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ABSOLUTE CALIBRATION OF SATELLITE ALTIMETRY USING LINEAR REGRESSION AND HARMONIC ANALYSIS

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Abstract. The calibration of satellite radar altimetry has been extremely important for altimetry community and studying sea level changes. The main purpose of this contribution is to provide ongoing absolute calibration of altimeter bias near the Southern seas of Iran using the Iranian tide gauge network that equipped with GPS receivers to measure the sea surface heights synchronously in the same geocentric reference frame as the corresponding altimetry records. The sea level time series of coastal tide gauges have been used to estimate the bias, drift and annual/semiannual constituents of altimeter range measurements using (i) linear regression and (ii) combination of linear regression and harmonic analysis. To this end, three Iranian tide gauges located at Bushehr, Bandar Abbas and Chahbahar ports as well as Geophysical Data Records (GDR) products of Topex/Poseidon, Jason-1and Jason-2 have been considered. The numerical results have indicated that the mean absolute biases of Topex/Poseidon, Jason-1 and Jason-2 are about –26.23, 120.21 and 205.17 mm, respectively. The reliability of method has been assessed via GPS vessel at the altimeter bin nearby the Bushehr tidal stations. The presented method is viable to perfectly estimate the systematic errors, and as such, it can address the demands of high-accurate applications.

Keywords: altimeter calibration, absolute bias, tide gauges, Topex/Poseidon, Jason-1, Jason-2, Persian Gulf and Oman Sea.

Introduction

Sea level variability and its effects on near coastal areas are among important aspects of consideration for geophysical, geodetic and oceanic applications. To this end, costal tide gauges have been increasingly used at a variety of ports throughout the world to provide onshore sea level information (Vignudelli *et al.* 2011). In addition, radar-based altimetry missions have been well-suited for detection of substantial climatic changes in open-ocean areas (Cazenave, Nerem 2004; Bindoff *et al.* 2007). Although satellite altimeters are "precise", they may not be necessarily "accurate"; which this implies that there still exist some systematic errors in satellite altimetry datasets (Prandi *et al.* 2015). It is therefore important to assess the bias and drift of the altimeters due to the instrumental imperfections, drawbacks of the applied correction models, as well as other means of random and systematic errors (Frappart *et al.* 2015). This goal can be realized through employing buoys equipped with Global Positioning Systems (GPS) in dedicated in-situ sites (e.g. Bonnefond *et al.* 2015; Watson *et al.* 2003, 2004, Babu *et al.* 2015; Peng, Lin 2016; Mertikas *et al.* 2015). Additionally, establishing a spatial link between the sea surface time series recorded by coastal tide gauges and altimetry missions can be considered as an alternative (Bonnefond *et al.* 2010). In this respect, several field calibration/validation campaigns have been performed to quantify the absolute bias and drift of consecutive missions since the launch time of Topex/Poseidon altimeter in August 1992 with an approximately 10-day repeat orbit. As an example, periodic calibration campaigns were carried out at the Harvest oil platform (Christensen *et al.* 1994;

Bonnefond *et al.* 2003). The Jason-1 radar altimeter was operated with the same repeat orbit from December 2001 until August 2002. This was subsequently followed by OSTM/Jason-2 satellite in June 2008 with a similar repeat orbit (Lambin *et al.* 2010). Accordingly, relevant calibration facilities including tide gauges and GPS-equipped buoys were provided at the crossover points of the ground tracks of Jason-1 and Jason-2 on the island of Ibiza, which was also adjacent to an Envisat pass (Pavlis *et al.* 2004). In order to allow a better extrapolation of the open-ocean altimetry data to onshore tide gauge data time series, the local marine geoid slope was applied to the ascending and descending ground tracks, which this resulted in improving the overall accuracy of the calibration process (Martinez-Benjamin *et al.* 2004). Moreover, altimetry-derived sea surface heights were compared with nearby sea levels measured by the UK tide gauges around the Mediterranean Seas to estimate the absolute biases of satellite missions (Dong *et al.* 2002), while a GPS-equipped buoy was used in Bass Strait in Australia for the same purpose (Watson *et al.* 2004, 2011). GPS-based estimates were also used in determining surface heights of both Harvest tide gauge systems, while in the validation of the T/P and Jason-1 datasets on Corsica in the formation flight phase allowed direct comparison of all geophysical corrections and the corrected sea-surface heights (Bonnefond et al. 2010).

