Report
on
DETERMINATION OF INSTANTANEOUS SEA LEVEL ON NW MEDITERRANEAN SEA FOR RA-2 ABSOLUTE RANGE CALIBRATION

REPORT 3

CONTRACT PROPOSAL CLS/DOS/02/3936

Prepared
by
COLLECTE LOCALISATION SATELLITES (CLS)

15 Avril 2003

TABLE OF CONTENTS

1 INTRODUCTION

1.1 SCOPE OF THE DOCUMENT

The objective of the ENVISAT RA-2 absolute range calibration was to retrieve an absolute value of the instrument range bias by comparing RA-2 measurements with independent measurements of the same range at the same place and time. This objective was achieved by means of a regional calibration plan located in the north-western Mediterranean Sea with the determination of the instantaneous sea level beneath the ENVISAT satellite passes.

The purpose of this document is to present the final results of the RA-2 absolute range bias which was computed by CLS during the first phase of the absolute calibration phase. This phase is ending at the end of October.

The work is done by CLS for ESA.

1.2 INVOLVED ORGANISMS

Several parties are involved in the ENVISAT calibration for this study:

- IESS-CSIC Research Unit from Barcelona, Spain is in charge of the collection of sea level elevations from light GPS buoys along the shorelines of Spain under ENVISAT tracks;
- Institute of Geodesy and Navigation from Munich, Germany is in charge of the collection of sea level elevations from four fixed GPS buoys near Menorca;
- LEGOS from Toulouse, France supplies the atmospheric data from their atmospheric model;
- A mention must be added to thanks the team of SONEL (Système d' Observation du Niveau des Eaux Littorales) which provided us a very useful help by supplying new tide gauge data;
- We (CLS) are in charge of the collection and the analyses of these data to provide an absolute calibration of the ENVISAT RA-2 instrument.

2 INVENTORY OF THE TIDE GAUGES USED

2.1 INTRODUCTION

In Report 1, a first status of the sea level stations which were supposed to be used in the RA-2 absolute calibration was done. However, due to technical constraints or administrative constraints, the list was modified. Several tide gauges were not included in the study but others were added. So as to calibrate the ENVISAT RA-2, several sea level stations using different systems are used in the Mediterranean Sea:

- Traditional coastal tide gauges;
- Mooring tide gauges (or deep ocean tide gauges);
- Fixed GPS buoys;
- Light GPS buoys.

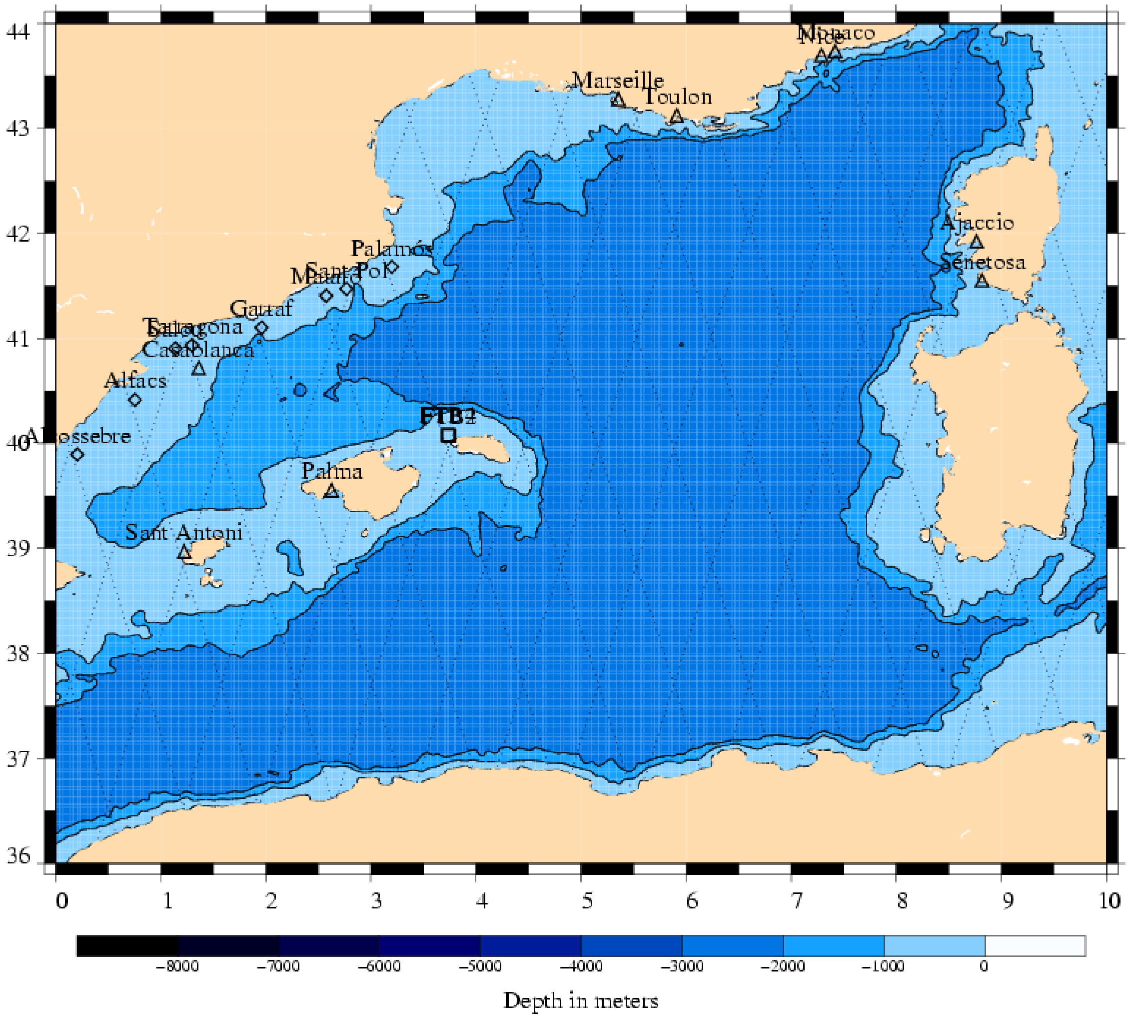


Figure 1: Location of the tide gauges used in the comparison (20 March 2003)

2.2 INVENTORY

2.2.1 *Coastal tide gauges*

Name	Longitude	Latitude	Provider	Available till
Palma	2.624600	39.552600	ICM	25 November 2002
Sant Antoni	1.301749	38.978470	IEMEDEA /ESA	16 November 2002
Casablanca	1.358330	40.717000	ICM/ESA	15 November 2002
Ajaccio	8.764000	41.920633	SONEL	24 November 2002
Marseille	5.353667	43.278833	SONEL	24 November 2002
Monaco	7.416667	43.733333	SONEL	24 November 2002
Nice	7.285600	43.695667	SONEL	24 November 2002
Toulon	5.908917	43.122300	SONEL	24 November 2002
Senetosa	8.814967	41.54985	CNES/LEGOS	16 September 2002

Table 1: Coastal tide gauges used in the calibration study

A few comments about these available tide gauges compared to the ones introduced in Report 1:

- Capria sea level station is not available for the study because of technical problems.
- For Marseille and Ajaccio, new data were used, extracted from the SONEL database.
- Toulon, Nice and Monaco sea level stations were added in the study at the beginning of March 2003, thanks to the help of the SONEL team.
- It must be noticed that the tide gauge of Sète, initially present in the listing, has been removed due to data acquisition problems.
- Barcelona tide gauge was initially in the listing but administrative problems prevent us from accessing the data.

2.2.2 *Deep ocean tide gauge*

Two deep ocean tide gauges are available for our study. They are based on bottom pressure tide gauges. However, they are not provided with an absolute reference and they can not be used in the calibration. However, we recall here information about these two bottom pressure tide gauges.

Name	Responsible	Longitude	Latitude	Provider	Status
PTG1	University of Dresden	3.741	40.075	University of Dresden/ IMEDIA	Available December
PTG2	University of Dresden	3.730	40.075	University of Dresden/ IMEDIA	Available December

Table 2: Deep ocean tide gauges deployed but not used in the calibration study

2.2.3 Fixed GPS buoys

Four fixed GPS buoys were anchored within the calibration area. Two were used for the study.

