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Improved satellite altimetry in coastal systems: Case study of the Corsica Channel (Mediterranean Sea)

S. Vignudelli,¹ P. Cipollini,² L. Roblou,³ F. Lyard,³ G. P. Gasparini,⁴ G. Manzella,⁵ and M. Astraldi⁴

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[1] The fidelity of corrections and processing are critical for a realistic use of official altimetric products close to the coast. A new processing strategy, which starts from the TOPEX/Poseidon GDRs with the addition of improved corrective terms, is proposed and evaluated in the area of the Corsica Channel. Sea level anomalies agree with the coincident sea truth (bottom pressure and tide gauge) within 2–3 cm rms for seasonal and longer time scales. Analysis for almost ten years of coincident mooring and altimetric velocities shows that a substantial reduction of uncertainty to ~ 4 cm s^{-1} may be possible after reasonable filtering of the noise introduced by more variable coastal sea surface states. The conclusion is that the altimetry success is still limited to seasonal time scales, and provided that the oceanographic signal ensures an adequate signature to be isolated from background noise. **Citation:** Vignudelli, S., P. Cipollini, L. Roblou, F. Lyard, G. P. Gasparini, G. Manzella, and M. Astraldi (2005), Improved satellite altimetry in coastal systems: Case study of the Corsica Channel (Mediterranean Sea), *Geophys. Res. Lett.*, 32, L07608, doi:10.1029/2005GL022602.

1. Introduction

[2] Satellite altimetry is a mature technology for studying open oceans, and one of the challenges now is to extend its use to near-coastal applications, even though the sampling strategy is not targeted for these purposes. The Mediterranean Sea is a suitable region where to assess the quality of available altimetric products and the achievable improvements therein. Over the past decade, work has been done at basin scale [e.g., *Larnicol et al.*, 1995] or in specific open sea regions [e.g., *Vignudelli et al.*, 2003]. Close to the coast, altimetric observations often are of lower accuracy or not interpretable due to a number of factors including footprint land contaminations (altimeter and radiometer), inaccurate tidal corrections and incorrect removal of atmospheric (wind and pressure) effects at the sea surface. *Vignudelli et al.* [2000] show that a number of data in official products would be flagged as “bad” but possibly recoverable after a more careful screening.

[3] New processing strategies are necessary to explore altimetric applications in such challenging conditions. This is a key task of the ongoing ALBICOCCA project (ALtimeter-Based Investigations in Corsica, Capraia and Contiguous Area), a joint French/Italian effort that also contributes to the Jason-1 and Envisat absolute calibrations. We avoided subjective human intervention in post-processing raw radar data nearby the coast. Rather, the approach was to merge accurate local modelling of corrections for environmental effects and to minimize data loss during the correction phase by improving the processing chain. A level 2-like product is being generated for the TOPEX/Poseidon (T/P) mission in the Western Mediterranean Sea. Here, we show results in the area of the Corsica Channel (Figure 1) and their validation against an independent corroborative record of ground-based measurements.

2. Study Area

[4] The area was chosen because: (i) it has the longest record of continuous current measurements in the Mediterranean Sea; (ii) it seems to be crucial for regional climatic change studies [*Vignudelli et al.*, 1999]; (iii) it is appropriate for an ad hoc coastal altimetry study being the site of long-established coastal and island gauge stations supplying invaluable “ground truth” for validation. The Corsica Channel, bounded by the coast of Corsica to the west and the Capraia Island to the east, provides a convenient constriction across which to measure the water exchange between the Tyrrhenian and Ligurian seas. Its regular shape cross section, very narrow below 100 m depth, makes a single mooring solution adequate to accurately estimate this exchange. Current meter records indicate an essentially one-way northward flow throughout the year, with strong seasonality. There is a clear intensification during the colder season (late autumn to early spring), which undergoes substantial interannual changes. The mechanism governing this variability is still subject to debate, although it is believed to be primarily of steric origin. Satellite altimetry has made possible a quantification of these effects [*Vignudelli et al.*, 2000].

