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The 2013 Ibiza Calibration Campaign of Jason-2 and SARAL Altimeters

F. FRAPPART,[1,2,3] N. ROUSSEL,[1,3] R. BIANCALE,[1,3,4]
J. J. MARTINEZ BENJAMIN,[5] F. MERCIER,[1,3,4]
F. PEROSANZ,[1,3,4] J. GARATE PASQUIN,[6] J. MARTIN
DAVILA,[6] B. PEREZ GOMEZ,[7] C. GRACIA GOMEZ,[5]
R. LOPEZ BRAVO,[5] A. TAPIA GOMEZ,[5] J. GILI RIPOLL,[5]
M. HERNANDEZ PAJARES,[5] M. SALAZAR LINO,[8]
P. BONNEFOND,[9] AND I. VALLES CASANOVA[5]

[1]Géosciences Environnement Toulouse (GET) UMR5563, CNRS/IRD/UPS, OMP, Toulouse, France
[2]Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS) UMR5566, CNES/CNRS/IRD/UPS, OMP, Toulouse, France
[3]Groupe de Recherche en Géodésie Spatiale, Toulouse, France
[4]Centre National d'Etudes Spatiales (CNES), Toulouse, France
[5]Department Geotechnical Engineering and Geosciences, Technical University of Catalonia (UPC), Barcelona, Spain
[6]Real Instituto y Observatorio de la Armada (ROA), San Fernando, Cadiz, Spain
[7]Puertos del Estado (PE), Madrid, Spain
[8]Universidade do Porto, Porto, Portugal
[9]Géoazur, CNRS/IRD/UNS, OCA, Valbonne, France

This study presents the results of the 2013 Ibiza (Western Mediterranean) calibration campaign of Jason-2 and SARAL altimeters. It took place from 14 to 16 September 2013 and comprised two phases: the calibration of the GNSS (Global Navigation Satellite System) buoys to estimate the antenna height of each of them and the absolute calibration to estimate the altimeter bias (i.e., the difference of sea level measured by radar altimetry and GNSS). The first one was achieved in the Ibiza harbor at a close vicinity of the Ibiza tide gauge and the second one was performed at » 40 km at the northwest of Ibiza Island at a crossover point of Jason-2 and SARAL nominal groundtracks. Five buoys were used to delineate the crossover region and their measurements interpolated at the exact location of each overflight. The overflights occurred two consecutive days: 15 and 16 September 2013 for Jason-2 and SARAL, respectively. The GNSS data were processed using precise point positioning technique. The biases found are of (¡0.1 § 0.9) and (¡3.1 § 1.5) cm for Jason-2 and SARAL, respectively.

Keywords satellite altimetry, calibration, GNSS buoys, tide gauge

Address correspondence to Frédéric Frappart, Observatoire Midi-Pyrénées, 14 Avenue Edouard Belin, Toulouse, 31400, France. E-mail: frederic.frappart@get.obs-mip.fr.

Introduction

Accurate monitoring of sea-level variations using satellite altimetry requires a precise determination of the error budget of the altimeter measurements. Calibration of the altimetry missions is crucial for estimating sea surface height (SSH) bias and assessing the error balance of the altimetry measurement system. Besides, it is necessary for combining both spatially and temporally sea surface height (SSH) from different altimeters. The absolute calibration of the altimeter missions is used to compare the altimetry-derived SSH with independent measurements and consists in determining the bias between the SSH measured by an altimeter and an external ground truth (e.g., Cancet et al. 2013). Global Positioning System (GPS) receiver on buoys were early used for precise sea level estimates (Rocken et al. 1990) and calibration of Topex/Poseidon altimeter measurements (Born et al. 1994). Local absolute calibrations are performed under the altimeter groundtrack using tide gauge records or GNSS measurements either during a dedicated campaign (e.g., Bonnefond et al. 2003; Martinez Benjamin et al. 2004 in the Mediterranean Sea) or at permanent calibration facilities or Calibration/Validation (Cal/Val) sites in Corsica, Western Mediterranean Sea (e.g., Bonnefond et al. 2013) at Harvest platform, Eastern Pacific Ocean (e.g., Haines et al. 2010) in Gavdos, Eastern Mediterranean Sea (e.g., Mertikas et al. 2010), and Bass Strait, between Australia and Tasmania (e.g., Watson et al. 2011).