Name	Type	Longitude	Latitude	Provider	Available till
FTB2 (Menorca SE)	Moored GPS Buoy	3.741666	40.009722	IfGN/IMEDIA/ESA	28 September 2002
FTB4 (Menorca NW)	Moored GPS Buoy	3.729722	40.020555	IfGN/IMEDIA/ESA	19 September 2002

Table 3: Fixed GPS buoys used in the calibration study

- Four fixed GPS buoys were anchored within the calibration area.
- Two buoys remain for the study.
- Since 6 April 2002 no more data are available from STB1.
- STB3 is out of order and its data are not exploitable.

2.2.4 Light GPS buoys

Nom	Orbit #	Asc/Desc	Lat/Lon	Provider
Palamós	344	Asc	41.69/3.194	ICM/ESA
Mataró	115	Asc	41.39/2.577	ICM/ESA
Garraf	387	Asc	41.09/1.960	ICM/ESA
Tarragona	158	Asc	40.94/1.290	ICM/ESA
Alfacs	430	Asc	40.41/0.748	ICM/ESA
Alcossebre	201	Asc	39.90/0.198	ICM/ESA
Sant Pol	237	Desc	41.54/2.789	ICM/ESA
Garraf	8	Desc	41.11/1.924	ICM/ESA
Salou	280	Desc	40.91/1.139	ICM/ESA
Alcossebre	51	Desc	39.92/0.092	ICM/ESA

Table 4: Light GPS buoys used in the calibration study

- Each ENVISAT time pass, ICM is collecting data thanks to their light GPS buoys.
- The light GPS buoys are not fixed. They are placed under ENVISAT tracks each time ENVISAT flies above the Mediterranean Spanish waters.
- ICM managed 44 experiments over the 45 planned surveys at sea.

3 CONCEPTS

3.1 PROBLEMATIC

The problem is to compare ENVISAT data with in situ tide gauges which are not under ENVISAT tracks. This is the reason why a specific model approach was performed. The solution was to propagate in-situ measurements towards the satellite tracks by the use of specific algorithms through geophysical models. A specific software was developed to automatically compute the Sea Surface Height (SSH) estimations at in-situ gauges location and at the nearest point on ENVISAT track.

SSH is approximated by the sum of:

- the Mean Sea Surface (MSS)
- the tidal elevation
- the sea level elevation due to atmospheric effects.

Those three geophysical corrections allow to link in situ measurements to ENVISAT measurements. New geophysical models were used:

- MSS : the CLS.01 MSS model [*Hernandez and Schaeffer*, 2001]
- Atmospheric effects : the Mediterranean MOG2D LEGOS atmospheric model [*Carrere and Lyard*, 2003]
- Tides : the FES99 LEGOS/CLS tide model [*Lefèvre et al.*, 2002]

3.2 DETERMINATION OF THE BIAS

With the three geophysical models introduced before, the ENVISAT bias can be computed according to the simple formula:

```
Bias = ΔENVISAT - ΔTG (+/- errors on models and measurements).
```

Figure 2 summarizes the processing to deduce the RA-2 bias at a location compared with the nearest tide gauge by propagating the in situ measurements toward the remote sensing measurements with the geophysical models.

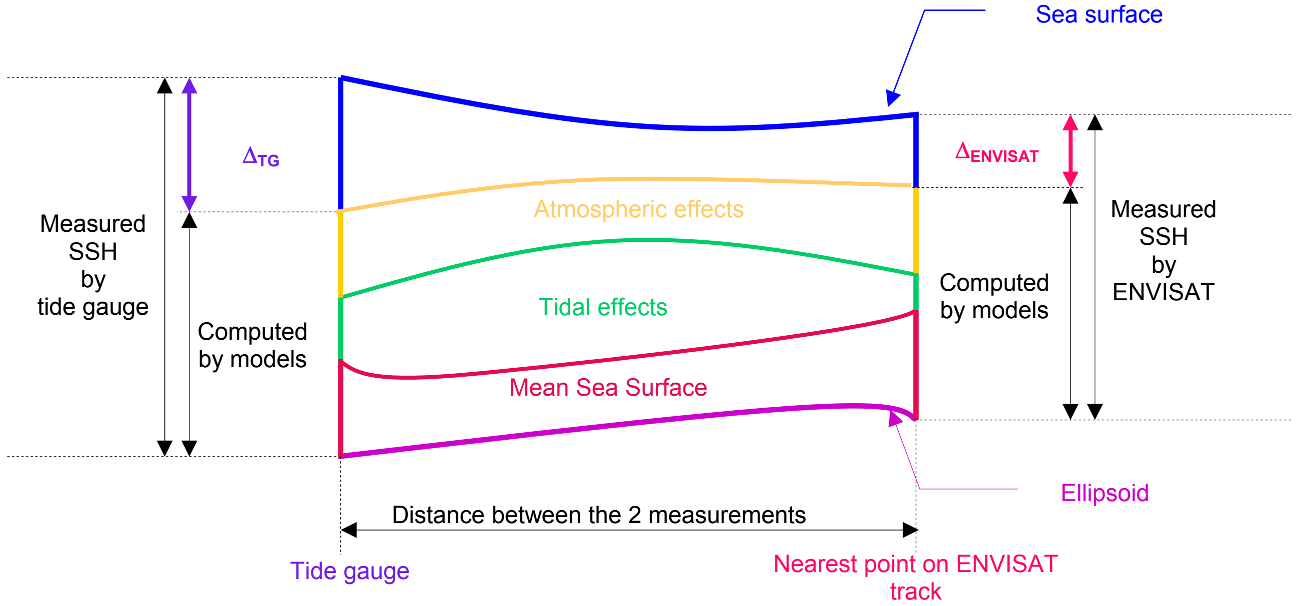


Figure 2: Determination of the RA-2 bias compared with in situ tide gauge measurement.

3.3 SATELLITE CORRECTIONS

Several corrections have to be applied to retrieve SSH from ENVISAT. Indeed, the SSH H_{sat} can be computed has:

```
Hsat=         alt_cog_ellip -
       (      ku_band_ocean_range     +
              mod_dry_tropo_corr      +
              mod_wet_tropo_corr      +
              ra2_ion_corr_ku         +
              sea_bias_ku             +
              solid_earth_tide_ht     +
              geocen_pole_tide_ht           )
```

If available, these fields were extracted from the ESA Pds files (Table 5).

Field number	Field name	Description in ENVISAT datasets	Correction
1	dsr_time	MDSR Time stamp. Time fields based on UTC are computed for each record and referred to the center of the averaged waveform	
4	Lat	Geodetic Latitude (positive N, negative S)	
5	Lon	Longitude (positive E, 0 at Greenwich, negative W)	
9	alt_cog_ellip	Altitude of CoG above reference ellipsoid	+
17	ku_band_ocean_range	Ku-band ocean range	-

39	mod_dry_tropo_corr	Model dry tropospheric correction	-
41	mod_wet_tropo_corr	Model wet tropospheric correction	-
43	ra2_ion_corr_ku	RA-2 ionospheric correction on Ku-band	-
49	sea_bias_ku	Sea state bias on Ku-band	-
103	solid_earth_tide_ht	Solid earth tide height	-
104	geocen_pole_tide_ht	Geocentric pole tide height	-

Table 5: Applied corrections to retrieve SSH from RA-2 measurements

3.4 SPECIFIC CORRECTIONS

In order to perform better comparisons, specific corrections were set for the calibration study. Thus, specific orbits and specific tropospheric corrections were computed.

We must notice that no specific correction was set for ionospheric field and the sea state bias. These two corrections were directly extracted from the ESA Pds files if available.

3.4.1 Specific orbits

Specific orbits (from 16 April to 13 September 2002) were computed by Remko Scharroo on the calibration area. The different orbits were used in the order of importance: short arcs if available, long arcs (DORIS orbit) if short arcs are not available and orbit extracted from ESA Pds files if no other orbits are supplied. In particular, from 13 September to the end of October we used the long arcs.

3.4.2 Specific dry and wet tropospheric corrections

The dry and wet tropospheric corrections (1 April 2002 to 28 October 2002) were computed by Antonio Martellucci from ESTEC. These corrections were distributed as fields which were optimized by taking into account better models so as to provide a Troposheric Zenith Delay (TZD). TZD is the sum of dry and wet tropospheric correction and is derived from ECMWF fields. The TZD provides a global coverage during the calibration phase.

