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Applications of spatial altimetry to studies of ocean dynamics in the Gulf of Cadiz

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ABSTRACT

Sea-level records, and their global and local spatio-temporal variations, are related to many oceanographic and geophysical features. The sea surface can also be visualised as the physical representation of the geoid, averaging the sea-surface records over long periods to eliminate the short periods of dynamic perturbation. Over the last ten years, orbit determination improvements have opened up the possibility of using, for ocean dynamic and sea-level variation studies, several altimetric satellites, accurate to the sub-decimetre level (ERS-1, ERS-2, Topex-Poseidon). Of these satellites, Topex-Poseidon makes it possible to measure the sea-level variation over global or regional zones with an accuracy better than 5 cm.

This paper presents the results of the sea-surface height measurements from Topex-Poseidon, corrected for wet and dry troposphere range delays, ionosphere delay, sea-state bias, the inverse barometer, loading effects and the oceanic, solid-earth and pole tides. The authors analyse the spatio-temporal stability of the geoid OSU91-a and the mean sea-surface OSUMSS95, comparing the behaviour of the dynamic signal using the two different surfaces along Topex profile 122, which overflies the Atlantic apertures of the Gulf of Cadiz. Long-term analysis has been done over several points located on the Iberian Atlantic continental margin using Topex Poseidon altimeter data collected from October 1992 (cycle 2) to October 1997 (cycle 186). The main findings of the data analysis present a semi-annual variation with peaks in autumn and winter, separated on the order of 20 cm, which could be explained by the seawater temperature seasonal variation and the doubtful use of the inverse barometer model to correct the response of the ocean to changes in atmospheric pressure. Records also show a secular variation in the regional sea level of roughly 3 mm/year, according to historical tide-gauge trends, which could also probably be explained by polar ice melting and a slight warming tendency of the ocean.

Key words: Satellite altimetry, spatial geodesy, ocean dynamics.

RESUMEN

Aplicaciones de la altimetría espacial al estudio de la dinámica oceánica del golfo de Cádiz

Los registros de la variación espaciotemporal del nivel del mar están relacionados con un gran número de procesos oceanográficos y geofísicos que afectan a la superficie del océano y que pueden representar físicamente la figura del geoide, al eliminarse las variaciones dinámicas de corto periodo una vez promediados los registros sobre largos periodos de tiempo. En el último decenio los desarrollos técnicos y las mejoras en los formalismos de corrección y cálculo de las órbitas han permitido misiones altimétricas de precisión subdecimétrica, especialmente diseñadas para el estudio de la variación del nivel del mar y la dinámica oceánica global y regional (ERS-1, ERS-2, Topex-Poseidon). Una vez corregidos los observables del altímetro conforme propone la Agencia AVISO, se han comparado las precisiones del geoide OSU91-a con la superficie media OSUMSS95, analizando los valores obtenidos en la señal dinámica en el perfil del Topex n1 122, al sobrevolar la zona del Atlántico ibérico.

Los autores presentan los resultados del estudio que han realizado de los datos obtenidos por el satélite Topex-Poseidon entre los ciclos 2 y 186 de sus órbitas (octubre de 1992 y octubre de 1997) en varios puntos del margen continental ibérico.

Los principales resultados presentan una variación, del orden de 20 cm, en el nivel del mar en los bajos de Gorringe de tipo semianual, justificable con la variación de la temperatura de las masas de agua superficiales entre otoño e invierno y un comportamiento inadecuado del modelo de barímetro invertido en las zonas de estudio. Una variación del mismo orden se detecta en el golfo de Cádiz, igualmente justificable por la variación estacional de la temperatura del océano en su superficie. Además de la variación semianual se detecta una variación secular del orden de 2 a 3 mm/año, probablemente de naturaleza global, compatible con los resultados obtenidos con mareógrafos clásicos, justificable por la fusión de hielos en los casquetes polares y un ligero aumento secular de la temperatura de las masas de agua del océano en la zona del margen continental ibérico.

Palabras clave: *Altimetría por satélites, geodesia espacial, dinámica oceánica.*

INTRODUCTION

Perhaps one of the most important geoscience objectives for the remainder of the century is the development of a global satellite perspective on the earth's crustal tectonic framework and the study of the processes that have influenced its development over geological time.

Because of its sensitivity in detecting sea-surface variation over the global oceans, satellite altimetry appears to be a specially useful tool for obtaining statically the mean sea-surface level (MSS), considered as a global figure that represents the position of the ocean surface averaged over an appropriate period to remove annual, semi-annual, seasonal and spurious sea-surface height signals.

So defined, the MSS contains highly accurate spatial frequency information along the satellite ground track that could be specially useful for the definition of a surface from which the time-variable sea topography can be removed, to yield the best geoid undulation estimates in ocean areas.

Geoid undulations were primarily, and up to the present, considered a long-wavelength phenomenon, and although they had been accurately modelled before the Topex-Poseidon satellite mission, new geopotencial models have become available during this programme which are a substantial improvement over the model OSU91-a, used in the simulations and initial phases of the Topex-Poseidon programme.

On the other hand, and to increase the geoid high-frequency information, the Joint Gravity Model JGM-3, which is complete to degree 70, was merged with the OSU91-a potential coefficient from degree 71 to 300 (Tapley *et al.*, 1994) to form the new Topex mission geoid JGM-3\OSU91-a, computed to degree 300 and with a resolution of its undulations of roughly 50 km.

It should be noted that the high frequencies of OSU91-a were computed using information in ocean areas covered by the Geosat mission, which may not represent accurately the true geoid undulations. Also, it should be noted that the effect of the neglected information over degree 360 is approximately 24 cm, which may be large in high-frequency signal ocean areas.