The main objective of the present study is to develop a reliable method for calibrating altimeter missions in the Southern seas of Iran based on (i) linear regression and (ii) combination of linear regression and harmonic analysis. The absolute bias, drift and annual/semiannual components of altimeter missions of Topex/Poseidon, Jason-1 and Jason-2 have been derived using three coastal tide gauges of Iranian tidal network in the study zones. Furthermore, a GPS-buoy campaign has been employed to verify the given results.

1. Materials and methods

We here aim at estimating the absolute bias and drift of the altimetry-derived sea surface heights with respect to the sea level datasets measured by adjacent tide gauges in the same geocentric coordinate frame, while the geoidal height differences have been considered through integration of GPS/leveling and geopotential models. As shown in Figure 1, the tidal measurements can be transferred into the same geodetic coordinate system if the ellipsoidal height of the tide gauge reference point has been obtained via GPS/leveling techniques. Therefore, we have:

$$h_t = h_{TGBM} - \Delta h_{TGBM}^{TG} + r_t \,, \qquad (1)$$

where h_t is the tidal records with respect to the reference ellipsoid, h_{TGBM} is the ellipsoidal height of the tide gauge benchmark (TGBM) derived from processing the relevant GPS carrier phase observations, Δh_{TGBM}^{TG} is the height difference between the tide gauge reference point and the tide gauge benchmark attained from the precise leveling operations, and r_t is the instantaneous SSH with respect to the tide gauge reference point (i.e. TG_0).

Accordingly, the altimeter bias β can be formulated as (Dong *et al.* 2002):

$$Sl_a - Sl_t \approx (h_a - h_t) - (N_a - N_t) = \beta \,, \qquad (2)$$

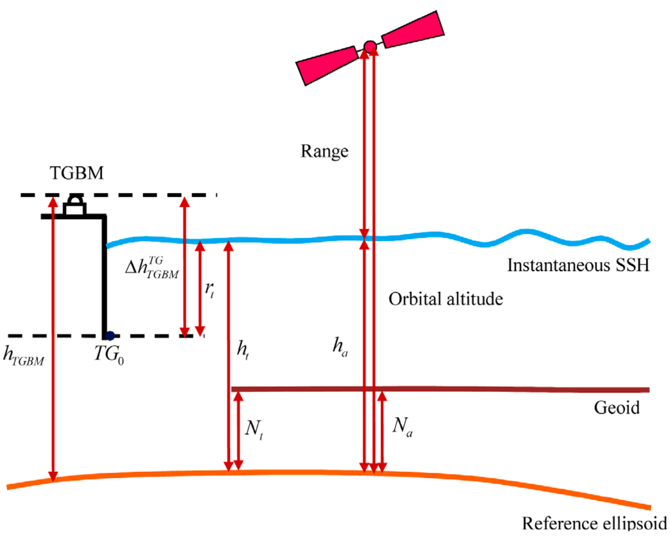

Fig. 1. Schematic view of relations between instantaneous sea surface heights measured by coastal tide gauge from the tide gauge reference point (TG_0) with respect to the reference ellipsoid and geoid

where Sl_a and Sl_t are the sea levels measured by satellite altimetry and the tide gauge in a similar geocentric frame, respectively, while h_a is the altimeter SSH measurement with considering all relevant corrections, and h_t denotes the sea level measured by a nearby tide gauge. Moreover, the geoidal heights at the locations of the altimeter bin, N_a, and the tide gauge, N_t, are required because of the fact that the measurements of the sea surface heights are collected at different geographical positions. An appropriate geoid model, which leads us to precisely local geoidal slope, is also of special importance in order to consider the required corresponding corrections to the coastal tide gauge measurements and altimeter sea surface heights.

