is the final report on this work.

However, whilst the results from CP4O were highly promising and confirmed the potential of SAR altimetry to support new scientific and operational oceanographic applications, it was also apparent that further work was needed in some key areas to fully realise the original project objectives. Thus additional work in four areas has been supported by ESA under a Contract Change Notice:

- Developments in SARIn data processing for Coastal Altimetry (isardSAT)
- Implementation of a Regional Tidal Atlas for the Arctic Ocean (Noveltis and DTU Space)
- Improvements to the SAMOSA re-tracker: Implementation and Evaluation & Optimised Thermal Noise Estimation. (Starlab and SatOC)
- Extended evaluation of CryoSat-2 SAR data for Coastal Applications (NOC)

This work was managed by SatOC. The results of this work are reported here.

SARIn data processing for Coastal Altimetry

In the main phase of the CP4O contract, isardSAT developed and tested a scheme for coastal processing of SARIn data that made use of the “Angle of Arrival” (or Phase Difference) waveform to identify the nadir echo and use this to generate a “seed” for re-tracking the returned SARIn echo. However, whilst this approach was found to provide a significant improvement on the standard processing, it was found to produce erroneous results in some situations with the re-tracker reverting to off-nadir bright echoes.

Thus for the CCN activity isardSAT implemented and tested further developments to their SARIn coastal processing approach. In the first two developments the waveform to be re-tracked was rebuilt to avoid the part contaminated by non-ocean / off-nadir echoes, either by interpolating over the contaminated part of the waveform, or by cutting the waveform to the range bins immediately around the nadir echo. Both developments provided improved results on the approach derived within the main phase of the project, especially when the contamination was relatively far away from the waveform leading edge, with the second approach (cutting the waveform) performing better than the first (interpolating the waveform).

However, some coastal echoes could still not be processed, and it was felt that the performance could be further improved. Also there was a requirement to develop an approach that was not restricted to SARIn data (i.e. did not rely on the Phase Difference waveforms) and could be more generally applied to SAR mode and LRM data. This third approach considered the Window Delay (or tracker range). Sudden jumps in window delay close to the coast could be assumed to be due to off-nadir echoes contaminating the echo, so the window delay was plotted and smoothed by a polynomial curve fitting. The window delay from the fitted polynomial was then used to seed the re-tracker (limited to the waveform range bins around the seed location). A further refinement could use the geoid as a guide if the window delay polynomial fitting fails. Good results were achieved from this approach, with tracking being maintained close to the coast and in ocean regions with complex land topography. The (20 Hz) standard deviation in Sea Surface Height from a test data set at the Cuba coast, calculated along individual track sections was reduced from 0.5819m for the standard ESA product to 0.2345m by adopting this new approach.

In a test of this approach on open ocean data, using the window delay to generate a seed for the re-tracker (but here applied to the whole waveform), a ~45% improvement in performance was found (in terms of standard deviation of retrieved sea surface height)

A Regional Tidal Atlas for the Arctic Ocean

The successful reprocessing of the CryoSat-2 data over the Arctic Ocean in the framework of the CP4O project, generated for the first time reliable sea surface height measurements to high latitudes (88°) in sea ice affected regions, and so provided an opportunity to implement a regional, high-resolution tidal model in the Arctic Ocean. Indeed, a better estimation of tides in this region would then improve the quality of the CryoSat-2 SSH and of all derived products.

The Arctic Tidal Model that was implemented was based on a development of the T-UGOm model (Toulouse Unstructured Grid Ocean model)[1], an unstructured grid 2D/3D hydrodynamic model developed at LEGOS (Laboratoire d'Etudes en Géophysique et Océanographie Spatiales), see LeBars et al. (2010).

The stages taken to implement the improved Arctic Tidal Atlas included:

- Refining the grid resolution of the regional tidal model to be implemented
- Tuning of the physical parameters of the hydrodynamic model to suit the regional conditions
- Ensemble simulations, varying key physical parameters and analysing model errors, to establish a geographical picture model sensitivity to these errors and hence the locations where data assimilation could most improve the model
- Processing of CryoSat-2 data (LRM, SAR mode and SARIn), 2010-2014, 55°-88°N, and Envisat data, 2002-2010, 55°-82°N, to extract Sea Surface Height and then tidal harmonic constituents.
- Assimilation of altimeter data, and tide gauge data.
- Generation of the tidal atlas

These steps were carried out and a regional Arctic tidal atlas was computed on an unstructured grid with a resolution ranging from a few hundred of meters on the shelves to about 40 km offshore. The atlas contains 8 assimilated tidal components (Semidiurnal: M2, S2, K2, N2. Diurnal: K1, O1, P1 and Q1), and was provided to ESA.

This model was validated against tide gauge and altimeter data, and its performance compared against global Tidal Atlases in the Arctic Ocean. Globally, all the validation results were coherent and demonstrated the better accuracy of the regional optimal tidal model in the Arctic Ocean, compared to the other available tidal models.

Some additional and independent validation activities are planned outside the scope of this project to further assess the quality of this regional tidal atlas. However, the model is recommended "as is" for ocean modeling and forecasting in the Arctic Ocean. It can also provide an improved tidal correction in the CryoSat-2 ocean products, and for altimetry missions with high-inclination orbits, such as Envisat, SARAL/AltiKa and Sentinel-3. The new atlas can also benefit the Copernicus Marine Environment Monitoring Service (CMEMS), which includes the Arctic Ocean as one of five priority European regional seas, and to other European Arctic observing systems.

One key limitation on the quality of the model is the availability of a reliable and accurate bathymetry. There are differences between the two available sources (IBCAO and R-Topo), indicating that both contain errors. It is believed that more accurate bathymetry models have been generated, but are not available at the present time for scientific use.

Further improvements could be made to the Arctic Model, by modifications to the hydrodynamic model, to provide a better representation of the main diurnal components (K1 and O1), and by adding a stage to the processing of the altimeter data to remove the annual variation in sea level prior to the estimation of ocean tide parameters.

[1] T-UGOm hydrodynamic model description: http://www.legos.obs- mip.fr/recherches/equipes/ecola/outils-produits/t-ugom-home-page

Improvements to the SAMOSA re-tracker: Implementation and Evaluation

An accurate representation of the thermal noise in the SAR waveform is a key parameter in re-tracking, as it directly affects the estimation of SWH. One of the activities in the initial CP4O contract was to develop an approach to include an estimation of the thermal noise within the current implementation of the semi-analytical SAMOSA model in the waveform re-tracking. This was achieved through an empirical method that measured the noise level directly on the SAR-Waveform in the range gates just before the waveform leading edge. Although an improvement in performance was observed, it was apparent that there were still problems at low wave heights and further optimisation was desirable

Thus the objective of this activity was to develop an optimised method for the estimation of thermal noise on the SAR waveforms, implement this in the operational SAMOSA re-tracker, generate a validation data set and carry out an independent evaluation. Depending on the results, a recommendation could be made to implement this optimised approach in SAR altimeter processing chains

A new approach for estimating the noise was developed, by optimising the location and number of range bins over which the thermal noise contribution to the signal was averaged. The finally adopted solution was to average the noise over three range bins, centred on a location 16 range bins before the start of the leading edge.

This solution was then implemented in a SAR altimeter L1B to L2 processing chain to a CryoSat-2 L1b data set produced by the CNES/CLS CryoSat Prototype Processor (CPP). This data set covered 14 months (01/11/2012 - 31/12/2013), over an area of the North-East Atlantic (30°-65*N, 20°-0° W) where in situ wave buoy data were available. Initial validation against the CPP L2 data set (produced independently with a different, numerical re-tracker) showed close correspondence between the two data sets, though some residual dependency of SSH errors on wave heights was observed. Also it was found that a surprisingly large proportion of waveforms could not be tracked.

An independent validation of the test data set was then carried out, again through comparison against the equivalent CPP data set for the same period, through statistical analyses, and through validation against wave buoy measurements. It was also concluded that the new implementation of SAMOSA provides an improvement to the current implementation of the SAMOSA models in the Sentinel-3 SRAL DPM, and a largely equivalent performance to a fully analytical implementation of the SAMOSA model (which is computationally expensive and not practical in an operational processing chain), except in the case of a larger bias seen against buoy SWH. When compared to the equivalent CNES-CPP product a largely equivalent performance was observed, in terms of direct comparisons, noise performances, and validation against buoys, except at low significant wave heights, where there remain significant discrepancies between the data sets.

Some items meriting further investigation were identified:

- A common way of computing the misfit between the different datasets should be applied.
- A large proportion of the altimeter echoes in the CNES-CPP L1B data could not be re-tracked by the new implementation of the SAMOSA model. It is a priority to develop a robust re-tracker that will operate reliably on uncontaminated open-ocean SAR echo data.
- A further investigation into the performance of the SAMOSA re-tracker at low wave heights is needed. The evidence of this work suggests that there is still a problem in accurately modelling SAR echoes at low wave heights.
- A high SSH noise was observed in both the SAR datasets in the open ocean. Further investigation is need to establish if this noise is due to geophysical or instrumental causes.

Extended evaluation of CryoSat-2 SAR data for Coastal Applications

Analysis carried out within CP4O highlighted the potential of CryoSat-2 in the coastal zone in terms of low measurement noise (Gommenginger and Cipollini, 2014). However, the analysis in the original contract was only able to consider a limited amount of data and did not taken into account the relative orientation of the tracks and the coastline (i.e. the angle of approach).

Activity supported by the CCN carried out an extended evaluation of CryoSat-2 SAR data for coastal applications, on a one-year data set (01/11/2012 – 31/10/2013) which included every pass within a 50km coastal strip around the British Isles. Level 2 data (sea surface height accompanied by atmospheric and geophysical corrections) were generated by two processors:

- CNES CryoSat Prototype Processor (CPP): a numerical retracker, very efficient, but not optimized for coastal zone (Boy and Moreau, 2013)
- ESRIN GPOD SAR altimetry processor (based on SARvatore) in a configuration optimized for coastal zone (using Hamming weighting, extended range window and FFT zero padding) –see Dinardo, 2014)

The assessment included both a verification of the SAR mode instrumental noise as a function of distance from the coast and coastal morphology, and a validation against tide gauges. The study established a number of useful results:

- Across-track and along-track distance from the coast are more suited than the ‘angle to coast’ as independent variables for this assessment. The angle to coast is ambiguous where the coastline is complex and its definition has a degree of subjectivity.
- The adoption of a specific processing configuration (Hamming filter, Zero padding, extended range window) improves the noise characteristics especially in the “last few km” from the coast.
- Precision (instrumental noise) versus across-track distance from coastline is comparable to conventional pulse-limited altimeters.
- With CryoSat-2 in favourable conditions (meaning a simple coastline and sub- satellite tracks orthogonal to the coastline, so that the across-track footprint is virtually unaffected by the coast until extremely close proximity to it) and coastally- optimized processing, measurements at 2 km from the coast display the same level of noise as over the open ocean and we can aim at recovering meaningful data up to 1 km.
- Validation against tide gauges yields encouraging results – with a fine tuning of the search radius (sometimes combined with an outlier removal procedure) we can get an RMS < 10 cm with search radii around ~20 km.

