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WP4000:
Extended evaluation of CryoSat-2 SAR data in the Coastal Zone

Paolo Cipollini and Francisco Mir Calafat

National Oceanography Centre

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National Oceanography Centre, Southampton
European Way, Southampton
SO14 3ZH, United Kingdom
Tel: +44 (0)23 80596413 Fax: +44 (0)23 80596400

DOCUMENT SIGNATURE TABLE

	Name	**Institution**	**Signature**	**Date**
Prepared by	P Cipollini FM Calafat	NOC		28/04/2016
Authorised by	P Cipollini	NOC		28/04/2016

DISSEMINATION

To:	Copies	Means
Jérôme Benveniste	1	Jerome.Benveniste@esa.int
Américo Ambrózio	1	Americo.Ambrozio@esa.int
Marco Restano	1	Marco.Restano@esa.int
David Cotton	1	d.cotton@satoc.eu

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REFERENCE DOCUMENTS AND APPLICABLE DOCUMENTS

[RD1] Gommenginger, C., Cipollini, P. and Snaith. H. CP4O – Cryosat Plus 4 Oceans WP4000 Product Development and Validation - SAR Altimetry over the Open Ocean & the Coastal Zone Product Validation Report (PVR), v 1.0, 23 June 2014, CP4O_WP4_SAR_OpenOceanCoastal_PVR_v1.0, available from http://www.satoc.eu/projects/CP4O/deliverables.html

[RD2] Dinardo, S., 2014: GPOD CryoSat-2 SARvatore Software Prototype User Manual, Available from https://wiki.services.eoportal.org/tiki-index.php?page=GPOD+CryoSat-2+SARvatore+Software+Prototype+User+Manual

[RD3] Passaro, M., Cipollini, P., Vignudelli, S., Quartly, G.D. and Snaith, H.M., "ALES: a multi-mission adaptive sub-waveform retracker for coastal and open ocean altimetry", *Remote Sensing of Environment*, Volume 145, 5 April 2014, Pages 173–189, http://dx.doi.org/10.1016/j.rse.2014.02.008

[RD4] Cipollini, P. (2011). A new parameter to facilitate screening of coastal altimetry data and corrections. Presented at the 5th Coastal Altimetry Workshop, San Diego, USA, available from http://www.coastalt.eu/files/sandiegoworkshop11/poster/P08_Cipollini_Coastal_Proximity.pdf

[RD5] Boy, F. & Moreau, T., 2013: Algorithm Theoretical Basis Document (ATBD) of the CPP SAR numerical retracker for oceans. CNES report reference S3A-NT-SRAL-00099-CNES, Version 1.0, 15/06/2013, 16 pp, available from: http://www.satoc.eu/projects/CP4O/docs/S3A-NT-SRAL-00099-CNES_SAR_ATBD.pdf.

List of Acronyms

ALES	Adaptive Leading-Edge Subwaveform retracker
ATBD	Algorithm Theoretical Baseline Documents
BODC	British Oceanographic Data Centre
CCI	Climate Change Initiative
CNES	Centre Nationale d'Etudes Spatiales
CP4O	CryoSat Plus for Oceans
CPP	CryoSat Processing Prototype (CNES Processor for CryoSat)
CryoSat-2	ESA altimeter satellite for polar ice investigations
DTU10	Mean Sea Surface model from Danish Technical University
ESA	European Space Agency
ESRIN	ESA European Space Research Institute in Frascati, Italy
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FFT	Fast Fourier Transform
GPOD	ESA Grid Processing on demand
GSHHS	Global Self-consistent, Hierarchical, High-resolution Geography Database
MSS	Mean Sea Surface
NOC	National Oceanography Centre
PVR	Product Validation Report
RADS	Radar Altimeter Data System maintained by TU Delft.
RD	Reference Document
RMS	Root Mean Square
SAR	Synthetic Aperture Radar
SatOC	Satellite Oceanographic Consultants
SCOOP	SAR altimetry Coastal & Open Ocean Performance (ESA-funded project)
Sentinel-3	ESA Remote sensing mission in the Copernicus programme
SEOM	Scientific Exploitation of Operational Missions (ESA programme)
SERCO	Outsourcing company based in Hook, UK
SSH	Sea Surface Height
SR	Search Radius
STSE	Support to Science Element
TG	Tide Gauge
TN	Technical Note

TU Delft	Delft University of Technology
TWL/TWLE	Total Water Level Envelope

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1 PURPOSE OF THIS DOCUMENT

This document represents the deliverable from the work in WP4000 of CP4O Contract Change Notice 1, presenting an extended evaluation of the capabilities of CryoSat-2 SAR mode altimetry to retrieve sea surface height (sea level) in the coastal zone.

2 RATIONALE AND BACKGROUND

2.1 Expected SAR mode benefits in the Coastal Zone

SAR mode altimetry is revolutionizing altimetry due to its improved performance, and ESA has supported the investigation into the oceanographic capabilities of SAR mode altimetry with a series of past and present projects including CP4O. One of the investigations in the original CP4O contract concerned the assessment of SAR mode altimetry in the Coastal Zone as part of WP4000 [RD1].

The coastal zone is expected to benefit significantly from SAR mode altimetry for a number of reasons:

1) the higher signal-to-noise ratio may enable the detection of smaller signals in the 'noisy' (from the point of view of altimetry observables) coastal environment;
2) the much higher along-track resolution (nominally ~300 m along-track for the SAR footprint vs 2-10 km for a conventional pulse-limited footprint) can be exploited to detect small-scale changes or can be traded off, all or in part, in exchange for further noise reduction;
3) reduced contamination by land and coastal targets (depending on their position), as well as access to individual echoes, enable editing out affected echoes or Doppler bins: this should allow a successful retrieval of geophysical parameters closer to the coastline than in conventional altimetry.

Confirming those expectations implies assessing both how *precise* and how *accurate* are the measurements in the coastal zone, and how close to the coast we can get within a given level of precision. Assessment of precision calls for a **verification** of the data – i.e. an assessment of the repeatability of the measurement depending essentially on instrumental noise. Conversely, an accuracy assessment calls for a **validation** to be carried out against independent measurements such as those provided by tide gauges, to check for the existence of biases or trends. Specific aspects of verification and validation procedures in the coastal zone include the dependence of the results on both the coastal morphology and the relative orientation of the sub-satellite track versus the coastline (i.e. the "angle of approach" or "angle to coast")

2.2 Summary of previous results from main CP4O project

The previous investigation was carried out by NOC Southampton using data from the SARvatore processor developed at ESRIN [RD2] and run over the coastal zone around the UK for two months (July 2012 and January 2013). Results are detailed in Section 8 of the corresponding Product Validation Report [RD1].

A first section in [RD1] concerned an attempted validation of the data versus tide gauges (TG). For the comparison we selected all CryoSat-2 passes within 50 km from each tide gauge and computed the TWLE (total water level envelope), i.e. the total sea level inclusive of ocean tides and atmospheric forcing (due to pressure and wind effects), therefore immediately comparable with the level recorded by a tide gauge. TWLE is a desirable quantity for validation, as avoiding additional corrections by models of tides and atmospheric effect renders the validation results immune from errors in those models.

In detail TWLE is 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.

We highlight that the TWLE is not corrected for the ocean tide, the pole tide and for the inverse barometer effect (similarly to what done by Fenoglio-Marc et al, 2008). Forthcoming improvements in wet troposphere corrections, sea state bias and regional high resolution tidal models are expected to improve the quality of TWLE. As Mean Sea Surface (MSS) we used the DTU10 MSS as in [RD3].

The results in terms of TWLE difference between altimetry and TG showed large biases (order of a few m) in each altimeter/TG match-up, for all the passes. This bias varies depending on the particular matchup. Even after removing an overall mean bias the comparison remained unsatisfactory, with differences altimeter/TG of the order of several tens of cm or even a few meters. The same problem was observed when using CryoSat-2 data from the RADS archive so it was not specific to the SARvatore processor but likely to be in the L1 data available at the time. It was concluded at the time that biases in Cryosat-2 test data (coming from L1) for CP4O impacted very negatively on the validation and the issue needed further investigation.

Much more encouraging results were obtained for the assessment of the instrument noise (verification) in 20-Hz Cryosat-2 heights and its variation as a function of distance from coast. As a proxy for noise we used (as done in [RD3]) the absolute value of the difference in TWLE amongst consecutive SAR mode resolution cells, which are only spaced by ~300 m along-track. This difference, typically of the order of a few cm, is essentially only due to ‘instrumental’ noise (by ‘instrumental’ in this note we mean thermal plus speckle noise on the range measurement) as the variation due to ocean dynamics over such a short distance is expected to be at mm level (one exception is the difference due to tides that may be at cm level in areas with large tidal gradients, so in those areas our proxy is an upper boundary for the instrumental noise). We can then use the absolute value of this difference as an estimate of noise in that particular location (i.e. the midpoint of the two 300-m cells) along the ground track, allowing a much finer localization of the estimates than the commonly used standard deviation of the 20-Hz samples in a 1-second block (which cover a ~7 km segment)

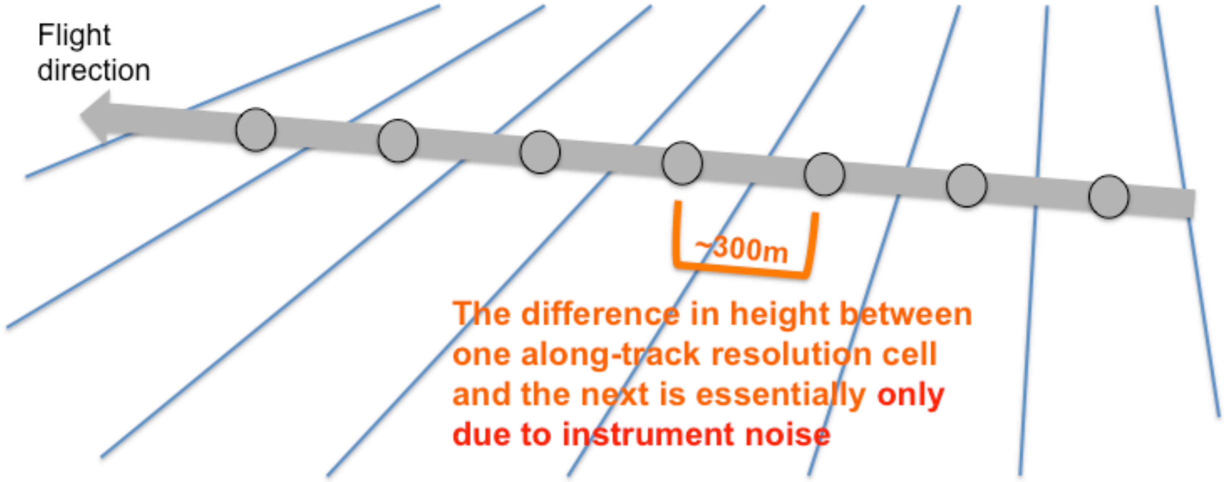

Figure 1: schematics of the use of difference in height between adjacent resolution cells as a proxy for instrumental noise.

