SALP, Lot 5 - Verification, operating and maintaining facilities operations for in situ CalVal

Final technical report 2010

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Acronyms

ALCIOM	ALtimetry Calibration with In situ Ocean Measurements
AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic Data
CalVal	Calibration Validation
CLS	Collecte Localisation Satellites
CNES	Centre National d'Etudes Spatiales
DEM	Digital Elevation Model
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
DNSC	Danish National Space Center
DNSC08MSS	Danish National Space Center 08 Mean Sea Surface
DSU	Digital Storage Unit
DTU	Danmarks Tekniske Universitet
EGU	European Geosciences Union
ENVISAT	Environmental Satellite
ERS	European Remote Sensing satellite
FES2004	hydrodynamic model based on Finite-Element Solution
GDR	Geophysical Data Records
GEOSAT	GEOdetic SATellite
GFO	Geosat Follow-On
GIM	Global ionosphere Maps
GOT99.2/GOT00.2	Global Ocean Tide model
GPS	Global Positioning System
LEGOS	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales
MLE4	Maximum Likelihood Estimator
MOG2D	Modèle aux Ondes de Gravité - 2 dimensions
MSL	Mean Sea Level
MSS	Mean Sea Surface
NASA	National Aeronautics and Space Administration
OCA	Observatoire de la Côte d'Azur
SALP	Service Altimétrie et Localisation Précise
SSH	Sea Surface Height
TOPEX	Topography Experiment
T-UGOm2D	Toulouse Unstructured Grid Ocean model 2D (ex-Mog2D)

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[DR4] SALP, Lot 5 – Audit, operating and maintaining facilities operations for Calval in situ – Activity report from 01/01/2010 to 31/03/2010: technical description - NOV-3838-NT-9051

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[DR7] Ocean Surface Topography Science Team – Lisbon 2010 meetings presentations web-site – http://www.aviso.oceanobs.com/en/courses/sci-teams/ostst-2010/index.html

[DR8] Cancet M. et al, Use of the Corsica site to compute altimeter biases for the ENVISAT, JASON-1 and JASON-2/OSTM missions and sensitivity studies, OSTST meeting Lisbon, 2010 (oral presentation)

[DR9] Cancet M. et al, Use of the Corsica site to compute altimeter biases for ENVISAT, JASON-1 and JASON-2/OSTM : absolute and regional CalVal methods, OSTST meeting Lisbon, 2010 (poster)

[DR10] Chimot J. et al, Absolute and offshore in situ calibrations of Jason-2 in SENETOSA: sensitivity analyses of the altimeter bias, OSTST meeting Lisbon, 2010 (poster)

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1. Introduction

This report summarizes the studies carried out by NOVELTIS in 2010 with respect to the absolute calibration of the Jason-1 and Jason-2 altimeter. This work was funded by CNES in the framework of the SALP activities.

The report aims at providing information and recommendations to the following audience:

- CNES, NASA, EUMETSAT and NOAA staff involved in the Jason-1 and Jason-2 products quality assessment;
- OSTST PIs and teams involved in CALVAL activities;
- OSTST scientists involved in coastal altimetry studies.

The report includes:

- An overview of the analysis and validation of the in situ tide gauges of the CNES absolute calibration site at Senetosa;
- The altimeter bias estimates obtained for Jason-1 and Jason-2 from the start of the missions, up to the end of 2010. Results obtained by NOVELTIS are presented and compared to the results obtained by the other CALVAL groups (Senetosa/OCA, Harvest, Bass Straight, Gavdos, EmacNET network);
- Sensitivity studies conducted to assess the influence of several parameters on the bias estimates. The studies mainly concern: the MSS near the Senetosa calibration site and the influence of the ocean local/regional ocean dynamics (tides as well as pressure and wind forcing).

The report draws conclusions and recommendations resulting from these studies.

2. Analysis and validation of the in situ sea surface heights

The *in situ* measurements in Senetosa are provided by two pairs of coastal pressure twin tide gauges called {M3, M7} and {M4, M5}, as shown in Figure 1. This redundancy of measurements is very important as it avoids gaps in the *in situ* SSH time series if one of the instruments breaks down or presents failures, such as drifts for example. Each time the tide gauge data are taken in, nearly every 3 months, they are computed and validated by NOVELTIS, in close collaboration with the OCA.

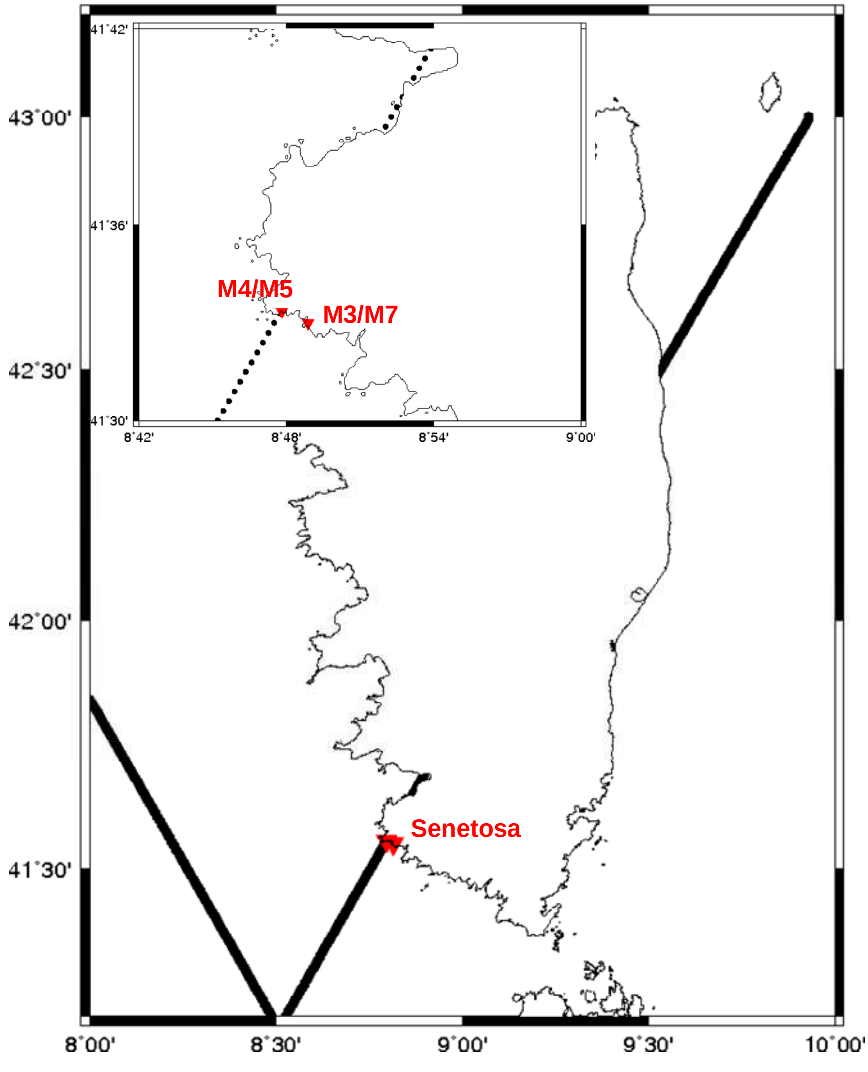

Figure 1: Positions of the 4 tide gauges at Senetosa and Jason-2 pass 085 groundtrack.

2.1. *In situ* data validation protocol

The *in situ* data quality control is a crucial step in the computation of the altimeter bias, since the tide gauge observations are considered as a reference to be compared with. Consequently, the validation protocol of the tide gauge time series has been designed in order to immediately detect problems in the data, as soon as the *in situ* measurements are collected and transmitted to NOVELTIS.

This quality control protocol can be detailed as follows:

- Comparison of the twin tide gauges (M3/M7 and M4/M5) direct measurements (temperature, pressure, and conductivity if available);
- Comparison of the twin tide gauges and cross-comparisons (M3/M4, M3/M5, M7/M4, M7/M5) of the SSH over the considered session and over a longer period (about 8 sessions). Analysis of the SSH differences;
- Analysis and comparison of the detided SSH (using a harmonic analysis method) and the long-period signals in the SSH in order to evaluate the coherency of the measurements at different time scales as well as to possibly detect drifts in the data.
- Comparison to the Ajaccio tide gauge if there is a doubt concerning the time definition for one of the sessions (winter or summer time instead of GMT for example). More precisely, as the tide signals of both sites are very well in phase, a shift of one hour in the measurements of a given session can be detected easily.

2.2. Analysis of the *in situ* data

These verification processes were applied to 30 sessions of *in situ* data available at Senetosa, covering a 9-year period, from 2002 to 2010. Various kinds of problems were revealed through this analysis, and several data sessions had to be eliminated from the time series. The data were systematically cross-checked by the OCA and NOVELTIS in order to identify as many issues as possible.

In particular, the M4 tide gauge showed a drift of 4cm from the session 41 to the session 43 (June 2008 to October 2008), until the instrument was replaced. Equally, a drift of about 2cm is visible in the M3 tide gauge measurements from the session 44 to the latest session 49 (October 2008 to September 2010). This is probably due to the fact that the instrument has not been calibrated since 2006, which is largely beyond the recommendations of the supplier.

Other problems were also detected, such as a bad time reference for a few sessions (the DSU was not settled to the GMT but to the local time, either in winter or in summer), incoherent data recordings because of flat batteries or flood, and even abnormally high SSH values for the M3 session 45 probably due to the displacement of the instrument by a diver. Finally, it was also observed that in some cases, the tide gauge first goes through a stabilization phase of typically several days, which generally shows in by a drift of a few centimeters, before giving steady measurements. The cross-comparison with the other tide gauge SSH is a reliable mean to identify this problem in a data time series. Moreover, the M7 tide gauge data are taken in every 6-month period whereas the other instruments are visited every 3 months, with a 1-month lag, in order to improve the detection of this kind of transitional phases.

All these events in the lives of the *in situ* instruments justify the fact that four instruments are maintained at Senetosa. Indeed, not only it increases the number of altimeter bias estimates, but it is certainly also the best way to obtain a complete and reliable long time series for the altimeter verification. The Figure 2 illustrates the fact that, even if it is difficult to retrieve good quality measurements in operational conditions at sea, it is possible to evaluate the altimeter bias at any time, thanks to the complementary instrumentation at Senetosa. It should also be noted that, thanks to the maintenance operations on the instruments, the proportion of exploitable data is above the mean proportion of the tide gauge data available in global data bases (typically around 50%).

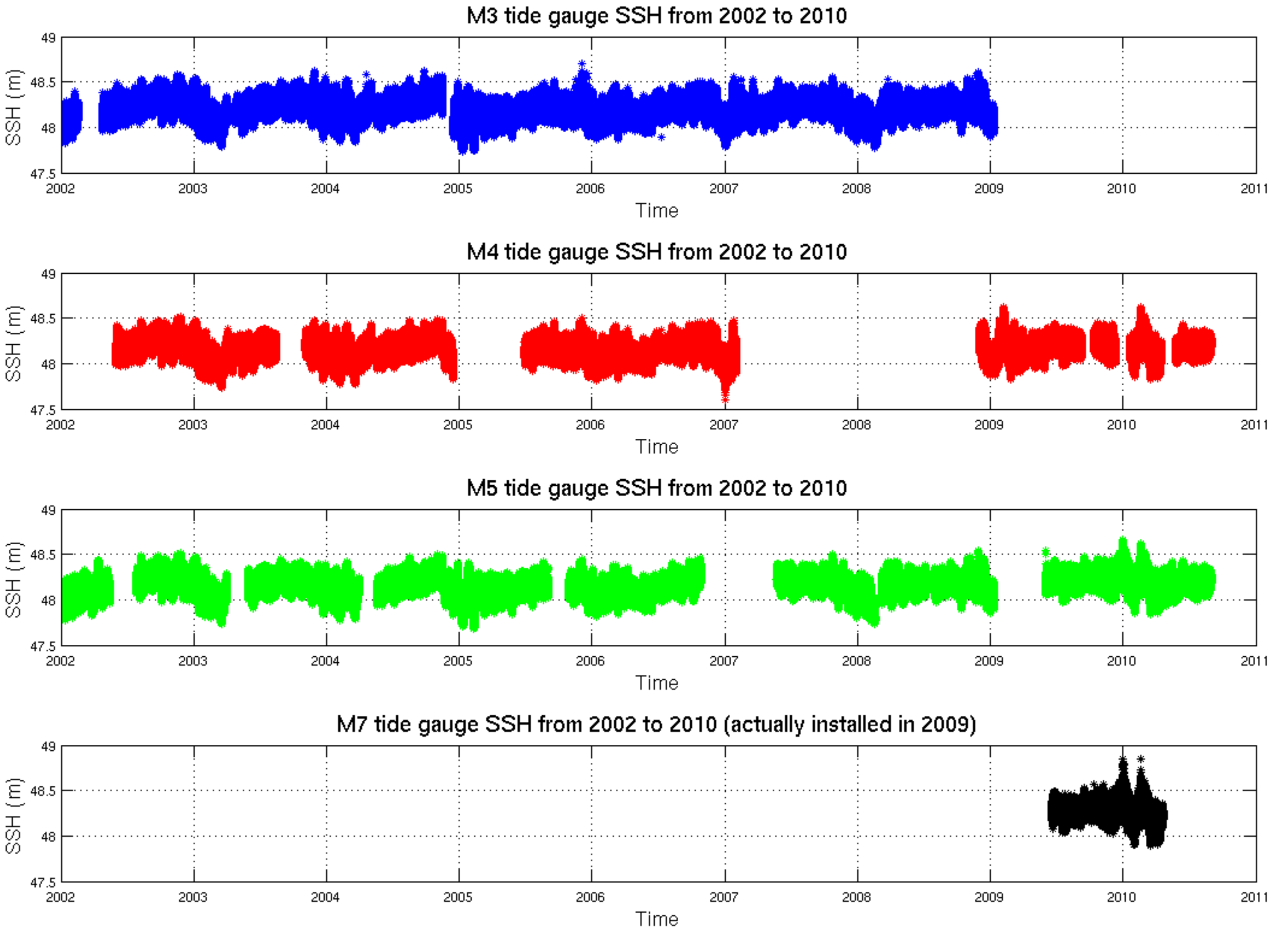

Figure 2: ***In situ*** **sea surface heights at Senetosa for each of the four tide gauges, from 2002 to 2010.**

Finally, such a systematic validation of the *in situ* data also helps in the management of the instruments, as it allows detecting rapidly which tide gauges should be replaced or recalibrated for the next session. Actually the analysis of the whole sessions showed that the instruments tend to drift rapidly and that a calibration every year is quite necessary.

