JASON-1 AND TOPEX/POSEIDON ALTIMETER CALIBRATION CAMPAIGNS IN THE WESTERN MEDITERRANEAN

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KEY WORDS: Calibration/Validation, GPS, Satellite Altimetry, Tide gauges

ABSTRACT: 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 and Topex/Poseidon, and the additional global coverage of the European satellite Envisat, have created significant advances in geodetic, oceanic and climate studies. Altimeter calibration is essential to obtain an absolute measure of sea level, as are knowing the instrument's drifts and bias. Specially designed tide gauges are necessary to improve the quality of altimetric data, preferably near the satellite track. Further, due to systematic differences among instruments onboard different satellites, several in-situ calibrations are essentials to tie their systematic differences. We present synthesis of the results obtained from Topex/Poseidon and the first results on Jason-1 altimeter calibration using the measurements from a GPS Catamaran and the derived marine geoid. They agree relatively well with results obtained at Corsica, Harvest and Bass Strait calibration permanent sites. Moreover, the geodetic activities (e.g., GPS, levelling) has permitted to build a very accurate (few mm) local network linked to the European one, with a reference frame compatible with the satellite altimetry missions (ITRF2000). The GPS kinematic data were processed using two different softwares allowing to check the consistency of the solutions.

1. INTRODUCTION

During the last years, complementary altimetric missions have notably permitted to compare instruments: relative calibrations have been achieved, global statistics and results show the power of such a technique. However, through these missions, problems have been discovered both in the algorithms and the instruments: the oscillator drift corrections for TOPEX/Poseidon and more recently in the JMR wet path delay correction for Jason-1. This has reinforced the interest of absolute calibration campaigns to detect such problems in near-real time. Beyond the calibration of the altimeters, the calibration sites also are very useful in assessing the various components of the altimetric systems, even if it is only a single-point verification. Absolute calibration of radar altimeters at the centimeter level or less is one of the most difficult challenges in Space Geodesy. Indeed, the realization of the closure equation - to compare terrestrial sea level measurements with sea heights deduced from satellite altimetry - requires a very specific area where several kind of quantities (sea level, terrestrial positioning, orbit, etc.) have to be precisely and simultaneously measured at each overflight of the altimeter satellite. This leads to perform, with a very high accuracy, comparisons between the used techniques (in situ and space ones) in a homogeneous geocentric reference frame. The global error budget of the absolute calibration experiment is thus very difficult to achieve, because of all kinds of possible systematic errors. The main absolute calibration experiments realized in the recent past (Born, G. et al., 1994, Ménard et al., 1994; Bonnefond et al., 2003b; Martinez-Benjamin, J.J.;2004) showed this difficulty clearly. As a consequence of the increased precision of the satellite altimetry technique (instrumentation, orbit, and corrections) over the last ten years, requirements are now at the centimeter level and even less for the altimeter bias determination. This makes absolute calibration a field campaign which can be very expensive economically, but remains strictly necessary for a given oceanographic mission and especially for a series of successive missions (over several decades).

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. A Spanish JASON-1 geoid gradient campaign with French support has been made in June 2003 at the Ibiza island in the NW Mediterranean Sea, following an experience at Cape of Begur made in 2002. The main objective has been to map with a new designed, builded and calibrated GPS catamaran, the local geoid gradient in three areas around Ibiza island under the ascending (187) and descending (248) Jason-1ground tracks. The catamaran equipped with two GPS antennas to perform continuous sea level measurements was towed by the Patrol Deva from the Spanish Navy. Five GPS reference stations were deployed on Ibiza island: one in Portinatx, two in San Antonio and two in Ibiza. The marine geoid has been used to relate the coastal tide gauge data from Ibiza and San Antonio harbours to off-shore altimetric data. In the framework of the campaign, the

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levelling of the Ibiza and San Antonio tide gauges to the respective GPS markers was performed.

2. ALTIMETER CALIBRATION METHODS

A description of the principles involved in the altimeter calibration methodology is given. In the Spanish campaigns, ocean surveying with GPS catamaran and/or wave-rider GPS buoys has been mainly oriented to:

- The direct estimation of the instrumental bias of the radar altimeter on board the satellite.