  These results are complementary to those that will be expected from the new ESA SEOM SCOOP study (which started in October 2015); together they should pave the way to the exploitation of Sentinel-3 data in the coastal zone.

ACRONYMS AND ABBREVIATIONS

Abbreviation	Meaning
AGU	American Geophysical Union
AltiKa	Ka band altimeter on SARAL mission
Arctic Hydro	Arctic Tidal Model (hydrodynamic model, no data assimilation)
BODC	British Oceanograpic Data Centre
CAL2	CryoSat-2 SIRAL on board calibration sequence
CCN	Contract Change Notice
CLS	Collecte Localisation Satellites, Toulouse, France
CMEMS	Copernicus Marine Environment Monitoring Service
CNES	Centre National d'Etudes Spatiales
COASTALT	ESA Project on development of COASTal ALTimetry
Copernicus	European programme for establishing a European capacity for Earth Observation
COSPAR	Committee on Space Research
CP4O	CryoSat Plus for Oceans
CPP	CryoSat Processing Prototype (CNES Processor for CryoSat-2)
CryoSat-2	ESA altimeter satellite for polar ice investigations
DTU-LARS	Specialised primary peak retracker developed at DTU
DTU Space	National Space Institute, Technical University of Denmark
DTUYY	Models (e.g Mean Sea Surface, or tidal models) produced by DTU, with year
DPM	Detailed Processing Model
EGM2008	Geoid Model
EGU	European Geophysical Union
EOT (11a)	Empirical Ocean Tide Model – with version number
Envisat	ESA Earth Observation Mission 2002-2012
ERS-1, 2	ESA Earth Observation missions 1991-2000, 1995-2011
ESA	European Space Agency
ESRIN	ESA Space Research Institute (ESA Centre for Earth Observation)
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FES2012 (14)	(Finite Element Solution) Tide Model (and implementation year)
FFT	Fast Fourier Transform
GOT (X.Y)	Global Tide Model provided with altimeter data (with version number)
GPOD	Grid Processing on Demand (ESA facility for processing Earth Observation data)
GSHHS	Global Self-consistent, Hierarchical, High Resolution Geography Data Base
IBCAO	International Bathymetric Chart of the Ocean
IEEE	Institute of Electrical and Electronic Engineers
IGARSS	IEEE International Geoscience and Remote Sensing Symposium
isardSAT	CP4O partner based in Barcelona, UK and Poland.
Jason-1, Jason-2	Radar Altimeter Satellites
LEGOS	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales
LRM	Low Rate Mode
L1b, L2	Processing levels for SAR altimeter data.

Abbreviation	Meaning (continued)
MSS	Mean Sea Surface
NOC	National Oceanography Centre, Southampton, UK
Noveltis	Noveltis, CP4O CCN partner, based in Toulouse, France
OSTST	Ocean Surface Topography Science Team
Pu	Waveform power value in output of the re-tracking stage
RADS	Radar Altimeter Database System. Radar Altimeter Data archive at TU Delft
RMS	Root Mean Square
R-Topo	Arctic Ocean bathymetry model
SAMOSA	SAR altimetry Mode Studies and Applications
SAR	Synthetic Aperture Radar
SARAL	Satellite with Argoss and AltiKa – French-Indian Altimeter mission
SARIn	SAR interferometric mode
SARvartore	SAR altimeter processing capability available on GPOD.
SatOC	Satellite Oceanographic Consultants
SCOOP	SAR Altimetry Coastal and Open Ocean Performance: Project funded by the ESA SEOM programme
SEOM	Scientific Exploitation of Operational Missions, ESA programme
Sigma0 (σ^0)	Radar Backscatter at nadir
SIRAL	LRM / SAR / SARIn mode radar altimeter on CryoSat-2
SR	Search Radius
SRAL	SAR mode altimeter on Sentinel-3
SSH	Sea Surface Height
STARLAB	Starlab LS, CP4O CCN partner based in Spain and UK
STSE	Support to Science Element
SWH	Significant Wave Height
S-3, Sentinel-3	Sentinel-3: ESA EO mission launched on 16 February 2016
TG	Tide Gauge
T-UGOm	Toulouse Unstructured Grid Ocean model
TPX08	Tidal model derived from Topex/Poseidon data.
TWLE	Total Water Level Envelope

1 INTRODUCTION

The ESA CryoSat-2 mission is the first space mission to carry a radar altimeter that can operate in Synthetic Aperture Radar (SAR) mode. Although the prime objective of the CryoSat-2 mission is dedicated to monitoring land and marine ice, the SAR mode capability of the CryoSat-2 SIRAL altimeter also presents significant potential benefits for ocean applications including improved range precision and finer along track spatial resolution.

The "CryoSat Plus for Oceans" (CP4O) project, supported by the ESA Support to Science Element (STSE) Programme and by CNES, was dedicated to the exploitation of CryoSat-2 data over the open and coastal ocean. The general objectives of the CP4O project were: To build a sound scientific basis for new oceanographic applications of CryoSat-2 data; to generate and evaluate new methods and products that will enable the full exploitation of the capabilities of the CryoSat-2 SIRAL altimeter, and to ensure that the scientific return of the CryoSat-2 mission is maximised.

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

However, whilst the results from CP4O were highly promising and confirmed the potential of SAR altimetry to support new scientific and operational oceanographic applications, it was also apparent that further work was needed in some key areas to fully realise the original project objectives. Thus additional work in four areas has been supported by ESA under a Contract Change Notice.

1. Developments in SARIn data processing for Coastal Altimetry (isardSAT)
2. Implementation of a Regional Tidal Atlas for the Arctic Ocean (Noveltis and DTU Space)
3. Improvements to the SAMOSA re-tracker: Implementation and Evaluation & Optimised Thermal Noise Estimation. (Starlab and SatOC)
4. Extended evaluation of CryoSat-2 SAR data for Coastal Applications (NOC)

The activities described started in January 2015, and the final results were presented at a workshop at ESA/ESRIN, Frascati on 10th December 2015. The presentations made at that meeting are available online at http://www.satoc.eu/projects/CP4O/CP4O_CCN.html

Each of the four activities and the respective major outcomes are described in separate sections below. A table of contract deliverables is provided in Annex 2.

2 DEVELOPMENTS IN SARIN DATA PROCESSING FOR COASTAL ALTIMETRY

2.1 Introduction

In the main phase of the CP4O contract, isardSAT developed and tested a scheme for coastal processing of SARIn data that made use of the "Angle of Arrival" (or Phase Difference) waveform to identify the nadir echo and use this to generate a "seed" for re-tracking the returned SARIn echo. However, whilst this approach was found to provide a significant improvement on the standard processing, it produced erroneous results in some situations with the re-tracker reverting to off-nadir bright echoes.

The aim of the CCN activity was to develop this approach to further improve performance, and ideally develop a coastal processing scheme that was not restricted to SARIn data and could be applied to altimeter data collected in other modes (SAR mode and LRM)

2.2 Processing Approaches

For the CCN activity isardSAT implemented and tested further developments to their SARIn coastal processing approach (Garcia, 2015). These approaches were applied to CryoSat-2 SARIn data over the west of Cuba (Figure 2-1).

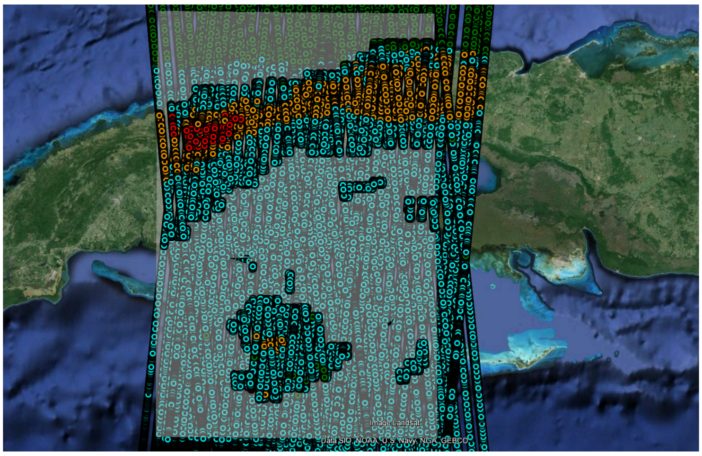

Figure 2-1 The Area of interest of the study (western end of Cuba, and the ground tracks of 104 CryoSat-2 SARIn products used.

For the first two developments the SARIn power waveform to be re-tracked was rebuilt to avoid the part contaminated by non-ocean / off-nadir echoes, either by interpolating over the contaminated part of the waveform, or by cutting the waveform to the range bins immediately around the nadir echo. Both developments provided improved results on the approach derived within the main phase of the project, especially when the contamination was relatively far away from the waveform leading edge, with the second approach (cutting the waveform) performing better than the first (interpolating the waveform).

However, some coastal echoes could still not be processed, with some signals not showing any range bin close to nadir, and it was felt that the performance could be further improved. Also there was a requirement to develop an approach that was not restricted to SARIn data (i.e. did not rely on the Phase Difference waveforms) and could be more generally applied to SAR mode and LRM data.

Therefore, a third approach was developed which used the Window Delay (or tracker range) to provide a seed for the re-tracker. Sudden jumps in window delay close to the coast could be assumed to be due to off-nadir echoes contaminating the echo, so the window delay was plotted and smoothed by a polynomial curve fitting. After various tests it was found a dynamic approach was needed to determine the optimum degree of polynomial to be fitted to each section of track. The window delay from the fitted polynomial was then extracted and used to seed the re-tracker (applied to a "cut" waveform limited to the waveform range bins around the seed location). A further refinement could use the geoid (EGM2008) as a guide if the window delay polynomial fitting fails, as happens when the tracker follows a coastal (non Nadir ocean) target in a continued series of records records along an entire sea section. In future improvements of the current approach, the geoid version used could be substituted by an alternative model with better performance. Note however that applying geoid approach could lose the ocean signal in some instances. Figure 2-2 shows the tracker window delay, fitted polynomial and and geoid for an individual track across the area of interest.