3.5 ERRORS ON MODELS

It is necessary to determine the confidence in the computed surface with the models. Indeed, it is needed to evaluate the errors introduced by the models so as to provide a confidence on the computed bias. This is the reason why specific model errors were computed for the study for the CLS.01 MSS model and the FES99 tide model. For the MOG2 atmospheric model, no error was computed.

CLS01 MSS error is a formal error and was computed according to an objective analysis algorithm (Figure 3).

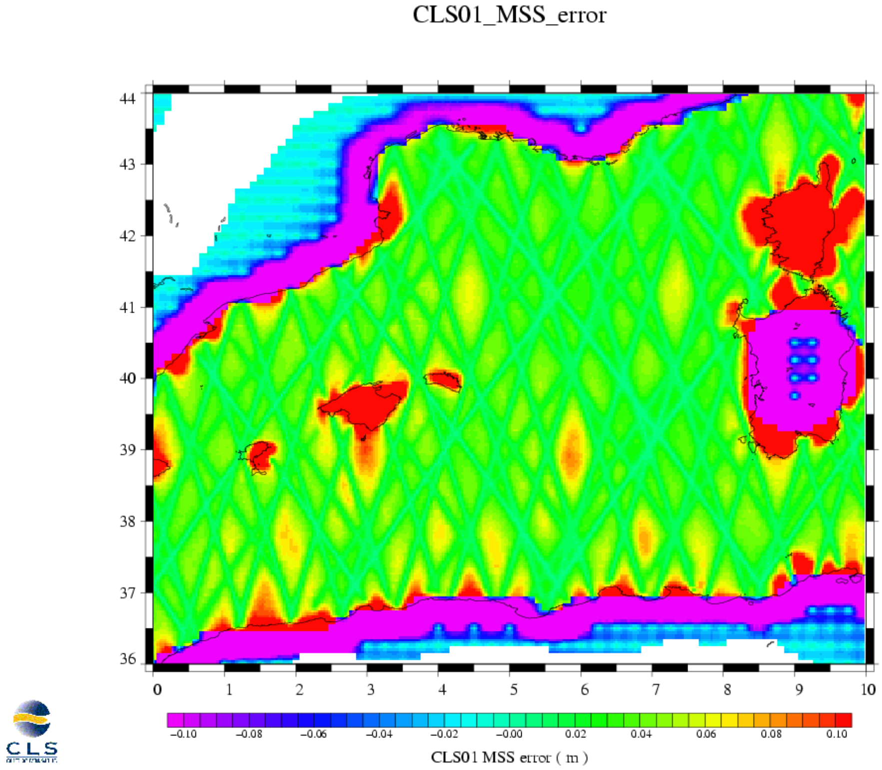


Figure 3: CLS.01 MSS error model

FES99 error on the Mediterranean area was computed by taking into account the bathymetry of the site and a set of tide gauge errors (Figure 4).

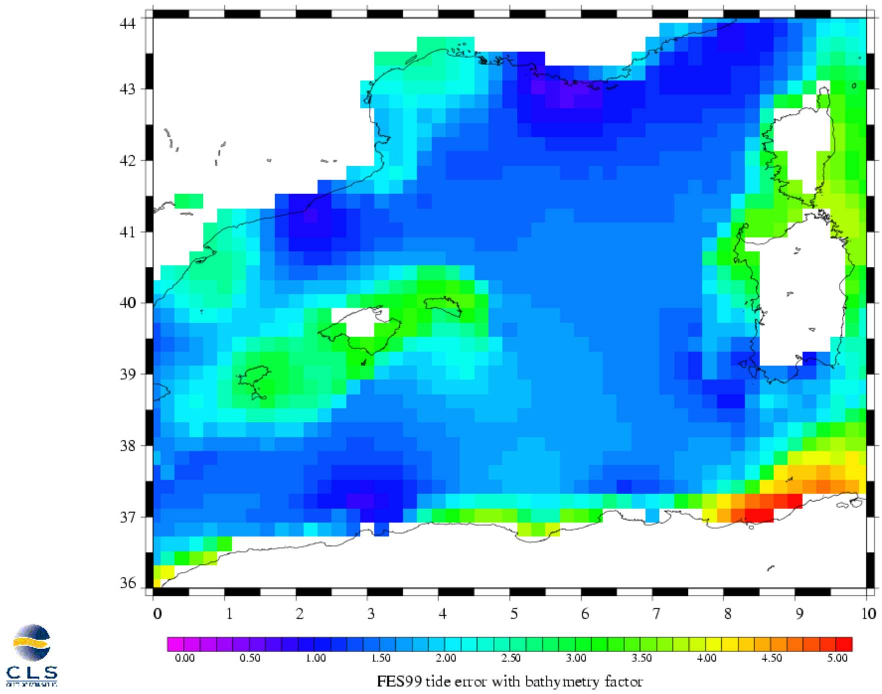


Figure 4: FES99 error model

It is noticeable that errors are stronger along shorelines.

4 SELECTION OF DATA FOR THE COMPARISONS

4.1 TIME PERIOD OF COMPARISON

ENVISAT is on its optimal orbit since 5 April 2002 (ENVISAT precedes ERS-2 by 28min 25s). Before this date, as we do not really know where ENVISAT was standing we will not compare RA-2 measurements and in-situ measurements.

ESA gives us access to ENVISAT data since 30 June 2002. Before, we tried to compare in-situ measurements provided by ICM and IfGN with ERS-2 data but the time lag between ENVISAT and ERS-2 prevented us from supplying accurate results (differences of several decimetres). As written before, ESA provided us with specific short arc orbits till mid September 2002 and specific tropospheric corrections till the end of October 2002. This is the reason why the different comparisons between the tide gauges and ENVISAT measurements were made from the end of June to the end of October 2002 (four months). This time period is overlapped by the measurement time period of the tide gauges specifically moored for the calibration phase, which allows us to compute a set of comparisons.

4.2 SELECTION OF THE ENVISAT DATA TO COMPARE

A specific algorithm was developed at CLS to compute the nearest points (on ENVISAT ground-tracks) of the different tide gauges involved in the study. Inputs of the algorithm are the locations of the tide gauges, outputs are the locations and time passes of the nearest ENVISAT points for each tide gauge. The results are given in In spite of the lack of ENVISAT data, a bias was computed during the calibration phase. The bias which must be the better is the bias computed without the coherent peak (cf. 6.5).

It will be useful to compute again the bias when the official GDRs are available during the calibration phase (cycles 1 to 9).

The methodology of the comparison of ENVISAT data and tide gauge measurements is now operational. In particular, dedicated efforts where done to include precise coastal tide gauges. It will be tested and validated in the future with a new set of ENVISAT data.

APPENDIX 1.

4.3 REMARKS ABOUT THE ENVISAT DATA

Due to tuning and technical problems during the calibration phase, a lot of gaps in the data remained in the first versions of the Pds files. We had to select the ENVISAT data before the comparisons. Thus we applied a set of constraints to get the satellite data to be compared:

- If an ENVISAT data is not ranged between the beginning of July and the end of October, we did not select it.
- If an ENVISAT data is away from more than 100 km from the tide gauge, we did not select it.
- If an ENVISAT data is on earth and not on sea, we did not select it.
- If an ENVISAT data is less than 20 km from earth, it is not selected, so as to prevent problems with the radiometer.
- If the ionospheric correction is flagged in the Pds file, we did not select the data.

- If the sea state bias correction is flagged in the Pds file, we did not select the data.

5 SPECIFIC STUDY FOR THE COASTAL TIDE GAUGES

5.1 PROBLEM WITH THE COASTAL TIDE GAUGES

A first study (which was presented during the validation workshop at ESRIN in December 2002) highlights problems with the coastal tide gauges. Indeed, the computed biases exhibited too high values (several meters in a few cases!). Thus, a dedicated study was made to understand this finding. It appears that the problem was meanly driven by very small confidence in the computation of the Mean Sea Surface in shallow waters and especially in coastal areas. Indeed, the MSS is computed with gravitational remote sensing measurements which are not accurate at the interface between the oceanic floor and the continental earth. This is the reason why we computed specific coastal MSS for each coastal tide gauge involved in the study.

For the purpose of a computer tidal analysis, the observed sea levels are separated into three components:

- Mean sea level
- Tidal levels
- Surge (or residual) levels

We developed a specific algorithm to compute local MSS at tide gauge locations according to the tide gauge measurements. Indeed, as we know the absolute reference of the different tide gauges, we were able to compute a local MSS by removing the tidal effect from the time series of the sea level elevations, and by calculating the mean of this detided signal. As we could not compute the influence of the atmospheric effect on each tide gauge location (we did not have access to local pressure measurements, and the model is not accurate on coastal areas), we did no take into account the atmospheric effects. But, this is not a crude approximation, as we computed the local MSS on several years of at least hourly time series. Indeed, the atmospheric effects cancel each other out on a long period of time.

