

Full Length Research Paper

Estimation of the geophysical parameters and the orbital error effect on the altimetric measurements for sea surface height determination

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The emergence of satellite altimetry has allowed us to determine the ocean surface with a great precision; it also allows a large contribution for most applications and oceanographic activities. The geometric principle of space altimetry is to measure the range between the satellite and the sea surface. The objective of this paper is to estimate the geophysical parameters (sea state bias, ocean tide and the orbital error) affecting the altimetric measurements for Jason-1 satellite, using the analytical and empirical models. The comparison of the estimated and provided values permit to minimize the default values for *SSB* and improve its estimation, and also improve the ocean tide estimation. The comparison of obtained results of six (6) years Jason-1 data processing on the western Mediterranean of every parameter with data transmitted in the satellite message permitted us to validate our developed methodological approach. The quality of these results permits the determination of the Western Mediterranean mean sea level.

Key words: Mean sea level, altimetry, estimation, sea state bias, ocean tide, orbit, Jason-1.

INTRODUCTION

The ocean have a major impact on earth's life and domestic needs, the aim of satellite altimetry is mainly to provide the height of the sea surface with regard to a referential, its principle is based on the analysis of the echo signal given out by the altimeter radar on board the satellite and reflected by the sea surface. Sea State Bias (*SSB*) is an effect in radar altimetry that arises both from the fact that wave troughs are better reflectors of radar energy than wave crests. This bias ranges between a few centimetres and a few decimetres. The current most accurate estimates are obtained using empirical models derived from analyses of the altimeter data. Based on the results of Gaspar et al. (1994, 1996) and others, the initial algorithms for Jason-1 compute the sea state bias from a bilinear interpolation of a table of *SSB* according to significant wave height (*swh*) and wind speed, based on parametric fits by Labroue (2004). For a typical (*swh*) of 2 m, the error in the *SSB* correction is approximately 1 to

2 cm (Aviso and PoDaac, 2008). Due to lack of data, the empirical model is not defined in some *swh*-wind speed regimes, and the *SSB* in these regimes are returned as default values.

The purpose of this paper is to improve the *SSB* estimation using the nonparametric (NP) method described by Gaspar and Florens (1998). This approach is based on the differences in sea surface height at crossover points (Gaspar et al., 2002). This version of the Sea State Bias model is empirically derived using the new altimetric data of Jason-1 (from cycle 001 to 250). The tide is considered as the sum of strictly periodic elementary tides called harmonic coordinates. Many global tidal models were developed, such as those of Eanes (CSR3.0), Ray (RSC94) and Egbert (TPXO.2) and those of Desai and Wahr (DW95.1), Kantha (KAN95) Le Provost (FES95.2), Matsumoto (ORI95) and Schrama and Ray (SR95) (Le Provost et al., 2001).

The ocean tide parameter is calculated by the model based on the Doodson development where the amplitude and the phase of the wave are extracted from the FES2004 model by a bilinear interpolation (Wäunsch et al., 2008). The reduction of orbital error is based on the

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Table 1. Polynomial coefficients for the wind speed determination (UserHandbook, 1996).

σ_{ob} limits	a_0	a_1	a_2	a_3	a_4
$\sigma_{ob} < 10.8$	51.045307	10.982805	1.8957084	-0.1748278	0.0054382
$10.8 \leq \sigma_{ob} \leq 19.6$	317.47430	-73.507895	6.4119781	-0.2486683	0.0036079
$\sigma_{ob} > 19.6$	0.0	0.0	0.0	0.0	0.0

processing at the crossover points (Bonfond and Exertier, 1994) after determination of the average profiles to eliminate some variable phenomena. The results obtained are compared with the value of the parameters provided in the Jason-1 satellite message, these results are sufficient for most altimetric applications as the determination of the Western Mediterranean sea surface height.