Figure 2 shows the distribution of values of the noise proxy as a function of distance from the closest coastline. The figure shows also the 25th, 50th and 75th percentiles[1] of the distribution (the 50th percentile is the median of the distribution). It is worth noting that the median of the distribution is virtually flat between 4 and 5 cm (which would be equivalent to ~1 cm on the 1-Hz averages if the noise in adjacent samples is assumed to be uncorrelated), up to 5 km from the coast, then it increases to about 7 cm at 3 km. In [RD1] we also showed that additional screening of the measurements based on the retracking misfit can improve the noise statistics. The misfit parameter captures the quality of the fit between the L1B waveform and the fitted model and is particularly well suited to detect and screen out waveforms whose fitting was suboptimal. For instance, using only those points where the misfit is less than 3 in the SARvatore processor, the median stays virtually flat at ~5 cm all the way to the coast (Figure 36 in [RD1]), but obviously the fraction of points passing the misfit condition decreases quickly (it is about 60% at 5 km from the coast, and less than 25% at 3 km in figure 37 of [RD1]).

[1] A percentile indicates the value below which a given percentage of observations in a group of observations fall. For example, the 20th percentile is the value below which 20 percent of the observations may be found.

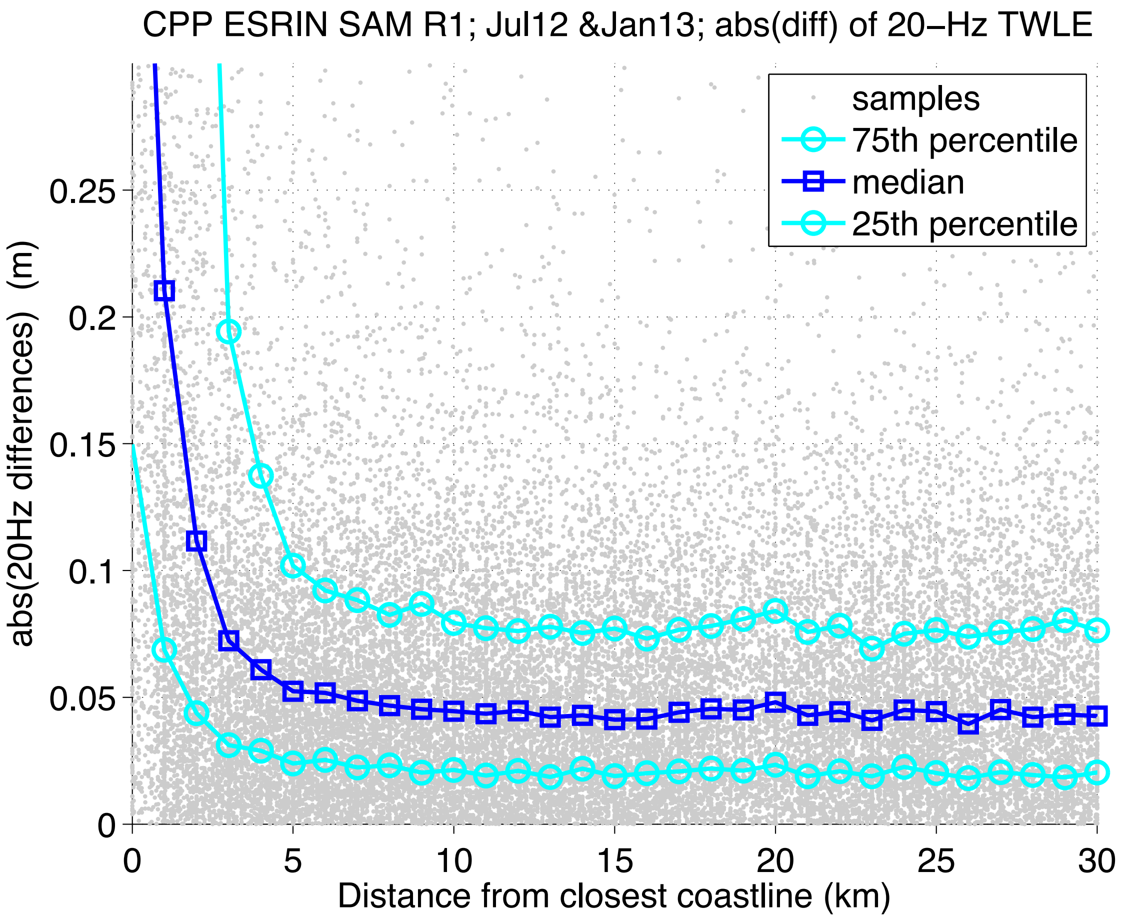

Figure 2: scatterplot of the absolute value difference between consecutive TWLE measurements against distance from coast, and the statistics of its distribution in 1-km distance bins. From [RD1].

Some further analysis was carried out on the same datasets immediately after the compilation of [RD1] to explore the dependence of the instrument noise on the angle to coast (also called "Angle of Approach" or AoA). Defining the angle to coast can be equivocal when the coast has a complex morphology and there are islands and/or headlands in the vicinity of the tracks. For this exploratory analysis we adopted a definition of 'angle to coast' based on the direction of the gradient of the coastal proximity parameter, which was first introduced within the ESA Sea Level CCI project [RD4]. In detail, the angle to coast is defined to be the angle between the direction of the sub-satellite track and the direction of the gradient of the coastal proximity parameter. This allows an objective definition and introduces the concept of a 'simplified' coastline in areas where the coastline is complex over short spatial scales. However, results of the noise analysis in terms of angle to coast were puzzling: there was no clear dependence (see Figure 3). With additional screening based on retracking misfit the median of the noise vs angle to coast becomes perfectly flat, as clearly shown in Figure 4, reinforcing the idea that angle to coast as an independent variable is not particularly useful for screening purposes.

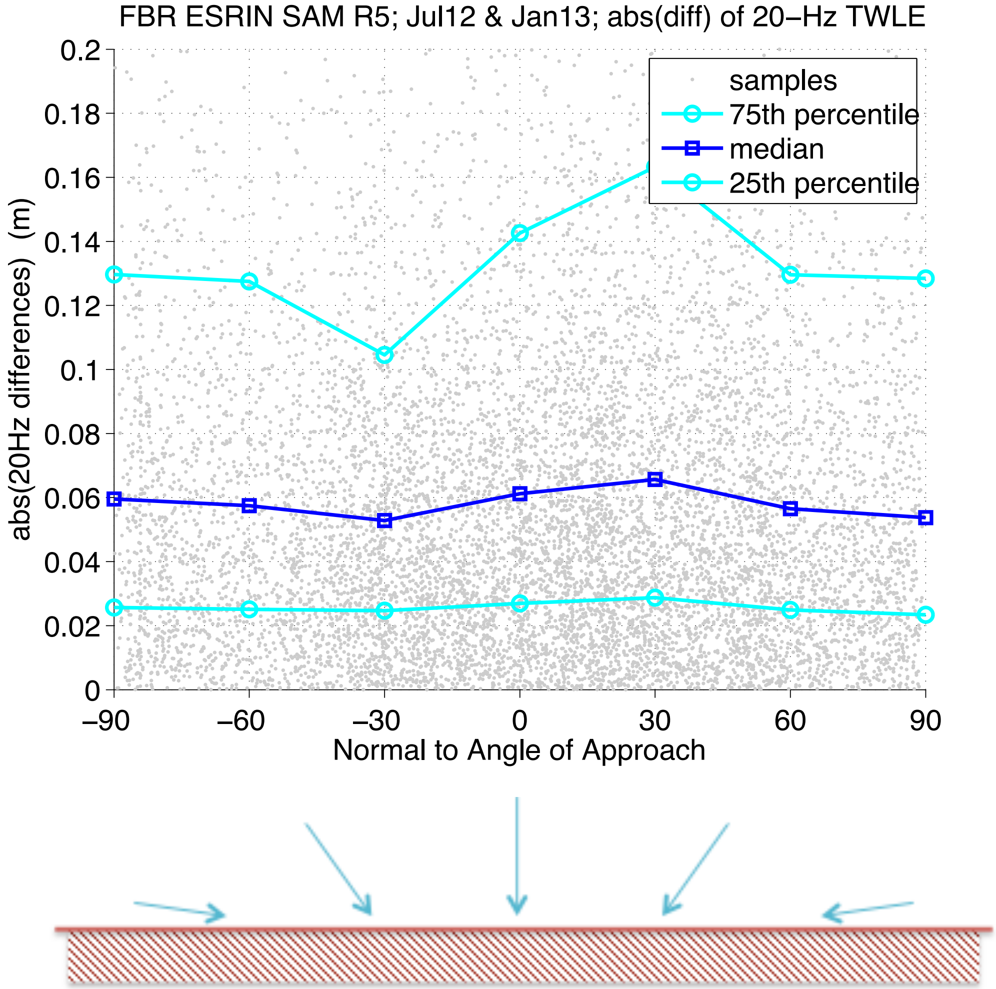

Figure 3: scatterplot of the absolute value difference between consecutive TWLE measurements against normal to angle to coast ("Normal to Angle of Approach": the corresponding orientation of the track versus the coastline is illustrated in the lower panel), and the statistics of its distribution in 30-degree angular bins.