In this way, the altimeter bias and drift can be estimated by a closure equation by comparing the measured altimeter sea surface heights with in-situ datasets over the mission lifetime extending from several to decadal years (Cheng 2004). Christensen *et al.* (1994) pointed out that referring to a closure as an altimeter bias was a misnomer because the closure could be contributed by both altimeter and field measurements. As such, one could consider the following linear regression formula for every altimeter in flight over each calibration site (Cheng 2004):

$$Sl_a - Sl_t = \beta + \Delta t\,\delta + e,\; e \sim (0,\ \Sigma), \tag{3}$$

where Δt is the time elapsed from the beginning of the altimeter operation, δ is the altimeter drift, and e is a component of the residual vector with zero mean and the variance matrix Σ. It is worth-mentioning that although δ is a function of time, it is treated as a linear drift in this study; in other words, the drift term is assumed to be fixed throughout the altimeter mission.

As the bias, β and the drift δ shown in Eq. (3) are non-random parameters, and considering the fact that the random error e is a stochastic variable that is not known, all variables cannot be solved using a single closure equation. Therefore, more closure equations must be presumed in order to estimate the altimeter bias and drift thanks to the least squares method. Overall, as the repeat periods of the Topex/Poseidon and Jason-1 are 9.915 days, annual and semi-annual signals must be taken into account for removing the effects of the dominant signals from altimeter SSH measurements. Hence, we can change Eq. (3) into the combination of linear regression and harmonic analysis as follows (Kruizinga 1997):

$$Sl_a - Sl_t = \beta + \Delta t\,\delta + C_1\cos(\omega_1\,\Delta t) + S_1\sin(\omega_1\,\Delta t) + C_2\cos(\omega_2\,\Delta t) + S_2\sin(\omega_2\,\Delta t) + e, \tag{4}$$

where $\{C_1,\ C_2,\ S_1,\ S_2\}$ are the harmonic constituents, whereas $\{\omega_1,\ \omega_2\}$ are the frequencies of the annual and semiannual signals that can be expressed as

$$\omega_1 = \frac{2\pi}{365}; \tag{5}$$

$$\omega_2 = \frac{4\pi}{365}. \tag{6}$$

If the both h_a and h_t have been measured precisely, it means that the annual and semiannual signals are removed for every altimeter in flight over the test field, and as a result only β and δ are remained to be estimated.

2. Numerical results and discussions

To demonstrate the advantages of the presented method, as the case study, the performance of Topex/Poseidon, Jason-1 and Jason-2 missions have been assessed using three coastal tide gauges located on the coasts of the Southern seas of Iran as shown in Figure 2. All three tide gauges, which are type of Ott mechanical float, are as part of the Iranian tidal network in the

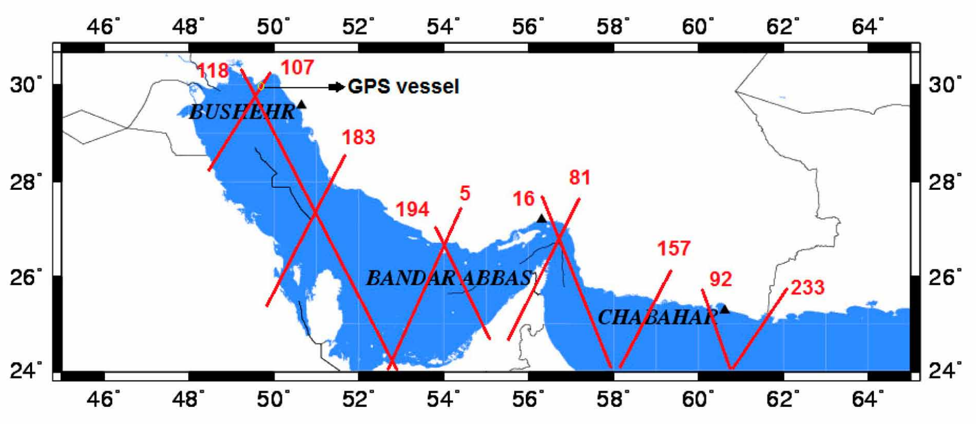

Fig. 2. Spatial distribution of study coastal tide gauges, within the Iranian tidal network, located at Bushehr, Bandar Abbas and Chabahar ports, GPS vessel deployment, and the altimetry ground tracks