RESEARCH METHODS

Sea state bias effect

In the past, the estimates of *SSB* used as input data either the differences in sea surface height at crossover points with time differences less than one repeat cycle (Gaspar and Florens, 1998) or consecutive cycle differences (CCD) (Zlotnicki, 1994). Actually it has become customary to use sea surface height differences from a time-mean sea surface (DFM; Vandemark et al., 2002). In this paper, the *SSB* estimation adopted is the method of Gaspar and Florens (1998). The *SSB* effect is an apparent value lower of instantaneous sea surface height (*ssh*) above a reference ellipsoid, than the true height. *SSB* is expressed by:

$$SSB = f(swh, \sigma_0) \approx f(swh, u) \quad (1)$$

where *swh* is significant wave height, σ_0 is the backscatter coefficient, and *u* is wind speed (Gaspar et al. 1994; Rodriguez et al. 1992). All estimates of *SSB* are empirical. Most of the original papers on *SSB*, consider $f(swh, u)$ as:

$$ssh_2 - ssh_1 = f(swh_2, u_2) - f(swh_1, u_1) + \varepsilon \quad (2)$$

where 1 and 2 indicate measurements taken at times t_1 and t_2 at the same geographical location (crossover point). For example (2) ascribes all differences between ssh_1 and ssh_2 that vary with *swh* and *u* to the *SSB* effect. ε is a random error term that includes residual geophysical errors, altimetric measurement error, and dynamic topography variation between 1 and 2 (Gaspar et al., 1998). Here, Equations (1) and (2) are solved using the kernel smoothing nonparametric approach (Gaspar and Florens, 1998; Gaspar et al., 2002), using more than 6 years continuous Jason-1 GDRs 1Hz dataset. We took all available pass data file, up till cycle 250, when Jason-1 assumed a new orbit midway between its original ground tracks (from January 15th, 2002 to October 19th, 2008). These data are available through: AVISO (<http://www-aviso.cnes.fr>) and PO.DAAC (<http://podaac.jpl.nasa.gov>). For a detailed description of Jason-1 GDR contents, readers are referred to Aviso and PoDaac User Handbook (2008). The final result is a grid (0.25 x 0.25) of *swh* and *u*, where each component (*swh*, *u*) is associated to a value of the *SSB*. For other values of *swh* and *u*, the value of *SSB* will be determined by a bilinear interpolation. We note that the significant wave height *swh* is estimated using the model

defined by (Gaspar et al., 1998):

$$swh = 2C\sqrt{\sigma_c^2 - \sigma_p^2} \quad (3)$$

where: *C* is the celerity, σ_c (in seconds) represents the delay due to the impulse on the sea and σ_p (in seconds) is the length of the echo.

The wind speed model function selected is the wind speed model defined by Witter and Chelton (1991). The model function is obtained by a least-square fit of a fifth order polynomial to the Modified Chelton and Wentz wind speed tabular model:

$$u = \sum_{n=0}^4 a_n (\sigma_{ob})^n \quad (4)$$

where *u* is the wind speed, in meters per second (10 m exposure wind speed), σ_{ob} is the biased backscatter coefficient: $\sigma_{ob} = \sigma_0 + d\sigma$ (in decibels), σ_0 is the backscatter coefficient and $d\sigma$ is a bias which is added to the backscatter coefficient to fit Geosat data. The bias value is the same for Jason-1 altimeter: $d\sigma = -0.63$ dB and a_0, a_1, a_2, a_3, a_4 are polynomial coefficients defined in Table 1.

Ocean tide effect

The tide curve of a wave is a sinusoid of the amplitude and the phase depend only on the position of observation. So, for Jason-1, the height of the ocean tide Δh_{OT} at an instant "t" can be expressed theoretically by the following formula (Lefevre, 2000).

$$\Delta h_{OT}(\varphi, \lambda, t) = \sum_i F_i (A_i \cos(\xi_i) + B_i \sin(\xi_i)) \quad (5)$$

where $\xi_i = \sigma_i t + X_i + U_i$, $A_i = Z_i \cos(\psi_i)$ and $B_i = Z_i \sin(\psi_i)$

F_i is the nodal correction coefficient of the amplitude of the wave *i*, U_i is the nodal correction phase of the wave *i*, X_i is the astronomical argument and σ_i represents the frequency of the wave *i* (extracted from Doodson table). The amplitude Z_i and the phase ψ_i of the wave can be extracted from the FES2004 model by a bilinear interpolation. The FES series (Finite Element Solution) of ocean tidal models was developed by Le Provost et al. (2001), these models stem from the finite element method for the solution of the hydrodynamic equations constrained with tide gage and past altimeter data, the spherical harmonics are given in the Schwiderski convention (Wäunsch et al., 2008).