In this direct calibration method the instantaneous SSH derived from the JASON-1 altimeter measurements, that is, the difference between the satellite orbit height (h_{orbit}) and the altimeter measurement (h_{alt}) which represents the raw range corrected basically of the media delays, troposphere and ionosphere, the sea state bias and the instrumental delay:

$$SSH_{JASON} = h_{orbit} - h_{alt} \quad \text{with } h_{alt} = h_{true} + BIAS$$

is compared with the same magnitude SSH_{GPS}, 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. By this comparison the bias of the altimeter is obtained:

$$BIAS = SSH_{GPS} - SSH_{JASON}$$

The direct calibration supposes the straight comparison of the altimeter and the buoy simultaneous sea surface heights at the same point, and is also called single point calibration. If BIAS>0 the meaning is that the altimeter is measuring too long thus h_{alt} is larger than h_{true}. If BIAS<0 the meaning is that the altimeter is measuring too short thus h_{alt} is smaller than h_{true}.

The single point calibration has been successfully performed in the calibration campaigns and has the advantage of needed neither geoid nor tidal modelling (is a direct comparison of measurements). The drawback is the fact that as the error in the estimation of the range bias decreases with the root square of the number of monitorized overflights, a major number of single point performances gives more reliable and accurate bias computation. Thus, it is desirable systematic performances of single point calibrations in order to minimize the error of the final range bias estimation. Unfortunately, this means continuous economic and manpower efforts that can not be performed during an undefined time.

Then the direct overflight is most accurate with the sea level independently measured by the GPS buoy directly underneath the satellite altimeter.

For GPS buoy the following instrumentation are required:
-calibration bath for fully equipped buoy to determine the waterline in undisturbed local sea water.
-boat.
-buoy.
-GPS receiver and antenna (data collection rate at 1/s for about one hour before and after the overflight).
-reference GPS site (1/s).
-meteorological data (surface pressure, temperature, humidity and wind speed) at the time of overflight.
-possible laser tracking of the satellite.

-More interesting is the GPS determination of the instantaneous marine sea level in view of the Mean Sea Surface (MSS). If we consider a nominal Jason-1 ground track and a +/-1km exterior and interior strip, after correcting all the measurements for tides (models) and environmental corrections it is computed the MSS for each location in the strip as the MSS_ALT(X,Y) given by altimetry, where X and Y are the along track and cross track coordinates.The shape of the MSS is very well known along the strip but no the absolute height of the MSS with respect the center of the Earth because the altimeter measurements are biased.

If MSS_TRUTH is the best estimate of the real MSS,
MSS_TRUTH(X,Y)=MSS_ALT(X,Y)+MSS_BIAS

It is needed to determine the MSS_BIAS using independent measurements, by example, using GPS buoys or GPS catamaran to estimate MSS_BIAS with mapping,

MSS_BIAS(X,Y)=MSS_GPS(X,Y)-MSS_ALT(X,Y)=SSH_GPS(X,Y)-Delta_Tide-MSS_ALT(X,Y)

where SSH_GPS is the instantaneous sea surface height measured by the GPS buoy/catamaran at the (X,Y) points of the strip and Delta_Tide is the tide gauge measurement minus a long term mean tide gauge measurement.

The MSS_BIAS is computed by,
MSS_BIAS=[SUM i=1,N of MSS_BIAS(i)]/N

The indirect calibration is really the reverse of MSS mapping but the MSS_BIAS has been taken into account. If an altimetric satellite crosses the strip at location (X_s,Y_s), the calculated instantaneous sea surface height SSH_CALC is

$SSH\_CALC(X_s,Y_s)=MSS\_TRUTH(X_s,Y_s) + DELTA\_TIDE$ *(at time of overflight)*

Delta_Tide calculated the same way as before except is it compute at the time the satellite flies over the strip.

The altimeter bias is then calculated according to,

$Altimeter\_Bias=SSH\_CALC(X_s,Y_s) - SSH\_ALT(X_s,Y_s)$

where SSH_ALT(X_s,Y_s) is the instantaneous sea surface height calculated by the altimeter measurement made by the satellite crossing the strip.

Then the indirect overflight is less accurate. Satellite altimeter passes close to a tide gauge (about 15 km) and sea level from tide gauge needs to be mapped (geoid and tide) to foot print of the altimeter.The mapping of the geoid can be achieved by surveying along the satellite ground track with a GPS catamaran or GPS buoy (observe each location about 1 hour at 1/s rate). This height is then corrected to the geoid by removing the tide derived from repeat track analysis. Using this method one assumes that the dynamic topography close to the coast is close to 0.

3. CAPE OF BEGUR CAMPAIGNS

3.1 Overview

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.