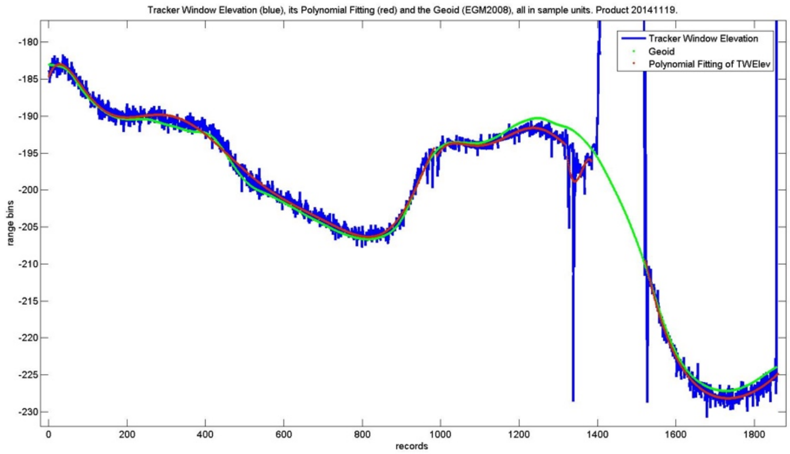

Figure 2-2: Window Delay fitting along the track of date 2014/11/19. Four different sections were fitted with different polynomial orders. The original Window Delay is shown in blue, the fitting result in red, and the geoid in green.

The land-sea mask used was retrieved from the Open-Street map coastal polylines, available online (http://openstreetmapdata.com/data/coast) . The ESA products and the GSHHS land-sea masks were not enough detailed for our purposes, due to the extremely complex coastal topography of this Area of Interest.

A database was generated covering all data in the region of interest for 2013 and provided to ESA. This database includes the sub satellite track position, re-geolocated echo location (ESA products), time, land-sea mask and retrieved Sea Surface Height from standard ESA processing, and from the new window delay approach.

2.3 Results

Good results were achieved from the “window delay” approach, with tracking being maintained close to the coast and in ocean regions with complex land topography (Figure 2-3).

To provide a numerical assessment of the improvements in 20 Hz SSH measurements resulting from this study, the standard deviation of each individual section of the dataset (a total of more than 300 sections) were computed. The benefits of the approach developed in this study were clearly seen in the averages of standard deviations of all the sections. The average SSH standard deviation from the new CP4O scheme was 0.2345m, 60% lower than that calculated from the ESA products (0.5819m). The improvement is even greater if only data close to the coast are considered.

Also the SSH along track differences versus distance to the coast were calculated for both ESA & CP4O series, in order to study the stability in the SSH data while approaching the coast. Here again, the results from the new approach demonstrated a much improved performance compared to the standard ESA product (Figure 2-4). The CP4O and ESA series presented similar SSH along track differences, around 14 cm, when far from the coast (more than 3500 meters), but when approaching the coast (right to left in Figure 2-4) a clear difference in behaviour was seen with CP4O SSH along track differences of up to 30 cm and ESA SSH along track differences of more than 60 cm for a distance offshore of few hundreds of meters. Again, an improvement of over 50% has been observed.

Finally, an assessment was done to assess the CP4O re-tracker performance for a 45km length of track over the Open Ocean. A quadratic polynomial was fitted to a 20 record running average window delay. This was then used to seed the re-tracker, this time applied to the whole SARIn power waveform. The standard deviation on the retrieved Sea Surface Heights was 12.07cm for the standard ESA product, and 7.51 cm for the new approach, a ~45% improvement in performance.

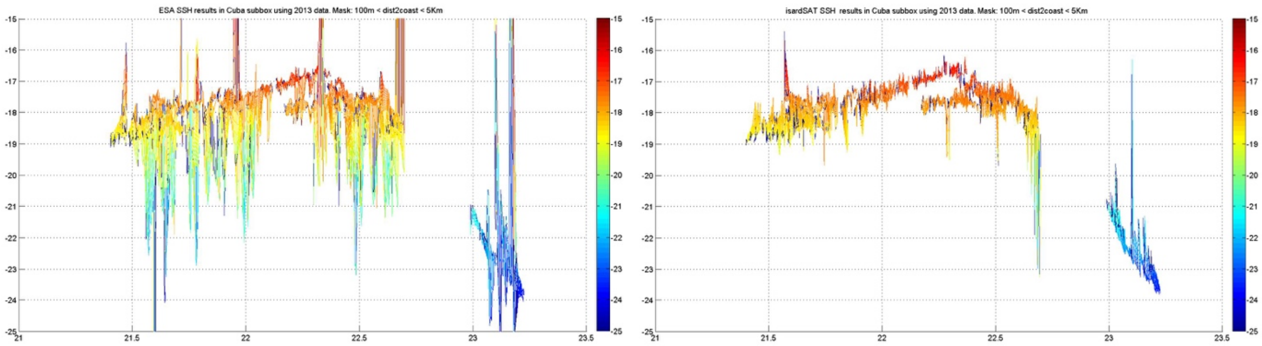

Figure 2-3: SSH profile versus latitude of ESA L2 (left) and CP4O (right) solutions

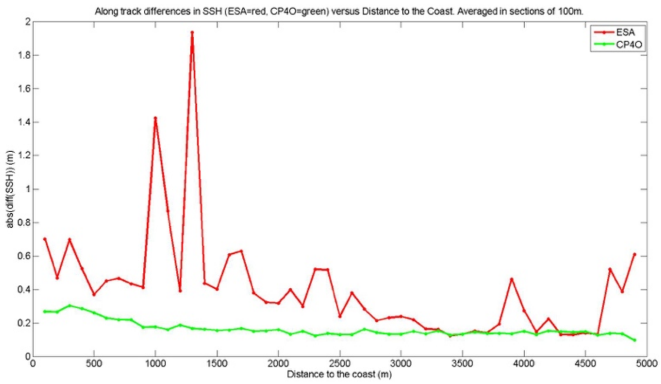

Figure 2-4: SSH differences along the track versus distance to the coast, averaged every 100m. ESA in red, CP4O in green.

2.4 Conclusions and Recommendations

A new approach for coastal processing of CryoSat-2 SARIn data has been developed, which is based on the tracking window delay, and can therefore also be applied to SAR mode and LRM data.

Assessment of a one-year database shows a ~60% improvement in performance in terms of 20Hz standard deviation in retrieved sea surface height, calculated on a track by track basis.

In terms of future work for improving the above solution for coastal altimetry, there are some ideas that could be developed for improving the current CP4O results. The SAR mode enables the possibility of a dedicated stack processing that could lead to a less contaminated multi-look waveform. The algorithms developed within this CP4O CCN activity could be combined with a stack processing in order to give the re-tracker not only a seed and a cut waveform to avoid contamination, but also work with an enhanced multi-look waveform pre-processed for better further SSH retrievals. For echoes very close to the coastline, steering could also be applied to further improve results. These would be major modifications to the current processing as they would require modification of the L1b SAR/SARIn processing.

An interesting option for further studies is to combine the two above approaches in a synergic solution that takes the best from both, and derive an enhanced SSH coastal mapping.

An interesting application of this new processing approach could be to develop a mean sea surface database of a selected area by processing a data series over a period of several years.

A validation exercise of such a dataset would be very interesting. From it, we would be in position to better discriminate the real measurement noise from the SSH variations due to the ocean dynamics (e.g. MSS variations in the Area of Interest).

Garcia (2015) provides a full report of this study.

3 DEVELOPMENT OF A TIDAL ATLAS IN THE ARCTIC OCEAN

3.1 Introduction

The Arctic Ocean is a challenging region for tidal modelling, partly because of its complex and poorly documented bathymetry, but also due to the intermittent presence of sea ice and the scarce availability of in situ tidal observations at such high latitudes. As a consequence, the accuracy of the global tidal models decreases by several centimetres in the Polar Regions, which has a large impact on the quality of the altimetry Sea Surface Height (SSH) in these regions (from ERS1/2, Envisat, CryoSat-2, SARAL and Sentinel-3 missions).

The successful reprocessing of the CryoSat-2 data over the Arctic Ocean, in the framework of the CP4O project, generated for the first time reliable sea surface height measurements to high latitudes (88°) in sea ice affected regions, and so provided an opportunity to implement a regional, high-resolution tidal model in the Arctic Ocean. Indeed, a better estimation of tides in this region would then improve the quality of the CryoSat-2 SSH and of all derived products.

The second activity supported under CP4O CCN1 was to develop, implement and validate a new Arctic Tidal Atlas, based on the availability of SSH CryoSat-2 data to high latitudes.

3.2 Approach

The Arctic Tidal Model implemented was based on a development of the T-UGOm model (Toulouse Unstructured Grid Ocean model), an unstructured grid 2D/3D hydrodynamic model developed at LEGOS (Laboratoire d'Etudes en Géophysique et Océanographie Spatiales) (LeBars et al., 2010).

The steps taken to develop and implement the improved Arctic Tidal Atlas are summarised below.

3.2.1 Mesh Refinement and Bathymetry

The first step was to establish an improved resolution mesh for the tidal model for the Arctic domain (55°-90°N), and to identify the best bathymetry model available. The mesh was based on a refinement of the existing FES2014 global model grid, so that the new model could be patched into the global model. The global mesh was locally increased using a set of tools developed at LEGOS. Over the whole Arctic Ocean, the resolution of the refined mesh was set to 4 km at the coast, with local refinements down to a few hundreds of meters, and reaching a maximum of 40 km offshore (compared with more than 80 km offshore for the initial FES2014 mesh, see Figure 3-1).