3. Calibration methods and altimeter bias assessments

The estimation of the bias between the altimeter and tide gauge measurements is performed with the ALCIOM software (NOVELTIS). Computation steps are described in the following sections, with a particular focus on the two methods used to obtain altimeter sea surface heights directly comparable with the *in situ* measurements: the absolute method for satellite passes flying directly over the *in situ* calibration site, and the regional method for remote satellite passes.

One of the constraints of the bias computation is that both types of data must be compared in the same geodetic reference. Given the fact that the geoid is currently not precisely known globally, a GPS catamaran survey campaign was carried out by the OCA in 1999. A precise mean sea surface grid was obtained, with a resolution of 5.10^{-4} degree in the Senetosa region, where the geoid slope is high (about 6cm/km). This catamaran mean sea surface is used to link the altimeter and tide gauge measurements in the same reference frame (ellipsoid), which implies that the altimeter bias can only be estimated over this surface.

3.1. Bias assessment methods

3.1.1. Altimeter sea surface heights

3.1.1.1. Absolute CalVal method

The Senetosa *in situ* calibration site is principally dedicated to the satellite missions on Topex passes (Topex, Jason-1 and Jason-2). The pass 085 is used for the absolute calibration as it directly overflies the site (Figure 3).

The altimeter sea surface heights (SSH) compared to the tide gauge measurements are computed with the ALCIOM software in several steps, including data quality assessment and data editing, as described in the following section. The altimeter data used in this study are Jason-2 GDR products distributed by CNES and NASA. In order to improve the selection of the data, and to get close to the coast, we used the high-frequency rate (20Hz data).

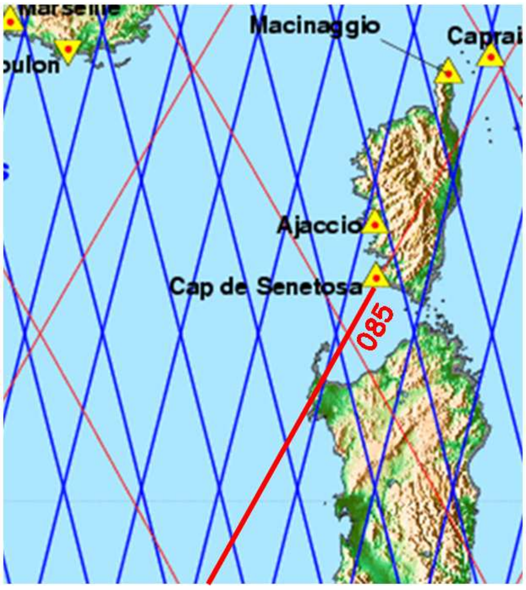

Figure 3: Senetosa configuration for absolute CalVal method on pass 085.

3.1.1.1.1 Sea surface heights at the observation points

First, the altimeter data are selected in the area of interest, that is to say on the catamaran surface presented above, taking into account their availability and accuracy. The SSH are computed along the pass, at each observation point and for each cycle, applying the following corrections included in the GDR-T products:

- wet troposphere correction from the ECMWF model (the radiometer correction is not used because of the land contamination effects in coastal regions [DR2]);
- dry troposphere correction from the ECMWF model;
- ionosphere correction from GIM (a priori more accurate than the altimeter dual-frequency correction, or the DORIS and BENT models) ;
- solid tide from the Cartwright and Taylor tidal potential tables;
- polar tide from the equilibrium model;
- load tide from the FES2004 geocentric ocean tide;
- sea state bias from an empirical model derived from 3 years of MLE4 Jason-1 data.

Then, an assessment of the SSH quality is performed in two steps, at each observation time, and the data matching the following criteria are rejected:

- SSH beyond the median value + 0.5m ;
- SSH beyond the mean SSH profile +/- 3 times the standard deviation.

3.1.1.1.2 Smoothed sea surface heights at observation points

In order to reduce the errors in the altimetry products (instrument noise, errors in the corrections), we compute smoothed SSH at each observation point and for each cycle, using a sea level anomaly averaged over the area of interest. A mean sea surface height profile is computed over all the available cycles, by interpolation of the SSH on regularly spaced ground-points, with a sampling of 5.10^{-3} latitude degrees. Then, the sea level anomaly is computed at each observation point and for each cycle, after interpolation of the mean sea surface height on the observation point (Eq. 1). For each cycle, the smoothed anomaly is the spatial average of the sea level anomalies computed at the observation points. An editing is also performed on this anomaly, with a maximum acceptable value of 0.5m.

$$\overline{\delta h} = \overline{\delta h_i} \quad \textbf{with} \quad \delta h_i = SSH_i - MSS_i \qquad \textbf{Eq. 1}$$

Where:

SSH_i = Sea Surface Height measurement at the observation point i;

MSS_i = Mean Sea Surface interpolated at the observation point i;

δh_i = Sea level anomaly at the observation point i;

$\overline{\delta h}$ = Smoothed sea level anomaly: average of the differences between the observed SSH and the MSS over the area of interest.

Finally, improved altimeter SSH with a reduced noise are reconstructed at each observation point and for each cycle, using the mean sea surface heights interpolated on the observation points and the smoothed anomaly available for each cycle (Eq. 2).

$$\overline{SSH_i} = MSS_i + \overline{\delta h} \qquad \textbf{Eq. 2}$$

Where:

MSS_i = Mean Sea Surface at the observation point i in the area of interest;

$\overline{SSH}_i$ = Improved Sea Surface Height at the observation point i with less instrumental noise.

The bias is estimated using these smoothed sea surface heights.

3.1.1.2. Regional CalVal method

The regional CalVal method developed by NOVELTIS aims at extrapolating the SSH observed on remote passes of whatever mission to the *in situ* calibration site. To that purpose, the differences between the mean sea surface heights at the crossover points are used to take into account the spatial gradient of sea surface between the altimeter measurement and the *in situ* calibration n site. This method, summarized by the Eq. 3 and illustrated in Figure 4, gives information about the spatial evolution of the altimeter bias and allows enlarging its statistical estimation to a wider area than the pass that overflies the *in situ* calibration site.

$$\overline{SSH}_{Senetosa} = \overline{SSH}_P + \sum_{i=1}^{N}(MSS_{i+1} - MSS_i) \qquad \textbf{Eq. 3}$$

Where:

$\overline{SSH}_{Senetosa}$ is the altimeter sea surface height extrapolated on each reference point of the catamaran surface near Senetosa;

N is the number of passes used to reach the calibration site (for example: Jason-2 passes 085 and 222 are needed to extrapolate JASON-2 pass 009 in Senetosa);

$\overline{SSH}_P$ is the smoothed altimeter sea surface height at the remote observation point;

$\sum_{i=1}^{N}(MSS_{i+1} - MSS_i)$ is the sum of the mean sea surface heights differences between two points of the same pass (in fact, between 2 crossover points).

The smoothed altimeter sea surface height $\overline{SSH}_P$ is computed according to the method presented in the absolute CalVal part (§ 3.1.1.1). As a first step, in the regional case, the observation point is chosen at the crossover point between the considered pass and the next one on the way to the calibration site. The smoothed sea surface anomaly used to compute the improved SSH is estimated on a portion of the considered pass, around the observation point. Not only this portion of pass must be long enough to eliminate the instrumental noise, but it should also be representative of the dynamics around the observation point.

The regional CalVal method allows consolidating the bias estimate as it increases the number of independent bias estimates. Moreover, this method is applicable to any satellite altimetry mission assuming that an accurate mean profile is available over the CalVal site to connect the offshore altimeter data with the *in situ* data.

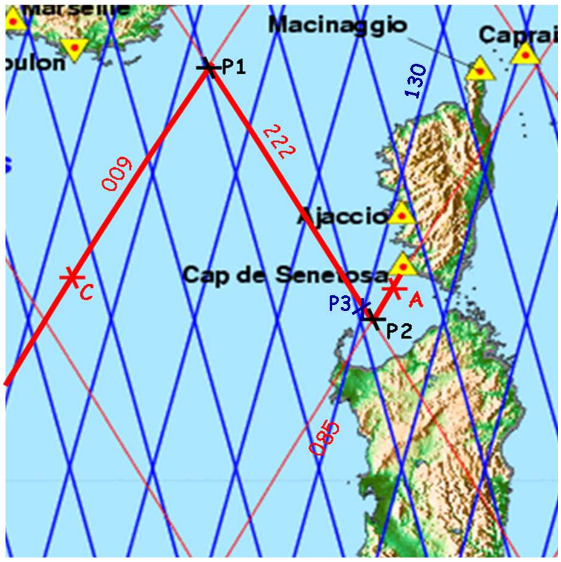

Figure 4: Senetosa configuration for regional CalVal method on passes 222 and 009.

3.1.2. *In situ* Sea Surface Heights

The *in situ* measurements in Senetosa are provided by four pressure tide gauges. The analysis method of these *in situ* measurements is presented in the previous part of this report (§ 2).

3.1.3. Bias estimation

As it was presented above, the altimeter and *in situ* SSH are not directly comparable because they are not exactly collocated. Consequently, the two datasets must be extrapolated on the high resolution catamaran mean sea surface as it provides a detailed description of the mean sea surface in the area close to the tide gauge.

The altimeter and tide gauge data are extrapolated on reference points on this catamaran surface. Then the bias is computed as follows (Eq. 4), after interpolation of the tide gauge data at the altimeter time of measurement:

$$\text{Altimeter Bias} = \overline{SSH_A} - SSHtg_A + MSSIS - MSSCata \qquad \textbf{Eq. 4}$$

Where:

$\overline{SSH_A}$ is the improved altimeter SSH extrapolated to the reference point A on the catamaran surface;

$SSHtg_A$ is the tide gauge SSH extrapolated to the reference point A on the catamaran surface;

$MSSIS$ is the mean sea surface at the tide gauge location in the catamaran surface reference;

$MSSCata$ is the mean sea surface at the reference point A on the catamaran surface.

The selection of several reference points on the catamaran surface is crucial in order to increase the accuracy of the bias. Indeed, an estimation of the bias stability can be performed over these points. Moreover, they must be carefully chosen in regions where the altimeter mean SSH is well defined. For example, because of the loss of much altimeter data when approaching the coast, which induces a decrease in the mean SSH accuracy, the satellite measurements must not be interpolated to close to the coast, in order to avoid land contamination effects.

3.2. Altimeter bias estimates

The results on the Jason-1 and Jason-2 bias estimates were presented at the OSTST meeting in Lisbon, in 2010 ([DR8] and [DR9]).

3.2.1. Jason-2 bias

The Jason-2 bias was assessed at the Senetosa calibration site using the absolute method on the pass 085 and the regional method on the passes 222 and 009. The configuration of the passes is illustrated in Figure 4. First of all, a sensitivity study was performed on the number and the positions of the reference points located on the catamaran surface and used to compute the bias. A configuration with 23 points linearly spaced between 41.4050°N and 41.4575°N, with a sampling of 0.0025 latitude degree was selected ([DR4]).

Table 1: Jason-2 bias estimates in Senetosa (74 cycles)

Weighted bias in Senetosa (cm)	Mean	Std	Nb of cycles
Pass 085 (absolute method)	17.4 ± 0.4	3.4	74
Pass 222	17.5 ± 0.3	2.6	73
Pass 009	15.7 ± 0.4	3.3	74
Mean regional bias	16.9 ± 0.4	3.1	74

The biases were estimated over 74 cycles of the Jason-2 GDR-T products, covering the period from August 2008 to July 2010. The Table 1 summarizes the bias estimates on each pass, computed as weighted means of the biases assessed with the four tide gauges. They consequently take into account the availability of the *in situ* SSH. It appears that the values of the bias on the passes 085 and 222 are very close, certainly because the second estimate was done at the crossover point between these two passes, located within a distance of 40km from Senetosa. The other noticeable point is the fact that the bias is 1.7cm lower on the pass 009. It is probably due to the ocean dynamics differential effect between this offshore crossover point and the calibration site (see §4.2 for the study of the impact of the tide and dynamical atmospheric corrections on the bias), but also to residual differences in the MSS at the crossover points. These cumulated differences can reach one centimeter, if the MSS are not well filtered. That is why it is important to compute accurate MSS profiles when using the regional calibration method.

Anyway, the results are very coherent and in the range of the bias estimates computed at other verification sites, as it is shown in the paragraph §3.3 of this document.

3.2.2. Jason-1 bias (initial and interleaved orbits)

Since the Jason-1 mission launch, NOVELTIS has been computing altimeter biases for this mission, on its original ground tracks. The first part of this study consisted in computing up-to-date Jason-1 bias estimates on the initial orbits, in the same configuration as the Jason-2 bias estimation. Then, the interleaved passes were considered to compute altimeter biases with the regional method. In this case, only the passes 085 and 222 could be used, as the crossover point between the passes 009 and 222 is very close to the coast and altimeter data may not be of sufficient quality and quantity to compute relevant mean sea profiles at this point (see Figure 5). It should be noticed that neither the tide nor the dynamical atmospheric corrections were applied to the data before computing the altimeter biases.

Finally, as it was presented above, one of the critical points of the altimeter bias computation is the choice of the reference points on the catamaran surface. A sensitivity analysis was presented on this subject in [DR4], for the Jason-2 mission, but changing the mission may require a change in these reference points. The same kind of sensitivity analysis was thus performed for the Jason-1 mission. It led to the conclusion that the same configuration as the Jason-2 one, with 23 reference points, was also adapted to the Jason-1 mission.

3.2.2.1. Jason-1 bias on the initial orbits

The previous estimates of the regional biases of the Jason-1 mission in Senetosa dated from 2004 and were published in [DR1]. Moreover, they were computed with GDR-A products and a small number of cycles (about 60). A new estimation was consequently performed, using the 259 available cycles of GDR-C products.

Table 2: Jason-1 bias estimates for the passes 085, 222 and 009, using cycles 1 to 259

Mean bias (cm)	Mean	Std	Nb of cycles
Pass 085 (absolute method)	9.1 ± 0.2	3.3	225
Pass 222	8.3 ± 0.2	2.5	223
Pass 009	8.3 ± 0.2	3.5	229
Mean regional bias	8.6 ± 0.2	3.1	226

These Jason-1 bias estimates, summarized in the Table 2, are about 3cm smaller than the previous ones ([DR1]), which reached 11.8cm. This is certainly due to the reprocessing of the GDR products which, among other things, is supposed to have improved the orbit determination and the Sea State Bias correction. Moreover, there are four times as many cycles available, which induce more accurate MSS profiles and better statistics on the bias.

Nevertheless, it can be noticed that there is a decrease of nearly 1cm in the bias between the pass 085 and the passes 222 and 009. Contrary to the Jason-2 case, the results obtained with the regional method are very close, which is probably due to really coherent MSS profiles at the crossover points, thanks to the larger number of cycles (74 for Jason-2, 259 for Jason-1). The degraded quality of the data near the coast may explain the higher bias obtained on the pass 085. Finally, these results are very close to the bias estimates obtained at other calibration sites (see §3.3).