Persian Gulf and Oman Sea (Hareide 2004) established and maintained by National Cartographic Center (NCC) of Iran. It is also worth-mentioning that there are vertical benchmarks equipped with GPS receiver and antenna (NAVCOM R100/NAVAN2004T) as nearby as these coastal tide gauges that GPS dataset has been processed by NCC organization via Bernese GPS Software 5.0 in order to reduce the sea level records with respect to the reference ellipsoid in integration with precise leveling, besides joining the tidal stations with precise Iranian leveling networks as the zero level of the national height systems. For more information about the accuracy of ellipsoidal height, readers can refer to NCC documents (NCC 2007). Next, three bins of the passes of satellite altimetry have been selected as nearby as the coastal gauges. A summary of the general information concerning these tide gauge stations and the corresponding altimeter passes/bins is listed in Table 1.

For comparing the tide gauge and satellite altimetry datasets, the times of both observations are synchronized at firsthand. Tidal modeling of hourly datasets from the tide gauges between January 1999 to December 2000 for Topex/Poseidon, January 2003 to January 2005 for Jason-1, and February 2010 to January 2011 for Jason-2 were considered for comparison with the altimetry SSHs, while the global geopotential EGM 2008 model has been used to apply the relevant geoidal corrections to the separations of tide gauges and altimeter bins. The altimeter SSHs have been derived through a MATLAB programming, which reads altimeter datasets provided by the NASA Jet Propulsion Laboratory (PODAAC 1996). This programming was developed at the University of Tehran to extract data from the Topex/Poseidon, Jason-1 and Jason-2 satellites in a particular area of interest within the respective satellite coverage. The MATLAB code was programmed to remove gross errors, calculate the true time lag, and categorize the observations of any bin of the satellite passes, and employ auto-correlation procedures for filling possible gaps in the observational time series. The analysis of the Topex/Poseidon is related to 1-Hz range and orbit datasets extracted from the most recent release, MGDR-B (Benada 1997), while those of Jason-1 and Jason-2 are based on the GDR-C and GDR-D products, respectively (PODAAC 2008). The ionosphere correction underwent similar treatments for both datasets as for the Topex/Poseidon MGDR-B data, by applying the dual–frequency ionosphere correction. Amongst254 passes of altimeter satellites on the globe, 12 ground tracks, namely 55, 168, 233, 92, 157, 16, 81, 194, 5, 118, 183 and 107 are within the Persian Gulf and Oman Sea.

Altimetry measurements have been corrected by using the Brat software as an altimeter data processing tool. More specifically, Topex/Poseidon measured ranges have been corrected for environmental perturbations like geophysical corrections using the meteorological model of the wet tropospheric correction supplied by either the French Meteorological Office for Topex/Poseidon or the European Centre for Medium-Range Weather Forecasts (ECMWF). For Jason-1 and Jason-2, some corrections due to dry troposphere, ionosphere, ocean wave influence and sea-state bias have been also considered, as the altimeter datasets as well as the tide gauge measurements account for tidal influences like ocean, earth, pole tide, and inverse barometer effects. The applied corrections are summarized in Table 2. Figures 3 and 4 show the historical SSH time series, as measured by the Topex/Poseidon and Jason-1, over a sixteen-year time span from 1993 to 2009 at the Bushehr and Bandar Abbas ports, respectively. According to these figures, conspicuous jumps could be related to natural phenomena such as earthquakes, tsunamis or huge oceanic storms.

