# Coastal Satellite Altimetry – Methods for Data Recovery and Validation

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## Abstract

This study addresses the problem of satellite altimetry data improvement near the shoreline. Methodologies for satellite altimetry data processing near the coast have been developed, leading to a significant percentage of recovered data.

The major land effects on ERS, Topex/Poseidon and Geosat data have been analysed. These data were processed using state-of-the art models for the geophysical corrections. The behaviour of the range measurement and each of the geophysical corrections in several ocean-land-ocean typical transition zones have been examined. Algorithms for the improvement of the corresponding altimeter products in coastal zones have been developed and applied to data. For the resulting products, the major remaining error is due to the ocean tide correction provided by the global model used, which can only be improved by local tidal modelling.

This paper presents a brief summary of the algorithms implemented for each satellite.

Derived products from recovered data are compared with the most recent global models of mean sea surface and gravity anomalies.

The topic of data validation is also addressed. Getting independent data for validation purposes is a major difficulty. Various adopted and proposed validation methods are presented, together with the benefits and weakness of each method.

**Keywords.** Altimetry, coastal zones, gravity anomalies

## 1. Introduction

At present, there is a vast set of satellite altimeter data avilable, from various satellites (Geosat, ERS, Topex/Poseidon, GFO, Jason and Envisat). These data have been playing a major role in the definition of the shape of the sea surface and the earth's gravity field.

These measurements have been mainly exploited in the open ocean. Close to the shoreline, data accuracy is degraded, due to the effects induced by land, both in the satellite measurement and in the modelling of some of the geophysical corrections applied to the measurements. The consequent rejection of possible valid points, limits the application of satellite altimetry in coastal regions.

The aim of this study is to implement methodologies to process satellite altimetry near the coast, aiming to recover the maximum number of measurements and improve the quality of derived altimetric products.

Previous studies have shown that the use of processing methodologies tuned for data recovery in island regions have advantages over the use of public domain altimeter data sets, Fernandes et al. (2000a), Fernandes and Antunes (2002).

## 2. Data analysis and methodology

### 2.1 Data used

The altimeter data analysed in this study comprise the following data sets:

- Geosat geodetic mission
- ERS-1: geodetic mission (phases E and F)
- 35-day repeat mission (phases C and G)
- ERS-2: Cycles 1 to 60
- Topex/Poseidon: Cycles 1 to 333

ERS data are the OPR02 precise geophysical products, provided by ESA. All analysed ERS 35-day data have been processed using OPR software version 6 (ESA, 1996). Available ERS-1 geodetic mission data have been processed using OPR software version 3 (ESA, 1994). Topex analysed data are the GDR-Ms products provided by AVISO (AVISO, 1996). Geosat geodetic mission data are the JGM-3 GDRs provided by NOAA, National

Oceanic and Atmospheric Administration, (NOAA, 1997) .

The total time span coved by these data is greater than ten years. This analysis has been centred in the Atlantic ocean region and surrounding island and continental land areas.

### 2.2 Land effects

The behaviour of the altimeter measurement and all of the geophysical corrections in the ocean-land-ocean transition zones have been studied, for all the mentioned altimeter missions. The main conclusions are summarised below.

The major land effect on ERS OPR data is caused by the wet tropospheric correction derived from the actual measurements made by the onboard microwave radiometer (radiometer wet correction - Wet_Rad). The corresponding effect on Topex/Poseidon is almost negligible. On Geosat this effect is not present, since there was no on-board radiometer and a model correction is used instead (NOAA, 1997).

The major correction that needs to be applied to the GDR-M Topex fields is the filtering of the ionospheric correction, computed from the dual frequency Topex measurements. Although this field is noisy, both over land and ocean, some additional outliers seem to be correlated with the land approximation.

Geosat major effect is on the significant wave height (SWH) and corresponding sea state bias (SSB) correction, which is a function of the SWH (NOAA, 1997). This effect may be caused by incorrect information on the land/sea boundary present in the Geosat GDRs.

### 2.3 Algorithms for data processing in coastal zones

Methodologies for data recovery and editing have been developed, aiming to minimise the above mentioned effects.

An algorithm for the correction of the radiometer wet tropospheric field (Wet_Rad) of ERS data has been developed and implemented (Fernandes and Bastos, 2002). The recovery of invalid measurements is based on two main types of algorithms:

– Interpolation procedures, whenever valid data exists on both sides of a zone of invalid measurements;
– Adjustment of the meteorological model for the wet tropospheric correction, to avoid data discontinuities, on the remaining cases.