Because of these geoid limitations, a new mean sea-surface was computed, the OSUMSS95, based on 1 year of Topex-Poseidon, 1 year of ERS-1 35-day cycle, 1 year of Geosat, and the first cycle of the 168-day repeat track of ERS-1. OSUMSS95 represents a significant improvement over previous models, both for ocean dynamic studies and for the geophysical interpretation of the high-frequency undulations related to active tectonic interactions, as occurs in the Iberian Atlantic close to the Azores-Gibraltar region.

Regarding ocean dynamics, until recently, our knowledge of the large-scale circulation of the world ocean relied mostly on classical hydrography, which includes water-mass analysis and geostrophic velocity computation.

Satellite altimetry presently provides the most powerful tool for observing sea-level variations globally and synoptically. When an altimetric satellite is tracked and its position computed with centimetric accuracy, and adequately corrected for a variety of geophysical effects and referenced to the geoid, altimetric data yield the most accurate global dynamic sea-level height associated with baroclinic and barotropic currents.

On the other hand, one widely accepted explanation of the predicted sea-level rise is that a possible increasing concentration of gases in the atmosphere could lead to a global warming trend, causing glacial melting and thermal expansion of the ocean. The thermal-induced mean sea-level change may vary over periods from months to years, due to the heat stored in the upper layers of the oceans and, over longer periods, due to the heat stored in the deeper oceans.

Recent studies using tide-gauge measurements suggest that the global mean sea level over the last century may be rising at a rate of approximately 1-3 mm/year, which could be attributed to the combined effect of a global rise in sea level due to thermal expansion of ocean water, ice melting, groundwater circulation, postglacial rebound, tectonic motion, local land subsidence, and a shift in the wind-driven oceanic circulation patterns (Douglas, 1991, 1995; Lambeck, 1990).

However, the fundamental problem with tide-gauge measurements is that they only measure sea-level change compared with a fixed crustal reference point, sufficient for measuring some local socio-economic impacts of sea-level rise, but of little interest for climate change studies. This is an important difference, since the long crustal rebound and tectonic uplift rates are, at many tide gauges, at the same level as the expected signal due to real sea-level rise.

Under these conditions, we need to validate the tide-gauge results using, as independent global measurement techniques, absolute gravimetry and precise space geodetic techniques to resolve the crustal motions at the required accuracy.

MATERIALS AND METHODS

Satellite altimetry

The altimeter is a form of radar installed on board some satellites that measures their altitude over sea level with high accuracy, in relation to the geodetic global reference system. Satellite altimeter measurements should, in principle, provide improved measurements of the global sea-level change over shorter averaging periods, because of their truly global coverage and direct tie to the geocentre through satellite tracking stations.

The first altimeter mission was GEOS-3 (1975-1978). Its radar altimeter was a crude instrument by present-day standards, with a precision of only 25 cm on 1 s average heights; the drift rate was found to be as high as 25 cm/h. Nonetheless, a credible orbit determination effort (1-2 m radial accuracy) and innovative analysis techniques yielded new maps of the marine geoid and sea-level variability. SEASAT (1978) was the first modern altimeter, having a precision of 5 cm, with a fundamental limitation in the accuracy of its orbit. At the time of the SEASAT, 2 m was a realistic target. Nevertheless, later studies with SEASAT data, using better models of gravity and other forces, made it possible to extract maximum information from the data, improving the satellite orbit precision to a level of 20 cm. The GEOSAT mission (1985-1989) started with prelaunch requirements of 1-m orbit accuracy, to adequately meet the marine geoid mapping mission's needs. Throughout the GEOSAT mission, an accuracy of 50 cm was routinely maintained.

According to these ideas, errors in the satellite orbit and corrections obscured the sea-level rate signal, reducing scientific productivity in the field of the dynamic oceanography during the first altimetric missions of the satellites Geos-3, Seasat and Geosat. Nevertheless, they made it possible to further develop technical instruments and improve tracking and scientific analysis, opening up the opportunity for the latest generation of altimetric satellites: ERS-1, ERS-2, and the NASA-CNES Topex-Poseidon.

The Topex-Poseidon (T/P) satellite flies in a nearly circular orbit at an average altitude of 1 336 km and inclination of 66.05°. It has a period of 112 min, and a ground-track repeat cycle of 9.9156 days after completing 127 revolutions. The rate of change for the argument of the perigee is near zero, to satisfy the frozen repeat orbit criteria. Orbit maintenance manoeuvres are carried out approximately every 3 months, to keep the orbit ground-track repeating within 1 km and the mean orbit eccentricity near zero. The rms radial orbit errors for T/P are inside 3-4 cm due largely to the improved gravity and non-conservative force models (Tapley *et al.,* 1994).

For past altimetric missions, the altimeter range and crossover residuals were widely used as an independent measure to quantify errors in the satellite radial position. However, for T/P, mesoscale sea-surface variations, uncertainties in modelling ocean tides, and the geoid are all large compared to the residual orbit error. T/P carries four independent data-tracking systems: Satellite Laser Ranging (SLR), Doppler Orbitography and

Radiopositioning Integrated by Satellite (DORIS), GPS demonstration receiver and the Tracking and Data Relay Satellite System (TDRSS).

A SLR station measures the time it takes for an optical pulse to traverse the distance from observer to satellite and back. DORIS is a one-way integrated Doppler, measuring the range difference between selected observation times. Corrections are made for path refraction delay effect and for the geometric distance of the instruments' phase centres with respect to the satellite's centre of mass.

For SLR the refraction errors are small, since optical wavelengths exhibit well-understood behaviour when traversing the atmosphere using the adopted Marini-Murray model. For elevation angles of 20° these corrections are accurate to < 5 mm. In addition, the T/P laser reflector array provides a very different target than the ideal specularly reflecting sphere. The target response is the sum of the individual corner cube responses, forming a complex and elongated pulse train in the domain of time. The waveform received at the detector is no longer a slightly distorted Gaussian pulse. The response of the electronic receiver to this complex signal requires modelling to maintain the laser correction at the centimetre level.

