Analysis of Geoid and Sea Level in the Area of the JASON-1 Calibration Campaign, IBIZA 2003

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ABSTRACT
Actual studies related to calibration of altimeters involves the use of GPS buoys and other systems for the determination of absolute bias in just purely geometric sense. Doing so it seems to be avoided the estimating a marine geoid or the mean sea surface. However, this is not at all true. On the one hand, we need the cross track sea level gradient in order to account the difference in the distance between the altimeter ground track and the position of the point to use in the comparison. On the second hand, an accurate estimation of the surface slope is also needed for linking offshore altimetric data and coastal tide gauges. This is the followed method used to process the Spanish/French JASON-1 calibration campaign, IBIZA 2003. This campaign took place in June 9th-17th, 2003. The area, close to a big island and in a singular place from a dynamic point of view, has a complex local geoid and mean sea surface around. For this reason, in this paper we present some comparisons and correlations between results from this campaign data and some previous results about geoid and mean sea surface in the area, completely independent (in time, and in the kind of data employed: gravimetry or satellite altimetry). The compared surfaces have been some mean sea surface models over the area and local marine geoids, built up from gravimetry and altimetry of ERS ESA satellite, with a higher spatial resolution.

Key words: geoid, sea surface topography, GPS, satellite altimetry.

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1. INTRODUCTION

The Western Mediterranean presents certain complexity from a dynamic point of view. It is very close to some particular features as the Algerian Currents or the Alboran Sea. But this part is itself a region with important ocean circulation. There is a zone of special circulation in the so-called Balearic Sea, the portion of water between the Balearic Islands and the Northeast coast of Spain. The Atlantic waters enter the Sardinian Channel, although part of it does not enter the Eastern Basin through the Straits of Sicily. This part of the water does not circulate in a normal geostrophic pattern due to interaction with other currents. It goes on around the Tyrrhenian Sea, leaves through the Corsica Channel and joins the Corsica Current to form an important cyclonic gyre, the Northern Mediterranean Current (Lehucher et al. 1997) also known as Ligurian-Provençal-Catalan Current.

Dense water forms under the influence of evaporation and surface cooling in the Gulf of Lions shelf. Another factor is the propagation in this zone of some very cold and dry continental winds (e.g. Tramontana and Mistral), produced by the mixing and convection process (Astraldi & Gasparini, 1992). There, the Atlantic water turns into Mediterranean water and becomes denser. The process occurs in the Western basin below 800 m. This is an important event that only happens in a few places such as some areas of the Artic and Antarctic and in the Red Sea. This formation drives a significant part of the Northern Mediterranean Current. The Current enters the area in question from the Gulf of Lions, continues to south-west, contouring the Western part of the Gulf and the Catalan Coast, and goes back along the northern slope of the Balearics (Canals et al. 1997).

Temperature regimes and wind speed guide ocean dynamics. In this case, the inflow of surface Atlantic waters through the west Balearic passages may also change the main circulation path. The area in question includes part of the Balearic Islands. It is a very complicated region because the islands act as a buffer, limiting the Alboran basin (interchange with Atlantic water) and Ligurian-Provençal basin (current).

Strong seasonal level changes are found over the area (Rodriguez & Sevilla, 2000). Great part of them are due to effects of water contraction and dilation resulting from heat fluxes at the ocean-atmosphere boundary. Moreover, there is a part due to imbalance between the coming and going out flows at Gibraltar and Alboran gyre.

The last oceanic feature observed in the area is that an anticyclonic gyre occupies most of the shelf on the Gulf of Valencia (from latitude $38^{o}8$N to $39^{o}5$N) where continental waters run off and recirculate (Lehucher et al. 1997).

Because all of these reasons, the estimation of gravity field and the geoid slope is not an easy task. Presently, there are several global models accomplished by free air gravity anomalies models, but they usually do not fit very well so they do not use to be enough to make accurate determinations.

The North Western Mediterranean has been chosen to perform several experiments of radar altimeter calibrations in 16th-19th March 1999, which was the first altimeter calibration ever developed in Spain, 4th-7th July 2000, 25-28th August 2002 and 9th-17th 2003. See for details Martinez-Garcia et al. (2002) and Martinez-Benjamin et al. (2004).

With all this jobs in the area, it is intended to test the possibility of developing a permanent calibration site.