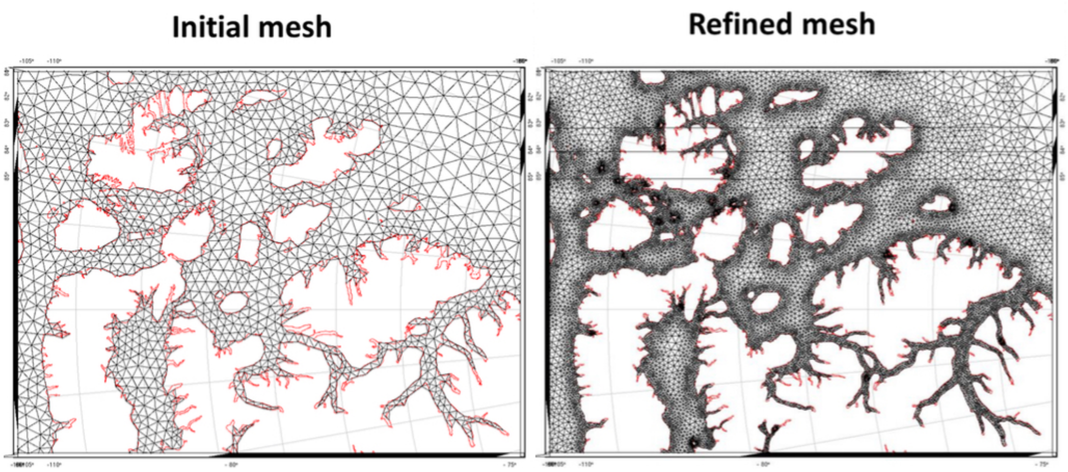

Figure 3-1: Local refinement of the Arctic Ocean Model mesh resolution in the North West Passage

The accuracy of the tidal model highly depends on the quality of the bathymetry data used as an input of the hydrodynamic model. In particular, the tidal processes interact with the bathymetry in the shallow water regions, which leads to the generation of non-linear tidal components. Errors in the bathymetry can consequently have large consequences on the model results and performances. Two bathymetry models were considered: IBCAO (International Bathymetric Chart of the Arctic Ocean), an international initiative that provides bathymetric data on a 500m spacing (Jakobsson et. al., 2012); and R-Topo, developed by Timmerman et al., which is a global bathymetry with some improvements at the poles using multi-beam survey data. An analysis of these models indicated IBCAO as the best option, though the comparison highlighted some shortcomings in the IBCAO model. It is thought there is still scope to improve the bathymetry model, which would have a major impact on the performance of the atlas.

3.2.2 Hydrodynamic model set-up and validation

The next step was the set-up of the hydrodynamic model, in terms of boundary conditions, and the tuning of key parameters related to the bottom friction and the wave drag (which characterises the energy transfer from the baroclinic mode to the barotropic mode). Ensemble simulations were run to identify the combinations of parameters that provided the best solution. During this part of the model set-up the importance of the contribution of sea-ice providing friction at the top of the ocean was identified, and it was established that different configurations for winter and summer were required, because of the different extent of sea-ice, and hence different contribution to friction, during these seasons.

3.2.3 CryoSat-2 Altimeter Data Processing and Assimilation

CryoSat-2 altimeter data for 2010-2014, in all modes (SAR, SARIn, and LRM) were used. The LRM data were extracted from the RADS altimeter archive, and edited using a custom made editing solution for Polar Oceans. The SAR and SARIn data were retracked with the specialised DTU-LARS primary peak re-tracker, also developed for use in sea-ice affected regions. Envisat Data (2002-2010; 55°-82°N) were also included. Tidal harmonic constituents were then determined from these two series of Sea Surface Height data. It was noted that the processing did not totally remove the annual signal, which meant that the diurnal components were not perfectly separated.

For data assimilation into the model the initially provided set of altimeter derived tidal constituents was sub-setted in the open ocean to a regular spacing of 200km between points, full available resolution was retained on the continental shelves.

Tidal constituents from a selection of tide gauges were also assimilated. However, in most cases the full time series of Tide Gauge data is not available, and this reduces the number of tidal constituents to be assimilated and prevents from verifying the accuracy of the tidal constituents' estimation.

Following the assimilation of the altimeter and tide gauge tidal constituents into the tidal model, the model was optimised and a final solution achieved.

The regional Arctic tidal atlas was provided on a structured grid of 1/60 degree (unstructured mesh resolution ranging from a few hundred meters on the shelves to about 40 km offshore), and contained 8 assimilated tidal components (Semi-diurnal: M2, S2, K2, N2. Diurnal: K1, O1, P1 and Q1).

3.3 Results – Validation of the Arctic Tidal Atlas

This model was validated against the full initial set of tide gauge and altimeter data (thus including the data assimilated into the model), and its performance compared against other Tidal Atlases in the Arctic Ocean.

The validation was carried out in the frequency domain, for each tidal component, by computing the vector differences between the optimal (i.e. assimilated) regional Arctic model and the validation databases. These vector differences were compared to the results obtained with the competitor global models in the same region and with the same validation databases.

Figure 3-2 and Figure 3-3 show the average vector difference computed for each model, for each tidal component, against the tide gauge and the altimetry databases, respectively. The results obtained with the prior hydrodynamic solutions (no data assimilation) of the FES2014 global model ("FES2014 hydro") and the regional Arctic model ("Arctic hydro") are shown for information. It should also be noticed that there was a strong improvement between the FES2012 and the FES2014 global solutions in the Arctic Ocean, as it is highlighted by these comparisons. The comparison between the "Arctic hydro" solution, in red, and the "Arctic assimilated" solution, in purple, shows the impact of the data assimilation on the regional tidal model. For most of the tidal components (M2, K1...), the improvement due to the assimilation is quite noticeable, for both validation databases. Again, as parts of these databases have been assimilated in the model (and are strongly correlated with the data that were not assimilated, in the case of the altimetry database), what is highlighted here is the fact that the assimilation worked well and the model was well constrained by the observations, as the differences are reduced. For some components, the improvement is small, but coherent with the amplitudes of these components (Q1).

In summary, all the validation results were coherent and demonstrated the better accuracy of the regional optimal tidal model in the Arctic Ocean, compared to the other available tidal models.

3.4 Conclusions

A new Arctic Tidal Atlas has been implemented, based on an implementation of the T-UGOm hydrodynamic model, with a refined regional grid for the Arctic, and on the assimilation of tide gauge data and altimetry data from CryoSat-2 and Envisat.

This model has been validated against Tide Gauge and altimeter data and the performance compared against other available tide models. The validation results demonstrate the high accuracy of the Arctic tidal atlas compared to the most recent global tidal atlases, when the differences are significant.

Some additional and independent validation activities are planned outside the scope of this project to further assess the quality of this regional tidal atlas. However, the model is recommended “as is” for ocean modeling and forecasting in the Arctic Ocean. It can also provide an improved tidal correction in the CryoSat-2 ocean products, and for altimetry missions with high-inclination orbits, such as Envisat, SARAL/AltiKa and Sentinel-3. The new atlas can also benefit the Copernicus Marine Environment Monitoring Service (CMEMS), which includes the Arctic Ocean as one of five priority European regional seas, and to other European Arctic observing systems.

One key limitation on the quality of the model is the availability of a reliable and accurate bathymetry. There are differences between the two available sources (IBCAO and R-Topo), indicating that both contain errors. It is believed that more accurate bathymetry models have been generated, but are not available for scientific use.

Further improvements could be made to the Arctic Model, by modifications to the hydrodynamic model, to provide a better representation of the main diurnal components (K1 and O1), and by adding a stage to the processing of the altimeter data to remove the annual variation in sea level prior to the estimation of ocean tide parameters.

A full report of this activity is given in Cancet and Andersen (2016).

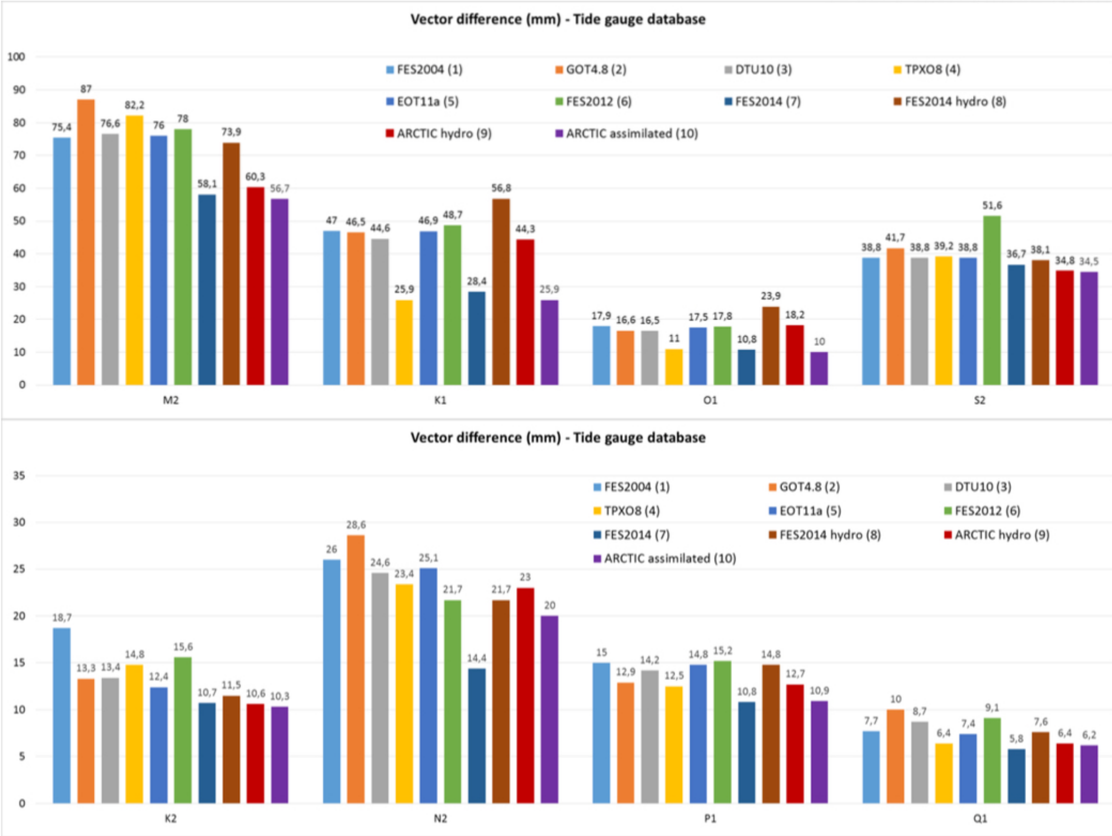

Figure 3-2: Vector differences between the tidal models and the tide gauge database for each tidal component

