DEVELOPMENT OF RADAR ALTIMETRY DATA PROCESSING IN THE OCEANIC COASTAL ZONE

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Report on validation of reprocessed height and waves

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Issue	**Date**	**Change**
1.0	18 June 2011	Initial Release – subject to update after final PM
1.1	13 July 2011	Fixed a few typos and reformatted at ESA's request
1.2	9 Jan 2012	Revised following ESA review
1.2b	10 Jan 2012	Minor reformatting

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1 Introduction

1.1 Purpose

This document represents the deliverable D5.2: Report on validation of reprocessed height and waves. The deliverable D5.2 presents the work done in the Work Package EWP 5.2: Validation of reprocessed heights and waves. This Work Package includes the following subtasks:

1. Development and application of innovative techniques for describing and understanding differences between altimetry and tide gauge observations
2. Comparison of retracked wave heights and wave model output

The main goal was essentially to demonstrate to which extent the new CGDR products developed in the COASTALT project are better (or at least as accurate as) standard "open ocean" altimetry products.

1.2 Content

- Section 1 introduces this document;
- Section 2 shortly describes the CGDR product as available at the end of EWP5.1;
- Section 3 illustrates and discusses the product quality checking and validation in the three pilot regions (West Iberian, West Britain, NW Mediterranean) plus Gulf of Cadiz;
- Section 4 discusses the results, summarizes identified issues and elaborates a set of recommendations for further development and improvements.

2 Description of the COASTALT product used

The COASTALT Project has developed a processor during the Phase-1 term to generate a new Envisat radar altimeter product in the coastal zone [RD1]. Its upgrading and improvement started in Phase-2 [RD2] and is still underway on the basis of EWP1. The software is now at revision 89. The version 2.0 of data has been released for validation according to EWP5.1. The data are available at 18 Hz for the ground track selected in the three pilot regions plus Gulf of Cadiz. A notable addition to the baseline product is the GPD correction for Wet Troposphere. A complete description of format and content of the product version 2.0 is given in D 4.1a [RD3]

3 Results and findings

This section documents results and findings of the analysis and comparison studies carried out using CGDR data. CGDR data are validated against the in situ data set which consists of quality-checked measurements of sea level and wave height as described in [RD4]. Indications about previous work carried out during Phase 1 which includes critical aspects are reported in [RD5] and [RD6].

3.1 West Iberia

3.1.1 Data and methods

Validation of COASTALT data at 18 Hz (product v2newmask, 18 Feb 2011) was carried out in the West Iberia region for passes 1 and 160 (cycles 10 to 68) using the tide gauges of Viana, Cascais and Sines (Figure 1, Annex II).

Data were inspected and extracted from the COASTALT netcdf datafiles using the BRAT software, and the following pre-processing steps were performed:

i) for each cycle, missing points within the track were inserted as NaN
ii) data collocation was carried out based on linear interpolation with latitude as an indicator of along-track position*
iii) missing cycles were inserted as NaN based on consecutive satellite times

* stacking was used to build time series along a reference (average) pass, but avoided whenever possible (e.g. the analysis of range and SWH values (sections 3.1 & 3.2) was performed on non-stacked data)

Sea level anomalies (SLA) were obtained for different options of retracker and geophysical corrections:

$$\text{SLA}=[\text{orbit} - (\text{range} + \text{ssb} + \text{iono} + \text{tides}^{j} + \text{dtc} + \text{wtc}^{k} + \text{uso}] - \text{mssht} \qquad (1)$$

orbit = satellite ellipsoidal height
range = Ku-band range from brown retracker
ssb = sea state bias correction
iono = ionospheric correction from brown retracker
tides = total ocean tide from (j=1) GOT, (j=2) WITM models + pole tide + earth tide
dtc = dry troposphere correction
wtc^{k} = wet troposphere correction from (k=1) a meteorological model (ECMWF), (k=2) the

Dynamically Linked Model (DLM) method and (k=3) GNSS-based approach (GPD)

uso = USO correction

mssht = mean sea surface height

From (1) the following 4 configurations were considered for validation purposes:

1) default

$$SLA_1=[orbit – (range + ssb +iono + tides^1 + dtc + wtc^1 + uso] – mssht \qquad (2)$$

2) ocean tide = WITM

$$SLA_2=[orbit – (range + ssb +iono + tides^2 + dtc + wtc^1 + uso] – mssht \qquad (3)$$

3) WTC = DLM

$$SLA_3=[orbit – (range + ssb +iono + tides^1 + dtc + wtc^2 + uso] – mssht \qquad (4)$$

4) WTC = GPD

$$SLA_4=[orbit – (range + ssb +iono + tides^1 + dtc + wtc^3 + uso] – mssht \qquad (5)$$

For comparison with the altimetry data, hourly tide gauge observations were detided either using the GOT 4.7 or the WITM models (in line with the procedure followed for the satellite data). Since the tide gauge observations are not corrected for pressure effects, the inverse barometer correction was not applied to altimetry observations. For the validation analysis the detided hourly tide gauge values were linearly interpolated to the satellite passage times.

3.1.2 Results

3.1.2.1 Retracked ranges

For assessment of retracked ranges the following quantity was considered:

$$retracked\text{-}height=orbit – (range^i + uso) \qquad (6)$$

where

orbit = satellite ellipsoidal height

$range^i$ = Ku-band range from (i=1) ocean, (i=2) brown and (i=3) mixed retrackers

uso = USO correction

The retracked heights were extracted for each cycle with no further data stacking or interpolation. Figure 2 (Annex II) shows the heights for all cycles of passes 1 and 160. The most obvious feature is the high variability in height due to proximity to land and the vertical bias in the heights retrieved with the same retracker due to the lack of USO correction in cycles 45 and 46.

As an illustration, the heights for cycles 10 (pass 1) and cycle 19 (pass 160) are plotted as along-track anomalies in Figures 3 and 4 (Annex II), respectively. Pass 1 crosses land in two different regions: near the Cascais tide gauge, near Lisbon, and at the south-west tip of Portugal mainland (Algarve). In the southern part the mixed retracker seems to perform better, but in the Lisbon area there is no significant difference between ocean, brown and mixed retracked heights in terms of closeness to coast. For pass 160 the brown and mixed retrackers allow to get closer to the coast.

Figure 5 (Annex II) shows the retracked height values for all cycles of pass 1, and confirms the large variability from cycle to cycle, depending on how close the actual trajectory of the track approaches the coast (with worst results for more “inland” cycles). The COASTALT mixed retracker doesn't seem to perform significantly better than the COASTALT brown retracker.

3.1.2.2 Significant Wave Height (SWH)

A similar analysis as for retracked ranges was performed for significant wave heights (SWH) from the COASTALT brown and mixed retrackers. Figure 6 (Annex II) shows the SWH values for all cycles of passes 1 and 160. The wave heights from the brown retracker seem to exhibit outlying values for a wider range of latitudes near crosses over land than the heights derived from the mixed retracker. This is illustrated in Figure 7 which shows the SWH values from the brown and mixed retrackers for cycle 15 plotted as along-track anomalies (pass 1). Anomalous wave heights are retrieved far from land (above latitude 35.9N) by the brown retracker (Figure 7 in Annex II, left) but not by the mixed retracker (Fig 7 in Annex II, right).

3.1.2.3 Time series of sea level anomalies (SLA)

Time series of sea-level anomalies were derived from stacked altimetry measurements as

SLA=[orbit – (range + corrections)] – mssht

The following quality control procedures were implemented:

i) SLA values outside the range]-2 , 2[m were set as missing
ii) for each SLA time series (at a given along-track location), outlying values were defined as values exceeding 2.5 times the standard deviation of the series over the whole period and set as missing

Figure 8 (Annex II) shows the number of missing cycles for each SLA time series in the 3 sub-areas closer to the tide gauges of Viana, Cascais and Sines, after implementation of the quality control procedures. At Viana and Cascais the number of missing SLA values increases considerably closer to the coast, while at Sines the track trajectory is farther from land and no data loss occurs.

The standard deviation of the SLA time series resulting from stacking and application of quality control procedures is shown in Figure 9 (Annex II) for the three validation sub-areas around the tide gauges. Except for the Sines region (for which the track passes far enough from land), the variability increases substantially (more than two-fold) when approaching the coast.

3.1.2.4 Wet tropospheric correction

The radiometer-derived wet tropospheric delays are problematic near the coast. In order to assess the effect of different strategies for the wet tropospheric correction, differences between COASTALT and tide gauge heights were considered. Heights from tide gauges at the satellite passage times were subtracted from sea level anomalies derived as indicated in (2), (4) and (5). The results are summarised for all along-track points in Figures 10 and 11 (Annex II), which display boxplots of the mean and standard deviation respectively of the differences between COASTALT and tide gauge values.

At Cascais and Sines tide gauges the mean of the differences is mostly negative, indicating that altimetry heights are lower than tide gauge heights while at the northernmost tide gauge, Viana, the altimetry heights are higher than the tide gauge values. For Cascais and Viana the mean of the differences is less than 2cm at most along-track points, but some differences are as large as 80cm for a few points very near the coast. In contrast, the range of mean differences is much smaller at Sines, reflecting the absence of points very close to land, but differences tend to be slightly higher (~3 – 4 cm) probably because the track is also farther from the tide gauge than in the other cases. In terms of the variability of the differences between COASTALT and tide gauge values, the standard deviation is typically below 15 cm, but can be of the order of 1 m for a few points very close to the coast at Cascais and Viana.

The comparison of differences between COASTALT and tide gauge heights shows very similar results for the three methods adopted for the wet tropospheric correction. The GNSS-based wet troposphere correction (GPD) yields slightly less variable and smaller differences to the in-situ tide gauge values, but not substantially different from the other two methods.

3.1.2.5 Tidal models

In order to assess the effect of applying a different tidal model to the COASTALT data, specifically using the GOT versus the local WITM model, a strategy similar to the one employed for the wet tropospheric correction was applied. Heights from tide gauges at the satellite passage times were subtracted from sea level anomalies derived as indicated in (2) and (3). Figure 12 shows the resulting boxplots for all along-track points of the standard deviation of the differences between COASTALT and tide gauge values.

The two tidal models give similar results in terms of the differences of the resulting sea level anomalies to the tide gauge heights. Variability is higher at Cascais and Viana tide gauges, inflated by some points closer to land, and considerably smaller (~20 cm) for the Sines tide gauge.

3.2 West Britain

3.2.1 Sea Level

This note describes work done with the COASTALT-2 netcdf files for Envisat passes 160 and 704 (west of Britain) provided by NOC in Southampton. Figure 1 (Annex III) shows where passes 160 and 704 are located, the former crossing Wales and Cornwall and crossing the Cornish south coast to the east of the Newlyn tide gauge station, the latter being relatively open-sea but passing close to the Holyhead tide gauge station on Angelsey. Envisat has a retrograde orbit so the satellite moves over the ground east to west.

The work has used largely the same code used for COASTALT. Several versions of netcdf files were inspected between the start of the project and the present time and any problems were reported to the data originators. The results presented here are using the latest ('v2newmask') files, although they did not seem materially different to earlier ones.

There were four sets of tracked sea surface heights to consider: the original SGDR data, Brown, Mixed and Specular. One then has to combine each one with a selection of correction terms, and of course there are many possible combinations. We have concentrated on those listed below, selection A being our reference one:

A (SGDR) : 18 Hz Ku band SGDR range and orbit, 1 hz wet (model = ECMWF), dry (model), SSB and iono (altimeter-derived) corrections

B (Brown): 18 Hz range, orbit and iono, 1 Hz wet, dry and SSB as in A

C (Mixed): 18 Hz range, orbit and iono, 1 Hz wet, dry and SSB as in A

D (Specular): 18 Hz range, orbit and iono, 1 Hz wet, dry and SSB as in A

E (SGDR-MWR): as A except 18Hz DLM MWR correction (hz18_mwr_wet_tropo)

F (SGDR-DORIS): as A except 1 Hz DORIS correction for the iono

G (SGDR-GIM): as A except 1 Hz GIM correction for the iono. This is available only for cycle 38 on.

H (SGDR-GPD): as A except 18 Hz GPD correction for the wet

I (BROWN-DORIS): as B except 1 Hz DORIS for the iono

J (SGDR-DORIS-GPD): as A except DORIS and GPD (i.e. a combination of F and H)

All data were adjusted with the Ultra Stable Oscillator (USO) correction where available. This was a big improvement as the absence of this correction in the earlier COASTALT project resulted in significant amounts of sea surface height data being rejected.

All data were also corrected for the solid earth body tide. We then had three options for further tidal and meteorological corrections:

(1) to use the provided (1 Hz) FES2004 geocentric tide and IB correction, where the ‘geocentric’ or ‘elastic’ tide means the combination of the ocean tide and its loading

(2) to use a NOC (POL)-derived ocean tide plus loading derived from FES2004 (thereby forming the geocentric tide) together with a set of storm surge model heights. We did not further investigate the use of the NOC models in this project as we did in COASTALT

(3) to apply no correction other than the load tide. In this case, the adjusted altimeter heights are uncorrected for ocean tide and meteorological effects and are therefore akin to those observed by a tide gauge (one notes that a tide gauge sits on the land and does not record changes in elevation due to either the body or load tides of the solid earth)

No corrections were made in any of these options for the geocentric (for altimetry) or oceanic (for tide gauge) pole tide which is known to be sub-cm in this area (Dong et al., 2002).

A first stage in the processing is to interpolate data for each cycle to a standard set of reference latitudes. Then the root-mean-square (rms) of sea surface height can be computed at each latitude using data for all available cycles, rejecting data for cycle 46 which is known to have USO correction problems. A recent email suggested that there may be USO problems with other cycles but we have not investigated further. It should be noted that cycle 46 has been corrected successfully for USO in a new version of CGDR (v2.0r2) which however did not come in time for analysis. No correction is made for cross-track mean sea surface slope (the longitudinal range of ground track is about 2 km for pass 160).

As an example, Figure 2 (Annex III) shows rms values as a function of latitude along pass 160 using selection A and the provided tide and surge corrections. The rms values are well over 10 cm which is understandable given, in particular, the known noise in the altimeter-derived ionosphere correction and errors in the tide and IB models in shelf areas. The latter is almost certainly responsible for the larger values further north, although it has been suggested by Dr. Vignudelli that orbit errors may also contribute; this suggestion requires further study. (As an aside, we note that the provided netcdf files contained only the original SGDR orbits and not the calculations from other centres e.g. RADS, which would have afforded a possibility for comparison of orbits and an assessment of their quality.)

It can be appreciated that the analysis generated more plots than can be copied here, so the following is a general description of findings.

As a first step, one needs to beat down the known noise in the ionosphere correction. For standard open-ocean processing, such as made in analyses using T/P/J data, the correction is low-pass filtered to remove the high-frequency noise. However, such a filtering approach is not consistent with the aims of COASTALT-2 of wanting to use data close to the coast (this is a fundamental conundrum with coastal altimetry). Consequently, it was decided to use DORIS-provided ionosphere corrections instead, DORIS data known to be similar to those provided by an altimeter but more smooth.

The same figure but using selection F for DORIS, or G for the GPS-supplied GIM correction which is also known to be smooth, resulted in lower rms values (order 10 cm) for latitudes less than 50 N (i.e. in the Channel and Western Approaches) and values around 20 cm north of 53 N, although the latter improvement was perhaps not so significant. Consequently, in further work we tended to use selection F as the use of DORIS provided significantly lower rms values and the GIM correction was not available for the whole data set (being introduced in CMA level 2 production software version 7.1 from cycle 38).

The corresponding figure for selection H (i.e. using the GPD correction) was identical to Figure 2 (Annex III) i.e. there was no clear benefit in using it. This was studied further by looking at the rms of the wet correction term itself, instead of the corrected sea surface height. The rms values in this case for the standard ECMWF model and the GPD one were again near-identical.

Similar findings to the above were also obtained using data for pass 704. For both passes it was noted that the SSB corrections were a major contributor to the overall rms, as expected from previous altimetry insight.

All the above was using SGDR data and various selections of correction terms. The analysis then turned to the use of the new Brown, Mixed and Specular retracker information. For the Brown retracker (selection B), Figure 3 (Annex III) can be seen to similar to Figure 2 (Annex III) but is much noisier, the additional noise necessarily coming from the retracker itself. Again, one could pursue this further using a low-pass filter but that seemed to be against the motivation for the project. The corresponding plots for Mixed and Specular (selections C and D) produced rms values off the scale and it was decided that data from those retrackers were probably unusable.

3.2.1.1 Comparisons to Tide Gauge Data

A separate analysis was conducted in which altimeter data close to the Newlyn (for pass 160) and Holyhead (for pass 704) tide gauges was compared to that from the gauge. In this case the altimeter data were not corrected for ocean tide or IB, so as to correspond as closely as possible to that from the gauge, although a load tide correction was applied to the altimetry as mentioned above for tidal correction option (3).

For pass 160 and selection A, the 49 cycles of data from both sources yielded an rms of the sea level difference of 6.8 cm (removing cycle 16 which appeared to be an outlier). Using selection F with DORIS data resulted in an rms of 3.7 cm from 50 cycles. The latter result is as good in our experience as using T/P/J data (cf. T/P/J altimeter bias papers by Dong et al. (2002, 2003) and Woodworth et al. (2004) in Marine Geodesy which made use of UK tide gauges).

A further test using selection J, with GPD data, gave an rms of 3.2 cm (after dropping one cycle outlier), so it seems that the use of GPD data does provide marginal improvement in this case. Figure 4 (Annex III) shows a time series of the difference between altimeter and gauge for selection J.

The above analysis uses 100 reference points (i.e. about 5 seconds of data) near to the gauge and also allows for an offset at cycle 38 when a major change in SGDR processing took place (in CMA level 2 production software version 7.1).

For pass 704, slightly higher rms values were obtained which is not surprising given the shallow waters and high tides of the eastern Irish Sea. Selections F and J resulted in an rms of 5.0 cm in both cases (Figure 5, Annex III).

Our conclusion from this exercise is that, with the right treatment, the provided SGDR data is not far from being of T/P/J quality. However, the use of the other retrackers resulted in much larger rms values. For example, selection B for the Brown tracker gave an rms of 7.3 cm from 50 cycles, while selection D for the specular tracker gave an rms of 26 cm.

3.2.1.2 Improvements Very Close to the Coast

At the request of Paolo Cipollini, a special inspection was made of the scope for more use of altimetry when as close to the coast as possible. The passage over Cornwall of pass 160 was used for this, where the pass crosses from sea to land on the north Cornish coast and from land to sea on the south coast at a point to the east of Newlyn (i.e. latitude ranges 50.25-50.30 and 50.0-50.01 respectively). We used the SGDR data for this and tested why amounts of data were rejected in these areas, using standard data selections. We did not use data from cycle 46. We did not test for the quality of the data in these particular bands, and also we did not test for the other retrackers in view of their noise.

In the case of close to the north coast and selection F, there were 855 reference points with data to begin with which reduced to 831 after testing for an acceptable SSB value and then to 811 after tests for all other parameters. On the south coast (the retracker having to adjust to coming off the land), the acceptable cutting was much stronger: there were 1701 reference points with data to begin with reducing to 1218 after SSB cut, then to 1194 after acceptable range and other parameters. In both cases it can be seen that the SSB correction seems to be the main criterion regarding data availability.

3.2.1.3 References

Dong, X., Woodworth, P.L., Moore, P. and Bingley, R. 2002. Absolute calibration of the TOPEX/POSEIDON altimeters using UK tide gauges, GPS and precise, local geoid-differences. Marine Geodesy, 25, 189-204.

Dong, X., Huang, C., Woodworth, P., Moore, P. and Bingley, R. 2003. Absolute calibration of the ERS-2 altimeter using UK tide gauges, in, Satellite Altimetry for Geodesy, Geophysics and Oceanography (C. Hwang, C.K. Shum and J.C. Li, eds.), IAG Symposium 126, pp. 91-97, Springer, Berlin.

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3.2.2 Waves

3.2.2.1 Introduction

Satellite radar altimeter data has been used to obtain estimates of significant wave height for many years, especially over the deep ocean. These data have proved invaluable for global wave monitoring and modelling. In general the wave height is estimated from the slope of the leading edge of the waveform of the radar reflection from the sea surface (see Figure 1, Annex IV). As the wave height increases the slope decreases. There is a dearth of wave data in the coastal zone however, as the different radar reflections from land and sea cause degradation of the waveform when land is included in the radar footprint (Gommenginger et al., 2010); at the same time the nearshore area is of importance and interest as waves change markedly up to the coast. In the COASTALT project we wish to investigate whether more nearshore wave data can be acquired by using new retracker algorithms and higher frequency radar data. COASTALT-2 has provided improved versions of these coded algorithms. This report compares the altimeter wave data with *in situ* wave observations and wave model results to examine the quality of the new wave data products.

Wave data were made available from satellite radar altimetry using the Envisat altimeter, RA-2, for 2 tracks west of Britain (Figure 2, Annex IV), referred to as tracks 160 and 704, both of which are descending i.e. the altimeter is moving from NE to SW. This is an update of the original report, using the phase 2 corrected, reprocessed altimeter wave data. Traditionally the radar return is averaged along-track from 18Hz to 1Hz, to reduce noise. The suite of RA-2 products is based on the principle of one main Geophysical Data Record (GDR), including the waveform data (SGDR). Information on the RA-2 instrument and data products is given in Resti et al. (1999) and in the ESA radar altimeter tutorial http://earth.eo.esa.int/brat/index.html. The original SGDR data were provided at a frequency of 1Hz (equivalent to an along-track separation of ~7.5km), with the new higher frequency products from the Brown and Mixed retrackers at 18Hz (equivalent to ~0.375km). Updates of these datasets have been provided in phase 2 of the COASTALT project.

Changes from and additions to the phase 1 report are as follows:

(i) Slightly different cycles are available for track 160. There is little change from phase 1 in terms of wave data availability or accuracy.

(ii) More information has been examined for track 160, including Aberporth wave buoy validation and noise-filtering. Track 160 crosses the coast several times in the northern Irish Sea, Cardigan Bay and the Bristol Channel, thus is of interest in capturing more nearshore wave data.

(iii) Extra model runs have been performed, selecting the highest wave height events for which altimeter data were available during 2002-2008.

3.2.2.2 Data

3.2.2.2.1 Altimeter Data

The Radar Altimeter-2 (RA-2) on ESA's Envisat bounces ~1800 radar pulses per second off the Earth's surface, in the 13.575 GHz (Ku Band), from a height of 800km, measuring their return time to the nanosecond to calculate the precise signal distance travelled. These data are then filtered to 18Hz to give improved accuracy by using a large number of independent observations. The total area illuminated (effective footprint) is related to the significant wave height (abbreviated to SWH or H_s), as shown in Table 1 (Annex IV). In the region of interest and for this dataset nearshore waves are generally less than 5m in height.

There appears to be little change in the altimeter wave data from Phase 1. There are minor changes in available data: specifically cycles 45 and 46 are now available for track 160 in SGDR data but only cycle 45 for Brown/Mixed data.

There are thus 55 or 56 cycles for track 160 and 51 cycles for track 704 (see Table 2, Annex IV). Track 704 follows track 160 with a 19-day lag. Table 2 gives the date/time of the start of each cycle. The fourth and final columns, respectively, show the wave height at

Aberporth wave buoy and Seven Stones LV at the time corresponding to the altimeter pass. Cycles highlighted in bold have corresponding model runs, with 5 cycles selected for track 160 and 4 for track 704, corresponding to the highest waves sampled at Aberporth and Seven Stones respectively. The wave height at 48.5N has also been extracted for use in model boundary conditions.

In general waves are higher along track 704 which is further offshore, but this is mainly due to the infrequent sampling, so that storm events may not coincide with an altimeter pass. The largest waves occur at the southern boundary (48.5N for 9 December 2007, on track 160, reaching 12.7m SWH). The largest wave height recorded by the altimeter at the Aberporth location was 4m for the same event. For Seven Stones the largest waves recorded were 6m for 14 November 2003, whereas the largest waves near the boundary were 6.5m on 8 December 2006.

3.2.2.2.2 In situ Wave Data

Wave data have been recorded at various locations within the area of interest over the period 2002-2008. These were identified from the CEFAS Wavenet web site: http://www.cefas.co.uk/data/wavenet.aspx and are listed in Table 2 of the phase 1 report. The most continuous recording was from Seven Stones Light Vessel at 50.1N, 6.1W. Due to time limitations these were the only data used in the phase 1 study. For phase 2 the Aberporth wave buoy data were also used. This buoy was located at 52.3N, 4.5W for 2002 until June 2003, then moved NW to 52.4N, 4.7W. Hourly data on wave height and period were available at each location. Only the significant wave height data are used here although the wave period could also be examined in future. No wave direction data are available from these locations.

The Seven Stones LV is located between the Scilly Isles and Lands' End, close to the Seven Stones rocks, in about 61m water depth (Bacon and Carter, 1989). It is very close to track 704 but in an area of variable depth (hence the rocks!) and strong tidal currents (1.5m/s at spring tide) which may cause variations in wave steepness.

The Aberporth wave buoy is within Cardigan Bay in a shoaling area where the altimeter is approaching the coast and thus is ideal for identifying the possibility of acquiring more nearshore wave data. The buoy is in water of depth ~20m. However the track passes inshore of the wave buoy in shallower water. Also the buoy was moved in the summer of 2003 to a slightly more offshore location. Thus there is not such good collocation.

3.2.2.3 Validation Methodology

3.2.2.3.1 Direct comparison with in situ wave observations

In-situ wave data have been extracted to coincide with the times of the altimeter over-pass as indicated in Table 2 (see Annex IV). The nearest time is 11:00 on the selected days, within a few minutes of the overpass. The agreement in spatial location is less close: for

Seven Stones the location is very close to the altimeter track geographically but, in an area of rapidly changing bathymetry, the depth is a controlling factor on wave height and may not be identical at the measurement station and nearest overpass location. The altimeter data are averaged over a distance of 4.5km for the SGDR data and 3.3km for the Brown/Mixed data in order to allow a coincident single data point to be identified for the same latitude as the *in situ* observation. For the Aberporth buoy 2 different locations are given for 2002-2003 and 2003-2008, the former being closer to the altimeter track although offshore of it, the latter being further offshore. Thus the *in situ* data are likely to be in deeper water and hence show larger wave heights than at the nearest altimeter point. The nearest altimeter point in latitude was again selected, with several along-track points being averaged for the higher-frequency samples (Brown/Mixed). The data have been compared as scatter plots of wave height and error statistics calculated, with and without removal of outliers.