5.2 FILTERING OF TIDES

5.2.1 Short theory on tide filters

To compute the local MSS, we developed two specific filters to retrieve the tide from a sea level time series. The purpose of this low-pass filter is to remove the tidal energy at diurnal and higher frequencies (semi-diurnal, quarter-diurnal…) from sea level elevations. Two filters were developed:

- The Doodson filter [*IOC*, 1985]
- The Demerliac filter [*Bessero*, 1985]

These powerful filters are used as running means. These filters prevent the user from computing the Fourier transform of the time series in the frequency domain to retrieve non desired frequencies and to compute the new inverse Fourier transform. The whole computations are made in the time domain (faster computations, better management of the gaps in the time series…).

A running mean $W(t)$ is built with a set of weights and is symmetric $W(t)=W(-t)$. For instance, if we consider $W(t)$ a $2N+1$ weights named : $W(t)=(W_1, W_2,\ldots,W_{2N+1})$. Then, Given a time series $H(t)$, the filtered signal $F(t)$ of $H(t)$ at the time t_0 is:

$$F(t_0) = \frac{1}{\sum_{k=-N}^{N} W(t_0)} \sum_{k=-N}^{N} W(t_0) H(t_0 + k)$$

5.2.2 Weight of the tide filters

The two filters were developed for hourly time series.

The Doodson filter (also known as the X0 filter) requires 39 hours of hourly data. Figure 5 presents the half of the filter weights (the filter is symmetric).

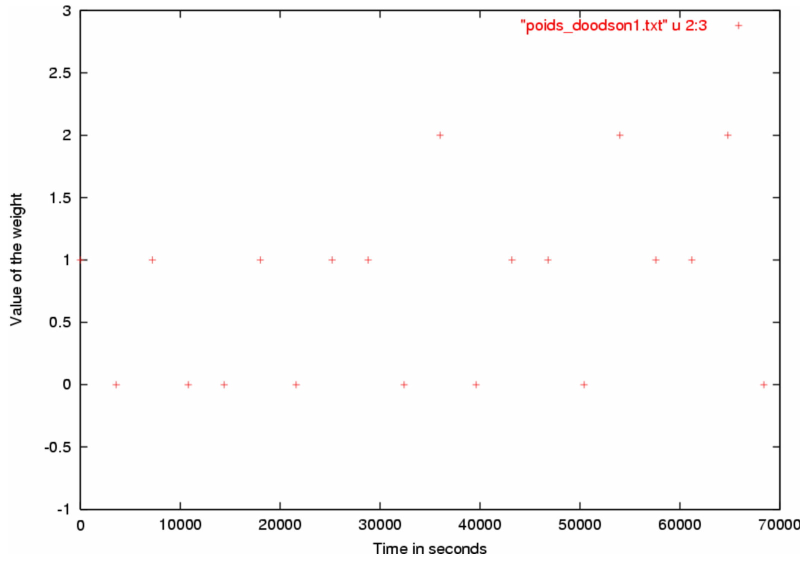


Figure 5: Weights of the Doodson filter

The Demerliac filter requires 71 hours of data. Figure 6 presents the half of the weights of the Demerliac filter.

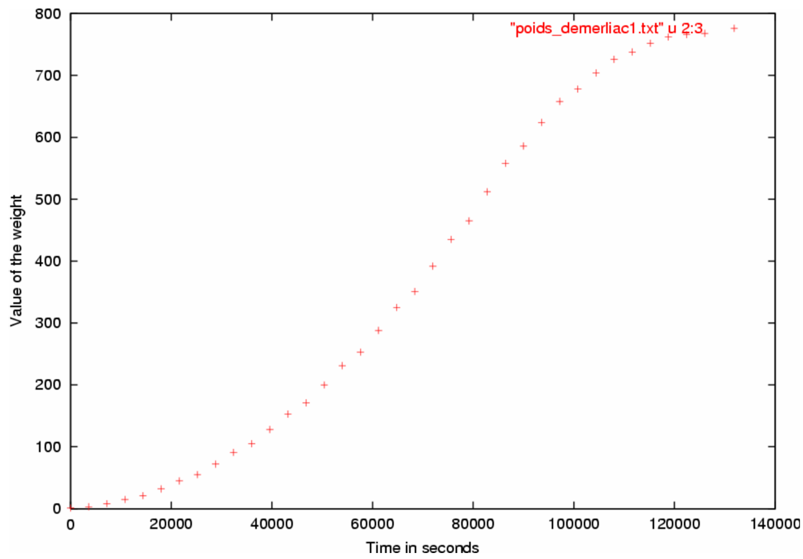


Figure 6: Weights of the Demerliac filter

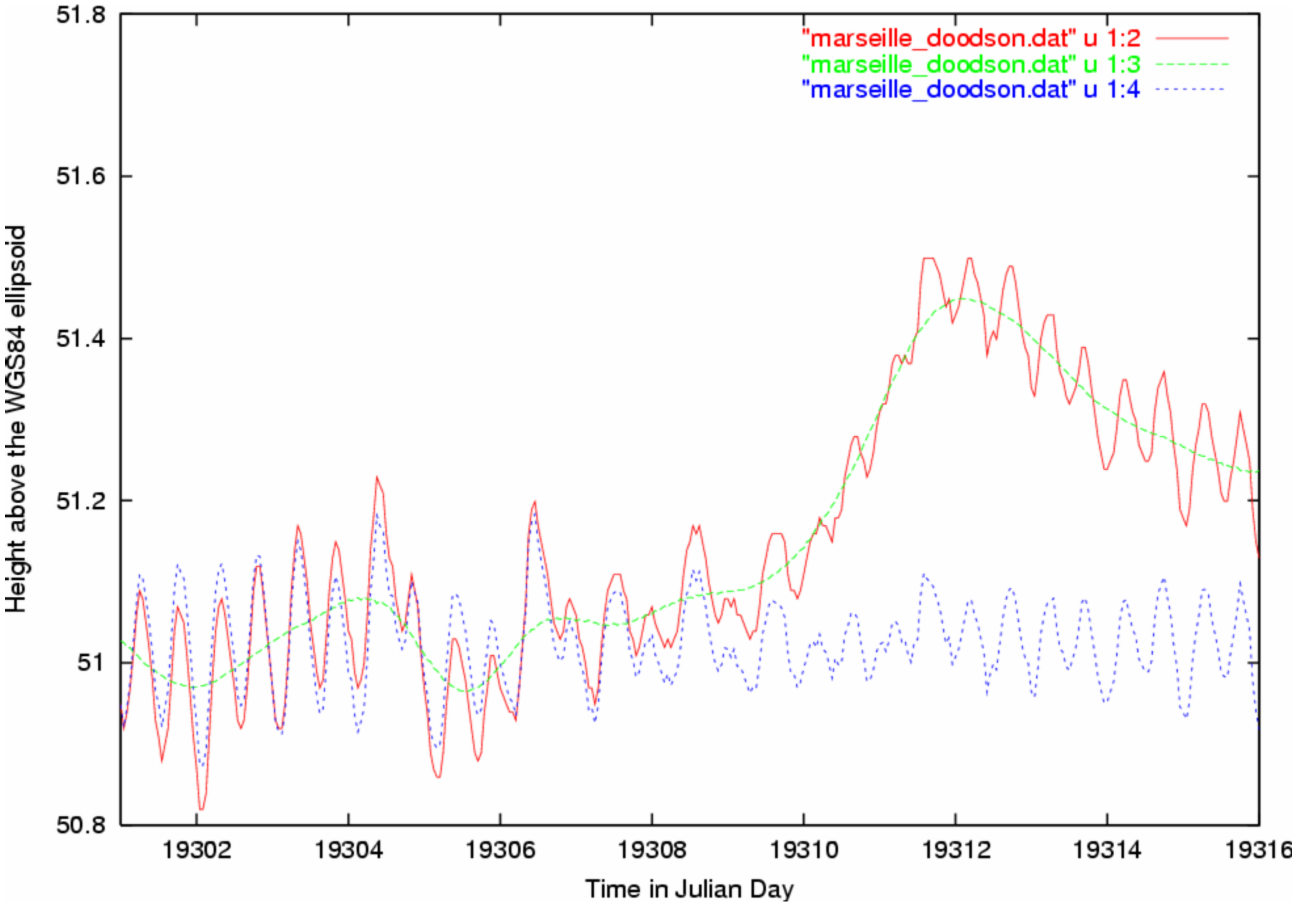
5.2.3 Improvements on the tide filters

The intrinsic construction of the Doodson filter made it only usable for hourly time series.