An altimetry calibration campaign was achieved in the Mediterranean Sea, close to the Ibiza Island (Baleares) area, September 2013 in the framework of a Spanish/French cooperation. Its goal was to estimate the absolute bias of AltiKa onboard SARAL, the first altimeter to operate in Ka band, through comparisons with GNSS measurements on buoys, and to compare it to Jason-2 absolute bias at a crossover of their respective groundtracks. A similar Spanish/French experiment was already performed for Jason-1 in June 2003 in this geographical area under the name IBIZA 2003 campaign (Martinez-Benjamin et al. 2004).

A direct absolute altimeter calibration estimating the Jason-2 and SARAL biases was performed from direct overflights using GNSS buoys. This method does not require any modeling of geoid and tidal error (Bonnefond et al. 2013; Cancet et al. 2013). The crossover point between Jason-2 and SARAL North of Ibiza (around 40 nm) and West of Mallorca island was found to be optimal for our purposes since it allows measurements at a one-day time-lag and a similar configuration of buoys for each satellite pass (Figure 1). Five buoys were deployed near a Jason-2/SARAL crossover point to determine the sea surface in the along-track and cross-track directions, to estimate by interpolation the SSH at the exact nadir point of the satellite. Here, we present the experimental settings of the campaign and the datasets used in this study, the methods used for comparing altimetry data with GNSS measurements, and the results of the absolute calibration.

Datasets

Altimetry Data

Jason-2. Jason-2 mission was launched on 20 June 2008 as a cooperative effort among CNES, EUMETSAT, NASA and NOAA. Its payload is mostly composed of the Poseidon-3 radar altimeter from CNES, the Advanced Microwave Radiometer (AMR) from JPL/NASA, and a triple system for precise orbit determination: the real-time tracking system DIODE of DORIS instrument from CNES, a GNSS receiver and a Laser Retroflector

Array (LRA) from NASA. Jason-2 orbits at an altitude of 1336 km, with an inclination of 66°, on a 10-day repeat cycle, providing observations of the Earth surface (ocean and land) from 66° latitude North to 66° latitude South. This orbit was formerly used by Topex/Poseidon, Jason-1 and 2, with an equatorial ground-track spacing of about 315 km. Poseidon-3 radar altimeter is a two-frequency solid-state altimeter that measures accurately the distance between the satellite and the surface (range) and provides ionospheric corrections over the ocean. It operates at Ku (13.575 GHz) and C (5.3 GHz) bands. Its accuracy is expected to be about 2 cm over ocean. Raw data are processed by SSALTO (Segment Sol multimissions d'ALTimétrie, d'Orbitographie).

SARAL. SARAL mission was launched on 25 February 2013 as a joint effort of CNES and ISRO. Its payload comprised the AltiKa radar altimeter and bi-frequency radiometer, and a triple system for precise orbit determination: the real-time tracking system DIODE of DORIS instrument, a Laser Retroflector Array (LRA), and the Advanced Research and Global Observation Satellite (ARGOS-3). SARAL orbits at an altitude of 790 km, with an inclination of 98.54°, on a 35-day repeat cycle, providing observations of the Earth surface (ocean and land) from 82.4° latitude North to 82.4° latitude South. This orbit was formerly used by ERS-1 & 2 and ENVISAT, with an equatorial ground-track spacing of about 85 km. AltiKa radar altimeter is a solid-state mono-frequency altimeter that provides accurate range measurements. It is the first altimeter to operate at Ka-band (35.75 GHz). Its accuracy is expected to be about 1 cm over ocean. More details about the AltiKa-SARAL mission can be found in (Verron et al. 2015).

The data used in this study come from the Geophysical Data Records (GDRs) for Jason-2 (GDR D) and SARAL (GDR T patch 2) and are made available by Centre de Topographie de l'Océan et de l'Hydrosphère (CTOH, http://ctoh.legos.obs-mip.fr/). Ranges are available every 20 Hz for Jason-2 and 40 Hz for SARAL. It corresponds to a measurement every 350 and 165 m, respectively, along the track. Range values suitable to derive *SSH* are retracked using MLE4 (Amarouche et al. 2004) and MLE3 (Rodriguez 1988) algorithms, Maximum Likelihood Estimator with 4(3) degrees of freedom, applied to the Brown model (Brown 1977). They are provided in the GDRs for both Jason-2 and SARAL for the first one, and only Jason-2 for the second one. The type of the corrections applied to the altimetry data for comparison with GNSS data is summarized in Table 1. As the environmental corrections affect both altimetry and GNSS data, they were not applied.