3.2.2.2. Jason-1 bias on the interleaved orbits

The Figure 5 presents the configuration of the Jason-1 passes near the Senetosa calibration site. The red circles indicate the crossover points where the bias was estimated in the case of the original orbits ($P_{009O/222O}$ and $P_{222O/085O}$, O meaning "old"), as well as the crossover points where the bias can be computed using the interleaved orbits ($P_{222N/009O}$, $P_{222N/085N}$ and $P_{085N/222O}$, N meaning "new").

In the case of the new pass 085, the way to Senetosa is simple, as it only uses the crossover point between old passes 222 and 085: **$P_{085N/222O}$ → $P_{222O/085O}$ → Senetosa**

For the new pass 222, there are several possibilities:

- From the crossover point with the new pass 085: **$P_{222N/085N}$ → $P_{085N/222O}$ → $P_{222O/085O}$ → Senetosa**
- From the crossover point with the old pass 009: **$P_{222N/009O}$ → $P_{009O/222O}$ → $P_{222O/085O}$ → Senetosa**

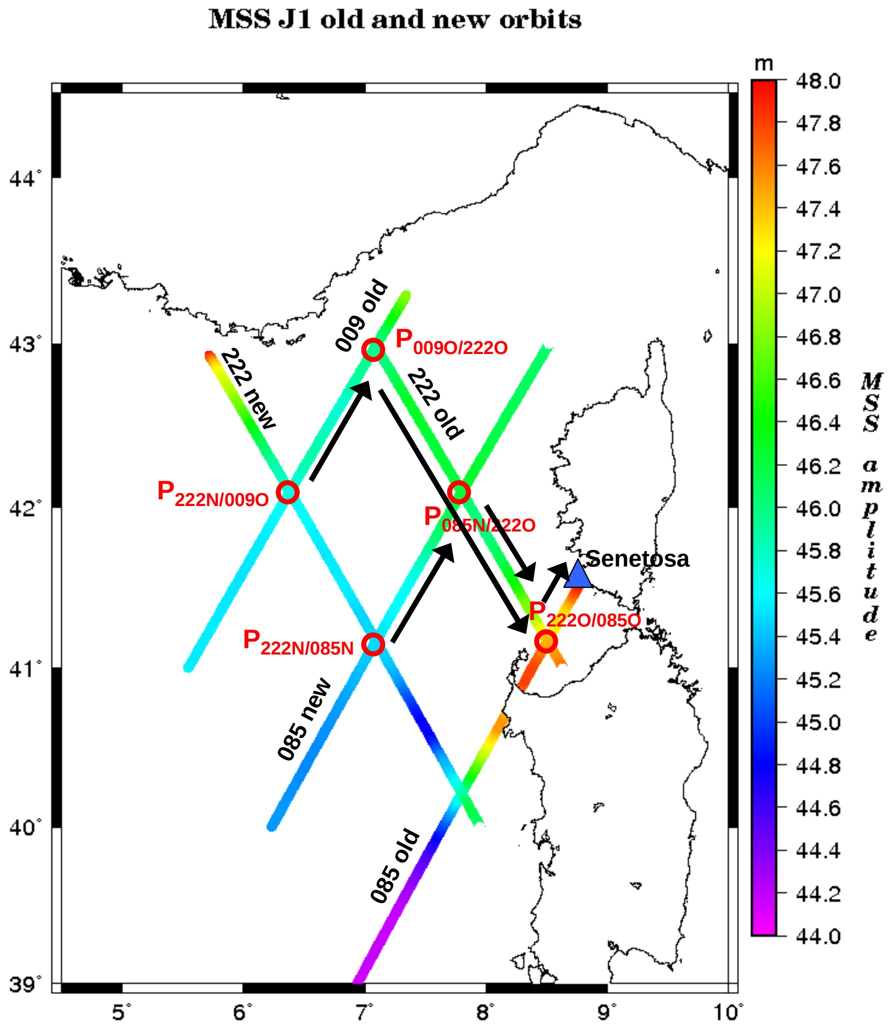

Figure 5: Regional CALVAL configuration at Senetosa for the Jason-1 mission, considering the original and interleaved ground-tracks. The colours indicate the MSS amplitude along the passes 085, 222 and 009. The black arrows show the paths used for the regional calibration.

In the case of the Jason-1 mission on the interleaved orbits, no pass directly flies over the Senetosa calibration site. Moreover, the mean profiles of two missions are available for the original ground-tracks: the Jason-2 (2008-2010) and the Jason-1 (2002–2008) mean profiles.

On the one hand, the Jason-2 mean profiles are computed on almost the same period as the Jason-1 biases on the interleaved orbits, but with a limited number of cycles (2 years). On the other hand, the mean profiles computed with the Jason-1 cycles, on the original orbits, are more consistent, due to the 7 years of data. Nevertheless, they are not computed on the same period as the biases.

Consequently, it is necessary to compare these mean profiles, in order to choose the mission which gives the steadiest ones.

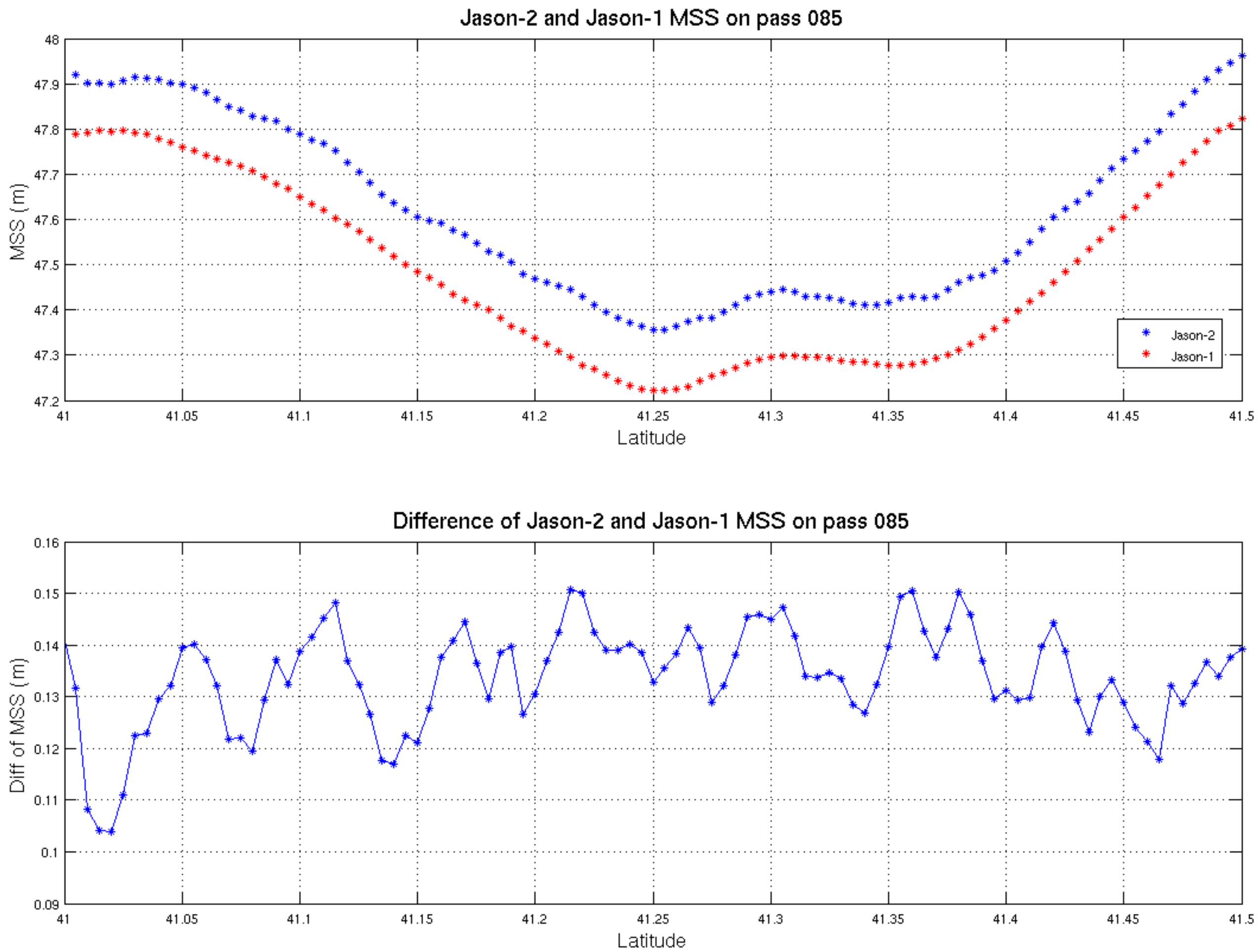

Figure 6: Comparison of the Jason-2 (in blue) and Jason-1 (in red) MSS profiles on the pass 085

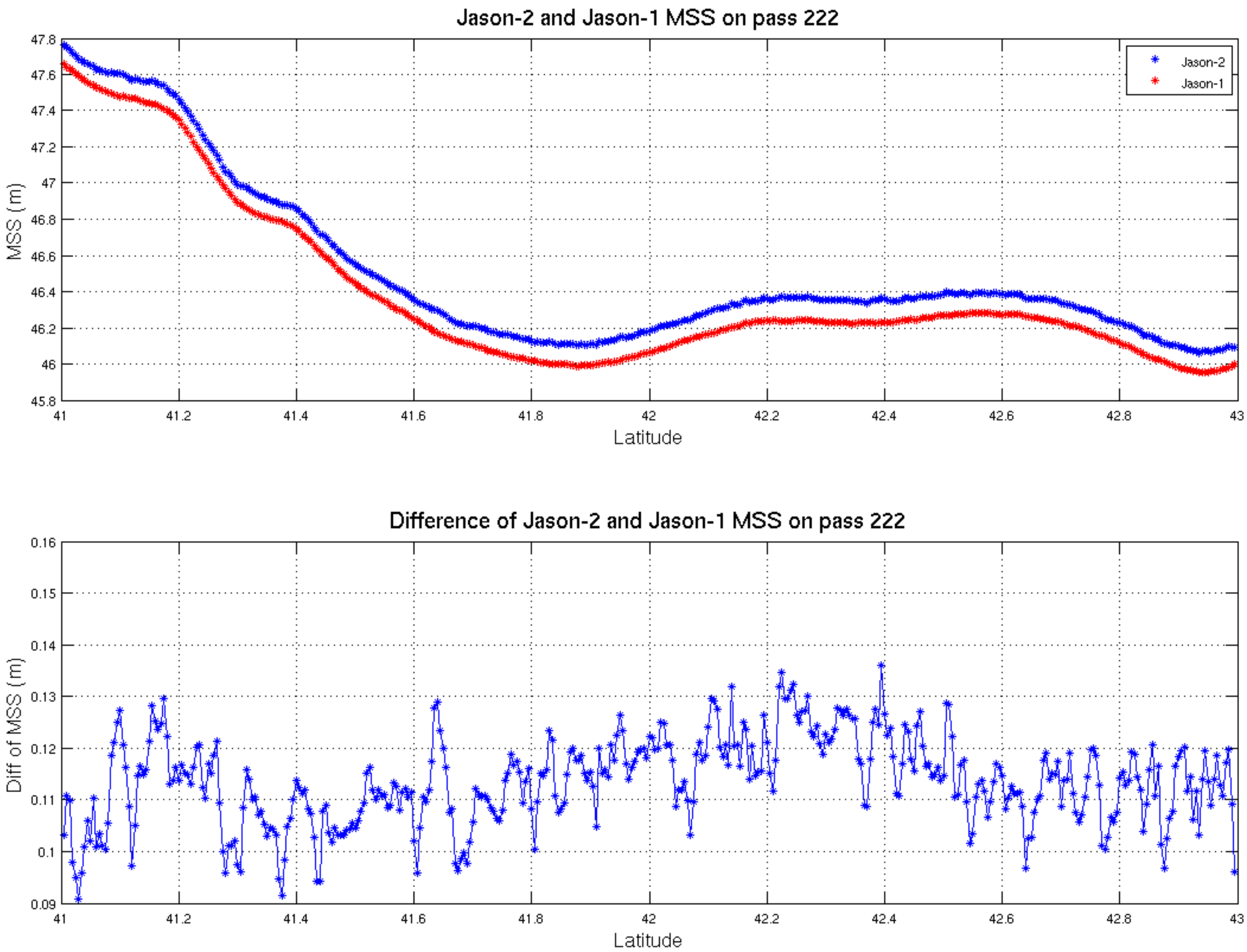

Figure 7: Comparison of the Jason-2 (in blue) and Jason-1 (in red) MSS profiles on the pass 222

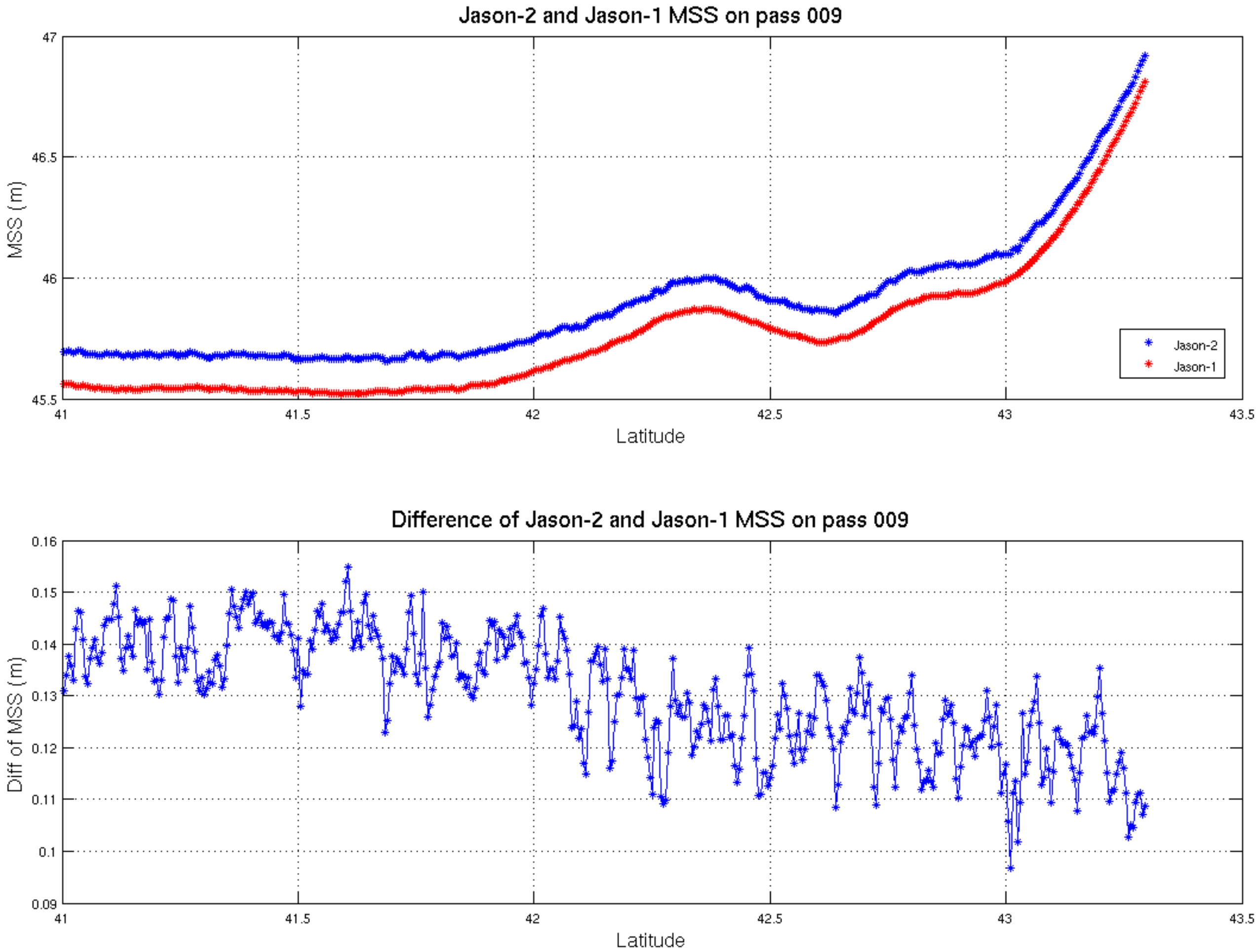

Figure 8: Comparison of the Jason-2 (in blue) and Jason-1 (in red) MSS profiles on the pass 009