A traditional dynamic orbit determination methodology is used to compute the precise orbit ephemeris (POE) for the mission, using as inputs the SLR and DORIS measurements. This approach is dependent upon and limited by the modelling of the complete set of forces acting on the T/P satellite and all components corrections to the tracking measurements.

During the 1990s, several gravity models of progressively improved quality were developed using improved data analysis techniques and ancillary models. These efforts culminated in a prelaunch Joint Gravity Model (JGM-1) and postlaunch JGM-2. JGM-2 incorporates SLR and DORIS data obtained during the first fifteen T/P 10-day cycles and was used to produce the POE. Subsequently, four cycles of GPS and eight additional cycles of SLR/DORIS tracking data of T/P were added to the JGM-2 gravity field solution to produce JGM-3 (Yunk *et al.*, 1994).

According to these ideas, it is of the greatest interest, for ocean dynamic studies and for the accurate assessment of the current rate of seal-level change, to find out, with the best possible accuracy, the radial component of the position vector of an oceanographic satellite, e.g. Topex-Poseidon, ERS-1 or ERS-2, with an altimeter on board.

Simple geometric methods based on the direct use of laser-tracking data, such as the short arc technique, have the potential to provide an improvement in the accuracy of the global orbit determination over limited geographical regions, with the advantage that they do not require a numeric orbit integration. Wakker, Ambrosius and Aardoom (1983), Sinclair and Appleby (1993), and Wagner and Melchioni (1989) have investigated such methods with results of a few centimetres' precision over arcs of about 2 000 km. A further problem is that laser stations, at best, track only about one-third of the available passes, due to the weather and other restrictions, so the number of tracks with good enough tracking for short-arc analysis would be small except in those regions that, as in Europe have dense laser-tracking station coverage.

Presently, in the Mediterranean-Gulf of Cadiz area, global orbit accuracy could be improved to the centimetre level and extended toward the Atlantic by applying short arc techniques, considered the most favourable geometry of the tracking network after the incorporation of the new SLR, to the terrestrial reference frame created for the permanent network of Satellite Laser Stations (SLS) that track the LAGEOS satellite on a routine basis (Bonnefond, 1994; Bonnefond *et al.*, 1995).

RESULTS

Altimetry: Fundamental equations

The Topex-Poseidon satellite carries two altimeters that share the same antenna and never operate simultaneously. The first altimeter is a dual-frequency altimeter developed by NASA (Topex), and the second is an experimental single-frequency solid-state altimeter (Poseidon) developed by the National Space Studies Centre (CNES) of France. After calibrations some relative biases were detected between the range measurements from these two altimeters of 15.5 cm, with Topex measuring short. The precision of the two altimeters is estimated to be on the order 3.2 cm rms for Topex and 3.7 cm rms for Poseidon. (Fu *et al.*, 1994).

We have used the merged Topex-Poseidon geophysical data records (GDR-M), as produced by AVISO (Archiving Validation and Interpretations of

Satellite Data in Oceanography) (Anon., 1993), to compute sea-level variation in the Mediterranean and Iberian Atlantic, between 20° and 50° N and 5° to 20° W.

As recommended by AVISO, we have applied the following geophysical corrections:

1. The inverse barometer correction.
2. Dry and wet troposphere.
3. Dual-frequency ionosphere correction for Topex and DORIS satellites, radio-positioning ionospheric correction for Poseidon;
4. Sea-state biases correction (Gaspar, Ogor and LeTraon, 1994);
5. Ocean tide, ocean loading, solid-earth and polar tides.

After taking these corrections into consideration, the sea-level height over the reference ellipsoid would be (see figure 1):

Sea-level height = satellite orbit altitude over the ellipsoid-range-corrections [1]

Assuming the geoid to be the surface of an ocean in equilibrium, the dynamic signal would be:

Dynamic signal = altitude-range-geoid undulation-corrections [2]

The preceding equation has many sources of errors and needs to be corrected, not only for the environmental and geophysical perturbations as stated previously, but also to refer the altimeter