GNSS Data

Five GNSS stations were installed on buoys (denominated on Figure 2c GRGS, LEGOS/INSU, IPGP, UPC 1 & 2). They are composed of three receivers TOPCON GB-1000

Table 1
Corrections applied to the altimetry data for each altimetry mission

	Geophysical corrections			
Altimetry mission	ionosphere	dry troposphere	wet troposphere	sea state bias
Jason-2	bi-frequency (C-Ku)	ECMWF-derived	radiometer-derived	empirical models
SARAL	GIM-derived	ECMWF-derived	radiometer-derived	empirical models

with TOPCON PG_A1+GP antennas and two receivers and antennas TOPCON HIPER. All of them were acquiring data at a sample rate of 1 Hz.

Tide Gauge Records

The Spanish Port Authority (Puertos del Estado, http://www.puertos.es) installed the tide gauge station of Ibiza harbor in January 2003. The station is part of the REDMAR network, at this moment comprising 21 stations distributed along the whole Spanish coast. The tide gauge deployed in Ibiza is also part of the European Sea-Level Service (ESEAS) network. The tide gauge station of Ibiza harbor (longitude = 1.44896° E and latitude = 38.91125° N) is a radar sensor installed by the Spanish Port Authority in September 24 2009, providing sea level measurements at a 1 min. time sampling. It was leveled during the IBIZA 2013 campaign. The leveling of the tide gauge consists in determining precisely the orthometric height (N_0) of the gauge zero as:

$$N_0 = H_0 - N \tag{1}$$

where H_0 is the ellipsoidal height of the gauge zero and N the undulation of the geoid at the location of the gauge.

The ellipsoidal height of the gauge zero was estimated using GNSS observations made on 14 September 2013 during 4 hours and converted into orthometric height using the mean value of the sea level in Ibiza or nivel medio del mar en Ibiza (NMMI). H_0 was found to be 0.324 m below the NMMI. NMMI value (N) is 49.166 m with reference to WGS84 ellipsoid (REDMAR 2013). The absolute sea level at the tide gauge ($SSH_{tide\ gauge}$) is finally given by:

$$SSH_{tide\ gauge}(t) = h_{tide\ gauge}(t) + N_0 \tag{2}$$

where $h_{tide\ gauge}$ is the stage value in the gauge record at time t.

Method

Ibiza Calibration Site and Experimental Design

The Spanish/French Jason-2 and SARAL calibration campaign IBIZA 2013 was carried out on 14–16 September 2013 in the area of Ibiza Island in the NW Mediterranean Sea (Figure 1). The experiment was composed of two phases: i) the pre-calibration of the 5 buoys by reference with the Ibiza tide gauge (Figure 2a) to level the GNSS antennas above the sea level, and ii) the absolute calibration of the altimeters at the cross-over point.

The absolute calibration took place on 15 and 16 September 2013 at around 7:38 UTC under the Jason-2 ascending track 187 and around 5:29 UTC under SARAL ascending track 315. The Spanish Navy supported the altimetry satellites calibration survey assigning the Patrol ship Toralla to the campaign (Figure 2b). She is a 133 Tn. ship, 28 m in length and 6.5 ms beam, and suitable for this kind of mission. The GNSS buoys were carried on the patrol boat deck to the calibration area. The crew placed the buoys on the sea, at the estimated observing points around the calculated satellite track two hours before the expected time of overflight. The boat kept sailing out of the survey area about

