Crossover analysis in the Canary-Azores region of ERS-1 altimetric data

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Abstract. ERS-1 satellite altimetry data corresponding to the second multidisciplinary phase of the satellite, were used over a zone in the North Atlantic, during fifteen months of mission. They have been corrected of all modelled effects. A data validation using criteria related to the observed and average statistical values has been done. Mean arcs are obtained from one year's data to take out the seasonal effects. With this data, crossover points between ascending and descending arcs are then determined. Residual differences are adjusted by least-squares. Two parameters are obtained for every arc. The mean sea surface obtained with the adjusted residuals is tested over the Canary Islands region with a gravimetric geoid.

1. Data

The data used are corrected sea-surface heights generated by the CLS Space Oceanography Division (Toulouse, France) and distributed on AVISO/altimetry CD-ROMs:

Corrected Sea Surface Height (SSH) = Orbit – Altimeter Range - Corrections

Data spatial coverage is $20° < \phi < 50°$, $315° < \lambda < 355°$ and the temporal coverage is of fifteen months from March, 95 to May, 96. Data correspond to the second multidisciplinary phase of the ERS-1 satellite with a 35-day repeat cycle, and Sun synchronous orbit. We took thirteen consecutive cycles for this study. The number of data is 564 797. Basic data are one per second, but there may be discontinuities if measurements are not available. They are corrected by CERSAT for all geophysical, media and instrumental effects, as well as for orbit errors (AVISO/Altimetry, 1996, Le Traon et al, 1995) as follows:

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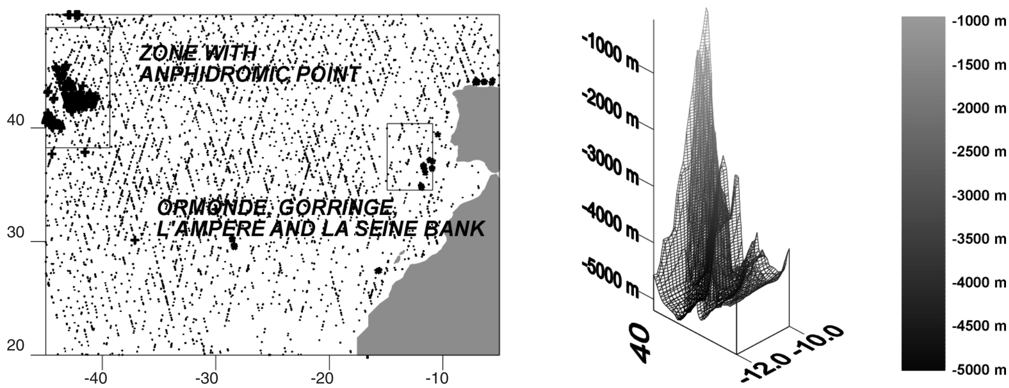

Fig. 1 – Spatial distribution of eliminated points: . points with $\Delta(h_{ssh}\text{-}h_{mss})/\Delta t$ >0.18 *m/s (3σ),* + points with $h_{ssh}\text{-}h_{mss}$>0.71 cms, and * points with large sea heights >1 m/s. On the right, bathymetry on the East Atlantic banks .

1. geophysical corrections: dry troposphere and inverse barometer effect using ECMWF data (update for the ERS-1 OPR products); wet troposphere using satellite radiometer information and the ionospheric delay computed with the Bent model;
2. tidal corrections: for ocean and loading tide the CSR3.0 (Center for Space Research. Univ. Texas at Austin) global model is used. The solid earth tide is computed with the Cartwright and Tayler (1971) model. Pole-tide correction is not applied on data;
3. orbit: data have been fitted to the more accurate TOPEX/Poseidon data with a global minimisation of dual crossover differences between them. No orbit error correction is calculated for T/P. In order to get more homogeneous mixed data, the TOPEX ellipsoid, of equatorial radius 6378.1363 km and flattening coefficient 1/298.257 has been used.

The mean sea surface used to estimate the residual sea height over the static and secular sea-surface topography was the OSU95 MSS model (Yi, 1995), time average surface, based on one year of mean TOPEX sea surface heights (February, 93 - March, 94), mean 35-day repeat ERS-1 SSH (November, 92 to November, 93), and of 17-day repeat Geosat data, (November, 86 - November, 87). This time interval was chosen to average out seasonal ocean variability as much

Table 1 - Edited points statistics.

