Determination of Evolution of the Altimetric Mean Level of the Western Mediterranean from the Jason-1 Data: Comparison with Analysis of Tidal Gauge Measurements

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M. HADDAD, H. ABDELLAOUI, N. AMRANE
National Institute of Cartography and Remote Sensing 123, Rue de Tripoli,
BP 430, Hussein-Dey 16040 - Algiers, Algeria.

Prf. M.F. BELBACHIR
University of Sciences and Technology of Oran, Signals and Systems Laboratory,
Institute of Electronics. BP 1505, Oran El M'naouer, Algeria.

Abstract: The sea surface topography, which is directly linked to the shape of the geoid and to oceanic effects, is only measurable thanks to the spatial and temporal resolution of satellite altimetry. The contributions of satellite altimetry study in the Mediterranean have been considerable. The first maps of the marine geoid, with relative accuracy of one to two decimetres depending on the methods used, have contributed greatly to the understanding of geophysical phenomena. Subsequently, thanks to reductions in orbital errors, improvements in gravitational models, and to the development of pseudo-geometrical orbit computations, the accuracy of determination of the absolute mean sea level has improved from several meters to a few centimetres. The study presented here aims to determine seasonal variations in mean sea level in the Western Mediterranean basin by analysis of Jason-1 data corrected of different perturbations like the geophysical phenomena, the ocean wave influence, the inverse barometer effect, and the orbit error. The analysis of altimetric data Jason-1 allowed us to observe a strong amplitude of variations of the average level in the Western Mediterranean basin, of the order of 20 cm, with a characteristic period of one year. The comparison of the variation of the average height sea level at the harbour of Algiers obtained from analysis of altimetric data Jason-1 and from the harmonic analysis of tidal gauge measurements, showed almost identical results.

Keywords. Jason-1, tide gauge, sea level, seasonal variations, Western Mediterranean sea.

1. Introduction

The United States were the first to have put in orbit an altimeter aboard satellites, on Skylab and Geos-c, then on Seasat in 1978 and Geosat in 1985.
Since the 90s, new altimetric missions were launched, ERS-1 (1991-1996), Topex/Poseidon (since 1992), ERS-2 (since 1995), Jason-1 (since 2001) and Envisat (since 2003).
This paper presents the methodology of processing and analyzing of Jason-1 altimetric data to determinate the seasonal variation of sea level of the Western Mediterranean sea.

2. Jason-1 mission

JASON-1 is a follow-on mission to the highly successful TOPEX/POSEIDON (T/P) mission. The main goal of this mission is to measure the height of sea surface at least at the same performance level of T/P.
Launched on December 7, 2001, the Jason-1 satellite measures the precise height of the sea surface using the POSEIDON-2 altimeter operating at 13.575 GHz (Ku band) and 5.3 GHz (C band), a system of positioning Doris (Doppler Orbitography and Radiopositioning by Satellite) in complement to the GPS receiver and Laser reflector and a Microwave Radiometer which provide the total water vapor content in the troposphere along the altimeter beam.

3. Principle of computation of the level of the sea

The radar altimeter embarked aboard a satellite gives out a signal to very high frequency to the vertical of this one in direction of soil, and receives in return the echo reflected by the surface of the sea.
The analysis of the echo permits to extract a very precise measure of time of round-trip journey between the satellite and the surface of the sea. This time is transformed then in distance by simple multiplication by the speed of light, speed to which propagates electromagnetic waves.
The height of the sea is therefore equal to the difference between the distance satellite-surface and the position of the satellite above the ellipsoidal reference.