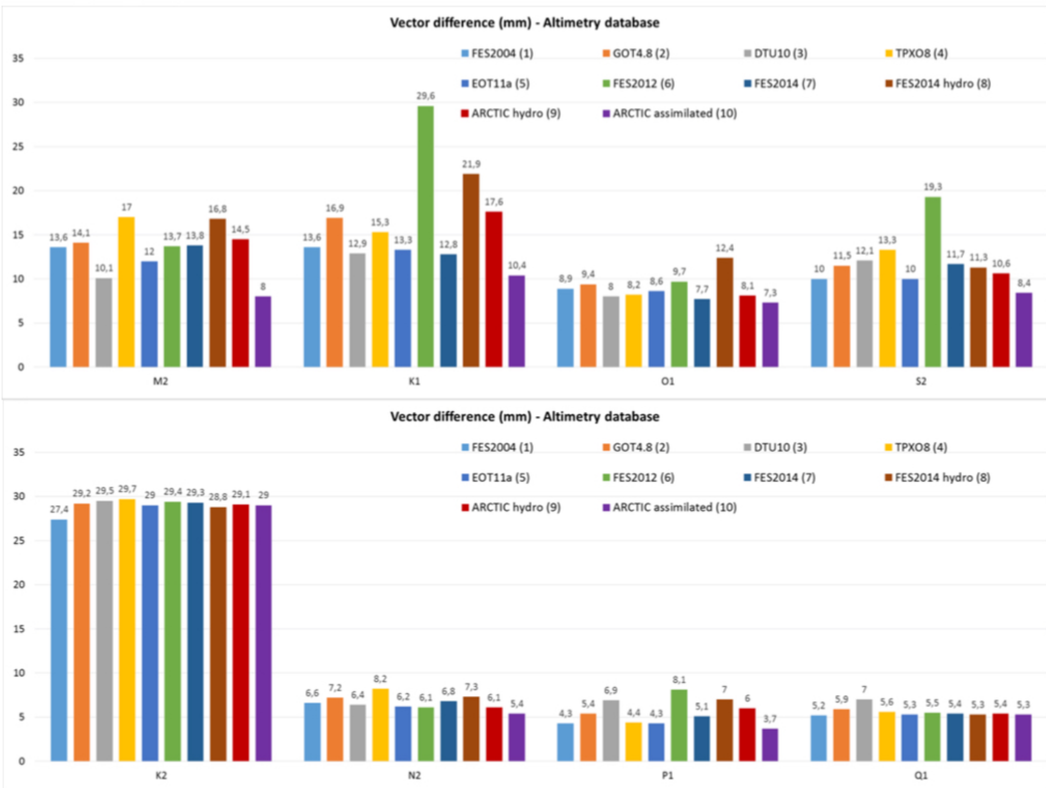

Figure 3-3: Vector differences between the tidal models and the altimetry database for each tidal component

4 IMPROVED ESTIMATION OF THE THERMAL NOISE IN THE SAMOSA RETRACKER

4.1 Introduction

An accurate representation of the thermal noise in the SAR waveform is a key parameter in re-tracking, as it directly affects the estimation of SWH. One of the activities in the initial CP4O contract was to develop an approach to include an estimation of the thermal noise within the current implementation of the semi-analytical SAMOSA model in the waveform re-tracking. This was achieved through an empirical method that measured the noise level directly on the SAR-Waveform in the range gates just before the waveform leading edge. Although an improvement in performance was observed, it was apparent that there were still problems at low wave heights and further optimisation was desirable

Thus the objective of this activity was to develop an optimised method for the estimation of thermal noise on the SAR waveforms, implement this in the operational SAMOSA re-tracker, generate a validation data set and carry out an independent evaluation. Depending on the results, a recommendation could be made to implement this optimised approach in SAR altimeter processing chains.

4.2 Development and Implementation of an Optimised Approach for Estimating Thermal Noise in the SAR Waveform

A new approach for estimating the noise was developed, by optimising the location, or “lag” (with respect to the waveform leading edge) and number of range bins (“margin”) over which the thermal noise contribution to the signal was averaged.

Different margins and lags were tested using Level-1b CPP products provided by CNES. The SSH, SWH, and Pu values provided by the CPP products were compared against those obtained by the modified SAMOSA retracker. The best results were obtained using a margin of 16 lags and a window length of 2-3 lags. The equations below give the recommended solution for estimating the thermal noise. Figure 4-1 illustrates the results as applied to example SAR altimeter waveforms.

leading_edge_span = 2*(waveform_peak_pos – half_power_pos),
leading_edge_starting_pos=waveform_peak_pos-leading _edge_span,
noise_calculation_position=leading_edge_starting_pos-(16),
noise_floor = mean(Waveform[noise_calculation_position– 1: noise_calculation_position +1]),

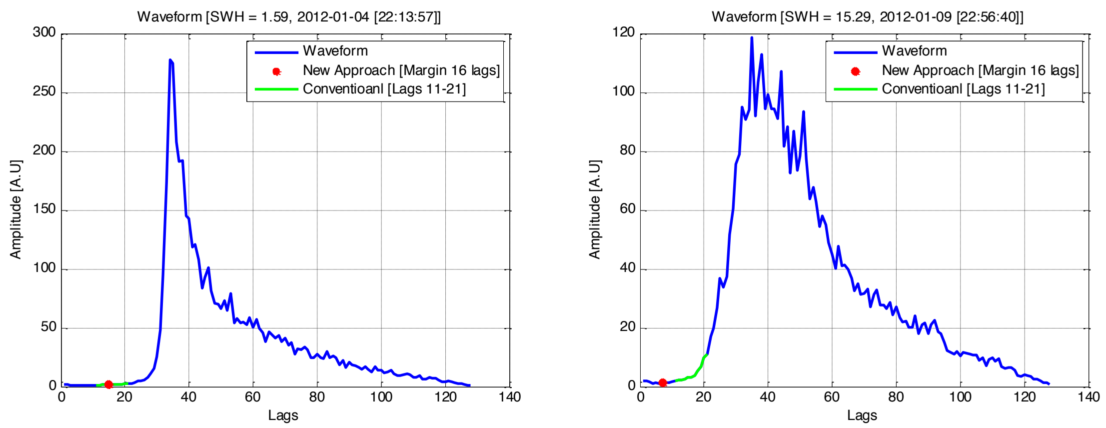

Figure 4-1: Optimum point for the noise floor estimation for two waveforms with SHW=1.59m (left) and SWH =15.29m (right)

This solution was then implemented in a SAR altimeter L1B to L2 processing chain to a CryoSat-2 L1b data set produced by CNES/CLS CryoSat Prototype Processor (CPP). This data set covered 14 months (01/11/2012 -0 31/12/2013), over an area of the North-East Atlantic (30°-65*N, 20°-0° W) where in situ wave buoy data were available. Initial validation against the CPP L2 data set (produced independently with a different, numerical, re-tracker) showed close correspondence between the two data sets, though some residual dependency of SSH errors on wave heights was observed. Also it was found that a surprisingly large proportion of waveforms could not be tracked.

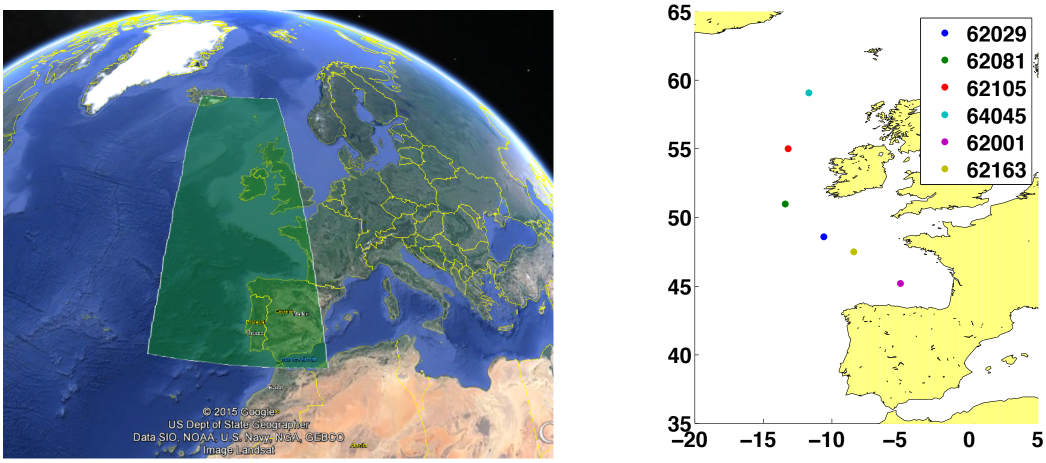

Figure 4-2: (Right) Location and extent of the CryoSat-2 SAR altimeter data set processed and validated and (left) location of the UK Met Office Wave Buoys used in the validation

4.3 Validation

An independent validation of the test data set was then carried out, through comparison against the equivalent CPP L2 data set, produced from the same source L1B data, through statistical analyses, and through validation against wave buoy measurements.

Figure 4-3 shows a scatter plot of SSH for CPP against the "improved" SAMOSA (labelled as "STARLAB"), and the dependency of the difference between the two on SWH, and Figure 4-4 shows the same figures for SWH.

The correlation between the two data sets is greater than 99% in both cases, but a dependency of the SSH bias on SWH is evident, and a lower correlation in SWH between the two data sets at low wave heights is evident.

