# SEA LEVEL DETERMINATION EXPERIENCES AT CAPE OF BEGUR USING ALTIMETRY AND TIDE GAUGES

J. J. Martinez Benjamin[a] , M. A. Ortiz Castellon[b], M. Martinez Garcia[a] , J. Talaya[b], G. Rodriguez Velasco[c], B. Perez[d] and E. Alvarez[d]

[a]Technical University of Catalonia (UPC), Dpt. Geotechnical Engineering and Geosciences, Barcelona, Spain , jj.benjamin@upc.edu
[b] Cartographic Institute of Catalonia (ICC), Barcelona, Spain
[c] Universidad Complutense de Madrid (UCM), Spain
[d] Puertos del Estado (PE), Madrid, Spain

**KEY WORDS:** Calibration, Altimetry, GPS, Tide gauges, Topex/Poseidon, Jason-1

**ABSTRACT:**

Three Begur Cape experiences on radar altimeter calibration and marine geoid mapping made on 1999, 2000 and 2002 are overviewed. The marine geoid has been used to relate the coastal tide gauge data from l'Estartit harbour to off-shore altimetric data. The necessity to validate and calibrate the satellite's altimeter due to increasing needs in accuracy and long term integrity implies establishing calibration sites with enhanced ground based methods for sea level monitoring. A technical Spanish contribution to the calibration experience has been the design of GPS buoys and GPS catamaran taking in account the University of Colorado at Boulder and Senetosa/Capraia designs. Altimeter calibration is essential to obtain an absolute measure of sea level, as are knowing the instrument's drifts and bias. Specially designed tidegauges are necessary to improve the quality of altimetric data, preferably near the satellite track. Further, due to systematic differences a month instruments onboard different satellites, several in-situ calibrations are essentials to tie their systematic differences. L'Estartit tide gauge is a classical floating tide gauge set up in l'Estartit harbour (NE Spain) in 1990. Data are taken in graphics registers from which each two hours the mean value is recorded in an electronic support. In the framework of a Spanish Space Project, the instrumentation of sea level measurements has been improved by providing this site with a radar tide gauge and with a continuous GPS station nearby. This will have a significant incidence in the satellite altimeter calibration activities. The radar tide gauge with data recorder and transmitter is a Datamar 3000C with 26 GHz frequency, 1mm resolution, 8º beam width incorporating a GPS receiver for automatic clock synchronization and a Thales Navigation Internet-Enabled GPS Continuous Geodetic Reference Station (iCGRS) with a choke ring antenna. It is intended that the overall system will constitute a CGPS Station of the ESEAS (European Sea Level) and TIGA (GPS Tide Gauge Benchmark Monitoring) networks. We present a synthesis of the sea level results results obtained from Topex/Poseidon and Jason-1 altimeter calibration campaigns using the direct measurements from GPS buoys and the derived marine geoid

## 1. INTRODUCTION

### 1.1 Satellite Altimetry

Satellite radar altimetry plays a critical role in monitoring the global oceans for scientific uses as well as navigation. The extreme accuracy of Jason-1 (Menard et al., 2003) and Topex/Poseidon, and the additional global coverage of the European satellite Envisat, have created significant advances in oceans and climate studies. Published examples include estimating heat storage in the oceans, detecting interannual waves around Antartica or interannual changes in the Mediterranean, relating physical and biological processes in the oceans, predicting changes in the rotation of the Earth and measuring the rate of change of global mean sea level. In addition precise tidal models were developed for the deep ocean all using T, and there are further developments, especially in shallow coastal waters. These tidal models are used for Precise Orbit Determination, Earth Rotation predictions, and to better understand energy dissipation in the Earth-Moon system.

The radar altimeter measures the instantaneous distance to the sea surface, as well as wind and waveheight. Several altimetric satellites will be the following: Jason-1, joint mission of NASA and CNES launched in December 2001 has been measuring in Ku band (13.575 GHz) and C band (5.3 GHz), and Envisat, mission from the European Space Agency ESA,launched in March 2002 measuring the RA-2 at 13.575 GHz and 3.2 GHz.