Orbital error

Before the reduction of the orbital error, we must calculate the average profiles using the averaging process to eliminate some variable phenomena whose period is less than the considered period. These phenomena can result from variations of the sea surface (seasonal variability, semi-annual, inter-annual) or of the dispersion of altimetric measurements (Bonfond and Exertier, 1994). The processing consists of averaging three parameters

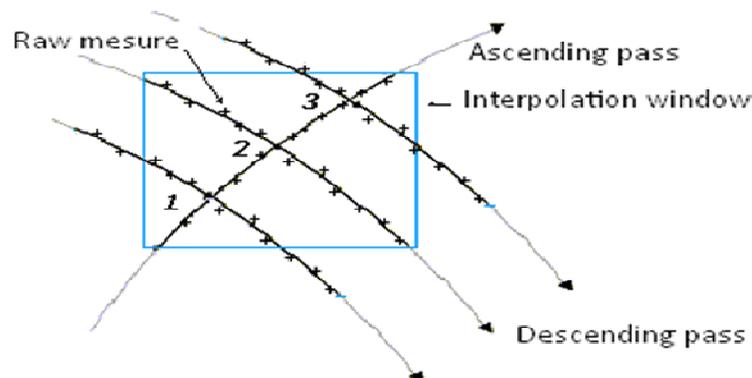


Figure 1. Altimetric measurement interpolation for Crossover points determination.

(latitude, longitude and height of the sea surface) by gridding of a window of 0.047° in latitude, which corresponds to the average spacing between two successive satellite measurements. To palliate the lack of measurement along the average profiles, and to increase the density of the zone, the sea surface heights are approximately processed by a second-order polynomial (function of the longitude and the latitude). The polynomial coefficients are calculated with the least squares method (Bonnefond and Exertier, 1994).

The reduction of the orbital error of the altimetric satellite can be obtained by the comparison of different altimetric measurements by processing at the crossover points of the satellite pass (Bonnefond and Exertier, 1994). For the crossover points (Figure 1), coincides two different measures of the sea level. The method used for the adjustment of mean profiles between them consists to apply the bias on profiles heights at the crossover point above the ellipsoid (a constant bias by profile). The difference between these two values must be corrected and distributed on the all measurements of the two intersected profiles in this point; for this we used the polynomial interpolation method.

DATA USED

For this application, the used data represent more 6 years continuous Jason-1 dataset available through: AVISO (<http://www-aviso.cnes.fr>) and PO.DAAC (<http://podaac.jpl.nasa.gov>). For a detailed description of GDR contents, readers are referred to User Handbook - IGDR and GDR Jason-1 Products (2008). Our interest area is defined by the following coordinates: 35°N - 45°N , 3°W - 11°E . To select the right track, we used a pass locator using Google Earth available through Aviso. The "best" Jason-1 tracks that pass over the western Mediterranean Sea are the # 009, 070, 085, 146, 161, 172, 187, 222 and 248 (up till cycle 250, when Jason-1 assumed a new orbit midway between its original ground tracks).

We took all available pass data file from cycle 001 to cycle 250 (from January 15th, 2002 to October 19th, 2008), Figure 2 represents the selected Jason-1 pass over the Western Mediterranean Sea. To retain only the most valid data, some filters are used (Table 2).

RESULTS AND DISCUSSION

Geophysical parameters

The obtained 3-D SSB NP (non-parametric) model, as a

function of significant wave height () and wind speed (), is shown in Figure 3. The SSB values vary between -0.15 and -18.94 cm. The mean value is -7.21 cm. Also, this NP model permits to reduce default values of per regime of about 60% and therefore is a good interpolation from this new grid (, ,). As an example, Figure 4 exhibits, for the track # 187 of cycle 050, the differences between the estimated and provided in Jason-1 GDR datasets. In this figure, the x-axis represents the corresponding number of altimetric datum along the selected track, the dark and gray graphs represent the estimated and provided respectively and the dashed graph represents the differences which are between -5.35 and 5.63 cm. These differences are due to the improvement of the estimation evaluated using 250 cycles of Jason-1 measurements while the provided values in Jason-1 GDR datasets are evaluated using a few cycles.