	MEAN	S.D.	MINIM.	MAXIMUM	RANGE
CORRECTED SEA SURF.HEIGHT	38.24 m	18.22	-17.18 m	69.84 m	84.01 m
OSU95 MEAN SEA SURFACE	38.25 m	18.23	-17.08 m	69.75 m	83.82 m
RESIDUAL HEIGHT	-0.6 cm	0.11	-1.13 m	1.04 m	2.17 m

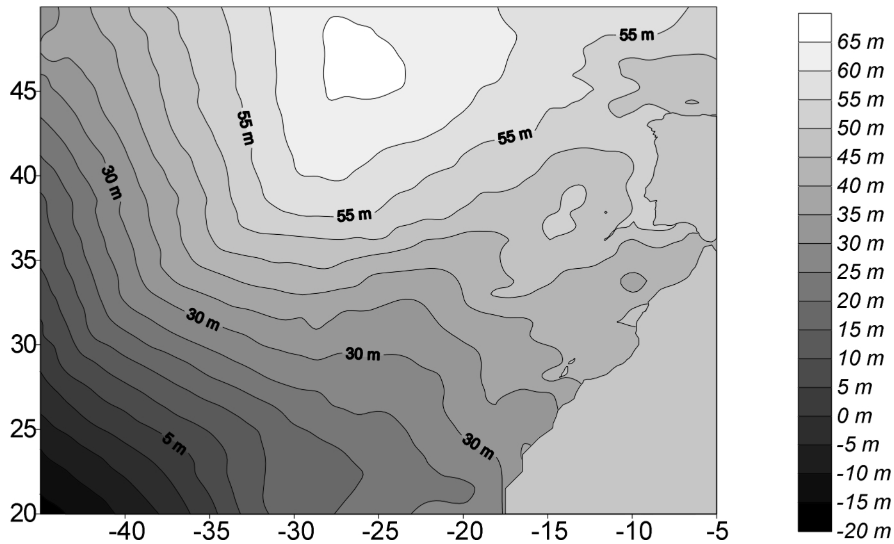

Fig. 2 – Mean sea surface contoured with 5 meter intervals.

as possible. A first cycle of the ERS-1 geodetic phase, 168-day repeat, (April, 94) was also added.

2. Validation process

During data acquisition from the AVISO CD-ROM, tracks with less than 23 points, not appropriate for a posteriori adjustments, are removed. Data have been fitted to TOPEX, so gross errors are not expected. The criteria of revalidation are related to the shape of the surface and how suitable it is to the mean surface. In order to establish these criteria, we looked for useful values as a limit for height gradient or linear approximation of height difference related to time difference between successive points, $\Delta h/\Delta t$; for differences between *SSH* and *MSS* at the same point, h_{ssh}- h_{mss} , and for gradient differences or *SSH* roughness related to *MSS'* one, $(\Delta h\text{-}\Delta h_{mss})/\Delta t$. The number of data is too big. We choose values of these quantities using statistics of them over two cycles only: the first one in summer and the second, six months later, in winter. With these values we wanted to see if uncorrected seasonal effects remain. There are no big differences between both results. That means that there is a proper correction and it is possible to choose

Table 2 - Stacked tracks statistics.