The last of these experiments, had as main objective to proceed to both: direct and indirect calibration of Jason-1 altimeter. The advantage of the second technique is that it makes possible to perform several point calibrations at every pass with the consequent improvement of the accuracy. But to use it, although the main issue is not to determinate nor the marine geoid either the mean sea surface, the level surface slope between the offshore altimetric measurements and coastal tide gauges is needed.

Within this background, we wanted to see the consistency of data from the last GPS campaign with other results such as altimetry data and gravimetry in the area. We chose data from catamaran because it covers a longer area than the GPS buoys used overall for the direct calibration, which is insufficient to perform the comparisons.

2. CALIBRATION CAMPAIGN

The Spanish JASON-1 calibration campaign, IBIZA 2003, with French support has been made in June 9th-17th 2003 in the area of Ibiza Island in the NW Mediterranean Sea. One of the main objectives has been to map the instantaneous sea level/local sea surface height gradient in three areas around the Ibiza island, with a GPS catamaran in the north area of Ibiza island at one crossing point of an ascending and descending JASON-1 satellite tracks and along these tracks at the SE and SW, as a complementary calibration site for altimetric missions. The IBIZA 2003 campaign has been made with funding from a Project R+D+I of the Spanish Space Program of the Ministry of Science and Technology, CICYT ref:ESP2001-4534-PE and support from the Spanish Navy.

The catamaran consisted of two wind-surf boards and a metallic structure on which the antennas have been fixed following the Senetosa design, (Bonnefond et al. 2003a). It is clearly a much more stable system than GPS buoys. In fact it is one of the most stable boat structures, especially for rolling. The catamaran was equipped with two GPS antennas from Trimble and Leica, in order to perform continuous sea level measurements at a convenient velocity without stopping the GPS data acquisition. Two radomes for protection were placed above the two GPS antennas (Fig. 1).

Figure 1. GPS Catamaran.

During the time it was used a Spanish Navy boat, the Patrol DEVA P29, tracked it at a ~~s~~low speed which allows not stopping GPS data acquisition and not to be corrupted by wave effects, as described in Bonnefond et al. (2003b). Two GPS receivers of the same trademarks than the antennas were used aboard the boat and linked to the antennas of the catamaran by cables independent of the towing rope, at a distance of some 30 m.

Measurements were made in three geographical areas around the Ibiza island at the SW (zone 1), North (zone 2) and SE (zone 3), covering wide areas that include JASON ascending and descending ground track. They can be seen in Fig. 2.

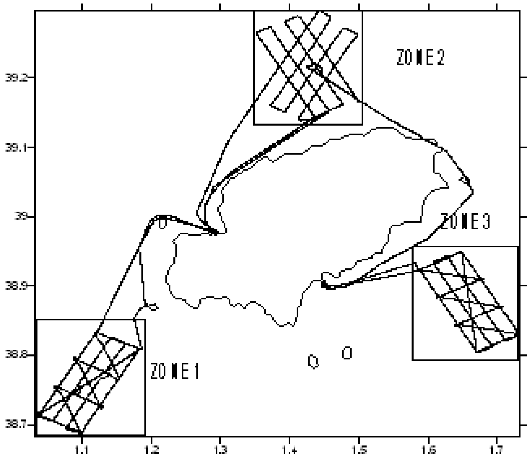


Figure 2. Spatial distribution of GPS catamaran data got during the campaign and designation of analysis zones.

Instantaneous sea level measurements were made in five terrestrial locations: Portinatx, two at San Antonio and two at Ibiza.

The GPS data processing can be divided into two parts. Firstly, very accurate absolute positions in a global reference frame (ITRF2000, epoch 2003.45) of the five GPS stations of reference are needed. This process was performed by the *Instituto Cartografico de Cataluña* using Bernese v4.2 software, fixing three EUREF GPS permanent stations: one in Mallorca, and two in the Peninsula.

Secondly, the datum for the kinematic processing of the GPS catamaran will be defined. The kinematic solutions are based on the high rate GPS data (1 Hz). The mobile receivers ellipsoidal heights are solved relatively to the coordinates of the reference stations chosen in the previous section using POSGPS v4.02 software, from Applanix (see Martinez-Benjamin et al. 2004 for details).

In this study we only use the results of Leica Antenna and receiver. The statistics of the resulting surface in the three analysis areas are shown in Table 1 and the isolines contoured at 5 cm interval in Fig. 3.