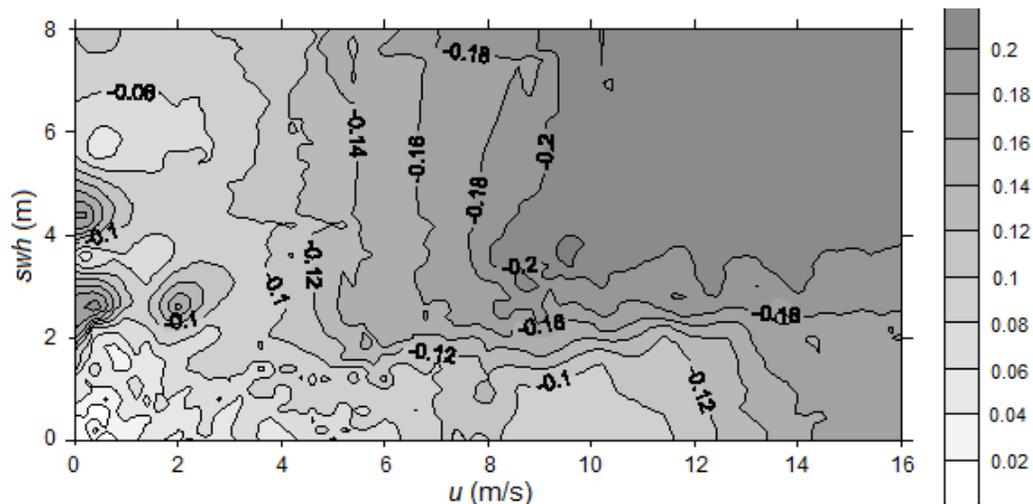
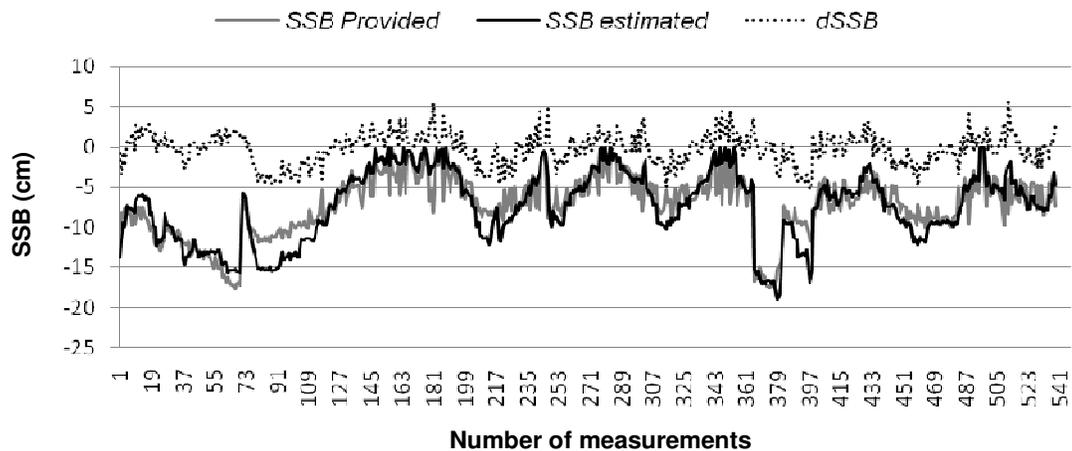
In Figure 5, the x-axis represents the corresponding number of altimetric datum along the selected track, the dark and gray graphs represent the estimated and provided tide effect respectively and the dashed graph represents the differences which are between -11 and -4.26 cm. This difference is mainly owed to the model employed, because we have used the FES2004 model that is based on tide gauge and altimetric measurements while the provided values are gotten by the FES99 model which is based on tide gauge measurement only. The implication of Topex/Poseidon and Jason-1 data with the tide gauge measurement permit us to determinate an ocean tide model (FES2004) which permits us to improve the ocean tide estimation.