3.2.2.3.2 SWAN model of along-track variation

The SWAN wave model (Booij et al., 1999; Ris et al., 1999), as used in phase 1, was extended to the area from 48.5°N to 55°N and 8°W to 3°W. The bathymetry was extracted from the 1.85km NOOS gridded data for the NW European continental shelf (Zijderveld and Verlaan, 2004). The model was run in stationary mode as before (see also Hargreaves et al., 2002), with winds from the Met Office mesoscale atmospheric model (~12km resolution). The SW boundary was forced with data extracted from the SGDR altimeter at 48.5°N. This assumes uniform wave conditions around the boundary, which will not be correct, but should not affect the internal solution too severely, as this will quickly adjust to the local wind and depth in the interior of the model. Output was generated along the two altimeter tracks as well as at the Seven Stones and Aberporth locations. Runs were carried out for the times highlighted in Table 2 (Annex IV), selecting the highest wave events recorded (except for February 2004 when there were some problems with the model wind data). In general these larger wave events correspond to winds from the SW and W, except for 8 Dec 2006 and 9 Dec 2007 when the winds were from NW. Most of the strong wind events are related to mid-latitude depressions from the North Atlantic passing from SW to NE to the north of the UK, in which the strongest winds, in the right-rear quadrant, are from SW. Occasionally there is a different pattern with the low pressure sitting over the northern North Sea with high pressure to SW of UK, leading to more intense NW winds, as on 8 Dec 2006, or the depression takes a more southerly track, as on 9 Dec 2007.

Examples of model output are shown in Figure 3 (Annex IV) for 9 December 2007 when the largest wave height occurred. Wave height, direction and period are shown. Only the wave height information is used in this study, although other parameters may be of interest in interpretation of the wave data.

3.2.2.4 Validation Results

3.2.2.4.1 In situ data

The wave height at Seven Stones LV is compared with the nearest point along track 704 in Figure 4 (Annex IV). The SGDR data is obviously giving reasonable estimates of wave height, but consistently higher than the in-situ data (but note possible error in exact position for comparison as discussed in section 3.2.2.2.2). The Brown retracker usually gives higher wave heights. The Mixed retracker gives very patchy results and much too low wave heights.

Figure 5 (Annex IV) shows the wave height at Aberporth wave buoy compared with the nearest point along track 160. In this case the SGDR is slightly low compared to the wave buoy (but note satellite track is inshore of buoy location, in shallower water). The Brown data give higher wave heights, whereas the Mixed data do not show much correlation with the *in situ* observations.

Statistics for the differences between the in-situ and altimeter data are shown in Table 3 (Annex IV). The best agreement with in-situ data is for the SGDR data. The Mixed retracker appears to have lower errors than the Brown retracker, although the latter appears to show little variation in wave height. A second set of statistics after removal of the outliers (>2s.d.) shows better agreement for the Brown data, and appears consistent with ‘eyeball’ estimates from the scatter plot. Thus the SGDR data has the lowest RMS error of 1m at Seven Stones and 0.4m at Aberporth with the Brown retracker slightly larger. Note that the RMS error for the Mixed retracker does not appear much worse but the correlation is poor. Further statistics such as scatter index or skill score could also be used.

3.2.2.4.2 West Coast Wave model results

Results from the 9 runs of the model for the along-track variation of wave height are shown in the Appendices: Appendix A shows the track 160 results and Appendix B the track 704 results. It is noteworthy that the Brown data are at 18 Hz whereas the SGDR data are at 1 Hz. The along-track distance for each dataset has been calculated from a fixed starting point: 54.9N and 3.1W for track 160 and 54.9N and 3.8W for track 704. Overall the along-track model data show similarity with the altimeter SGDR data. As in phase 1, the Brown data appear similar but much more noisy, probably due to the different along-track resolution. The Mixed retracker grossly underestimates the wave height and sometimes shows little variation along-track with a similarly large variability to Brown.

Next we discuss some details of the model-altimeter comparison with reference to the event of 9 Dec 2007 (largest wave height in Celtic Sea near S boundary). The upper panel of Figure 6 (Annex IV) shows results for this event in which it may be seen that there is quite good agreement between the model and SGDR. Unfortunately the model data do not exactly correspond to the altimeter locations. The Brown data are somewhat higher and have more scatter. The lower panel shows some details of the results over Cardigan Bay, as the altimeter track approaches the Welsh coast. The black ellipse indicates an area where there may be a promising additional amount of data from the Brown data. However, as already mentioned, these data are very noisy and it appears necessary to do some averaging. The solid and dashed red lines show a running-mean box-car filter applied to the Brown data, of length 10 and 4 respectively, in order to apply some noise reduction (note, if a value of 18 is chosen this is almost the same as the effect of the sub-sampling of the SGDR data). As expected, the longer filter gives more smoothing, but the shorter filter is almost as good in this area, giving values just a little larger than SGDR while retaining more data nearer to the coast.

The problem remaining is that there are quite large, apparently spurious wave heights, nearer to the coast. It seems necessary to apply some quality control filters to the data, before or after smoothing. Removing values which exceed 20m or fall to zero is effective at removing some spurious data. Another option is to remove data points which exceed some threshold for successive along-track change in wave height. Some tests were made for this (e.g. a maximum difference of 3m between successive data points provides a useful filter for this dataset, in Cardigan Bay) but no satisfactory universal threshold was identified. This could be the subject of further work.

As mentioned above the model track differs from the altimeter track, and this is for 2 reasons: (i) the model line was linearly interpolated (in SWAN) between the start and end point defined latitude/longitude coordinates, but does not follow a great circle path as for the altimeter data and (ii) the model resolution (1.8km) is too coarse to properly resolve the coastal zone. Further work would be needed to rerun the model with lines exactly corresponding to the altimeter track. The discrepancy between the tracks is illustrated in Figure 7 (Annex IV) for Cardigan Bay (approximately the mid-point of the model where the discrepancy is largest). It may be seen that the model track is nearer to the shore than the altimeter track. The offset is about 7km. The effect of this is that the model track cuts the coastline sooner than the altimeter track and thus is shorter. The model resolution could be improved with higher resolution bathymetry but this is difficult and/or expensive to acquire.

3.2.2.5 Acknowledgments

Thanks to the Met Office for observed wave data for Seven Stones LV and Aberporth wave buoy.

3.2.2.6 References

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3.3 NW Mediterranean

This sub-section show what has been done in this region. An important effort was dedicated to the development of the processing tools following a previous recommendation [RD5]. The automation of processing tasks is seen as an important aspect to make the validation everywhere. Quality checking of the ranges and corrections is a pre-requisite to any successful use of Sea Surface Height (SSH) and SSH Anomaly (SSHA) in the Cal/Val activities. In particular, no good correction will help us to get good SSH if the range is bad of several meters [RD5].

3.3.1 Methodology

The quality checking and validation process includes three different steps: collecting reference in situ data sources, elaborating the validation strategy and assessing the accuracy of the product. The actual status from the COASTALT processor is that the output is in netcdf format for a selected pass (track) and one file per cycle is generated [RD6]. Each file is a collection of parameters as function of rate, latitude, longitude and time, however, along track positions of parameters are not coinciding for different cycles. CGDRs data are not directly usable for comparisons with in situ data. The processor is not actually co-locating altimeter data for different cycles. Our workaround was to make off-line data co-location and export co-located data in ASCII tables. For the future, it is recommended that this step has to be done within the processor.

Our strategy was:

1) to generate altimeter data – This means to select a coastal zone of interest where to indentify relevant passes. Then running the processor to get all cycles for all selected passes and finally extracting land/sea interface, e.g. coastline or DEM.

2) to reorganize altimeter data – This means permitting parameters to be viewed along track (space) and along cycle (time). This is done by building one ASCII file per one point at 1 Hz using IDL script running in batch mode. Each file contains a 2-D table of parameters vs cycle maintaining the correspondence between 1 Hz and 18 Hz fields.

3) to process altimeter data – This means using Matlab scripts to automate tasks such as: detecting spikes and flagging them; computing new variables, e.g. SSH or other quantities; comparing in situ observations; enabling ad-hoc visualizations).

The first step is the quality control of the product. Focus is on ranges and corrections. Open ocean is our reference. The general idea is to identify anomalies (offsets, trends, jumps, malfunctioning, etc.). Priority is on ranges (as roughly corrections have values that are much less than range as said previously). Orbit minus range is our indicator of anomalies. The parameter visualization is along track for a specific cycle, along cycle for a specific ground point, along track and along cycle providing 2-D stacked plots (all cycles or all ground points) coming from different sources (e.g. Range, Wet Tropo, Iono). Some key quantity are also estimated (e.g. std, Avg).

A quality control strategy is also applied in two steps: (i) there is a check cycle by cycle on each variable; (ii) there is a check on a specific variable coming from different sources; (iii) there is a check moving from open ocean to coast.

An important aspect is also the data collocation. The definitive solution if we really want to co-locate things would be (i) to project the measurements (orthogonally) onto a nominal track (accounting for the across track gradients) and then (ii) to interpolate along-track data onto the nominal point . Point 2) is only going to have a minor effect if we are working with 18Hz data, spaced by 350 m actually. A quick look on some CGDRs showed that the spacing varies between 371 and 376 m depending on the orbit which is of course variable. So an average value for the 1Hz spacing is 7.47 Km. We have assessed the various options to co-locate data and we concluded that at this stage the best way was to stack data along cycle (time) dimension taking into account the minimum distance from a nominal orbit. Our strategy is also supported by the fact to maintain data as they are in origin. Other methods such as the co-location to reference (e.g. at 20 s spacing for the Envisat satellite mission the step would be roughly 0.33333 km) involve some kind of interpolation and we don't know in advance what happens (e.g. introduction of artifacts).

We are aware that there are along-track and cross-track geoid variations (these translate in an error due to different sampled geoid signals from one repeat cycle to another). These errors have been shown to be as large as 10 cm rms in the vicinity of steep geoid features. There are ways to correct data for these gradients, but this is out of scope of our task. However, we feel these errors in our case-studies are negligible, as we are looking at 18 Hz data (order of 300 m in distance between consecutive points at same cycle). The geoid or MSS gradients in the study area we selected for validation (i.e. Porto Torres) are not large and this supports our strategy.

The second step is the validation. The focus is on SSH/SLA. In situ data is our reference. The general idea is to compute SSH/SLA along cycle for a specific ground point and stack more ground points in a 2-D plot. The SSH which is the satellite's distance at a given instant from the reference surface has to be calculated by subtracting from the altitude the range corrected for atmospheric (ionosphere, dry and wet troposphere), environmental (SSB) and others (loading and solid earth body tide) effects. The SSH is also usually corrected for “unwanted” metocean (ocean tidal and meteorological) effects when linked to oceanographic studies. The objective is to measure of how closely the altimeter-derived sea level estimates correspond to the in situ values. In our tests, no tidal and meteo (IB ad winds) correction was applied because these effects are also sensed by tide gauges.

3.3.2 Toolbox

This toolbox has been developed to automate some processing tasks during the quality checking and validation phase. It was conceived as a flexible environment, proposing a friendly and intuitive interface to assess (qualitatively and quantitatively) the improvement gained from the adoption of specialized retrackers and corrections in the coastal zone. The toolbox is still in the experimental phase. However, the modular structure permits that users can add new components and/or incorporated the existing ones into their own processing software.

The toolbox can be divided into two major groups:

(i) a pre-processing tool (IDL based software) required to generate a colocated product in a selected study area to be used as input for the quality control and validation;

(ii) a collection of tools (Matlab based software) required to produce high-quality 2D and 3D outputs based on standard Matlab built-in functions

The IDL code starts from two input products: SGDR and CGDR as described in detail respectively in [RD7] and [RD8]. A subset of basic parameters (e.g., ranges, corrections) that are necessary for the quality control and validation tasks are extracted along a selected ground track segment and then colocated on a nominal orbit using an algorithm based on the distance of the single orbits. The complete list of the parameters is listed in a file (see Annex VI). One ASCII file for each 1Hz position is generated. Each file is organized in a tabular format and contains the cycle-by-cycle fields at 20Hz rate. The number of ASCII files depends on the length of the selected ground track segment. These ASCII files serve as input for the quality control and validation.

A command-line user interface to select parameters (cycle, retracker, correction), create plots (geo-referenced or stacked) and zoom in/out locally can be invoked. Parameters can be visualized along track for a specific cycle (or all cycles in 2-D), along cycle for a specific ground track point (or a subset of ground track points in 2-D), along track and cycle (all cycles for selected ground points in 3-D). Interactive functionality to remove residual outliers using mouse gestures is added. All the following processing is done using the cleaned data set. A Matlab Graphical User Interface permits to select ground track points and decide which range and corrections to be used in SSH computation. This enables comparison using parameters coming from different sources (e.g. Range, Wet Troposphere, Ionosphere, etc.). Some examples were presented at previous progress meeting to show the main functionalities. Procedures based on linear de-trending with flagging of all data that deviate more than 2σ from that have been developed to detect and reject along track poor-quality CGDR data.

3.3.3 Data Quality control and validation

Compared to Phase-1, no updating was done to the retrackers and related dual-frequency ionospheric correction computed by the processor. There are well known issues coming from the raw data set: orbits are not those computed by other centres (e.g. RADS) that benefit of a quality assessment and improvement; GIM ionopsheric correction is not available for the whole data sets. The new things are: USO correction applied which resulted in Phase-1 in a significant amount of SSH data rejected; availability of GPD and all the other necessary corrections at 18 Hz (through interpolation).

We select Porto Torres as case-study to show here (Figure 1, Annex V). The reason is that we have two Envisat ground tracks (descending pass 160 and ascending pass 887) near the tide gauge which is located in the port (Figure 2, Annex V). Figure 3 shows a zoom of the area near the tide gauge. We quality checked all ranges (SGDR, ICE, Brown, Mixed and Specular). We found that Mixed and Specular exhibit an off-set at meter level when compared to Brown (see Figure 4) and they also appear too noisy at this stage. It is clear that they need some additional optimization before moving to validation. After checking all available corrections, we decided to retain Dry Tropospheric correction (ECMWF – interpolated at 18 Hz), Ionospheric correction (DORIS – interpolated at 18 Hz), Wet Tropospheric correction (DLM and GPD interpolated at 18 Hz) and SSB (interpolated to 18 Hz). We realized that data editing is a pre-requisite before doing validation. We found some isolated spikes, anomalous cycles, noisy data especially near coast, etc. At this stage we used our script to produce a cleaned data set. But in the future, we need to develop an automatic data editing strategy tailored for the coastal zone. Figure 5,6,7,8 (Annex V) show the cleaned retrackers. Figure 9,10,11,12 (Annex V) show the cleaned corrections. Figure 13 (Annex V) shows a typical example of raw correction (SSB) that needs to be cleaned before exploitation. We see that DLM and GPD provide similar results for wet tropo correction. By using the toolbox, we estimated SSH in different conditions (without any correction applied, with one or more correction applied and with all correction applied). Figure 14 (Annex V) shows the averaged SSH with all corrections applied in both cases (passes 130 and 887). One can see that there is a minor bias (at cm level) in Brown retracker that however will be fixed in future products. It should be also noted that when the altimeter moves from land to sea (pass 887) the systems take some time before working properly. We have also compared the estimated SSH to the sea level measured by tide gauge. Figure 15 (Annex V) shows the rms of the difference at selected 18 Hz altimeter points in the segment between 10 and 40 km from the tide gauge. The accuracy is within 10-15 cm for ICE (pass 65) showing that with specialized retrackers we can get an improvement. This an encouraging result considering that the rms difference is estimated at level of raw data. With a filtering in time space (depending on the scales of interest) we should expect lower accuracy levels.

3.4 Gulf of Cadiz

3.4.1 Introduction

In this section we analyze the accuracy of ENVISAT RA-2 wave measurements in the Gulf of Cadiz, addressing the problem of satellite altimetry data improvement near the shoreline. The Gulf of Cadiz is a wide basin located in the southwestern of the Iberian Peninsula connecting the Atlantic Ocean and the Mediterranean Sea through the Strait of Gibraltar (Figure 1, Annex VI). The continental shelf from the east of Cape Santa Maria to the west of the Bay of Cadiz has a broad width (~ 50km). The coast is predominated by marshes, beaches and estuarine zones, and receives significant fluvial inputs associated with the discharge of major rivers such as the Guadiana and the Guadalquivir (23). This crucial environment has undergone substantial rapid agricultural, fisheries, and anthropogenic development, particularly in recent decades.

Here we will assess the performance of new ENVISAT datasets, processed with specialized routines under the frame of the COASTALT project, in order to enhance data accuracy and resolution closer to the coast. The main task is to demonstrate that these derived products at coastal regions perform as well as standard altimetry in the open ocean, aiming to achieve the maximum number of records. We will focus on a diagnostic, testing strategy to ensure a thorough validation of the data. The results can be used to highlight interesting aspects of this coastal zone where altimetric data are often flagged as spurious and consequently, rejected. Thus, another aim is focused on expanding the ongoing most ambitious applications of altimeter data for its use to infer useful oceanographic conclusions in synergy with modelling tools and other data sources.

3.4.2 Methods

3.4.2.1 Altimetric data

Geophysical parameters derived from the dual-frequency Radar Altimeter (RA-2) at full and low rates (20 Hz and 1 Hz, respectively) were assessed in this analysis distributed with the more recent available updates (24,11). The data stream was extracted from the beginning of the mission covering the period of cycles 11 through 84 and spanning eight years (2002-2009). The along-track selected corresponds to the descending pass 223 that crosses the continental shelf of the Gulf of Cadiz in front of the Guadalquivir River mouth (Figure 1, Annex VI), with a 35-day repeating cycle. The dataset consists of the parameters of SWH (Significant Wave Height) at a frequency of 1 Hz (7-7.5 km along track spacing). This data corresponds to the standard Geophysical Data Record (GDR) distributed by ESA. In addition, SWH at high rate: 20 Hz (350 m along-track spacing) from the COASTALT processor was also validated. In a first step, SWH from the COASTALT processor at 20 Hz were converted into 1 Hz resolution data by averaging every twenty points and utilized in the inter-comparison with wave measurements of the GDR data at 1 Hz. For the work presented here, the quality checks applied to the data in order to remove remaining spurious records included testing the land flag, peakiness value, zero or default values in the wave height fields and “Nval” (SWH) > 18 (with “Nval” being the number of 20Hz valid measurements). Flagged data indicating errors in the measurements were eliminated. The time series were further processed with the removal of all the observations for which SWH > 15 m or SWH < 0.15 m. These control procedures were performed to the fully corrected along-track data allowing an increase in the statistical confidence. In a second step, we validated high rate SWH data against ground-truth data available in the study area.

3.4.2.2 In-situ Measurements

We used several coastal stations deployed in the Gulf of Cadiz for validation. The field data are the significant wave heights. Buoy and moored data were obtained from an array of instruments corresponding to two networks. The first one operated by the Instituto de Ciencias Marinas de Andalucia-Spanish National Research Council, ICMAN - CSIC (25). The second dataset was provided by OPPE (Organismo Publico de Puertos del Estado), which uniformly samples Spanish coasts with high quality (www.puertos.es). AWAC-AST (A) coastal buoy belonging to ICMAN-CSIC have been continuously operating in the last years, measuring wave variables (10 km separation from coast). Wave data were also collected by Gulf of Cadiz (G) exposed mooring from the independent sets of OPPE network, with a distance of 55 km to coast. With the mentioned data streams, rigorous quality control was undertaken, consisting of the flag or the complete removal of records containing default or null values. The time series were processed further using a filtering process, all the observations for which SWH > 15 m or SWH < 0.15 m were discarded. The station names and positions of the instruments are listed in Table 1, which also shows general information about them, such as the time period coverage and availability, network, measured variables and collection time intervals. Also, other surface meteorological data were retrieved from the buoys as ancillary data. The locations of the in-situ are shown in Figure 1 (Annex VI).

3.4.2.3 Relative calibration and satellite/in-situ comparisons

Relative calibration between the GDR and COASTALT 1 Hz SWH data were performed for assessing and monitoring the products, with an evaluation of both datasets. Thereby, because one of the main goals of this activity is to check and determine the quality of satellite data at this coastal region, it is also necessary to make comparisons with reliable and independent observations. Then, we have assessed the altimeter-derived SWH against concurrent field measurements to obtain a set of collocated data. So far, buoy observations are considered the most reliable observations, but they are limited to some locations along this coast. Comparisons between satellite and field data are complicated by the fact that each of them is measuring different aspects of the temporally and spatially varying field, and hence may differ, even in the case that both instruments are making accurate estimates (26). The above-mentioned problem has been aware by the altimetric community for many years (27). Usually, a temporal window and a spatial separation of acceptability are established between the altimeter track and the buoy location. In the space domain, the size of the window ranges from 0 km to 150 km; while in the time domain, it varies from 0 h to 1.5 h. Based on assessments of the spatial and temporal variation of the wave field, Monaldo proposes collocation criteria of observations occurring within 50 km and 30 min of one another, being widely adopted as the standards. Furthermore, for data near the coast, the determination of an optimal size is very often a puzzling task because of the conflicting requirements involved. Usually, to eliminate interference from land, stations were required to be at distances greater than 50 km offshore. This condition is defined because if buoys are too close to the coast, altimeter overpasses will generally occur seaward of the buoy location, thus sampling generally higher wave conditions (28). This will affect the collocation statistics, particularly the bias, so excluding buoys that are too close to the coast mitigates this problem. In order to extent the recovery of this valuable information to the coast, it is therefore necessary to use an expert system configured to successfully deal with the complex echo shapes of the altimeter signals.

For each comparison between sets of collocated wave height measurements from satellite and buoy we adopted the following procedure. Altimeter GDR data are available every 1.1 seconds and at distances of about 7 km apart. Buoy measurements are recorded at hourly intervals, giving a maximum time difference from a satellite overpass of less than 10 min (Table 1). This temporal separation difference should have only a small effect on the comparison. One of objectives of this work is to recognize the influence of land on altimetric data and to strictly define the sufficient distance to avoid coastal contamination at this area, thus limitation on the separation from the shore-line was not applied. The number of total altimeter data points selected was 15, with a maximum distance of 85 Km from the buoy stations (Figure 1, Annex VI). The accuracy specifications for buoy data are typically 5% for SWH, while satellite measurements aim for lesser accuracies of 10% or 0.5 m (29). The differences between altimeter products and observations were also quantified by computing some standard monitoring statistics, generally used to evaluate the results. The most common for specific observations are the bias, root-mean- square (rms) error, and linear correlation coefficient (R). Observations that deviate out of the 95 % confidence intervals of the scatter are identified as outliers and removed from the data. These controls were compiled to ensure the consistency and the relevance of the statistics performed on results once we get closer to coast.

3.4.3 Results

The relative calibration of SWH 1 Hz from GDR and COASTALT based products is provided in this section.

SWH values at 1 Hz from the GDR datasets were compared against COASTALT records in order to enhance the performance of both datasets nearshore. A statistical evaluation of the altimetric measurements is presented with nearly eight years of data (2002-2009). Results of regression analysis are showed in Figure 2 (Annex VI), with the scatter of the 15 satellite 1Hz control points. Overall, good statistics are founded with a slight positive general bias (0.08 m) in the COASTALT data. The rms difference between the two datasets was founded to be 0.84 m with a large correlation of 0.72 (N=837). The first point of the along-track closer to coast (big black dots in Figure 2 in Annex VI) indicated an intense overestimation of SWH in the GDR observations. Moreover, point 2 (squares in Figure 2 in Annex VI) had similar behavior but less accentuated. Figure 3 (Annex VI) shows the along-track results (rms, bias and R) of each 1Hz point individually with respect to the distance to land. The two closest altimeter points to the land show the lower correlation (R below 0.5) and are quite noisy with high rms, especially the last point declared as “ocean”. The remaining 1Hz points presented the higher correlation, with most regression line slope close to, but slightly more than 1.0, confirming the underestimation of the SWH from GDR data. The degradation of quality data is quite evident at distances to land lower than 18km,where the major disagreements between both datasets are found. The correlation increased as we moved away from coast (R maximum=0.98 for point 13), also with a reduction in noise (rms minimum=0.30 m for point 13). The underestimation of GDR records respect to COASTALT data is almost constant along-track (points 3 to 15) with positive bias of about 0.28 m.

The comparative statistics of both datasets are very similar and a good agreement is inferred with the exception of the two closest points to coast (less than 18 km) presenting a severe overestimation of GDR data. This interference is a common feature in altimeter measurements nearshore and is associated to land contamination, sampling generally higher wave conditions (28). Moreover, the proximity of land is affecting in a very different way the retrieval of SWH, when using the ESA standard retracking processing, respect to the processing developed in COASTALT. For distances to land higher than 18km, the COASTALT processor performs as well as the standard processor used by ESA.

3.4.4 Validation with in-situ data

We have collected, assessed, and compared the SWH data from the altimeter-derived products (GDR and COASTALT) with two in-situ stations separately (AWAC-A and Gulf of Cadiz-G). The results of regression analysis of the buoy in exposed location (G) showed very high correlation for both datasets GDR (N=797) and COASTALT (N=787), and were statistically significant at the 95% level, with most regression line slope close to, but slightly more than 1.0. The closest 1Hz track point to the buoy (20 km) offered the best fit in both data streams: 0.17 m rms, 0.006 m bias and R=0.97 (GDR) and 0.15 m rms, 0.007 m bias and R=0.96 (COASTALT), presenting consistent altimeter products typical of more offshore locations.