While the results of the verification in [RD1] demonstrate clearly that CryoSat-2 maintains an excellent measurement performance well into in the coastal zone, the puzzling results in terms of angular dependency and the unsatisfactory results from the comparison with tide gauges called for further analysis and a more thorough validation. These activities are part of the CP40 contract extension (CCN1) and are covered by the present document.

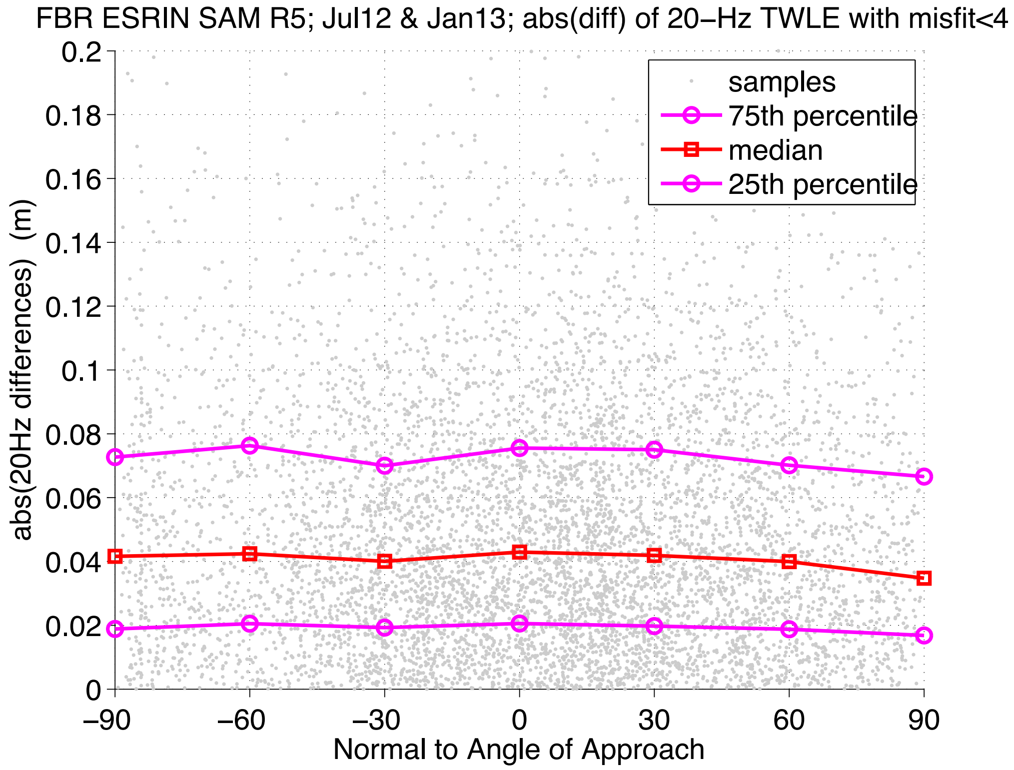

Figure 4: as in figure 3, only for those data with retracking misfit <4.

3 OBJECTIVES

This study has two main objectives:

- **Verification**: to analyse the SSH noise performance (precision) of CryoSat-2 in SAR mode in the coastal zone, assess how close to the coast the data can be used given a precision threshold, and investigate the effects (on the precision) of the orientation of the satellite track with respect to the coastline;
- **Validation**: to define a strategy for comparison of the CryoSat-2 SAR mode data with tide gauges and to present the results of such a comparison with a number of tide gauges around the UK coasts.

Both objectives are addressed with a more voluminous dataset that the one used in [RD1], covering one full year and extended to the whole coastal area of the British Isles, not just to the UK. Data are from two different L1 to L2 processors, as described in detail in the next section.

4 DATA AND METHODS

4.1 Data

For this study we used one full year (1 November 2012 to 31 October 2013) of CryoSat-2 Level-2 data including every pass within a 50-km coastal strip around the whole of 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 [RD5];
- 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) [RD2].

The characteristics of the two processors are summarized in Table 1. The rationale for this dual choice is that we use CPP as an example of an 'open-ocean' processor that shows the instrument baseline performance, and then we assess the improvements, if any, deriving from the specific processing configuration in the GPOD processor.

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 we performed an additional visual quality control on the time series, both before and after removing the tidal signal by harmonic analysis, to exclude the presence of jumps.

4.2 Methods

Instrumental noise is assessed in terms of the absolute value of the difference amongst consecutive 20-Hz heights, as done in [RD3] and discussed in section 2.2 above. The median, 25th and 75th percentiles of that difference over bins in distance or as a function of the angle to coast are plotted to give an idea of the distribution. The median in particular is a robust indicator of the expected noise level.

While in [RD1] the distance from the closest coastline was chosen as a preliminary independent variable for screening, here we have decided to consider separately the distance from coast in the along-track and across-track directions. The latter is expected to be particularly important given that the narrow SAR footprint extends (and is pulse-limited) in the across-track direction. Distances have been computed using the Global Self-consistent, Hierarchical, High-resolution Shoreline Database (GSHHS) available from http://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html .

SAR L1b Processing Options	CPP	GPOD
Hamming Weighting Function	Not Applied	Applied only in Coastal Zone
Beam Steering	Approximated	Approximated
Radar Window Size	Normal (128 bins)	Extended (256 bins)
Range pre-FFT Zero Padding	Not Applied	Applied
SAR L2 Processing Options	**CPP**	**GPOD**
SAR Return Waveform Model	Numerical Solution with real antenna pattern & real PTR	SAMOSA 2 with LUT for alpha_p (PTR width)
Delay Doppler Map (DDM) Masking	Applied	Applied

Table 1: Summary of SAR altimetry processors configuration choices.

The validation against TGs of CryoSat-2 data presents a challenging aspect. As already discussed in [RD1], for satellite missions with a repeat orbit pattern validation can be naturally carried out by comparing time series of heights in each point along track of the altimeter with the time series of the sea level measured by the tide gauges at the times of each satellite overpass, as done for instance in [RD3]. This is not possible for CryoSat-2 due to the very long orbit repeat cycle (369 days, essentially a non-repeat orbit from the point of view of ocean and coastal dynamics). A different strategy must be attempted for the validation, which aims at exploiting all the altimeter passes in the vicinity of a tide gauge, even if those passes are irregularly spread out in both time and space. In practice we take all the passes within a given 'search radius' around the TG and we form a time series with the median value of each pass. We compare that time series with the time series of TG data interpolated onto the times of the altimeter overpasses. One question is then how far away from the tide gauge should we go in selecting the altimeter data, i.e. what is the optimal value of the search radius. This has been explored by looking at the variation of the RMS difference between altimetry and tide gauge measurements as a function of the search radius and the results are given in section 5.4.

As in [RD1] the quantity used for the comparison is the Total Water Level (TWL or TWLE), for the reasons already discussed in section 2.2.

5 RESULTS

5.1 Verification of precision versus distance from coast

Contrarily to conventional pulse-limited altimetry, where the effect of land or coastal bright targets in the altimeter footprint is expected to be virtually independent on the azimuthal angle at which those targets are seen, the behaviour of SAR altimetry when approaching the coast is expected to be strongly anisotropic. This is due to the shape of the SAR footprint that is very narrow (~ 350m) and essentially beam-limited (due to the synthetic aperture processing) along-track, while extending by 2–10 km across-track where it can be considered pulse-limited. Therefore it is logical to explore the noise separately as a function of distance to the coast in both *across-* and *along-track*. Figure 5 shows those two quantities, computed using the GSHHS coastal vector database, for a region with very complex coastal morphology in the west of Scotland.

