IMPROVED OCEANOGRAPHIC MEASUREMENTS WITH CRYOSAT SAR ALTIMETRY: APPLICATION TO THE COASTAL ZONE AND ARCTIC

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ABSTRACT

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 summarized here. Detailed information regarding the CP4O project can be found at: http://www.satoc.eu/projects/CP4O/

1. 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 nadir 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 information) 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 for this new approach. Fig.1 illustrates the results,
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), it was found to show a ~45% improvement in performance (in terms of standard deviation of retrieved sea surface height).
See Garcia (2015) for further details.

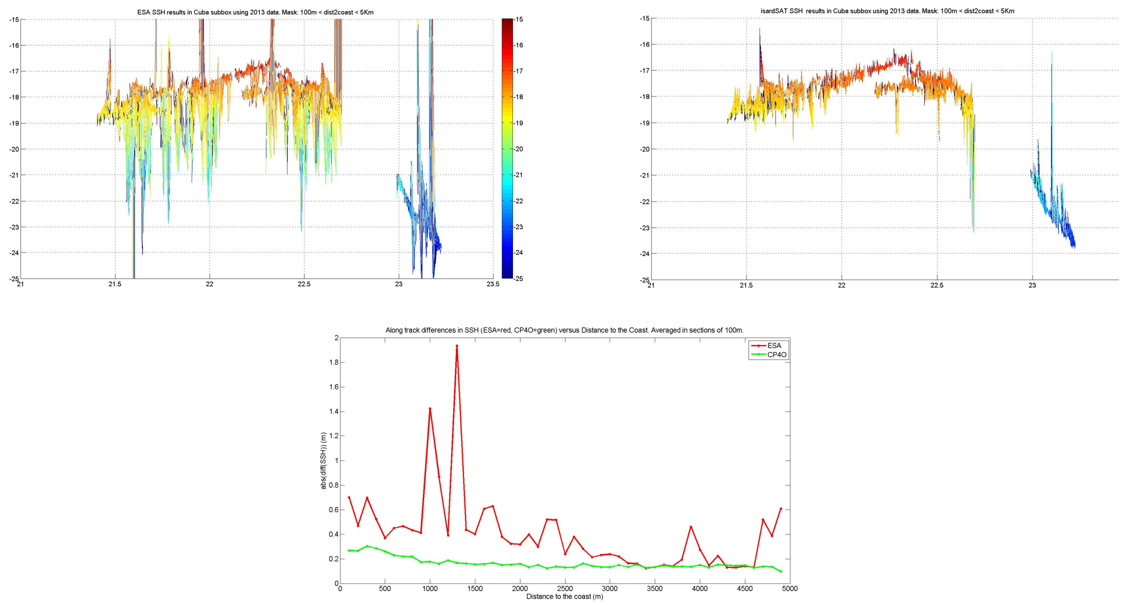

Figure 1. Results from Window Delay Processing approach of SARin data by isardSAT at the Cuban coast. Top Left, retrieved Sea Surface Height profile (versus latitude) from ESA L2 product; Top right, retrieved Sea Surface Height profile (versus latitude) from CP4O processing (window delay approach); Bottom, Sea Surface Height differences along track versus distance to coast, averaged every 100m, ESA in red, CP4O in green.

2. 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, better 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 (Fig. 2).

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

- 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 (See Fig.3 for the comparison against Tide Gauges). 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.

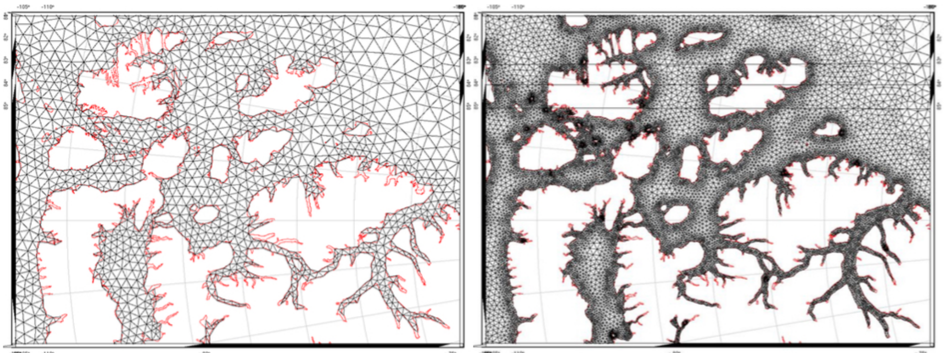

Figure 2. Local refinement of the Arctic Ocean Model mesh resolution in the North West Passage (Left: initial mesh, right, refined mesh)