The tide gauge data at Bushehr port over a 1-year time span for Topex/Poseidon (1999–2000), 2-year time span for Jason-1 (2003–2005), and 1-year time

Table 1. A summary of general information corresponding to the study tide gauge stations and their associating altimetry ground tracks and bins

Tide gauge-Station	Tide gauge Geodetic latitude (ϕ)	Tide gauge Geodetic longitude (λ)	Tide gauge Geoidal heights (m)	Ellipsoidal heights of the tide gauge benchmark with respect to WGS84(m)	Nearest altimeter Pass numbers	Bin geodetic latitude (ϕ)	Bin geodetic longitude (λ)	Bin geoidal heights (m)
Bandar Abbas	27°06′N	056°04′E	−29.7213	−26.4241	16	26°54′N	056°41′E	−29.3232
Bushehr	28°59′N	050°50′E	−22.1471	−20.1495	118	28°57′N	049°59′E	−21.1912
Chabahar	25°18′N	060°37′E	−28.9260	−26.3076	92	25°12′N	060°19′E	−29.4743

span for Jason-2 (2010–2011) were respectively used to perform the calibration/validation tasks. Figures 5–7 show the SSH time series that are simultaneously measured by Topex/Poseidon, Jason-1and Jason-2 versus the coastal tide gauge at Bushehr port as examples. From these figures, one can perceive the periodic nature of the satellite biases and drifts.

Table 2. Altimetry datasets and their corresponding corrections within this study

Item	Topex/Poseidon mission	Jason-1 mission	Jason-2 mission
Altimeter range	MGDR-B	GDR-C	GDR-D
Earth tides	MGDR-B	GDR-C	GDR-D
Ocean tides	MGDR-B models	FES 2004	FES 2004
Ionosphere	MGDR-B	GDR-C	GDR-D
Dry troposphere	ECMWF	ECMWF	ECMWF
Wet troposphere	MGDR-B	GDR-C	GDR-D

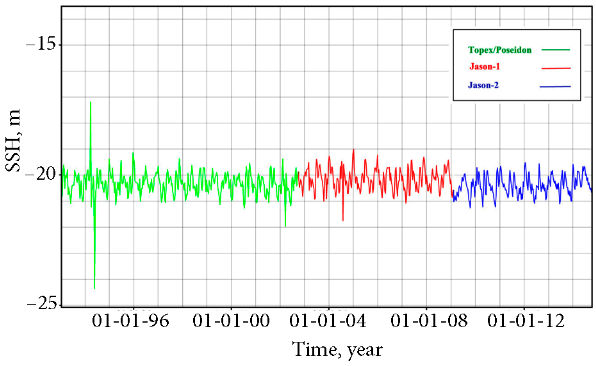

Fig. 3. Altimetry SSH time series at Bushehr port derived from Topex/Poseidon, Jason-1 and Jason-2 over a 22-years span from 1993 to 2014

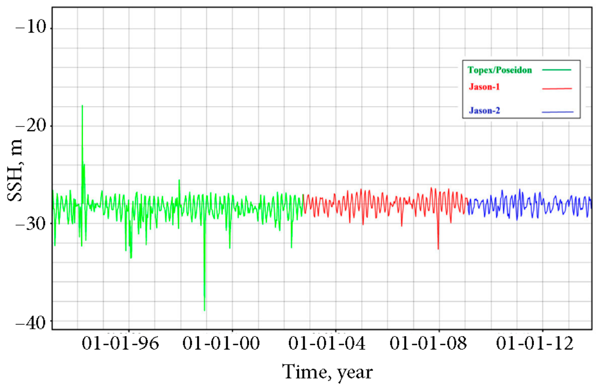

Fig. 4. Altimetry SSH time series at Bandar Abbas port derived from Topex/Poseidon, Jason-1 and Jason-2 over a 22-year span from 1993 to 2014