3. In Situ Measurements

[5] Current measurements from a mooring (M) deployed in the Corsica Channel, in a depth of ~ 460 m, started in November 1985 and are still ongoing. From May 1996, a bottom pressure (BP) recorder has been almost continuously operating at Capraia Island [see *Vignudelli et al.*, 2000]. Here we use the BP data collected every 20 min from May 1996 to September 2003 and the speed and

¹Istituto di Biofisica, Consiglio Nazionale delle Ricerche, Pisa, Italy.

²National Oceanography Centre, Southampton, UK.

³Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS), Centre National de la Recherche Scientifique, Toulouse, France.

⁴Istituto di Scienze del Mare, Consiglio Nazionale delle Ricerche, La Spezia, Italy.

⁵Ente per le Nuove Tecnologie, l'Energia e l'Ambiente, La Spezia, Italy.

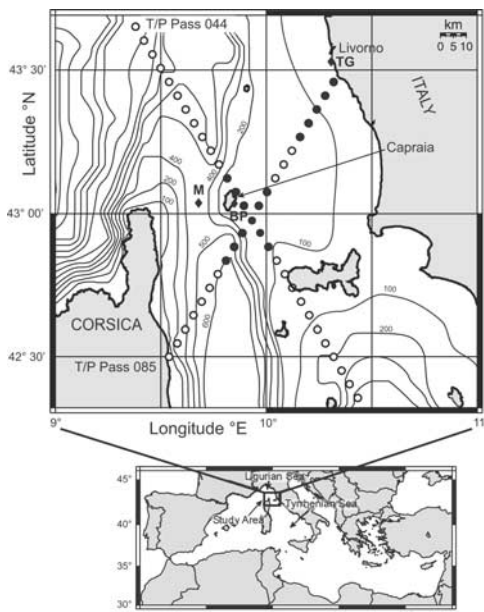


Figure 1. Study area showing the paths (depicted by series of points) of the T/P satellite, bottom topography (meters) and positions of the bottom pressure (BP), tide gauge (TG) and mooring (M).

direction record of currents (measured every 30 min by the current meter at ~ 70 m depth) which overlap with the T/P time series, from September 1992 to August 2002. Sea level was also measured routinely in the Livorno harbour from July 1998 to December 2003 by an acoustic tide gauge (TG).

4. Altimetric Data Set

[6] The basic input are the T/P GDR (Geophysical Data Record) data stream at a rate of one-per-second (6–7 km along track spacing) distributed by AVISO [1996], with the addition of updated orbit solutions and latest corrective terms, including those based on local modelling as described below. We focus on the T/P ground tracks (passes 044 and 085) that cross the study area with a 10-day repeating cycle. Major details concerning the technical solutions for pre-processing improvement are given by Roblou and Lyard [2004]. Briefly, all corrective terms (e.g. wet and dry troposphere, ionosphere, sea state bias or pole tide) are recomputed using Bézier interpolation curves based on the valid data for each correction, validity being defined with new and experimental editing criteria. This original methodology permits to recover data which would otherwise be lost due to excessive classical criteria in coastal areas. Then, an inversion method is applied to derive a new mean sea surface and thus sea level anomalies (SLAs). Here we show some examples of the quality checks that were made.

[7] One of the reasons for the large (>10 cm) spikes often displayed by T/P in coastal seas is the presence of outliers of diverse origin in the corrections; one example is the wet tropospheric component from radiometer measurements, shown in Figure 2a; this cannot be replaced by low-resolution model estimates. A large number of SLAs can

also be of suspicious quality or even useless because of erroneous mean removal (Figure 2b). In most of these circumstances an accurate interpolated correction can still be attempted, and a meaningful T/P datum recovered. This substantially increases the amount of valid data in open sea up to few tens of km from the coast, while much closer to it the successful retrieval may still decrease, possibly due to land contamination in footprints.

[8] As an alternative to the CSR 3.0 tidal model available in the T/P GDRs, LEGOS has selected an optimised tidal spectrum for the Mediterranean Sea, mainly based on MOG2D tidal solutions [Roblou, 2004] and combined with global models (e.g., FES2002 and GOT00) for the diurnal components. The amplitude and phase lag of the major tidal constituents of both CSR 3.0 and LEGOS models have been compared to the Capraia and Livorno in situ values, deduced by harmonic analysis of sea level measurements, by means of bilinear interpolation within the model grids (Table 1¹). As one can expect in a region where tides show very little spatial variability, the two tidal models give close results, although more significant differences may appear for single constituents. The ocean response to short-period atmospheric forcing is classically poorly resolved by applying the inverted barometer correction. Following Carrère and Lyard [2003], a similar modelling approach has been carried out in the Mediterranean Sea from a regional mesh. Compared to the inverted barometer correction (Table 2¹), the correction computed from the model simulations leads to a residual rms of the sea level reduced by a factor >1.5 at both stations.