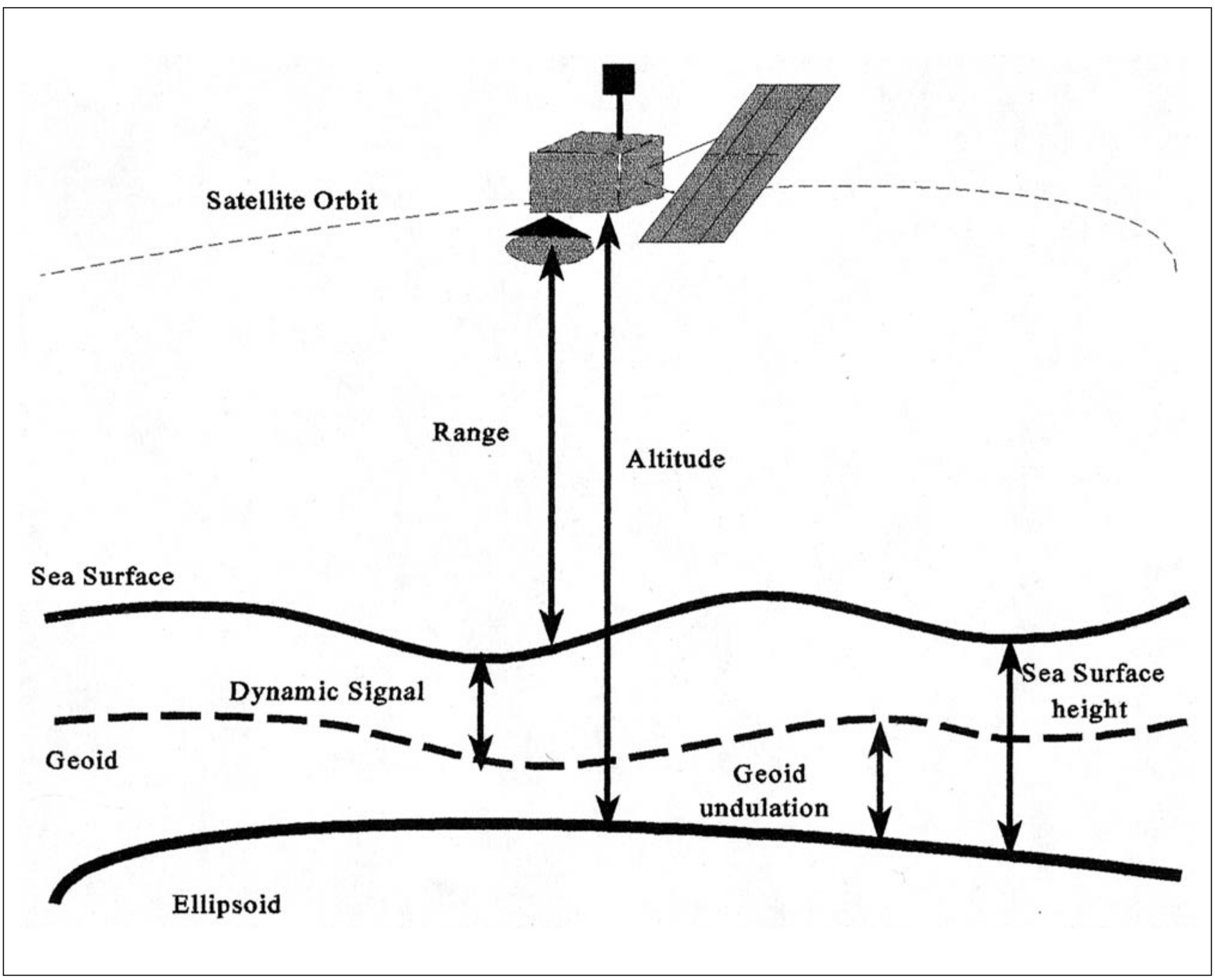

Figure 1. The radar altimeter on board a satellite measures the orbit altitude over sea with an accuracy of a few centimetres. Presently the orbit of a satellite, e.g. Topex-Poseidon, can be known with the same accuracy as the ellipsoid of reference allowing to get the sea-level surface variation throughout the whole mission with the same accuracy

measurements to the geoid as an equipotential surface of the Earth's gravity field, closely associated with the location of the surface of an ideal ocean in equilibrium.

A comparison, along profiles of the Topex-Poseidon satellite, of the geoid and mean sea surface in Iberian Atlantic

Considering the high precision and accuracy that can be achieved using altimeter techniques, we decided to compare the Geoid OSU91-a with the mean sea-surface OSUMSS 95, studying their differences over the complex geophysical zone that forms the Iberian Atlantic environment. To do so, we have used alternatively, in equation [2], the two surfaces comparing the time stability of the dynamic signal along the ground satellite tracks crossing the zone. We have also made a final long-term check, computing the sea-level variation throughout the Topex Mission between October 1992 and October 1996 (cycles 2-149).

In the present study, we have used the following Topex-Poseidon orbits that cross the Atlantic Iberian area: 198, 122, 35, 213, 137 (figure 2F). Orbit 198 overflies north-northwest the inner Gulf of Cadiz, passing over Cape San Vicente toward the Atlantic west of the Galician bank. Orbit 122 overflies the outer Gulf of Cadiz, crossing north-northwest over the Gorringe bank. Orbit 035 overflies north-northeast the inner Gulf of Cadiz, close to the Atlantic aperture of the Straits of Gibraltar. Orbit 137 crosses north-northeast from the Canary Islands, overflying the banks of Ampere and Gorringe towards Portugal north of the Nazare fault.

Figure 3 presents, for these profiles and along the satellite tracks, the direct comparison of mean sea-level model (OSUMSS95), the Geoid OSU91-a and bathymetry suggesting the following results:

1. Profile 198 (figure 2A) presents, in its mean sea-level measurements, a variation along its track in the Gulf of Cadiz, from 40 m off the coast of Africa ascending to 55 m at Cape San Vicente. On the Atlantic coats, the MSS maintain a value of 55 m, descending at latitude 39.51°N to 47 m and ascending later to 59 m, as the satellite crosses up the Atlantic, west of the Galician bank and north of the relic Iberia-Eurasia plates boundary. The differences between the geoids OSU91-a and the OSUMSS95-a present, along the open Atlantic side, oscillations of almost 1 m of amplitude and 21 m of spatial wavelength in the Gulf of Cadiz, with a difference of 0.7 m at 36.21, close to Cape San Vicente.

2. Profile 122 (figure 2B) presents at the mean sea level a variation, along the outer side of the Gulf of Cadiz, from 40 m off the coast of Africa, ascending to 55 m on the bank of Gorringe and descending, at latitude 38° N, to 45 m, then ascending towards the open ocean to 60 m. The differences between the geoids OSU91-a and the OSUMSS95-a along the bank of Gorringe are striking, almost 2 m, probably related to the bathymetry, which repeats between latitudes 39° N and 40° N.

3. Profile 35 (figure 2C) presents a slow variation in the mean sea level, when crossing the Gulf of Cadiz close to the Straits of Gibraltar, from 40 m near the coast of Africa descending toward 40 m in the central zone of the Gulf of Cadiz, at 35° N, and ascending to 45 m on the coast of Spain when it overflies the zenith of the city of Cadiz. The differences between the geoids OSU91-a and the OSUMSS95-a present a strong variation of almost 1m, in the middle of the profile at latitude 35.5° N.

4. Profile 213 (figure 2D) presents a mean sea level variation from 42 m at latitude 35° N to 55 m at Cape San Vicente. The differences between the geoids OSU91-a and OSUMSS95 present, along the outer Gulf of Cadiz, a variation of more than 1 m.