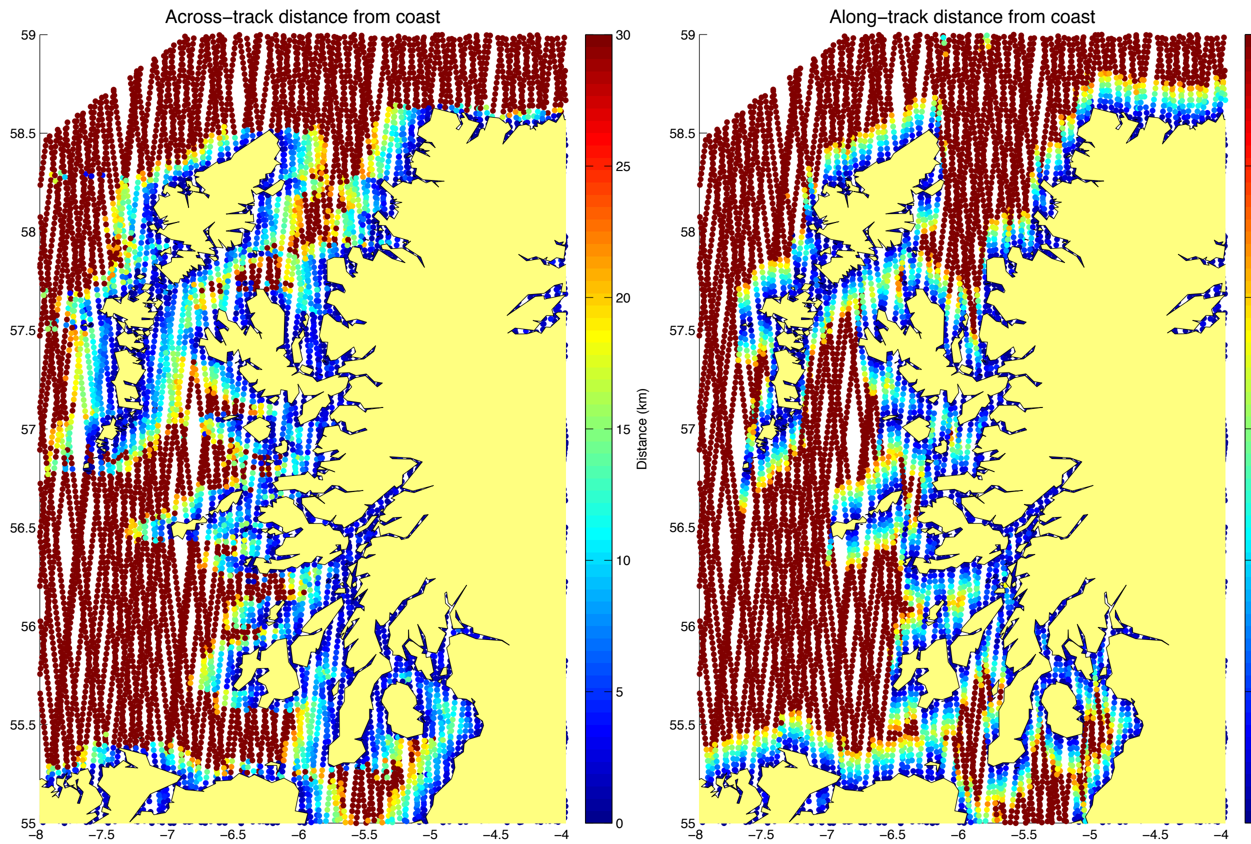

Figure 5: across-track and along-track distance from coast for CryoSat-2 passes around the Western coast of Scotland.

Figure 6 and Figure 7 show the noise proxy as a function of across-track distance from the coast for the CPP and GPOD datasets, respectively. For both datasets the noise starts increasingly significantly at about 5 km from the coast, which is comparable to what reported in [RD3] for pulse-limited altimeters such as Envisat and Jason-2. This is not a surprise, since across-track the SAR altimeter is essentially pulse-limited. It can be noticed that the specific coastal processing used in the GPOD run gives only a slight reduction of the noise (~5 to ~4.5 cm) away from the coast, but improves it significantly in the last 5 km yielding a noise of ~9cm at 3 km from the coast.

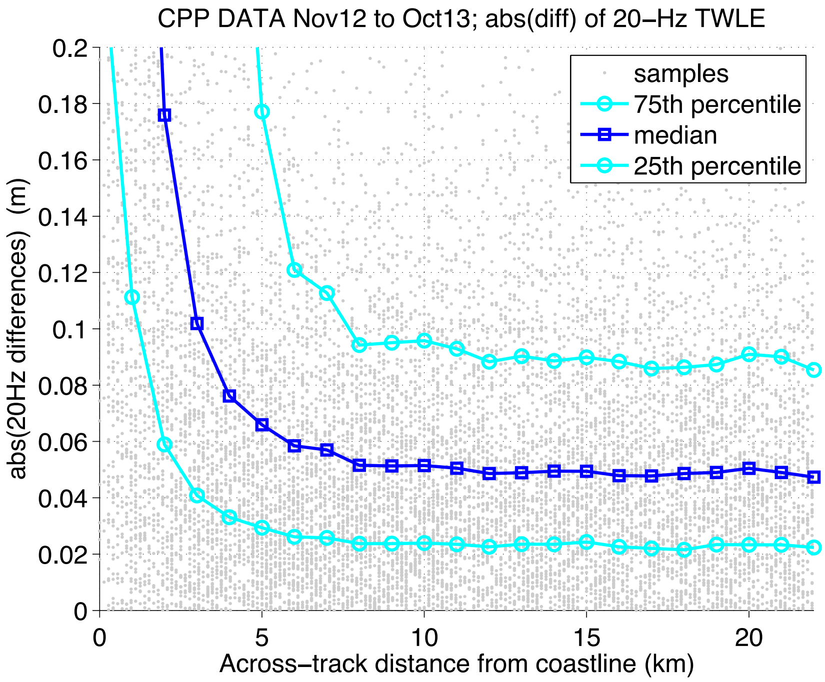

Figure 6: scatterplot of the absolute value difference between consecutive TWLE measurements against ***across-track*** *distance from coast, and the statistics of its distribution in 1-km distance bins, for the CPP dataset.*

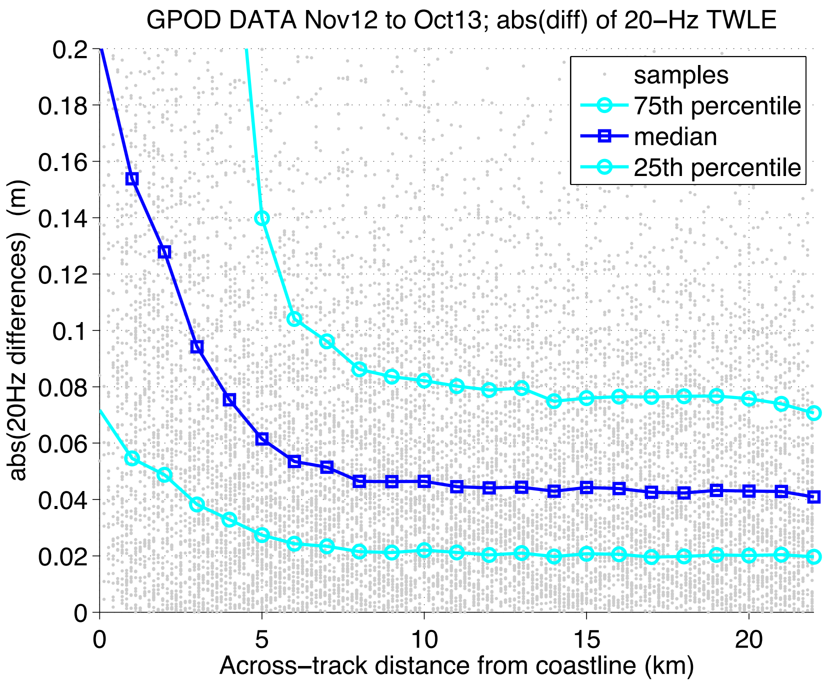

Figure 7: as in figure 5, for the GPOD dataset.

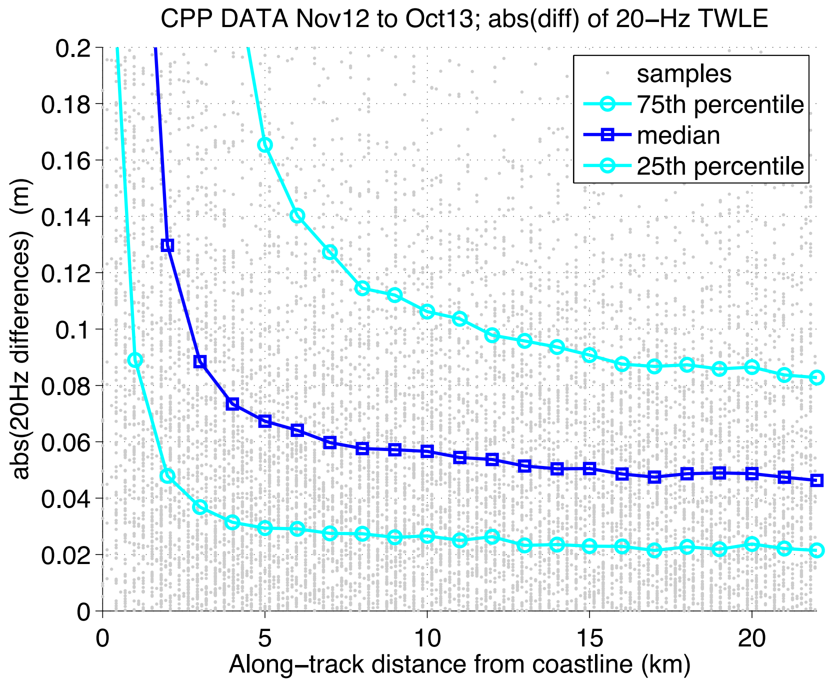

Figure 8: scatterplot of the absolute value difference between consecutive TWLE measurements against ***along-track*** *distance from coast, and the statistics of its distribution in 1-km distance bins, for the CPP dataset.*

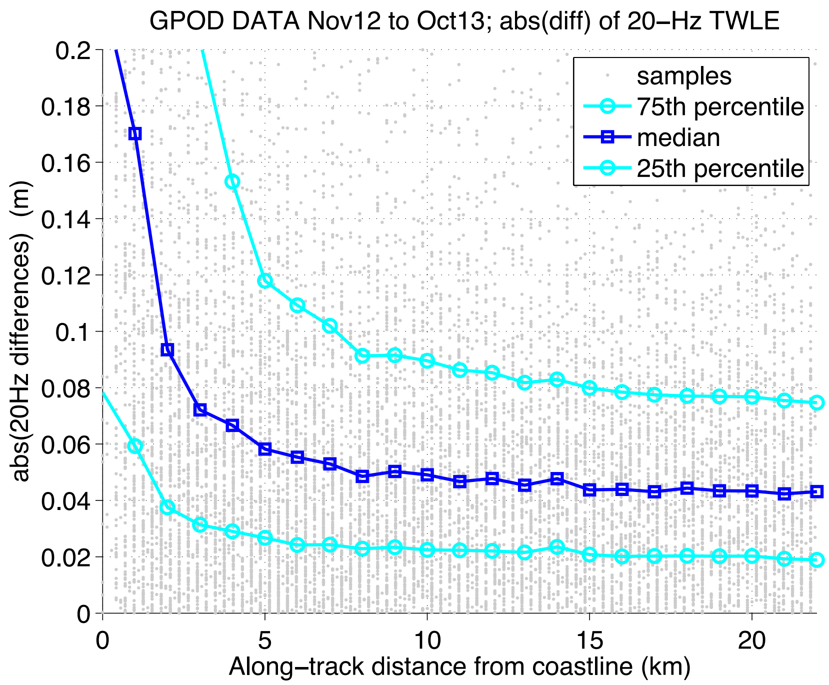

Figure 9: as in figure 7, for the GPOD dataset.