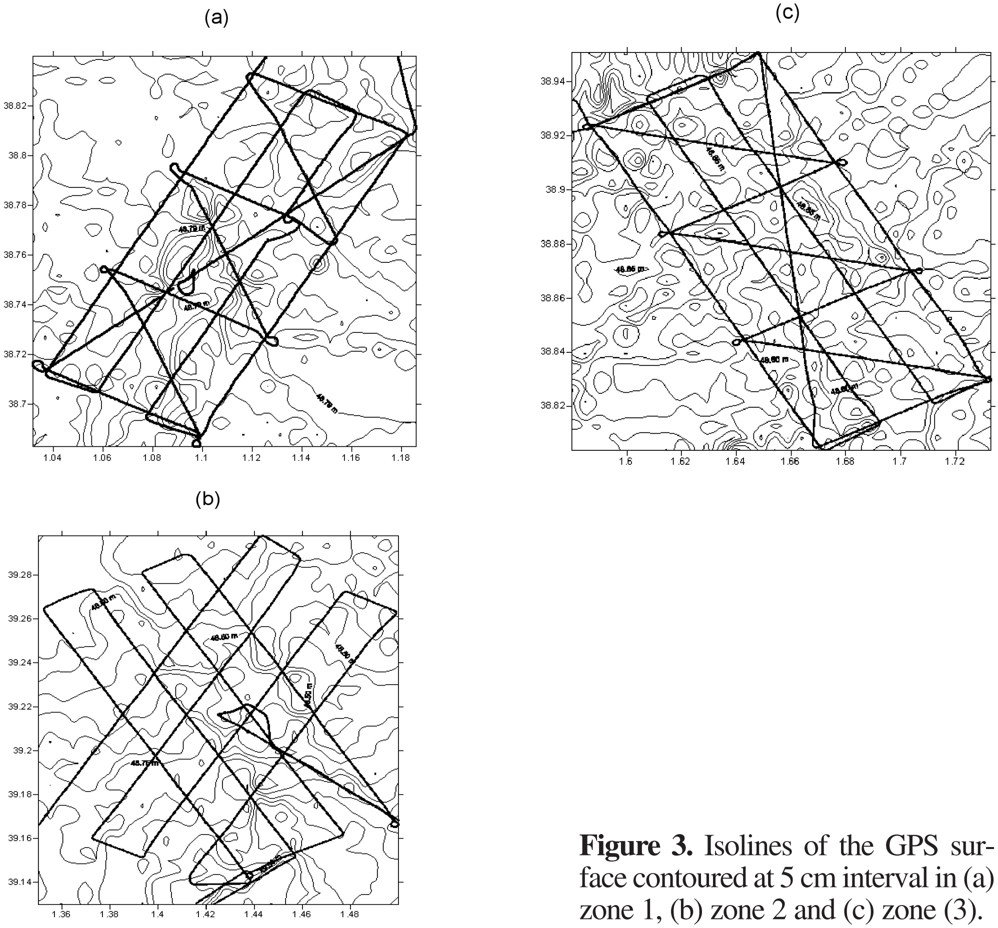


Figure 3. Isolines of the GPS surface contoured at 5 cm interval in (a) zone 1, (b) zone 2 and (c) zone (3).

Table 1. Statistics of the GPS surface over the areas of comparison.

	Mean (m)	S.D. (m)	Min (m)	Max (m)
Z1	48.81	0.23	47.67	49.73
Z2	48.64	0.22	47.73	49.45
Z3	48.73	0.16	48.24	49.54

3. ALTIMETRIC SURFACE

We computed a local mean sea surface over the Western Mediterranean Sea, using sea surfaces heights data from ERS satellite. The data covers one cycle of the geodetic phase (phase E), with repeat period of 168 days. We chose these data because the high repeat period produces a dense spatial distribution and hence are suitable for conducting a study of such a small area. We had 69487 points covering the whole Mediterranean Sea (see Fig. 4), what means 13972 points in the western part.

Data were edited in order to detect and remove some remaining incorrect measurements. We obtained residual heights h_r by subtracting the contribution of a global mean sea surface model MSS, namely the OSU95MSS from Yi (1995).