5. The mean sea level varies in profile 137 (figure 2E) from 45-55 m on the bank of Gorringe, descending to 45 m at 38° N and ascending to 58 m on the coasts of Portugal close to Porto. The differences between the geoids OSU91-a and OSUMSS95-a are specially high along the Gorringe bank, with a strong variation that reaches almost 3 m at 36.5° N.

We have checked the spatial accuracy of the mean sea surface OSUMSS95 and the geoid OSU91-a, comparing their spatial variation with the ocean dynamic signal, computed according to formula [2], using alternatively both surfaces for several Topex-Poseidon cycles.

To do the comparison, we selected orbit 122, which overflies the strong geoid gradient zone of the Gorringe banks. Figure 3 presents, in its central window, the space evolution of the dynamic signal

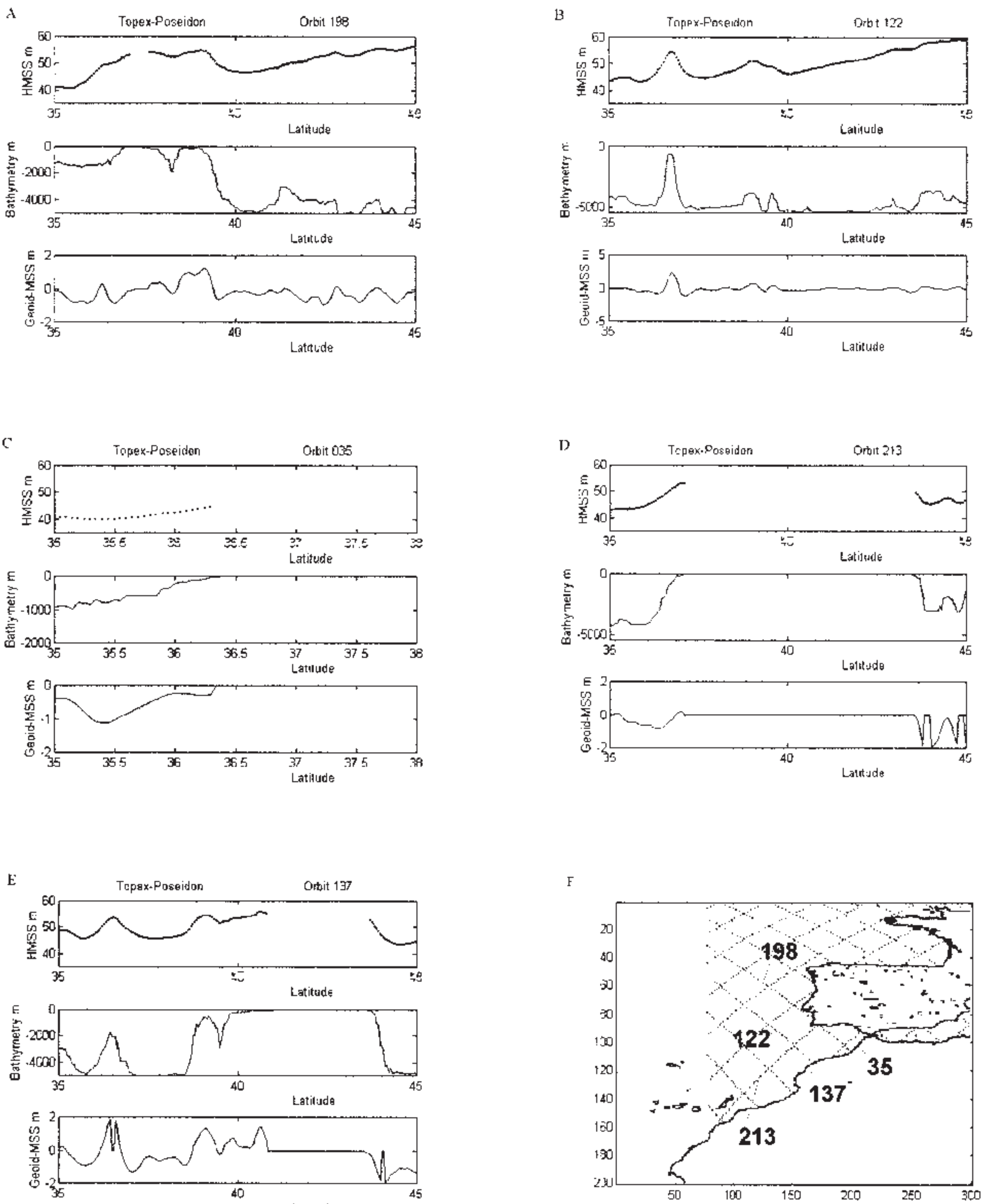

Figure 2. A,B,C,D,E, and F present, in their upper window, the space evolution of the mean sea level (OSUMSS95) along the satellite tracks. The middle window presents the variation in the bathymetry and the lower the differences between the geoid OSU91-a and the mean sea level OSUMSS95. All values are evaluated along the satellite ground track as a function of latitude. F presents the Topex-Poseidon orbits used in the study