5. Comparison to Sea Levels

[9] T/P provides sea level measurements to a single-pass accuracy of 5 cm rms, which can be further improved working with anomalies [Fu et al., 1994]. Some local comparisons made between ground-based and T/P readings of SLAs prove that rms differences of 2 cm can be statistically achieved on monthly and longer time scales [e.g., Verstraete and Park, 1995]. In this study, the TG site is ~ 8 km from the closest approach of the T/P ground track (085). Distances from the BP site to the T/P tracks are over 9 km (085) and 4 km (044). A subset of T/P ground track points nearest to Capraia and Livorno (filled circles in Figure 1) are used to form comparison time series. The BP record is converted into equivalent sea levels using the hydrostatic approximation, adding the steric component from the equation of state. To ensure consistency with the satellite results, BP and TG sea level records are demeaned and corrected in the same way and then sub-sampled to the exact times of overpass of each T/P pass. Following Mitchum [1994], each of the altimetric time series is first analyzed separately. Ascending (085) and descending (044) passes falling on either side of Capraia yield an rms difference over time of 5.3 cm and 5.1 cm, respectively. At Livorno, where data from one pass only (085) can be compared, a larger mismatch (8 cm) arises. This difference may be attributed in part to the fact that altimeter values

¹Auxiliary material is available at <ftp://ftp.agu.org/apend/gl/2005GL022602>.

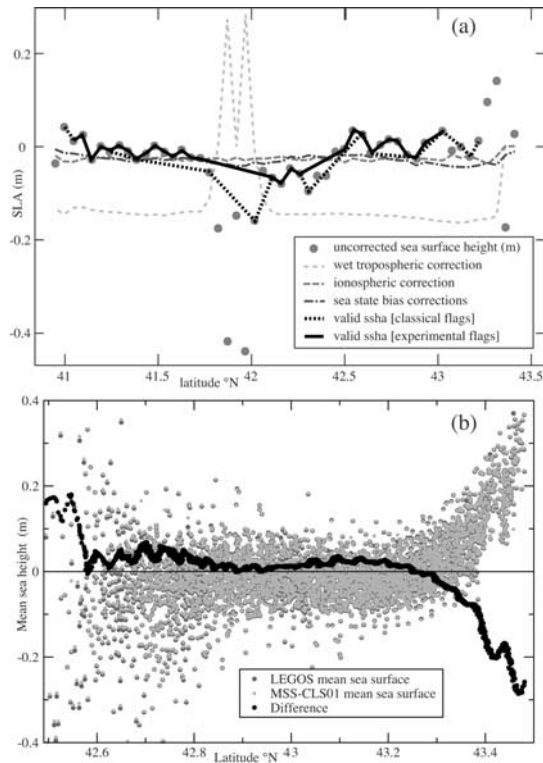


Figure 2. Data re-editing differences as observed on SLA along track for a given cycle (a) and departures (cm) of the LEGOS mean sea surface from MSS CLS01 product (b) under T/P ground track 085.

reflect offshore sea state, but also to the more open location of Capraia, as opposed to Livorno, where the continental shelf extension may have significant local effects. Assuming BP and TG stations working properly, any unexplained differences that lead to overall poor correlations are probably due not only to spatial mismatch between point-wise values (in cases of in situ data) and satellite footprints or to the systematic errors in models and multiple altimeter corrections, but rather could reflect, at least in part, the noisier radar returns from a generally rougher sea surface condition than usually found in deep oceans. When equally low-passed with a Gaussian filter (30-day half-amplitude with cutoff period at 15 days), the rms difference drops to ~ 4 cm at Livorno, with the best agreement (~ 2 – 3 cm) at Capraia. The BP and TG time series contain a substantial amount of energy at seasonal scales, which is well reproduced in each altimetric record (Figure 3). Focusing our attention to Capraia the altimeter is registering seasonal variations of the order of 20 cm to within 3 cm rms accuracy equivalent to a signal-to-noise-ratio of about 7.