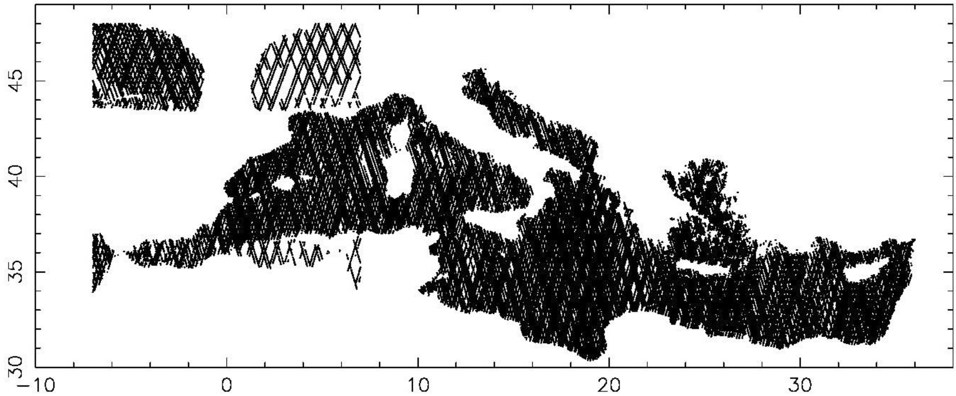


Figure 4. Altimetric data over the Mediterranean Sea.

The residuals were used to detect incorrect data. The measurements should not differ very much from the mean sea surface since the dynamic part does not exceed two meters (Arabelos & Tziavos, 1996). In consequence, we rejected points where residual were over 2 meters. Also, were rejected standard deviations higher than 25 cm respect the whole track and these arcs with less than 23 points, since a crossover adjustment was going to be applied and we tried to avoid an arc with less observations than parameters to determine (Arabelos et al. 1993). 12420 points resulted of this validation procedure. No tidal correction was applied since we did not have the exact data acquisition.

A crossover adjustment was performed with the validated residuals and a mean sea surface is got adding the model back. Statistics of the resulting surface over the area are shown in Table 2. and the contour lines in Fig. 5.

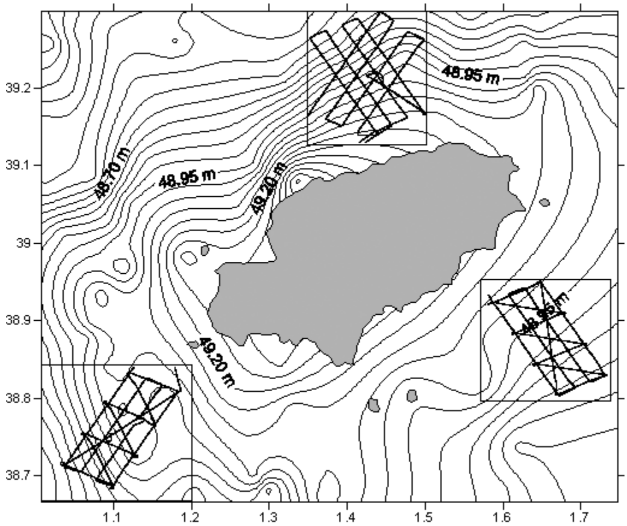


Figure 5. Isolines of the satellite altimetry surface contoured at 5 cm interval.

Table 2. Statistics of the altimetric surface over the areas of comparison.

	Mean (m)	S.D. (m)	Min (m)	Max (m)
Z1	48.92	0.05	48.75	49.06
Z2	48.94	0.15	48.7	49.12
Z3	48.93	0.10	48.89	48.97

We have compared the resulting surfaces over the three zones. From figures, the features are very similar though the sea surface provided by satellite data is higher. In order to do this comparison, weighted average from catamaran data is computed in each point of the altimetric surface. Points up to 0.3 min arc are considered, and the used weight was the inverse of the distance to the point. In almost all the cases, the differences found were positive.

1. In the zone 1 the differences go from -8 to 24 cm.
2. In the second zone the differences are higher from 18 to 48 cm.
3. In the zone 3 the discrepancies are all around 27 cm.