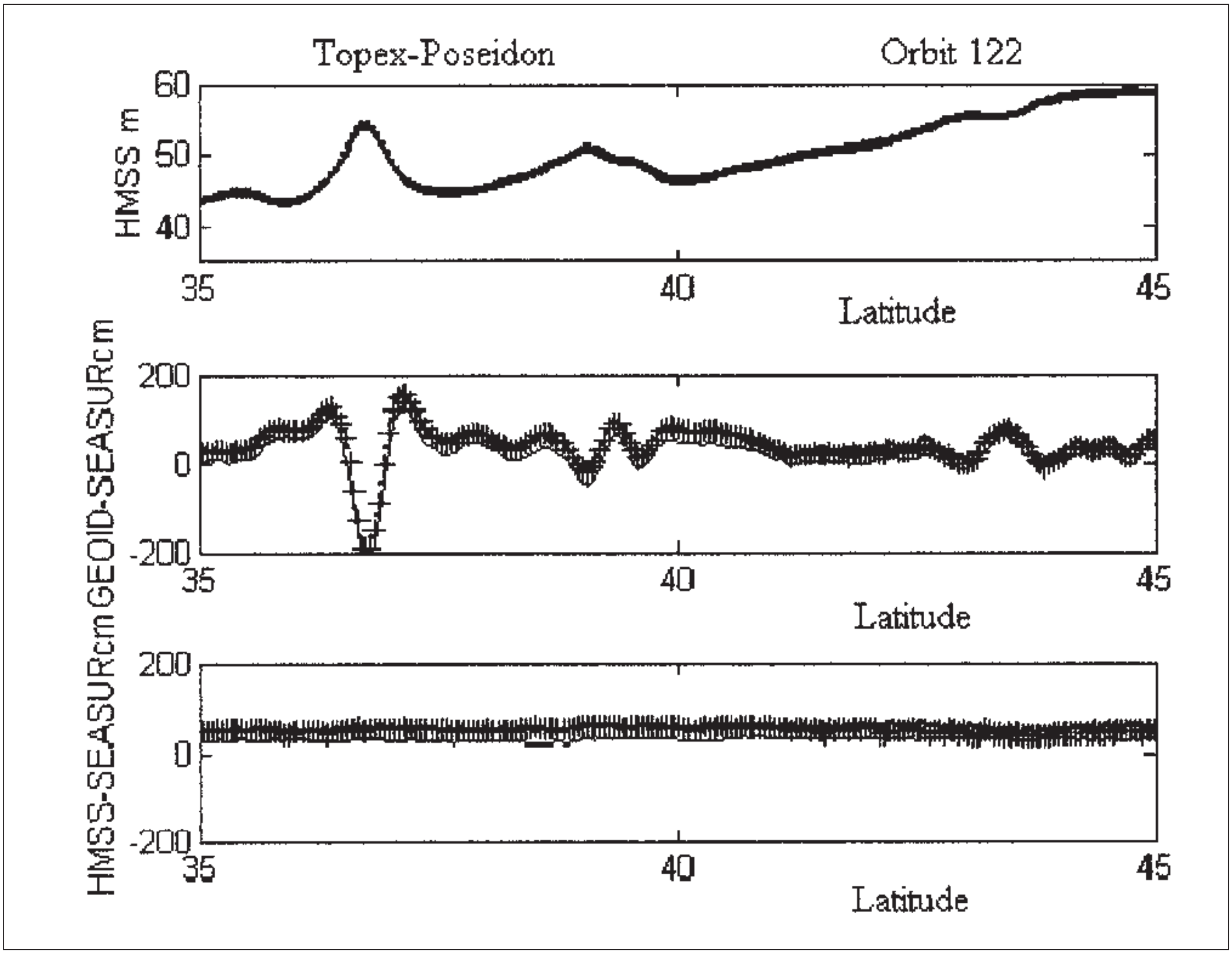

Figure 3. The upper window presents the mean sea level OSUMSS95 variation as a function of latitude along Topex orbit 122. The middle window presents the dynamic signal computed using the geoid OSU91-a, and the lower the same dynamic signal with OSUMSS95, showing the high spatial stability of the dynamic signal during the different Topex cycles

computed with the Geoid OSU91-a and, in the lower window, the same parameter computed with the OSUMSS95. The results shows the high spatial stability of the ocean dynamic signal when using the OSUMSS95, which remains close to zero throughout the entire 122 Topex orbits. The results using the geoid OSU91-a present strong variations in the dynamic signal over the zone of the Gorringe banks, due to their lack of spatial definition along the ground tracks of the satellite.

A Topex-Poseidon satellite sea level variation analysis on selected points of the Iberian Atlantic

Figure 4 presents the sea level variation in two different places of the Iberian Atlantic region, computed after applying equation [1] to the Topex-Poseidon cycles 2 (October 1992) to 148 (October 1996). To avoid the short wavelength noise, we have made our analysis averaging the sea level variation over a window of 21×21, centred on the following geographic positions:

- 36° N and 348° for the value over the point selected in the bank of Gorringe;
- 34.5° N and 352.5° for the Gulf of Cadiz.

In both figures, we can see that autumn presents a maximum in the sea surface level, probably due to the warming of the upper layers of seawater during the summer. Just to give an order of magnitude, we can make a short estimate of the amplitude of this effect using a simple formalism, which allows for a change in the seawater density, between sum-