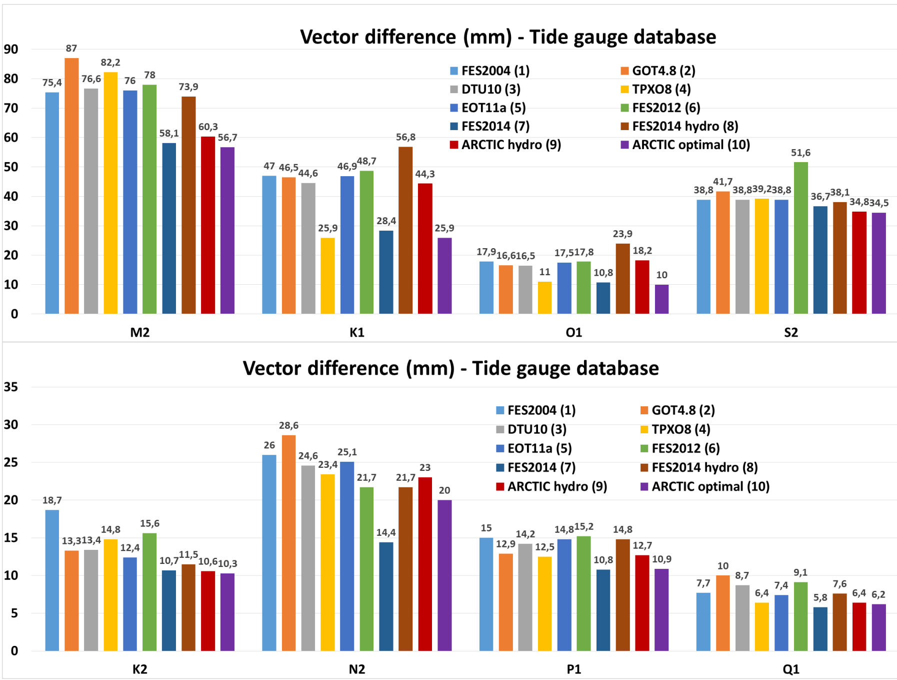

Figure 3. Vector differences between the tidal models and the tide gauge database for each tidal component. The performance of the new Arctic model is shown in the last two columns (red- unassimilated, purple – assimilated).

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.
See Cancet and Andersen (2016) for more details.

3. IMPROVEMENTS TO THE SAMOSA RE-TRACKER: IMPLEMENTATION AND EVALUSATION

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 (see Fig 4.).
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 was for just over 1 year (01/11/2012 - 31/12/2013), for 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.

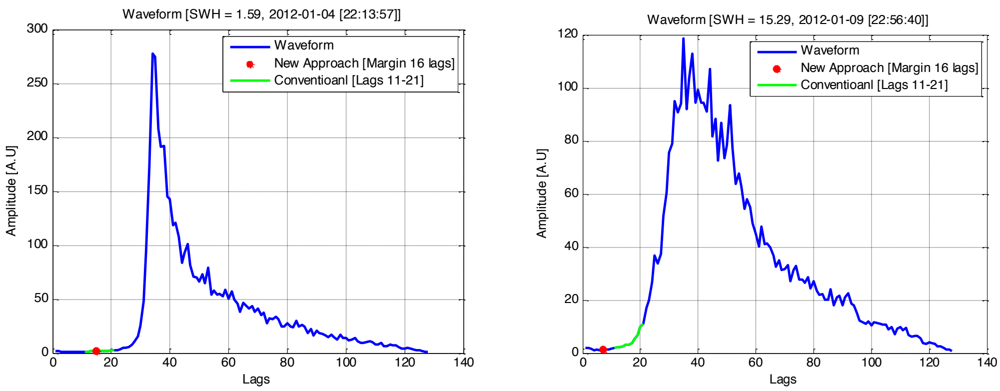

Figure 4. Optimum point for the noise floor estimation for two waveforms with SHW=1.59m (left) and SWH =15.29m (right)

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.