The advantages of SAR altimetry with respect to conventional altimetry, especially when a dedicated coastal processing is employed, become apparent when noise is plotted versus along-track distance from coast, as illustrated by Figure 8 and Figure 9. While the CPP noise in Figure 8 is slightly higher than the one in Figure 6 at distances higher than 5 km, reflecting the fact that for some of those locations the coastline can be closer across-track than along-track, inshore of 5 km the statistics improve with respect to the across-track distance plot. This is because in a number of cases, where the instrument is approaching the coast at angles close to normal, the across-track SAR waveform is little affected by the coast, so noise stays lower (for instance, ~ 9 cm at 3 km).

The specialized coastal processing in GPOD improves things much further (~7 cm at 3 km and ~9.5 cm at 2 km), as shown in Figure 9, and some screening based on retracking misfit, whose results are shown in Figure 10, allows the noise curve to stay virtually flat at 5 cm or less up to 3 km from the coast, and then to feature the relatively low values of 6 cm and 9 cm at 2 km and 1 km from the coast, respectively, even if the number of points passing the screening is reduced as shown in the lower panel of Figure 10 (it is ~50% at 2 km).

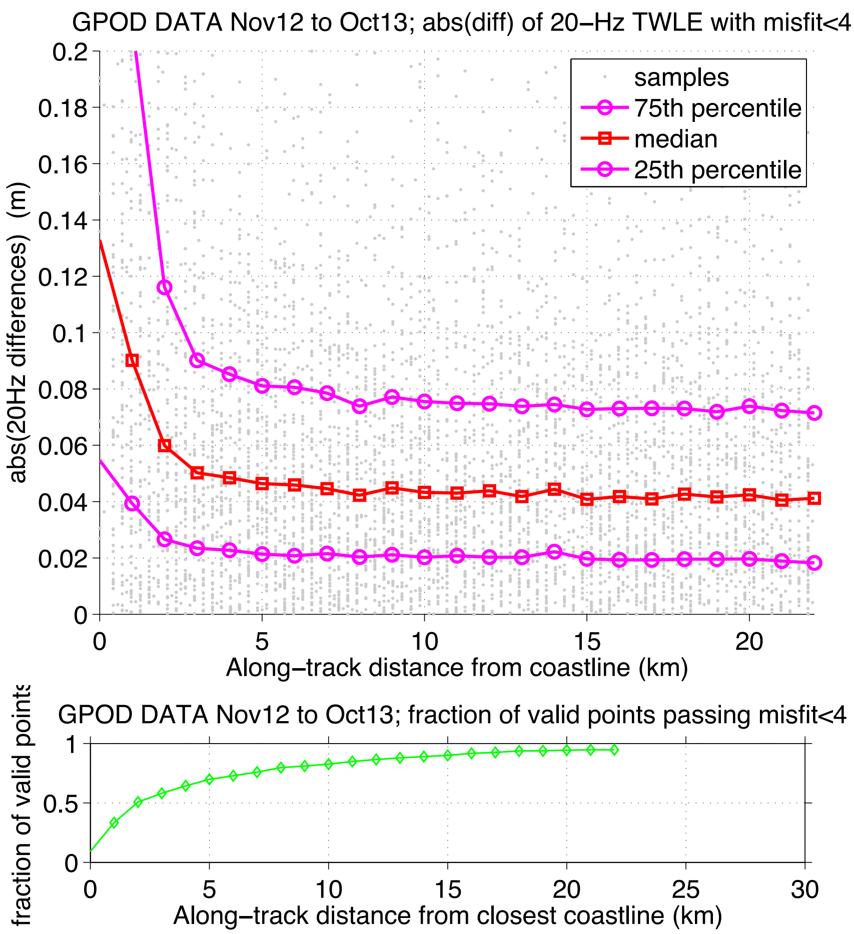

Figure 10: as in figure 8, but only those data from the GPOD processor with a misfit <4. The lower panel details the fraction of points passing the screening.

5.2 Verification of precision versus angle to coast

For this part of the analysis we have first computed the angle to coast (or 'angle of approach') as the angle between the direction of the sub-satellite track and the direction of the gradient of the coastal proximity parameter [RD4], and then we have binned the results in 30° bins of the 'Normal to Angle to Coast' (so a Normal to Angle to Coast of 0° means the track is approaching the coastline orthogonally, as shown in the bottom panel of Figure 3). The analysis has been carried out for all data irrespective of their distance from coast, i.e. using every 20-Hz data point in every pass within the 50-km coastal strip.

CPP data show a very weak dependence of instrumental noise on track orientation, as shown in Figure 11. Noise is ~6.5 cm for normal approach and grows to ~7.5 cm for tracks approaching the coast next to parallel. The weakness of this dependence reinforces our previous suggestion that the across-track distance is a better way to screen SAR data than the angle to coast. This is further confirmed by the equivalent figure for the GPOD dataset (Figure 12), where the coastal-oriented processing results into a noise behaviour very independent from angle, and virtually flat at about 5.5–6 cm.

However, angles do matter if along-track distance from coast is used as the independent variable for the screening, as one would expect from simple geometrical considerations. This is illustrated in Figure 13 and Figure 14 where it is clear that approaches close to normal (class i00) or slightly oblique (class i30) have low noise until comparatively short distances from coast (2-3 km). Once again the results are better for the coastally-optimized run from the GPOD processor which shows a noise of 7.5 cm at 2 km for the near-normal class (i00).

All the results in this section consistently point to an excellent performance of the SAR altimeter in the last few km from the coastline, especially when the processing is optimized for the coastal zone. The noise characteristics (precision) of the instrument remain comparable to those over the open ocean closer than 5 km from the coast, and up to 2 km in the most favourable cases. In the next subsection we further illustrate this finding with a case study along the Southern England coast.

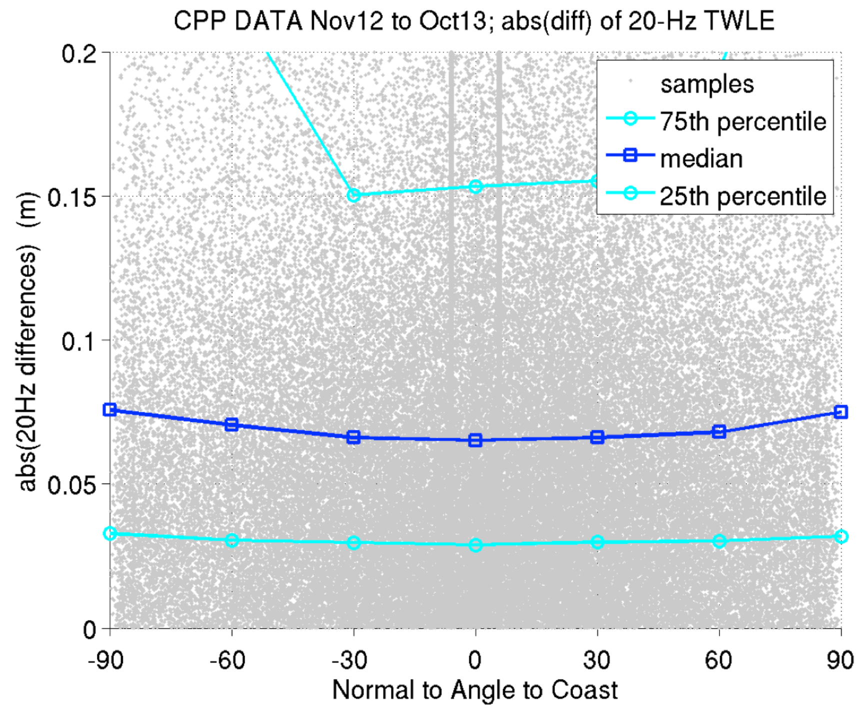

Figure 11: scatterplot of the absolute value difference between consecutive TWLE measurements against normal to angle to coast, and the statistics of its distribution in 30-degree angular bins, for the CPP dataset.