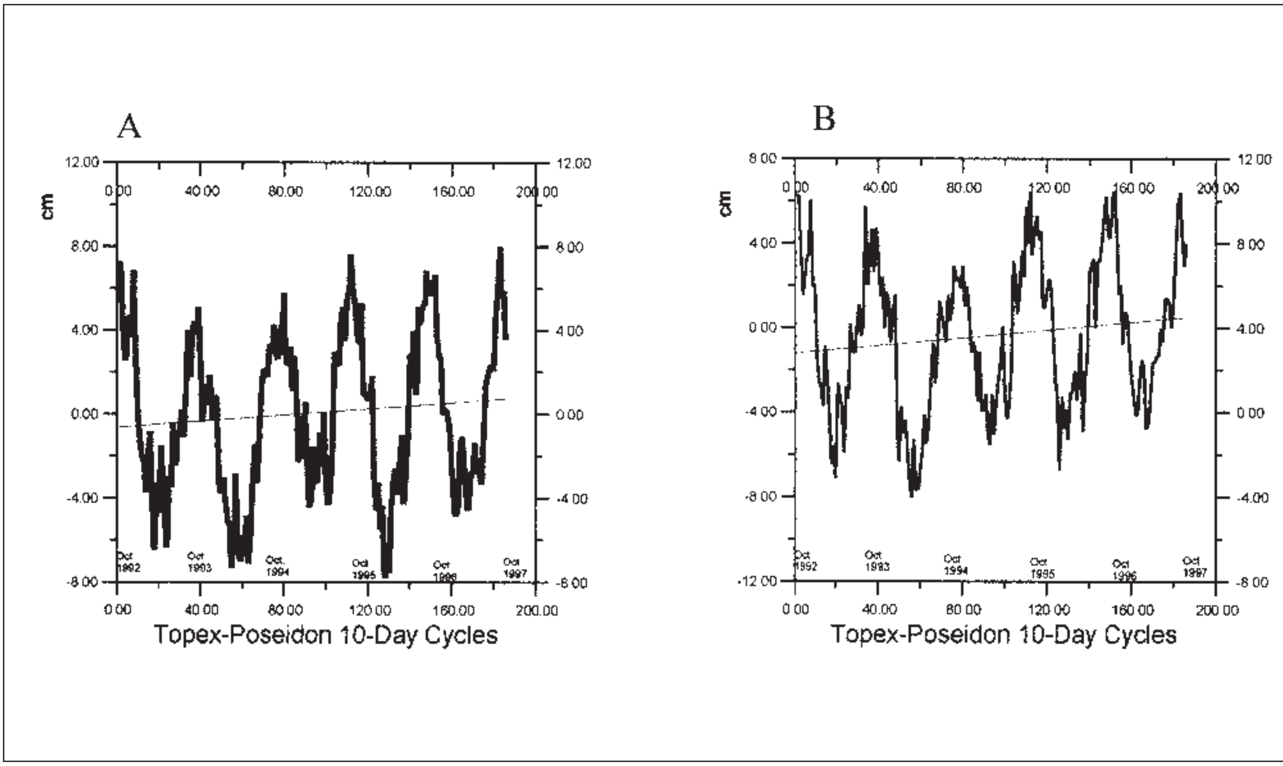

Figure 4. Sea level variation at two different places in the Iberian Atlantic region, computed using equation [1], for the TOPEX-POSEIDON cycles 2 to 186. To avoid short wavelength noise, we computed the sea level by averaging its value over a 21 × 21 window centred on the following geographic positions: 36° N and 348° for the value over the bank of Gorringe, and 34.5° N and 352.5° for the Gulf of Cadiz. Figure 4A,B show a semiannual seasonal variability, reaching a peak-to-peak variation of 18 cm on the Gorringe bank and 14 cm in the Gulf of Cadiz between autumn and winter, which could be explained in part with the ocean masses' thermal expansion, but mainly by the doubtful use of the inverse barometer correction recommended to compute the sea level variation from the altimeter time-series. The peak-to-peak variation shows few variations for the years studied (1992-1997). (A): Sea level variation at Gorringe Baks October 1992-October 1997; (B): Sea level variation at Gulf of Cadiz October 1992-October 1997. The figures also show a secular sea-level variation of 1.6 cm on Gorringe bank and 0.7 cm in the Gulf of Cadiz during 4 years (4 mm/year on Gorringe and 1.7 mm/year at Cadiz) which could be explained by a general increase of global temperature

mer and autumn, from 1 020 kg/m^3 to 1 030 kg/m^3, which could justify a seasonal sea level change of 3 cm.

Figure 4A,B present a higher observed seasonal variation, which could be explained by the doubtful use of the inverse barometer correction in altimeter measurements, following the simple static model that assigns at a 1 mbar of atmospheric pressure variation a sea level change of 1 cm. Figure 5 presents the clear correlation that appears between the sea level series, corrected for inverse barometer effect, and the pressure series time variation in the same location that suggests a failure in the use of the proposed pressure-model correction.

Nevertheless, and following Anon. (1993) recommendations, we decided to apply the standard inverse barometer-model correction, although there is evidence that significant errors can occur, mainly in the cases of high-frequency atmospheric pressure forcing.

Figure 4A,B show that, throughout the 4-year Topex mission, there is a secular sea-level variation trend of 1.6 cm on the Gorringe bank and of 0.7 cm in the Gulf of Cadiz (4 mm/year at Gorringe and 1.7 mm/year at Cadiz), which could be explained because a slight polar ice melting and a possible general increase of global temperature, which heats the deep of the global oceans.

CONCLUSIONS

The use of satellite altimetry in dynamic oceanography studies has its limit in the accuracy of the satellite orbit determination, so gravity modelling improvements in support of the Topex-