The comparison shows big differences. In order to explain them we have to take into account several circumstances. On the one hand, data from ERS (geodetic phase) were chosen because of the high density due to the repeated period of 168 days, that makes them very proper for such a small area. But they certainly are not the most accurate available altimetric data. On the other hand, satellite altimeter data pose, in general, several problems in areas close to coastal lines and in shallow waters. Firstly, they can be less accurate due to uncertainties in the applied corrections, especially inaccurate tide estimations and, in this case, this correction has not even applied. Even if we have accurate corrected data, several obstacles remain. Basins such as the test area are subject to large seasonal changes as it is explained in Tapley et al. (1994), Knudsen (1994) or Rodriguez & Sevilla (2002). Moreover, these basins are usually small and the islands and irregular coastline shapes may cause data interruptions, which must be removed or else the results may contain major biases. In such an event, the period of time taken into account in the computations becomes a very important factor to consider.

4. GRAVIMETRIC GEOID

The GPS measurements provide the instantaneous mean sea level. The satellite data, with the appropriate treatment, show the mean sea surface. This surface mostly reflects the marine geoid, N. However, due to the ocean dynamics and other circumstances, this result is not an equipotential surface of the gravity field, so it still is not the geoid. The differences between them establish the sea surface topography, SST. The SST is mainly composed of a constant or almost stationary part, SST_o, and a variable part, or mean sea surface variability, much smaller than the first. See for example Heck & Rummel (1989), Rummel (1993) and Visser et al. (1993). For this reason, if we use GPS data to get geoid slope, we will be assuming as zero the SST, so loosing accuracy.

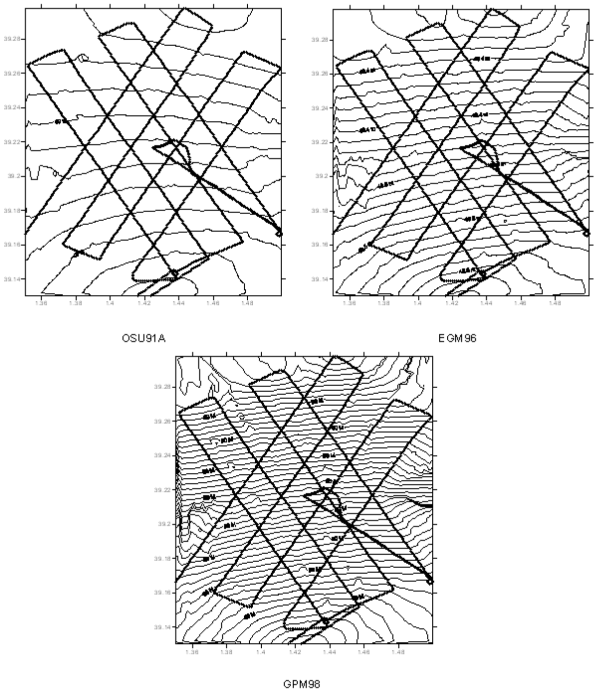
In order to see if the amount of such differences was physically reasonable, we performed the following comparisons.

The geoids that we have used have been computed applying the classical remove restore technique. The geoidal heights were split into three components, as follows:

$$N = N_{MOD} + N_{RTM} + N_{comput}$$

N_{MOD} represents the long wavelength part of the gravity field and is computed from a set of coefficients which represents a geopotential model. N_{RTM} is the topography effect or contribution of high frequencies to the gravity field and N_{comput} the part of the geoid to be computed from the gravity values.

Related to N_{MOD}, there actually are several models available and except for areas with very poor data coverage presented in old models, the differences between them are almost negligible. This is the case for the considered area. In order to be sure of this fact, we have made a sample of data for each zone: 1614 points for zone 1 and 1938 and 1527 points for zones 2 and 3, respectively. We have checked the solutions provided by some of the most commonly used models: OSU91A from Rapp et al. (1991), EGM96 from Lemoine et al. (1997) both of them complete to degree and order 360, and GPM98cr to degree and order 720 (Wenzel, 1998). In all the cases, due to the small area, the obtained surfaces are quite flat, with a low range of variation and short standard deviation. Consequently, the corresponding level lines show parallel curves more or less dense depending of the range of variation of the model. In the three comparisons, the GPM model presents a higher surface and a bigger range of variation but not always parallel from one model to other. As an example, we can see the contour lines corresponding to N_{mod} for the models taken into account in zone 2 (Fig.6). The features in all of them are very similar but the structure of the level lines from OSU91A to GPM model is varying from less to more comprised. This is not surprising since the corresponding standard deviations were 0.02, 0.06 and 0.11 m. Because of these characteristics, the comparisons show also similar features: structure of parallel lines. In general we can say that in all the considered zones, OSU91A show grater discrepancies than the other models. We can see the complete comparison in Tables 3 and 4.