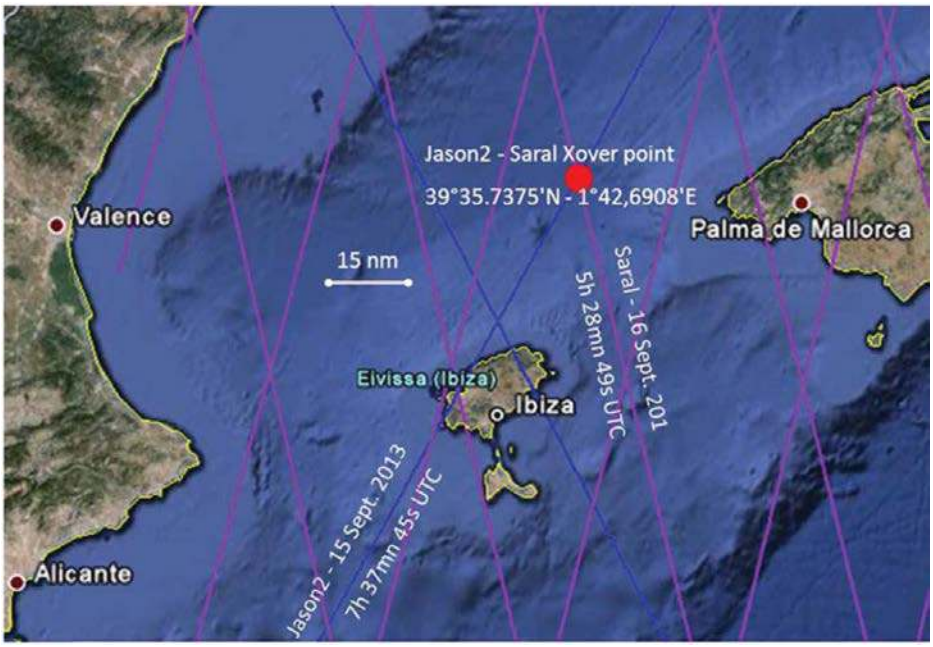

Figure 1. The geographical configuration of IBIZA 2013 absolute calibration campaign. Jason-2 tracks are represented with blue lines and Saral ones with purple lines. The white circle with a black dot represents the location of the Ibiza tide gauge used for calibration of the GNSS buoys the 14 September 2013 and the red one the crossover of Jason-2 track 196 (15 September 2013) with Saral track 274 (16 September 2013) at 40 km northwest of the Ibiza Island.

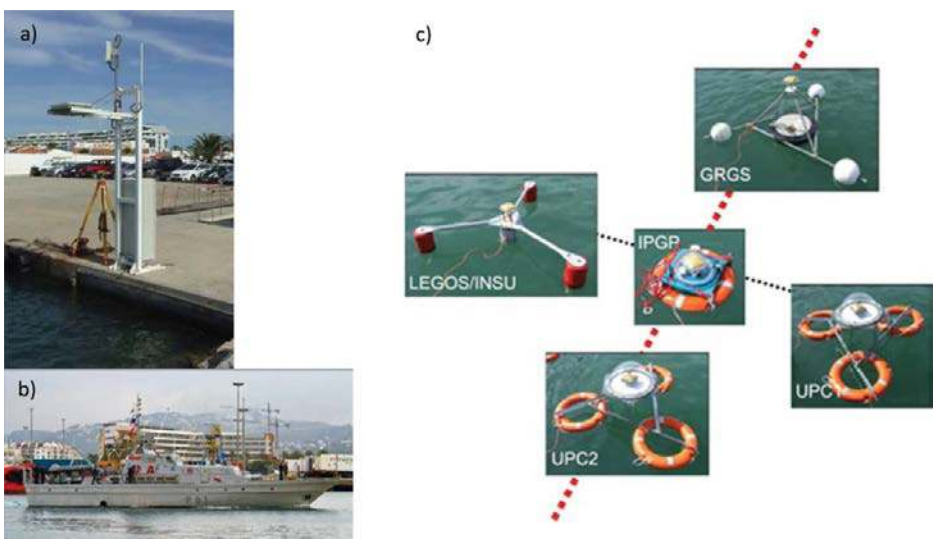

Figure 2. (a) Ibiza tide gauge (Puertos del Estado) with the GNSS used for levelling, (b) the Patrol ship Toralla from Spanish Navy (Armada Española) during the IBIZA 2013 campaign, (c) the instrumental configuration of IBIZA 2013 absolute calibration campaign. The dotted red and black lines represent the along and cross-track directions of the altimeter passes, respectively, along with the location of the buoys.

4 hours, and then she proceeded to remove the buoys from the water. The same operation achieved for the calibration of Jason-2 was repeated the day after for SARAL. The buoys were hence deployed at least 4 hours on site to allow a precise determination of their position using GNSS Precise Point Positioning (PPP) technique. The locations of buoys deployment were estimated from Jason-2 and SARAL orbit predictions obtained from the GINS/GRGS software fitting SLR data from previous days and current and wind predictions from Mercator and Météo-France to predict the drift of the buoys between their deployment and the overflight of the satellite.