Table 3: Mean and standard deviation of the differences between the Jason-2 and Jason-1 MSS profiles

Diff MSS (Jason-2 – Jason-1)	Mean	Std
Pass 085	13.39cm	0.97cm
Pass 222	11.36cm	0.84cm
Pass 009	13.04cm	1.13cm

Figure 6, Figure 7 and Figure 8 show that for each pass, both mean profiles have the same features, with a bias. Nevertheless, when looking at the differences, one can notice that they vary in a range comprised between 9 and 16cm. In the case of the pass 085, the profiles were plotted only in the zone of interest, between 41°N and 41.5°N. Indeed, high variations appear in the profile when considering a wider zone, due to the proximity of the coasts. Consequently, the mean and standard deviation presented in Table 3 are computed with fewer points for the pass 085 than for the two other passes. The mean difference between both missions for the pass 222 appears to be lower than the mean computed for the pass 085, with a decrease of 2cm. The standard deviations are equivalent for these two passes.

The pass 009 shows a very particular behavior, with a decrease of the bias between both missions when going north. Around 43°N, at the location of the crossover point between the passes 009 and 222, the mean difference between both missions is about 11.5cm, which is close to the mean difference on the pass 222.

The low number of the Jason-2 cycles, compared to the Jason-1 cycles, may explain this behavior, as a large number of cycles is probably necessary to correctly resolve the complex dynamics in the middle of the basin (between 41°N and 42°N). It would be interesting to investigate the evolution of these mean profiles as the number of the Jason-2 cycles increases.

The mean profiles of the two missions being very close, except for the biases, we chose to compute the altimeter biases for both cases. The results are gathered in the Table 4.

Table 4: Jason-1 weighted biases using the regional CALVAL method on the passes 085 and 222, for cycles 263 to 307. Using either the Jason-1 or the Jason-2 MSS profiles

Weighted bias (cm)	Using the Jason-1 MSS profiles			Using the Jason-2 MSS profiles		
	Mean	Std	Nb of cycles	Mean	Std	Nb of cycles
Pass 085 (at crossover point with old 222)	8.1 ± 0.4	2.7	39	8.4 ± 0.4	2.7	39
Pass 222 (at crossover point with new 085)	9.1 ± 0.6	3.6	39	9.4 ± 0.6	3.6	39
Pass 222 (at crossover point with old 009)	7.6 ± 0.5	3.0	39	7.2 ± 0.5	3.0	39
Mean regional bias	8.3 ± 0.5	3.1	39	8.3 ± 0.5	3.1	39

The bias estimates are very close in both cases, with slight differences of a few millimetres in the means. The estimations on the pass 222 are about 1cm higher than the others, and it may be due to the ocean dynamics differential effects, as no tide or dynamical atmospheric corrections were applied. Nevertheless, the mean regional bias is only 3mm lower than the estimation obtained on the original orbits, which is quite coherent.

This is a very important result, as it shows the reliability of our bias estimations, especially in the case of the regional method, which requires highly accurate MSS profiles. It is all the more crucial because this calibration method is currently the only one to allow computing *in situ* biases on the interleaved passes of the Jason-1 mission and following their temporal evolutions. It consequently appears that the Jason-1 bias has not been impacted by the orbit change and is still around 8.5cm in Senetosa.

3.3. Comparison with other calibration sites

Several *in situ* calibration sites are disseminated around the world (Figure 9). The collaboration between these different teams mainly exists thanks to the OST-ST conferences. This collaboration should also enable each of the teams to identify long-term work needed to consolidate the results of the *in situ* CalVal method.

The objective of this section is to provide a comparison between the altimeter bias results obtained by the various *in* situ calibration teams, in particular for the five following *in situ* calibration sites:

- Harvest (USA), results obtained by B. Haines et *al.* [[DR7]];
- Bass Strait (Australia)), results obtained by Watson et *al.*, [DR7];
- Gavdos (Greece), results obtained by S.P. Mertikas' team, [DR7];
- eMACnet (Greece), results obtained by E. Pavlis' team. [DR7] ;
- and Senetosa in Corsica (France))
    - with absolute calibration results obtained by P. Bonnefond et *al* [DR7],
    - and regional calibration results obtained by NOVELTIS [DR7].

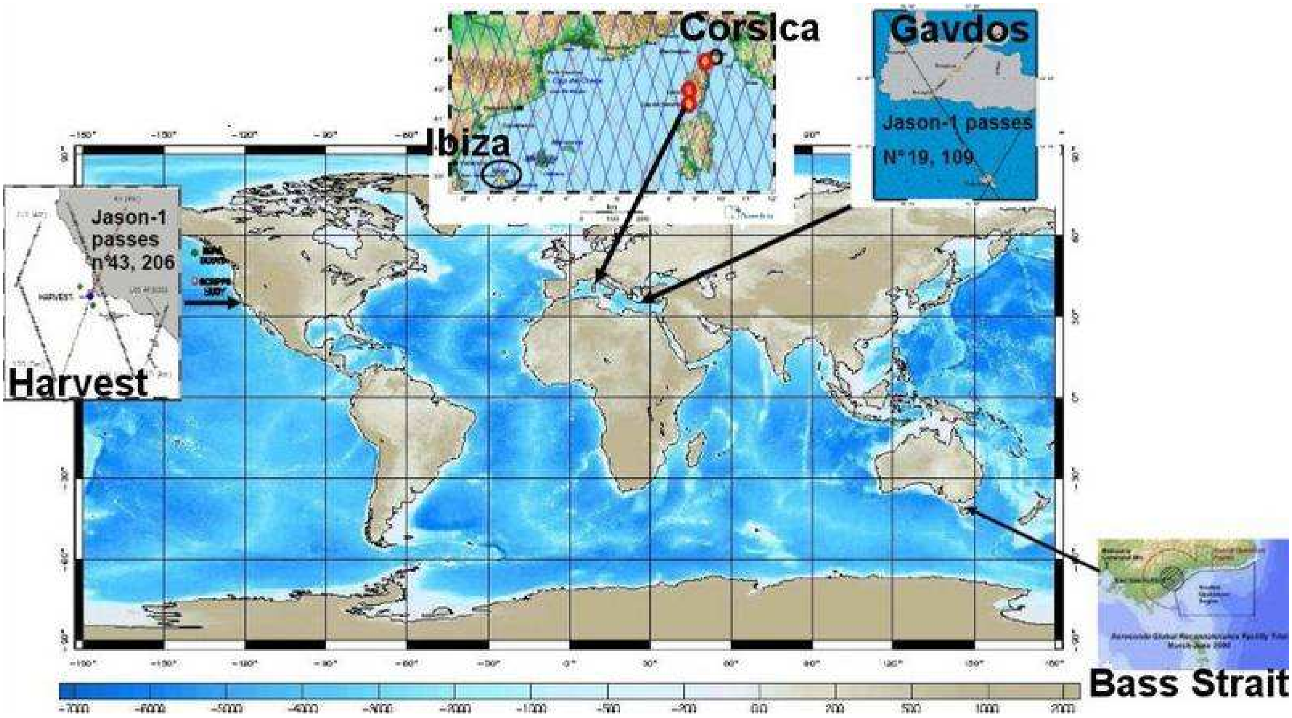

Figure 9: Various *in situ* calibration sites around the world

Figure 10 presents the bias estimates in terms of mean and error values for the Jason-1 altimeter: the lowest bias value (64.3mm) is computed by P. Bonnefond's team at the Corsica site and the highest bias value (99.4mm) is computed by Watson's team at Bass Strait (Australia).

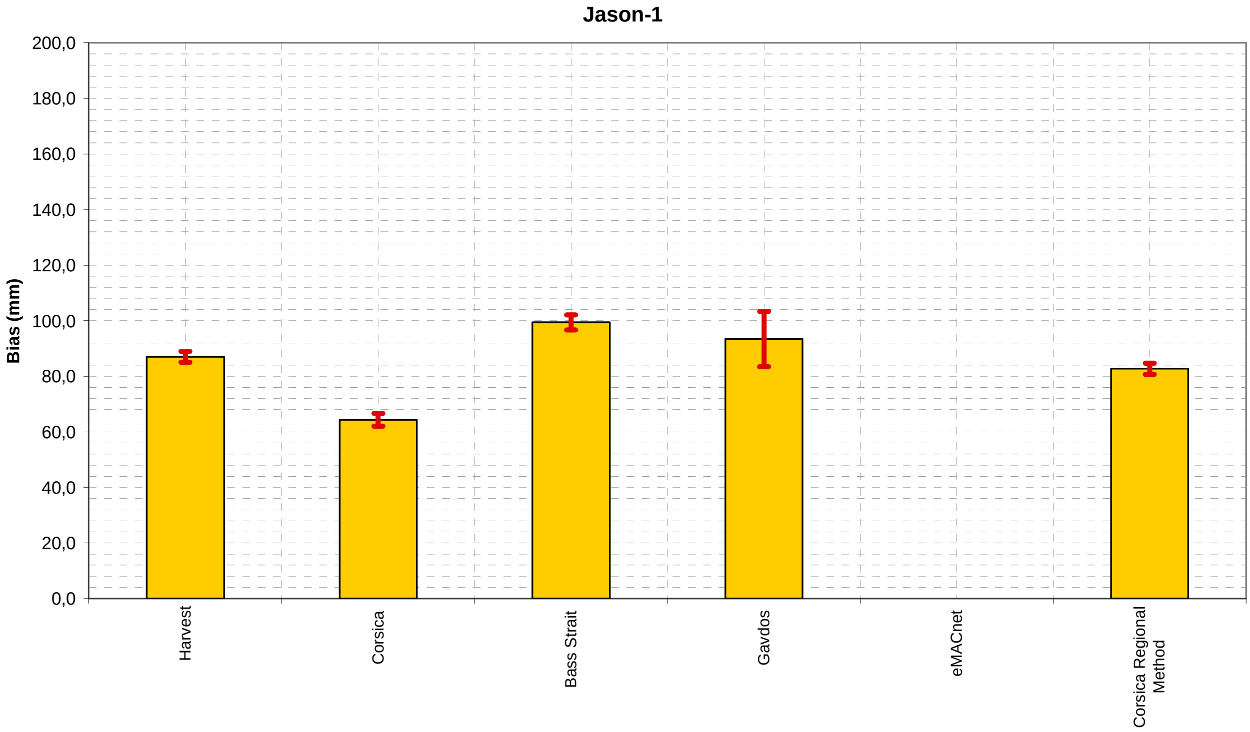

Figure 10: Jason-1 bias computed by the various teams

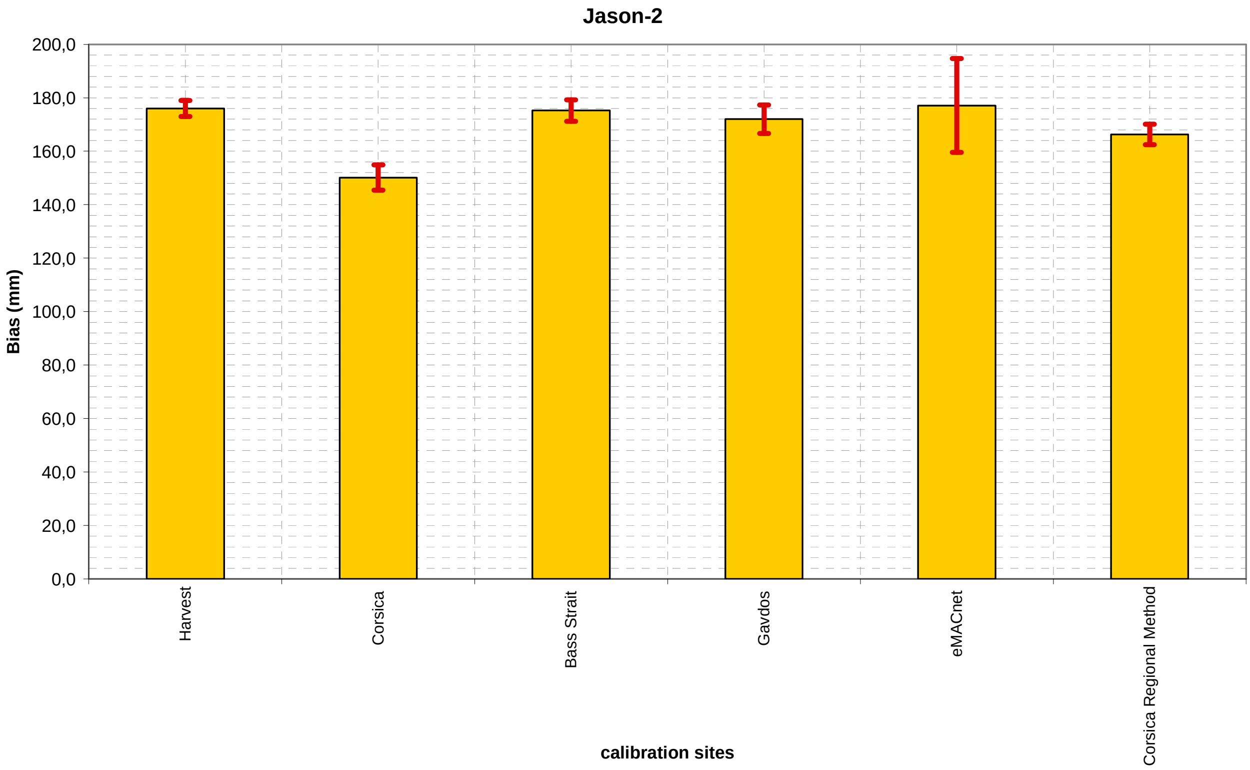

Figure 11: Jason-2 bias computed by the various teams

The Figure 11 presents the bias estimates in terms of mean and error values for the Jason-2 altimeter: the lowest bias value (150.2mm) is computed by P.Bonnefond's team at the Corsica site and the highest bias value (177.1mm) is computed by Pavlis' team in Greece.