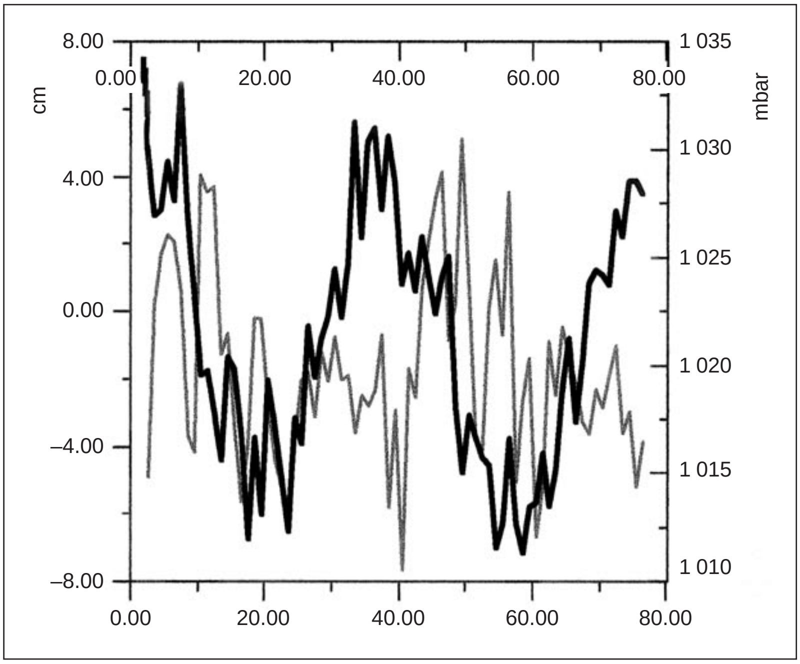

Figure 5. One assumption generally made in the reduction of altimeter time-series is that open and closed ocean response to atmospheric pressure variation closely follows the well-known inverse barometer effect, assuming that 1 mbar variation in the pressure field yields a sea level variation close to 1 cm. The figure shows a clear correlation, with a phase difference of 1801, between the sea level series corrected with the inverse barometer model (in black) and the pressure time local variation (in grey) at a point close to the Gorringe Bank. This correlation suggests that the simple inverse barometer model as a correction in the altimeter time-series should be reconsidered. Leyend: Topex-Poseidon 10-day cycles o2 to 76. Pressure in grey; sea level variation in black (latitude: 35° N and Longitude: 347° N)

Poseidon project began at the Goddard Space Flight Centre in 1983. Error covariance studies done on Goddard Earth Model (GEM-L2) revealed that gravity model improvement of about one order of magnitude would be required to attain the 10-cm accuracy goals of the Topex-Poseidon satellite.

During the 1990s, several gravity models of progressively improved quality were developed using improved data analysis techniques and ancillary models. These efforts culminated in the prelaunch geoid OSU91-a and postlaunch mean sea surface OSUMSS95, which incorporate Topex-Poseidon tracking data. The ocean tide models in the Topex first-generation orbits were based on the Schwiderski model, changing during the mission to the Texas University model (CSR-3), which includes data obtained during the mission.

To analyse the spatio-temporal accuracy of OSU91-a and OSUMSS95, we compared the dynamic signal over the zone, computed using alternatively the two surfaces. The results confirm the high accuracy of OSUMSS95, which appears stable enough to be used for ocean dynamic studies in places that, like the Iberian Atlantic, present strong geoid gradients.

Finally, and noting the Topex satellite orbit accuracy, we computed the sea level variation during cycles 2 to 148 (october 1992 to october 1996) at two points in the Iberian Atlantic, the Gulf of Cadiz and the Gorringe bank. Figures 4A and 4B show, between autumn and winter, a semi-annual seasonal variability that reaches 18 cm of peak-to-peak variation at the Gorringe bank and 14 cm in the Gulf of Cadiz, which could be explained in part by the expected ocean masses thermal expansion, but mainly by errors in the recommended inverse barometer correction applied to the altimeter series. The peak-to-peak variation shows few variations for the years studied (1992-1996).

Figures 4A and 4B also show a secular sea-level elevation trend of 1.6 cm at Gorringe bank and 0.7 cm in the Gulf of Cadiz during 4 years (4 mm/year at Gorringe and 1.7 mm/year at Cadiz). This secular variation could be explained by a general increase of the global temperature, difficult to compute, because the heat stored annually in the upper layers of the oceans is heated and stored, over longer periods, in the deeper oceans.

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REFERENCES

Anon. 1993. *User handbook, Merged TOPEX-POSEIDON Products (GDRs).* Second Edition. AVISO Altimetrie. CNES. Toulouse, France: 35 pp.

Bonnefond, P. 1994. *Method geometrique de trajectrigraphie par arcs courts. Application a l'analyse des mesures altimetriques des satellites TOPEX\POSEIDON et ERS-1 en Mediterranee.* Doctoral thesis. Observatoire de Paris: 80 pp.

Bonnefond, P., P. Exertier, P. Schaefer, S. Bruinsma and F. Barlier. 1995. Satellite altimetry from a short arc orbit technique. Application to the Mediterranean. *Journal of Geophysical Research* 100 (12): 25365-25382.

Douglas, B. C. 1991. Global sea level rise. *J. Geophys. Res.* 96: 6981-6992.

Douglas, B. C. 1995. Global sea level change: Determination and interpretaton "US Natl. Rep. Int. Unioneod. Geophysic. 1991-1994". *Rev. Geophys.* 33: 1425-1432.

Fu, L., E. Christensen, M. Yamarone, M. Lefevre, Y. Menard and P. Escudier. 1994. Topex Poseidon mission overview. *J. Geophys. Res.* 99: 24369-24381.

Gaspar, P, P. Ogor and Y. LeTraon. 1994. Estimating the sea state bias of the Topex-Poseidon altimeters from cross over differences. *J. Geophys. Res.* 99: 24981-24994.

Lambeck, K. 1990. Glacial rebound sea level change and mantle viscosity. *Journal Royal Astronomical Society* 31: 1-30.

Sinclair, A. T. and G. M. Appleby. 1993. A short arc method for determination of station coordinates and baselines applied to the Mediterranean Area. Contributions of Space Geodesy to Geodynamics. *Crustal Dynamics* 23: 389-396.

Tapley, B. D., G. W. Ries and R. J. Davis. 1994. Precision orbit determination for Topex- Poseidon. *J. Geophys. Res.* 99 (C12): 24383-24404.

Wagner, C. and E. Melchioni. 1989. On using precise laser ranges to provide vertical control for satellite altimetric surfaces. *Manuscripta Geodaetica* 14: 305-338.

Wakker, K. F., B. A. C. Ambrosius and L. Aardoom. 1983. *Precise orbit determination for ERS-1.* ESA Contract Report. Delft, Holanda: 104 pp.

Yunk, T. P., W. Bertiger, Y. Wu, S. C. Bar-Server, E. S. Christensen, B. S. Haines and S. M. Lichten. 1994. First assessment of GPS based reduced dynamic orbit determination on Topex Poseidon. *Geophys. Res. Lett.* 21 (17): 541-544.