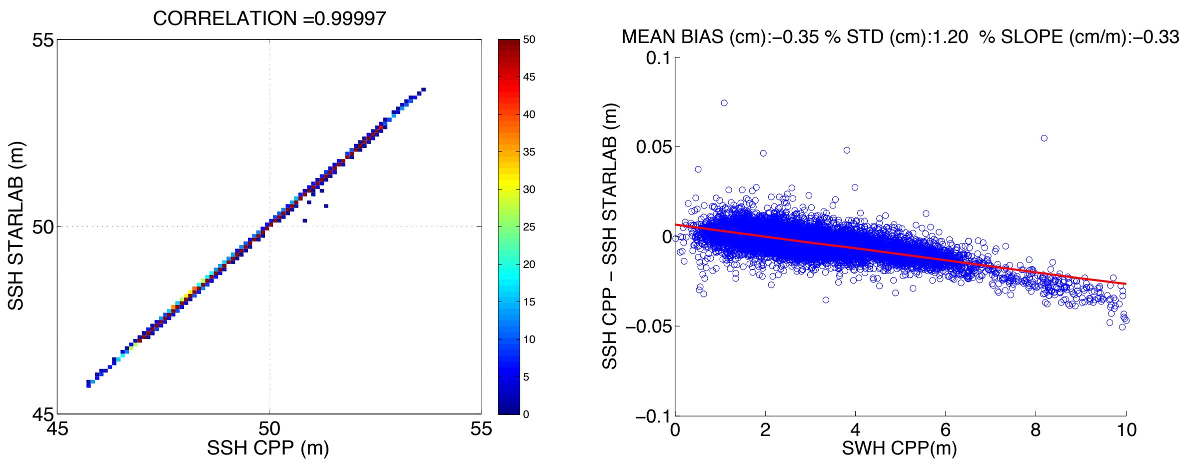

Figure 4-3: (Left) Scatter plot of SSH from the improved SAMOSA, (or "STARLAB") against CPP, and (right) difference of SSH CPP and SSH STARLAB against SWH

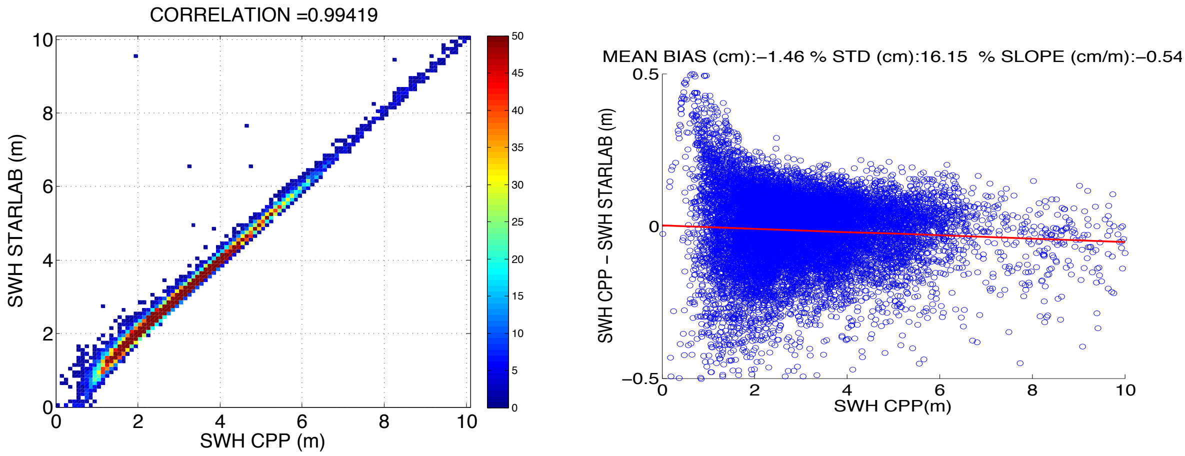

Figure 4-4: (Left) Scatter plot of SWH from the improved SAMOSA, (or “STARLAB”) against CPP, and (right) difference of SWH CPP and SWH STARLAB against SWH

Analysis of 20Hz noise in SSH and SWH along track is used as a way of measuring expected measurement precision (on the basis that the geophysical signal is not varying on this length scale). Figure 4-5 presents the 20Hz noise in SWH (left) and SSH (right), as a function of buoy SWH. In each case, the plot also shows the noise estimates from the Jason-2 LRM data obtained for the same set of buoys over the same months. As a note of interest, the statistics obtained using the outer buoys (64045, 62105 and 62081) were used for validation, because a high SSH noise was observed at the location of the most internal buoys (62029, 62163, 62001).
It could be hypothesised that higher noise might be related to the presence of significant variability across the European continental slope, in terms of tides, geophysical corrections and mean sea surface: and this could explain why Jason 2 statistics are not affected by the different set of buoys, as the RADS product of Jason 2 SSH (as used here) includes the corrections.

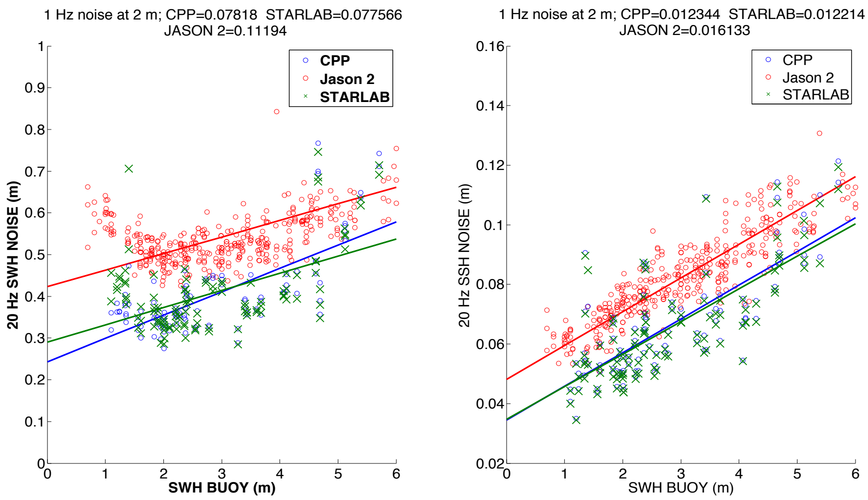

Figure 4-5: SSH 20Hz Noise against buoy SWH for CNES-CPP, Starlab and Jason-2 LRM at the same buoys over the same period, for “outer” buoys 64045, 62105 and 62081.

One of the purposes of the task was also to investigate if implementing the new approach to estimating the thermal noise resulted in an improvement on previous implementation of the SAMOSA model. Table 4-1 summarises the results from the CP4O CCN validation activity, and compares them to results from a similar analysis carried out in the main CP4O project (Gommenginger and Cipollini, 2014). In this table “ESRIN R1”, refers to full implementation of the SAMOSA model without any approximations: and “ESRIN R6”: refers to the implementation of the SAMOSA model in current Sentinel-3 DPM, which is semi-analytical, excludes some terms and applies some approximations to others. The improved estimation of thermal noise developed in this activity has been implemented on the version of the SAMOSA model here referred to as ESRIN R6. It should be noted that the results in (Gommenginger and Cipollini, 2014) were gained from a validation data set with different coverage from that considered in this report, so the statistics are not precisely comparable.

Run	1 Hz noise at 2m		SWH v buoy		CNES-CPP – SAMOSA difference			CNES-CPP – SAMOSA trend / m v SWH		
	SSH (cm)	**SWH (cm)**	**Bias (cm)**	**Std (cm)**	**SSH (cm)**	**SWH (cm)**	**Pu**	**SSH (cm)**	**SWH (cm)**	**Pu**
CNES-CPP	1.23	7.82	-12.0	30.0	-	-	-	-	-	-
Starlab (this study)	1.22	7.76	-13.5	28.7	-0.35	-1.46	0.00	-0.33	-0.54	0.00
ESRIN R1	1.22	8.62	5.1	22.5	0.0	1.2	3.42	-0.28	0.39	-0.013
ESRIN R6	1.25	9.25	-10.9	25.4	-0.3	17.4	-13.9	0.11	-4.76	0.002
Jason 2	1.61	11.19	6.7	45.1	-	-	-	-	-	-

Table 4-1: Summary diagnostics for C2 SAR CNES-CPP and STARLAB results. The values for ESRIN R1 and R6 are taken from RD4.

It was concluded from the validation that the new implementation of SAMOSA provides an improvement to the current implementation of the SAMOSA models in the Sentinel-3 SRAL DPM ("ESRIN R6", and a largely equivalent performance to a fully analytical implementation of the SAMOSA model ("ESRIN R1" - which is computationally expensive and not practical in an operational processing chain), except in the case of a larger bias seen against buoy SWH. When compared to the equivalent CNES-CPP product a largely equivalent performance was observed, in terms of direct comparisons, noise performances, and validation against buoys, except at low significant wave heights, where there remain significant discrepancies between the data sets.

4.4 Summary and Recommendations

An improved approach to estimating the thermal noise in the SAR waveform has been developed and implemented in the the SAMOSA based waveform re-tracker. Analysis of a 1 year data set showed this resulted in a product with a largely equivalent performance to the CNES-CPP product, and improved results compared to the SAMOSA re-tracker currently implemented in the Sentinel-3 SRAL DPM.

The following issues were identified as priorities for further investigation:

- A common way of computing the misfit between the different datasets should be applied.
- A large proportion of the altimeter echoes in the CNES-CPP L1B data could not be re-tracked by the SAMOSA model. It is a priority to develop a robust re-tracker that will operate reliably on uncontaminated open-ocean SAR echo data.
- A further investigation into the performance of the SAMOSA re-tracker at low wave heights is needed. There is still a problem in accurately modelling SAR echoes at low wave heights.
- The high SSH noise in SAR datasets away from the coast underlines the need of including geophysical corrections and mean sea surface to derive SSH statistics, and of determining the reason (geophysical or instrumental) of such a high variability within 7 km of along-track data.

This work is reported in more detail in Martin (2016), and Passaro and Cotton (2016).

5 EXTENDED EVALUATION OF CRYOSAT-2 SAR DATA IN THE COASTAL ZONE

5.1 Introduction

Analysis carried out within CP4O has highlighted the potential of CryoSat-2 in the coastal zone in terms of low measurement noise. The analysis looked at the differences of consecutive 20-Hz measurements around the coast of the UK in order to derive an estimate of the noise, and found that CryoSat-2 20-Hz data feature a 5-cm noise level up to 5km from the coast.

However, the analysis was only able to consider two months of data and has not taken into account the relative orientation of the tracks and the coastline (i.e. the angle of approach).

Thus an extended evaluation of CryoSat-2 SAR data at the coast was proposed which would include a reassessment of the 20-Hz noise as a function of both distance from coast and angle of approach, and would carry out a more complete validation of altimeter derived estimates of Total Water Envelope (TWLE) against Tide Gauge levels from the UK network.

A 14 month data set (01/11/2012 – 31/10/2013) was used for this study which included every pass within a 50km coastal strip around the British Isles. Level 2 data (sea surface height accompanied by atmospheric and geophysical corrections) were generated by two processors:

- CNES CryoSat Prototype Processor (CPP): a numerical retracker, very efficient, but not optimized for coastal zone (Boy and Moreau, 2013)
- ESRIN GPOD SAR altimetry processor (based on SARvatore) in a configuration optimized for coastal zone (using Hamming weighting, extended range window and FFT zero padding) - see Dinardo, 2014.

Tide gauge data were obtained from the data archives of the British Oceanographic Data Centre (BODC). The temporal resolution of the sea level data is 15 minutes for records stored at the BODC. These data are quality controlled by BODC but additional visual quality control on the time series was applied for the purposes of this work.