Altimeter calibration is essential to obtain an absolute measure of sea level, as are knowing the instrument's drifts and bias. Specially designed tidegauges are necessary to improve the quality of altimetric data, preferably near the satellite track. Further, due to systematic differences a month instruments onboard different satellites, several in-situ calibrations are essentials to tie their systematic differences.

The main technique for positioning moving platforms with GPS, both in post-processing (offline), and in real time, is the kinematic method. It uses the geometric strength of simultaneous observations of several satellites made with a suitable receiver, to determine the instantaneous position of any vehicle, without the need to have a realistic model of the dynamics of the platform, something usually difficult to model mathematically. Since high accuracy can be obtained in this way with GPS, this approach is universally used today. The static method is used when GPS is used to find the position of a fixed site, and that position is treated as constant (after correcting for small site displacements, such as the earth tide).

Finally, one can subdivide all GPS positioning methods into two further categories:

(1**)** Differential Positioning (or 'network approach'), if the data from the roving receiver are combined with that from fixed (reference) receivers at known locations, by forming the differences of simultaneous observations of the same satellites, made from the rover and the fixed receivers, to eliminate common errors (such as in transmitter and receiver clocks), and mitigate others (such as GPS orbit errors, etc.). Precise orbits of the GPS satellites in view, and precise coordinates for the fixed (reference) sites, are needed. Also, high-end, dual-frequency receivers, capable of receiving signals transmitted on the two GPS carrier frequencies (L1 and L2).

(2**)** Point Positioning, when only GPS data from the vehicle's receiver are used; in its most precise form, this method is usually known as Precise Point Positioning (PPP). For PPP, accurate satellite orbits and clock corrections have to be used, along with high-quality, dual-frequency receivers.

Buoys positioned with GPS relative to nearby land-based reference receivers are increasingly being used as instruments for in situ calibration of satellite-born altimeters, (Colombo et al., 2000)

### 1.2 Absolute Sea Level Variations

Sea level is an environmental variable which is widely recognised as being important in many scientific disciplines as a control parameter for coastal dynamical processes or climate processes in the coupled atmosphere-ocean systems, as well as engineering applications.

A major source of sea-level data are the national networks of coastal tide gauges, in Spain belonging to different institutions as the Instituto Geográfico Nacional (IGN), Puertos del Estado (PE), Instituto Hidrográfico de la Marina (IHM), etc.

Tide gauges measure sea level relative to land. Good tidal models exits for the western Mediterranean. They are critically dependent on accurate bathymetric information, which has improved recently. Long-term sea level change has been quantified recently using a decadal data records from Topex/Poseidon and ERS-1/ERS-2 and using long term (several decades to 100 years) tide gauge records.

The currently observed sea level change of 1.1-1.4 mm/yr from tide gauges (Tsimplis and Baker, 2000;Woodworth et al., 2003), and 2.2 mm/yr from satellite altimetry (1996-2000) (Cazenave et al.,2002) indicate substancial regional variability (rise of sea level in the Eastern Mediterranean and a drop of sea level in the western Mediterranean). The validity of the use of satellite altimetry for sea level studies critically depends on instrument calibration and monitoring to determine the relative instrument biases and their potential drifts.

## 2. BEGUR CAPE CALIBRATION SITE

### 2.1 Methodology for Direct Altimeter Calibration

A comparison of the instantaneous sea surface height (SSH) estimated by two independent techniques at the same geographical location and time was the methodology followed [1]. This technique is the so-called direct calibration method. The instantaneous SSH derived from the JASON-1 measurements, that is, the difference between the satellite orbit height ($h_{orbit}$) and the altimeter measurement ($h_{alt}$), which represents the corrected basically raw range of the media delays, troposphere and ionosphere, the sea state bias and the instrumental delay:

$$SSH_{JASON} = h_{orbit} - h_{alt}$$

is compared with the same magnitude $SSH_{tide\ gauge}$, which can be considered a 'true' measurement of the instantaneous sea level, estimated from the measurements of the GPS buoys placed underneath the ascending T/P satellite ground track. The bias of the altimeter is obtained from this comparison :

$$BIAS = SSH_{JASON} - SSH_{tide\ gauge}$$

Three pilot experiments at Begur Cape (NE Spain) were carried out in March 1999 and July 2000 for TOPEX/POSEIDON and August 2002 for JASON-1, as part of the JASON-1 CalVal Team. The first Spanish 1999 campaign using a GPS buoy (Born et. al. 1994; Kruizinga, 1997) included the first direct absolute altimeter calibration of TOPEX Altimeter Site B in the western Mediterranean (Martinez-Benjamin et al. 2000).

The CNES/NASA Jason-1 project has already equipped two devoted calibration sites: at the Senetosa Cape in Corsica for the French side (Bonnefond et al., 2003), and on the Harvest Oil platform off the Californian coast for the USA side (Haines et al., 2003).

Other sites are already equipped, or in installation phase for in situ measurements mainly using tide gauges, in order to help the verification of altimeter range measurements. This is the case for Bass Strait, Tasmania (Australia) (Watson et al.,2003), Gavdos Island (Greece) (Pavlis et al., 2002), Lake Eire (USA) (Shum et al., 2003) and Ibiza / Cape of Begur (Spain) (Martinez-Benjamin et al, 2004.).

### 2.2 L'Estartit float tide gauge

Apart from the in-situ measurements of the SSH made by the GPS buoys, two tide gauges were used in the first campaign. A gauge based in a pressure sensor (AANDERAA) and another one based on a float-operated shaft encoder with and integrated data logger (Thalimedes) were installed at Llafranc harbor. Both tide gauges were referred to a geodetic benchmark provided with a GPS receiver at the harbor jetty and also they were periodically calibrated for monitoring the agreement between their measurements. The AANDERAA pressure sensor at 1meas/min provided with a mean value of the sea level from sets of 15 instantaneous measurements. The float gauge, inside the tube (wave mechanic filtering) provided with instantaneous measurements of the sea level at 1meas/min. Fom the series of sea level measurements collected from 30$^{th}$ March until 6$^{th}$ April 1999, when no important seiches occurred, the agreement between the two independent devices was about 0.45mm with a rms of 7.2mm. In the second campaign a permanent permanent gauge placed at l'Estartit harbor was considered (figure 1).

With respect the monument and instrumentation of the l'Estartit tide gauge, the installation is a traditional floating gauge placed in the inner wall of l'Estartit harbor. It provides with sea level measurements every 2 hours. The accuracy of the height measurements is about 2 mm. The tide gauge heights are geo-referenced to a benchmark in the adjacent jetty identified as number 314 094 002 in the Cartographic Institute of Catalonia (ICC) classification:
UTM coordinates, X= 517199.76m, Y=4655985.52m and Z=+1.72m from the zero reference height of the tide gauge. The coordinates of this geodetic mark have been calculated in 1999 by a precise leveling survey in order to connect the benchmark to the local EUREF sub-network that includes the permanent GPS IGS-IRTF station at Creus Cape, CREU. By carrying out a series of episodic GPS surveying campaigns it would be possible to detect any vertical land movement of the benchmark.

Figure 1: L'Estartit float tide gauge

## 2.3 L'Estartit altimeter calibration area

The contribution of the l'Estartit tide gauge measurements has three important components:

a)Calibration of the GPS buoy. By floating the GPS buoy near the tide gauge one can find if there is any systematic errors in the GPS derived water measurement.

b) Mean Sea Surface Mapping (MSS) during GPS buoy campaign. The GPS buoy measures the instantaneous sea level and is necessary to correct this measurement for the ocean tide and the inverse barometer correction which is measured by the tide gauge taking in account the long term mean sealevel at the tidegauge. Normally it is needed a tide gauge record of 18 years to determine well the mean sea level. Now the l'Estartit float tide gauge is arriving to this period from the start in 1990.

c)Using the same method described in b it is then possible to do altimeter calibration for other times when there is an overflight of any altimeter satellite and no GPS buoys are in the water. Basically the MSS mapping provides a reference to which one can reference the new altimeter measurement. The tide gauge would then provide the time variable part of sealevel. In a way the tide gauge would be the calibration instrument.