This algorithm allows a recovery of 80% to 90% of the invalid measurements. Figure 1 shows the amount of rejection that would be obtained, in one ERS-2 cycle, in the region of Europe, if all measurements with invalid Wet_Rad were deleted. Figure 2 shows the effect of applying the FCUP algorithm to the same data set.

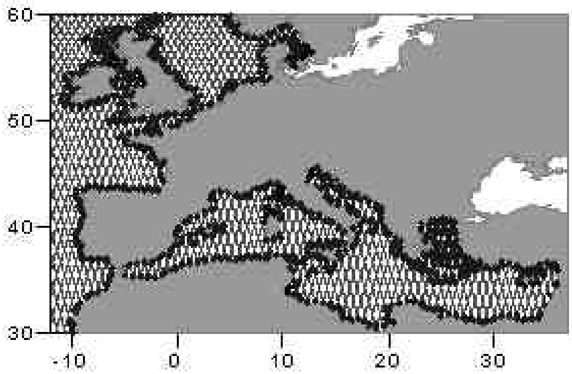


Fig. 1. Valid measurements (in grey) and points that would be rejected due to the WET_Rad correction (in black), for an ERS 35-day cycle, in the region of Europe.

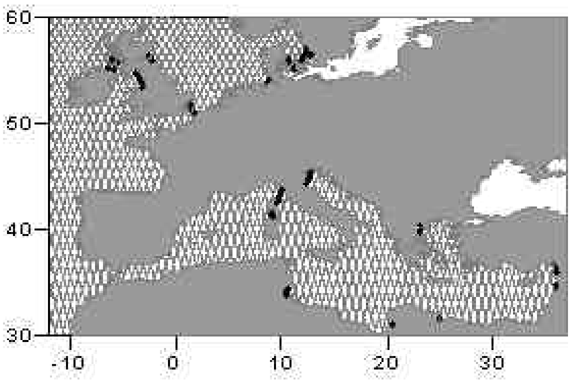


Fig. 2. Rejected points due to the WET_Rad field (in black), after application of the FCUP recovery algorithm, for the same data set shown in Fig. 1.

The Topex dual frequency ionospheric correction has been filtered using a second order Butherworth filter with a cut-off period of 20 sec. Prior to this, a median filter has been applied to remove gross outliers. The result of this filtering is similar to the procedure referred by Imel (1994), who used a 20 sec averaging window, with the advantage that the effects of discontinuities introduced by data gaps or land regions are minimised. This is achieved by separating the data into continuous segments and treating each segment using appropriate methodologies for minimising edge effects.

Table 1 presents the statistics of the differences between the original and filtered ionospheric correction field for one Topex cycle.

Figure 3 illustrates an example of the application of the filtering algorithm to a Topex track. To show the land location, the radiometer land flag is also represented. It can be shown that data smoothing is obtained, without any significant data loss in the edges of segments, including on coastal regions.

Figure 4 illustrates the SWH and SSB fields for a Geosat track crossing a land region. The land proximity causes outliers in these fields that need to be eliminated in the processing. These outliers were removed by applying a median filter to the SSB field.

For all data sets points over land and at distance to land below 5 km were removed.

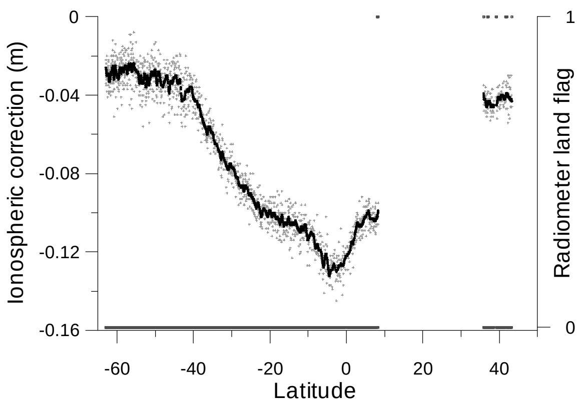


Figure 3 - Example of the filtering of the dual frequency ionospheric correction for Topex (grey points: original ionospheric correction; black points: filtered correction). In the right axis, the radiometer land flag is shown. Points with this flag equal to 1 are close to land.

## 3. Results and validation

By applying the described algorithms, corrected Sea Surface Heights (SSH) were generated for all data sets. From these corrected SSHs the following products were computed:

- T/P 10-day and ERS 35-day mean tracks, using collinear data;
- Filtered data from ERS-1 and Geosat geodetic missions.