5.2 Methodology and Results

5.2.1 Verification of precision versus distance from, and angle to, the coast

The Global Self-consistent, Hierarchical, High Resolution Shoreline data base (GSHHS) was used to define the coastline, and algorithms applied to determine the along-track and across-track distances of each data point to the coast (Figure 5-1). Note that whilst SAR processing reduces the effective along-track footprint to ~350m, the across track footprint remains pulse limited across track (2-10 km depending on sea state).

In general, the altimeter derived water level parameter used was the Total Water Level Envelope, defined as:

TWLE = Orbit Latitude - Corrected Range - Mean Sea Surface +

- (Solid Earth Tide + Load Tide)

where

Corrected Range = Range + Instrumental corrections + Dry Tropospheric Correction + Wet Tropospheric Correction + Sea State Bias + Ionospheric Correction.

TWLE is not corrected for ocean tide, pole tide and the inverse barometer effect. DTU10 MSS was used for the Mean Sea Surface (MSS).

As a proxy for noise, the performance of the CPP and GPOD data was assessed in terms of the absolute value of the difference in TWLE amongst consecutive SAR mode resolution cells.

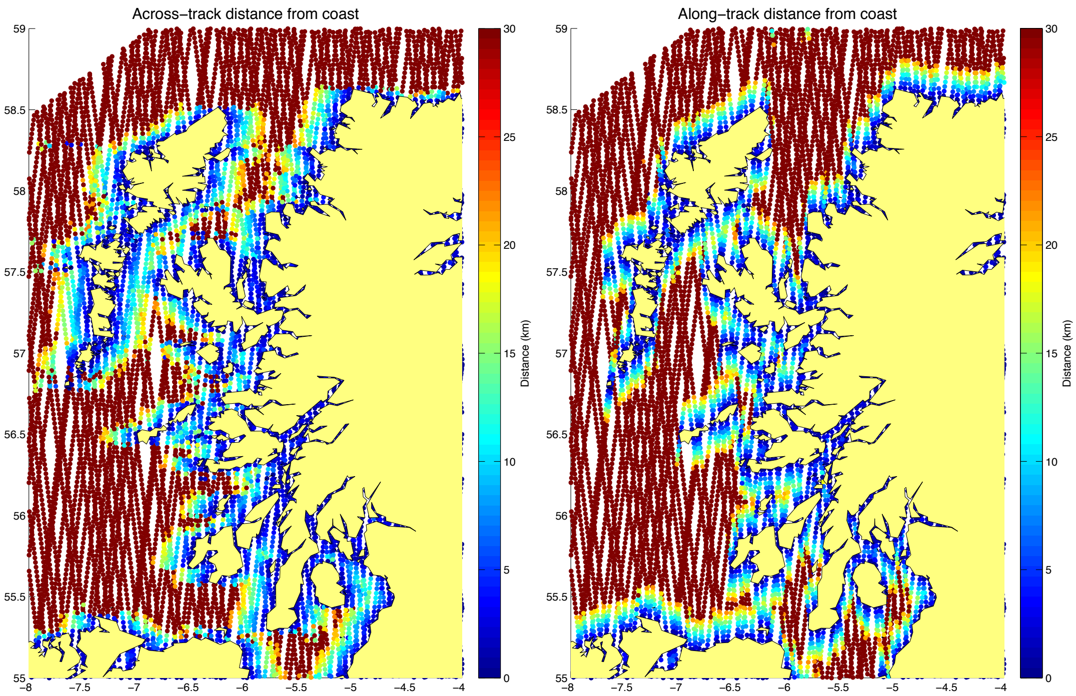

Figure 5-1: across-track and along-track distance from coast for CryoSat-2 passes around the Western coast of Scotland

Figure 5-2 show the noise proxy vs distance from the coast (along track and across track for both CPP and GPOD data. The GPOD data can be seen to give better performance, in terms of lower values, especially close to the coast (~7 cm at 3 km, and ~9.5 cm at 2 km, considering median trends). It was found that if additional data screening was applied, based on the misfit parameter, then the noise curve stays virtually flat at 5 cm or less up to 3 km from the coast, and then increases to 6 cm and 9 cm at 2 km and 1 km from the coast, respectively. The number of points passing the screening is 50% at 2km.

The dependence of precision against angle of arrival to the coast was also investigated, but no strong evidence of any dependence could be found. This reinforced the suggestion that across track distance is a better way to screen data than the angle of the satellite track to the coast.

5.2.2 Validation via comparison against tide gauges

To estimate the accuracy of the SAR data in the coastal zone the retrieved TWLE values were compared to a number of tide gauges around the UK, with tide gauge data taken from the BODC data archives and quality controlled as detailed above. In each location a search radius of 5 km is initially applied and then increased to 50 km in 1-km steps. For each value of the search radius (SR) all the altimeter overpasses intersecting the search circle are selected and a time series of altimeter and tide gauge TWLE is built, the RMS difference of the time series also being computed. The mean bias between the altimetric and TG time series is removed before computing the RMS difference as there are absolute differences between the tide gauge and altimeter data baselines.

This approach may sometimes require manual intervention to remove outliers, as some of the match-up pairs can be negatively affected by residual errors in orbits or altimetric corrections. Figure 5-3 shows the RMS against search radius for Newhaven and Aberdeen.

Thus for Newhaven the RMS difference between the tide gauge and altimeter TWLE increases steadily with Search Radius, whereas for Aberdeen there appears to be an optimal Search Radius at ~20km where the RMS is at a minimum. Clearly the validation at each location will be dependent on local conditions, the location of the tide gauge, the coastal topography and the dynamics at the coast.

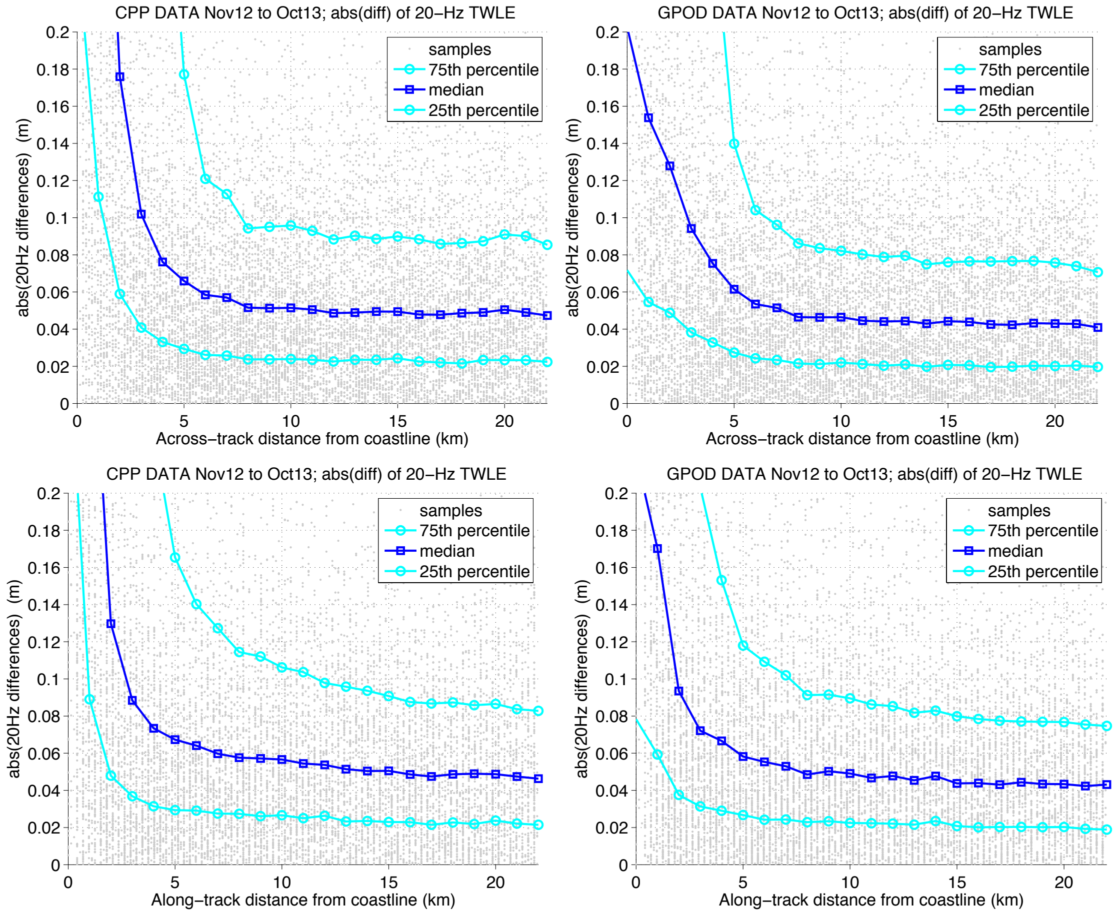

Figure 5-2: Scatterplots of the absolute value difference between consecutive TWLE measurements, and the statistics of its distribution in 1-km distance bins, against along track distance (top panels), and across-track distance (lower panels), CPP data in the left panels, and GPOD data in the right panels).

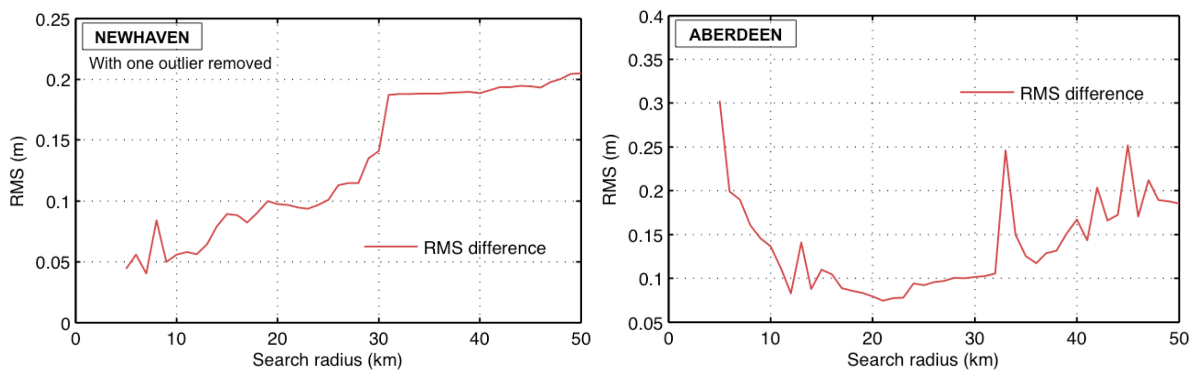

Figure 5-3: RMS difference between de-meaned time series of TWLE from altimetry and from the tide gauge at Newhaven (left) and Aberdeen (right), as a function of the search radius around the tide gauge. For the Newhaven plot an outlier at SR=18km was removed.