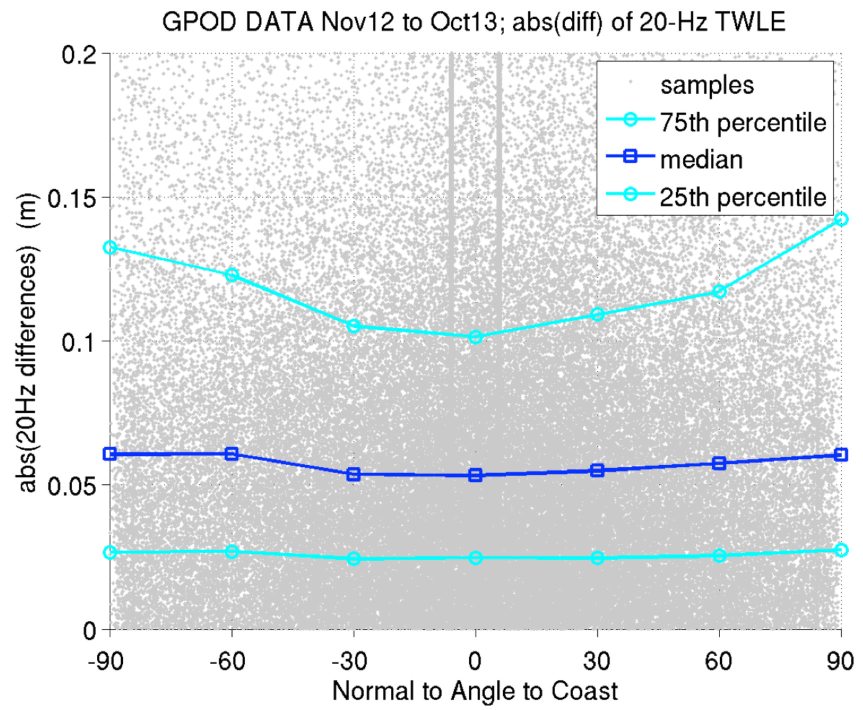

Figure 12: scatterplot of the absolute value difference between consecutive TWLE measurements against normal to angle to coast, and the statistics of its distribution in 30-degree angular bins, for the GPOD dataset.

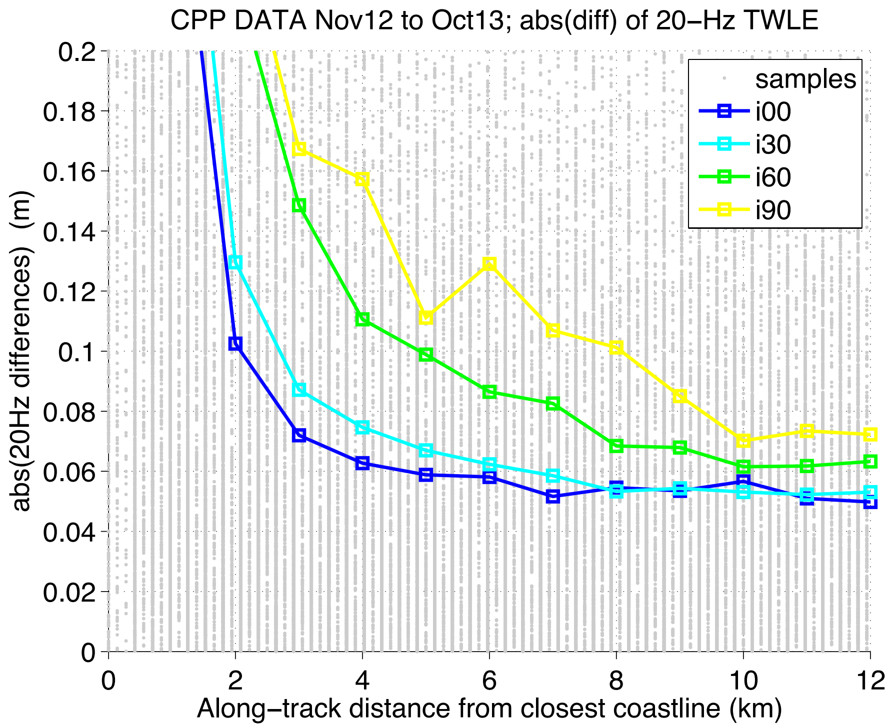

Figure 13: scatterplot of the absolute value difference between consecutive TWLE measurements against ***along-track*** *distance from coast, and the median in 1-km distance bins for four 30°-wide classes of Normal to Angle to Coast, for the CPP dataset.*

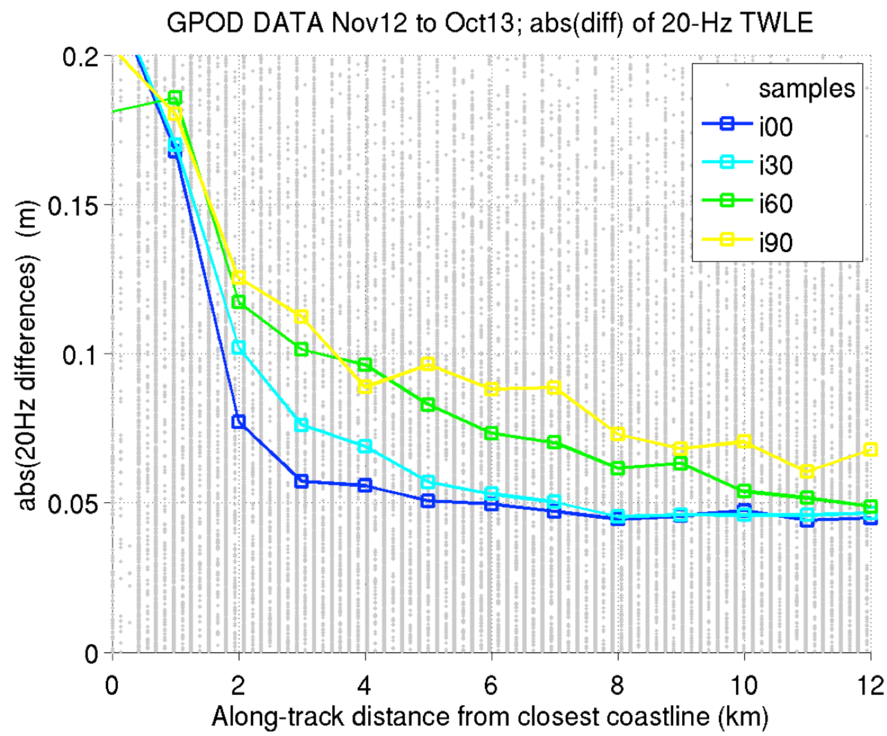

Figure 14: as in Figure 12, for the GPOD dataset.

5.3 Verification case study: the Brighton Box

To illustrate the excellent performance of SAR altimetry in the coastal zone in favourable conditions (meaning a simple coastline and sub-satellite tracks nearly orthogonal to the coastline, so that the across-track footprint is virtually unaffected by the coast until in extremely close proximity to it) we have repeated the analysis over tracks intersecting a polygon around Brighton in Southern England, shown in Figure 15. This polygon is intersected by 25 sub-satellite tracks.

Figure 16 shows the absolute value differences amongst consecutive 20-hz samples, as done in the previous section, for the November 2012 to October 2013 data from the CPP processor over the Brighton Box. The statistics (median and 25th and 75th percentiles, also shown in the figure) have some oscillations due to the relatively small number of tracks available over this box but it is clear that the median 20-Hz noise remains below 6 cm up to 3 km from the coast and is still less than 9 cm at 2 km. This proves that also non-specifically-optimized data such as those from CPP can 'get close to the coast', with noise at levels comparable to those over open ocean up to 2-3 km from the coastline.

The results with the GPOD-reprocessed data are in Figure 17. This is the most favourable result, in that the specific processing choices for the coastal environment yield a level of noise lower than 5 cm up to 2 km from the coast.

For completeness we present also the analysis done (for the GPOD data) versus across-track distance from coast (Figure 18): as expected the degradation of the noise characteristics start a bit further than for the along-track case, i.e. at around 4 km.

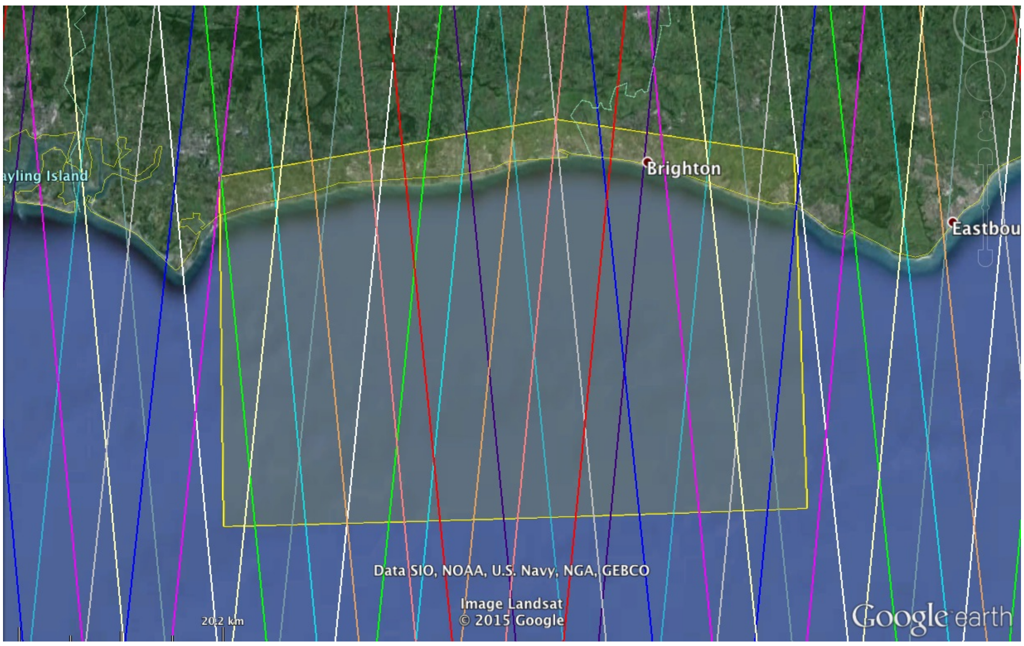

Figure 15: Polygon around Brighton on the Southern Coast of the UK ("Brighton Box") used in this case study, and the CryoSat-2 ground tracks in the dataset (November 2012 to October 2013).