This method is called indirect absolute calibration because a mapping is involved to map the tide gauge measurement to the ground track of the satellite. The indirect term really refers to the fact that not a GPS buoy was exactly underneath the ground track during overflight but all the GPS buoy solutions help to adjust the shape model of the MSS to give an absolute reference surface which then can be used to calculate the altimeter bias for any satellite that crosses the strip (in general nominal track ± 1 km). For this reason indirect calibration is less accurate then for instance direct calibration where the GPS buoy is directly underneath the satellite during overflight.

## 2.4 Begur calibration campaigns

Three preliminary campaigns for TOPEX/POSEIDON (T/P) were made in March 1999 and July 2000 and for JASON-1 in August 2002, in the NW Mediterranean Sea at the Begur Cape area.

The instrumentation consists on the reference station at the coast and the GPS buoys. The near tide gauge is only used when performing the indirect method. The reference station close to the satellite ground track is needed in order to achieve kinematic buoy solutions within centimeter accuracy level, which is the typical error assumed for the range measurement of the altimeter.

The GPS data have been processed with the GIPSY/OASIS-II software (JPL). In the three campaigns the GPS data processing has been split in two parts: First, positioning of the reference station at the coast near the calibration area (free-network solution) and, second, differential positioning of the buoy respect to the reference (fiducial) site off the coast (differential kinematic solution).

In all the campaigns, the buoy solution has been computed by using a differential kinematic strategy with short baselines, assuming common atmosphere corrections (ionosphere and specially troposphere) between the fix receiver and the rover. The mean value of the baselines is of 14.3 km and 14.9 km in 1999 and in 2000, respectively, and of 22.4 km in 2002. Previously, the coordinates of the fiducial site at the coast (triangles in fig.1) have been fixed by computing the free-network solution (Zumberge, 1997) that involves several permanent IGS-ITRF stations of the ICC in Catalonia.

The toroidal GPS buoy used in the three experiments (figure1) was performed at the ICC based on the original design of the Colorado University (Born et al., 1994), improving the stability and minimaxing the distance between the sea surface and the center of phase of the antenna..

The models follows some functional requirements as to offer protection to the GPS antenna against the sea water, bad sea conditions and any eventual accident. The radome must allow the GPS signal reception with a minimum disturbance. The small size and manoeuvrability and the stable and recyclable structure for future calibration campaigns was considered. The buoy was provided with a TRIMBLE DORNE MARGOLIN antenna and connected to the receiver on the boat by a coaxial watertight cable (figure 2). The area of calibration is showed in Figure 3.