Absolute Calibration Technique

An absolute calibration of both Jason-2 and SARAL was achieved. It consists of the determination of the absolute altimeter bias that requires simultaneous measurements of *SSH in situ* and by an altimeter in the same terrestrial reference frame at the exact same location or comparison point. The absolute altimeter bias ($Bias_{altimeter}$) is estimated as follows (Ménard et al. 1994):

$$Bias_{altimeter} = SSH_{altimeter} - SSH_{in\ situ} \tag{3}$$

where $SSH_{altimeter}$ and $SSH_{in\ situ}$ are the SSH estimated from altimeter and *in situ* measurements, respectively, with *SSH* from altimeter given by Chelton et al. (2001):

$$SSH_{altimeter} = h - \left(R + \sum \Delta R_{propogation}\right) \tag{4}$$

where h is the height of the centre of mass of the satellite above the ellipsoid estimated using precise orbit determination (POD) technique, R is the nadir altimeter range from the center of mass of the satellite to the sea surface taking into account instrumental corrections, $\sum \Delta R_{\text{propogation}}$ is the sum of the geophysical correction to apply to the range, respectively.

$$\sum \Delta R_{propogation} = \Delta R_{ion} + \Delta R_{dry} + \Delta R_{wet} + \Delta R_{SSB} \tag{5}$$

Where ΔR_{ion} is the atmospheric refraction range delay due to the free electron content associated with the dielectric properties of the ionosphere, ΔR_{dry} is the atmospheric refraction range delay due to the dry gas component of the troposphere, ΔR_{wet} is the atmospheric refraction range delay due to the water vapor and the cloud liquid water content of the troposphere, and ΔR_{ssb} is the range correction due to the interaction of the electromagnetic pulse emitted by the altimeter with the scatterometers within the footprint. It is known as sea state bias (*SSB*) and is the sum of the electromagnetic (*EM*), skewness, and tracker biases.

Altimetry data processing to obtain the SSH and selection at the cross-over were performed using the Multimission Altimetry Processing Software (MAPS, Frappart et al. 2015). A negative bias indicates that the measure of the *SSH* by the altimeter is too low, either the altimeter range being too long, or the orbit is biased downwards (Bonnefond et al. 2013).

The *SSH* was observed at the comparison point using five *GNSS* buoys located along and cross track (Figure 2c). The *GNSS*-derived *SSH* were either distance-weighting interpolated at the exact location of the of the satellite groundtrack on the sea surface at the

exact time t of the satellite overflight of the buoys or directly compared if one or several buoys are in the groundtrack of the satellite at the exact time t of the satellite overflight.

Calibration of the GNSS Buoys

The calibration is an essential phase that allows to estimate the antenna height over the sea surface and determine the systematic errors and accuracy of the *GNSS*-derived *SSH* measurements (Bonnefond et al. 2003; Martinez Benjamin et al. 2004). It consists in putting into the water the buoys equipped with GNSS receiver and antenna in a close vicinity of the tide gauge for several hours. Antenna heights ($h_{antenna}$) are determined as follows:

$$h_{antenna} = h_{GNSS}(t)_{\mathrm{T}_0 = 1mn} - SSH_{tide\ gauge}(T)_{T_1 = 4\ \mathrm{hours}} \tag{6}$$

where h_{GNSS}=$SSH_{in\ situ} + h_{antenna}$ is the elevation estimated from GNSS measurements at time t, T_0 is the sampling time of the tide gauge, $SSH_{tide\ gauge}$ is the absolute sea level at the tide gauge, and T_1 is the observation period close to the tide gauge.

Processing of the GNSS Measurements

As the cross-over point is located more than 50 km from the closest permanent GNSS station on the coast, PPP technique was chosen rather than classical differential GNSS (DGNSS) method to obtain positions with a centimeter-level accuracy. This alternative technique is powerful in such context because it does not require reference stations. Fund et al. (2013) has already demonstrate the potentiality of PPP for processing GNSS observations of sea level from buoys Nevertheless, precise GNSS satellite orbit and clock solutions given in a well-defined reference frame are needed. We used precise products from the International GNSS Service (Dow et al. 2009) and from JPL/NASA. However, compared with the DGNSS technique, PPP requires longer convergence times (typically 2 hours) estimating additional parameters (troposphere and clocks offsets), using dual-frequency receivers, and more refined observation (e.g., antenna phase center offsets and variations, phase wind-up) and earth deformation (e.g., solid earth tide, ocean loading) models (Laurichesse et al. 2008, 2009). The attitude angle of the buoy is not taken into account in the phase windup model. This error affects all observations, so it only impacts receiver clock estimates but not position solutions. Besides, the accurate solution is mainly based on carrier phase data (in order to avoid any doubt, or deeper discussions, regarding the pseudoranges which are not affected by the missing wind-up term).