	MEAN	S.D.	MINIMUM	MAXIMUM	RANGE
STACKED HEIGHT RESIDUALS	0.67 cm	0.06	-37.2 cm	59.4 cm	92.1 cm

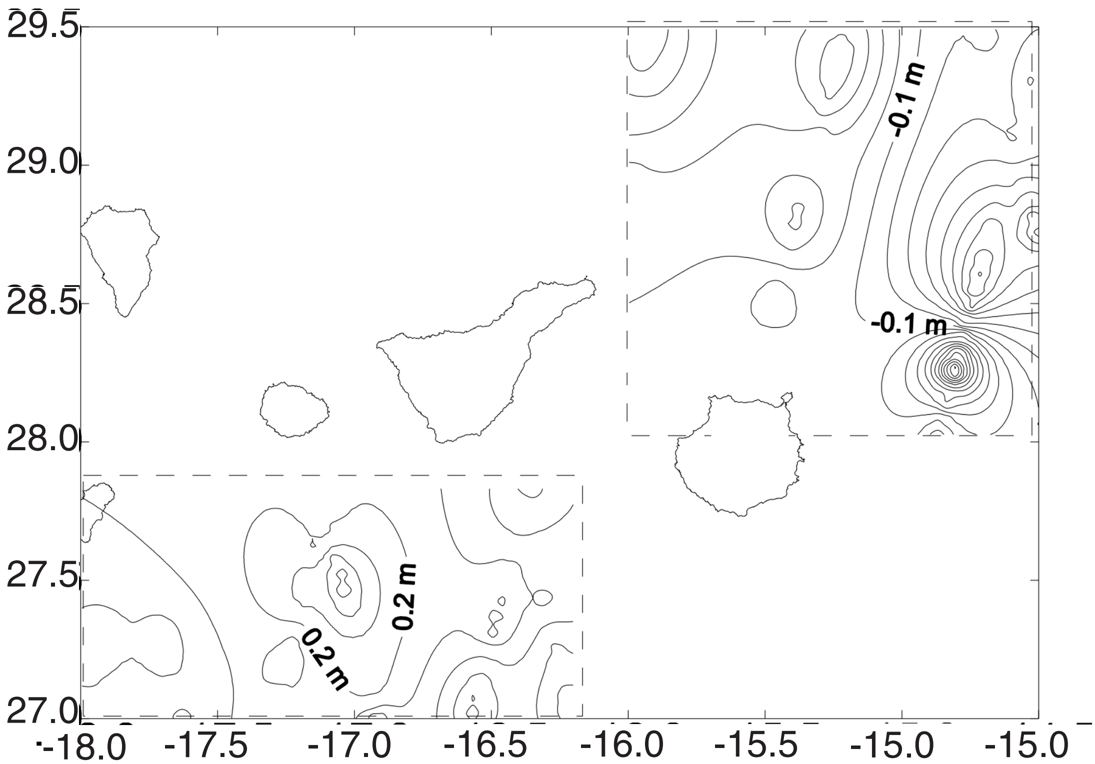

Fig. 3 – Differences between mean sea surface and gravimetric geoid contoured with 5 cm intervals.

some uniform values as limits for the editing procedure. They are:

1. The corrected surface should be quite smooth, so the height gradient must be less than 1 m/s. Some authors are against this, due to the correlation between *SSH* and bathymetry. Using this height gradient, 63 points are rejected, (0.01% of total, 1.4 % of rejected points), mostly placed over shallow waters where we found a depth of only 18 meters (L'Ampere and Josephine Banks), 33 meters (Gorringe Bank) and 86 meters (Seine Bank) in the middle of much deeper waters;
2. the absolute value of the differences between *SSH* and *MSS* should be less than an half-rank variation of such magnitude, 0.71 meters ($/ h_{ssh} - h_{mss} / > 0.71$ *m rejected).* With this criterion 332 points are rejected (0.06% of total of data and 7.3% of eliminated data). In the thirteen

Table 3 – Parameter statistics.

	MEAN	S.D.	MINIMUM	MAXIMUM	RANGE
BIAS	-0.001 m	0.05	-0.24 m	0.07 m	0.31 m
TILT	-0.01	0.05	-0.31	0.27	0.58

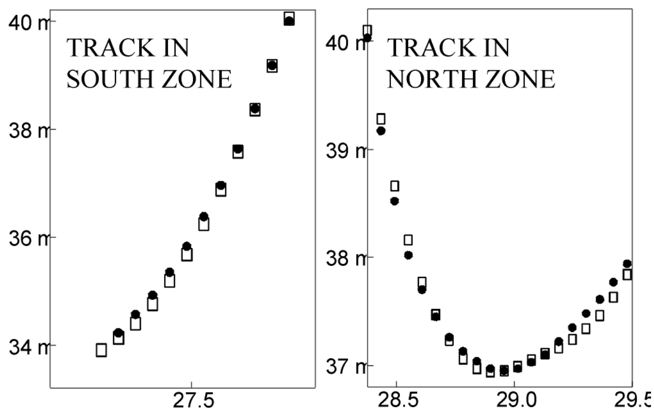

Fig. 4 – Differences along two tracks: • for ERS-1 surface and □ for gravimetric geoid height.

cycles, points not verifying this condition are located in the same zone (northwest of the region). In different tidal models amphidromic points appear close to that zone. Considering different waves, their positions change slightly but always remain nearby;

3. shape changes of SSH should be similar to the MSS ones. So, its roughness is accepted only if it is not too much bigger than MSS. As the sample is quite big, it must have a normal distribution and close to 99% of data has to verify $/(\Delta h - \Delta h_{mss}) / \Delta t /> 3\sigma = 0.18$ *m/s.* There are 4136 rejected points (0.73% of total, 91.3% of rejected points). Its geographical distribution is random and not the same in each cycle. There are 41 531 rejected points (Fig. 1). Table 1 shows statistics of validated points.