From the above two data sets (collinear and geodetic) a mean sea surface (MSS) and a gravity anomalies (GANO) model have been derived. These models are referred as the FCUP models.

Data used in the computation of the MSS and GANO models:

- Geosat, geodetic mission
- ERS-1, geodetic mission
- ERS-1, 35 day, phase C (19 cycles)
- ERS-2, 35 day, cycles 1 - 52
- Topex/Poseidon, 10 day, cycles 21 to 315

The total time span of the data used in the MSS and GANO computation is approximately 10 years.

Table 1 – Statistics of the differences between the original and filtered ionospheric correction field for cycle 21 of Topex (metres).

| N. Pts | average | rms | min | max |
|---|---|---|---|---|
| 144192 | 0.000 | 0.006 | -0.027 | 0.033 |

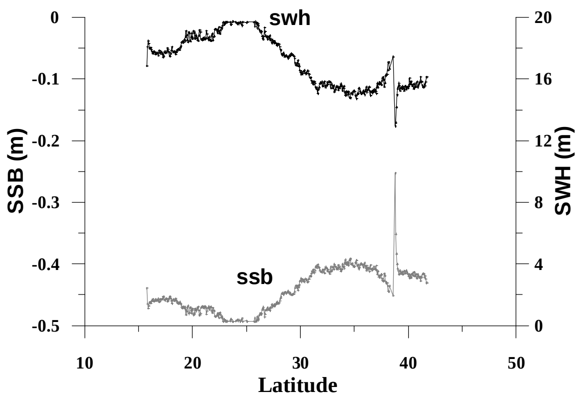


Figure 4 - Example of a Geosat track, showing a land effect on the significant wave height (SWH) field and sea state bias (SSB) correction.

In the computation of the MSS grid, the kriging method, implemented in the commercial software SURFER was used.

The gravity anomalies have been computed from the residual mean sea surface heights, relative to the high degree geopotential model GPM98C (Wenzel, 1998), using the remove-restore procedure, with the central step performed by Fast Fourier Transform (FFT) techniques. No residual terrain model correction has been applied.

After developing and applying the described algorithms, aiming to improve data accuracy and recovery in coastal regions, one important step is the validation of the results. This is a major task, since, in most regions of the world, no independent data are available to perform an adequate validation.

The validation of improved SSH and MSS model can be performed by comparison with the following data sets:

- Residual SSH of satellite data not used in the MSS solution;
- MSS global models, e.g.: GSFC00, Wang (2001); KMS2001, Andersen (2001); CLS_SHOM 98.2, Schaeffer et at (1998);
- Airborne altimetry;
- Regional geoid and oceanographic models;
- Tide gauge data.

The validation of the gravity anomalies can be done by using the following data sets:

- Airborne gravity obtained with dumped and strapdown systems;
- Marine gravity;
- Satellite derived global models of gravity anomalies, e.g.: GSFC00, Wang (2000); KMS2001, Andersen (2001).

At present, only some of these methods have been used. The results obtained, although preliminary, give some insight into the main achievements and problems to solve.

One test that has been performed was to compute the residual sea surface heights (SSH) of a set of Topex/Poseidon cycles (316 to 333) and a set of ERS-2 cycles (53 to 60) relative to the FCUP and three MSS global models (GSFC00, CLS_SHOM 98.2 and KMS2001), for a test area in the North Atlantic region (30º<φ<60º, -40º<λ<40º). These cycles have not been used in the computation of none of these models. The results are presented in tables 2 and 3. The statistics are presented for all points in this region and for points that are at a distance to land within the range from 5 km to 50 km.

The analysis of these results show that, for Topex/Poseidon, the FCUP model is very similar to the GSFC00 MSS, the other two models reveal larger residuals in this region. This result was somewhat expected, since, in the areas close to the Topex/Poseidon tracks, the information from this satellite dominates the final grid. Since the only improvement that has been performed on Topex/Poseidon data was the filtering of the ionospheric correction, which does not have a clear land contamination effect, this explains why the FCUP model has a performance close to the global models, along the Topex/Poseidon tracks.