The GNSS data from the pre- (14 September 2013) and post-calibration (16 September 2013) and from the absolute calibrations of Jason-2 (15 September 2013) and SARAL (16 September 2013) were processed using:

- the Géodésie par Intégrations Numériques Simultanées (GINS) software from the French Space Agency (Centre National d'Etudes Spatiales–CNES), available upon request from http://grgs.obs-mip.fr/en/research/software;
- the GPS Inferred Positioning System and Orbit Analysis Simulation Software (GIPSY-OASIS) from Jet Propulsion Laboratory (JPL), available upon request from https://gipsy-oasis.jpl.nasa.gov; and
- the Canadian Spatial Reference System–Precise Point Positioning (CSRS-PPP, http://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php) which is an online

Table 2
Characteristics of the PPP processing for GINS and GIPSY softwares, and CSRS-PPP online service

PPP Softwares	GINS (Marty 2013)	GIPSY (Zumberge et al. 1997)	CSRS-PPP (CSRS-PPP 2013)
Models			
Orbit products	GRG-IGS	flinnR-JPL	IGS
Observation frequency	L3 (Ionospheric-Free)	L3 (Ionospheric-Free)	L3 (Ionospheric-Free)
Zenithal hydrostatic delay	ECMWF	ECMWF	GPT
Mapping functions	Global Mapping Functions	Niell Mapping Function	Global Mapping Functions
Parameters			
Data sampling	1 Hz	1 Hz	1 Hz
Buoy position and clock	1 per epoch / no constraint	1 per epoch / no constraint	1 per epoch / no constraint
Zenithal wet delay	Every 2 hours+ linear interp.	Every second with a random-walk process and the recommended value for slowly moving objects: 5E-8 km/sqrt(sec) ~ 3 mm/hr, zenith tropospheric delay and its horizontal gradients	Every second with a random-walk process and the recommended value for slowly moving objects: 5E-8 km/sqrt(sec) ~ 3 mm/hr, zenith tropospheric delay and its horizontal gradients
Phase ambiguities	1 / pass (real solution)	Undifferenced amb. Fixing (Bertiguer et al. 2010)	1 / pass (real solution)
Data weighting	Range: 50cm / Phase: 5mm	Range: 100cm / Phase 1cm	Range: 200cm/Phase 1.5cm
Cut off angle	10 degrees	7 degrees	10 degrees

application from the Natural Resources Canada's (NRC) Geodetic Survey Division (GSD) that allows the computation of higher accuracy positions of raw GNSS data in Rinex format.

The main characteristics of the PPP processing, which allows a centimeter error level GNSS zero-differenced positioning, are summarized in Table 2.

Post-processing of GNSS Measurements

The GNSS measurements from the five buoys are first smoothed using a 5 min. averaging window and then interpolated at the exact location and time of the altimeter pass, taking into account the elevation of the antenna for each buoy obtained during the pre-calibration phase achieved in the Ibiza harbor. The corresponding sea level is then compared to the altimetry measurement to determine the absolute bias for each the altimeter following (e.g., Ménard et al. 1994; Martinez Benjamin et al. 2004; Bonnefond et al. 2013; Cancet et al. 2013).

Results

Determination of Antenna Height Above Sea Level

The buoys equipped with GNSS receiver and antenna were put into the water in a close vicinity of the Ibiza tide gauge for several hours on 14 September 2013 from 9h45 to 13h45 UTC for three of them (GRS, LEGOS/INSU, and IPGP) and on 16 September 2013 from 14h to 18h UTC for the remaining two (UPC1 and UPC2). Precise positions of the centre of phase of the antenna with a temporal resolution of 1 second were obtained computing kinematic double-difference solutions of the GNSS buoys with a static GNSS receiver TOPCON GB-1000 with a TOPCON PG_A1+GP antenna located a few meters away from the buoys in the Ibiza harbor (Figure 2a). They were averaged on a 1-minute window for comparison with the records from the Ibiza tide-gauge. The antenna height for each buoy were estimated as the mean difference between the altitude of the center of phase of the antenna and the sea level measured by the tide gauge over the common observation period. We finally obtained the following antenna height above sea level for each buoy: (0.765 ± 0.007) m, (0.349 ± 0.005) m, (0.163 ± 0.013) m, (0.409 ± 0.004) m, (0.402 ± 0.003) m for GRGS, LEGOS, IPGP, UPC1, and UPC2, respectively.