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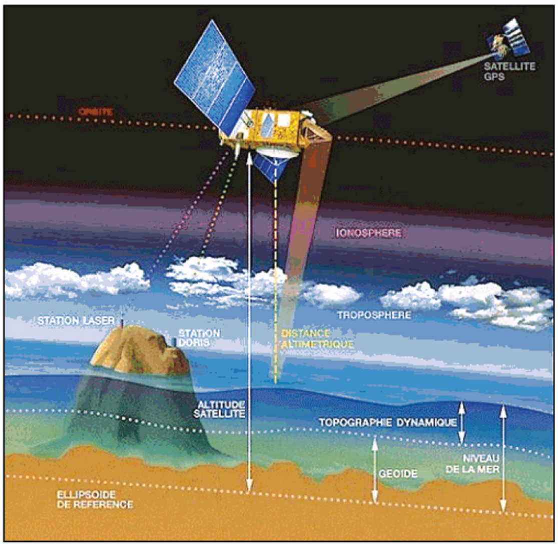

Fig. 2 Geometric principle of altimetry.

4. Sources of errors

Altimetric measurements have many sources of errors. For instance, they need to be corrected for environmental perturbations like the geophysical corrections (wet troposphere, dry troposphere and ionosphere), the ocean wave influence (sea state or electromagnetic bias). Also, the tide influence (ocean tide, earth tide and pole tide) and inverse barometer effect have to be accounted for.

4.1 Troposphere and ionosphere influence

The atmosphere slow down the velocity of radio pulses at a rate proportional to the total mass of the atmosphere (dry troposphere influence), the mass of water vapor in the atmosphere (wet troposphere influence), and the number of free electrons in the ionosphere (ionosphere influence).

• The dry meteorological tropospheric range correction is principally equal to the surface pressure multiplied by -2.277mm/mbar, with a small adjustment also necessary to reflect a small latitude dependence (Rummel, 1993):

$$Dry\_Corr = 2.227\ \left(1+0.0026\ \cos(2\varphi)\right)P_S \quad (1)$$

where P_s is surface atmospheric pressure in mbar, φ is latitude, Dry_Corr is the dry troposphere correction in mm.

• The wet troposphere correction expression is (Rummel, 1993):

$$Wet\_Corr = 2.227\left(\frac{1255}{T_S}+0.05\right)E_S \quad (2)$$

where P_S is surface atmospheric pressure in Pascal, φ is latitude, E_S is the partial pressure of the water steam and T_S is the temperature in Kelvin.

• The ionosphere correction for an altimeter bi-frequency is given by (Rummel, 1993) :

$$Iono\_Corr = \frac{f_1^2}{f_1^2-f_2^2}\ \frac{40.2\ E}{f_2^2}\ -\ \frac{f_2^2}{f_1^2-f_2^2}\ \frac{40.2\ E}{f_1^2} \quad (3)$$

where E represent the total content in electron (TEC) and f_1 and the f_2 frequencies.

4.2 Sea state bias

Due to the large footprint radar measurements, the sea surface scattering elements do not contribute equally to the radar return: troughs of waves tend to reflect altimeter pulses better than do crests. Thus the centroid of the mean reflecting surface is shifted away from mean sea level towards the troughs of the waves. The shift causes the altimeter to over-estimate the height of the satellite above the sea surface. The Sea State Bias (SSB) is the difference between the apparent sea level as measured by an altimeter and the true mean sea level.
The nature of the sea state bias has been investigated using airborne radars and lasers capable of determining for various sea states the strength of the vertically reflected signal as a function of the displacement of the reflecting area from mean sea level. It is given as a function of wind speed and the skewness and kurtosis of the probability distribution of sea surface elevation due to the waves on the sea surface.

4.3 Ocean tide

It represents the response of the ocean to motion of the moon, the sun and the other planets. It translates itself by a transport of water masses.
This correction is calculated from global models of tide : an empirical model GOT99.2 of the Goddard Space Flight Center or the FES 95.2 finite-element hydrodynamic model of the university of Grenoble.

4.4 Solid Earth Tide

The solid Earth responds to external gravitational forces similarly to the oceans. The Earth responds fast enough for it to be considered to be in equilibrium with the tide generating forces.
Then, the surface is parallel with the equipotential surface, and the tide height is proportional to the potential. The proportionality is the so-called Love number.