The outcomes of the sheltered water moored AWAC located in the estuarine zone of the Guadalquivir River (10 km from coast), a very dynamic area, are presented in Figure 4 (Annex VI). The regression analysis gives large correlation for both datasets and good agreement is inferred for the track points located 10-15 km away from the shoreline. The rms (m), bias (m) and R values along-track for each altimeter point and for the two data streams are displayed with respect to distance to coast and the separation to the in-situ station. Due to nearshore ground-truth data availability the number of observation is lower than offshore station, with N=161. The comparison against GDR dataset shows that the bias obtained indicates that the altimeter overestimates SWH respect to the buoy measurements over the entire segment of along-track analyzed, especially in the first two points. The bias slightly increases as the along-track 1Hz points are far from the buoy. Figure 4 (Annex VI) also indicates that rms in the present comparison are reduced monotonically when satellite/buoy distances are restricted. The best fit corresponds to the minimum along-track point’s distance to the buoy (~11 km in point 4). Figure 5 (Annex VI) presents the scatter of SWH from ground-based observations against altimeter GDR retrieval of this track point number 4 (dots), showing that the total collocations are situated above the 1:1 line with a positive bias in the satellite data. Average scatter about the regression line amounts to 0.36 m rms, 0.28 m bias, and 0.78 R. It is known that in coastal systems the background energy may significantly vary within the region and affect the wave spectra differently (30). Firstly, the effects associated with the remaining dispersion are interpreted due to local variations in wave climate because the proximity to land. Secondly, the low correlation of the last two track points 1 and 2 (1.5 and 9 km distance from coast, respectively) demonstrated that, in addition to the coastal processes, the effects of land contamination in the altimeter footprint might distort the retrieval of SWH.

The COASTALT records show quite a good correspondence with the in-situ data, similar to the GDR data, with a total of 120 collocations (Figure 4 in Annex VI). Overall, there is a positive bias in the altimeter data (higher nearshore). This agrees well with previous work and with the GDR comparisons, suggesting that altimeter systematically overestimates SWH respect to ground-truth observations. We observe an improvement in statistics as we get closer to the ground-based emplacement (same as GDR data). Accordingly, the best fit appeared in the track point number 5, at 20 km from the buoy, with a correlation factor of 0.82, 0.49 m rms and 0.47 m bias. The scatter of this point 5 can be observed in figure 5 in Annex VI (crosses), presenting an overestimation of the satellite data observed in the regression line slope, more than 1.0.

In general, the rms between the two respective data streams was found to be similar, with the exception of the two closest points to coast, presenting lower errors in COASTALT data. In fact, the second 1Hz point (COASTALT) presents rms and bias values of the same order of magnitude than offshore points. For Geosat/buoy validations, Monaldo defined scatter of about 0.4 m rms. While this is close to that displayed for most comparisons in the SWH studies, results using smaller comparison distances show the buoys to be more precise than this. This characteristic is founded in the present analysis; as we move away from buoy, rms values increase. Indeed, the closest the tracks are to the buoy, the better the estimate of the bias between altimetric and in-situ data is. Apart from the discrepancy in the two nearshore points, the comparative statistics of both analyses in terms of significant wave height are very similar. Both the COASTALT and GDR records persistently overestimate the wave conditions in the control region with respect to the in-situ observations. In general, the results stated extremely in good agreement between the buoy and the altimeter GDR and COASTALT measurements, roughly consistent with the accuracies planned for each system. RA-2 estimates of SWH are characterized by stable and precise performance, indicating that the spatial and temporal variability of the wave field is well reproduced in this coastal region. The current outcomes of the SWH validation synthesized accuracy data at the boundary of 10-20 km from coast. The effect of slight spatial variations in wave climate over the 10 to 100 km distances used in the comparisons can explain different statistics values, and appears typically in nearshore regions due to the differences in swell and wind wave properties. This could reflect, at least in part, the noisier radar returns from a generally rougher sea surface condition than usually found in deep oceans. Some of the systematic error could be due to buoy imprecision in measuring waves, and some may be due to the indirect nature of the satellite measurement. In addition, the results of the two points closest to shore clearly manifested the influence of land contamination in the retrieval of the SWH in both GDR (more intensely) and COASTALT retrackers. However, the retracker used in COASTALT seems to retrieve less noisy SWH in this particular region, when compared to the in situ data and, in essence, allow recovery of a meaningful SWH measurement closer to the coast w.r.t the SGDR.

3.4.5 Acknowledgments

The authors thank the ESA for distributing the RA-2 ENVISAT data used in this study and the OPPE (Organismo Público de Puertos del Estado) for in-situ data. This work was financially supported by the Junta de Andalucía Project P09-RNM-4853, the Spanish Research&Development Programme (Project Id: CGL2008-04736) and ESA (COASTALT project Id: AO/1-5429/07/I-LG. Isabel Caballero is supported by a grant of the Junta de Andalucía fellowship programme. Acknowledgments

3.4.6 References

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4 Issues and recommendations

A series of quality control and validation exercises in the three pilot regions plus Gulf of Cadiz provided qualitative and quantitative figures of the product accuracy.

The issues identified in the product version 2.0 are:

(i) Retrackers

The COASTALT dataset for the 8 year period between January 2002 to December 2008 still lacks the optimization of the specialized (Mixed and Specular) retrackers. These are noisy and exhibit a significant bias with respect to the Brown one (which is also slightly noisier than the SGDR data) and therefore are not yet useful for scientific work. The standard SGDR data seem to approach the quality of T/P/Jason data for use in the open sea. The examination of retracked ranges from the Brown and Mixed retrackers shows that the performance of the various retrackers is variable from cycle to cycle, particularly depending on how close to the coast the actual track for a given cycle actually is. In some cases the Brown and Mixed retrackers give comparable results (e.g. Figure 3, Annex II) in other cases the Brown and Mixed retrackers allow to get closer to the coast (e.g. Figure 4, Annex II). Therefore it seems highly desirable to have an optimisation procedure for selecting the best retracker for each situation. The COASTALT Mixed retracker doesn't seem to perform significantly better than the COASTALT Brown retracker. Overall, retracking needs to be improved to get valid measurements very close to the coast. For example in the Lisbon area (ascending pass 1) a significant amount of invalid ranges is obtained after the satellite crosses land, particularly for cycles with tracks closer to the coast (e.g. Figure 5, Annex II). For SWH retrievals the brown retracker yields episodic spurious values, while wave heights retrieved using the mixed retracker seem to be unaffected by such events (e.g. Figure 7, Annex II). The value of the retracked range is the fundamental parameter to get useful measurements close to the coast. If the retracked ranges are not accurate, even the most perfect model for the geophysical corrections is not able to improve the altimetric data. This is notorious in the very large standard deviations obtained from points very close to the coast and with problematic retracked heights.

(ii) USO

The USO correction does improve things overall (for all cycles) so it is disappointing that it has not been consistently applied, in spite of Southampton having asked for help from ESA on many occasions. This missing correction was a major reason for rejecting data in COASTALT so it is frustrating it had not been properly estimated for the present project. One case in point was that of cycle 46, not corrected in v2.0newmask for lack of a correction file on ESA side, but clearly in need of a correction of several meters. Since then ESA has made the correction file available, and the latest version of the processor does apply any correction which is available at runtime, so the USO issue is now fixed in product V2.0r2 which however did not come in time for this validation work.

(iii) Distance from coast

It is irritating that problems remain with fundamental programming such as provision of distance from coast flags. Distance from coast field is empty in product v2.0. (this is now fixed in product V2.0r2 which however did not come in time for this validation work).

(iv) Specialized corrections

DORIS seems to offer an acceptable ionosphere correction rather than the altimetry-supplied one. The GPD correction does show some benefit in the comparison to Newlyn tide gauge data (see Figure 4, Annex III) but its overall benefit needs further study; the limited benefit shown here may be due to the small number of GPS stations with suitable data that were included in the GPD analysis in this region. For the examined geophysical corrections, specifically the wet tropospheric correction and ocean tides, the impact of applying different models for the corrections is very small in the West Iberia area. This is not necessarily a universal feature, since for example local effects can significantly influence tropospheric delays. In the west Iberia the wet tropospheric correction is not very large, but in areas of very large gradients the performance of the different wet tropospheric corrections can be more variable than in the Iberia case. The apparent small impact of differing models for the geophysical corrections has two main explanations: (1) the value of the retracked range is the fundamental parameter to get useful measurements close to the coast – if the retracked ranges are not accurate, even the most perfect model for the geophysical corrections is not able to improve the altimetric data. This is notorious in the very large standard deviations obtained at Cascais and Viana from points very close to the coast and with problematic retracked heights; (2) tide gauge and altimetry are not necessarily measuring the same thing, and the difference between tide gauge and altimetry heights remains much larger than the difference between different versions (different models of geophysical corrections) of the altimetric data.

(v) Filtering – especially for Iono & SSB

More fundamentally, the question of how to smooth or filter data near the coast remains. We are not sure that there will be an universal answer to this question, but it seems to be an important one to ask for coastal altimetry before we go much further. It should be noted that a large bias in the Brown S-band resulted in a ionospheric correction with a large offset w.r.t the one in the SGDR (this is now fixed in product V2.0r2 which however did not come in time for this validation work). Therefore DORIS has been used in all examples showed. DORIS is also the correction of choice after the failure of S-Band at cycle 56.

(vi) Quality Control

Quality control procedures were implemented in order to discard outlying sea level anomalies. Selection criteria were based on the resulting range of computed anomalies and on the variability of the corresponding time series over a given period. The application of these criteria resulted in the loss of more than half of the cycles close to the coast (Figure 8). On one hand one wants to keep as much as valid measurements as possible close to the coast, on the other hand outlying values need to be correctly identified as invalid. Therefore it is recommended to better examine and optimise data selection criteria.

(vii) Waves

It is still difficult to reach any conclusion about improved wave height data from the altimeter using the new retracker algorithm, for the west of Britain data. The Brown 18Hz waves show much larger along-track variability than SGDR but this probably does not represent the variability of the real sea state. A degree of further smoothing appears to be essential to produce sensible results. The *in situ* and model data certainly suggest the Brown retracker may be satisfactory but not the Mixed retracker. Both the SGDR and Brown data are generally higher than the Seven Stones data. The nearshore location of the Light Vessel is interesting: although it is still in ~70m water depth, the waves appear to be disturbed by the presence of the Scilly Islands. Comparisons along track 160, which crosses Cardigan Bay and passes near the Aberporth wave buoy, also show good agreement with SGDR and Brown and confirm the poor quality of the Mixed data. There is some indication that with further quality control and smoothing there may be a possibility of acquiring more nearshore wave data, over a few kilometres nearer to the coast. The examples over the Gulf of Cadiz are particularly encouraging in that respect: in that region the COASTALT significant wave height get closer to the coast than the SGDR.

According to what was found in the Gulf of Cadiz, a consistent agreement between satellite and corroborative ground-based SWH values is precise enough to suggest that both SGDR and COASTALT Brown are within the design specifications. The additional difference between the mean altimeter/buoy relationship for the coastal stations reduces when comparison are limited to distances less than a restricted maximum. The above conclusion exposed the importance of using only the smallest possible distances when validating sensors performances. The scatter in the data may be ascribed to spatial variability in wave climate, with clear local effects in a complex area such as Guadalquivir estuary, or attributed to atmospheric stability effects and phenomena at different temporal-spatial scales, where the continental shelf extension may have significant local impacts with significantly varying background energy within the area not characteristic of offshore regions. The current validation of COASTALT SWH offered good quality altimeter data much closer to the coast than routinely achieved. Even though the maximum correlation position of the data are all less than 50 km of the coast (between 10 and 35 km), we still cannot provide optimized SWH right up to the coastline since the altimeter waveforms and radiometer signals remain contaminated by land reflections. Hence, ongoing research directed to enhance the new generation of products may better fulfill the requirements of a coastal-oriented processing. Over the Gulf of Cadiz area, we expose that it is possible to build an accurate data set yielding more rigorous records closer to the shoreline than previous studies with the typical 50 km coastal-band (80% closer). To conclude, achievable goals during this exercise were encouraging, allowing to infer useful oceanographic conclusions looking for trends (seasonal and longer time scales) in ocean conditions extending to satellite's life period. Accordingly, altimetry may also be used to appropriately monitor the coast for a variety of regional studies, and would benefit and optimize the conditions of models over the Gulf of Cadiz area, a key region of complicated dynamics and with relevant social, economic and ecological strategic importance. The questions raised in this part of the work may be generalized to altimeter-derived wind speed, sea level, or even to other geophysical parameters derived from space-borne radiometers, scatterometers and synthetic aperture radars. In this sense, the outcomes obtained here may serve as a guideline in this coastal region becoming an irreplaceable tool for multiple coastal applications.

Based on the analyses that were performed by the teams in the three pilot sites on the product version 2.0, the overall recommendation is that a new reprocessing should seek to correct the deficiencies and provide better ranges and ultimately more accurate corrections (the latest v2.0r2 datasets addresses several of those deficiencies). However, we feel that the very availability of a processor that we can ‘play with’ as the one developed in COASTALT is already a significant step forward in itself. Today, we have a full data set at 18 Hz to be explored. This surely opens new avenues for the coastal altimetry community as well as for possible applications.

In summary, we recommend the continuous updating of the processor. We also suggest that it would be appropriate to have an independent set of product testers, who would report problems to the data originators, and who would complete their work before making files available for potential scientific use.

Annex I: Reference documents

[RD1] Development of Radar Altimetry Data Processing in The Oceanic Coastal Zone - Phase 1, ESA ref. Contract n. 21201/08/I-LG, December 2007.

[RD2] Development of Radar Altimetry Data Processing in The Oceanic Coastal Zone - Phase 2, ESA ref. contract n. 21201/08/I-LG - CCN 3, December 2009.

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[RD4] WP5.1 - Deliverable 5.1 - Validation Plan, Version 1.0, 28 November 2008, 17 pp

[RD5] WP 5.2 & 5.3 – Deliverable 5.2 & 5.3 - Validation and Performance Assessment for NW Mediterranean and West of Britain, Version 1.0, 19 October 2009, 38 pp

[RD6] EWP1 – Deliverable D1.1 - Product Specification Document, VERSION 2.0 rev 1, 31 January 2011, 59 pp

[RD7] RA-2/MWR Product Handbook, Issue 2.2, 27 Feb 2007: http://envisat.esa.int/dataproducts/

Annex II: Figures (West Iberia)

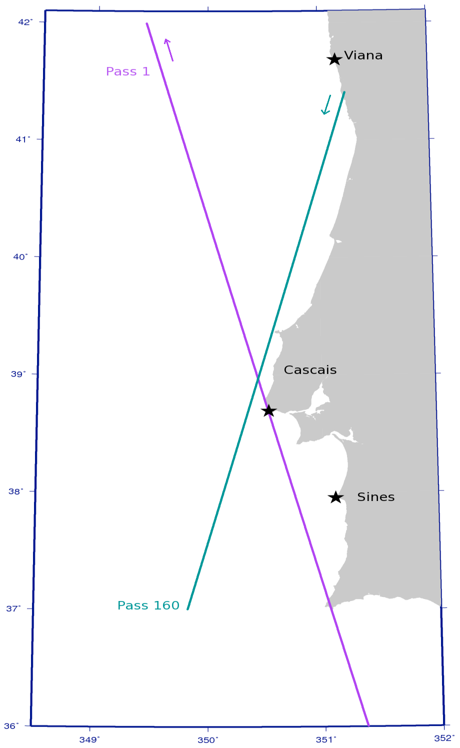

Figure 1: West Iberia validation area

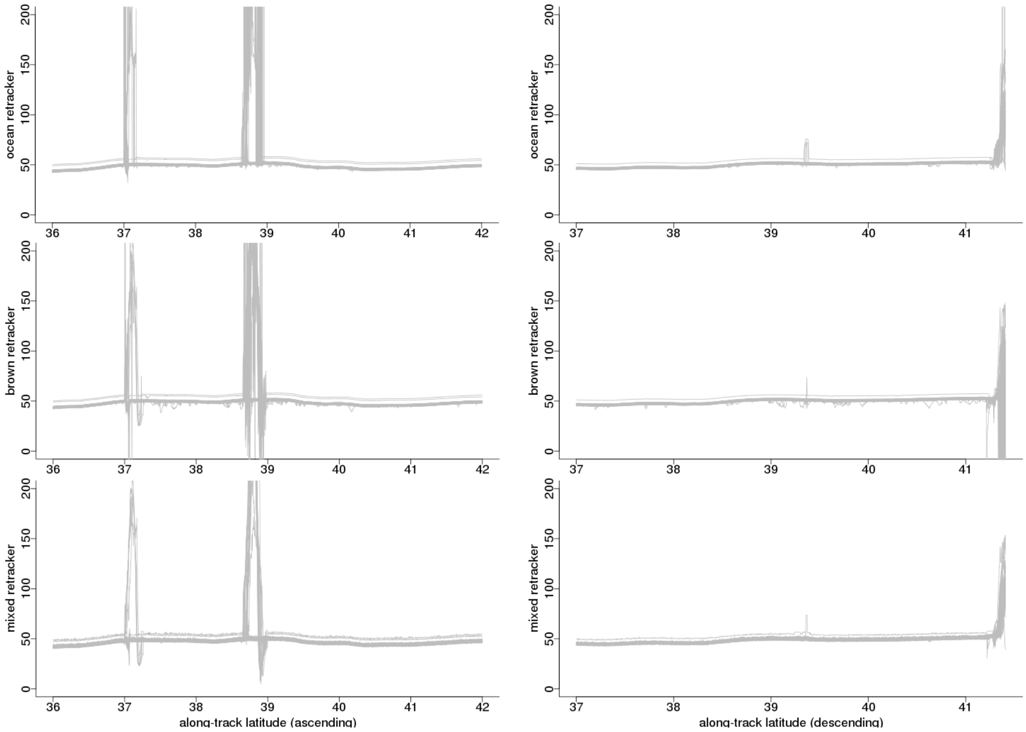

Figure 2: Retracked heights (m) for all cycles of pass 1 (left) and pass 160 (right)

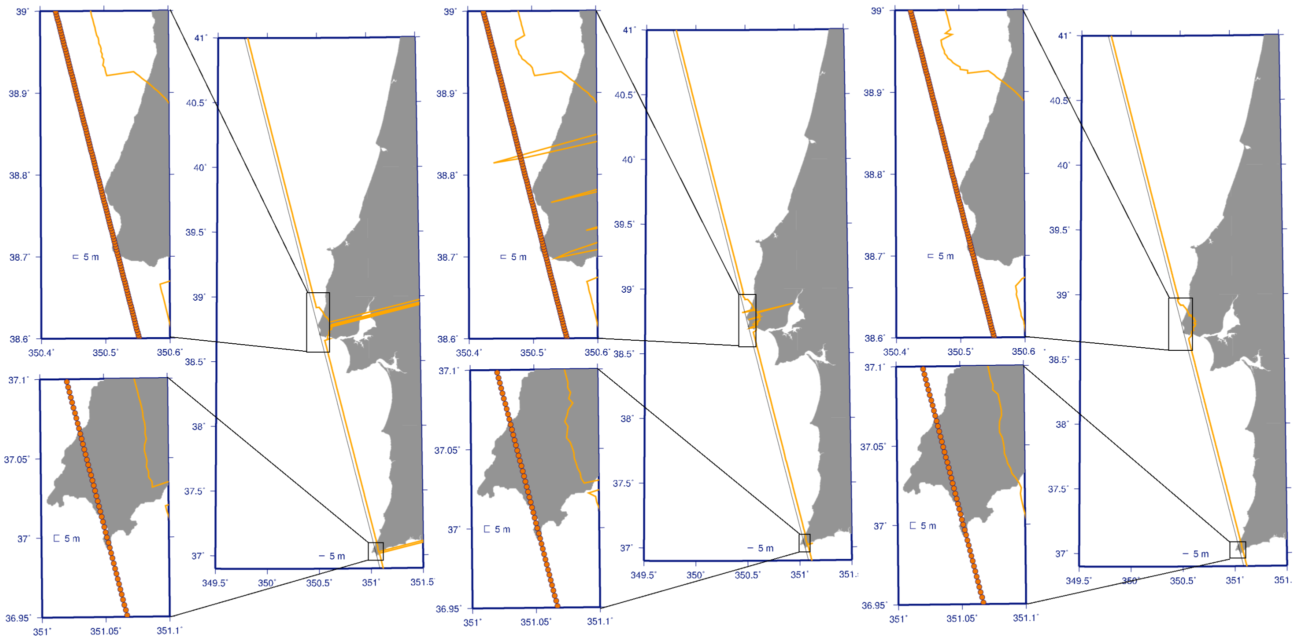

Figure 3: Retracked heights from (left to right): ocean, brown and mixed retrackers (pass 1, cycle 10)

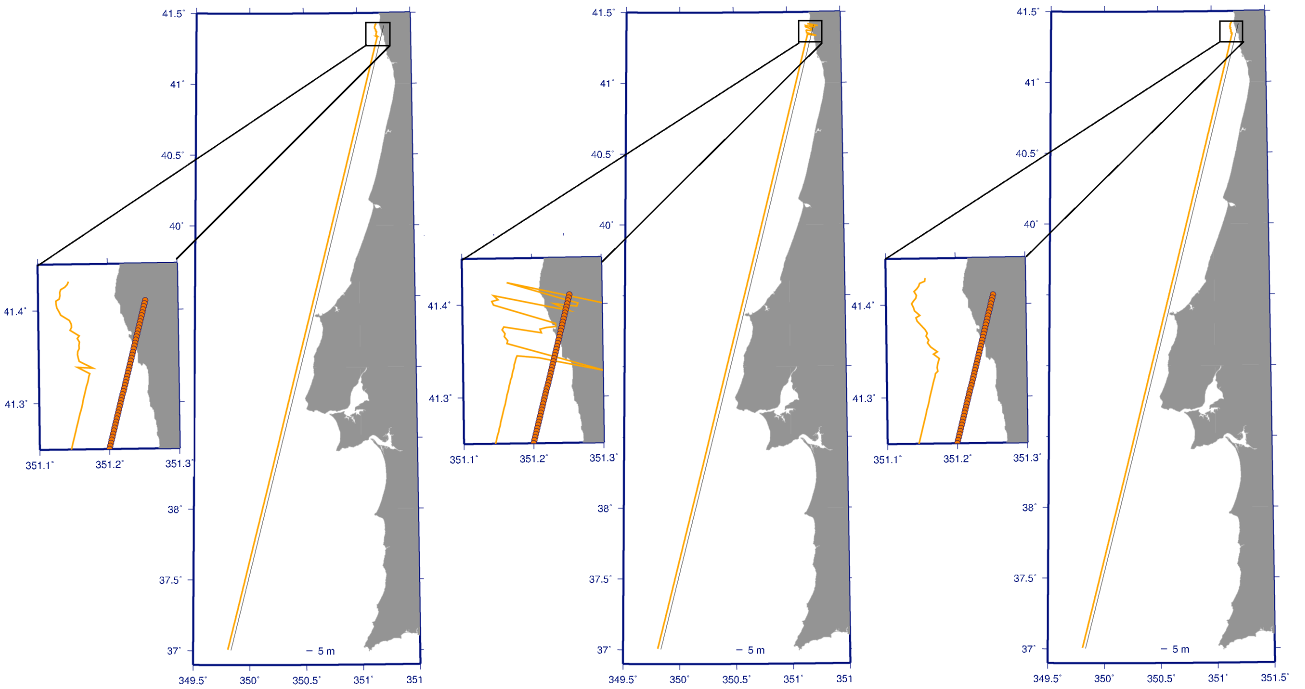

Figure 4: Retracked heights from (left to right): ocean, brown and mixed retrackers (pass 160, cycle 19)

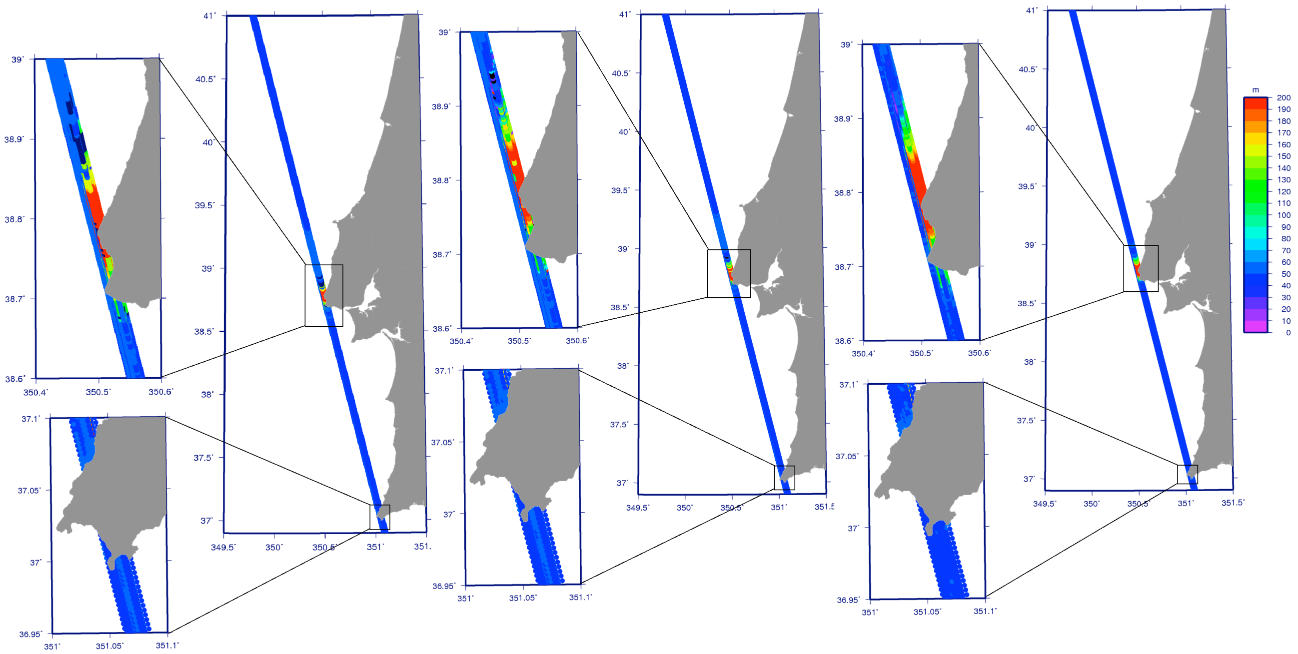

Figure 5: Retracked heights from (left to right): ocean, brown and mixed retrackers (pass 1, cycle 10)