Table 5: Jason-1 bias computed by the various *in situ* calval team

	Cycles	N	Bias (mm)		
Jason-1			Mean	Err	sd
Harvest	1-259	210	87,0	2,0	28,0
Corsica	1-259	155	64,3	2,3	29,1
Bass Strait	1-259	211	99,4	2,7	39,2
Gavdos	239-259	18	93,4	10,0	42,3
eMACnet					
Corsica Regional Method	1-259	259	82,7	2,0	31,0

Table 6: Jason-2 bias computed by the various *in situ* calval team

	Cycles	N	Bias (mm)		
Jason-2			Mean	Err	sd
Harvest (Haines et al.)	1-74	72	176,0	3,0	26,0
Corsica (Bonnefond et al.)	0-74	53	150,2	4,8	34,8
Bass Strait (Watson et al.)	1-76	66	175,2	4,0	32,5
Gavdos (Mertikas et al.)	2-74	72	172,0	5,3	44,9
eMACnet (Paviis et al.)	13-33	35	177,1	17,6	104,3
Regional Cancet et al.)	1-64	64	166,3	3,8	30,7

The main differences (Table 5 and Table 6) between the bias computation methods are:

- Firstly, the various tests applied to the data, the different ways to edit the data, and the uncertainties coming from various sources: tide gauge calibration, levelling precision and geographically correlated orbit errors.
- Secondly, the use of different corrections:
    - Indeed, whereas the NOVELTIS regional calval method uses the ECMWF model wet troposphere correction, most of the other calval teams use the radiometer wet troposphere correction. Moreover, when P. Bonnefond uses the ECMWF model wet troposphere correction instead of the radiometer one, he obtains a bias value 2cm higher, that is to say close to the value obtained with the regional method ([DR7]).
    - And concerning the ionosphere correction, NOVELTIS uses the GIM correction whereas the other teams use the bi-frequency correction.

For the Jason-1 bias, the mean value obtained by the 5 *in situ* calval sites is 85.4mm and for the Jason-2 bias, the mean value obtained by the 6 *in situ* calval sites is 169.5mm: NOVELTIS Jason-1 and Jason-2 bias estimates (respectively 82.7mm and 166.3mm) are absolutely consistent with these results. Finally, it should be noticed that the figures show the error bar (ratio between the standard deviation and the square root of the number of cycles). A further statistical hypothesis testing should be conducted in order to state whether the results are statistically equivalent.

4. Sensitivity studies

4.1. Sensitivity analysis of the Jason-2 altimeter bias to the mean sea surface

4.1.1. Introduction

Whatever the CalVal method considered (absolute CalVal for the passes near the coast or regional CalVal for remote passes), the extrapolation of the altimeter measurement from the observation point to the reference points situated on the catamaran surface is performed by taking into account the variation of the Mean Sea Surface Height profiles computed on the passes (and between the crossover points for the regional method). The situation of the catamaran MSS is illustrated in Figure 18 and described in the section 4.1.4.1.

At the time of the study, the Jason-2 altimeter biases have been estimated by using the Mean Sea Surface heights based on the Jason-2 measurements themselves, which were limited to 64 cycles, *i.e.* less than two years of data. As a consequence, there is a strong interest in considering other Mean Sea Surfaces retrieved from measurements over a longest period.

However, the main difficulty is based on the necessity to have the most accurate description of the MSS near the Senetosa coast. Thus, sensitivity analyses ([DR10]) have been performed on three reference MSS: CLS01, CNES/CLS10 and DNSC08. These analyses aim at giving a first view of the impact of these MSS on the computation of the biases and then, at providing a comparison with the catamaran surface, near the coast. The purpose of this study is to verify if these 3 MSS allow computing accurate Jason-2 altimeter biases at the Senetosa calibration site.

4.1.2. Short description of the three MSS considered

4.1.2.1. CLS01

The CLS01 MSS was determined by CLS using altimeter data along the TOPEX/POSEIDON, ERS-1, ERS-2 and GEOSAT ground tracks [DR6]. The T/P data used cover a seven-year period (1993-1999). ERS mean profile is estimated over 5 years of data (1993-1999) and the GEOSAT mean profile over 2 years (1987-1989). The T/P SSH were processed with the most recent geophysical corrections at that time (GOT99.2 tidal model and tailored inverse barometer corrections). This mean profile is chosen as the reference of the CLS01 MSS. Whereas the ERS mean profiles are corrected with the same altimetric correcting model as the T/P SSH whenever it is possible, the GEOSAT mean profile had to be adjusted to both T/P and ERS mean profiles.

The MSS determination technique is focused on a local least square collocation method on a 6 minutes grid where altimetry data are selected in a 200km radius. The estimation on a 2-minute grid is based on the EGM96 values. The inverse method uses local isotropic covariances.

On continents, the MSS is filled up with the EGM96 geoid. The connection between the MSS and the EGM96 geoid on the continents, in the coastal areas, corresponds to a smoothed gradient surface. As a result, the MSS corresponding value is not the MSS but a quantity between the MSS and the geoid. Thus, there is a risk to have some discrepancies between these altimetry MSS and the catamaran MSS.

The grid of the MSS is regular with a spatial resolution of 1/30° (2 minutes): *i.e.* ~4km.

4.1.2.2. CNES/CLS10

The CNES/CLS10 Mean Sea Surface has been computed by CLS using 13 years of TOPEX/POSEIDON data, 8 years of ERS-*2* data, ERS-1 geodesic data (2 phases at 168-days), 7 years of GFO, 7 years of Envisat and 7 years of Jason-1 ([DR3]). All these data have been referenced to the 1993-1999 period and corrected by the ocean topography variable signal.

The spatial resolution is the same as the CLS01 MSS one.

Over lands, the MSS is filled up with the EIGEN_GRACE-5C geoid. As performed with CLS01, in the islands or shoreline/coastal areas, the MSS corresponds to a smooth extrapolation / interpolation of the ocean values toward the EIGEN_GRACE_5C geoid over land. Thus, the MSS corresponding value is not the MSS but a quantity between the MSS and the geoid.

4.1.2.3. DNSC08

The DNSC08 was estimated by the DNSC (Danish National Space Center) by adjusting 8 years of ERS-2 onto 12 years of TOPEX/POSEIDON+Jason-1, ENVISAT onto ERS-2 (in the Arctic Ocean) and ICESAT onto ENVISAT and onto ERS-2 (in Arctic Ocean) [DR5]. The DNSC08 bathymetry was considered. The corrections used were derived from GOT00 for the ocean tide correction and from inverse barometer models.

The spatial resolution of the regular grid is 1 minute by 1 minute (2 km by 2 km). The geoid model used over land is EGM2008.

4.1.2.4. Summary

Table 7 gives a summary of the main characteristics of the three previous MSS.

Table 7: Description of the relevant characteristics of the CLS01 – CNES/CLS10 - DNSC08 MSS considered

Name of the MSS	CLS01	CLS10	DNSC08
Reference ellipsoid	TOPEX / POSEIDON	TOPEX / POSEIDON	TOPEX / POSEIDON
Geoid model used (over land and shoreline / coastal areas)	EGM96	EIGEN_GRACE_5C	EGM2008
Spatial resolution	2min (4km)	2min (4km)	1min (2km)
Altimetric dataset	TOPEX/POSEIDON - 7 years ERS - 5 years GEOSAT - 2 years	TOPEX/POSEIDON - 13 years ERS-2 - 8 years ERS-1 - 2 phases at 168 days GFO - 7 years ENVISAT - 7 years	TOPEX/POSEIDON - 12 years ERS-2 - 8 years JASON-1 - ENVISAT - ICESAT

4.1.3. Computing the Jason-2 altimeter biases depending on the Mean Sea Surface

To illustrate the impact of the Mean Sea Surfaces (CLS01, CNES/CLS10 and DNSC08) on the *in situ* CalVal method, Jason-2 altimeter biases have been computed considering each of them, on the Senetosa site, and finally, using Sea Surface Height mean profiles, obtained by averaging the Jason-2 measurements on the passes 085 / 222 / 009, over one complete year (cycle 1 to 38, 15th July 2008 – 15th July 2009) with a spatial resolution of 0.005° in terms of latitude (~0.5km). Figure 12 to Figure 14 illustrate this impact and Table 8 allows quantifying the impact of the different MSS on the altimeter biases calculation.

The results can be summarized as follows:

- Strong inconsistencies in the values of the biases are observed on the pass 085 (Absolute CalVal method). Whereas the values seem correct with the mean profile, the three other MSS provide biases with a difference around 15cm;
- Smaller dispersions are observed with the passes 222 and 009 (Regional CalVal method). By comparing to the SSH mean profile, the differences vary from 1 to 6cm;
- The stronger biases values are obtained with the mean profile on the pass 085 and with the DNSC08 MSS on the two other passes;
- On the pass 222, biases obtained with the CNES/CLS10 MSS present weaker variations than when using the mean profile;
- On the pass 009, biases obtained with the CLS01 MSS present close values with the mean profile.

At a first glance, the three MSS compared in this study provide incorrect bias values only for the pass 085, where the considered observation points are near the coast. When the regional CalVal method is applied to the two other passes (*i.e.* when the considered observation points are on a remote pass), the differences on the biases are weaker.

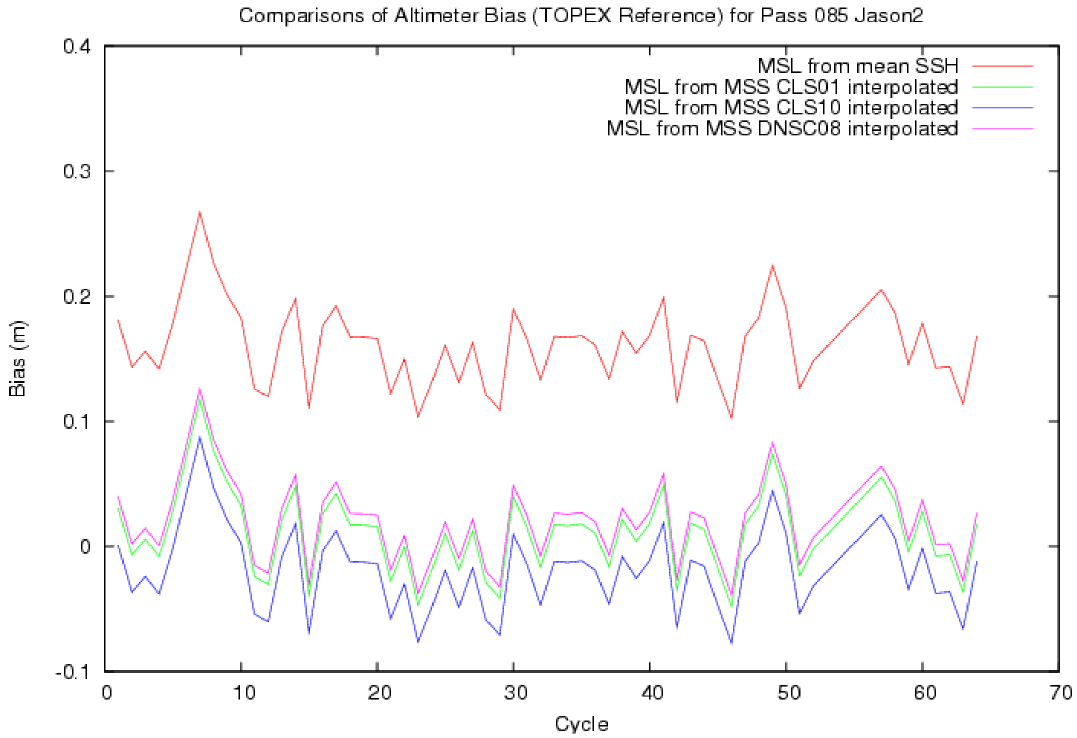

Figure 12: Temporal Jason-2 altimeter bias profiles on the Senetosa area as a function of MSS used for extrapolating the observation points to the catamaran surface – Cycle 1 to 64 – M4 Tide gauge – Pass 085 – 20Hz data.

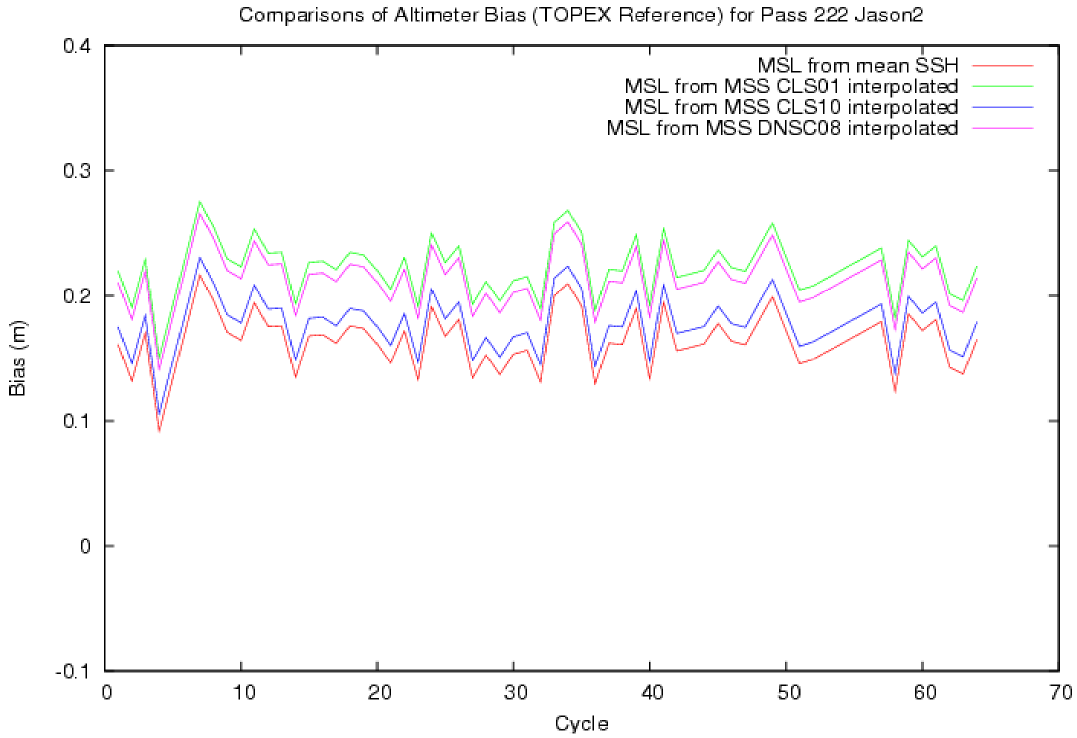

Figure 13: Temporal Jason-2 altimeter bias profiles on the Senetosa area as a function of MSS used for extrapolating the observation points to the catamaran surface – Cycle 1 to 64 – M4 Tide gauge – Pass 222 – 20Hz data.