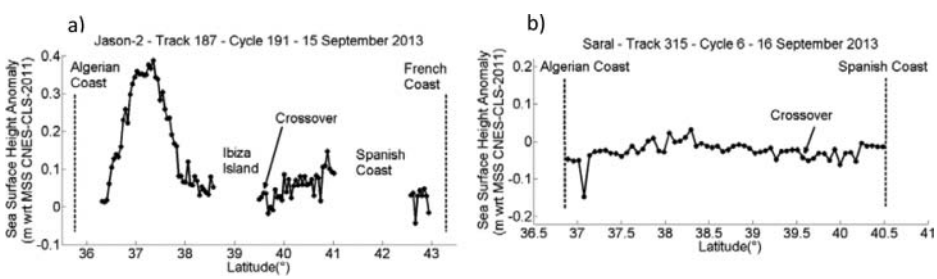

Figure 3. Differences between the altimetry-derived SSH and the MSS (CNES-CLS-2011) along Jason-2 track 187 (cycle 191–15 September 2013) (a) and SARAL track 315 (cycle 6–16 September 2013) (b).

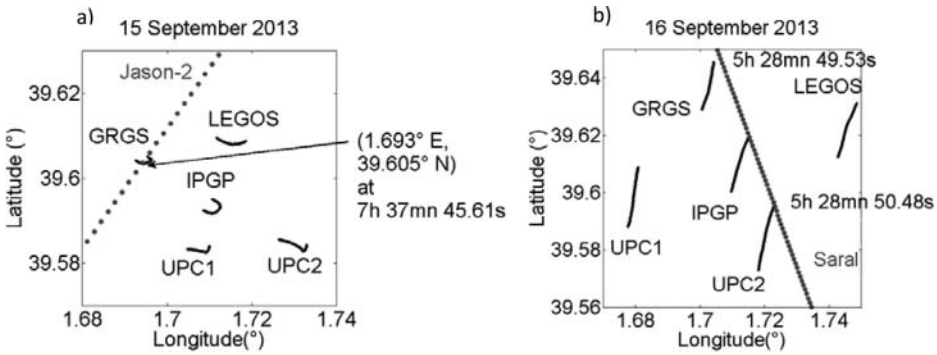

Figure 4. Location of the altimeters track (each grey point corresponding to a *SSH* measurement) and of the buoy drifts on 15 September 2013 along Jason-2 track 187 (a) and on 16 September 2013 along SARAL track 315 (b).

Uncertainties on antenna height are generally lower than 0.7 cm. Larger uncertainty is found for IPGP buoy with a standard deviation (std) of 1.3 cm. This is consistent with the larger sensitivity of this buoy to sea state (i.e., swell and waves).

Validation of Altimeter-based SSH

The along-track altimetry-derived SSH were compared to the mean sea surface (MSS) over the whole portion of the Mediterranean Sea overflown by each altimeter. Here we used the CNES-CLS-2011 MSS. Results are presented for both altimeters in Figure 3.

The differences are generally lower than 0.1 to 0.2 m (especially for SARAL), except close to the Algerian coast for Jason-2 where it reaches 0.4 m, likely due to a typical intense anticyclonic gyre in the area of the Algerian Basin. They remain lower than 0.5 m as expected for the Mediterranean Sea (see, e.g., Cancet et al. 2013) and are less than 0.1 m around the crossover point. SSH from both altimeters do not present any obvious outlier in the vicinity of the crossover point.