Table 2 – Residual SSH of T/P Cycles 316 to 333, relative to various MSS.

| | | mean | sigma | min | max |
|---|---|---|---|---|---|
| TP-GSFC | all points | 0.018 | 0.096 | 1.455 | 1.444 |
| TP-KMS | all points | 0.188 | 0.125 | 1.530 | 1.494 |
| TP-CLS | all points | 0.021 | 0.102 | 1.509 | 1.476 |
| TP-FCUP | all points | 0.014 | 0.100 | 1.377 | 1.730 |
| TP-GSFC | 5<d<50 | 0.006 | 0.114 | 1.128 | 1.119 |
| TP-KMS | 5<d<50 | 0.224 | 0.181 | 1.102 | 0.896 |
| TP-CLS | 5<d<50 | 0.014 | 0.134 | 0.959 | 1.282 |
| TP-FCUP | 5<d<50 | 0.006 | 0.120 | 0.870 | 1.051 |

Table 3 – Residual SSH of ERS Cycles 53 to 60, relative to various MSS.

| | | mean | sigma | min | max |
|---|---|---|---|---|---|
| ERS2-GSFC | all points | 0.112 | 0.116 | 3.588 | 2.356 |
| ERS2-KMS | all points | 0.094 | 0.143 | 4.206 | 1.969 |
| ERS2-CLS | all points | 0.117 | 0.123 | 3.513 | 2.176 |
| ERS2-FCUP | all points | 0.108 | 0.117 | 3.452 | 2.269 |
| ERS2-GSFC | 5<d<50 | 0.096 | 0.155 | 2.888 | 1.838 |
| ERS2-KMS | 5<d<50 | 0.131 | 0.210 | 2.939 | 1.722 |
| ERS2-CLS | 5<d<50 | 0.105 | 0.182 | 2.836 | 1.817 |
| ERS2-FCUP | 5<d<50 | 0.097 | 0.149 | 2.414 | 2.251 |

The same does not apply to the ERS 35-day tracks. The results presented in table 3 show a small but clear improvement of the FCUP model, in the coastal region (5 km < d < 50 km), relative to all global models. It is believed that, after an appropriate treatment of the ocean/land discontinuity, the improvement will be more evident.

The gravity anomalies have been compared with a set of gravity anomalies available in the region of the Azores archipelago. The available data sets comprise:

- airborne and marine gravity, collected during a campaign that took place in this region, in 1997, in the scope of the EU project

AGMASCO. These measurements have been made with a LaCoste &Romberg S99 air/sea gravimeter, Fernandes et al. (2000b);

- strapdown airborne gravity derived by GPS/INS integration (Bastos et al., 2002);
- satellite derived gravity anomalies from global models (GSFC00, KMS2001 and CLS_SHOM 98.2).

Figures 5 to 9 show the comparison between several of these data sets along a profile around the island of S. Miguel. From these results we highlight the similarity between the satellite derived FCUP anomalies and the GPS/INS solution. Note that these solutions are completely independent. By comparison, in this close to land region, the global models GSFC00 and KMS2001 reveal signals which are not present in none of the other two solutions. These signals are believed to be data artefacts in the global models.

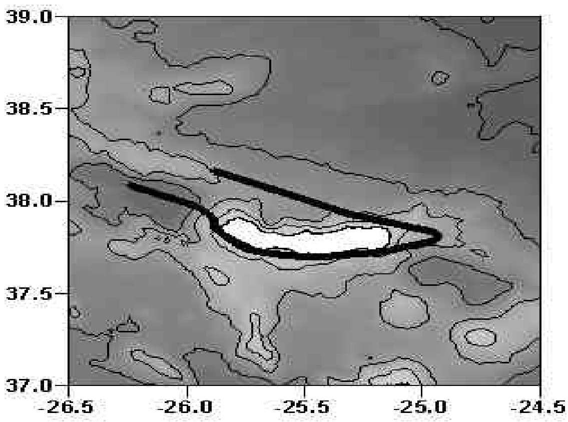


Figure 5 – Profile around S. Miguel island. The bathymetry is shown in the background.