It should be noted that, although the Love number is largely frequency independent, an exception occurs near a frequency corresponding to the K1 tide constituents due to a resonance in the liquid core (Wahr 1985). Such a tide is computed as described by Cartwright and Tayler (1971) and Cartwright and Edden (1973).

4.5 Pole tide

The Earth's rotational axis oscillates around its nominal direction with apparent periods of 12 and 14 months. This result in an additional centrifugal force which displaces the surface. The effect is thus indistinguishable from tides, and it is called the pole tide. The period is long enough to be considered in equilibrium for both the ocean and the solid Earth.
The complete pole tide (in mm) expression is (Wahr, 1985):

$$H\_Pole = -69.435 \sin(2Lat\_Tra) \times \begin{pmatrix} (x_{Pole} - x_{Pole-avg})\cos Lon\_Tra \\ + (y_{Pole} - y_{Pole-avg})\sin Lon\_Tra \end{pmatrix} \quad (4)$$

where: *Lon_Tra, Lat_Tra are* longitude and latitude of measurement point, x_{pole}, y_{pole} is axis in the direction of the IERS reference meridian and axis in the direction 90°west longitude, $x_{pole\_avg} = 0.042$ arc sec and $y_{pole\_avg} = 0.293$ arc sec.

4.6 Inverse barometer effect

As atmospheric pressure increases and decreases, the sea surface tends to respond hydrostatically. The ocean rises and falls, that is, a one mbar increase in atmospheric pressure depresses the sea surface by about 1 cm.
The instantaneous correction is computed using as input the surface atmospheric pressure (P_atm, in mbar) which is available indirectly via the dry tropospheric correction obtained from meteorology (Dry_Corr, in mm):

$$P\_atm = \frac{Dry\_Corr}{\left[(-2.277)\left(1 + \left(0.0026 \cos\left(2\,Lat\_Tra\, 1.10^{-6}\, \pi / 180.0\right)\right)\right)\right]} \quad (5)$$

The inverse barometer correction (Inv_Bar, in mm) is then:

$$Inv\_Bar = -9.948\left(P\_atm - 1013.3\right) \quad (6)$$

4.7 Orbital errors

The effect of the orbital errors is directly visible to the height in intersections between ascending and descending altimetric tracks (crossover point).

The correction of this effect is based on the principle of polynomial interpolation of residues on height at the crossover points.

5. Processing and analysis

The assessment of seasonal variations in mean sea level from the Jason-1 data made on a zone Covering the Western Mediterranean sea: zone understood between $35.5^{\circ} \le \varphi \le 44.5^{\circ}$ and $0^{\circ} \le \lambda \le 10^{\circ}$.

5.1 Jason-1 data used

The used Jason-1 data are supplied by AVISO (Archivage, Validation et Interprétation des données des Satellites Océanographiques) under GDR Products DVD, containing the cycles from 079 to 132 which correspond to dates from February 27, 2004 to august 16, 2005.
The pass numbers used for this application are illustrated in the following figure:

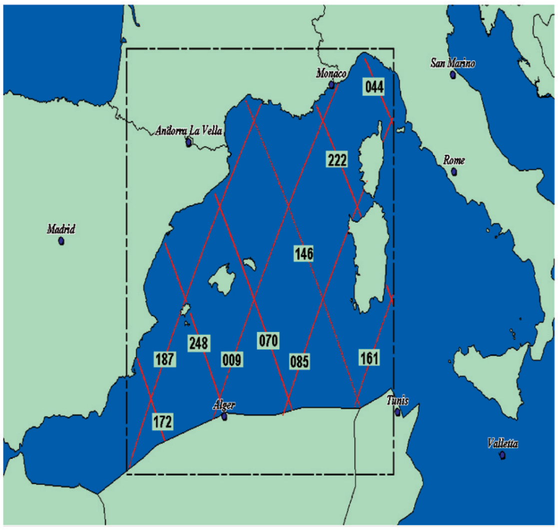

Fig.3 Jason-1 tracks over Western Mediterranean sea.