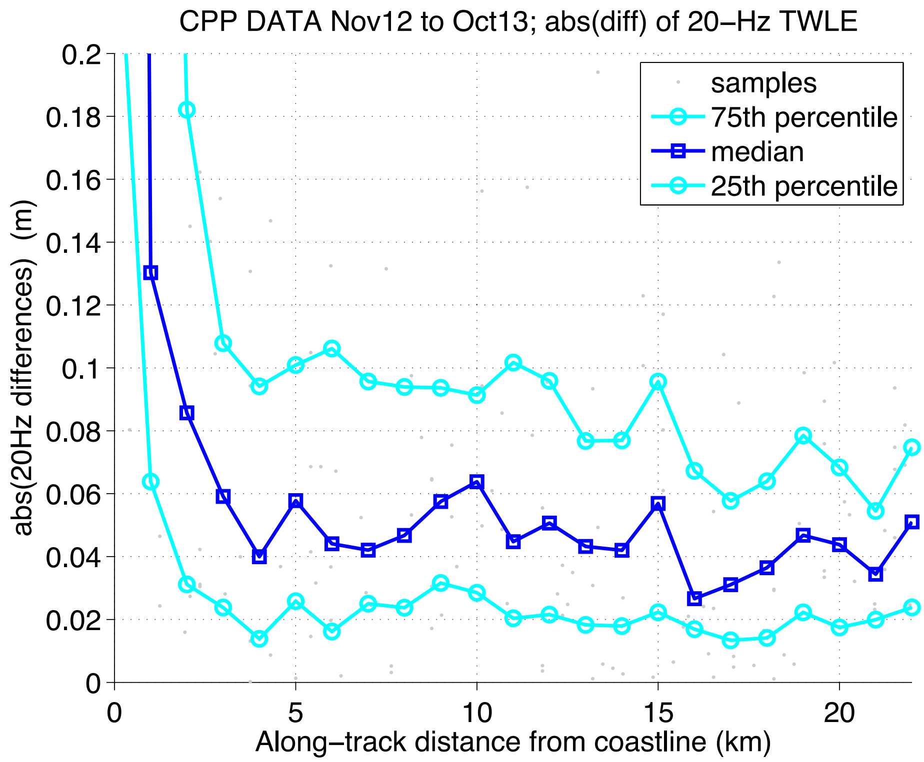

*Figure 16: scatterplot of the absolute value difference between consecutive TWLE measurements against **along-track** distance from coast, and the statistics of its distribution in 1-km distance bins, for the CPP-reprocessed passes in the "Brighton Box".*

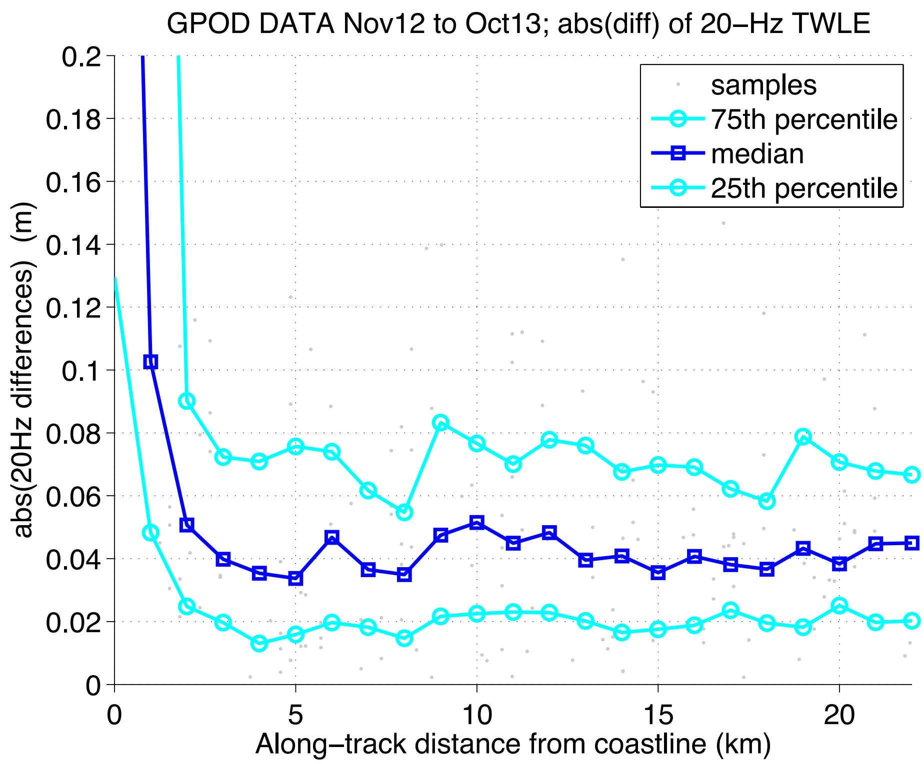

Figure 17: as for Figure 15, for the GPOD-reprocessed passes in the "Brighton Box".

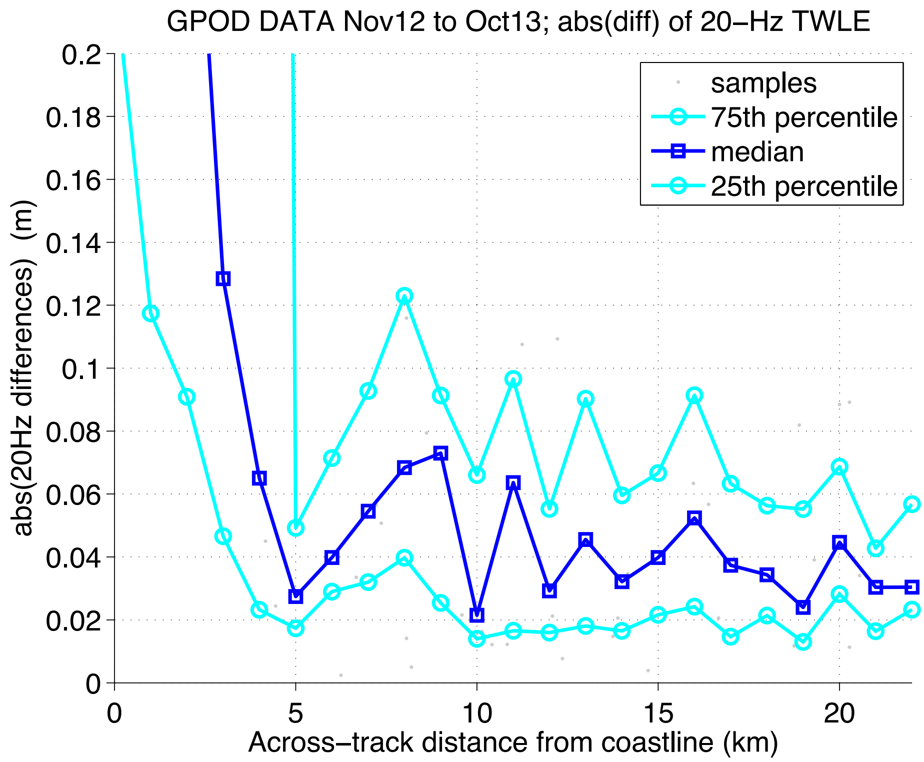

*Figure 18: as for figure 16, but analysis done against **across-track** distance from coast.*

5.4 Validation via comparison against tide gauges

To estimate the accuracy of the SAR data in the coastal zone we have compared them with tide gauges around the UK, taken from the BODC data archives and quality controlled as detailed in 4.1. Here we present the results for the Newhaven tide gauge (east of Brighton in the "Brighton Box") and for the TG at Aberdeen in Scotland. In each location we start with a search radius of 5 km and increase it to 50 km in 1-km steps. For each value of the search radius (SR) we select all the altimeter overpasses intersecting the search circle and build time series of altimeter and tide gauge TWLE as described in section 4.2, and compute the RMS difference of the time series. Note that at the present stage of research we are still dealing with 'relative' validation, i.e. we remove the mean bias between the altimetric and TG time series before computing the RMS difference (in practice we achieve that by de-meaning the two time series separately). [RD3] has shown that also 'absolute' validation is possible when there is accurate ellipsoidal height information for the TG, but procuring that information and accounting for changes in the MSS from non-colocated measurements would require resources beyond those available in the present project.

This validation exercise may sometimes require the removal of outliers, as some of the match-up pairs can be negatively affected by residual errors in orbits or altimetric corrections. Figure 19 and Figure 20 illustrate such a case around Newhaven. The altimeter vs TG RMS difference is lower than 10 cm until SR is increased from 17 km (where the number of passes is 17) to 18 km causing the inclusion of one more pass which however turns out to be a clear outlier (see the bottom left panel of Figure 20). Removal of this outlier brings the RMS down and below 10 cm up to a SR of 25 km, as shown in Figure 21.

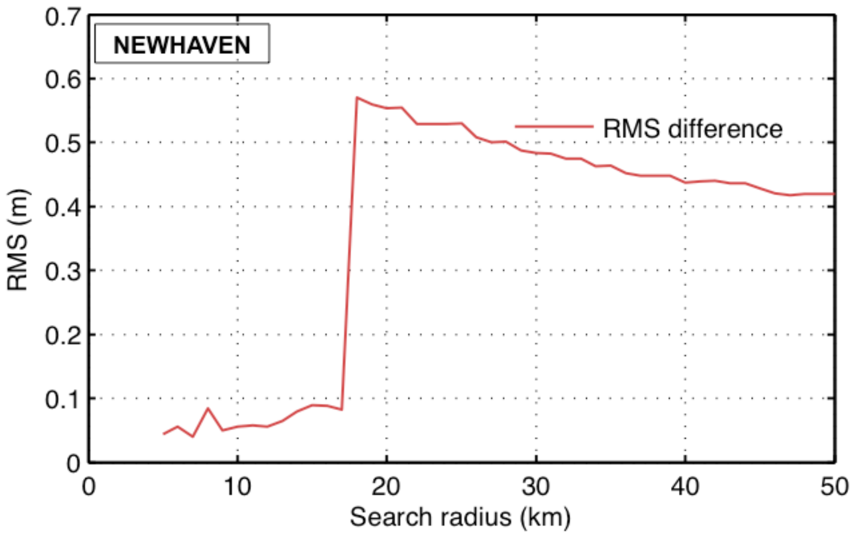

Figure 19: RMS difference between de-meaned time series of TWLE from altimetry and from the tide gauge at Newhaven, as a function of the search radius around the tide gauge. No outlier was removed. Note the sharp increase when search radius goes from 17 km to 18 km.