That is not the case for the Demerliac filter. Thus, we adapted this filter for time series which are not especially hourly time series. This was useful as a few coastal time series, delivered by our partners, were not hourly time series (Sant Antoni, Palma…). We used the Doodson filter to check the validity of our job on the Demerliac filter. Then, for the Demerliac filter, if we used hourly data, we needed 71 centre values of the time series to compute a filtered value. For half hourly time series we needed 143 values… We also improved the filter to take into account the gaps into a time series.

5.2.4 Example of tide filtering

So as to illustrate the use of the tide filters we developed, we present here a filtering of the Marseille tide gauge over a 1/2 month period with the Demerliac tide filter. The red line is the complete sea level elevation. The green line is the detided signal (the one used to compute the local MSS). The blue one is the tide signal (+ the mean of the total signal to fit the blue line in the graph).



5.3 COMPUTATION OF A LOCAL MSS

By applying the tide filtering on each time series of the tide gauge data, we extracted a detided signal for each of the tide gauges. The computation was made for the following tide gauges:

- Ajaccio

- Marseille
- Nice
- Monaco
- Toulon
- Senetosa
- Sant Antoni
- Palma

Then, we calculated a specific local MSS from each of this detided signal for each of the tide gauge.

5.4 ABSOLUTE REFERENCE OF THE COASTAL TIDE GAUGES

5.4.1 Choice of a reference ellipsoid

In order to compare a coastal tide gauge with ENVISAT data, it is needed to apply measurements with the same reference. The chosen reference is the ellipsoid WGS84 (the chosen ellipsoid of the ERS1 and ERS2 missions as well as the ENVISAT mission). The World Geodetic System 1984 (WGS84) is the geodetic reference system used by GPS. WGS84 was developed for the United States Defence Mapping Agency (DMA).

It must be highlighted that several French coastal tide gauges are referenced to the GRS80 ellipsoid. But, except for a small difference in the flattening term, the reference ellipsoid used with WGS84 is essentially the same as the Geodetic Reference System 1980 (GRS80) ellipsoid used with ITRF. Table 6 presents the difference between the two ellipsoids.

Ellipsoid	Semi-major axis	Inverse flattening
GRS80	6 378 137 m	298.257222101
WGS84	6 378 137 m	298.257223563

Table 6: GRS80 and WGS84 reference ellipsoid parameters

In our study we considered that GRS80 and WGS84 are the same. Thus, all the tide gauges used in the calibration are referenced to the WGS84 ellipsoid.

5.4.2 Reference and errors

Each tide gauge used in the study was referenced to the WGS84 ellipsoid thanks to the cooperation of various organisms in Spain (IMEDEA…) and France (SHOM, IGN…). For each tide gauges, an estimated error was recovered from the technical services in charge of the measurement of the absolute references.

Tide gauge	Responsible of the absolute reference	Responsible of the measurements	Absolute reference of the measurements / WGS84	Estimated error on the measurements
Ajaccio	IGN	SHOM	47.38 m	~2cm
Marseille	IGN	SHOM	48.61 m	~1cm
Nice	SHOM	SHOM	48.41 m	~5cm
Monaco	SHOM	SHOM	47.45 m	~10cm
Toulon	SHOM	SHOM	48.13 m	~5cm
Senetosa	?	CNES	46.09 m	~5cm
Sant Antoni	?	IEMEDEA	Directly referenced	~5cm
Palma	?	ICM	46.42 m	~5cm

Table 7: Tide gauge absolute reference and error

5.4.3 Remarks on the Sant Antoni tide gauge

The instrument is located inside a bay where natural bay oscillation always occurs (seiche). IEMEDA measured that Sant Antoni bay oscillates with a period of about 17 min and an amplitude of about 10-20 cm. This oscillation is not present out of the bay so, it is not recorded by the satellite. The sea level was measured with a 2 minutes time interval, thus, this oscillation is properly recorded and may be filtered out from the data. Filtered data are expected to be a better representation of sea level outside the bay. However, no comparison where made with this tide gauge because of the lack of ENVISAT data near Sant Antoni location over the four months of the calibration phase.

6 NUMERICAL RESULTS

6.1 DETERMINATION OF THE BIAS

So as to summarize what is written before, we recall here the linear processing to compute the bias for each tide gauge. A global processing system was developed to access the SSH deduced from the in situ measurements and the SSH computed from the RA-2 measurements. Thus, specific modules were developed for the calibration study:

- To compute the nearest point of a tide gauge location on ENVISAT track by a specific algorithm;
- To select ENVISAT measurements;
- To interpolate tide gauges measurements at ENVISAT time passes by a specific algorithm;
- To compute the SSH at ENVISAT and tide gauge locations by a specific algorithm;
- To interpolate short arc orbits by a specific algorithm;
- To interpolate Troposheric Zenith Delay fields by a specific algorithm;
- To compute a detided signal for the local tide gauges by a specific algorithm;
- To compute a local MSS for each local tide gauge by computing the mean of the detided signal.

6.2 DETERMINATION OF THE BIAS ERRORS

For each tide gauge and for each correction, an error was introduced to provide a confidence on each comparison. Thus, for each bias computation a formal error was computed. The formal error is the sum of:

- A systematic error (which is the same for each tide gauge location)
- A random error: the whole set of measurements (temporal and spatial) is assumed not to be correlated (so if the number of observations is infinite the random error tends to be zero).

The total mean error of the bias depends on the number n' of different tide gauges and the number n of different observations (n >>n'):

$$\overline{\varepsilon_f} = \frac{\overline{\varepsilon_s}}{\sqrt{n'}} + \frac{\overline{\varepsilon_r}}{\sqrt{n}}$$

It is a rough job to distinguish in the tide gauge error which part is due to systematic error and which part is due to random error. Thus, we assumed that half of the error is systematic and half is random.

The whole set of other errors are assumed to be random errors.

6.3 COMPUTATION OF THE BIAS

Figure 7 illustrates the SSH deduced from ENVISAT data compared to the nearest location of tide gauges used in the comparisons.

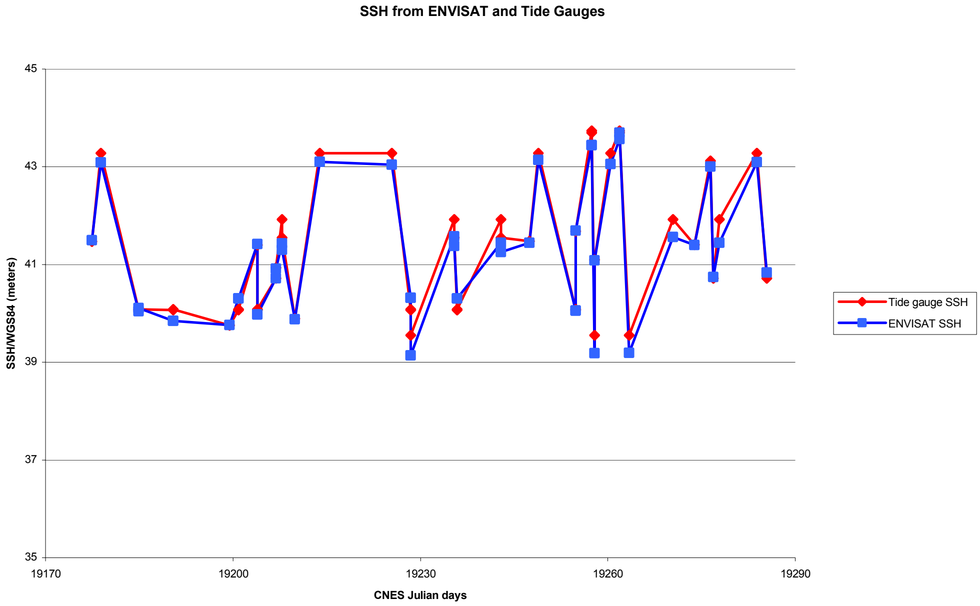


Figure 7: Sea Surface Height measured and computed from ENVISAT data and from tide gauges

According to the different specific algorithms, a unique bias was calculated for each of the tide gauge measurements compared to ENVISAT data. By collecting the whole set of altimetric measurements available and computed at ESRIN, biases without error bars were calculated (Figure 8).