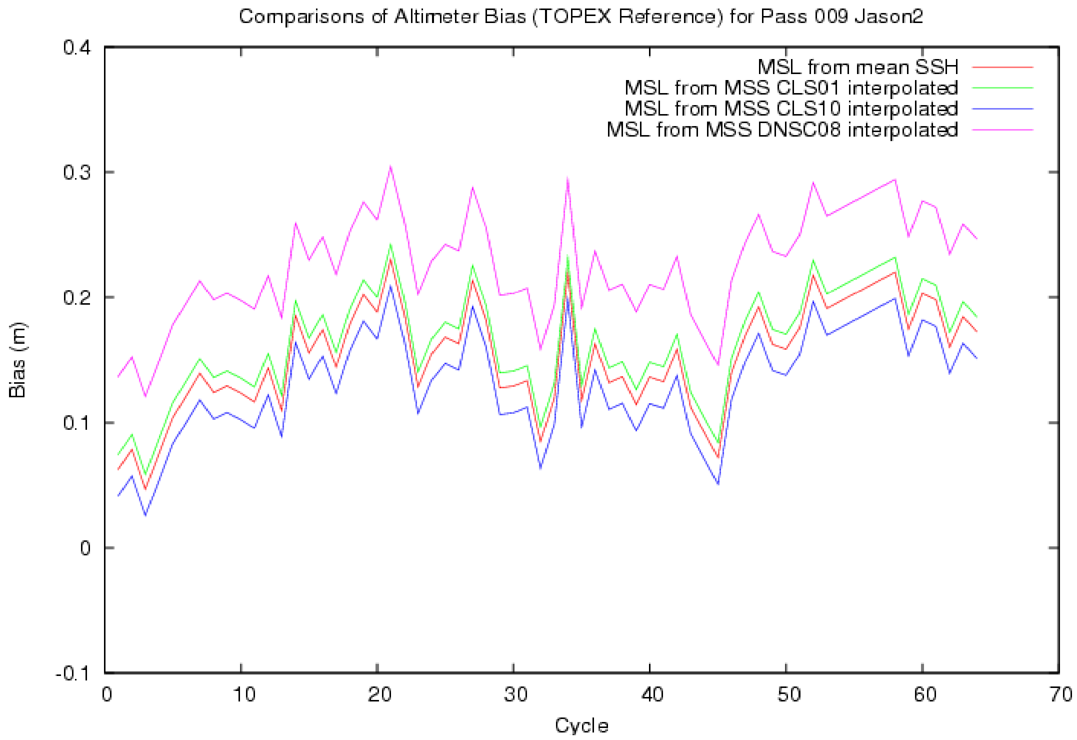

Figure 14: Temporal Jason-2 altimeter bias profiles on the Senetosa area as a function of MSS used for extrapolating the observation points to the catamaran surface – Cycle 1 to 64 – M4 Tide gauge – Pass 009 – 20Hz data.

Table 8: Temporal averaging of the Jason-2 altimeter biases at Senetosa using different MSS (cm) – Cycle 1 to 64 – M4 Tide gauge - Passes 085 / 222 / 009 – 20Hz data.

	Name of the MSS			
Pass	**Mean profile SSH**	**CLS01**	**DNSC08**	**CNES/CLS10**
085	16.1	1.1	1.9	-1.9
222	16.4	22.3	21.4	17.8
009	15.0	16.2	22.4	12.9

To compare the values of the three MSS with the SSH mean profile, a spatial interpolation is performed on the locations of the mean profile. For each location where to interpolate, the value is obtained from the four original MSS points around the location point and by weighting by the distance between the location and each of these original points. Therefore, three mean profiles are deduced from the MSS and are compared with the Jason-2 mean SSH, as illustrated in Figure 15 to Figure 17.

Whatever the passes, the differences between the original profiles and the three interpolated MSS can vary from 10cm to 20cm, depending on the locations. However, the most important feature to analyze is not these differences themselves but the dispersions of these differences along the latitude. Indeed, the altimeter bias calculation is based on the variations of the Mean Sea Surface between the reference points on the catamaran area (around 41.45 deg of latitude) and the considered observation points.

Whereas the differences between the MSS present a smaller variability (as a function of latitudes) for the passes 009 and 222, one can notice that on the pass 085:

- There is a dispersion between 7cm and 12cm in the area 41.4° - 41.5° (*i.e.* the area where the observation points are considered for computing altimeter biases on the pass 085);
- There is a dispersion between 2cm and 10cm in the area 41.1° - 41.5° (*i.e.* the area where the crossover point between the passes 222 / 085 is used for computing altimeter biases corresponding to the pass 222).

As a consequence, these three MSS present errors in coastal areas, which prevents from computing realistic values of the altimeter biases in these areas, especially with the absolute in-situ CalVal method. This strong impact on the bias calculation may be caused by the interpolation / extrapolation performed between the MSS and the different geoid models considered over continents and in shoreline areas. Moreover, the spatial resolution associated with each MSS does not seem to be adapted for achieving *in situ* CalVal, in local areas. Therefore, to better understand the instability of these MSS in the coastal area of Senetosa, a comparison is made with a higher spatial resolution MSS.

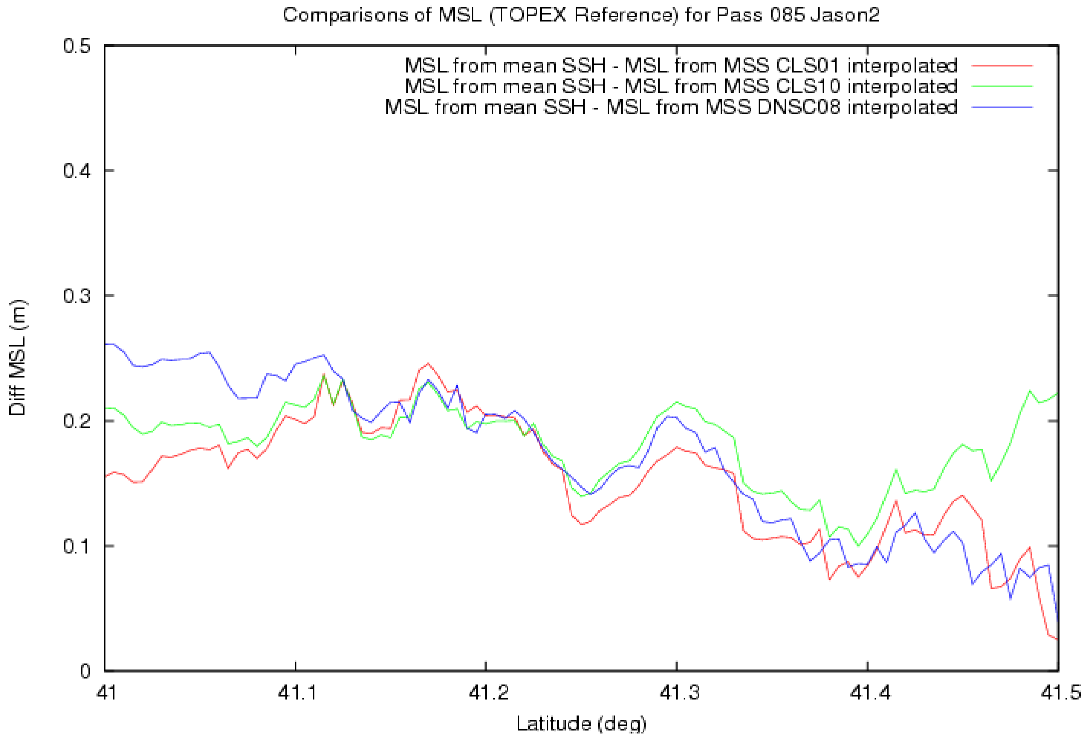

Figure 15: Differences between the Mean Sea Level obtained by averaging the Jason-2 Sea Surface Heights over 38 cycles and each of the three MSS considered (CLS01 – CNES/CLS10 – DNSC08) interpolated on the Mean Sea Level as a function of the latitudes – Pass 085.

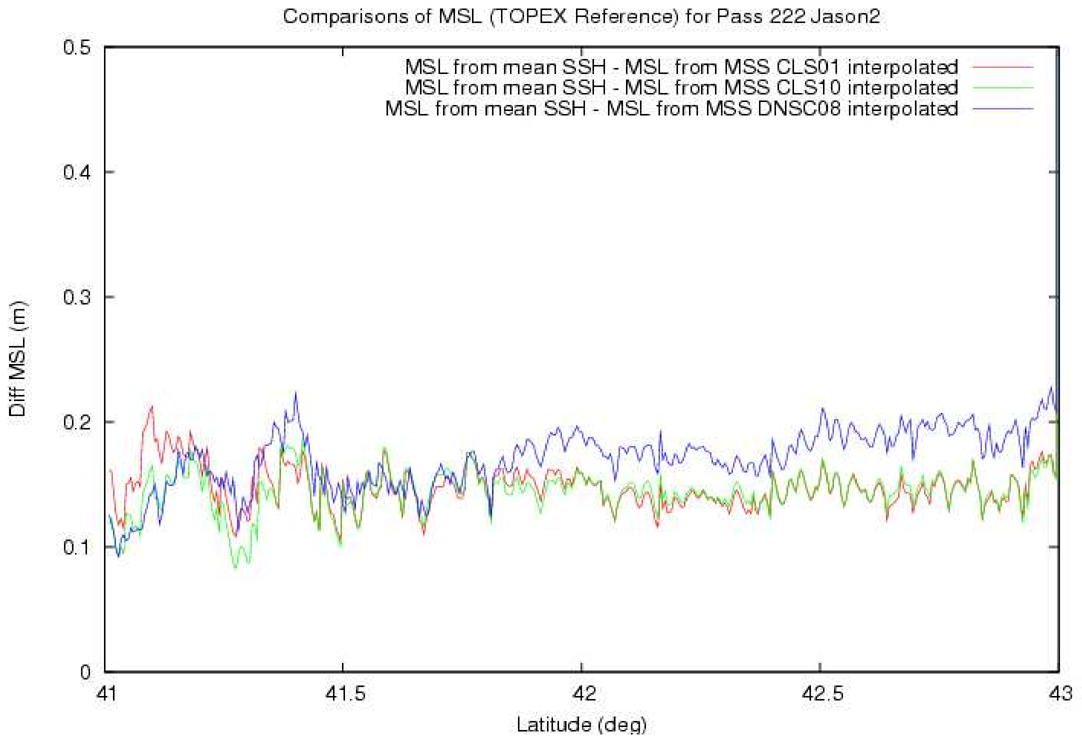

Figure 16: Differences between the Mean Sea Level obtained by averaging the Jason-2 Sea Surface Heights over 38 cycles and each of the three MSS considered (CLS01 – CNES/CLS10 – DNSC08) interpolated on the Mean Sea Level as a function of the latitudes – Pass 222.

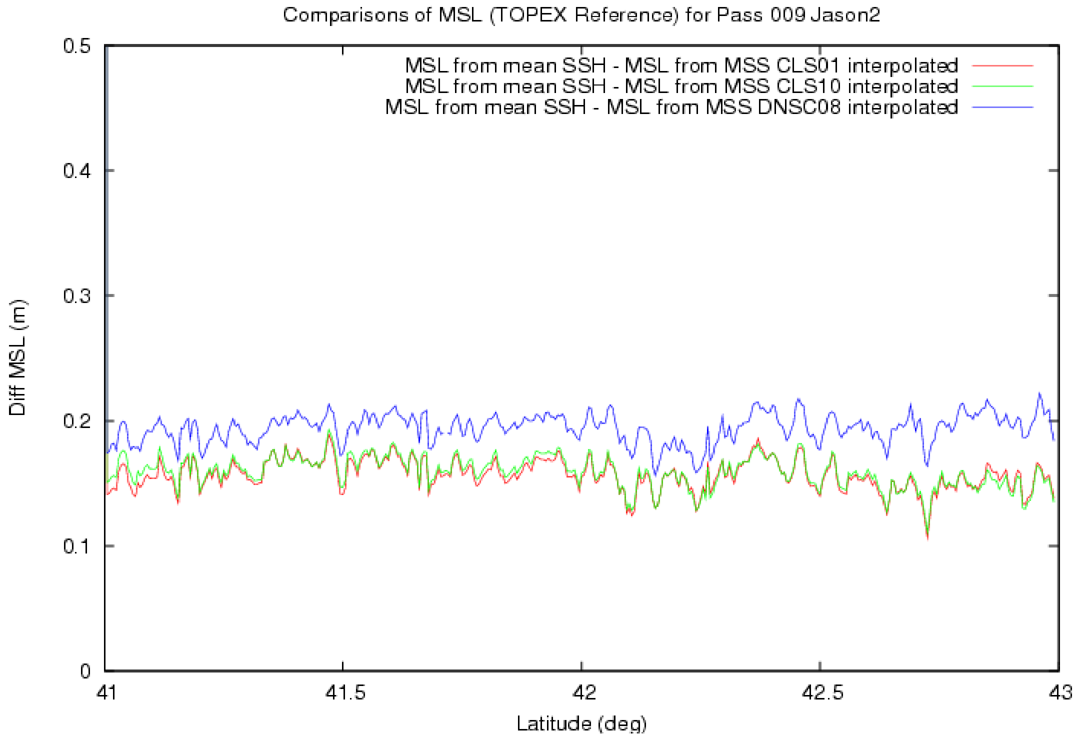

Figure 17: Differences between the Mean Sea Level obtained by averaging the Jason-2 Sea Surface Heights over 38 cycles and each of the three MSS considered (CLS01 – CNES/CLS10 – DNSC08) interpolated on the Mean Sea Level as a function of the latitudes – Pass 009.