Figure 2: GPS Buoys used ain the calibration campaigns at l'Estartit area

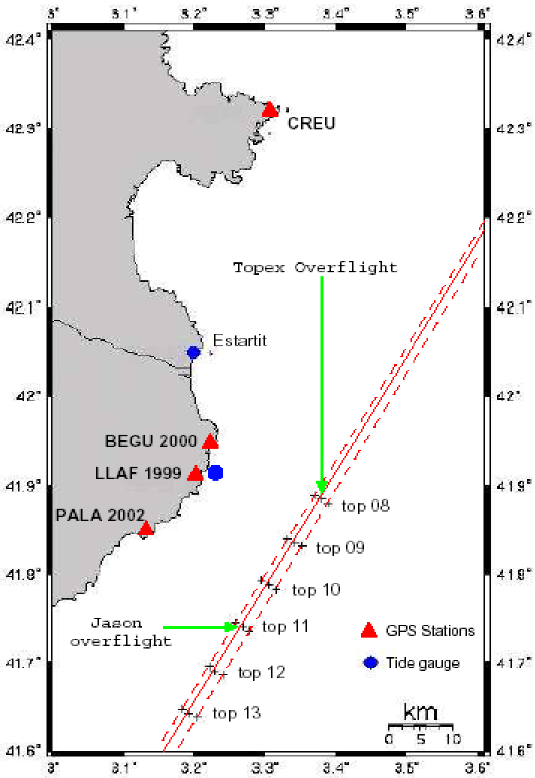


Figure 3: General distribution of the calibration area offshore Begur Cape indicating the surveying points on both the 1999-2000 and the 2002 campaigns. It is represented the nominal T/P ground track in the center and the parallel internal and the external ground tracks for the mapping of the sea surface.

The GPS observables from a network consisted of three permanent ICC stations (Bellmunt de la Segarra, BELL,; Creus Cape, CREU, and Llivia, LLIV), and the temporal site in the coast (station at Begur Cape, BEGU) was processed (Martinez Garcia et al., 2000) following a free-network solution strategy (Zumberge et al., 1997) with the GIPSY-OASIS II software developed by JPL.

The SSH measured by the altimeter at the overflight is compared with the same magnitude derived from the buoy solution. Thus the range bias is computed by the methodology below:

1st.- The straight average of the estimated $SSH_{GPS}$ along a $\approx 5$ min time window centered at the overflight instant and the rms respect to the mean value are computed.

2nd.- The LSQ adjust of the SSHalt along a $\approx 20$-observations window centered at the overflight instant and the rms of the window respect to the adjust are computed. They are M-DGR products for the T/P and I-GDR products for the Jason-1.

3rd.- The averaged $SSH_{GPS}$ and the adjusted $SSH_{alt}$ at the overflight are subtracted in order to compute the $SSH_{BIAS}$. Thus $SSH_{BIAS} = SSH_{GPS} - SSH_{alt}$ and

$$rms_{BIAS} = \sqrt{rms_{GPS}^{\;2} + rms_{alt}^{\;2}}$$

| Overflight (UTC time) | $SSH_{GPS}$ (m) | $SSH_{alt}$ (m) | $SHH_{BIAS}$ (cm) |
|---|---|---|---|
| 18/03-08:45:41 T/P 239 | $49.12 \pm 0.319$ | $49.05 \pm 0.04$ | $6.50 \pm 32.10$ |
| | $49.09 \pm 0.323$ | $49.05 \pm 0.04$ | $3.70 \pm 32.60$ |
| 07/07-07:34:47 T/P 287 | $49.24 \pm 0.074$ | $49.21 \pm 0.04$ | $3.43 \pm 7.96$ |
| 28/08-15:37:07 J23 | $49.29 \pm 0.061$ | $49.18 \pm 0.08$ | $10.52 \pm 10.3$ |

Table 1: $SSH_{BIAS}$ estimation by single point experiments over point TOP-08 for TOPEX-B and over point TOP-11 for Jason-1 radar instruments. The two values in 1999 corresponds to both similar GPS buoys used simultaneously at that campaign (UPCB and JPLB buoys, respectively).

In table 1 the straight averages of the estimated $SSH_{GPS}$ are collected with their corresponding rms. The LSQ adjust of the $SSH_{alt}$ provides with the altimeter measurement of the instantaneous sea surface at the overflight instant. The associated rms for these measurement are 4.03 cm for the TOPEX Alt-B [Fu and Cazenave, 2001] and 8.34 cm for Jason-1, in agreement with [Haines et al., 2003].

The most scattered $SSH_{GPS}$ estimations (higher rms) corresponds to 1999, mainly due to the SA, that was turned off on 2nd May 2000. Both the rms values in 2000 and in 2002 experiments present similar order of magnitude. Also, as the baseline is longer in 2002 than in 2000 or 1999, it is expected that the common tropospheres assumption is less realistic in the last campaign than in the others, which supposes less accurate vertical coordinate estimation in 2002 than in 2000 or 1999.