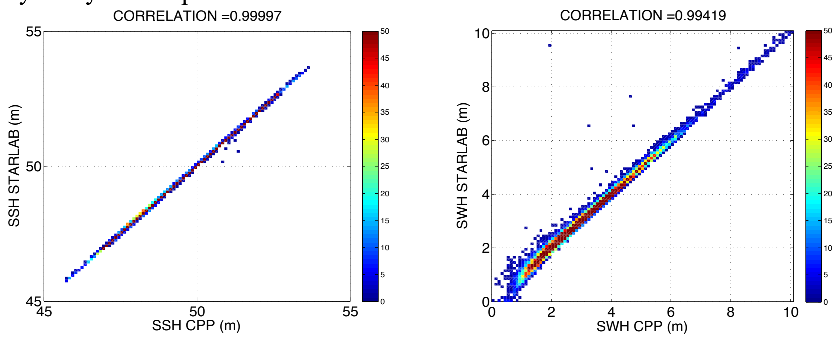

Figure 5. Scatter plots from the improved SAMOSA, (or "STARLAB"), y-axis, against CPP, x-axis, for Sea Surface Height (left) and Significant Wave Height (right).

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. See Fig. 5.

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.

See Martin (2016) and Passaro and Cotton (2016) for further details.

4. 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 take 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 50-km 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 the coastal zone (Boy and Moreau, 2013)
- ESRIN GPOD SAR altimetry processor (based on SARvatore) in a configuration optimized for the 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 from the British Oceanographic Data Centre (BODC) archive. The quantity used was the Total Water Level Envelope (TWLE). i.e. the sea level inclusive of tidal and atmospheric signals, and the temporal resolution of the tide gauge data is 15 minutes. 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. This is evident in figure 6 where the noise of the GPOD data (right-hand panels) in the

last 5-6 km from the data is lower than the noise in the GPP data (left-hand panels).

- Precision (instrumental noise) versus across-track distance from coastline is comparable to conventional pulse-limited altimeters (5-6 cm at 5 km and 9-10 cm at 3 km from the coast, as seen in the top panels of figure 6). Noise statistics improve versus along-track distance as can be seen in the lower panels of figure 6.
- 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 in 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 (plots not shown).
- 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.

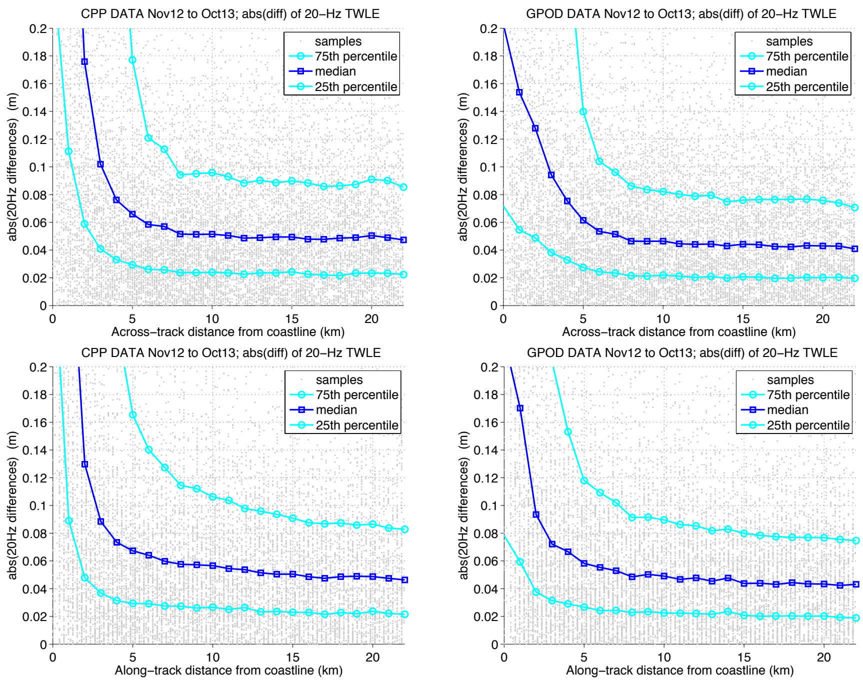

Figure 6. Scatterplots of the absolute value difference between consecutive TWLE measurements (a proxy for instrumental noise), and the statistics of its distribution in 1-km distance bins, against across-track distance (top panels), and along-track distance (lower panels), CPP data in the left panels, and GPOD data in the right panels).

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

See Cipollini and Calafat (2016) for further details.

5. ACKNOWLEDGMENTS

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