GDR (Geophysical Data Records) files contain ten-day repeat cycles data. It contains all relevant data and corrections needed to calculate the sea surface height: location, altimeter range, troposphere and ionosphere corrections, Solid Earth, ocean and polar tide corrections, inverse barometer correction…

5.2 Model of computing sea height

The formulation of the model of computing sea surface height (SSH) is given as follows:

$$SSH = Hp\_Sat - (H\_Alt + \Sigma) \quad (7)$$

where Hp_Sat is the DORIS altitude of satellite center of mass above the GRS 80 reference ellipsoid, H_Alt is the altimeter range in Ku band and Σ is the sum of corrections to be added to the altimeter range:

$$\Sigma = Dry\_Corr + Wet\_Corr + Iono\_Corr\_ku + INV\_Bar + H\_Eot\_FES + H\_Set + H\_Pol \quad (8)$$

where: Dry_Corr is the dry meteorological tropospheric correction, Wet_Corr is the wet meteorological tropospheric correction, $Iono\_Corr\_ku$ is the altimeter ionospheric correction on ku band, SSB_Corr_k1 sea state bias correction in Ku-band, INV_Bar is the inverted barometer height correction, H_Eot_FES is the geocentric ocean tide height computed from FES 95.2 model, H_Set is the solid earth tide height and H_Pol is the pole tide height.

5.3 Processing and results

For this application, each of Jason-1 cycle is treated independently of the others to obtain a sea surface height.

Afterward and in case if crossover points exist with a significant difference of sea surface height between an ascending and descending altimetric arcs, an adjustment of the height of the sea along altimetric arcs is done. Next, the sea surface height is compared point by point to the EGM 96 global geoid model that is closely associated with the location of the mean sea surface.

The average differences obtained by cycle between sea heights stemming from Jason-1's instantaneous profiles and the EGM 96 geoid surface is represented in the following figure:

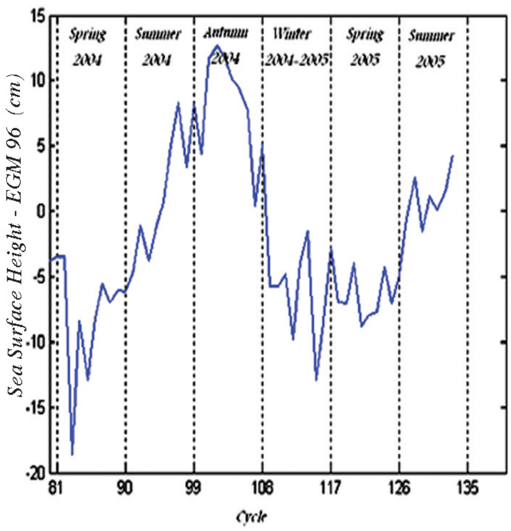

Fig. 4 Average differences between the altimetric sea heights and the EGM 96 geoid surface.

The temporal variations in the Western Mediterranean basin between the instantaneous height of the sea and the EGM96's geoid have amplitude about 20cm, with a maximum and a minimum respectively in autumn and in winter: this phenomenon is due mostly to the thermic expansion/contraction of the water under the influence of temperature variations. The combination of Jason-1 cycles from 079 to 132 has provided an altimetric mean level surface over the Western Mediterranean sea. The comparison of this surface with the EGM 96 geoid stands out differences between -50 cm and 50 cm with a average of 2 cm :