[10] The fact that at Capraia the temporal sampling of T/P is twice as dense suggests investigating an ensemble comparison combining data from both passes (the time lag being 38.4 hours) into a single time series. Averaging of the two passes for each 10-day cycle was best used in the past to reduce aliasing rather than to double the temporal resolution. While it is possible that the merging

of the two passes be more effective in some parts of the time series than others, this does not necessarily improve the spectrum at the seasonal scales. When pairing for each pass all T/P SLAs with the closest BP values, we obtain different values of the scatter estimate [Mitchum, 1994], despite the BP station lies close to both tracks. This is not surprising because in coastal systems the background energy may significantly vary within the region and affect spectra differently [Gille and Hughes, 2001].

6. Comparison to Velocities

[11] Altimeter-derived current velocities are obtained from along-track SLA slopes assuming geostrophy. Their consistency has been evaluated against point-based measurements from moored current meters [e.g., Skagseth et al., 2004] and basin-wide measurements from drifting buoys [e.g., Uchida and Imawaki, 2003]. The 3 – 5 cm s^{-1} rms value for the California Current System [Strub et al., 1997] gives an indication of the achievable accuracy in open ocean places. Recent studies [e.g., Wang et al., 2003] extended the comparison to the shelf region, but the limitations of official altimetric products greatly influenced the resulting agreement.

[12] In the Corsica Channel, the flow is strictly polarized towards the northern sector (the principal axis is oriented $\sim 12^\circ$ counterclockwise from north). The T/P

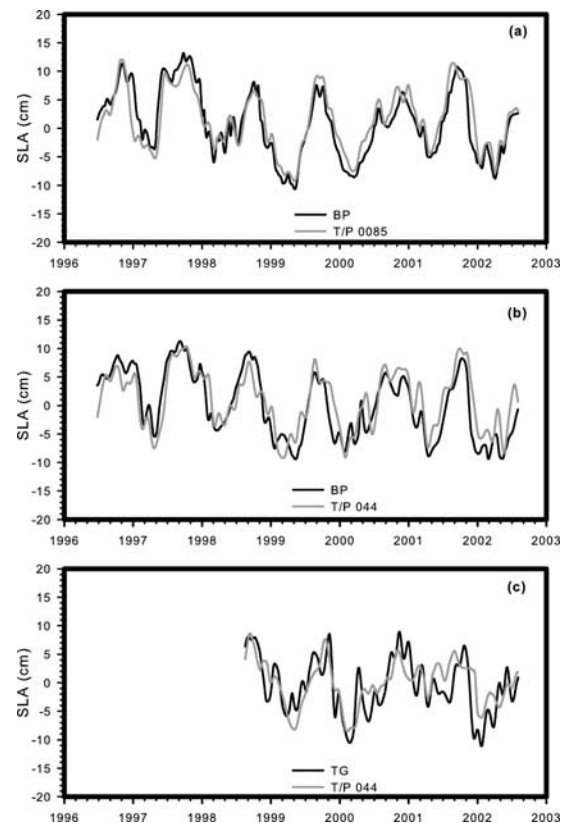


Figure 3. Time series of T/P (in grey) against in situ SLAs (in black) at (a) and (b) Capraia (Bottom Pressure (BP)) and (c) Livorno (Tide Gauge (TG)).

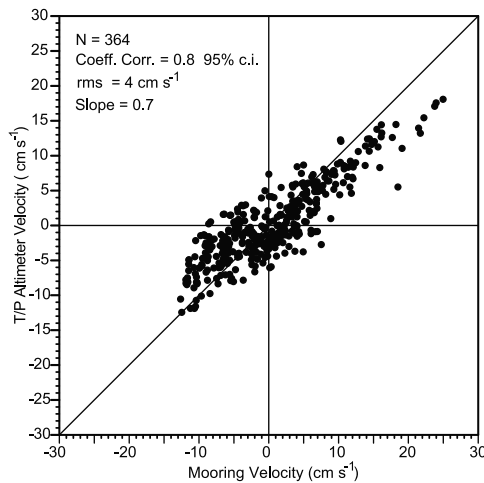


Figure 4. Scatterplot of T/P against mooring surface velocity anomalies. Number of observations (N), difference between the two quantities (rms), correlation coefficient (c.c) and regression coefficient (Slope) are also reported.