We can see on this figure that the biases are around 40~50 centimetres. We notice that a sort of coherent peak stands around the Julian day 19210 (beginning of August). The comparisons with the tide gauges are coherent, so we suspect a local bias in ENVISAT data around this date. This is the reason why we also calculated the bias without this peak (2 measurements of ICM, 1 of Ajaccio, A of Casablanca, 1 of Senetosa and one of Marseille were cancelled).

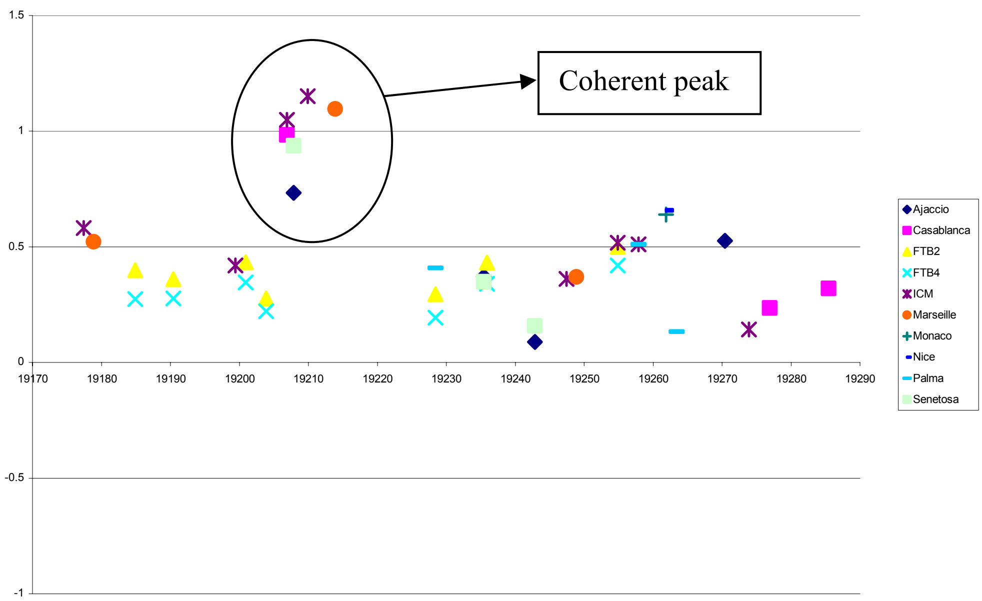


Figure 8: Complete comparisons of RA-2 measurements with tide gauge measurements

6.4 COMPUTATION OF THE ERRORS

Figure 9 shows the error bars which computed for each calculated bias.

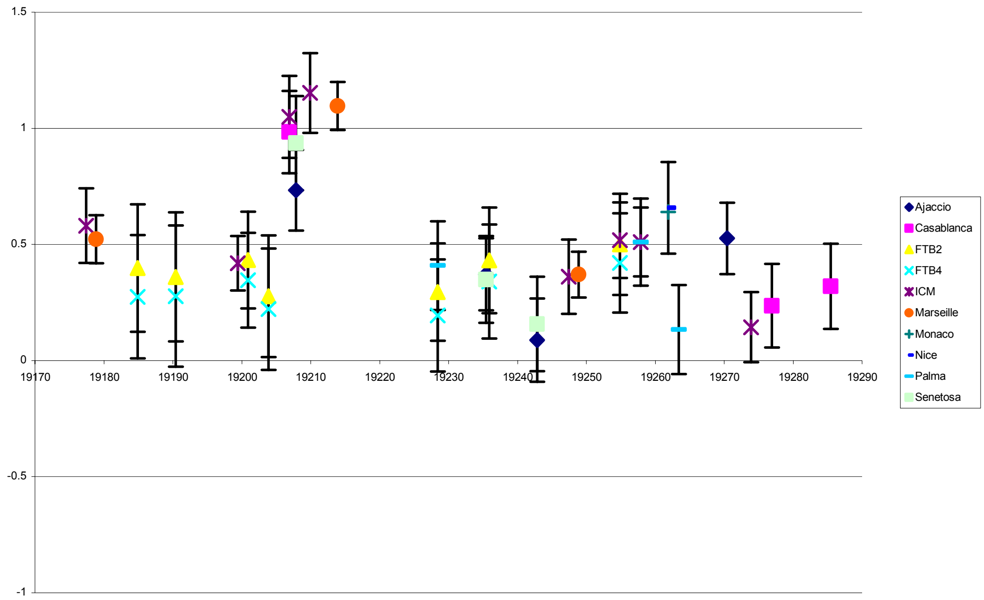


Figure 9: Complete comparisons of RA-2 measurements with tide gauge measurements and with error bars

6.5 VALUE OF THE BIAS

As written before, we computed two biases depending on the consideration of the finding peak around the beginning of August or not.

6.5.1 Bias with the peak

By considering the period of time raging from July to October, and by taking into account only the peak:

- The computed bias is 47.2 cm
- The computed error on the bias is 3.5 cm with:
  - A formal error of 1.0 cm
  - A random error of 2.5 cm
- For information the standard deviation of the bias is 26.8 cm

6.5.2 Bias without the peak

By considering the period of time raging from July to October and by not taking into account the peak:

- The computed bias is 38.3 cm
- The computed error on the bias is 4.0 cm with:
  - A formal error of 1.1 cm
  - A random error of 2.9 cm
- For information the standard deviation of the bias is 15.9 cm

We point out that the error associated to the bias computed without considering the peak is higher than the error computed for the bias with the peak. Indeed, with fewer observations, the random error is higher.

7 REMARKS AND CONCLUSIONS

7.1 IMPROVEMENT DONE IN THE STUDY

- For the absolute calibration study, the different comparisons between the tide gauges and ENVISAT measurements were made from the end of June to the end of October 2002.
- Specific coastal MSS were computed to better link the measured coastal sea level elevations to the nearest ENVISAT location.
- New near real time tide gauges measurements were added in the study so as to increase the number of independent observations. They were mainly provided by SONEL.

7.2 IMPROVEMENT TO BE DONE

- Due to a lack of information, several fields were not taken into account for the computation of the errors:
    - the atmospheric corrections,
    - the sea state bias,
    - the solid earth tides,
    - the polar tides.
- A specific ionospheric correction for the study has to be set.
- The sea state bias has to be further validated and an error has to be set to provide a confidence on the correction.
- A better knowledge of errors will allow reducing susceptibility to systematic errors and, thus, to better estimating the altimeter bias.

7.3 CONCLUSIONS

In spite of the lack of ENVISAT data, a bias was computed during the calibration phase. The bias which must be the better is the bias computed without the coherent peak (cf. 6.5).

It will be useful to compute again the bias when the official GDRs are available during the calibration phase (cycles 1 to 9).

The methodology of the comparison of ENVISAT data and tide gauge measurements is now operational. In particular, dedicated efforts where done to include precise coastal tide gauges. It will be tested and validated in the future with a new set of ENVISAT data.