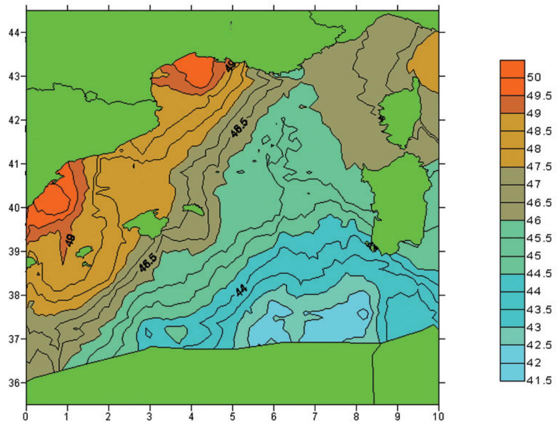

Fig. 5 Altimetric mean level over the Western Mediterranean sea (in meter).

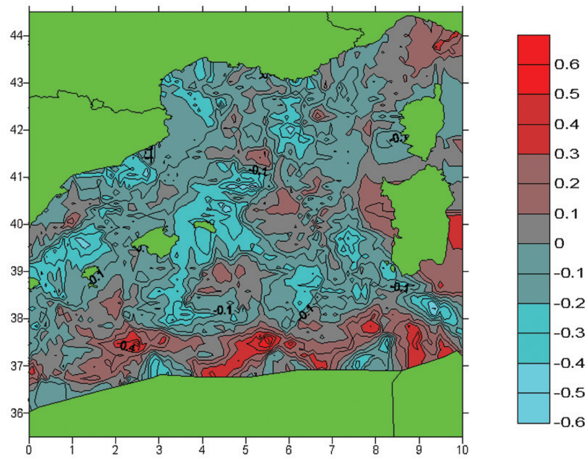

Fig.6 Differences in meters between the altimetric mean level solution and the EGM 96 geoid (in meter).

6. Comparison with tidal gauge measurements

The average Jason-1 altimetric height by cycle interpolated at the Algiers harbour is compared to the mean sea level obtained by the harmonic analysis

of tidal gauge measures, obtained from analogical and automatic tide gauge installed at the same site of Algiers harbour. The periods of tidal gauge measurements analyzed are obviously equivalents to altimetric cycles.
These differences results of variation of the mean sea level at the Algiers harbour are very similar:

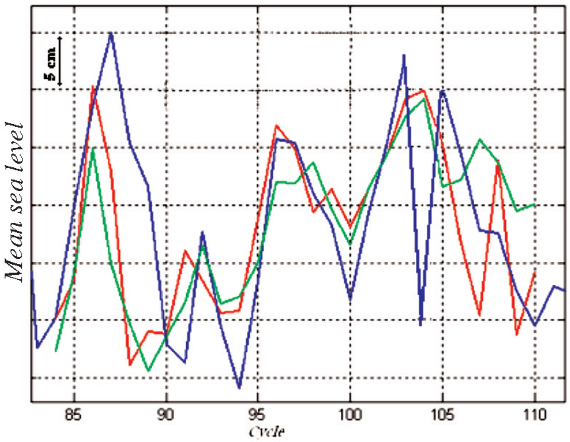

Fig. 7 Comparison between the mean altimetric level Jason-1 (in blue) and the mean level obtained by harmonic analysis of the tidal data of the analogical tide gauge (in red) and the automatic tide gauge (in green).

7. Conclusion

The analysis of altimetric data Jason-1 allowed us to observe strong amplitude of variations of the average level in the Western Mediterranean basin, of the order of 20 cm, with a characteristic period of one year.
The comparison of the variation of the average height sea level at the harbour of Algiers obtained from analysis of altimetric data Jason-1 and from the harmonic analysis of tidal gauge measurements agrees well.
In terms of perspectives, the combination, on a bigger scale of time, of the data of Jason-1 with the data of the other missions of spatial altimetry such as Topex, Envisat, will allow certainly to observe with a good precision the main characteristics of the circulation in the Western Mediterranean basin and notably the seasonal swings.

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