Altimeter Calibration

Jason-2 overflew the GRGS buoy on 15 September 2013 at 7h 37 mn and 45.61 s UTC at 1.639° E and 39.605° N (Figure 4a) whereas SARAL overflew the crossover zone on 16 September 2013 at 5h 28 mn between 49.53 and 50.48 s UTC at from 1.7261° E and

Table 3
Absolute bias estimates for Jason-2 and SARAL using PPP technique with GINS, GIPSY and CSRS-PPP

	Absolute bias = $SSH_{altimeter}$ - SSH_{GNSS}(m)		
Altimeter (Retracking)	GINS	GIPSY-OASIS	CSRS-PPP
Jason-2 (MLE4)	0.008	−0.009	−0.002
Jason-2 (MLE3)	−0.008	−0.025	−0.018
SARAL (MLE4)	(−0.018 ± 0.023)	(−0.047 ± 0.025)	(−0.029 ± 0.022)

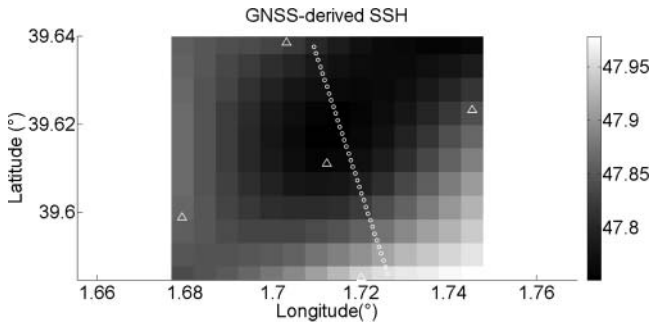

Figure 5. *SSH* (m) derived from the measurements of the GNSS buoys (white triangles). The SARAL altimetery measurements are represented by white dots.

39.5860° N to 1.7093° E and 39.6376° N (Figure 4b). The trajectories of the buoys differ significantly from one day to the other due to changes in the directions of both the oceanic currents and the winds. The *SSH* from Jason-2 was directly compared to the smoothed value, using a 5-minute moving average, of *SSH* from the GRGS buoy. The *SSH* from SARAL was compared along the transect to the smoothed using a 5-minute moving average window *SSH* interpolated from GRGS, LEGOS IPGP, UPC1, and UPC2 data. The results are presented in Table 3.

The bias on the *SSH* for Jason-2 for one comparison point vary from −0.9 to 0.8 cm for altimeter ranges processed using the MLE4 retracker and from −1.8 to −0.8 cm with MLE3, depending on the type of GNSS processing (Table 4). GINS, GIPSY-OASIS, and CSRS-PPP processings provide similar estimates. These results are in good agreement with Jason-2 absolute bias value of from OSTST (2013).

For SARAL, *SSH* presents a standard deviation (std) of 3.6 cm over an along-track distance of 5.7 km. The GNSS-based *SSH* was interpolated under the altimeter track using GRGS, LEGOS, IPGP, UPC1 and UPC2 GNSS buoy measurements at the exact time of the overflight (Figure 5). The absolute bias of SARAL was estimated along the transect using 35 altimeter measurements. Very consistent values of biases were obtained using different PPP processing. Values of (−1.8 ± 2.3), (−4.7 ± 2.5), and (−2.9 ± 2.2) cm along the transect were obtained using GINS, GIPSY-OASIS, and CSRS-PPP, respectively.

Conclusion

The 2013 Ibiza calibration campaign allowed to estimate the absolute biases of the AltiKa sensor onboard SARAL, that is, the first altimeter to function in Ka band, and Jason-2 at a crossover point during two consecutive days over the open ocean. The major originalities of this campaign are the use of several GNSS buoys to eventually estimate the bias in different locations along the track during the altimetry overflight, the use of the *PPP* technique for processing the GNSS measurements, and to compare the results obtained with three different software programs. Similar bias estimates were obtained using the three *PPP* GNSS processing software for both altimeters: (−0.1 ± 0.9) and (−3.1 ± 1.5) cm for Jason-2 and SARAL, respectively. The first one is in good agreement with the Jason-2 bias value from OSTST (2013). Since Jason-2 reprocessing (GDR-D products) instrumental errors discovered by the project (∼ 15.6 cm on the range, see Bonnefond et al. 2012 for details) have been applied leading to remove the SSH bias that is now close to 0 as

assessed by OSTST (2013). Concerning the SARAL/AltiKa SSH bias, the origin is not currently known but other studies found similar values (−5 cm) either from *in situ* (Babu et al. 2015; Bonnefond et al. 2015; Mertikas et al. 2015) or global comparisons with Jason-2 (Prandi et al. 2015; Desai and Haines 2015).

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