Orbital error

The obtained standard deviations indicate the existence of variability, so the existences of dispersion between the cycles of the same pass and the quality of altimetric data. The differences of heights at the crossover points for cycle

Table 2. Data editing criteria (User handbook, 2008).

Number of valid points > 10
0 mm < RMS of 1/sec range < 200 mm
-130 000 mm < (altitude – range_ku) < 100 000 mm
-2500 mm < dry tropospheric correction < -1900 mm
-500 mm < wet tropospheric correction < -1 mm
-400 mm < ionospheric correction < 40 mm
-500 mm < sea state bias correction < 0 mm
-5000 mm < ocean tide correction < +5000 mm
-1000 mm < solid earth tide correction < +1000 mm
-150 mm < pole tide correction < +150 mm
0 mm < significant wave height < 11 000 mm
7 dB < sigma naught < 30 dB
0 m/s < altimeter wind speed < 30 m/s
-0.2 deg ² < square of off nadir angle from waveforms < 0.5 deg ²

**Figure 3.** Sea state bias NP model (in meters).**Figure 4.** SSB effect of the pass 187 cycle 050.

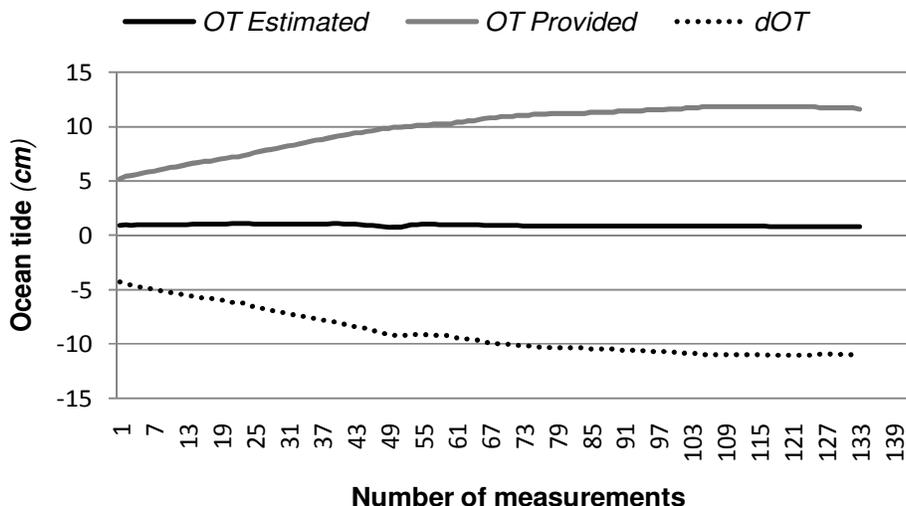


Figure 5. Ocean tide effect of the pass 187 cycle 050.

050 are given in Table 3. The effect of the orbital error is calculated with a precision of 1 cm. we can say that the processing at the crossover points is the best method to eliminate the orbital error effect.

Sea surface height

ssh is the difference between altimetric measurement and satellite altitude. The corrected range is estimated from altimetric measurement minus known orbital error and environmental and geophysical effects, namely: tropospheric and ionospheric corrections, *SSB* effect, tide effects and inverse barometer correction. The tropospheric effect, based on the pressure at sea level, temperature and partial pressure of water vapor, is obtained from the Jason-1 Microwave Radiometer (JMR) measures (Rummel, 1993). The ionosphere correction is determined from the dual frequency measurements from the altimeter (Rummel, 1993). Solid earth is computed as described by Cartwright and Edden (1973). The pole tide is easily computed as described by Wahr (1985). The inverse barometer correction is computed from ECMWF (European Centre for Medium Range Weather Forecasting) atmospheric pressures. The mapping of the mean *ssh* along the Jason-1 tracks, by a regular grid of $0.25^\circ \times 0.25^\circ$ in longitude and latitude, is done using a linear interpolation (Delaunay triangulation). Figure 6 represents the mean sea surface height over the Western Mediterranean Sea.