5.3 Conclusions

This study assessed the capability of CryoSat-2 in SAR mode to measure sea level in the coastal zone using one year of data from two different processors: an efficient numerical retracker (CPP), and the GPOD SARvatore run in a specific configuration optimized for coastal retrievals. The assessment has included both a verification of the SAR mode instrumental noise as a function of distance from the coast and coastal morphology and validation against tide gauges.

The study has established a number of useful results, summarized here:

- Across-track and along-track distances from the coast are more suited than the 'angle to coast' as independent variables for this assessment. The angle to coast is ambiguous where the coastline is complex and its definition has a degree of subjectivity.
- The adoption of a specific processing configuration (Hamming filter, zero padding and extended range window) improves the noise characteristics especially in the "last few km" from the coast.
- Precision (instrumental noise) versus across-track distance from coastline is comparable to conventional pulse-limited altimeters.
- With CryoSat-2 in favourable conditions (meaning a simple coastline and sub- satellite tracks orthogonal to the coastline, so that the across-track footprint is virtually unaffected by the coast until extremely close proximity to it) and coastally- optimized processing, measurements at 2 km from the coast display the same level of noise as over the open ocean and we can aim at recovering meaningful data up to 1 km.
- Validation against tide gauges yields encouraging results – with a fine tuning of the search radius (sometimes combined with an outlier removal procedure) we can get an RMS < 10 cm with search radii around ~20 km.

These results are complementary to those that will be expected from the new ESA SEOM SCOOP study (which started in October 2015); together they should pave the way to the exploitation of Sentinel-3 data in the coastal zone.

A full report of this work is available in Cipollini and Calafat (2016).

6 OUTREACH: PUBLICATIONS AND ACCESS TO PROJECT OUTPUTS

CP4O CCN project results and deliverables are available at:
http://www.satoc.eu/projects/CP4O/CP4O_CCN.html, A full list of presentations using CP4O and CP4O CCN results is available at:
http://www.satoc.eu/projects/CP4O/presentations.html

Meeting	Venue	Date
6th Coastal Altimetry Workshop	Riva del Garda, Italy	20-21 September, 2012
OSTST	Venice-Lido, Italy	27-28 September, 2012
AGU Fall meeting	San Francisco, USA	3-7 December 2012
CryoSat -2Third User Workshop	Dresden, Germany	12-14 March 2013
EGU General Assembly	Vienna, Austria	07-12 April 2013
1st SAR Altimetry Expert Group Meeting	Southampton, UK	26-27 June 2013
ESA Living Planet Symposium	Edinburgh, UK	9-13 September 2013
OSTST	Boulder, USA	8-11 October 2013
AGU Fall meeting	San Francisco, USA	9-13 December 2013
40th COSPAR Scientific Assembly	Moscow, Russia	2-10 August 2014
OSTST	Lake Constance, Germany	28-31 October 2014
AGU Fall meeting	San Francisco, USA	15-19 December 2014
IGARSS 2015	Milan, Italy	26-31 July, 2015
EGU General Assembly	Vienna, Austria	12-17 April 2015
Sentinel-3 for Science Workshop	Venice, Italy	2-5 June 2015
EUMETSAT Meteorological Satellite Conference	Toulouse, France	21-25 September 2015
AGU Fall meeting	San Francisco, USA	14-18 December 2015
AGU Ocean Sciences	New Orleans, USA	21-26 February 2016
EGU General Assembly	Vienna, Austria	17-22 April 2016
ESA Living Planet Symposium	Prague, Czech Republic	9-13 May 2016
Liège Colloquium	Liège, Belgium	23-27 May 2016
COSPAR	Istanbul, Turkey	30 July-7 August 2016

Table 6-1: Table of meetings at which CP4O and CP4O CCN results have been presented

7 CONCLUSIONS

Four activities have been supported under a CCN to the CP4O project.

Developments in SARIn data processing for Coastal Altimetry (isardSAT)

This work developed and tested new approaches to processing SARIn data at the coast. A processing scheme based on the use of tracker window delay has been developed, and demonstrated to be efficient at retrieving sea surface height in complex coastal topography. This approach can also in principle be applied to SAR mode and LRM altimeter data.

Implementation of a Regional Tidal Atlas for the Arctic Ocean (Noveltis and DTU Space)

Noveltis and DTU Space have worked together to implement and validate a new Arctic Regional Tidal Atlas, using reprocessed CryoSat-2 and Envisat data. The CryoSat-2 data were processed by DTU using a scheme developed for application in polar oceans where sea ice is present. The new model was shown to perform better than other available models.

Improvements to the SAMOSA re-tracker: Implementation and Evaluation & Optimised Thermal Noise Estimation. (Starlab and SatOC)

Starlab developed and implemented modifications to the currently operational version of the SAMOSA re-tracker, though an improvement to the estimation of the Thermal Noise in the SAR echo, which was aimed at improving re-tracker performance at low wave heights. This modified re-tracker was used to generate a test data set which was independently evaluated by SatOC, and was confirmed to improve the estimation of the geophysical parameters, with a largely equivalent performance to the numerical re-tracker implemented in the CPP chain, except at low wave heights. Some issues remain, however, with regard to the large number of ocean echoes that could not be re-tracked.

Extended evaluation of CryoSat-2 SAR data for Coastal Applications (NOC)

An extended evaluation of CryoSat-2 SAR data at the coast was carried out by NOC, which included both a verification of the SAR mode instrumental noise as a function of distance from the coast and coastal morphology, and a validation against tide gauges. The study established that with coastally-optimized processing, measurements at 2 km from the coast display the same level of noise as over the open ocean and we can aim at recovering meaningful data up to 1 km. Validation against tide gauges also yielded encouraging results – with a fine tuning of the search radius (sometimes combined with an outlier removal procedure) an RMS of under 10 cm with a search radius close to 20 km was achieved.

Together, these activities have further demonstrated important new capabilities offered to ocean applications by CryoSat-2 SAR data.

8 ACKNOWLEDGEMENTS

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We wish to acknowledge the support of CNES and CLS who kindly provided the CNES- CPP data used in this work. CNES-CPP products were developed by CNES and CLS in the frame of the "Sentinel-3 SRAL SAR mode performance assessment" study.
We are grateful to Francois Boy of CNES for providing the CPP data in a very timely fashion, and to Salvatore Dinardo of SERCO/ESRIN (now at EUMETSAT) for his assistance with the GPOD run and for the many fruitful technical discussions

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IMPORTANT WEB LINKS

CP4O (and CCN) Project: http://www.satoc.eu/projects/CP4O/
SAMOSA Project: http://www.satoc.eu/projects/samosa/
SAMOSA Configuration Control: http://www.satoc.eu/projects/samosa/samosa_config.html
ESA: http://esa.int
ESA Earth Observation: http://earth.esa.int
STSE: http://due.esrin.esa.int/stse/
ESA GPOD (Grid Processing on Demand): https://gpod.eo.esa.int/services/CRYOSAT_SAR/
CryoSat-2: http://earth.esa.int/web/guest/missions/esa-operational-eo-missions/cryosat
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9 ANNEX 1 - ABSTRACT

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

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The ESA CryoSat-2 mission is the first space mission to carry a radar altimeter that can operate in Synthetic Aperture Radar "SAR" (or delay-Doppler) and interferometric SAR (SARIn) modes. Studies on CryoSat-2 data have analysed and confirmed the improved ocean measuring capability offered by SAR mode altimetry, through increased resolution and precision in sea surface height and wave height measurements, and have also added significantly to our understanding of the issues around the processing and interpretation of SAR altimeter echoes.

We present work in four themes, building on work initiated in the CryoSat Plus for Oceans project (CP4O), each investigating different aspects of the opportunities offered by this new technology.

The first two studies address the coastal zone, a critical region for providing a link between open-ocean and shelf sea measurements with those from coastal in-situ measurements, in particular tide gauges. Although much has been achieved in recent years through the Coastal Altimetry community, (http://www.coastalt.eu/community) there is a limit to the capabilities of pulse-limited altimetry which often leaves an un-measured "white strip" right at the coastline. Firstly, a thorough analysis was made of the performance of "SAR" altimeter data (delay-Doppler processed) in the coastal zone. This quantified the performance, confirming the significant improvement over "conventional" pulse-limited altimetry. In the second study a processing scheme was developed with CryoSat-2 SARIn mode data to enable the retrieval of valid oceanographic measurements in coastal areas with complex topography. Thanks to further development of the algorithms, a new approach was achieved that can also be applied to SAR and conventional altimetry data (e.g., Sentinel-3, Jason series, Envisat).

The third part of the project developed and evaluated improvements to the SAMOSA altimeter re-tracker that is implemented in the Sentinel-3 processing chain. The modifications to the processing scheme should support improved performance in terms of accuracy and efficiency in retrieving oceanographic geophysical parameters from altimeter data.

Finally, we describe the development of a state of the art tidal atlas for the Arctic Ocean with CryoSat-2 altimeter data. Through its high inclination orbit, the CryoSat-2 mission provides the most complete altimeter data set ever used in this region, and so should enable the production of a highly accurate Arctic tidal model. This in turn will improve the quality of CryoSat-2 Sea Surface Height measurements and all derived products (e.g. mean sea surface, mean dynamic topography).

Together these studies provide an important foundation for exploiting data from the Sentinel-3 and Sentinel-6/Jason-CS missions.

The work described in this presentation was supported by an extension to the CryoSat Plus for Oceans project funded by ESA (STSE). We also acknowledge the support of CNES who provided the CNES-CPP CryoSat-2 Products used in these studies. CNES-CPP products were developed by CNES and CLS in the frame of the "Sentinel-3 SRAL SAR mode performance assessment" study.

10 ANNEX 2 – CP4O CCN DELIVERABLES

Deliverable	Title	Responsible
D1	Test Data Set with guidance notes including high level SARIn processing and results.	isardSAT
D2.1	Polar Tidal Atlas Technical Report	Noveltis
D2.2	Polar Tidal Atlas	Noveltis
D3.1	Technical Note on SAMOSA model	Starlab
D3.2	Evaluation Data Set	Starlab
D3.3	Technical Note on evaluation of Data Set	SatOC
D4	Technical Note on CryoSat-2 SAR performance in the coastal zone	NOC
D5	Final CP4O CCN Report	SatOC