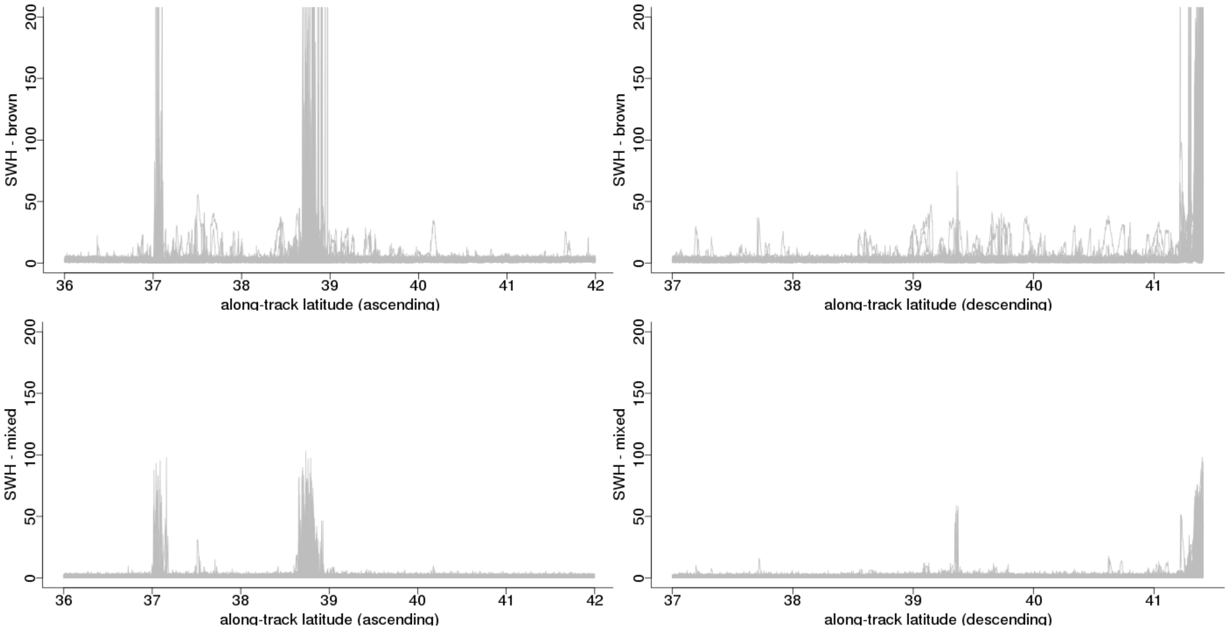

Figure 6: Wave heights (m) for all cycles of pass 1 (left) and pass 160 (right)

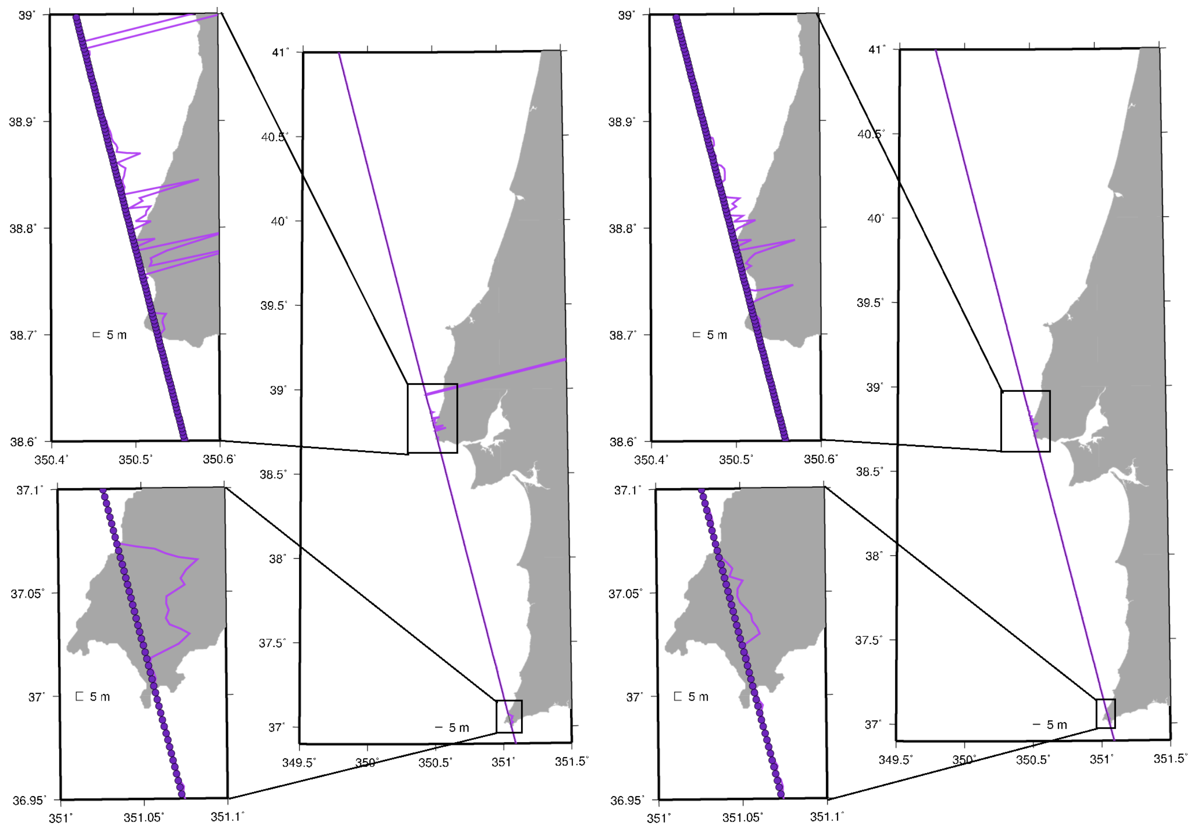

Figure 7: SWH from the brown (left) and mixed (right) retrackers (pass 1, cycle 15)

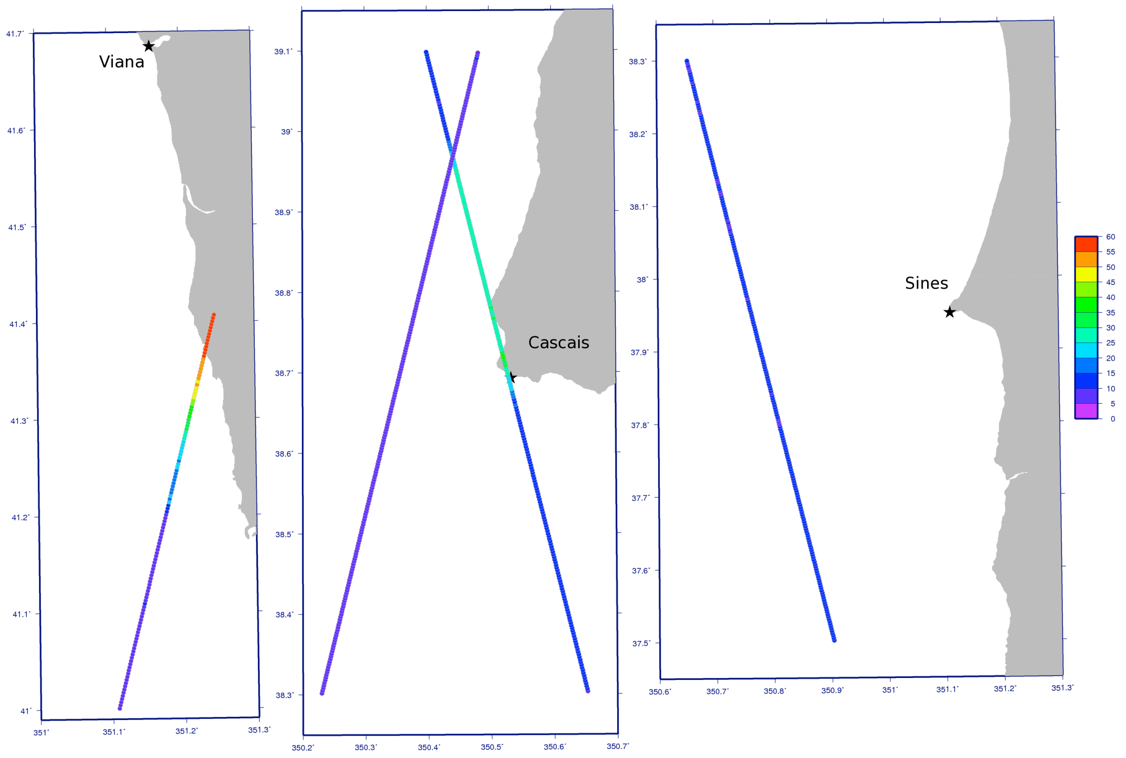

Figure 8: number of missing values (cycles) for SLA time series in the three validation sub-regions

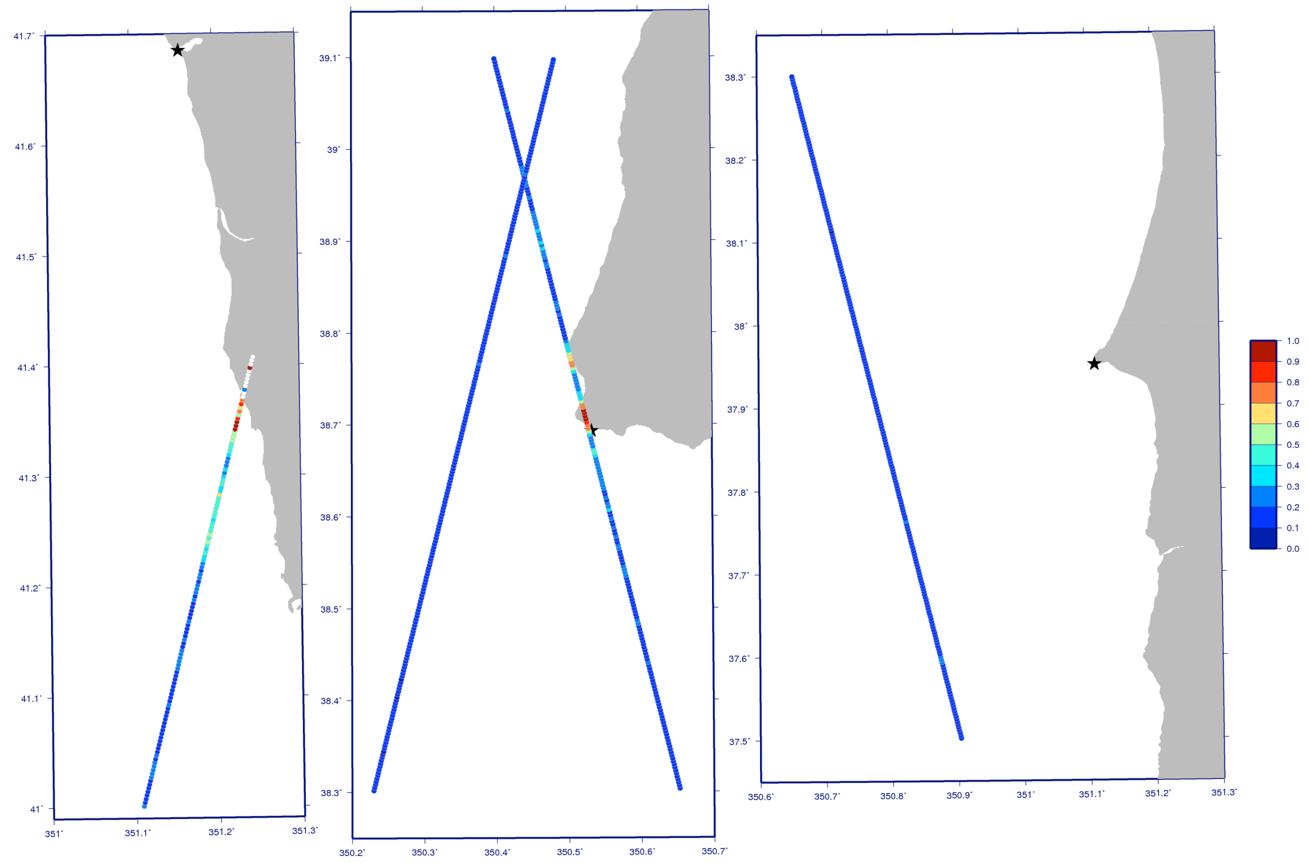

Figure 9: standard deviation (m) of SLA time series

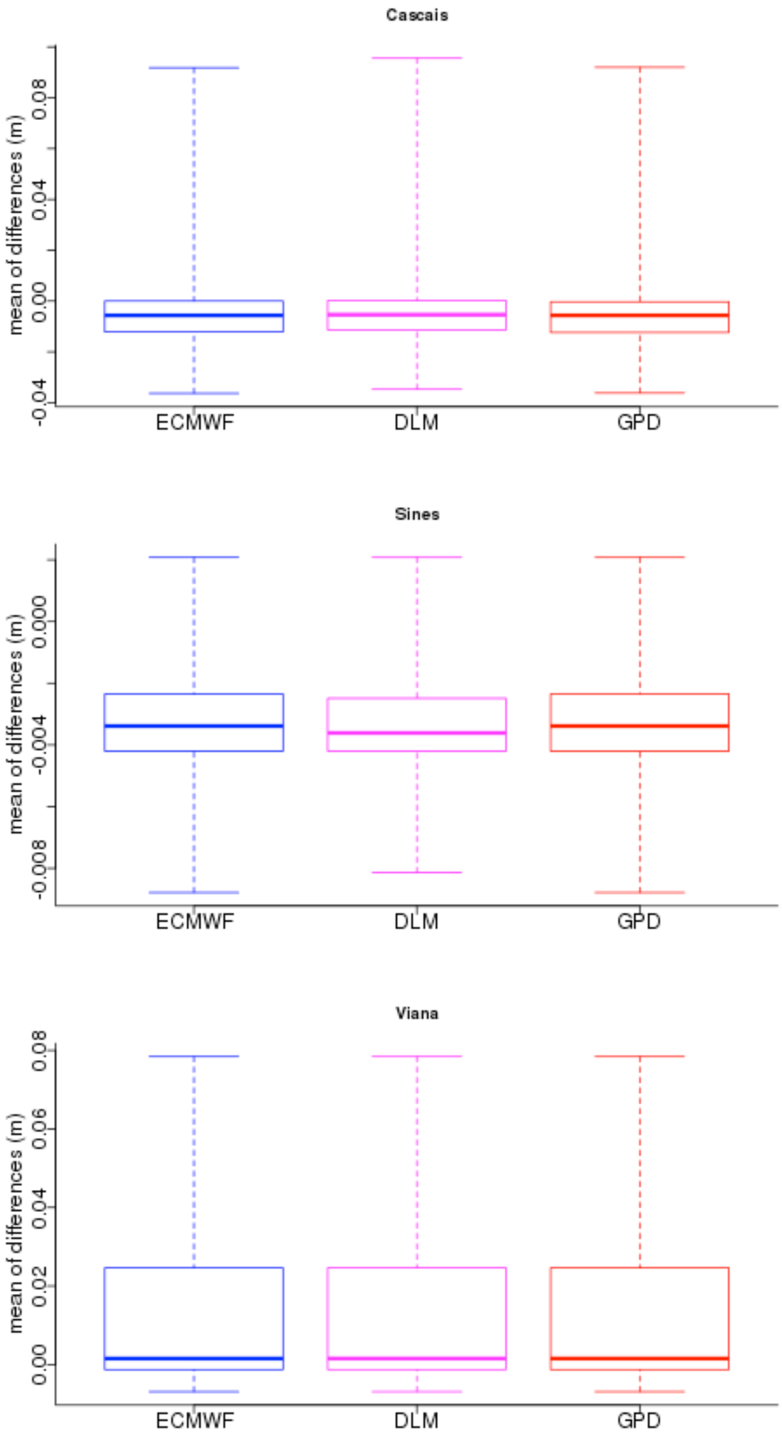

Figure 10: Box plots for all along-track points of the mean of the differences between COASTALT and tide gauge values.

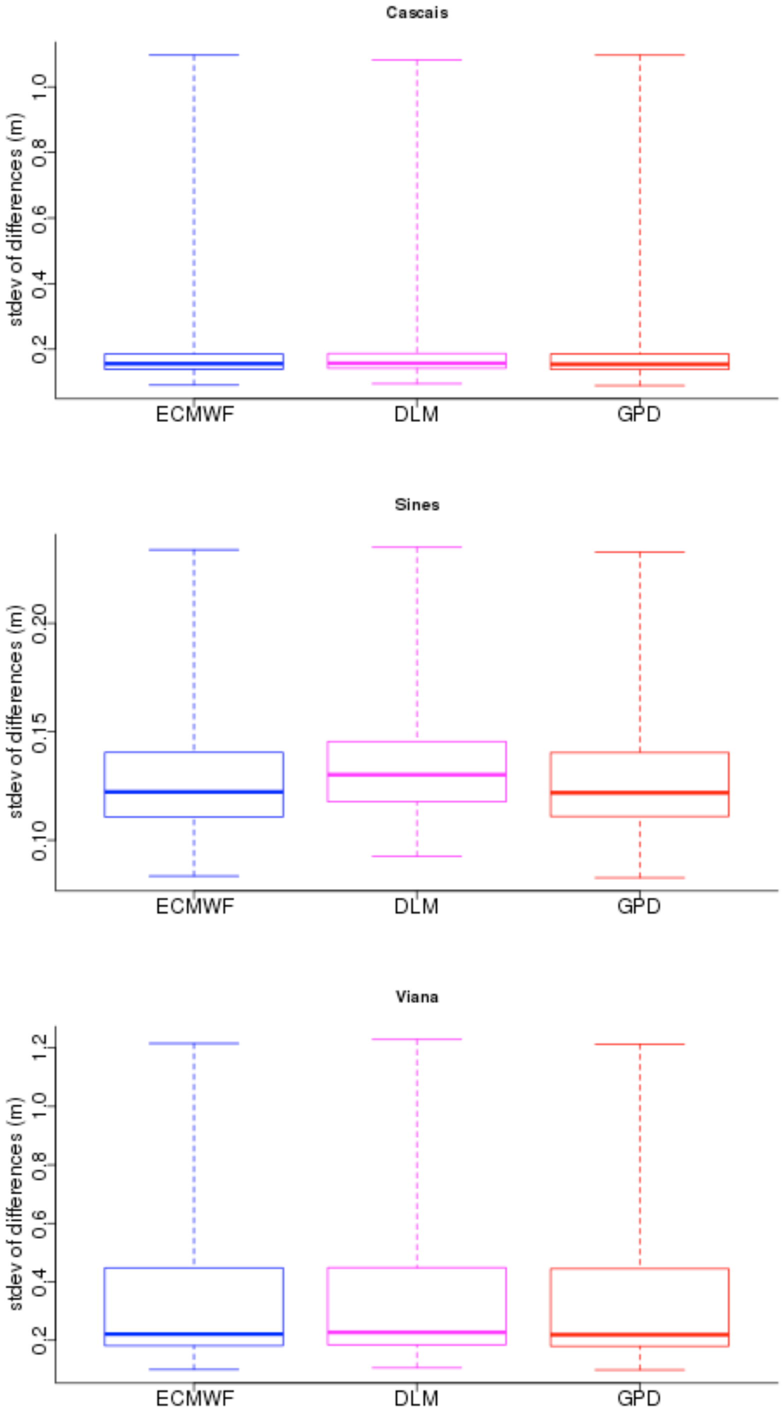

Figure 11: Boxplots for all along-track points of the standard deviation of the differences between COASTALT and tide gauge values.

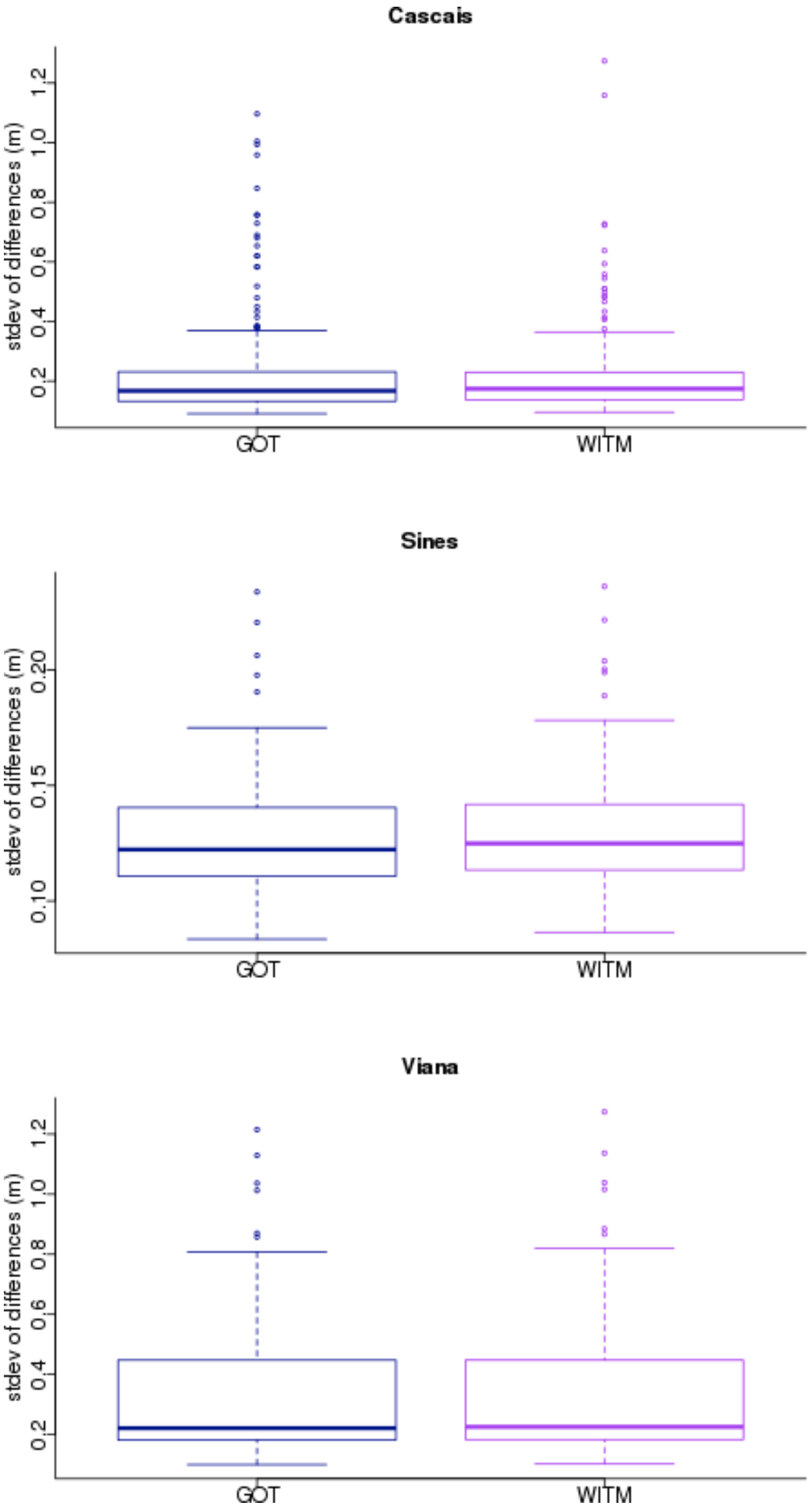

Figure 12: Boxplots for all along-track points of the standard deviation of the differences between COASTALT and tide gauge values for the two tidal models considered

Annex III: Figures (West Britain) – Sea level

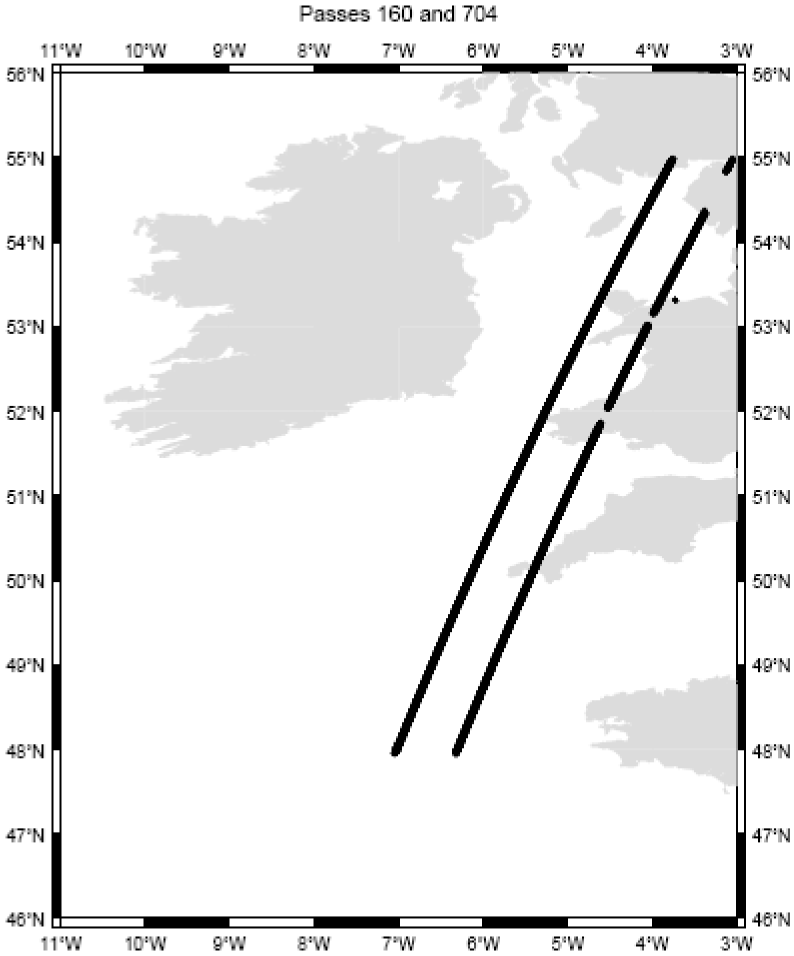

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Figure 1: Passes 160 (the easternmost of the two) and 704 ground tracks

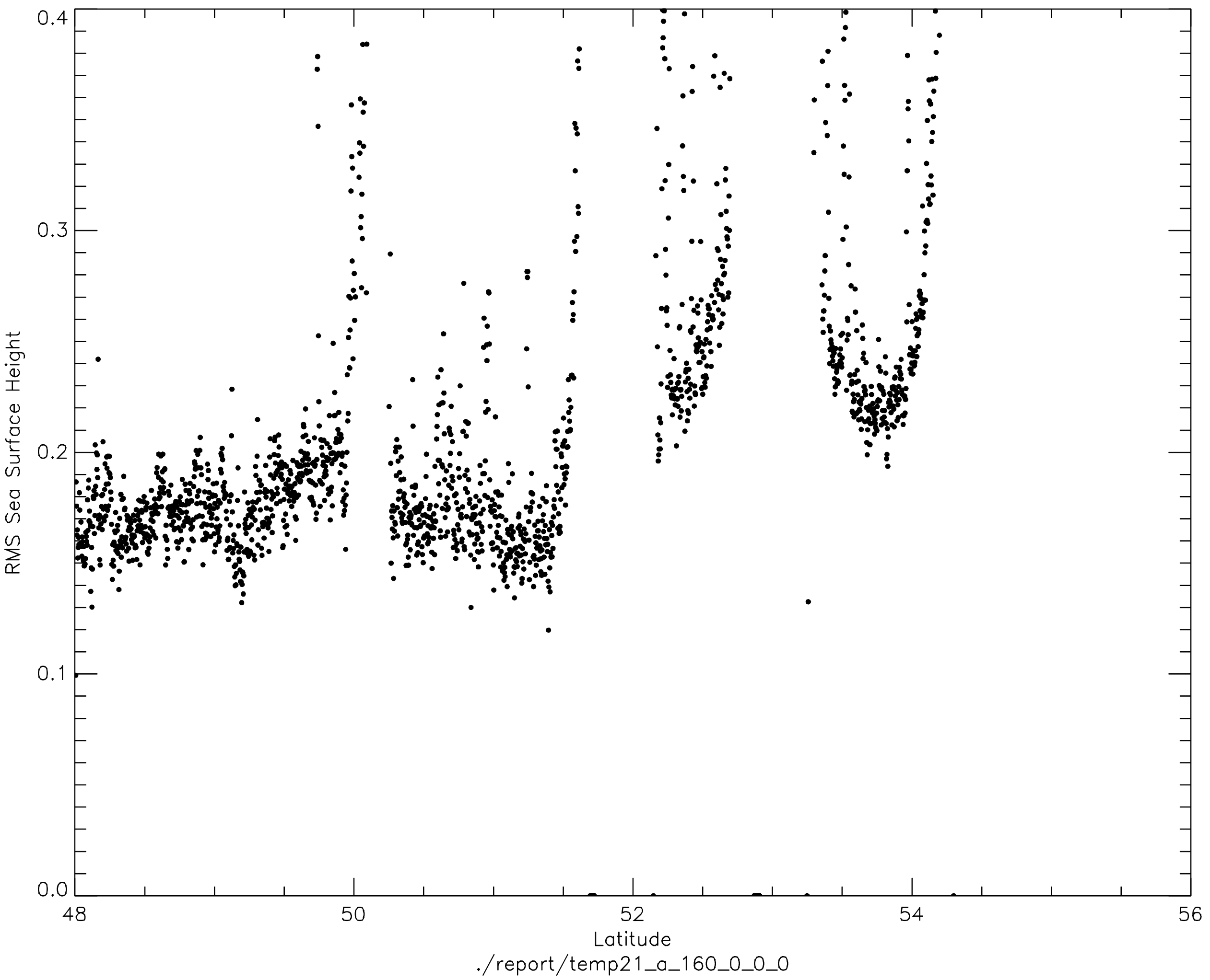

Figure 2: RMS variability along pass 160 using selection A

The data gaps indicate passage over land (Cornwall, south and north Wales).