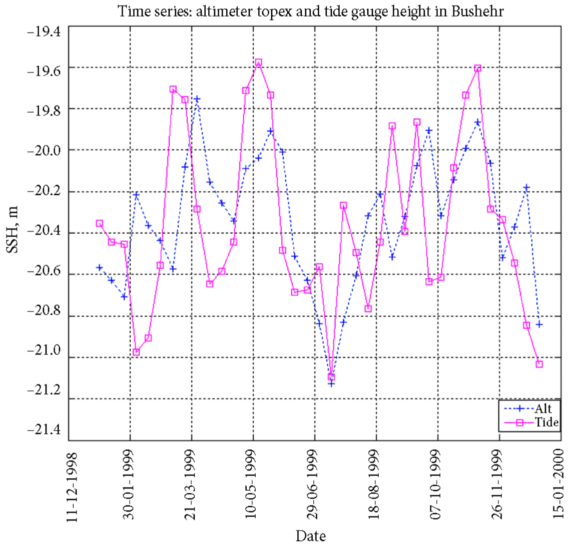

Fig. 5. SSH time series obtained from Topex/Poseidon against those of Bushehr tide gauge over a 1-year time span from 1999 to 2000

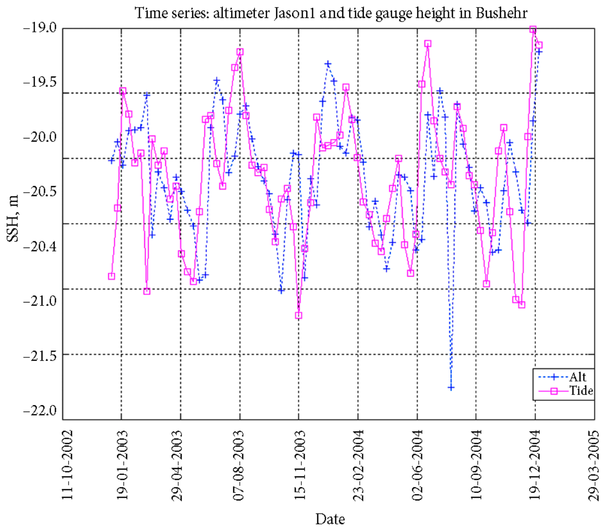

Fig. 6. SSH time series obtained from Jason-1 versus those of Bushehr tide gauge over a 2-year time span from 2003 to 2005

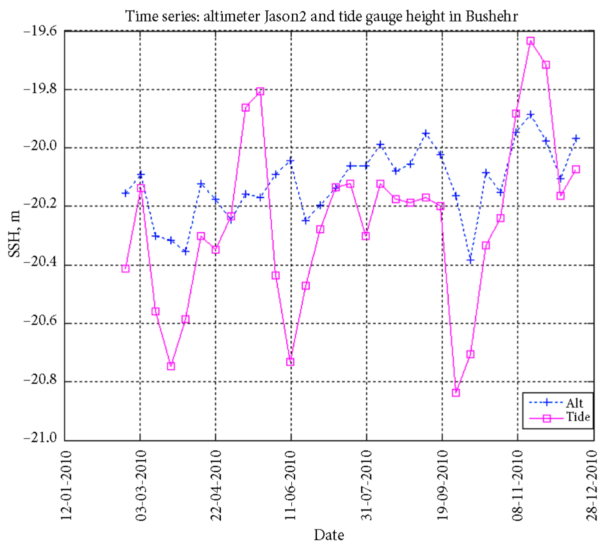

Fig. 7. Sea surface height time series obtained from Jason-2 against those of Bushehr tide gauge over a 1-year time span from 2010 to 2011

Tables 3 and 4 summarize the information relating to the biases and drifts of Topex/Poseidon and Jason-1 satellite missions by applying Eq. (3). It should be noted that the absolute altimeter biases were determined at the mean epoch of the time series in terms of the mean values of the differences between altimetry and tide gauge SSH time series. According to these tables, it seems that the difference in the estimated results between the Bushehr port and the other two tidal stations could be due to the variations in the proximity, and more generally, variations in the ocean dynamics.

Tables 5 and 6 list the bias, drift and annual/semiannual constituents of Topex/Poseidon and Jason-1 estimated by applying Eq. (4).