4.1.4. Comparisons of the three Mean Surfaces (CLS01 – CNES/CLS10 – DNSC08) with the catamaran surface at Senetosa

4.1.4.1. Short description of the catamaran surface

As it has been explained in part 3.1, in order to compare the altimeter and tide gauges data in the same geodetic reference, it is crucial to have an accurate description of the sea surface near the Senetosa site.

The catamaran GPS survey campaign carried out by OCA has provided a precise Mean Sea Surface grid with a resolution of 5.10^{-4} degree (~0.05km). This MSS grid is the Mean Sea Surface with the highest spatial resolution available in coastal areas, near the Senetosa site where as we have already mentioned the geoid slope may reach about 6 cm/km. As a consequence, this Mean Sea Surface can be considered as the reference MSS and can be compared with the MSS CLS01, CNES/CLS10 and DNSC08 in order to quantify more precisely their defaults in this area.

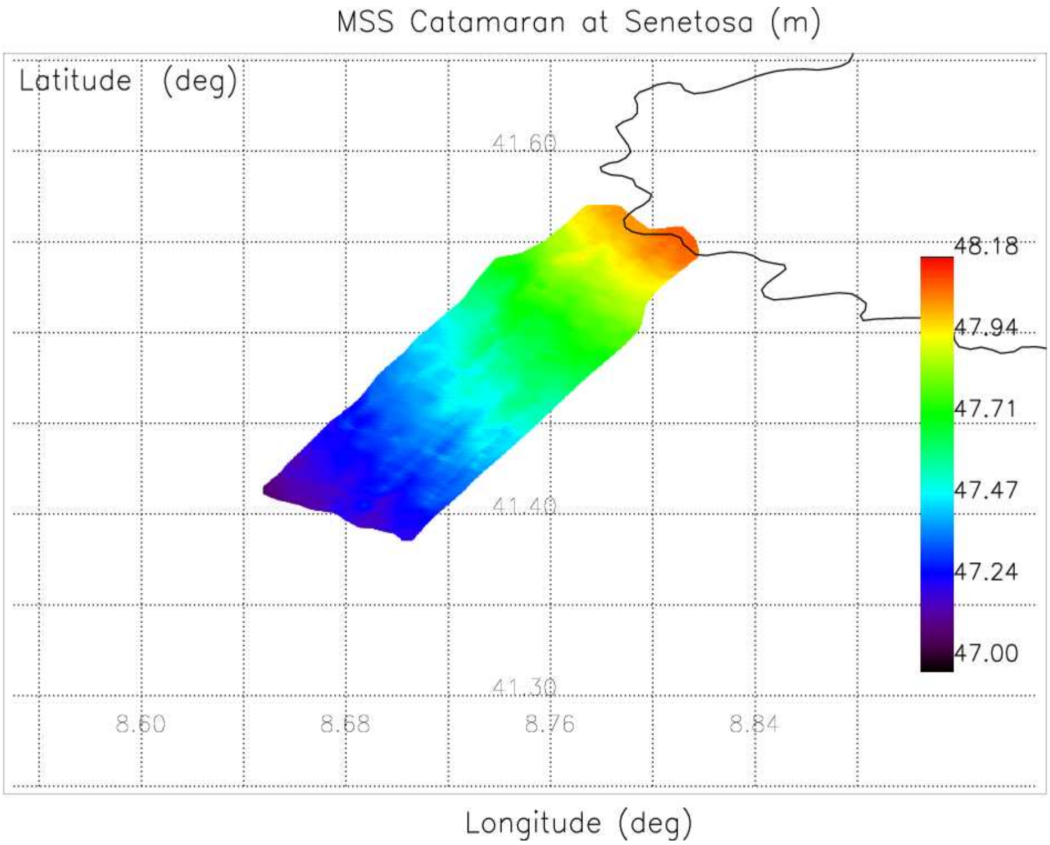

Figure 18: Catamaran Mean Sea Surface at Senetosa

4.1.4.2. Analysis of the differences between each Mean Sea Surface and the catamaran area

In order to compare each MSS (CLS01 – CNES/CLS10 – DNSC08) with the catamaran surface, a spatial interpolation is performed following the same method as explained in the previous part (see section 4.1.3), on the catamaran area at Senetosa. Whatever the MSS, the differences present dispersion between -20cm and 44 cm. Table 9 provides the statistics of the differences between the points which are the closest spatially (less than 3 cm) between each MSS and the catamaran area.

The results can be summarized as follows:

- The CNES/CLS10 MSS presents the smallest differences with a mean of 2.9cm;
- The CLS01 MSS presents the highest differences with a mean of 15.3cm;
- The differences with the DNSC08 MSS provide the smaller dispersions (a standard deviation of 3.1 cm);
- Whatever the MSS considered, the differences are not homogenous along the catamaran area. Generally, the higher values are very near the Senetosa coast and they decrease continuously while the distance from the coast increases;
- The CLS01 MSS shows the strongest differences near the continent (about 40cm) whereas, on the same area, the CNES/CLS10 MSS is similar (differences of about 2cm).

As a conclusion, these maps (Figure 19 to Figure 21) illustrate clearly the link between the coastal areas and the defaults of the three MSS considered close to the coast, which is not surprising, since near the coast, the altimetry MSS are not based on reliable altimetry measurements. However, the differences themselves are not the most important. Indeed, for the altimeter bias calculation, the catamaran area is used for estimating the spatial gradient between the points of interest (*i.e.* the tide gauge measurement and the reference points). Thus, the value of the MSS on its own is not of first interest: but it is the spatial gradient on each MSS which is the more important for computing the biases.

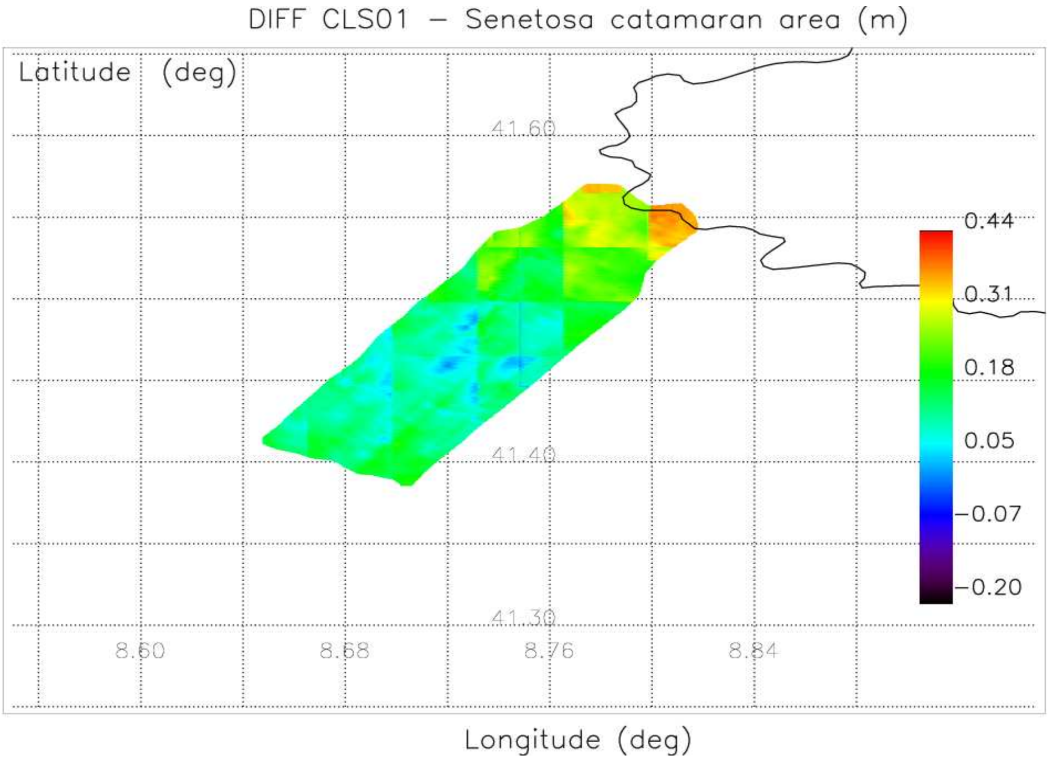

Figure 19: Differences between the catamaran surface and the Mean Sea Surfaces CLS01 interpolated on the catamaran surface at Senetosa.

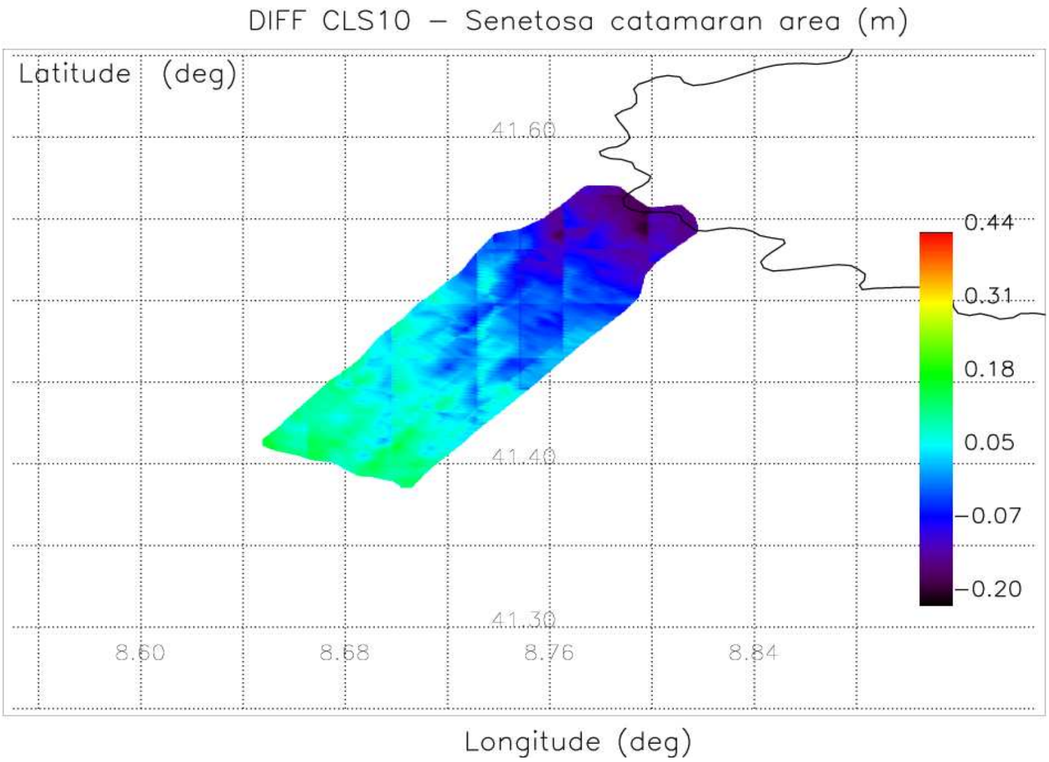

Figure 20: Differences between the catamaran surface and the Mean Sea Surfaces CNES/CLS10 interpolated on the catamaran surface at Senetosa.

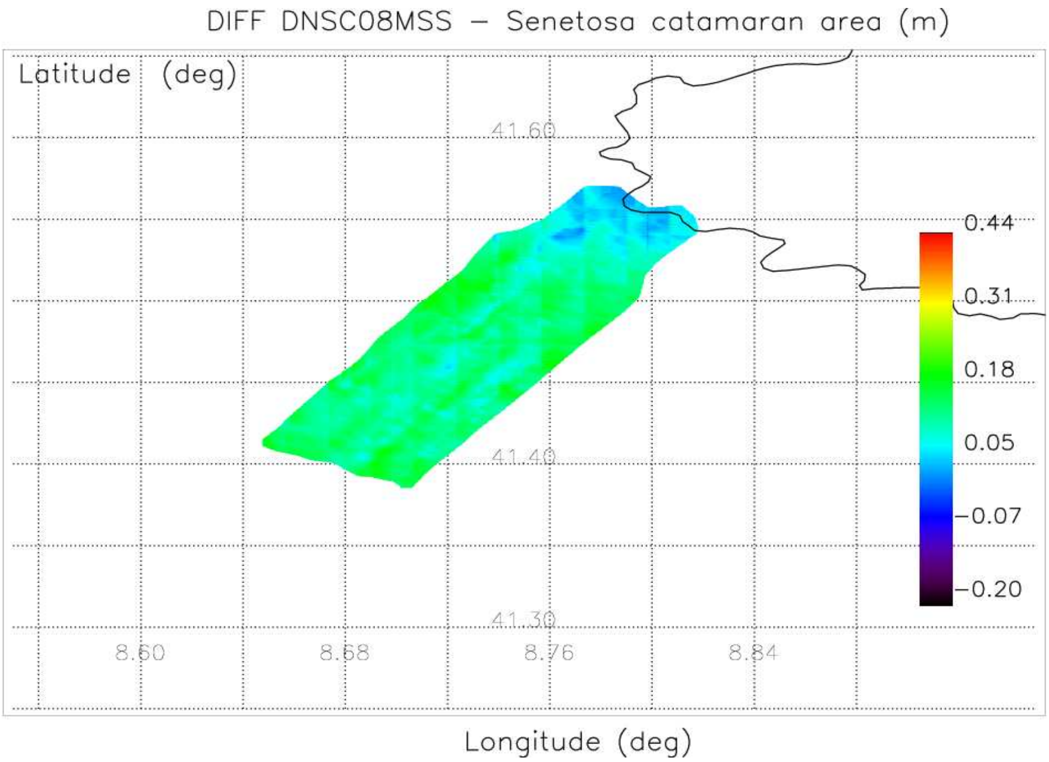

Figure 21: Differences between the catamaran surface and the Mean Sea Surfaces DNSC08 interpolated on the catamaran surface at Senetosa.

Table 9: Statistics of the differences of the three MSS with the catamaran surface – Comparisons with the closest points.

	CLS01 - Senetosa	DNSC08 - Senetosa	CNES/CLS10-Senetosa
Mean (cm)	15.3	13.1	2.9
Standard Deviation (cm)	6.2	3.1	7.0

4.1.4.3. Analysis of the differences in terms of slope between each Mean Sea Surface and the catamaran area

The analysis made in this part aims at estimating the differences between the three MSS and the catamaran surface in terms of spatial gradient. Thus, the location of the M3 tide gauge, on the Senetosa coast, is considered. Between its location and each point available in the Mean Sea Surfaces, a spatial gradient is computed. Please, note that what we called here a spatial gradient corresponds to a difference of MSS between a point on the coast (more exactly, the location of the tide gage M3) and a point on the area of the MSS analyzed. Thus, the unit associated to it is in meters. The spatial gradients, as a function of the distance from the coast, are presented in Figure 22. The statistics are available in the Table 10.