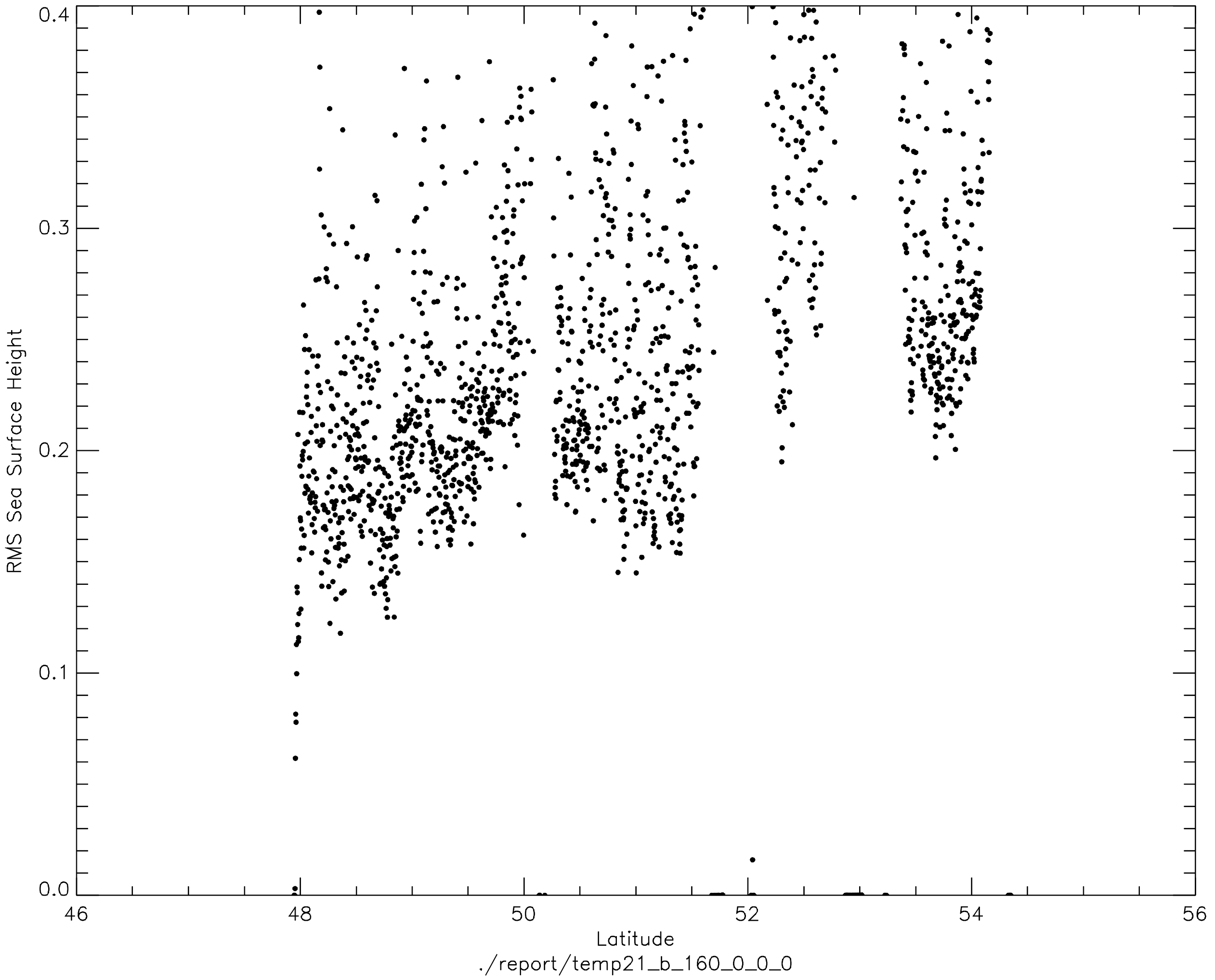

Figure 3: RMS variability along pass 160 using selection B

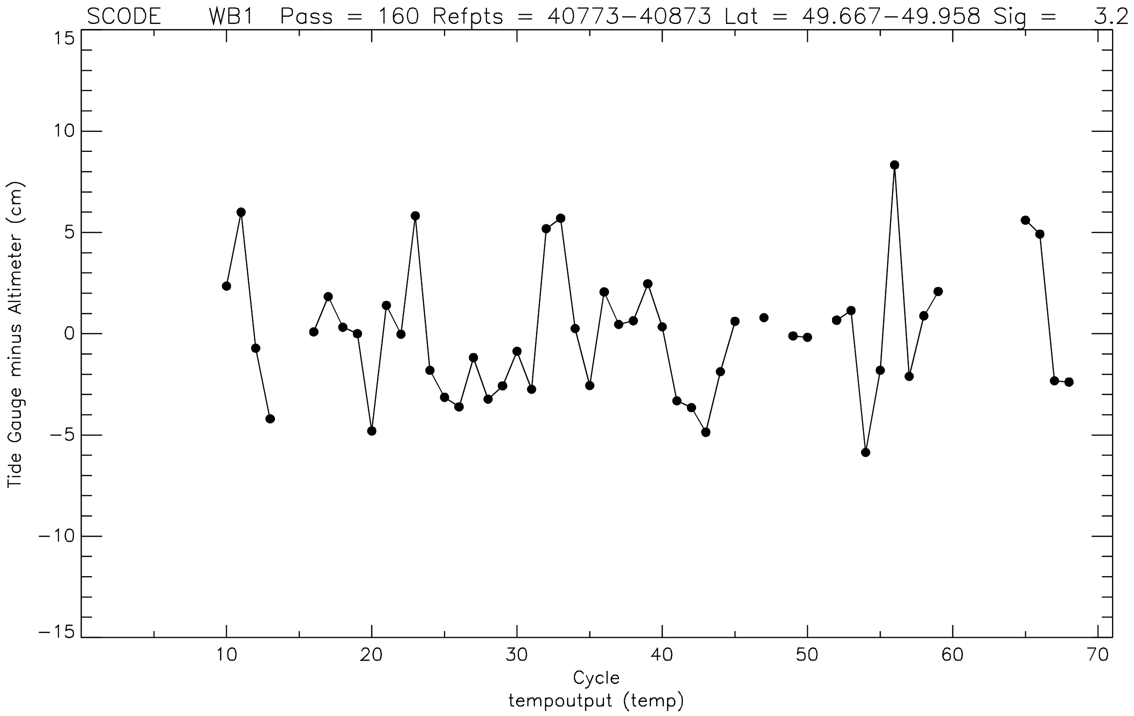

Figure 4: Pass 160 altimetry (selection J) and Newlyn tide gauge comparison

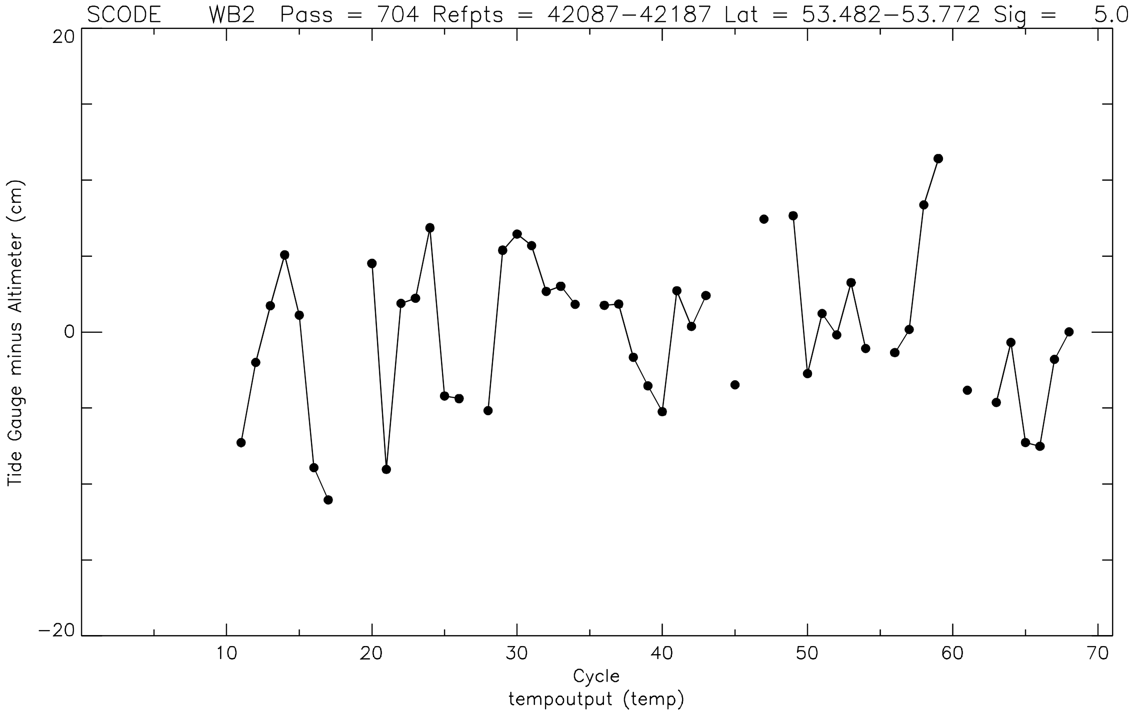

Figure 5: Pass 704 altimetry (selection J) and Holyhead tide gauge comparison

Annex IV: Figures & Tables (West Britain) – Waves

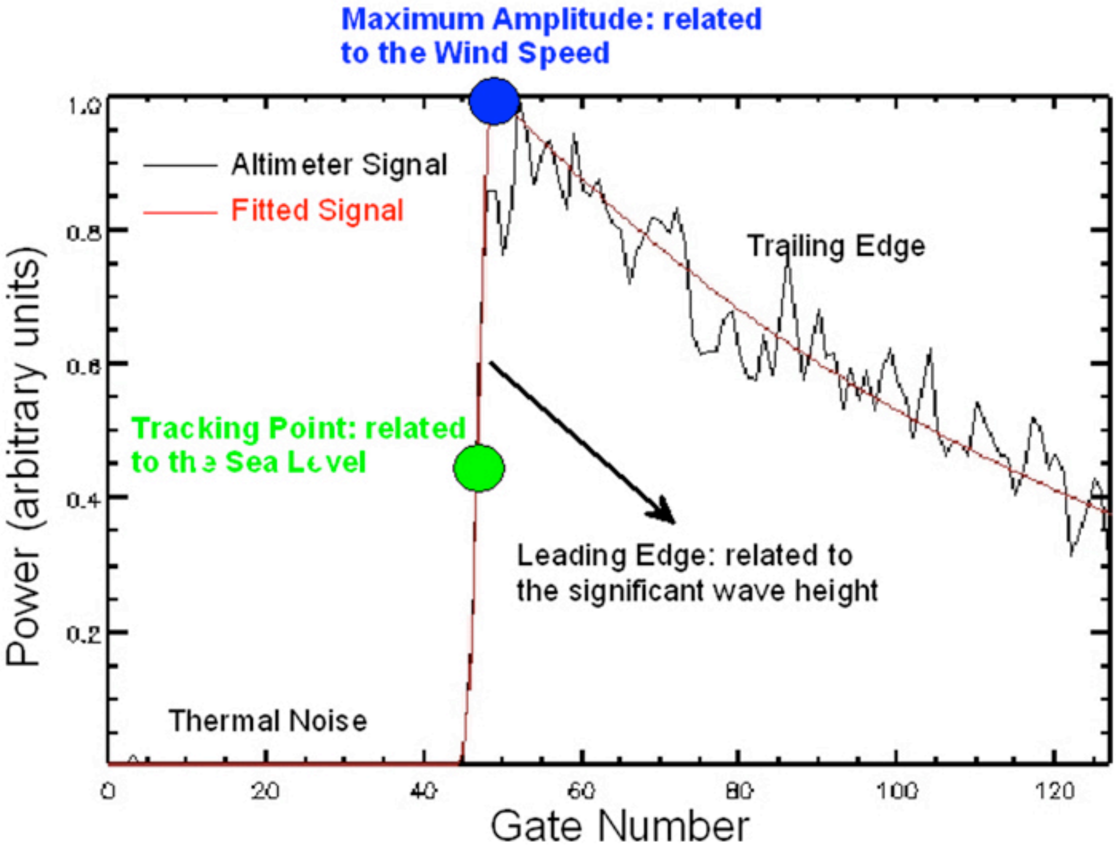

Figure 1: Estimating sea level, wind speed and significant wave height from the waveform of the radar return signal (after Gomez-Enri et al. (2009)).

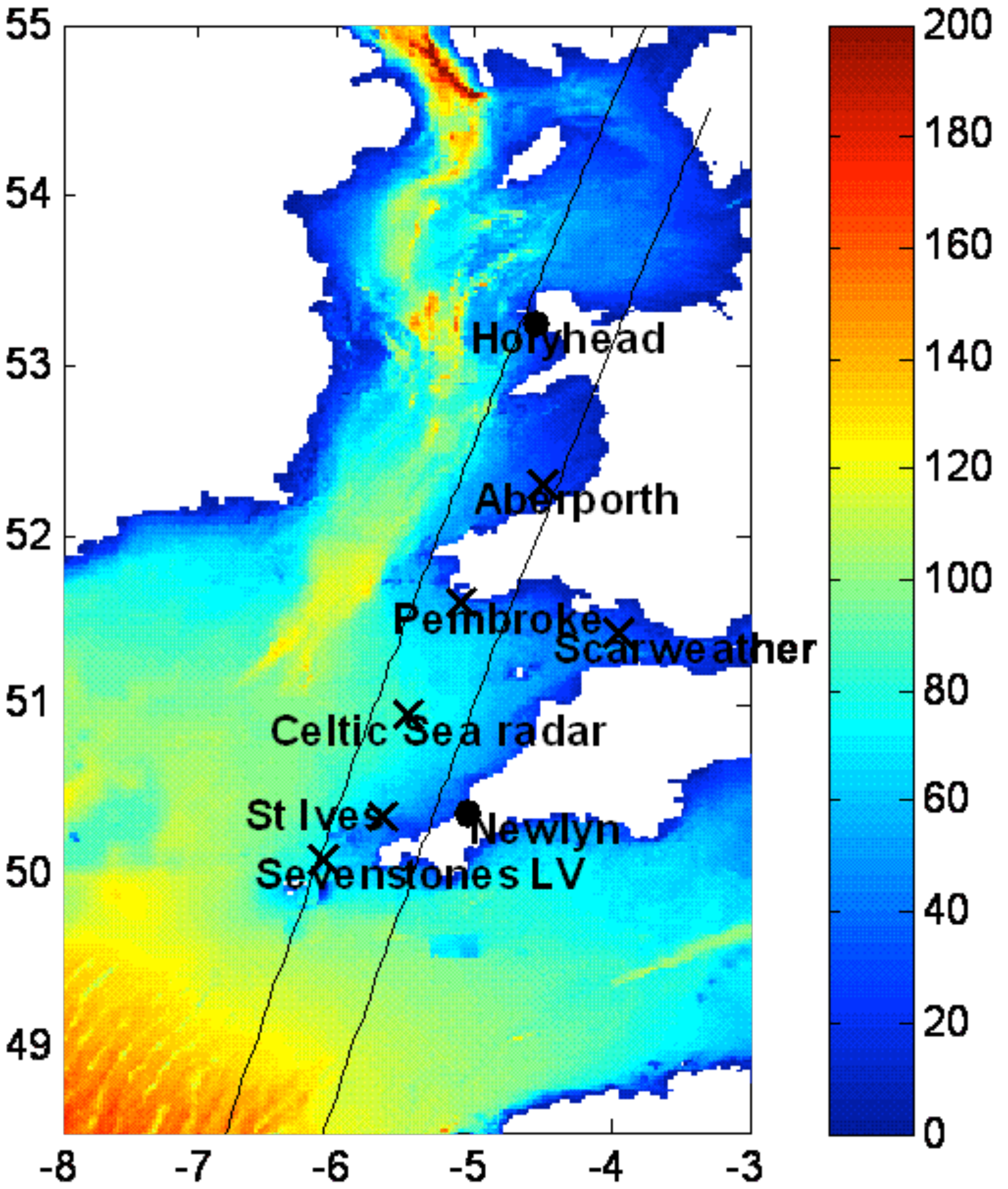

Figure 2: Map of the west coast of the UK showing bathymetry, satellite tracks (black lines), location of wave observations (black crosses) and coastal tide gauges at Newlyn and Holyhead (black circles). Bathymetry is shown for the wave model extent for the south-west coastal area of UK (1.85km, from NOOS bathymetry for NW European continental shelf – see Zijderveld and Verlaan, 2004). N.B. the position of the Aberporth wave buoy for 2002-3 is shown, it was later moved to the NW of this position.

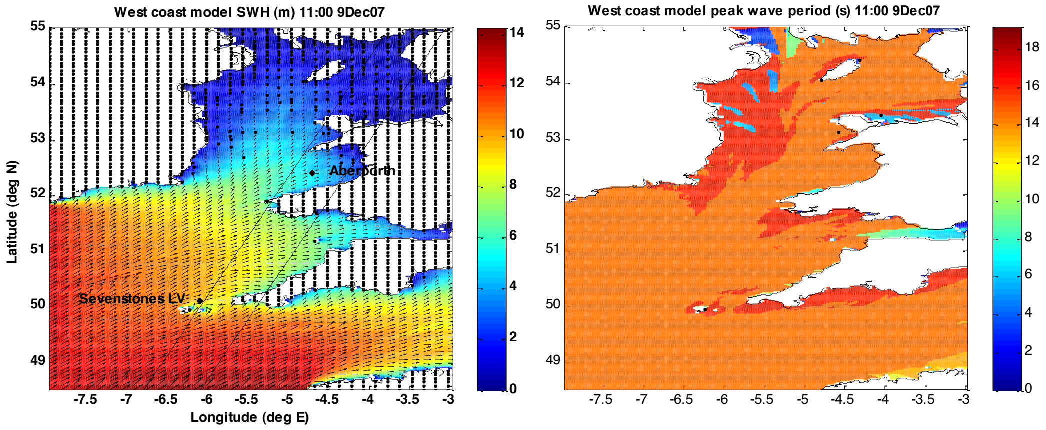

Figure 3: SWAN West Coast wave model results for 9 Dec 2007; left panel – wave height in metres (colour contours), arrows represent peak wave direction, with length proportional to wave height; right panel – peak wave period in seconds.

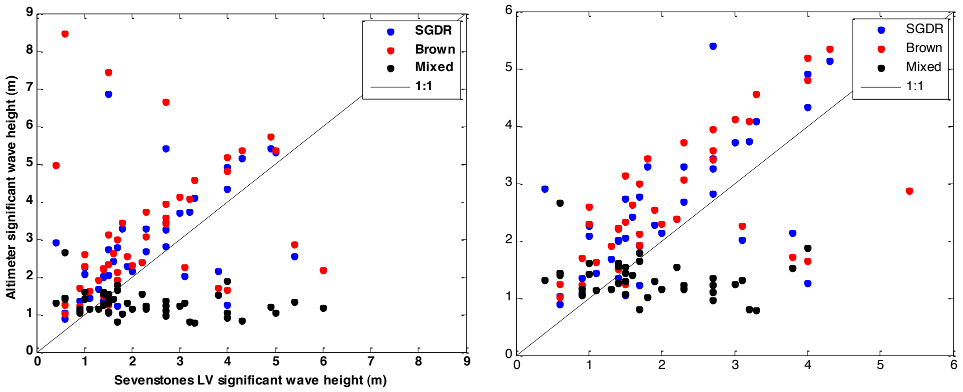

Figure 4: Comparison of altimeter (vertical axis) versus Seven Stones LV (horizontal axis) wave height for track 704, (a) raw data (b) after removal of outliers

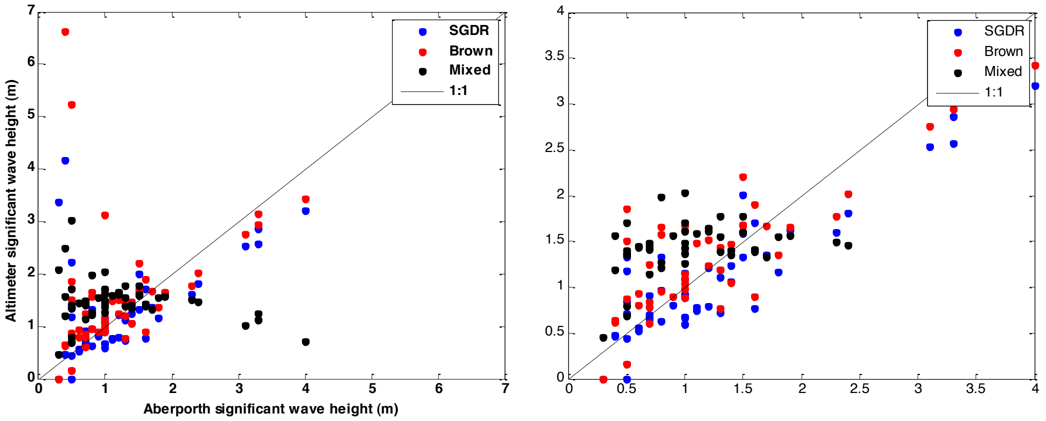

Figure 5: Comparison of altimeter (vertical axis) versus Aberporth wave buoy (horizontal axis) wave height for track 160, (a) raw data (b) after removal of outliers

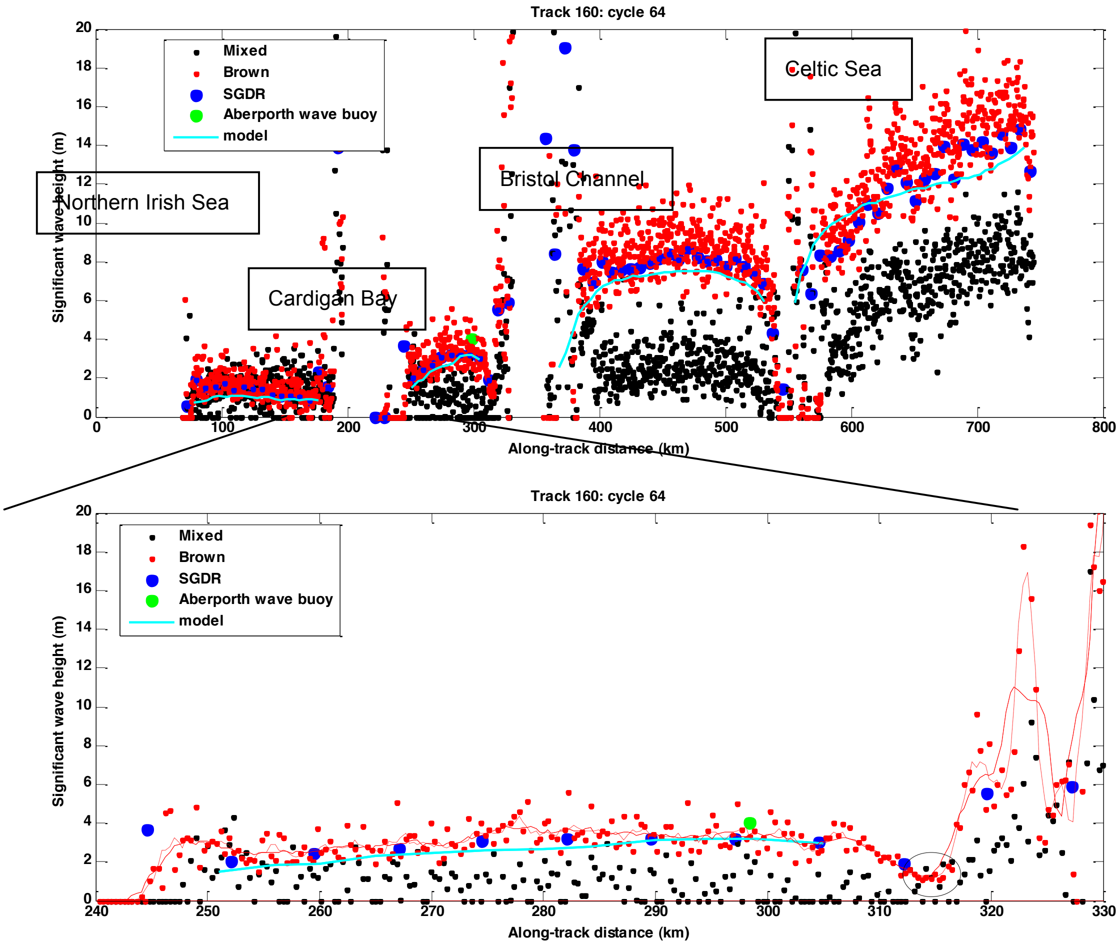

Figure 6: Upper panel: Altimeter track 160, 9 Dec 2007. Lower panel: Altimeter track 160 crossing Cardigan Bay, (max wave height at Aberporth = 4m in 20m water depth). Red solid and dashed lines represent running mean filter on Brown data with length 10 and 4 respectively. Ellipse indicates possible extra good data from Brown retracker.