ground track, ascending pass 085, crosses the flow south of the mooring place (~ 15 km at the closest approach) at an angle nearly perpendicular to it, thus providing a cross-track velocity suitable for a direct comparison against a coincident mooring component. The time series of mooring velocities (positive towards the NW sector) was computed from the hourly data as anomalies relative to a long-term mean (9.2 cm s^{-1}) similarly to altimetry, low-passed with a Hanning filter (20-day half-amplitude point) to avoid aliasing [Gille and Hughes, 2001] and then sub-sampled at the T/P times. The time series of altimetric velocities (positive to the NW of the track) was constructed from along-track slopes estimated over the portion of the track overhanging the channel. Without smoothing, each individual estimate would be potentially in error by 10 cm s^{-1} over the channel scale assuming point-wise single-cycle SLAs really accurate to 5 cm.

[13] Direct comparison of the two time series roughly produces an rms difference of 8 cm s^{-1} , which is of the same order of magnitude of the rms variability (10 cm s^{-1}) of the current system itself. The discrepancy is substantial at the short time scales, as also confirmed by non-coincident spectra. It may be constrained by inevitable differences in the method of observation. However, such an apparently poor performance may be largely reflective of the noisy nature of T/P data in the coastal strip. When both data sets are equally low-passed with a 30-day Gaussian filter, the rms difference reduces to $\sim 4 \text{ cm s}^{-1}$ (correlation of 0.80), suggesting that at longer time scales the goal of retaining sufficiently accurate information may be achieved. Departures from simple geostrophy and spatial mismatch between mooring and altimeter may be responsible for unexplained differences. The scatterplot in Figure 4 shows that the level of agreement varies with the range of speed. The altimeter underestimates the actual value by about 20–30 % the theoretical fit for events with measured values greater than 10 cm s^{-1} . A noticeable scatter overlaps the general trend in the remaining part. Again, error characteristics appear to

depend on season, with the scatter index (rms difference normalized with the averaged mooring velocity for a specific period) growing to $\sim 40\%$ in the warming season (late spring to early autumn). A possible explanation is that weak flow conditions associated with this season would not ensure a consistent signature in the altimeter data to be isolated from background noise.

7. Concluding Remarks

[14] A novel strategy to process T/P GDR into SLAs shows the extent to which reprocessing could improve accuracy in a coastal system. The accuracy goal in the range 2–3 cm may be realistically achievable, although the only way altimetric data can be used reasonably with this confidence is for looking at long time scales (seasonal and longer). Although a comparison derived from only one place is not sufficient to draw definitive conclusions, we tentatively identify appropriate uses of the altimetric estimate of the currents in the area of the Corsica Channel. We suggest that velocities taken from T/P are accurate enough to be converted to water transport information and used as “climatology” of changes over long time scales. We expect that the new generation of altimetric products from the currently operating Jason-1 and Envisat missions may better fulfil the requirements of a coastal-oriented processing, yielding more usable data closer to the coastline than was possible with T/P.

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- M. Astraldi and G. P. Gasparini, Istituto di Scienze del Mare, Consiglio Nazionale delle Ricerche, Forte Santa Teresa, I-19036 La Spezia, Italy.
- P. Cipollini, Laboratory for Satellite Oceanography, National Oceanography Centre, Southampton, European Way, Southampton, SO14 3ZH, UK.
- F. Lyard and L. Roblou, Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS), Centre National de la Recherche Scientifique, 14 Avenue Edouard belin, F-31400 Toulouse, France.
- G. Manzella, Ente per le Nuove Tecnologie, l'Energia e l'Ambiente, Forte Santa Teresa, I-19036 La Spezia, Italy.
- S. Vignudelli, Istituto di Biofisica, Consiglio Nazionale delle Ricerche, Via Moruzzi 1, I-56124 Pisa, Italy. (vignudelli@pi.ibf.cnr.it)