3. Stacking procedure and crossover adjustment

The sea level has a seasonal variability (higher in summer and autumn and lower in winter

Table 4 - Crossover adjusted results statistics.

	MEAN	S.D.	MINIMUM	MAXIMUM	RANGE
ADJUSTED RESIDUAL HEIGHTS	0.05 cm	0.04	-0.68 m	0.39 m	1.07 m
DIFFERENCE R.M.S. WITH STACKED TRACKS	0.67 cm	0.06	-0.37 m	0.55 m	0.92 m

Table 5 – Mean sea surface statistics.

MEAN	S.D.	MINIMUM	MAXIMUM	RANGE
38.3839 m	18.05	-17.09 m	66.75 m	83.84 m

Table 6 – Differences between altimetric surface and gravimetric geoid over the two zones of comparison.

	MEAN	S.D.	MINIMUM	MAXIMUM	RANGE
MSS (NORTH)	38.64 m	1.41	36.52 m	42.52 m	5.57 m
GRAV.GEOID (NORTH)	38.75 m	1.45	36.94 m	42.63 m	5.69 m
DIFFERENCES (NORTH)	-0.11 m	0.22	-0.53 m	0.55 m	1.08 m
MSS (SOUTH)	35.94 m	1.76	32.83 m	40.00 m	7.17 m
GRAV.GEOID (SOUTH)	35.84 m	1.74	32.93 m	40.05 m	7.12 m
DIFFERENCES (SOUTH)	0.09 m	0.10	-0.1 m	0.35 m	0.45 m

and spring) (Tapley et al., 1994; Knudsen,1994), so we selected data from one whole year in order to cover four full seasons.

Due to the exact repeat orbit, there are different data over the same geographical position. The collinear tracks were stacked to produce mean tracks. In so doing we avoid having different SSH values in the same points. With these two procedures, the number of data is significantly reduced. 429 790 points were selected from one year, and by stacking them we got 47 594 subsatellite points. This procedure reduces orbital error effects and the long wavelength variability statistical results of residual heights are shown in Table 2.

1157 crossover points were found from the 122 mean tracks. Thus, an adjustment of bias and tilt was made for each track, removing the rank deficiency by a low weight (10^{-5} in this case) hybrid norm. Results are shown in Tables 3 and 4.

Bias and tilt in north and south going arcs are slightly different. The first are both quite smaller and negative, while in the second case tilts are smaller and biases positive. The crossover differences, after adjustment, are significantly reduced as expected.

4. Mean sea-surface and external comparisons

The corrections applied in the first section have removed main ocean and solid Earth tides and geophysical effects. Making means, in the period of one year, seasonal changes in sea level are averaged out. With the crossover adjustment, uncorrected orbital errors are eliminated, so adjusted residual plus the stationary height over the ellipsoid should be a good approximation for the marine geoid in the zone, even if longer period dynamic sea topography still remains. Table 5 shows statistics of values obtained, and Fig. 2 shows the geoid surface.

To verify the results, we made several comparisons in the Canary region. Two zones were selected: the first one in the north (28°.5< ϕ<29°.5, -16°.0 <λ < 15°.5) and the second one in the south (27°.0 < ϕ< 28°.0, -18°.0 <λ <16°.0). In these areas, we wanted to see the behaviour of crossover treatment on both sides of islands with very high topography like these. We compared our results with a gravimetric geoid on the area computed using the Fast Fourier transform (Sevilla et al., 1997). The differences are generally small, even close to the islands. Their statistics are shown in Table 6. Gravimetric geoid heights over the tracks in the two zones fit quite well with the altimetry results.

Fig. 3 shows the location of the two zones and level lines of the obtained differences. In Fig. 4 the sea-surface heights reproduced over two tracks by both surfaces are depicted.

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