OSU91A EGM96

GPM98

Figure 6. N_{MOD} for the different models in one of the zones of comparison contoured at 1 cm interval.

Table 3. Statistics of N_{mod} over the three areas.

		Mean (m)	S.D. (m)	Min (m)	Max (m)
Z1 (1614 points)	**OSU91A**	49.22	0.06	49.12	49.33
	EGM96	48.62	0.05	49.51	49.73
	GPM98	49.77	0.11	49.56	49.98
Z2 (1938 points)	**OSU91A**	49.36	0.02	49.31	49.43
	EGM96	49.46	0.06	49.35	49.61
	GPM98	49.78	0.11	48.54	49.88
Z3 (1527 points)	**OSU91A**	49.43	0.05	49.32	49.51
	EGM96	49.87	0.03	49.78	49.92
	GPM98	49.89	0.11	49.69	49.98

Table 4. Comparisons for N_{mod} provided by different geopotencial models.

		Mean (m)	S.D. (m)	Min (m)	Max (m)
Z1 (1614 points)	**OSU-EGM**	-44.3	2	-40.3	-35.7
	OSU-GPM	-55.1	5	-65.1	-43.7
	EGM-GPM	-14.8	6	-27	-4
Z2 (1938 points)	**OSU-EGM**	-10.4	3.7	-18.3	-3.7
	OSU-GPM	-42.7	9.3	-59..9	-22.8
	EGM-GPM	-32.3	5.6	-41.6	-19.1
Z3 (1527 points)	**OSU-EGM**	-43.4	2.9	-48.9	-37.5
	OSU-GPM	-47.3	6.2	-59.9	-36.4
	EGM-GPM	-3.9	8.9	-20.7	10.4

If we compare these N_{mod}s with the sea level mapped with GPS described in section 2, we do not expect a good agreement since they really represent different surfaces. The obtained discrepancies are into the expected values (mean values between 40 cm and one meter, being the smaller values obtained in zone 1 meanwhile the greatest are found in zone 3), since they include the part of the geoid contained in the terms N_{RTM} and N_{comput} plus the sea surface topography representing the separation of the whole geoid from the instantaneous sea level.

For the comparisons with the campaign data, firstly two gravimetric geoids were computed using the least-squares collocation (LSC) procedure in the area bounded by: $38^{\circ}5<\Phi<41^{\circ}5$, $355^{\circ}<\lambda<2^{\circ}$. The data used was 9013 free air gravity anomalies from several sources: *Instituto de Astronomía y Geodesia* (IAG), *Instituto Geográfico Nacional Español* (IGNE) and NIMA The data were validated and referred to the same Geodetic Reference System, GRS80.

N_{MOD} was computed from OSU91A model and N_{RTM} was determined taking into account the deviations of real topography from a mean topography (residual terrain model) following Fosberg (1984). The corrections were made by using prism integration. The digital terrain models used were the MDT200 of the IGNE with a resolution of 200 m x 200 m. A coarse model (with resolution of 1 km x 1 km) and a reference model (with resolution of 42 kilometers in longitude and 56 kilometers in latitude) were then generated by applying an average filter on them. The calculation radii used around the point were 15 kilometers for the inner zone and 100 kilometers for the outer zone.

N_{comput} was obtained by least square collocation from the validated residual free air anomalies. The model of covariance function used was selected from Tscherning & Rapp (1974). We employed an empirical covariance function generated from marine and land data together to avoid coastal edge effects. Only minor discrepancies arise between using them separately or together.

The difference between the procedure for creating both geoids was the selection of two separate samples of residual free air anomalies, distributed as homogeneously as possible to avoid prediction biases caused by an irregular distribution. These were used to generate empirical covariance functions. We will call N_1 and $N_{2,}$ respectively. They are fairly similar.

Geoid predictions were made over a grid of five minutes interval in both (latitude and longitude) directions. The result is a fairly smooth surface, especially in the marine part of the area.