8 APPENDIX 1

For each tide gauges the nearest ENVISAT points are given.
Column 1 : date of pass of the nearest ENVISAT point
Column 2 : hour of pass of the nearest ENVISAT point
Column 3 : CNES Julian date of pass of the nearest ENVSAT point
Column 4 : latitude of pass of the nearest ENVISAT point
Column 5 : longitude of pass of the nearest ENVISAT point
Column 6 : cycle number (a= ascending, d = descending) of the nearest ENVISAT point
Column 7 : distance between the nearest ENVISAT point and the location of the tide gauge

```
#######################################################
Casablanca            1.358330  40.717000
07-JUL-2002 10:25:08:000000 19180.434120   1.127937  40.772884 280d   20.4
02-AUG-2002 21:24:52:000000 19206.892269   1.309095  40.730109 158a    4.4
11-AUG-2002 10:25:08:000000 19215.434120   1.127937  40.772884 280d   20.4
06-SEP-2002 21:24:52:000000 19241.892269   1.309095  40.730109 158a    4.4
15-SEP-2002 10:25:08:000000 19250.434120   1.127937  40.772884 280d   20.4
11-OCT-2002 21:24:52:000000 19276.892269   1.309095  40.730109 158a    4.4
20-OCT-2002 10:25:08:000000 19285.434120   1.127937  40.772884 280d   20.4
#######################################################
Palma                 2.624600  39.552600
14-JUL-2002 21:21:39:000000 19187.890035   2.424886  39.528142 387a   17.4
20-JUL-2002 10:16:55:000000 19193.428414   2.813264  39.347352 466d   28.0
18-AUG-2002 21:21:39:000000 19222.890035   2.424886  39.528142 387a   17.4
24-AUG-2002 10:16:55:000000 19228.428414   2.813264  39.347352 466d   28.0
22-SEP-2002 21:21:39:000000 19257.890035   2.424886  39.528142 387a   17.4
28-SEP-2002 10:16:55:000000 19263.428414   2.813264  39.347352 466d   28.0
27-OCT-2002 21:21:39:000000 19292.890035   2.424886  39.528142 387a   17.4
#######################################################
Sant Antoni           1.301749  38.978470
17-JUL-2002 21:27:14:000000 19190.893912   1.175527  38.948059 430a   11.4
23-JUL-2002 10:22:46:000000 19196.432477   1.260934  38.990878   8d    3.8
21-AUG-2002 21:27:14:000000 19225.893912   1.175527  38.948059 430a   11.4
27-AUG-2002 10:22:46:000000 19231.432477   1.260934  38.990878   8d    3.8
25-SEP-2002 21:27:14:000000 19260.893912   1.175527  38.948059 430a   11.4
01-OCT-2002 10:22:46:000000 19266.432477   1.260934  38.990878   8d    3.8
30-OCT-2002 21:27:14:000000 19295.893912   1.175527  38.948059 430a   11.4
#######################################################
Marseille             5.353667  43.278833
05-JUL-2002 21:05:27:000000 19178.878785   5.486427  43.195366 258a   14.2
17-JUL-2002 10:10:06:000000 19190.423681   5.522998  43.094364 423d   24.7
09-AUG-2002 21:05:27:000000 19213.878785   5.486427  43.195366 258a   14.2
21-AUG-2002 10:10:06:000000 19225.423681   5.522998  43.094364 423d   24.7
13-SEP-2002 21:05:27:000000 19248.878785   5.486427  43.195366 258a   14.2
25-SEP-2002 10:10:06:000000 19260.423681   5.522998  43.094364 423d   24.7
18-OCT-2002 21:05:27:000000 19283.878785   5.486427  43.195366 258a   14.2
30-OCT-2002 10:10:06:000000 19295.423681   5.522998  43.094364 423d   24.7
#######################################################
Toulon                5.908917  43.122300
21-JUL-2002 21:02:33:000000 19194.876771   6.237162  43.105152 487a   26.7
02-AUG-2002 10:07:16:000000 19206.421713   6.190606  42.950998 151d   29.8
25-AUG-2002 21:02:33:000000 19229.876771   6.237162  43.105152 487a   26.7
06-SEP-2002 10:07:16:000000 19241.421713   6.190606  42.950998 151d   29.8
29-SEP-2002 21:02:33:000000 19264.876771   6.237162  43.105152 487a   26.7
11-OCT-2002 10:07:16:000000 19276.421713   6.190606  42.950998 151d   29.8
#######################################################
```

```
Nice                     7.285600  43.695667
14-JUL-2002 10:04:12:000000 19187.419583   7.150462  43.625052 380d   13.4
18-JUL-2002 20:56:59:000000 19191.872905   7.445443  43.742091 444a   13.9
18-AUG-2002 10:04:12:000000 19222.419583   7.150462  43.625052 380d   13.4
22-AUG-2002 20:56:59:000000 19226.872905   7.445443  43.742091 444a   13.9
22-SEP-2002 10:04:12:000000 19257.419583   7.150462  43.625052 380d   13.4
26-SEP-2002 20:56:59:000000 19261.872905   7.445443  43.742091 444a   13.9
27-OCT-2002 10:04:12:000000 19292.419583   7.150462  43.625052 380d   13.4
#######################################################
Monaco                   7.416667  43.733333
14-JUL-2002 10:04:12:000000 19187.419583   7.150462  43.625052 380d   24.6
18-JUL-2002 20:56:59:000000 19191.872905   7.445443  43.742091 444a    2.5
18-AUG-2002 10:04:12:000000 19222.419583   7.150462  43.625052 380d   24.6
22-AUG-2002 20:56:59:000000 19226.872905   7.445443  43.742091 444a    2.5
22-SEP-2002 10:04:12:000000 19257.419583   7.150462  43.625052 380d   24.6
26-SEP-2002 20:56:59:000000 19261.872905   7.445443  43.742091 444a    2.5
27-OCT-2002 10:04:12:000000 19292.419583   7.150462  43.625052 380d   24.6
31-OCT-2002 20:56:59:000000 19296.872905   7.445443  43.742091 444a    2.5
#######################################################
Ajaccio                  8.764000  41.920633
27-JUL-2002 09:56:04:000000 19200.413935   8.700557  41.909921  65d    5.4
03-AUG-2002 20:53:31:000000 19207.870498   8.895920  41.665934 172a   30.4
31-AUG-2002 09:56:04:000000 19235.413935   8.700557  41.909921  65d    5.4
07-SEP-2002 20:53:31:000000 19242.870498   8.895920  41.665934 172a   30.4
05-OCT-2002 09:56:04:000000 19270.413935   8.700557  41.909921  65d    5.4
12-OCT-2002 20:53:31:000000 19277.870498   8.895920  41.665934 172a   30.4
#######################################################
Senetosa                 8.814967  41.549850
27-JUL-2002 09:56:09:000000 19200.413993   8.600043  41.617689  65d   19.4
03-AUG-2002 20:53:31:000000 19207.870498   8.895920  41.665934 172a   14.6
31-AUG-2002 09:56:09:000000 19235.413993   8.600043  41.617689  65d   19.4
07-SEP-2002 20:53:31:000000 19242.870498   8.895920  41.665934 172a   14.6
05-OCT-2002 09:56:09:000000 19270.413993   8.600043  41.617689  65d   19.4
12-OCT-2002 20:53:31:000000 19277.870498   8.895920  41.665934 172a   14.6
#######################################################
FTB2                     3.741666  40.069722
01-JUL-2002 10:13:50:000000 19174.426273   3.772072  40.081457 194d    2.9
11-JUL-2002 21:16:03:000000 19184.886146   3.691087  40.049531 344a    4.9
05-AUG-2002 10:13:50:000000 19209.426273   3.772072  40.081457 194d    2.9
15-AUG-2002 21:16:03:000000 19219.886146   3.691087  40.049531 344a    4.9
09-SEP-2002 10:13:50:000000 19244.426273   3.772072  40.081457 194d    2.9
19-SEP-2002 21:16:03:000000 19254.886146   3.691087  40.049531 344a    4.9
14-OCT-2002 10:13:50:000000 19279.426273   3.772072  40.081457 194d    2.9
24-OCT-2002 21:16:03:000000 19289.886146   3.691087  40.049531 344a    4.9
#######################################################
FTB4                     3.729722  40.080555
01-JUL-2002 10:13:50:000000 19174.426273   3.772072  40.081457 194d    3.6
11-JUL-2002 21:16:03:000000 19184.886146   3.691087  40.049531 344a    4.8
05-AUG-2002 10:13:50:000000 19209.426273   3.772072  40.081457 194d    3.6
15-AUG-2002 21:16:03:000000 19219.886146   3.691087  40.049531 344a    4.8
09-SEP-2002 10:13:50:000000 19244.426273   3.772072  40.081457 194d    3.6
19-SEP-2002 21:16:03:000000 19254.886146   3.691087  40.049531 344a    4.8