Conclusion

This study improves the Sea State Bias estimation with nonparametric model evaluated using 250 cycles of

Jason-1 measurements. An enhanced three-dimensional (3D) *SSB* correction model as a combination of significant wave height (*swh*) and wind speed (*u*) is performed as a grid of 0.25×0.25 . The NP model based on the long period of Jason-1 altimetric data measurements is very effective to estimate the *SSB* effect. It permits to reduce by 60% the default values of *SSB* per *swh-u* regime and therefore a good interpolation of the *SSB* for measurements along the altimetric tracks over the Western Mediterranean Sea. On the same zone, the model based on the Doodson development of the tide potential generator using the global tidal model FES2004 has improved the determination of ocean tide with few centimetres.

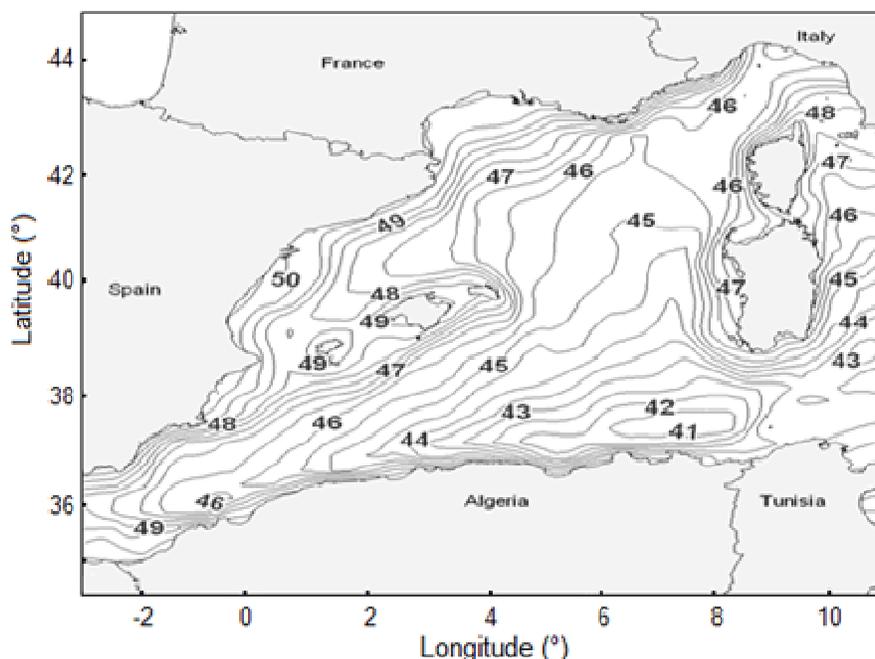
The processing at the crossover point of the average profiles has reduced the orbital error with a high precision. The obtained results allowed us to correct the Jason-1 datasets which we dispose from the differences between the apparent sea level as measured by the altimeter and the true mean sea level. The corrected 250 cycles of altimetric Jason-1 tracks measurements of *SSB* effect, environmental and geophysical effects and orbital error permit us the determination of mean sea surface height (*ssh*) over the Western Mediterranean Sea. In perspective, for precise geophysical parameters estimation, we project to use altimetric measurements from several altimeters for longer time. The introduction of Envisat and Jason-2 data, will certainly improve geophysical parameters and orbital error and therefore a better determination of the mean sea surface height of Western Mediterranean Sea.

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Table 3. Heights differences at the crossover points (cycle 050).

N°	Ascending pass	Descending pass	Longitude (°)	Latitude (°)	Difference (cm)
1	009	070	4.248	39.219	3.9
2	009	146	5.665	41.175	4.3
3	009	248	2.831	37.108	-7.3
4	085	146	7.083	39.218	7.9
5	085	070	5.666	37.107	3.3
6	161	146	8.500	37.107	-1.8
7	187	070	2.831	41.176	-19
8	187	172	0.004	37.108	-1.7
9	187	146	4.248	42.988	18.3
10	187	248	1.414	39.220	14.3

**Figure 6.** Sea surface height (in meters) of Western Mediterranean Sea determined from Jason-1 data (2002-2008).

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