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 (fig.2) was performed at the ICC based on the original design of the Colorado University (Born et al., 1994).

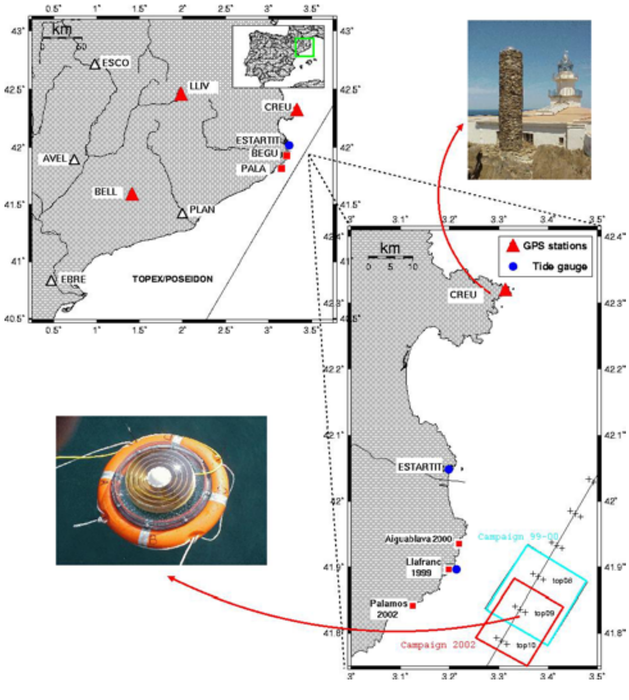

Figure 1: General distribution of the calibration site of Begur. The GPS network of the ICC in Catalonia and the calibration area offshore Begur Cape indicating the surveying points on both the 1999-2000 and the 2002 campaigns. It is represented the nominal T/P ground track in the center and the parallel internal and the external ground tracks for the mapping of the sea surface.

3.2 Direct Calibration

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 ≈ 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 ≈ 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

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

The analysis have been made using the Altimeter products, M-GDR Topex Alt B in 1999 and 2000, and I-GDR Jason-1in 2002.

Overflight (UTC time)	SSH_{GPS} (m)	SSH_{alt} (m)	SHH_{BIAS} (cm)
18/03-08:45:41 T/P 239, 1999	49.12 ± 0.319	49.05 ± 0.04	6.50 ± 32.10
	49.09 ± 0.323	49.05 ± 0.04	3.70 ± 32.60
07/07-07:34:47 T/P 287, 2000	49.24 ± 0.074	49.21 ± 0.04	3.43 ± 7.96
28/08-15:37:07 J23, 2002	49.29 ± 0.061	49.18 ± 0.08	10.52 ± 10.3

Table 2: 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 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.

4. IBIZA CALIBRATION CAMPAIGN

4.1 Overview

A Spanish (with French support) JASON-1 calibration campaign, IBIZA 2003, was carried out in June 9-17, 2003 around Ibiza in the NW Mediterranean Sea. The main objective of the campaign was to map the instantaneous sea level/local geoid gradient in three areas around Ibiza: at the crossing point of ascending and descending JASON-1 tracks located to the north of the island, and along these tracks to the SE and SW of the Island. The campaign was based on the experience gained from three previous pilot experiments at Begur Cape (NE Spain).

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., 2003b), 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), Capraia Island (Italy) , Gavdos Island (Greece) (Pavlis et al., 2002), Lake Eire (USA) (Shum et al., 2003) and Ibiza / Cape of Begur (Spain).

A catamaran equipped with two GPS antennas to perform continuous sea level measurements at a convenient velocity was built up using two wind-surf boards and a metallic structure onto which the antennas were fixed. The design followed the model used in Senetosa measurements (Bonnefond et al., 2003a), and is stable enough to be towed by the Patrol Deva P29, from the Spanish Navy, (Figure 3) at a convenient speed without stopping GPS data acquisition. Two radomes for protection were placed above the two GPS antennas, a Trimble (CATL), and a Leica (CATR). Two GPS receivers, Trimble and Leica, were used aboard the Deva and linked to the antennas of the catamaran by cables independent of the towing rope at a distance about 30 m. Measurements were made in the harbours of San Antonio and Ibiza, with the catamaran close to the GPS buoy and at the same time as tide gauge records.