For the Jason-2, in addition to the sea levels of Bushehr tide gauge in a 1-year time span from 2010 to 2011 (Fig. 7), a vessel equipped by GPS was also deployed at the pass 107 for 12 days in 2013 to calibrate/verify satellite altimetry ground track observations (see Fig. 2). Information about the deployment of GPS vessel can be seen in Table 7. The data of GPS vessel has been also processed by NCC organization via Bernese GPS Software 5.0, in kinematic mode by using precise IGS products (NCC 2007). Figure 8 shows the SSH time series of GPS vessel versus those of Jason-2 altimeter. Table 8 summarizes the information relating to the bias and drift of the Jason-2 satellite mission by applying Eq. (3), while Table 9 lists the estimated bias, drift and annual/semiannual constituents obtained through Eq. (4). Note that due to providing just only 12 experimental points, the harmonic analysis could not estimate the bias and drift of Jason-2 correctly, therefore, it is not given in Table 9.

Table 3. Bias and drift of Topex/Poseidon estimated by the coastal tide gauge stations located at Bushehr, Bandar Abbas and Chabahar ports

Tidal station	Pass No.	Sea depth at bin location (m)	Distance bin position to the coastline (Km)	Bias β (mm)	Precision σ_β (mm)	Drift δ (mm/year)	Precision σ_δ (mm)
Bushehr	118	44	82	–21.36	2.5	2.22e-007	1.6e-08
Bandar Abbas	16	28	65	–29.26	4	–9.36e-007	1.8e-08
Chabahar	92	24	30	–28.08	3.5	2.20e-007	1.7-08

Table 4. Bias and drift of Jason-1 estimated by the coastal tide gauge stations located at Bushehr, Bandar Abbas and Chabahar ports

Tidal station	Pass No.	Bias β (mm)	Precision σ_β (mm)	Drift δ (mm/year)	Precision σ_σ (mm)
Bushehr	118	113.41	23	–3.23e-006	6.3e-09
Bandar Abbas	16	174.53	28	6.39e-006	6.35e-9
Chahbahar	92	72.69	11	–2.67e-006	6.48e-9

Table 5. Bias, drift and annual/semiannual constituents of Topex/Poseidon estimated by the coastal tide gauge stations located at Bushehr, Bandar Abbas and Chabahar ports

Tidal station	Pass No.	Bias β (mm)	Precision σ_β (mm)	Drift δ (mm/year)	Constituent C_1 (mm)	Constituent C_2 (mm)	Constituent C_1 (mm)	Constituent C_2 (mm)
Bushehr	118	–37.1	22	1.64e-05	59.68	185.4	–41.4	79.4
Bandar Abbas	16	–38.7	8	–3.9e-07	17.62	12.84	113.50	19.38
Chahbahar	92	–47.65	12	5.2e-06	–435.19	–75.18	–233.04	118.9

Table 6. Bias, drift and annual/semiannual constituents of Jason-1 estimated by the coastal tide gauge stations at Bushehr, Bandar Abbas and Chabahar ports

Tidal station	Pass No.	Bias β (mm)	Precision σ_β (mm)	Drift δ (mm/year)	Constituent C_1 (mm)	Constituent C_2 (mm)	Constituent C_1 (mm)	Constituent C_2 (mm)
Bushehr	118	134.31	30	–3.9e-006	157.18	3.462	–28.129	–67.884
Bandar Abbas	16	115.32	25	8.18e-06	144.06	115.09	183.533	89.75
Chabahar	92	43.6	12	–1.71e-06	137.92	73.821	9.144	–14.76

At this step, we compare the results of bias estimations taken at Bushehr with those derived from other calibration sites that are located in the Corsica region of the western Mediterranean (Bonnefond *et al.* 2003), the UK (Dong *et al.* 2002), and the Bass Strait in Australia (Watson *et al*. 2004, 2011). Table 10 shows the results of this comparison. According to this table, in the present study, the absolute altimeter biases of –21.36 mm, 113.41 mm, and 205.17 mm are estimated for Topex/Poseidon, Jason-1, and Jason-2, respectively. In general, these results are in relative agreement with those published by other authors listed in Table 10.