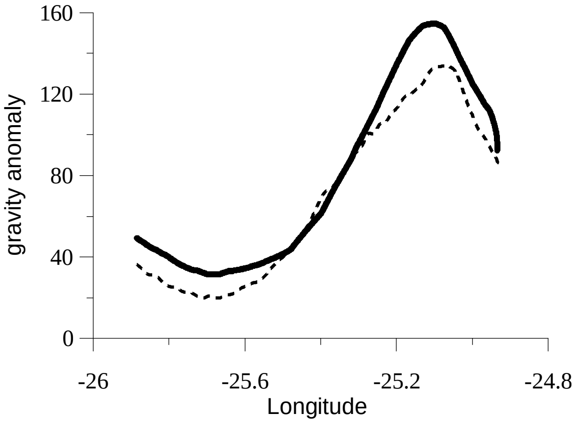


Figure 6 – Gravity anomalies along profile around S. Miguel island (north). Continuous line: FCUP; dashed line: GPS/INS

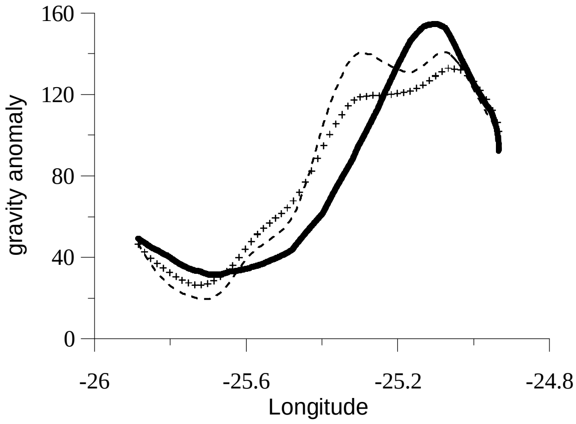


Figure 7 – Gravity anomalies along profile around S. Miguel island (north). Continuous line: FCUP; dashed line: GSFC; small crosses: KMS.

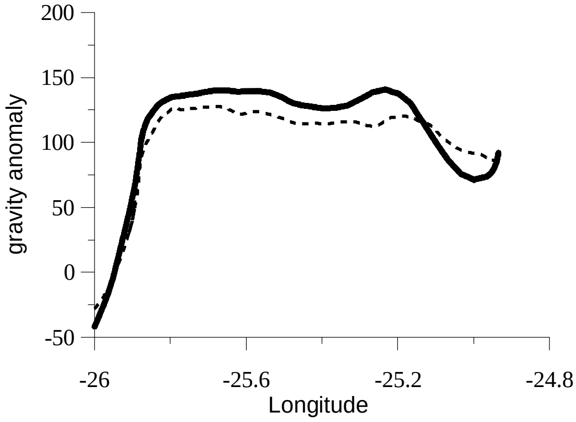


Figure 8 – Gravity anomalies along profile around S. Miguel island (south). Continuous line: FCUP; dashed line: GPS/INS.

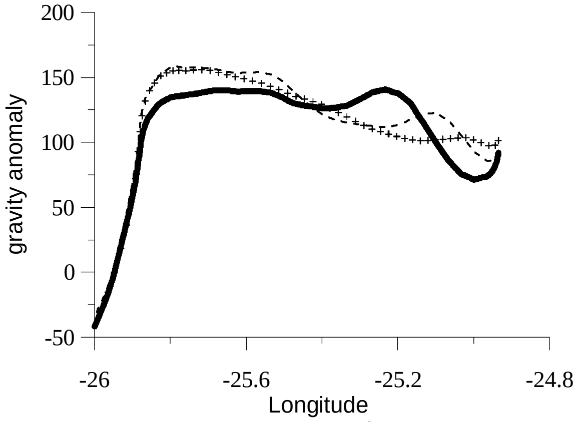


Figure 9 – Gravity anomalies along profile around S. Miguel island (south). Continuous line: FCUP; dashed line: GSFC; small crosses: KMS.

Further validation methods, as referred above, can be applied to data, to give insight into the actual accuracy of the improved data sets.

For the purpose of MSS validation, airborne altimetry can be an important tool, provided adequate regional tidal and oceanographic models exist to correct data. The comparison with regional geoids and oceanographic models, where available, will also be exploited.

For the purpose of GANO validation, several data sets of airborne gravity, which became recently available to the authors, will be used together with the most recent marine gravity data from international data banks.

## 4. Conclusions and future work

Overall the results show that the applied algorithms improve the altimetric products. Due to the fact that gravity anomalies vary very slowly with time, it is easier to find data sets for the validation of gravity anomalies than for the MSS.

Results show that data griding method used in the MSS and derived GANO models is a key issue. The full potential of the improved altimeter data sets can only be exploited if the griding methods do not mask the actual data sampling and resolution in the coastal regions. To achieve this goal, methods for treating ocean/land data discontinuity present in the altimeter data have to be developed.

Exploitation of data validation methods and the treatment of data discontinuity close to land are the major topics of future work.

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