The geoid of the Iberian Peninsula (Sevilla, 1995) has been computed by application of Fast Fourier Transform. The geopotential model used was OSU91A and the topography effect was computed by using the Helmert second condensation reduction with a digital terrain model of resolution 1000 m x 1000 m. This Iberian geoid was controlled by GPS points, with an estimated accuracy of 1 ppm, that means, at 1 kilometer distance, the difference between the variations of GPS heights and gravimetric geoid is 1 millimeter. If we compare it with the previous results, we found that all the compared results match well, and only differ in terms of centimeters. Unfortunately, the biggest differences are located in mountainous areas and also in the south of Ibiza Island. In the first case, the discrepancies may be due to the different treatment of the topographic masses, but we do not know the reason for the differences found over the study area.

The isolines of one of these geoids in the analysis area are depicted in Fig. 7 and the statistics are shown in Table 5.

Table 5. Statistics of the geoids over the areas of comparison.

		Mean (m)	S.D. (m)	Min (m)	Max (m)
Z1	$\mathbf{N_1}$	48.89	0.15	48.64	49.11
	$\mathbf{N_2}$	48.88	0.16	48.63	49.14
	$\mathbf{N_{IBE}}$	49.1	0.26	48.73	49.41
Z2	$\mathbf{N_1}$	49.32	0.03	49.26	49.4
	$\mathbf{N_2}$	49.28	0.05	49.2	49.33
	$\mathbf{N_{IBE}}$	49.11	0.43	48.48	49.82
Z3	$\mathbf{N_1}$	48.94	0.19	48.55	49.2
	$\mathbf{N_2}$	48.95	0.21	48.55	49.24
	$\mathbf{N_{IBE}}$	49.63	0.18	49.3	49.9

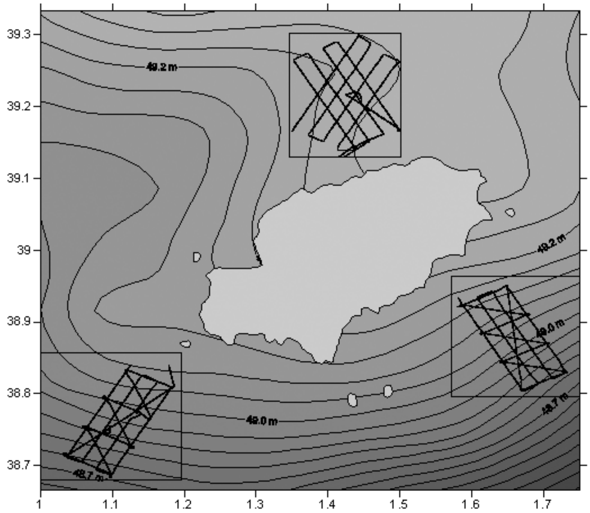


Figure 7. Isolines of one of the gravimetric geoids got by collocation contoured at 5 cm interval.

In the comparison, we compute again the corresponding value from the catamaran in the point where we have the geoid by weighted mean of all the measurements up to a certain radio, usually 0.3 min arc, although in two cases it has reached 0.42 because there were not catamaran points so close.

As both geoids obtained by collocation are very similar, results of comparisons are also very close. Iberian geoid shows bigger discrepancies with catamaran measurements. In all the cases, geoid is a higher surface than instantaneous sea surface level. No biases are observed. The order of magnitude is consistent with SST, because it can measure up to two meters (in open seas), although it tends to measure around 50 cm.

1. In the zone 1 we found differences from 15 to 18 cm. No points from Iberian geoid in the area.
2. In the zone 2 the differences were from 48 to 82 cm, although major part remains a bit under half a meter. The differences with Iberian geoid reach 60 cm.
3. In the third zone, the discrepancies with the two first gravimetric geoids were smaller than in the previous area, going from 10 to 28 cm. However, greater discrepancies with Iberian geoid were observed: from 87 to 98 cm.

These comparisons do not give us lights about which geoid result fits better the area, because as we mention before, the sea level does not reproduce completely the geoid due to the existence of the SST. We only can affirm that the amount of the studied discrepancies does not show any gross error.

5. CONCLUSIONS

From data obtained from a campaign of calibration of JASON-1 altimeter conducted at Ibiza island in June of 2003, an instantaneous mean sea level is determined. We use it as a reference for developing several external comparison. The surfaces involved in this study were mean sea surface models over the, area and local marine geoids. The results found make us to reject the existence of proofs of gross errors in any of the quantities since the obtained order of magnitude is quite realistic. Further studies will be performed with geopotential models obtained from airborne gravimetry when the order of such models were comparable (nowadays the available order is quite lower).

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