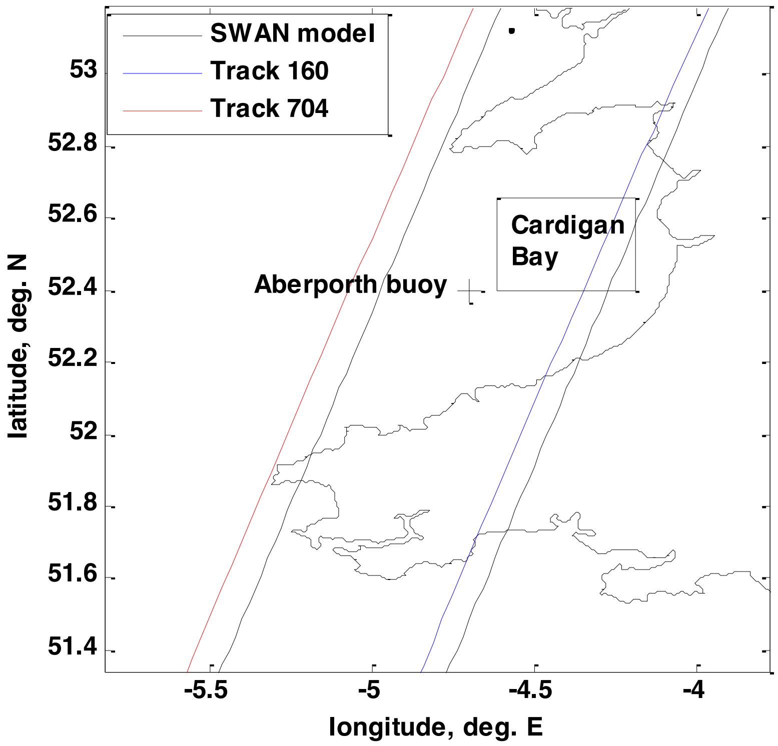

Figure 7: Model and altimeter tracks in Cardigan Bay

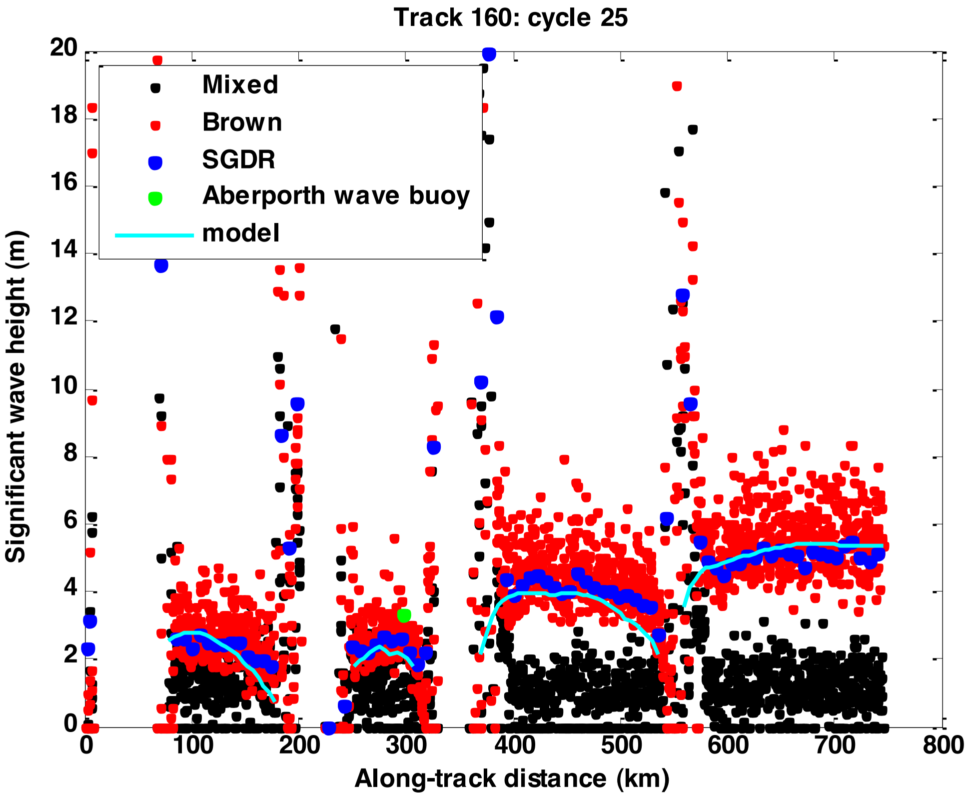

Figure A1: Model-altimeter comparisons for track 160 (14 March 2004)

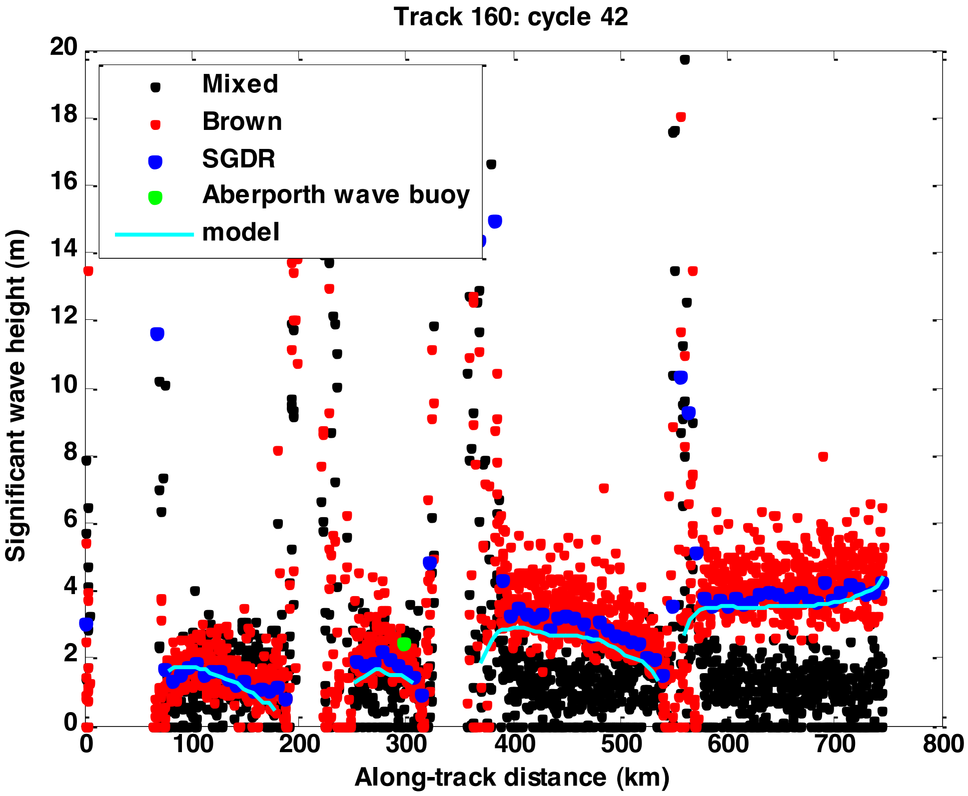

Figure A2: Model-altimeter comparisons for track 160 (30 October 2005)

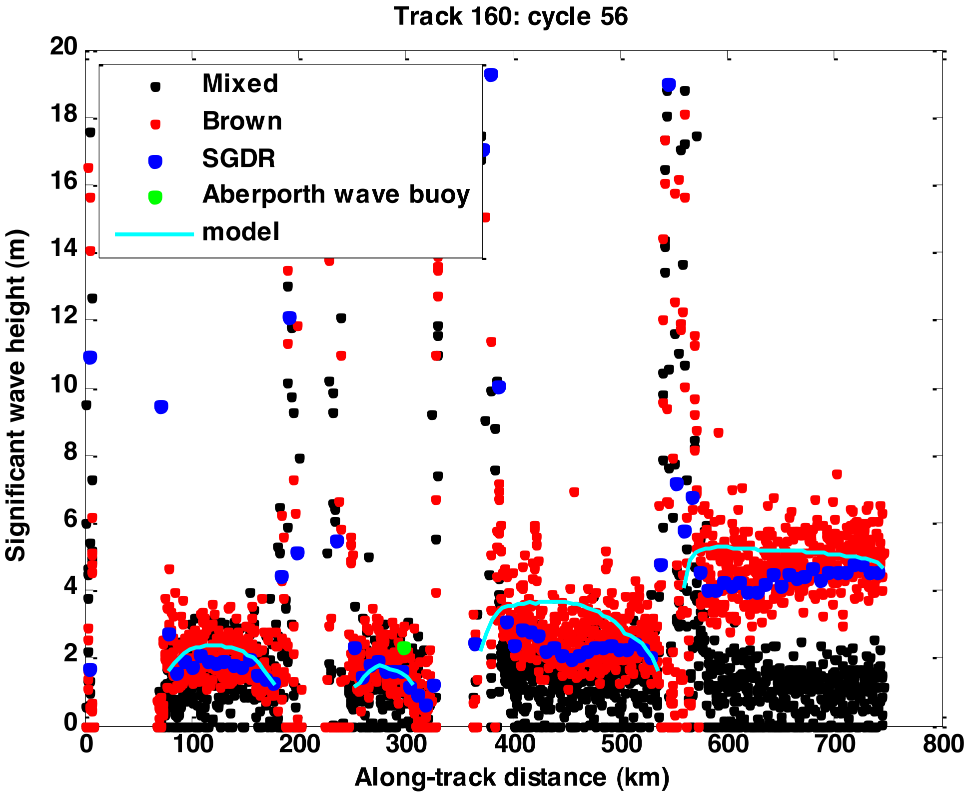

Figure A3: Model-altimeter comparisons for track 160 (4 March 2007)

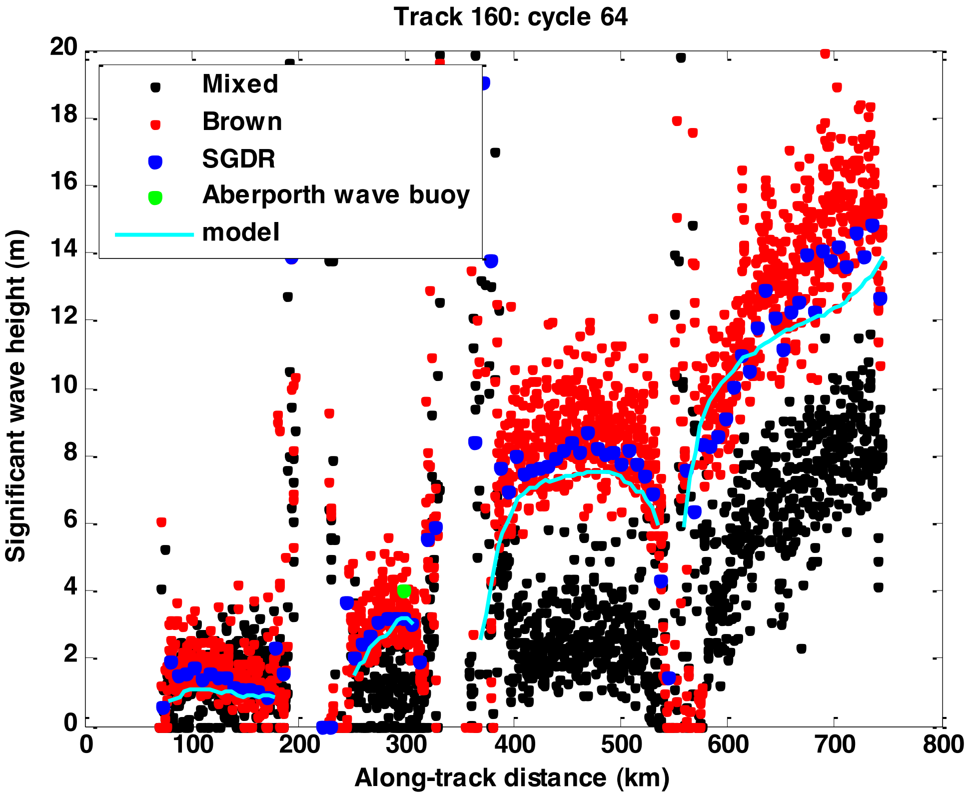

Figure A4: Model-altimeter comparisons for track 160 (9 December 2007)

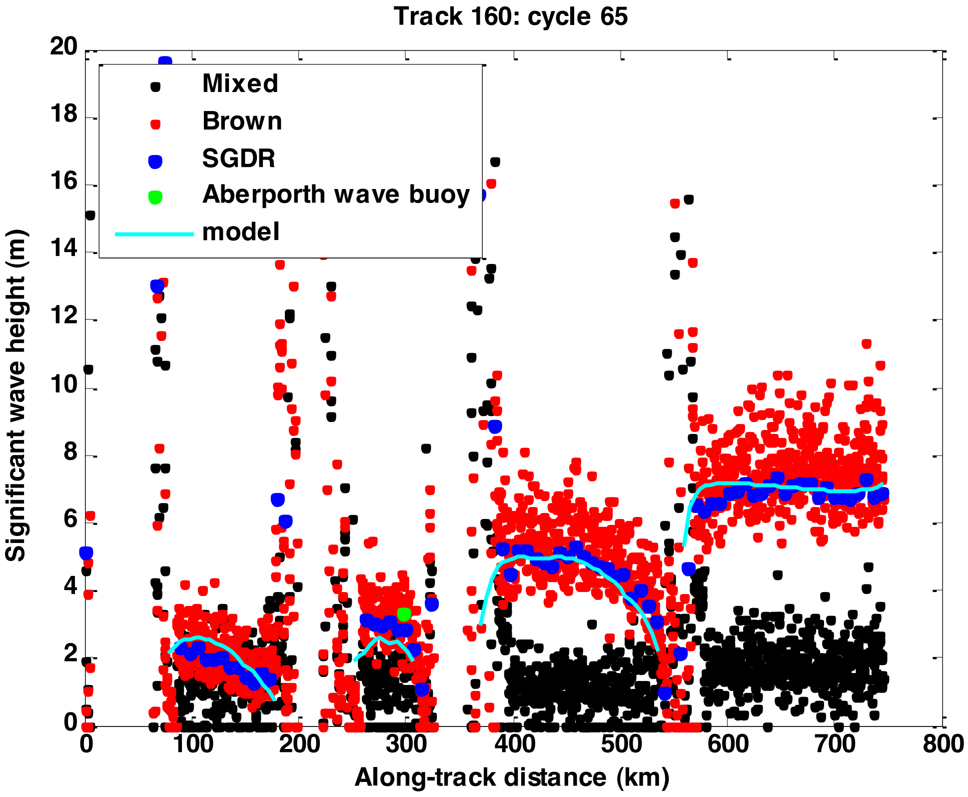

Figure A5: Model-altimeter comparisons for track 160 (13 January 2008)

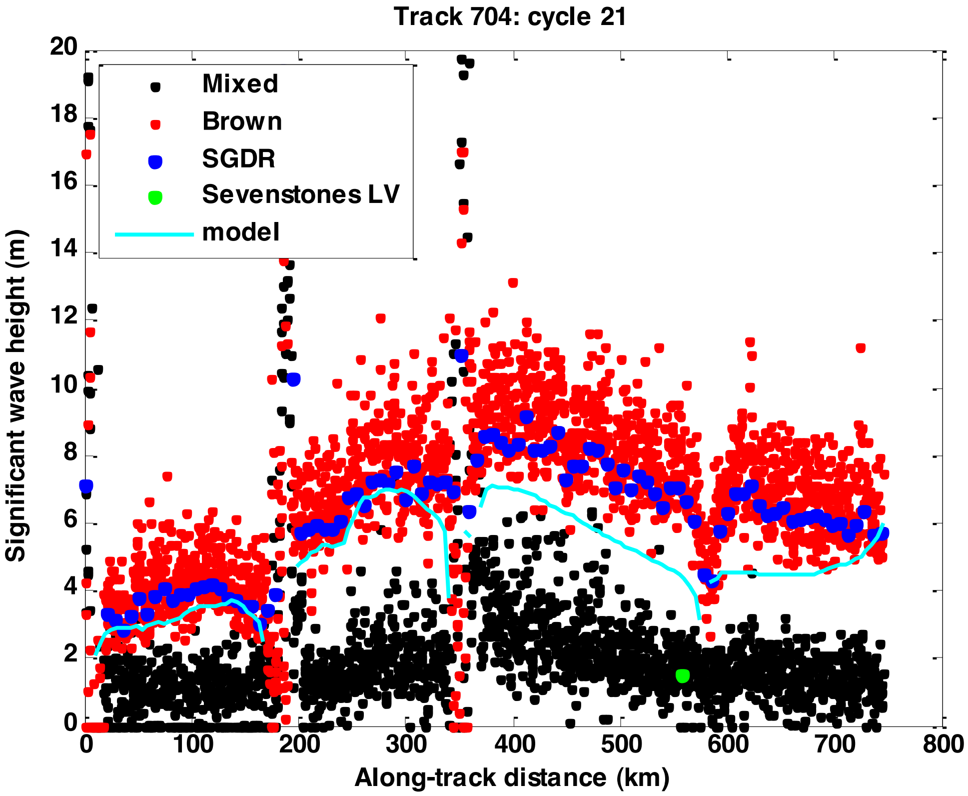

Figure B1: Model-altimeter comparisons for track 704 (14 November 2003)

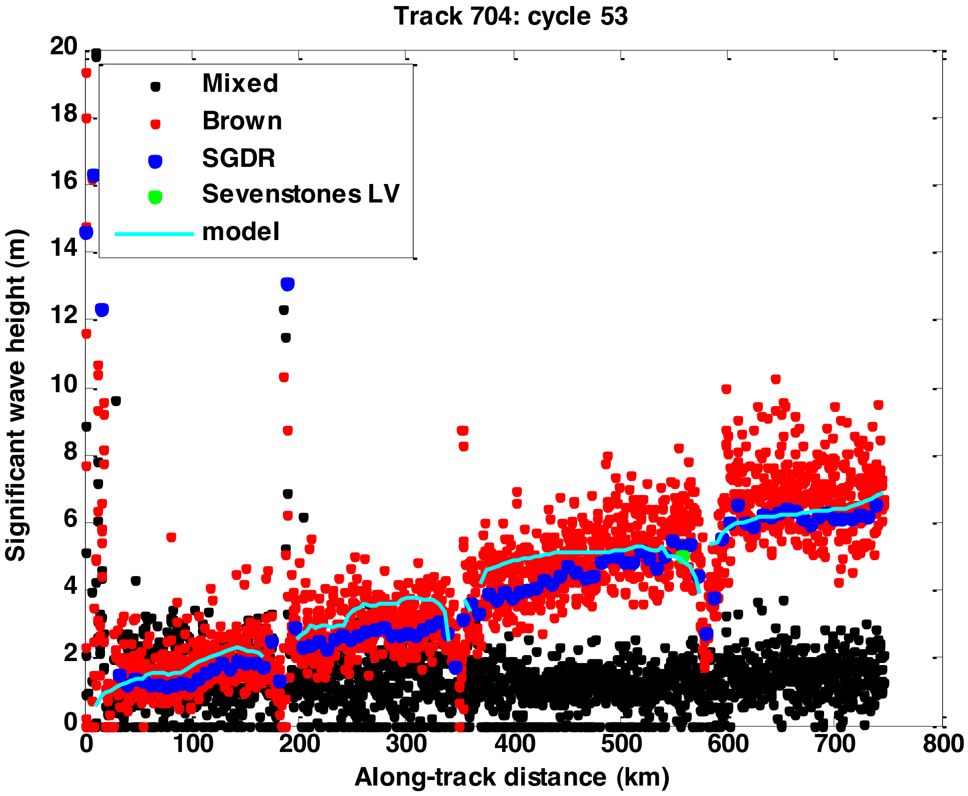

Figure B2: Model-altimeter comparisons for track 704 (8 December 2006)

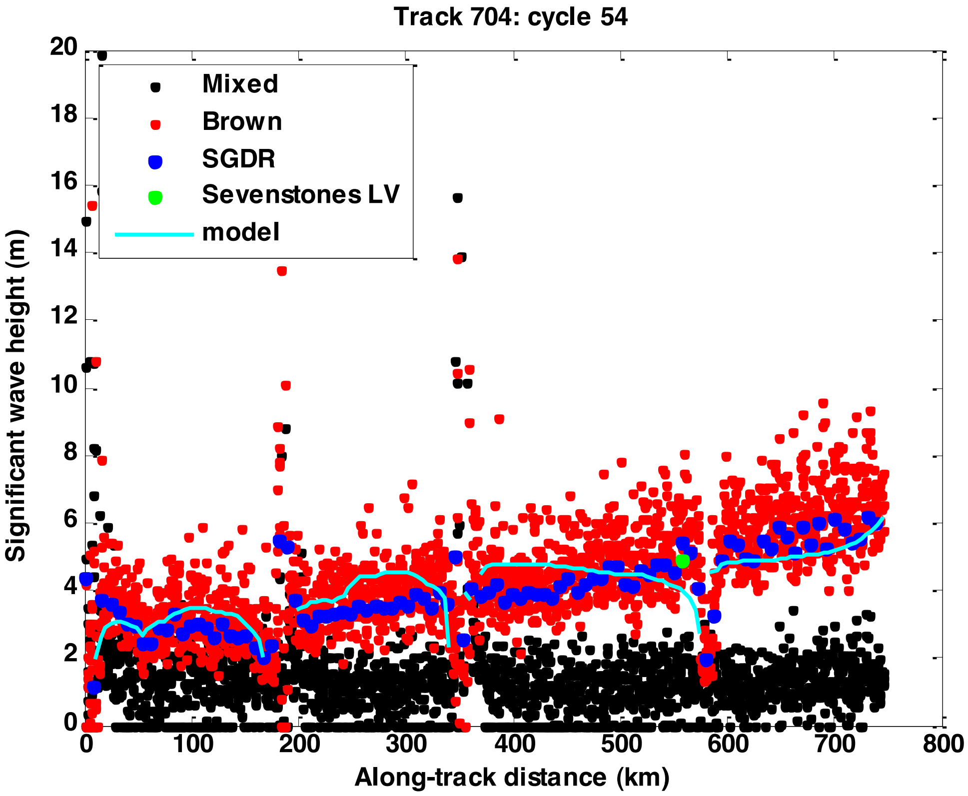

Figure B3: Model-altimeter comparisons for track 704 (12 January 2007)

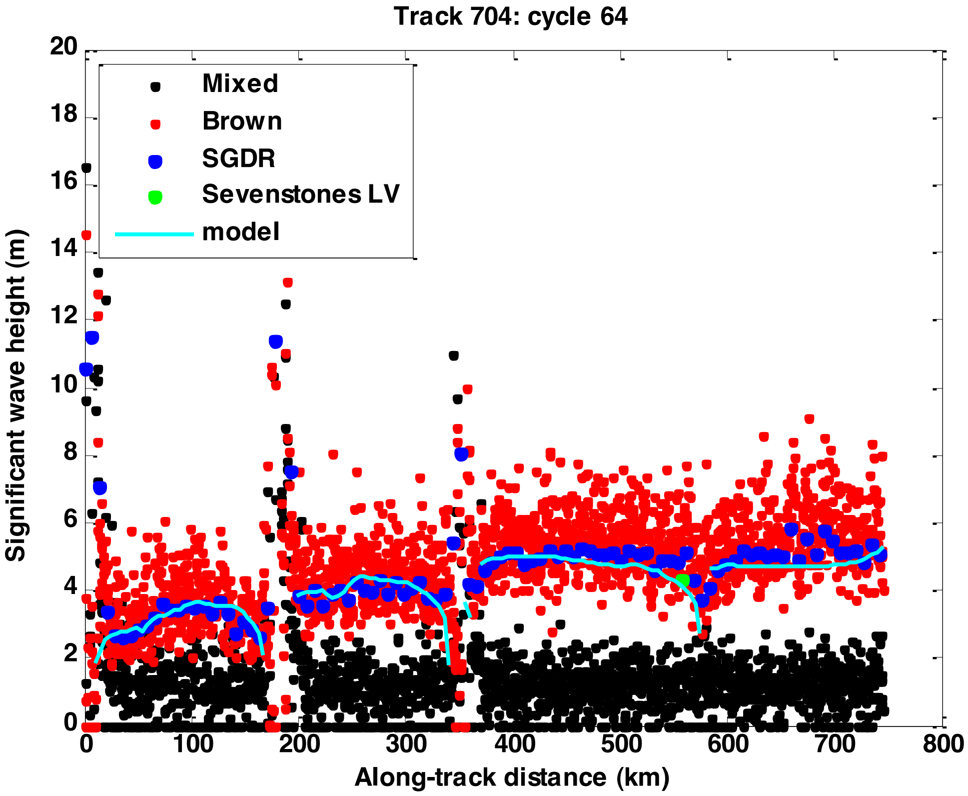

Figure B4: Model-altimeter comparisons for track 704 (28 December 2007)

Table 1: Effective footprint diameter of altimeter (after Chelton et al., 1989)

	Effective footprint diameter (km)	
H_s (m)	ERS-1/2, Envisat (800 km altitude)	Topex, Jason-1/2 (1335 km altitude)
0	1.6	2.0
1	2.9	3.6
3	4.4	5.5
5	5.6	6.9
10	7.7	9.6
15	9.4	11.7
20	10.8	13.4

Table 2: Observed significant wave height for satellite tracks 160 and 704. The first column gives the date/time of the start of each cycle. The fourth and final columns, respectively, give the wave height at Aberporth wave buoy and Seven Stones LV at the time corresponding to the altimeter pass. Cycles highlighted in bold have corresponding model runs, with 5 cycles selected for track 160 and 4 for track 704. The third column gives the wave height at 48.5N extracted for use in model boundary conditions.