14-OCT-2002 10:13:50:000000 19279.426273   3.772072  40.081457 194d    3.6
24-OCT-2002 21:16:03:000000 19289.886146   3.691087  40.049531 344a    4.8
#######################################################
Palamós                  3.198000  41.680000
04-JUL-2002 10:19:08:000000 19177.429954   2.864378  41.655135 237d   27.9
11-JUL-2002 21:16:31:000000 19184.886470   3.140208  41.686939 344a    4.9
08-AUG-2002 10:19:08:000000 19212.429954   2.864378  41.655135 237d   27.9
15-AUG-2002 21:16:31:000000 19219.886470   3.140208  41.686939 344a    4.9
12-SEP-2002 10:19:08:000000 19247.429954   2.864378  41.655135 237d   27.9
```

```
19-SEP-2002 21:16:31:000000 19254.886470   3.140208  41.686939 344a    4.9
17-OCT-2002 10:19:08:000000 19282.429954   2.864378  41.655135 237d   27.9
24-OCT-2002 21:16:31:000000 19289.886470   3.140208  41.686939 344a    4.9
########################################################
Mataró                2.573000  41.405000
04-JUL-2002 10:19:13:000000 19177.430012   2.764491  41.362855 237d   16.7
30-JUL-2002 21:19:18:000000 19203.888403   2.530674  41.368056 115a    5.4
08-AUG-2002 10:19:13:000000 19212.430012   2.764491  41.362855 237d   16.7
03-SEP-2002 21:19:18:000000 19238.888403   2.530674  41.368056 115a    5.4
12-SEP-2002 10:19:13:000000 19247.430012   2.764491  41.362855 237d   16.7
08-OCT-2002 21:19:18:000000 19273.888403   2.530674  41.368056 115a    5.4
17-OCT-2002 10:19:13:000000 19282.430012   2.764491  41.362855 237d   16.7
########################################################
Garraf                1.958000  41.100000
14-JUL-2002 21:22:06:000000 19187.890347   1.900526  41.107590 387a    4.9
23-JUL-2002 10:22:10:000000 19196.432060   1.955748  41.097136   8d    0.4
18-AUG-2002 21:22:06:000000 19222.890347   1.900526  41.107590 387a    4.9
27-AUG-2002 10:22:10:000000 19231.432060   1.955748  41.097136   8d    0.4
22-SEP-2002 21:22:06:000000 19257.890347   1.900526  41.107590 387a    4.9
01-OCT-2002 10:22:10:000000 19266.432060   1.955748  41.097136   8d    0.4
27-OCT-2002 21:22:06:000000 19292.890347   1.900526  41.107590 387a    4.9
########################################################
Tarragona             1.295000  40.933000
07-JUL-2002 10:25:05:000000 19180.434086   1.186939  40.948323 280d    9.2
02-AUG-2002 21:24:55:000000 19206.892303   1.250154  40.905551 158a    4.9
11-AUG-2002 10:25:05:000000 19215.434086   1.186939  40.948323 280d    9.2
06-SEP-2002 21:24:55:000000 19241.892303   1.250154  40.905551 158a    4.9
15-SEP-2002 10:25:05:000000 19250.434086   1.186939  40.948323 280d    9.2
11-OCT-2002 21:24:55:000000 19276.892303   1.250154  40.905551 158a    4.9
20-OCT-2002 10:25:05:000000 19285.434086   1.186939  40.948323 280d    9.2
########################################################
Alfacs                0.750000  40.413000
07-JUL-2002 10:25:15:000000 19180.434201   0.991215  40.363457 280d   21.2
17-JUL-2002 21:27:39:000000 19190.894201   0.697085  40.411047 430a    4.5
11-AUG-2002 10:25:15:000000 19215.434201   0.991215  40.363457 280d   21.2
21-AUG-2002 21:27:39:000000 19225.894201   0.697085  40.411047 430a    4.5
15-SEP-2002 10:25:15:000000 19250.434201   0.991215  40.363457 280d   21.2
25-SEP-2002 21:27:39:000000 19260.894201   0.697085  40.411047 430a    4.5
20-OCT-2002 10:25:15:000000 19285.434201   0.991215  40.363457 280d   21.2
30-OCT-2002 21:27:39:000000 19295.894201   0.697085  40.411047 430a    4.5
########################################################
Alcossebre            0.203000  39.892000
01-JUL-2002 21:30:22:000000 19174.896088   0.161341  39.857885 201a    5.2
26-JUL-2002 10:28:15:000000 19199.436285   0.126740  39.922052  51d    7.3
05-AUG-2002 21:30:22:000000 19209.896088   0.161341  39.857885 201a    5.2
30-AUG-2002 10:28:15:000000 19234.436285   0.126740  39.922052  51d    7.3
09-SEP-2002 21:30:22:000000 19244.896088   0.161341  39.857885 201a    5.2
04-OCT-2002 10:28:15:000000 19269.436285   0.126740  39.922052  51d    7.3
14-OCT-2002 21:30:22:000000 19279.896088   0.161341  39.857885 201a    5.2
########################################################
Sant Pol              2.765000  41.470000
04-JUL-2002 10:19:11:000000 19177.429988   2.804360  41.479773 237d    3.5
30-JUL-2002 21:19:19:000000 19203.888414   2.510751  41.426516 115a   21.8
08-AUG-2002 10:19:11:000000 19212.429988   2.804360  41.479773 237d    3.5
03-SEP-2002 21:19:19:000000 19238.888414   2.510751  41.426516 115a   21.8
12-SEP-2002 10:19:11:000000 19247.429988   2.804360  41.479773 237d    3.5
08-OCT-2002 21:19:19:000000 19273.888414   2.510751  41.426516 115a   21.8
17-OCT-2002 10:19:11:000000 19282.429988   2.804360  41.479773 237d    3.5
########################################################
Garraf                1.917000  41.088000
14-JUL-2002 21:22:06:000000 19187.890347   1.900526  41.107590 387a    2.6
```

```
23-JUL-2002 10:22:10:000000 19196.432060   1.955748  41.097136   8d    3.4
18-AUG-2002 21:22:06:000000 19222.890347   1.900526  41.107590 387a    2.6
27-AUG-2002 10:22:10:000000 19231.432060   1.955748  41.097136   8d    3.4
22-SEP-2002 21:22:06:000000 19257.890347   1.900526  41.107590 387a    2.6
01-OCT-2002 10:22:10:000000 19266.432060   1.955748  41.097136   8d    3.4
27-OCT-2002 21:22:06:000000 19292.890347   1.900526  41.107590 387a    2.6
######################################################
Salou                     1.135000  40.900000
07-JUL-2002 10:25:06:000000 19180.434097   1.167244  40.889845 280d    2.9
02-AUG-2002 21:24:55:000000 19206.892303   1.250154  40.905551 158a    9.7
11-AUG-2002 10:25:06:000000 19215.434097   1.167244  40.889845 280d    2.9
06-SEP-2002 21:24:55:000000 19241.892303   1.250154  40.905551 158a    9.7
15-SEP-2002 10:25:06:000000 19250.434097   1.167244  40.889845 280d    2.9
11-OCT-2002 21:24:55:000000 19276.892303   1.250154  40.905551 158a    9.7
20-OCT-2002 10:25:06:000000 19285.434097   1.167244  40.889845 280d    2.9
######################################################
Alcossebre                0.038000  39.755000
01-JUL-2002 21:30:21:000000 19174.896076   0.180541  39.799370 201a   13.2
26-JUL-2002 10:28:18:000000 19199.436319   0.069133  39.746508  51d    2.8
05-AUG-2002 21:30:21:000000 19209.896076   0.180541  39.799370 201a   13.2
30-AUG-2002 10:28:18:000000 19234.436319   0.069133  39.746508  51d    2.8
09-SEP-2002 21:30:21:000000 19244.896076   0.180541  39.799370 201a   13.2
04-OCT-2002 10:28:18:000000 19269.436319   0.069133  39.746508  51d    2.8
14-OCT-2002 21:30:21:000000 19279.896076   0.180541  39.799370 201a   13.2
```

9 BIBLIOGRAPHY

Bessero, G., *Marées*, Service Hydrographique et Océanographique de la Marine, Brest, 1985.

Carrere, L., and F. Lyard, Modeling the barotropic response of the global ocean to atmospheric wind and pressure forcing - comparisons with observations, *Geophys. Res. Let.*, *30* (6), 8-1 to 8-4, 2003.

Hernandez, F., and P. Schaeffer, The CLS01 Mean Sea Surface: A validation with the GSFC00.1 surface, pp. 14, CLS, Toulouse, 2001.

IOC, Manual on Sea Level Measurement and Interpretation - Volume I: Basic Procedures, *Manual and Guides*, *No.14* (Volume I), 1985.

Lefèvre, F., F. Lyard, C. Le Provost, and E.J.O. Schrama, FES99 : a tide finite element solution assimilating tide gauge and altimetric information, *J. Atm. Oceano. Tech.*, *19* (9), 1345-1356, 2002.