## 3. FUTURE ACTIVITIES

### 3.1 Monitoring sea level at l'Estartit

Moreover with the adquisition of an Ashtech GPS system of geodetic quality (iCGRS system), that is being installed at l'Estartit close to a Jason-1 ascending track, (complementing the main observations at Ibiza), and a radar tide gauge DATAMAR 3000C (Figure 4), it will be possible to carry out not only sea level studies with tide gauge observations but indirect altimeter calibration using the spanish networks from the IGN, Instituto Geográfico Nacional, and ICC, Cartographic Institute of Catalonia.

Figure 4: Radar tide gauge devices incorporating a GPS receiver for automatic clock synchronization ready to be installed at L'Estartit harbour. This modern installation will work in a parallel way to the classical floating gauge active since 1992. Images and deployments provided by Geonica sl, Earth Sciences.

### 3.2 Preparation of Lidar airborne flights

Airborne lidar data, spaceborne laser altimetry and spaceborne gravimetry are becoming technologies very useful to be applied to the l'Estartit sea/land area. It is expected to make an airborne campaign at Begur Cape area with a CESSNA Caravan 2083 (ICC) carrying an Optech Lidar ALT-3025 (Figure 5).

The main reason of it is to test the potential of Lidar to connect sea level measurements from tide gauges at the coast with satellite (as Jason-1 or Envisat) altimetry measurements offshore.

The calibrated airborne Lidar can then be used over ocean to detect the sea surface height. In consequence, the objective is to check that the coastal sea level can be observed with GPS buoys and may be Lidar campaigns for get detailed regional geoid and sea surface topography models for referencing satellite altimeter measurements.

In fact, the coastal sea level can be observed with GPS buoy, and may be Lidar airborne campaigns.

Figure 5: Lidar/airplane

The campaign to be made in May/June 2007 will follow the trajectories showed in Figure 6. The crossing point is near l'Estartit harbour where are located the tide gauges. The objective would be to study the feasibility of the determination of sea surface topography based on airborne laser altimetry and GPS buoy measurements as a contribution of an international effort to establish European calibration altimeter sites.

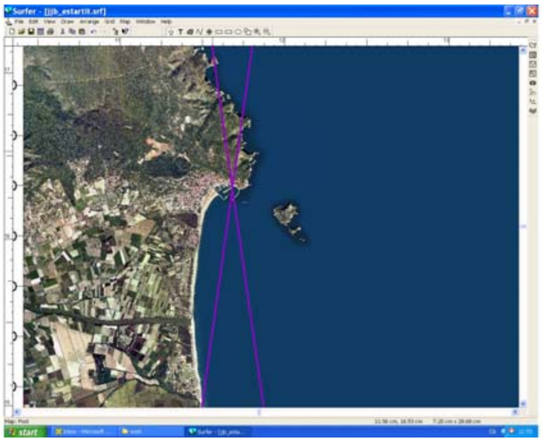

Figure 6: Expected trajectories of the Lidar airborne flight near l'Estartit harbour.

## REFERENCES


Bonnefond, P., P. Exertier, O. Laurain, Y. Menard, A. Orsoni, G. Jan, and E. Jeansou. 2003. Absolute Calibration of Jason-1 and TOPEX/Poseidon Altimeters in Corsica, *Marine Geodesy*, 26(3-4), 261-284.

Born, G.H., M.E. Parke, P. Axelrad, K.L. Gold, J. Johnson, K.W. Key and D.G. Kubitscheck. 1994. Calibration of the TOPEX altimeter using a GPS buoy. *J. Geophys. Res.* 99(C12), 24517-24526.

Cazenave, A., Cabanes,C.,Dominh,K. And Mangiarotti,J. 2001. Recent sea level changes in the Mediterranean Sea revealed by Topex/Poseidón satellite altimetry, Geophys. Res. Let., 28(8), 1607-1610.

Colombo, O.L., A.G. Evans, M.I. Vigo-Aguiar, J.M. Ferrandiz and J.J. Benjamin. 2000. Long-baseline (>1000km), sub-decimeter kinematic positioning of buoys at sea, with potential application to deep-sea studies. Proceedings ION GPS 2000 Meeting, 19-23 September 2000, Salt Lake City, USA.