Cycle	**Track 160**			**Track 704**		
	Date/time (start)	**48.5N**	**Aberporth**	**Date/time (start)**	**48.5N**	**Seven Stones**
10	06/10/2002 11:01	1.2	0.5	25/10/2002 11:04	3.2	2.3
11	10/11/2002 11:01	3.0	1.5	29/11/2002 11:04	6.1	4.0
12	15/12/2002 11:01	2.7	1.0	03/01/2003 11:04	3.5	2.3
13	19/01/2003 11:01	5.3	1.5	07/02/2003 11:04	3.3	1.5
14	23/02/2003 11:01	3.1	1.0	14/03/2003 11:04	2.9	2.2
15				18/04/2003 11:04	2.6	2.0
16	04/05/2003 11:01	2.4	1.5	23/05/2003 11:04	2.5	2.7
17	08/06/2003 11:01	2.3	1.0	27/06/2003 11:04	2.2	1.5
18	13/07/2003	0.9	0.5			

	11:01					
19	17/08/2003 11:01	1.0	0.5			
20	21/09/2003 11:01	1.9				
21	26/10/2003 11:01	1.9	1.0	**14/11/2003 11:04**	**5.7**	**6.0**
22	30/11/2003 11:01	2.6	1.4	19/12/2003 11:04	2.1	1.5
23	04/01/2004 11:01	1.9	0.8	23/01/2004 11:04	2.7	3.8
24	08/02/2004 11:01	2.8	3.1	27/02/2004 11:04	4.3	5.4
25	**14/03/2004 11:01**	**5.1**	**3.3**	02/04/2004 11:04	4.6	2.7
26	18/04/2004 11:01	4.1	1.2	07/05/2004 11:04	2.4	1.7
27	23/05/2004 11:01	1.6	0.3	11/06/2004 11:04	1.6	
28	27/06/2004 11:01	3.1	1.3	16/07/2004 11:04	1.4	
29	01/08/2004 11:01	1.5	0.5	20/08/2004 11:04	2.6	
30	05/09/2004 11:01	2.1	0.8	24/09/2004 11:04	1.6	
31	10/10/2004 11:01	3.7	1.3	29/10/2004 11:04	4.1	
32	14/11/2004 11:01	1.8	0.7	03/12/2004 11:04	1.6	
33	19/12/2004 11:03	4.5	1.6	07/01/2005 11:04	4.7	4.0
34	23/01/2005 11:01	4.3	1.1	11/02/2005 11:04	4.6	2.7
35	27/02/2005 11:01	3.0	0.6			
36	03/04/2005 11:01	1.7	0.8	22/04/2005 11:04	2.0	1.8
37	08/05/2005 11:01	1.2	1.3	27/05/2005 11:04	1.5	1.0
38	12/06/2005 11:01	1.0	0.7	01/07/2005 11:04	2.7	1.7
39	17/07/2005 11:01	1.0	0.3	05/08/2005 11:04	2.5	3.1
40	21/08/2005 11:01	1.4	0.4	09/09/2005 11:04	1.7	1.0
41	25/09/2005 11:01	2.6	1.9	14/10/2005 11:04	1.1	
42	**30/10/2005 11:01**	**4.2**	**2.4**	18/11/2005 11:04	1.9	1.5
43	04/12/2005 11:01	3.1	1.7	23/12/2005 11:04	1.6	1.7
44	08/01/2006 11:01	1.8	0.7	27/01/2006 11:04	3.2	1.4
45	12/02/2006	1.4	1.8	03/03/2006 11:04	4.2	2.7

	11:01					
46	19/03/2006 11:01	4.0	1.1			
47	23/04/2006 11:01	1.3	1.0	12/05/2006 11:04	0.9	0.4
48						
49	02/07/2006 11:01	1.2	0.5	21/07/2006 11:04	1.4	0.9
50	06/08/2006 11:01	1.2	0.7	25/08/2006 11:04	2.1	0.6
51				29/09/2006 11:04	2.2	1.4
52	15/10/2006 11:01	2.5	1.2	03/11/2006 11:04	2.6	0.9
53	19/11/2006 11:01	2.1	1.4	**08/12/2006 11:04**	**6.5**	**5.0**
54	24/12/2006 11:01	2.2	1.0	**12/01/2007 11:04**	**6.0**	**4.9**
55	28/01/2007 11:01	1.0	1.6			
56	**04/03/2007 11:01**	**4.5**	**2.3**	23/03/2007 11:04	1.6	1.1
57	08/04/2007 11:01	1.3	0.5	27/04/2007 11:04	2.2	1.3
58	13/05/2007 11:01	3.3	0.9	01/06/2007 11:04	2.4	1.6
59	17/06/2007 11:01	0.9	0.5	06/07/2007 11:04	3.1	3.0
60	22/07/2007 11:01	1.1	0.4	10/08/2007 11:04	1.2	1.4
61	26/08/2007 11:01	1.4	1.0	14/09/2007 11:04	1.0	0.6
62	30/09/2007 11:01	1.5	0.6	23/11/2007 11:04		
63	04/11/2007 11:01	1.7	0.4	23/03/2007 11:04	2.3	1.9
64	**09/12/2007 11:01**	**12.7**	**4.0**	**28/12/2007 11:04**	**5.1**	**4.3**
65	**13/01/2008 11:01**	**6.9**	**3.3**	01/02/2008 11:04	4.5	3.2
66	17/02/2008 11:01	2.1		07/03/2008 11:04	4.0	3.3
67	23/03/2008 11:01	2.6		11/04/2008 11:04	5.5	4.0
68	27/04/2008 11:01	2.0		16/05/2008 11:04	0.8	0.6

Table 3: Errors in altimeter data

	Seven Stones			**Aberporth**		
All data	**SGDR**	**Brown**	**Mixed**	**SGDR**	**Brown**	**Mixed**
Mean bias (m)	0.40	0.88	-1.04	0.03	0.93	0.27

RMS (m)	1.46	2.11	1.85	0.81	3.29	1.04
Correlation	0.49	0.25	-0.31	0.52	-0.01	-0.07
Remainder after outliers removed	41/44	39/44	37/44	49/52	46/52	44/52
Mean bias (m)	0.46	0.52	-0.54	-0.15	0.08	0.38
RMS (m)	1.01	1.10	1.17	0.39	0.44	0.62
Correlation	0.75	0.71	-0.21	0.90	0.65	0.32

Annex V: Figures (West Mediterranean)

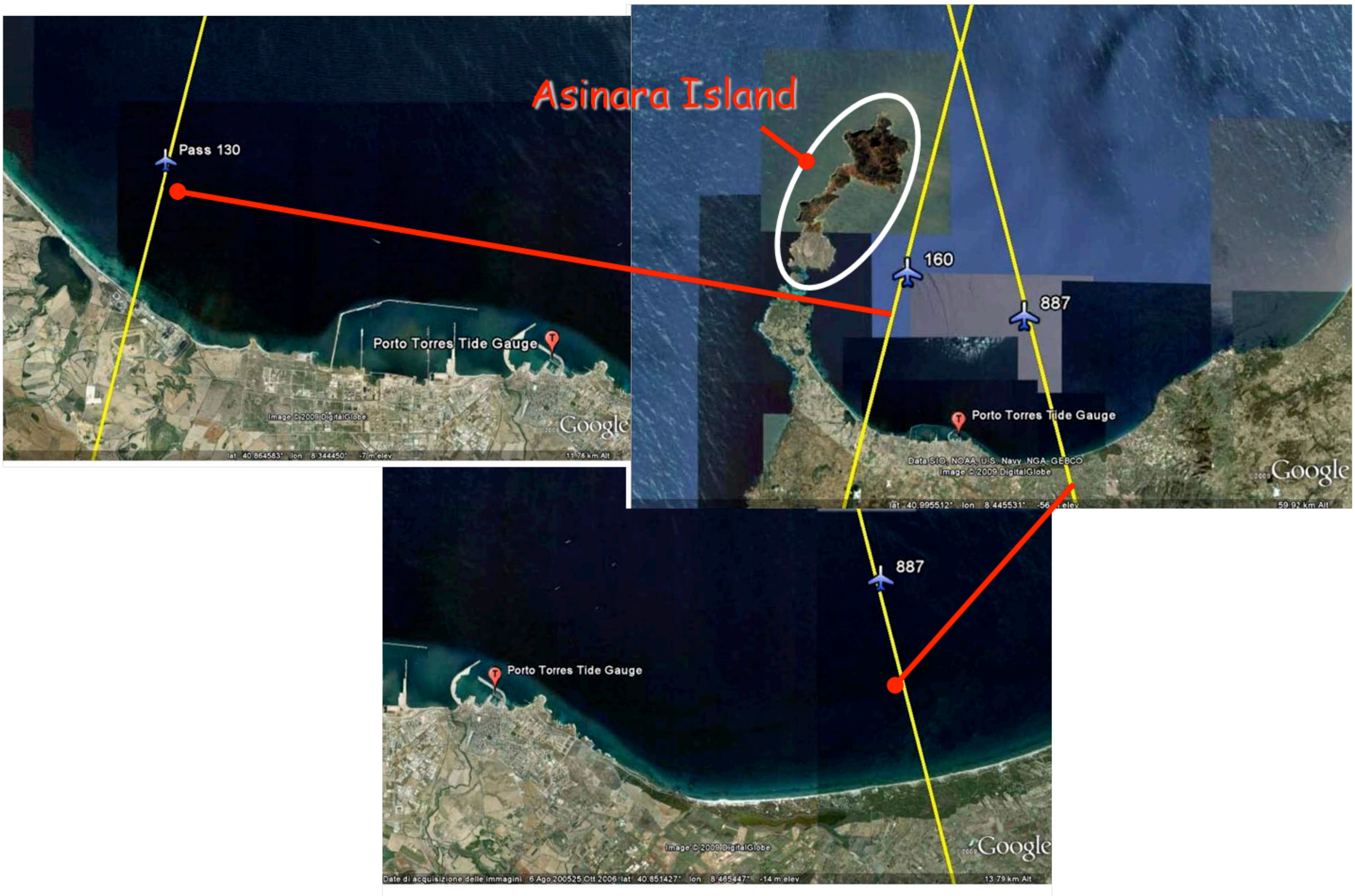

Figure 1: Study area showing location of the tide gauge and Envisat passes 160 and 887