A zodiac from the Spanish Navy was also used to deploy a light wave-rider GPS buoy at Ibiza and San Antonio harbours. The objective was to provide instantaneous geocentric sea-level measurements with the instantaneous nearby GPS data obtained with the catamaran (an optical levelling was carried out in both harbours). A direct altimeter absolute calibration was made (on June 14) with the catamaran and the GPS buoy near the crossover point located to the north of the island.

The role of the tide gauge measurement in the Ibiza campaign had three main components:

-Calibration of the GPS buoy. Before and/or after calibration campaigns the GPS buoy is deployed at tide gauge locations to make direct comparisons of sea level determination. By floating the GPS buoy near the tide gauge one can find out is there are systematic errors in the GPS derived water measurement. For this it is assumed that there are no errors in the tide gauges, which is not necessary true, but we have handmade water level measurements to compare and to look at if they matched well.

-Mean Sea Surface Mapping MSS during GPS catamaran campaign. The GPS catamaran measure the instantaneous sea level and we need to correct this measurement for the ocean tide and inverted barometer correction which is measured by the tide gauge. We can only do it if it is known the long term mean sea level at the tide gauge. Normally it is needed a tide gauge record of 18 years to determine this mean sea level well. GPS buoy measurements also provide the sea height variations due to waves.

-Using the same method described before it is then possible to do altimeter calibration for other times when there is an overflight of JASON-1 (or any other altimeter satellite) and no GPS catamaran or 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 sea level. This is a cheap way of calibration and only a tide gauge on shore would be required. In a way the tide gauge would be the calibration instrument.

Figure 2. Inter-calibration catamaran/GPS buoy at the Ibiza harbour

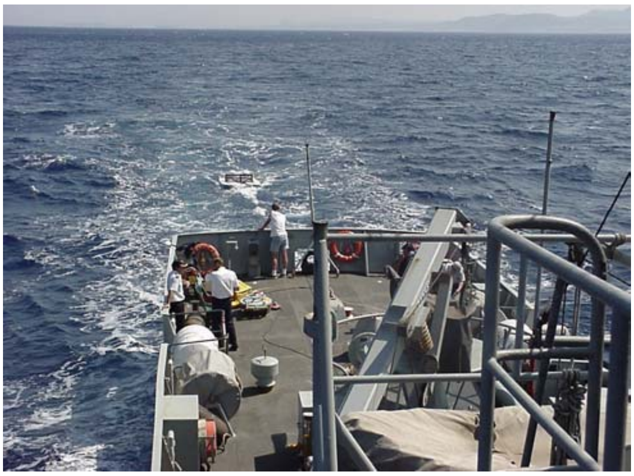

Figure 3. The catamaran towed by the Spanish Navy Patrol Deva

4.2 GPS data processing

The GPS data processing was divided into two parts: first we need very accurate absolute positions (particularly in the vertical component) in a global reference frame coherent with the one commonly used for T/P and Jason-1 mission (ITRF2000). In a second part, these reference stations will define the datum for the kinematic processing of the GPS catamaran and buoy data but will be also used to determine the absolute sea level heights derived from tide gauges data.

For the GPS static analysis, it has been used three software/methodologies: Bernese (computation by ICC), GIPSY-OASIS II (computation by ROA) and GAMIT/GLOBK (computation by OCA-GEMINI). All these solutions are based on 30 s time sampling GPS data.

The kinematic solutions are based on the high rate GPS data (1 Hz). The mobile receivers (Catamaran and buoy) ellipsoidal heights are solved relatively to the coordinates of the reference stations chosen in the previous section (OCA-GEMINI solution). This processing has been realized independently by ICC (POSGPS Software) and OCA-GEMINI (TRACK software).
OCA-GEMINI Solution

GEMINI solution:
The kinematic solution has been processed using TRACK software developed at MIT. Details on the TRACK processing and standards can be found in Watson et al. (2003). In order to reduce the impact of distance in the kinematic GPS processing SANA, IBIB and PORT have been chosen as reference stations (fixed) and CATL and CATR have been processed independently. IBIB has been chosen instead of IBIA because it was equipped with the same antenna/receiver than CATR. However, there were lots of data gap for the Leica receiver (CATR) and also lots of satellite lost so the solution was very difficult to process and results were very uncertain because of too few fixed ambiguities. We have then decided to use only the CATL solution for processing the GPS sea level map.

ICC Solution:
For computing GPS kinematic sessions ICC used POSGPS v4.02 software, from Applanix. The computation of each trajectory was done in three steps: a forward filtering (positive in time), a backward filtering (negative in time) and a final combination of the two previous processes (smoothing), assigning weights at each epoch according to certain quality parameters. This software has also the possibility to combine different solutions computed from several GPS permanent stations.