Fu L.L., A. Cazenave, 2001, *Satellite altimetry and Earth sciences, A Handbook of techniques and applications.* International Geophysics Series, 69, Academic Press, San Diego.

Haines, B.J., D. Dong, G.H.Born and S.K.Gill. 2003. The Harvest experiment: Monitoring Jason-1 and TOPEX/POSEIDON from a California offshore platform, *Marine Geodesy*, 26(3-4), 239-259.

Kruizinga, G., B. Haines, J. Martinez Benjamin, M. Martinez Garcia, J. Talaya, M.A. Ortiz and B. Perez, The CATALA experiment, preliminary results of Alt-B calibration using GPS buoys off the Catalonia coast (Spain), Alt-B Calibration Workshop, April 22, Goddard Space Flight Center, Greenbelt, Maryland, USA, 1999.

Martinez-Benjamin, J. J., M. Martinez-Garcia, M. A.Ortiz, J. Talaya, J. Garate, J. M. Davila, J. M. Ferrandiz, M. I. Vigo-Aguiar, B. Perez and E. Alvarez. 2000. The CATALA campaigns: indirect calibration technique for ENVISAT altimeter calibration, Proceedings CD-ROM SP-461, 7 pages, ESA ERS-ENVISAT Symposium, 16-20 Oct. 2000, Gothenburg, Sweden.

Martinez-Benjamin, J.J,M. Martinez, S. Gonzalez,A.Nunez, F. Buill,M. Espino,J. Lopez, J.Martin Davila,J. Garate,C. Garcia,P. Bonnefond,,O. Laurain,A.M. Baron,M.A. Ortiz,J. Talaya,B. Perez,E. Alvarez,G. Rodriguez,D. Gomis,M. Marcos,Y. Menard,G. Jan,E. Jeansou,F. Lyard, and L.Roblou.Ibiza Absolute Calibration Experiment: Survey and Preliminary Results, *Marine Geodesy*, Special Issue on Jason-1 Calibration/Validation, Part 3, Vol. 27, No. 3-4, 2004.

Menard, Y., Fu, L.L., Escudier, P., Parisot, F., Perbos, J., Vincent, P., Desai, S., Haines, B. And Kunstmann, .2003. The Jason-1 Mission. *Marine Geodesy* 26:131-146.

Pavlis, E.C. and the GAVDOS Team. 2002. Absolute Sea Level Monitoring and Altimeter Calibration at Gavdos, Crete. Proceedings of the Jason-1 SWT Meeting, 10-12 June 2002, Biarritz, France.

Shum, C.K., Y. Yi, K. Cheng, C. Kuo, A. Braun, S. Calmant and D. Chambers. 2003. Calibration of JASON-1 Altimeter over Lake Eire, *Marine Geodesy*, 26(3-4), 335-354.

Tsimplis, M. and Baker, T. 2000. Sea level drop in the Mediterranean Sea: An indicator of deep water salinity and temperature changes. *Geophys. Res. Let.*, 27, 1731-1734.

Watson C., R. Coleman, N. White, J. Church. And R. Govind. 2003. “Absolute Calibration of TOPEX/Poseidon and Jason-1 using GPS Buoys in Bass Strait, Australia”, *Marine Geodesy*, 26(3-4), 285-304.

Woodworth, P., 2003. Some comments on the long sea level records from the northern Mediterranean, *J. Coast. Res.*, 19(1):212-217.

J. Zumberge, M. Heflin, D. Jefferson, M. Watkins and F. Webb, Precise point positioning for the efficient and robust analysis of GPS data from large networks, J. Geophys. Res, 102, 1997.

## ACKNOWLEDGEMENTS

All of these campaigns have been supported by the Spanish Ministery of Science and Technology under projects of the National Space Program ref: ESP1997-1816-CO4-03 and ESP2001-4534-PE.