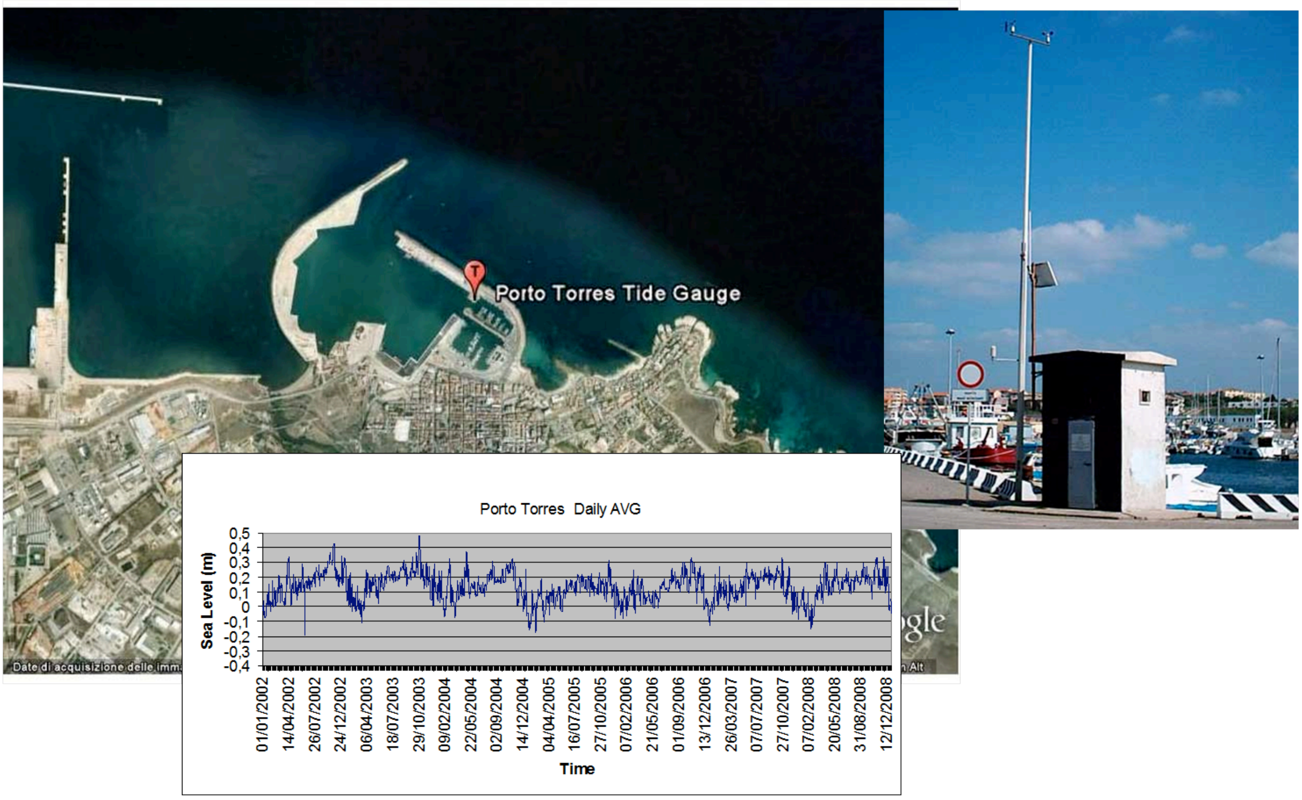

Figure 2: Tide gauge station and sea level time series

Figure 3: A zoom near tide gauge

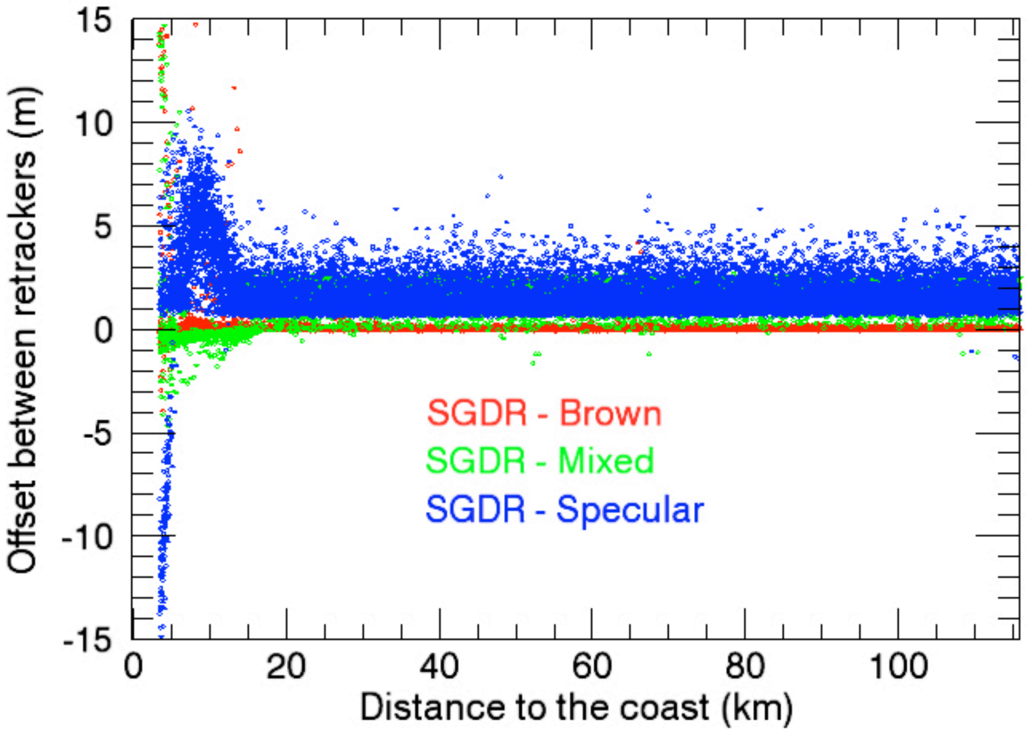

Figure 4: Off-set between retrackers as a function of distance to the coast

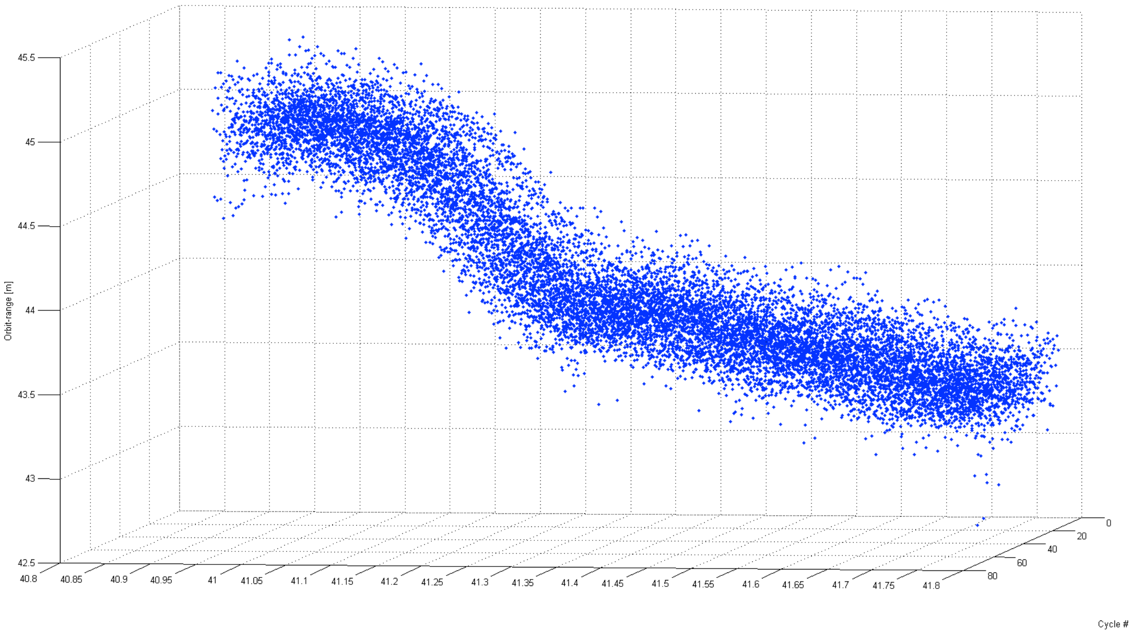

Figure 5: Orbit minus range (SGDR) – Pass 887

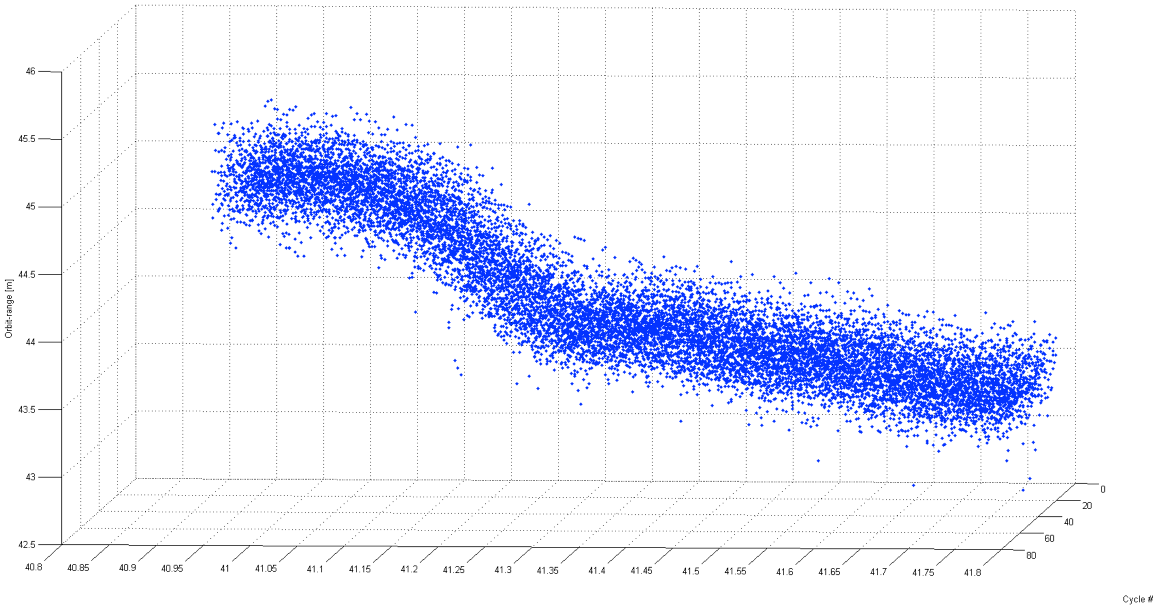

Figure 6: Orbit minus range (ICE) – Pass 887

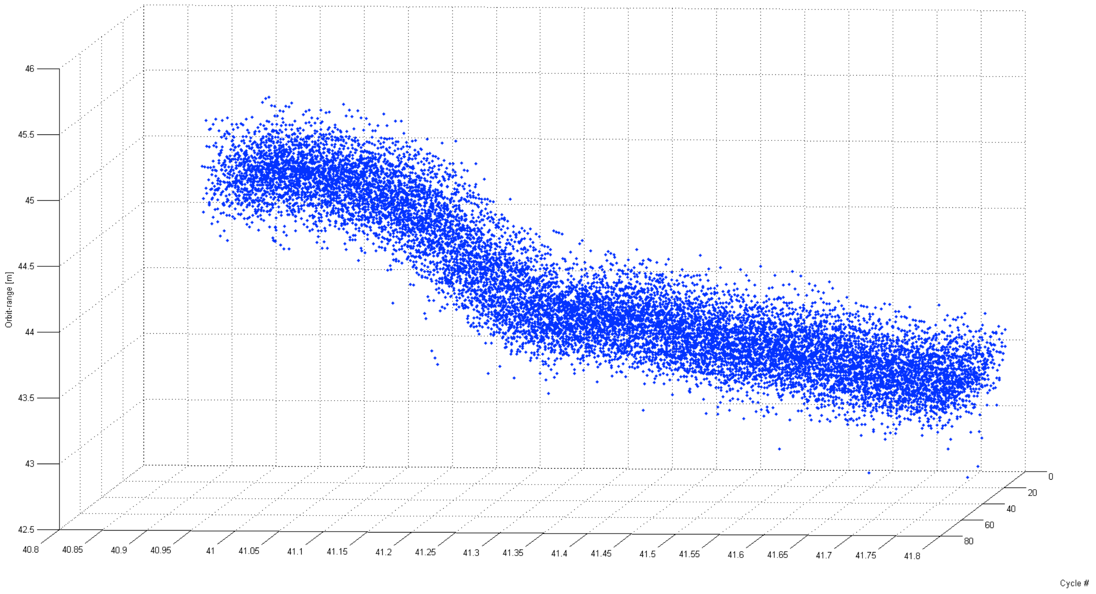

Figure 7: Orbit minus range (Brown) – Pass 887

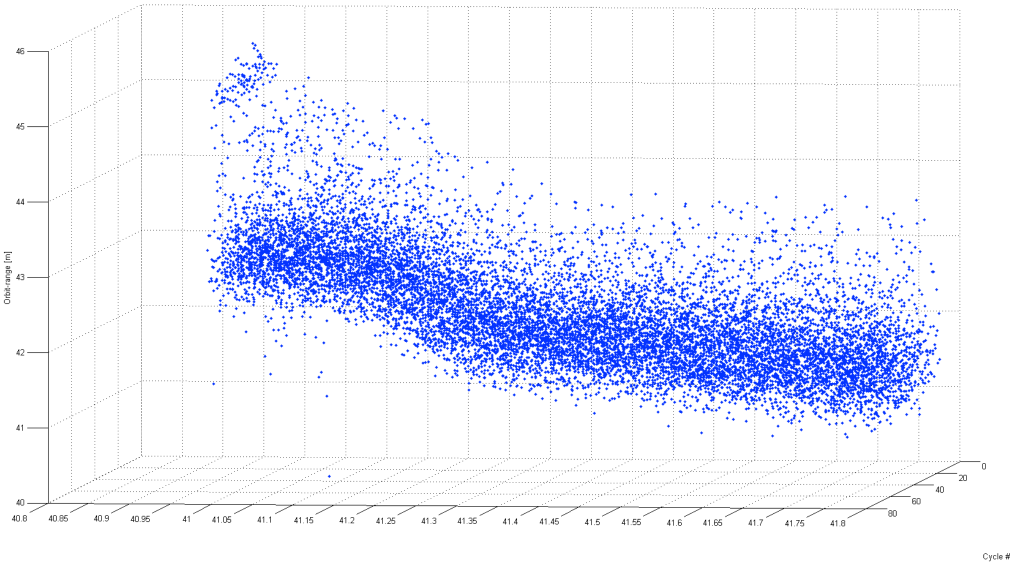

Figure 8: Orbit minus range (Mixed) – Pass 887

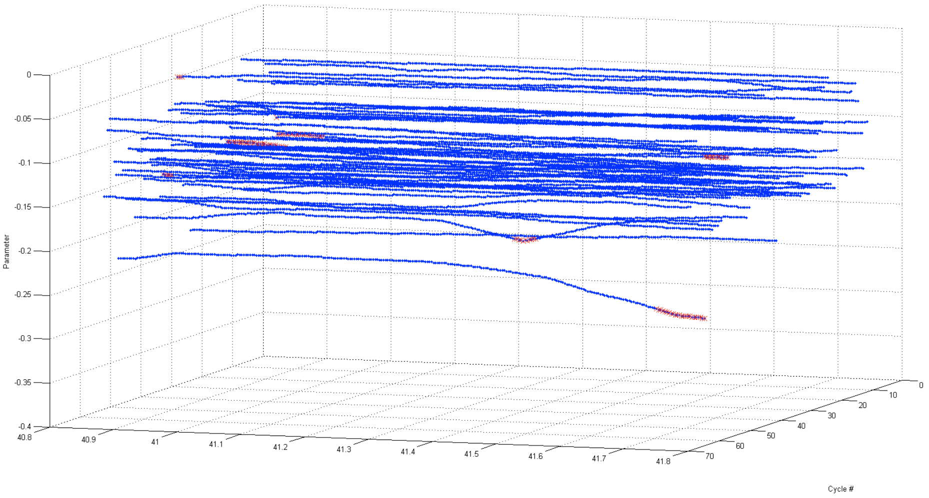

Figure 9: Wet tropospheric correction (DLM) – Pass 887

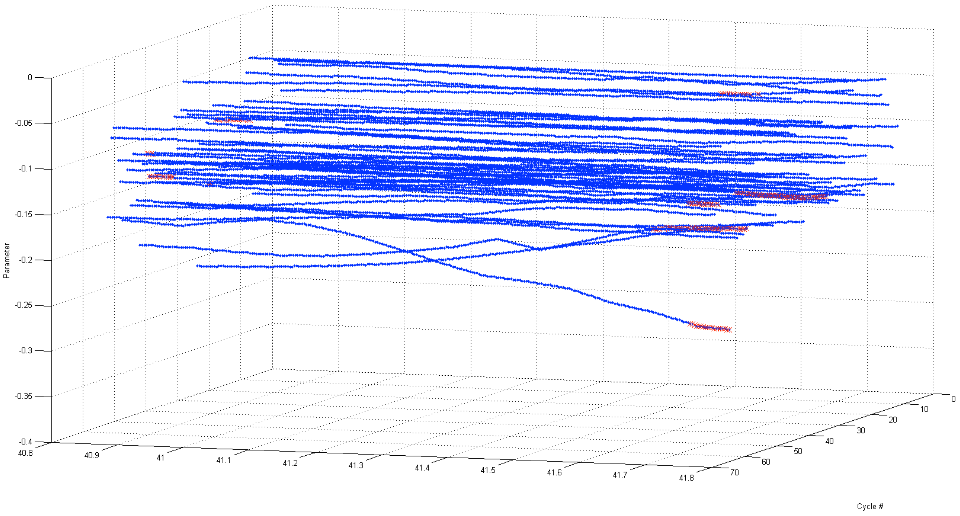

Figure 10: Wet tropospheric correction (GPD) – Pass 887

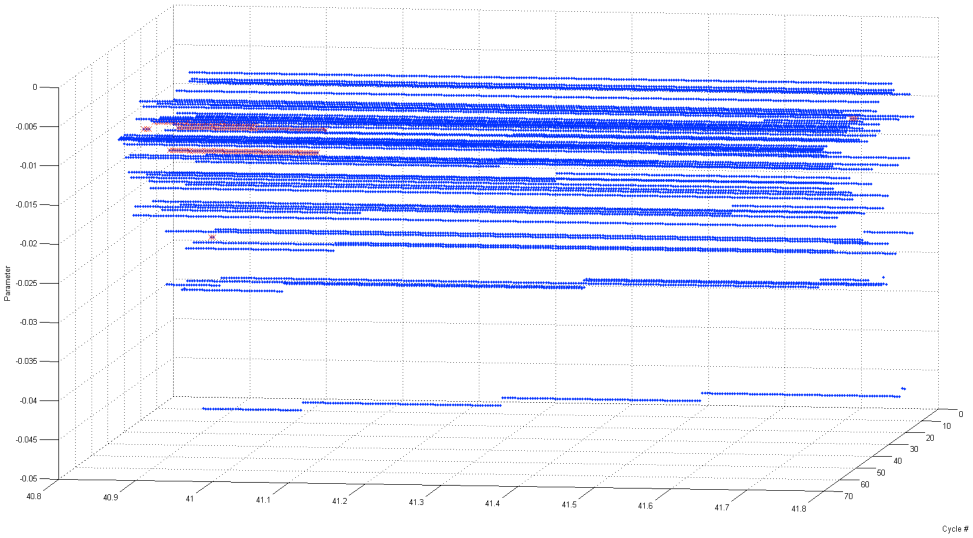

Figure 11: Ionospheric correction (DORIS) – Pass 887

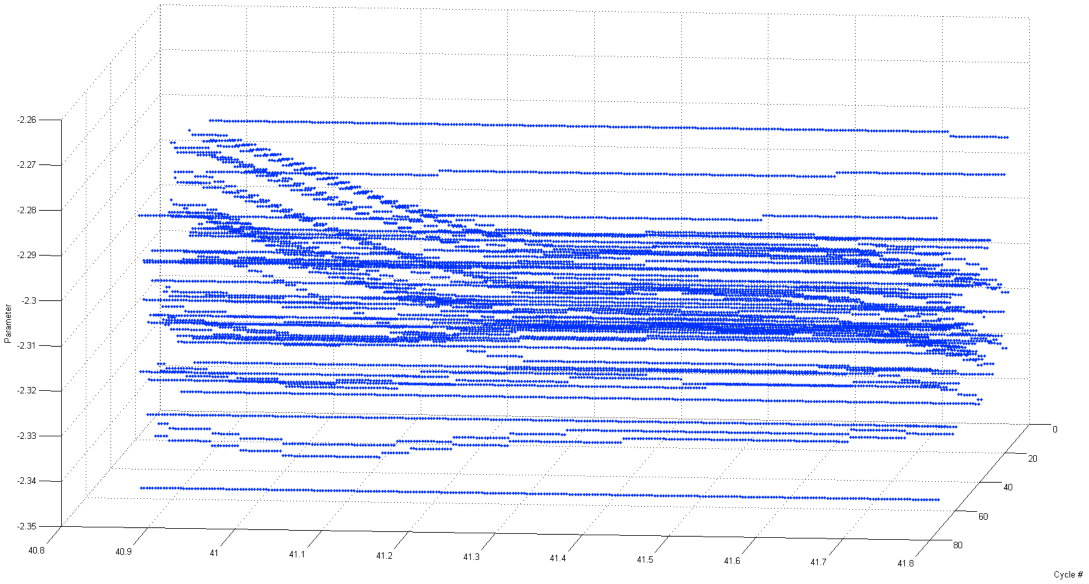

Figure 12: Dry tropospheric correction (ECMWF) – Pass 887

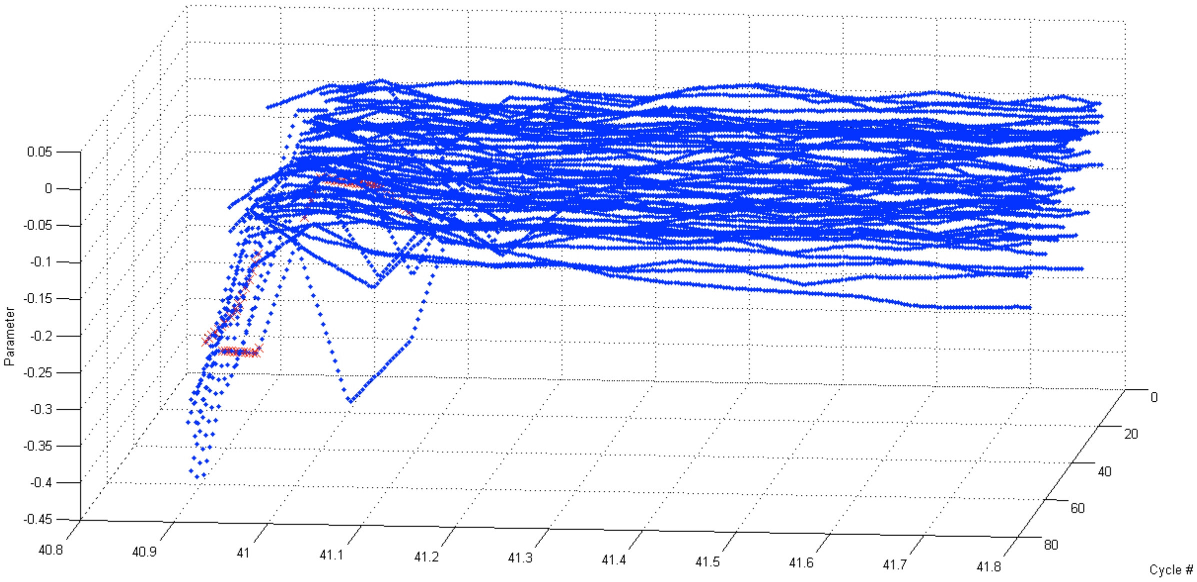

Figure 13: SSB – Pass 887

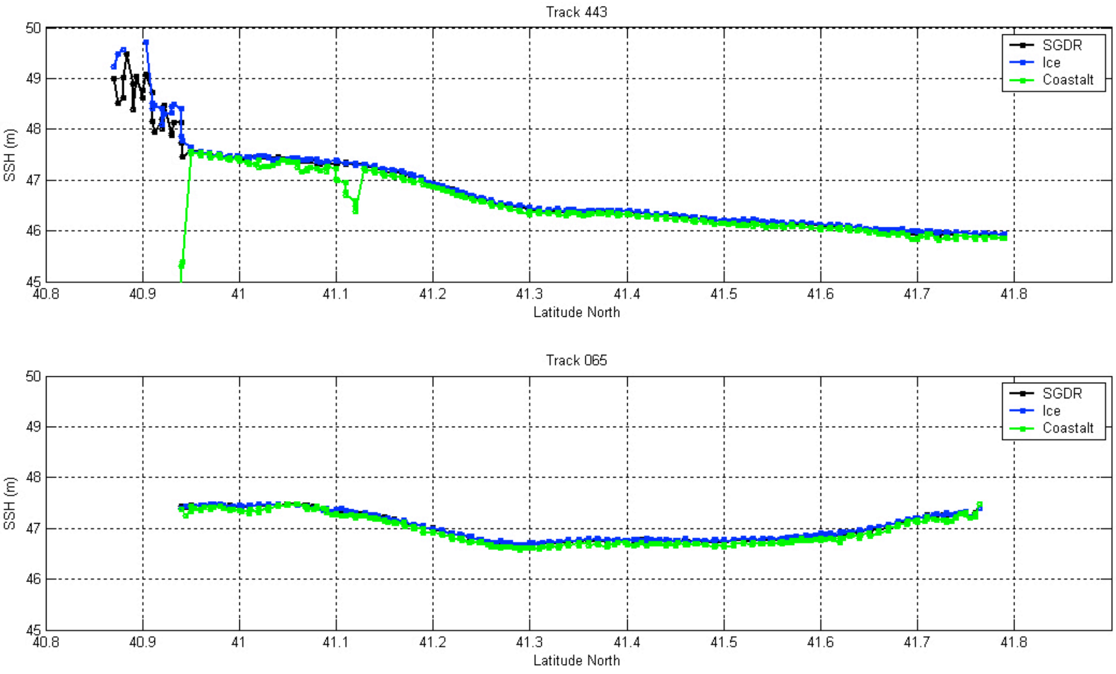

Figure 14: Averaged SSH corrected for SGDR (black), Ice (bleu) and Brown (green) – Pass 887 (track 443) and pass 130 (track 065)

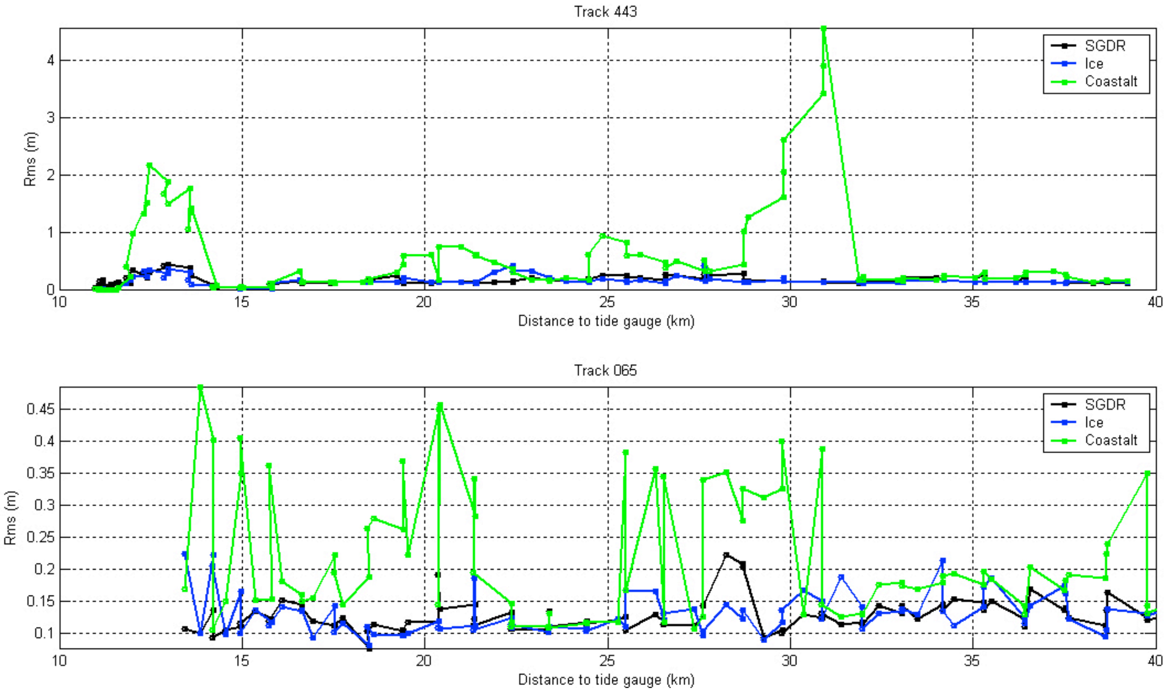

Figure 15: Rms of the difference between SSH corrected for SGDR (black), Ice (bleu) and Brown (green) and sea level observed at tide gauge – Pass 887 (track 443) and pass 130 (track 065)

Annex VI: Figures & Tables (Gulf of Cadiz)

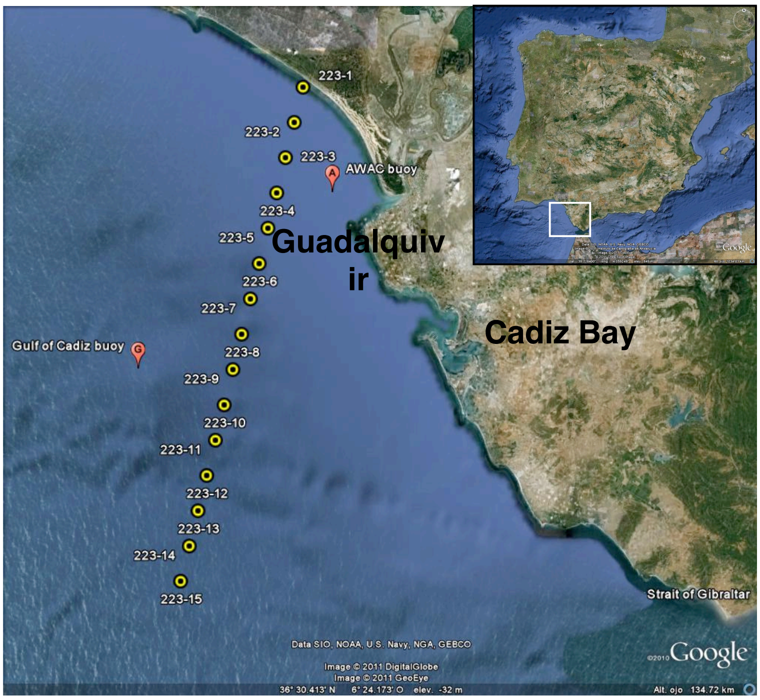

Figure 1: Location of the study area showing the descending altimetric track 223 and the AWAC (A) and Gulf of Cadiz (G) coastal buoys. Ground tracks are depicted with yellow dots indicating the position of the 1 Hz measurements (Google Earth copyright).

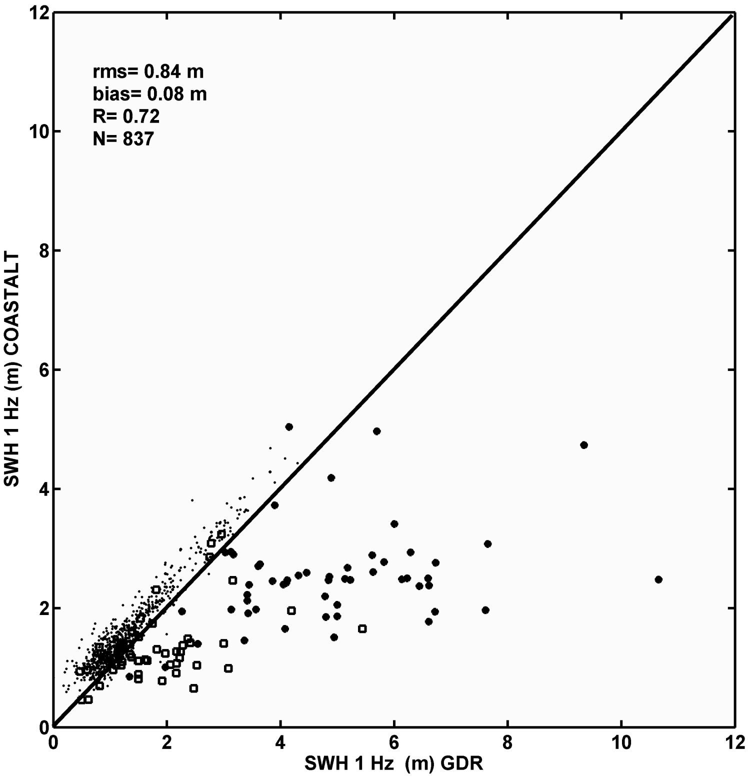

Figure 2: Comparison of significant wave height values at 1 Hz frequency measured by the ENVISAT RA-2 altimeter from the Geophysical Data Records (GDRs) and from the COASTALT project. Large dots indicated 1Hz track point 1, squares the 1Hz track point 2 and small dots the rest of the 1Hz points from 3 to 15. Regression results are included in the figure.

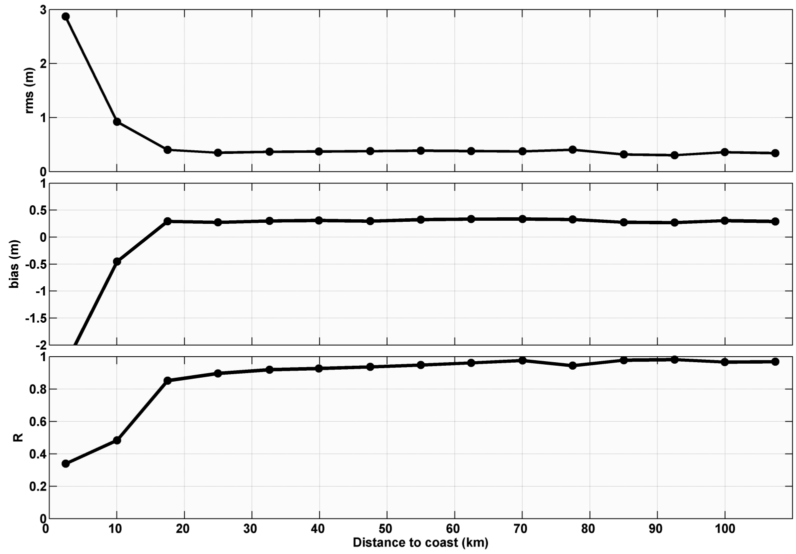

Figure 3: Statistics (rms, bias and R) of the comparison of GDR and COASTALT significant wave height 1 Hz products with respect to the distance to coast. Track points are indicated with dots.

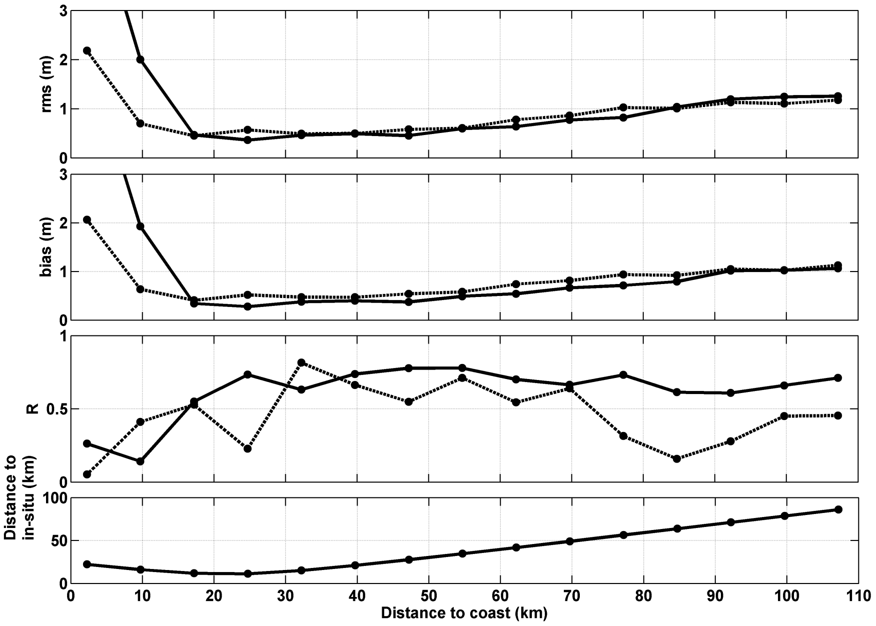

Figure 4: Statistics (rms, bias and R) resulting of the validation of significant wave height from the altimeter products against in-situ observations from the AWAC coastal buoy with respect to the distance to coast. Continues lines correspond to GDR datasets and dashed lines to COASTAL records. The distance to in-situ emplacement of each track point in the bottom of the plot.

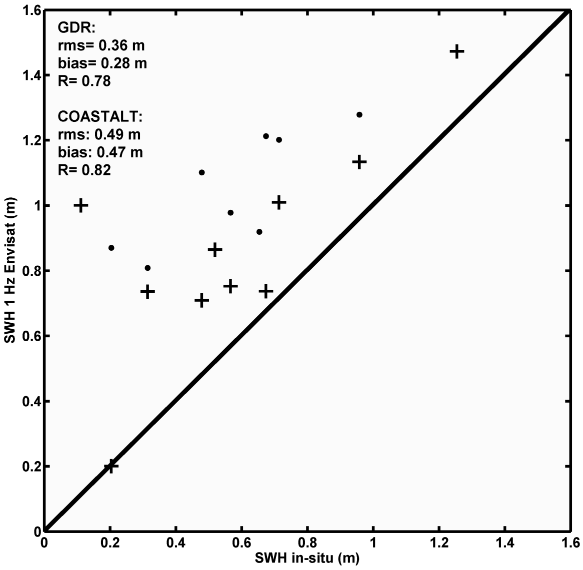

Figure 5: Comparison of significant wave height records from the AWAC coastal buoy versus altimeter 1Hz of the track point 4 from the GDR data streams (dots) and of the track point 5 from COASTALT measurements (crosses).

Table 1: Specific features of the in-situ datasets used in this study.

Station name	Coordinates (Lat/Lon)	Temporal coverage	Variable	Network	Time record (min)
Gulf of Cadiz Buoy	36°28'37.20"N/6°57'46.80"W	1997-2010	SWH	OPPE	60
AWAC moored	36°48'6.48"N/6°30'56.16"W	2008-2009	SWH	ICMAN-CSIC	60

Annex VII: Software

This toolbox was developed in the software MATLAB 7.0.1. We used the GUIDE graphical tools to build a user-friendly interface to be used for selection of ranges and corrections. The Matlab and IDL source code is maintained at COASTALT web site under directory /utilities/validation

file_for_sv_cinco_v20_rev66.pro – to colocate data
LoadCoastalTxt.m – To load ASCII files
LoadGaugeTxt.m – To load tide gauge files
PLTAlongTrack.m - (To visualize data along track)
PLTvsTIME.m - To visualize data along cycle
PLTvsTIME3D.m - To visualize and clean data along track and cycle
PLTGaugeVsRange.m – to compare data

Functions:
Plotal.m
GUIRangeSel.m
GUICorrSel.m

Other code:
PLTGauge.m
NETCDF2MAT01.m
retrack01.m

Annex VIII: List of acronyms

ASCII - American Standard Code for Information Interchange
AWAC-AST – Acoustic WAve and Current – Acoustic Surface Tracking
BRAT - Basic Radar Altimetry Toolbox
CEFAS - Centre for Environment, Fisheries and Aquaculture Science
CGDR – Coastal Geophysical Data Record
CMA - Multimission Altimetry Center
DEM – Digital Elevation Model
DLM - Dynamically Linked Model
DORIS – Doppler Orbit and Radio Positioning Integration by Satellite
ECMWF – European Center for Medium-Range Weather Forecasting
ERS – European Remote Satellite
EWP – Extended Work Package
GDR – Geophysical Data Record
FES - Finite Element Solution
GIM - Global Ionosphere Map
GOT – Goddard Ocean Tide
GPD - GNSS-derived Path Delay
IB – Ionospheric Barometric
ICMAN-CSIC - Instituto de Ciencias Marinas de Andalucia-Spanish National Research Council
IDL – Interactive Data Language
GPS – Global Positioning System
MWR – Micro Wave Radiometer
NE – North East
NOC – National Oceanography Center
NOOS - North West Shelf Operational Oceanographic System
OPPE - Organismo Publico de Puertos del Estado
POL – Proudman Oceanographic Laboratory
RA – Radar Altimetry
RADS - Radar Altimeter Database System
RMS – Root Mean Square
SGDR – Sensor Geophysical Data Record
SGDR – Sensor Geophysical Data Record
SLA – Sea Level Anomaly
SSB – Sea State Bias
SSB – Sea State Bias

SSH - Sea Surface Height
SSHA - SSH Anomaly
SW – South West
SWAN - Simulating WAves Nearshore
SWAAN – Surface WAves ANalysis
SWH – Significant Wave Height
USO - Ultra Stable Oscillator
WITM – West Iberia Tide Model