4.3 Sea Height Processing

The chosen boat velocity was about 4.2 m/s, (~8 knots) so the cut-off period in the time domain has been chosen to be 400 s (~1.7 km in the space domain) in order to homogenize along-track and across-track (~2 km) wavelengths. This filtering also allows reducing the high frequency sea level variations due to both GPS processing uncertainty and sea state. Only results on the filtered GPS sea heights are given in this paper.

For the data editing a global velocity criteria (between 3.7 and 4.7 m/s) has been chosen in order to avoid speed-dependent sea-height variations. Some parts of the solutions have been also excluded due to very poor results for both ICC and OCA-GEMINI solution (large crossover values,, …): the longer period removed is for the long diagonal of the south west area because the boat have to be stopped to reinforced the towing rope; in fact during this period the GPS cable were too tense and the connector were unscrewed leading to many satellite lost. From a total of 158400 only 74505 GPS data have been kept for the final solution (Figure 4).

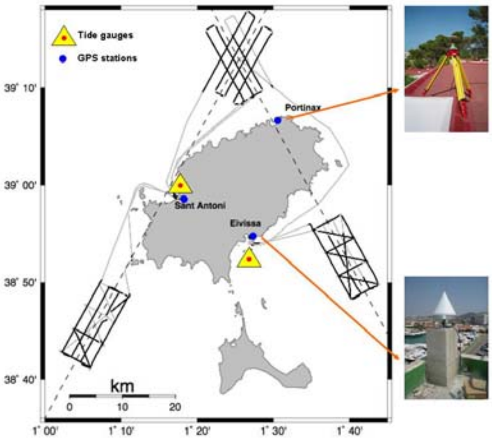

Figure 4. GPS data collected (gray) and kept (black). Dashed lines represent the Jason-1 passes: ascending N°187 (South West – North East) and descending N°248 (North West –. South East).

On the other hand, Jason-1 altimetric data was analyzed from cycle 9 (beginning of San Antonio tide gauge data) to cycle 62 (Table 2).

	Ibiza		San Antonio	
Pass	Mean (mm)	σ (mm)	Mean (mm)	σ (mm)
187	169.0	33.4	119.0	23.4
248	177.0	24.5	122.0	27.4

TABLE 2 Statistics of the Jason-1 altimeter bias for passes 187 and 248 using Ibiza and San Antonio tide gauges.

The bias found at San Antonio is very close to that found at other calibration sites notably the Corsica one where the geographically correlated errors should be comparable (orbit, sea state,..): +138 ± 7 mm at Harvest (Haines et al., 2003), +120 ± 7 mm at Corsica (Bonnefond et al., 2003b) and +131 ± 11 mm at Bass Strait (Watson et al., 2003).

4.4 Conclusions

In all the three Begur's Cape campaigns: in-situ radar altimeter calibrations during the overflight of the satellite were done obtaining single point estimations of the altimeter biases for both the T/P-side B and the Jason-1 by means of GPS buoys. In 2000-2002 campaigns: the determination of the marine geoid using GPS buoys was performed. These campaigns included mapping the sea surface along the Jason-1 ground tracks.

In the Ibiza campaign the marine geoid gradient was determinated: GPS techniques (i.e. simultaneous GPS buoys and catamaran measurements) were applied to estimate the geoid slope between the locations of the open-ocean altimeter measurements and the coastal tide gauges located at Ibiza and San Antonio harbours.

The bias found in San Antonio was very close to found at other calibration sites notably the Corsica one where the geographically correlated errors should be comparable (orbit, sea state). More dedicated calibration sites, as Ibiza or San

Antonio, can help to control the geographically correlated errors that are significant at single sites.

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5.1 Acknowledgements

These campaigns were 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.

The IBIZA 2003 Team was formed by Cristina Garcia, Gema Rodriguez ,Jaime Lopez Marco,Sergio Gonzalez, Amparo Nuñez, Nieves Lantada, Felipe Buill, Begoña Perez, Enrique Alvarez, Damia Gomis, Marta Marcos, Marta Satre, Miriam Moysset, Ana Serrano, Manuel Espino, Yves Menard, Eric Jeansou, Jan Gwenaele, Florent Lyard, Olivier Laurain and Laurent Rroblou. Special thanks to TN Enrique Rodriguez de Santiago and the crew of Patrol Deva of the Spanish Navy.