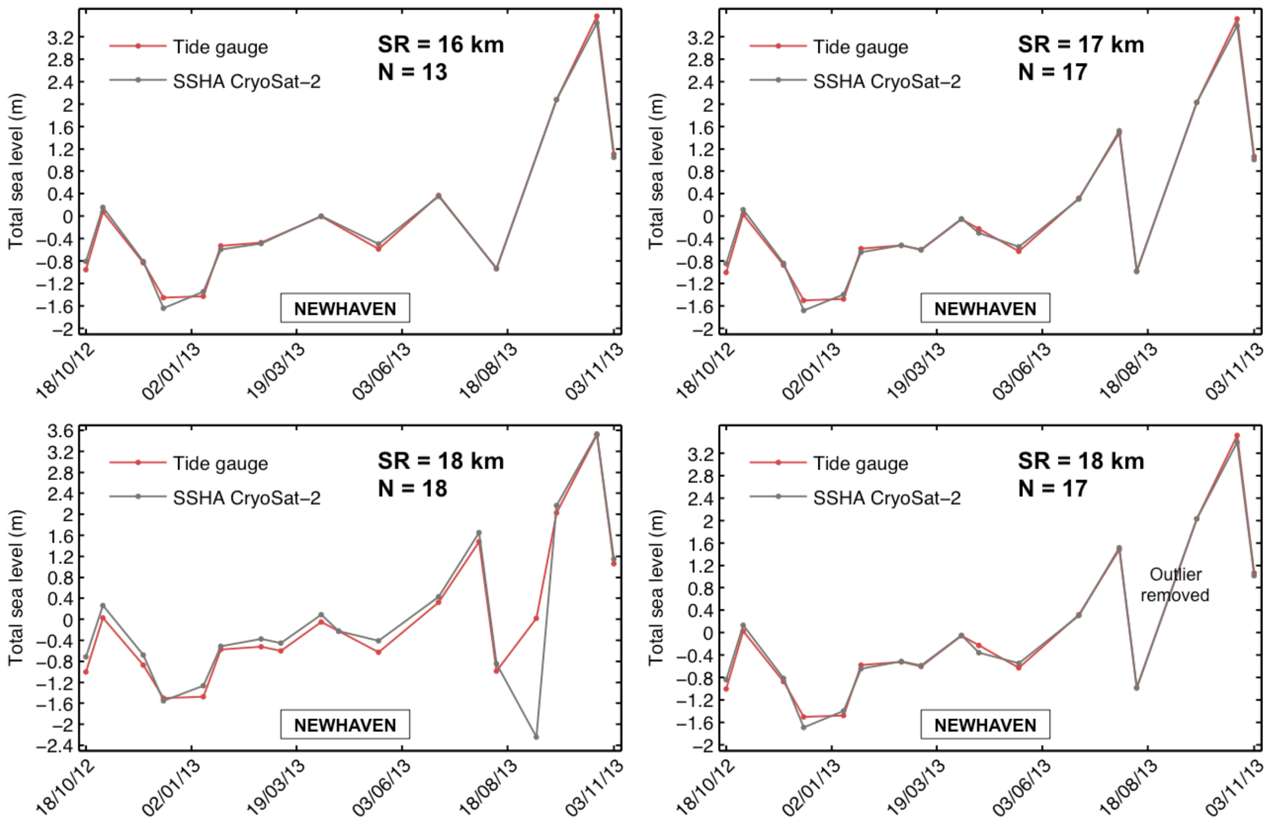

Figure 20: De-meaned time series of TWLE from the TG at Newhaven and from CryoSat-2 overpasses within different values of the search radius: (top left) 16 km; (top right) 17 km; (bottom left) 18 km; (bottom right) 18 km, with an outlier removed. N is the number of passes within the given search radius.

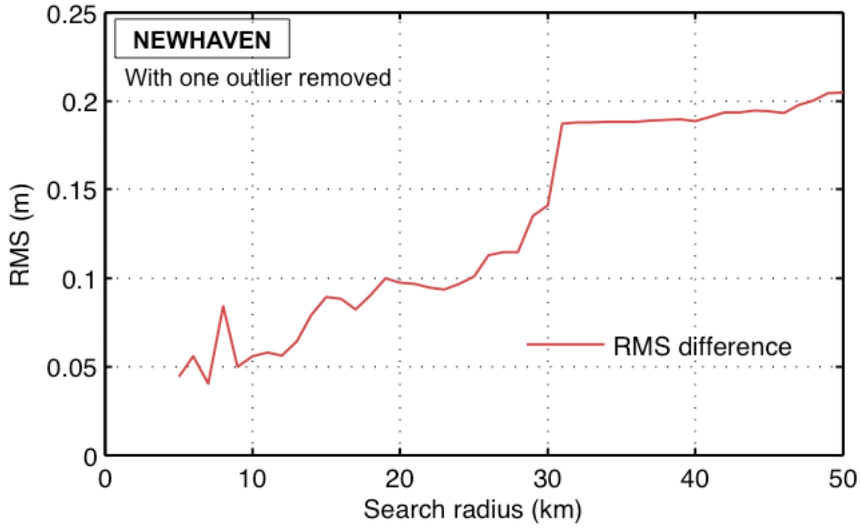

Figure 21: as for figure 18, but with an outlier removed at SR=18 km.

In other cases outlier removal is not necessary. Figure 22 shows the RMS difference around Aberdeen as a function of SR. There appears to be an 'optimal' search radius of 21 km where the RMS difference goes below 7.5 cm, a very encouraging result for this type of validation. The relevant time series is shown in Figure 23.

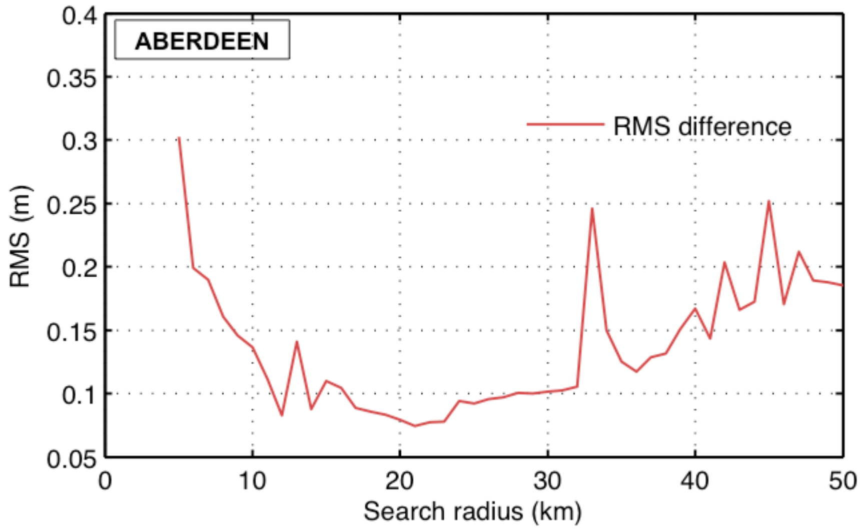

Figure 22: RMS difference between de-meaned time series of TWLE from altimetry and from the tide gauge at Aberdeen, as a function of the search radius around the tide gauge. No outliers were removed for this plot.

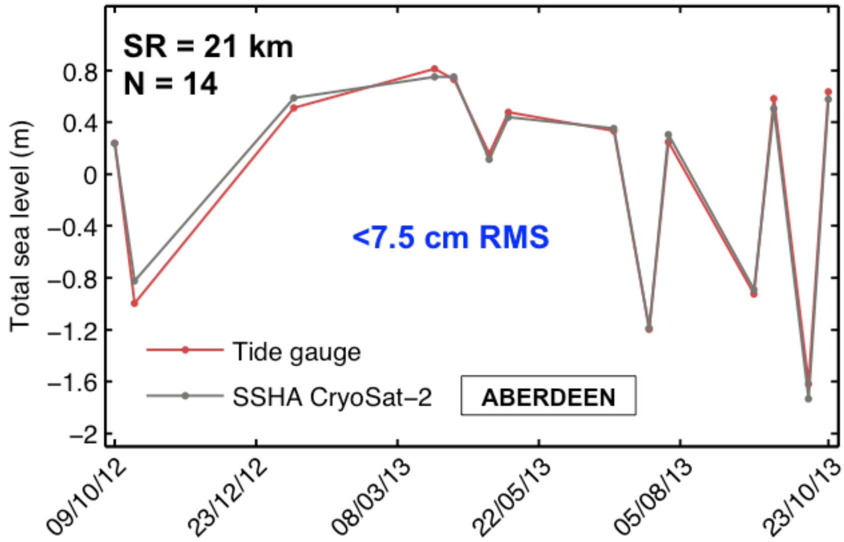

Figure 23: De-meaned time series of TWLE from the TG at Aberdeen and from CryoSat-2 overpasses within a search radius of 21 km.

6 CONCLUSIONS

In this study we have 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 a 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 (see Figure 17)
- 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.

7 ACKNOWLEDGMENTS

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8 BIBLIOGRAPHIC REFERENCES

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