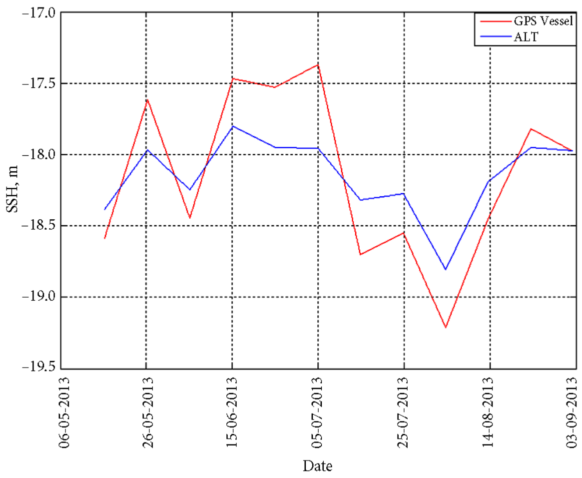

Fig. 8. Sea surface heights derived by GPS vessel and satellite altimetry with RMSE of 0.256 mm

Some discrepancies may be regionally biased, and the characteristics of the region may introduce some specific random as well as systematic effects on the SSH differences. We intended to show that both methods can be applied in the case of a single calibration station. It is believed that involving more calibration sites in the closure process would help improve the overall accuracy of the bias and drift estimations.

Conclusions and outlook

In this study, mean absolute altimeter bias of Topex/Poseidon was estimated to be –26.23 mm at three tidal gauge stations based on the linear regression and according to the different distances with respect to the intended satellite track. Similarly, the mean bias of Jason-1was estimated to be 120.21 mm in the region

Table 7. Main experimental features of GPS vessel employed in this study

Start time of deployment	End time of deployment	Geodetic latitude (ϕ)	Geodetic longitude (λ)	Sampling rate (Hz)
2013/05/16-	2013/08/23	29°56.4X N	49°40.8X E	1

Table 8. Bias and drift of Jason-2 estimated by the coastal tide gauge and GPS vessel located at Bushehr port

Campaign	Pass No.	Spatial separation (km)	Bias β (mm)	Precision σ_β(mm)	Drift δ (mm/year)	Precision σ_σ (mm)
Bushehr tide gauge	118	82	205.17	36.8	–5.03e-06	2.3e-06
GPS vessel	107	2.86	222.44	49	–1.29e-005	0.7e-05

Table 9. Bias, drift and annual/semiannual constituents of Jason-2 estimated by the coastal tide gauge stations at Bushehr port

Campaigns	Pass No.	Bias β (mm)	Precision σ_β(mm)	Drift δ (mm/year)	Constituent C_1 (mm)	Constituent C_2 (mm)	Constituent C_1 (mm)	Constituent C_2 (mm)
Bushehr tide gauge	118	190.68	16.2	–4.84e-6	–63.19	–7.03	65.60	78.04

Table 10. Comparison of the estimated results at Bushehr port with those in the Corsica region of the western Mediterranean, the UK and Bass Strait in Australia

Satellite mission	Bias estimate			
	Bushehr tide gauge, Iran	The Corsica region, the western Mediterranean	The coastal Tide Gauges, the UK	Bass Strait, Australia
Topex/Poseidon (mm)	–21.36	–17	–32	–15
Jason-1 (mm)	113.41	109	129	93
Jason-2 (mm)	205.17	190	---	172

of the Persian Gulf and Oman Sea, and for Jason-2 the absolute bias was to be 205.17 mm. During calibration process, the accuracy of the procedure in a particular area could be increased considerably by comparing tide gauge datasets at near shore with altimeter data and using GPS mounted onboard marine platforms at an offshore location. Introducing calibration parameters to the control system can improve system accuracy globally especially nearby the coastal regions. The relatively short lifetime of satellite altimetry missions and cross-calibration between consecutive satellites are among fundamental issues encountered to measure changes in sea level variations. Therefore, calibration and validation of satellite missions are urgent issues of public interest and are important for scientific investigations. This project can be considered as an attempt towards improving sea observations through calibration of satellite altimetry so as to provide infrastructure for studying long-term changes of water level in the Persian Gulf and Oman sea region.

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