Whereas, in the previous part, the CNES/CLS10 MSS presented the smallest differences with the catamaran MSS, the DNSC08 MSS seems to be the most consistent with the catamaran surface in terms of spatial gradient (a bias with a mean of -8.5 cm and a dispersion of 3.3 cm is noticed). Even though the CLS01 MSS presents a smaller mean (in terms of spatial gradient differences) of 7.9cm, the dispersion is stronger (~6.4cm). One can notice that the CNES/CLS10 MSS shows the most important bias with the catamaran MSS, despite the fact that it is an update of the CLS01 MSS.

As a conclusion, the three MSS present strong differences with the catamaran surface (even in terms of spatial gradient). These values indicate that they should not be used in the coastal area of Senetosa, for computing Jason-2 altimeter biases. Indeed, this statement is confirmed by the unrealistic values obtained for Jason-2, on the pass 085. As a first explanation, the interpolation / extrapolation performed between the MSS and the geoid model available on the continents may be the problem which explains the inconsistencies noticed in the previous parts. Furthermore, the spatial resolution seems not to be well adapted for the bias calculation in the Mediterranean area, as illustrated with the differences between the values for the passes 222 and 009. The same spatial resolution and precision as the catamaran surface should be more relevant.

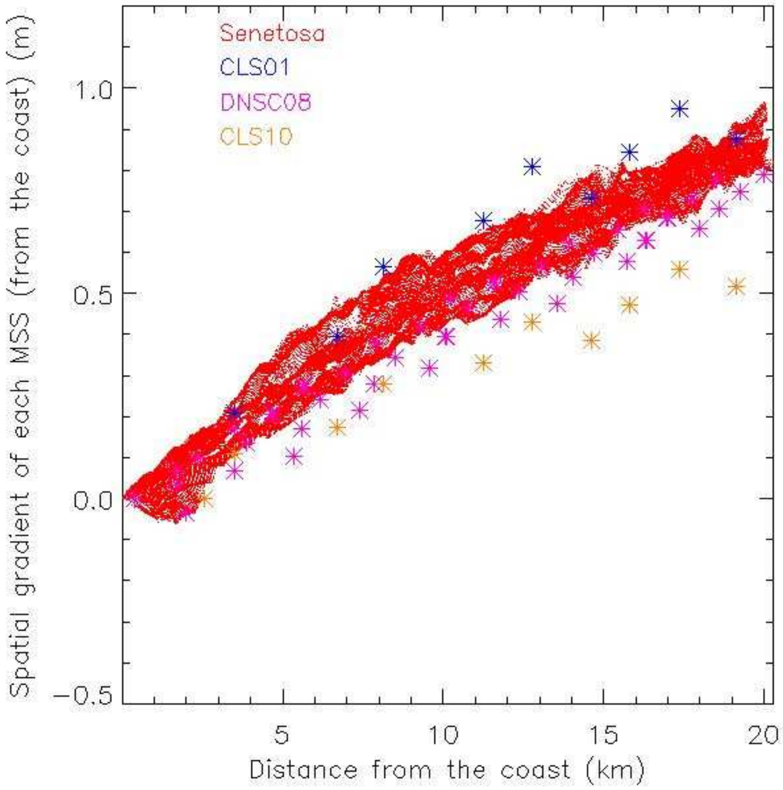

Figure 22: Comparisons of the "spatial gradients" of each MSS between the coast and the points available as a function of the distance from the coast.

Table 10: Statistics (Mean and standard deviation) of the differences of the spatial gradients between the three MSS (CLS01 – DNSC08 – CNES/CLS10) and the catamaran surface – Comparisons with the closest points.

	CLS01 - Senetosa	DNSC08 - Senetosa	CNES/CLS10-Senetosa
Mean (cm)	7.9	-8.5	-17.4
Standard Deviation (cm)	6.4	3.3	8.5

4.1.5. Conclusions and recommendations

Sensitivity analyses of the JASON-2 altimeter bias to the Mean Sea Surface were carried out considering three MSS (CLS01 – CNES/CLS10 – DNSC08) and comparing with the bias obtained through SSH mean profiles along the passes. The conclusion is that using these three MSS for computing the biases in the Mediterranean area is not adapted. Indeed, they were developed at a global scale and the spatial resolution is not optimized for the *in situ* CalVal methods. More particularly, inconsistencies are observed when the biases are estimated in the Senetosa coastal area. These inconsistencies have been confirmed by the comparisons of the spatial gradient with the catamaran surface (a mean difference of 7.9cm for CLS01, -8.5cm for DNSC08 and -17.4cm for CNES/CLS10), which is the reference MSS in this area. These differences may be induced by the extrapolation/interpolation performed between the MSS and the geoid model available on the continents.

In conclusion the study shows that using the three MSS (CLS01 – CNES/CLS10 – DNSC08) for computing the biases in the Mediterranean area is not recommended. Nonetheless, the comparison exercise performed here can be used in order to assess altimetric MSS in coastal areas, where precise and fine-scale MSS obtained by other means are available.

4.2. Sensitivity analysis of the Jason-2 altimeter bias to the ocean dynamics

4.2.1. Introduction

As it was presented in the section 3.2.1 as well as in [DR4] and [DR2], the Jason-2 altimeter bias decreases by more than 1.5cm between the absolute estimation at the Senetosa calibration site and the offshore pass 009. One of the reasons of such a gap in the bias between the remote pass and the coastal area near Senetosa may be the ocean dynamics, as some altimetry points are 200km far from the calibration site. Applying tide and dynamical atmospheric corrections to the altimeter and tide gauge data thus appears necessary in order to eliminate these effects in the bias computation.

4.2.2. Tide correction: FES2004 and GOT00.2 models

In order to eliminate as much tidal signal as possible in the data, we chose to compute the *in situ* tide correction by applying a harmonic analysis to the tide gauge time series. 66 wave contributions were retrieved from this processing over 9 sessions (40 to 48), that is to say more than 2 years of *in situ* observations with a temporal resolution of 10 minutes for M3, M4 and M5, and 30 minutes for M7. It should be kept in mind that only 9 months of data are available for the M7 tide gauge, which may be a little short to accurately determine the contribution of each wave.

Because of the shortness of the altimetry time series (less than 2 years), and the known aliasing effects due to the 10-day repeat cycle of the Jason-2 mission, it is not possible to use the same method to remove the tide from the altimetry data. Predictions from a tide atlas are necessary, at each point and each time of measurement of a cycle.

Two ocean tide corrections are available in the GDR products: FES2004 and GOT00.2 models. The altimeter bias was estimated in both cases, as it is presented in Table 11.

Table 11: Jason-2 weighted bias at Senetosa for passes 085, 222 and 009, considering different tide corrections.

Weighted bias (cm)	Jason-2 cycles 1 to 74 with no tide correction		Jason-2 cycles 1 to 74 with GOT00.2 tide correction		Jason-2 cycles 1 to 74 with FES2004 tide correction	
	Mean	Std	Mean	Std	Mean	Std
Pass 085	17.4 ± 0.4	3.4	17.3 ± 0.4	3.5	17.4 ± 0.4	3.5
Pass 222	17.5 ± 0.3	2.6	17.9 ± 0.3	2.8	17.9 ± 0.3	2.9
Pass 009	15.7 ± 0.4	3.3	15.6 ± 0.4	3.8	15.7 ± 0.4	3.7
Regional mean bias	16.9 ± 0.4	3.1	16.9 ± 0.4	3.4	17.0 ± 0.4	3.3

As it can be observed in Table 11 using a tide correction from a global model has no significant impact on the weighted bias. Even if the tide correction reaches about 18cm, we can only observe a slight increase of 3 to 4mm in the weighted bias standard deviation for the passes 222 and 009. Consequently, the tidal differential effect between the offshore altimeter points and the tide gauges at the calibration site is not sufficient to explain the gap of more than 1.7cm in the bias computed on the passes 085 and 222 and the value on the pass 009.

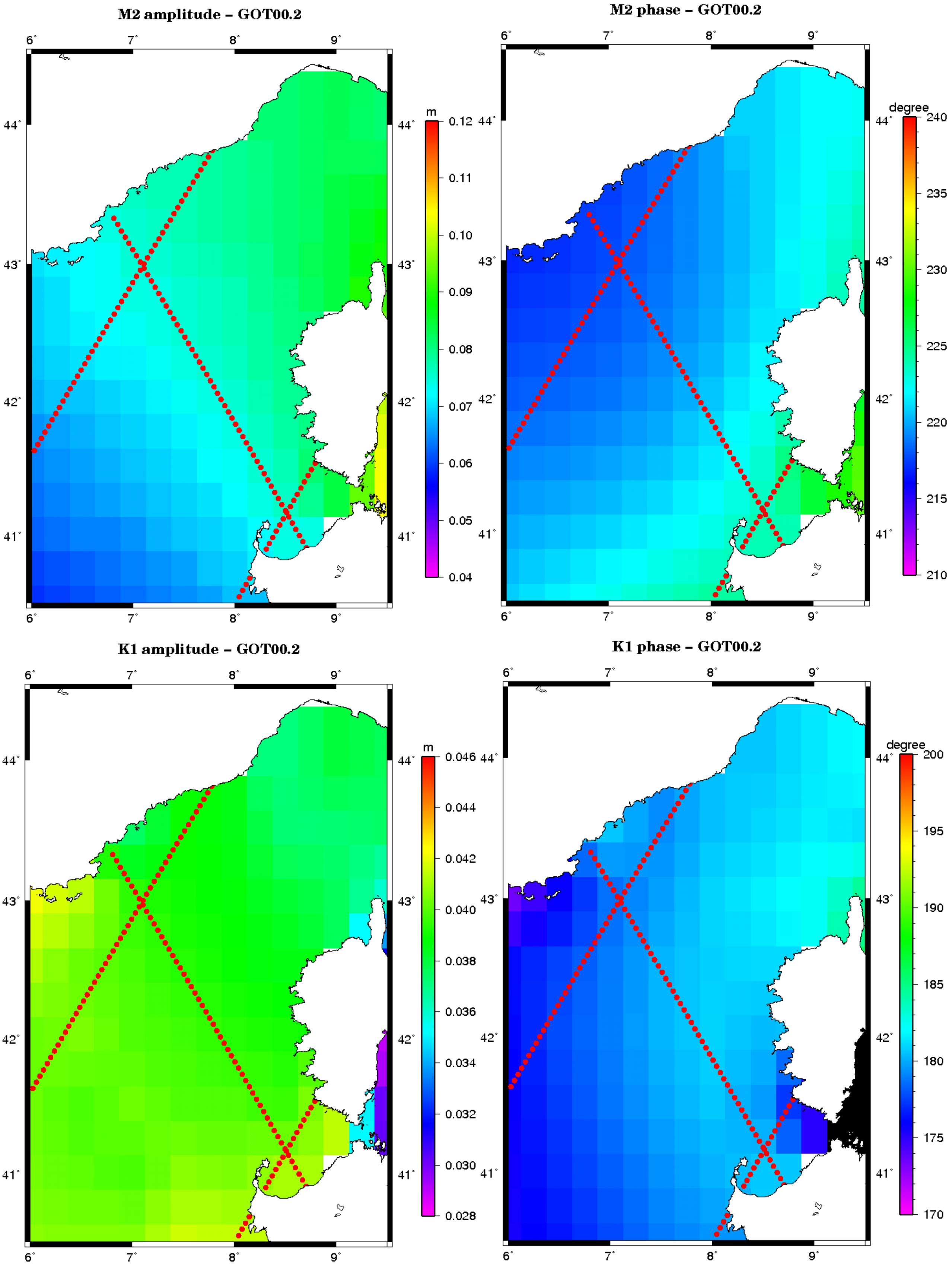

Figure 23: Amplitude and phase of the main tidal constituents (M2 and K1) in the Senetosa region. The altimeter points of passes 085, 222 and 009 are superimposed in red dots.

Figure 23 actually shows that even for the most important tide waves in the Mediterranean Sea (M2 and K1), the spatial variations of the amplitude are very weak, which explains the fact that the difference between the offshore bias and the bias at the coast remains when a tide correction is applied. The dynamical atmospheric correction may present greater spatial variations in the zone and be the cause of such discrepancies.

It should be also noticed that other models, such as TUGO and GOT4.7, better represent the coastal dynamics, because of its finer spatial resolution for the former, and the assimilation of satellite and *in situ* data in the latter, but they are not distributed in the altimetry products yet.

4.2.3. Dynamical atmospheric correction

The wind and the pressure effects on the sea surface heights can also be eliminated by using a model. Dynamical atmospheric corrections are distributed in the GDR data and are based on the inverted barometer formula for the low frequency signal and on MOG2D high frequency analyses for periods shorter than 20 days. For correction homogeneity reasons, the same dynamical atmospheric correction must be applied to the tide gauge data, but it is not available at the *in situ* locations.

Consequently, we chose to use the global configuration of the TUGO 2D model which is available at LEGOS. The model solutions can be extracted at each altimeter point and cycle, as well as at each tide gauge time of measurement.

For this study, the configuration of the TUGO model used the high resolution global grid (the same as used by CNES to compute the GDR products) and ECMWF 3-hour atmospheric forcing fields. This correction contains the whole model solution, that is to say the low frequency part (which was shown to be really close to the inverted barometer in the Mediterranean Sea, see [DR11]), and the high frequency part, corresponding to phenomena between 1 and 20 days.

The biases were computed with 74 cycles of the Jason-2 mission. They are plotted in Figure 24 for each pass (085, 222 and 009) and for both cases: with and without the TUGO dynamical atmospheric correction.

Table 12: Jason-2 weighted bias at Senetosa for the passes 085, 222 and 009, considering the TUGO dynamical atmospheric correction.

Weighted bias (cm)	Jason-2 cycles 1 to 74 with no dynamical correction		Jason-2 cycles 1 to 74 with TUGO dynamical correction	
	Mean	Std	Mean	Std
Pass 085	17.4 ± 0.4	3.4	17.6 ± 0.4	3.3
Pass 222	17.5 ± 0.3	2.6	16.9 ± 0.3	2.5
Pass 009	15.7 ± 0.4	3.3	16.1 ± 0.4	3.2
Regional mean bias	16.9 ± 0.4	3.1	16.9 ± 0.4	3.0

Table 12 and Figure 24 show that the impact of the dynamical atmospheric correction is weak for the pass 085. Indeed, there is no significant change in the bias when using the correction on this pass, except for the cycles 38 and 48, where, respectively, an augmentation and a diminution of the bias can be seen, which probably correspond to local atmospheric events (wind blows for example). Concerning the pass 222, it appears that the correction induces a global diminution of the bias, leading to a mean decrease by 0.6cm (Table 12). The temporal effect of the correction is clearly visible in the case of the pass 009, with variations of several centimetres at the various cycles, resulting in an increase by 4mm in the mean bias. The ocean dynamics is probably more different at the crossover point between the passes 009 and 222 than at the crossover point between the passes 085 and 222, compared to the dynamics at the Senetosa calibration site.

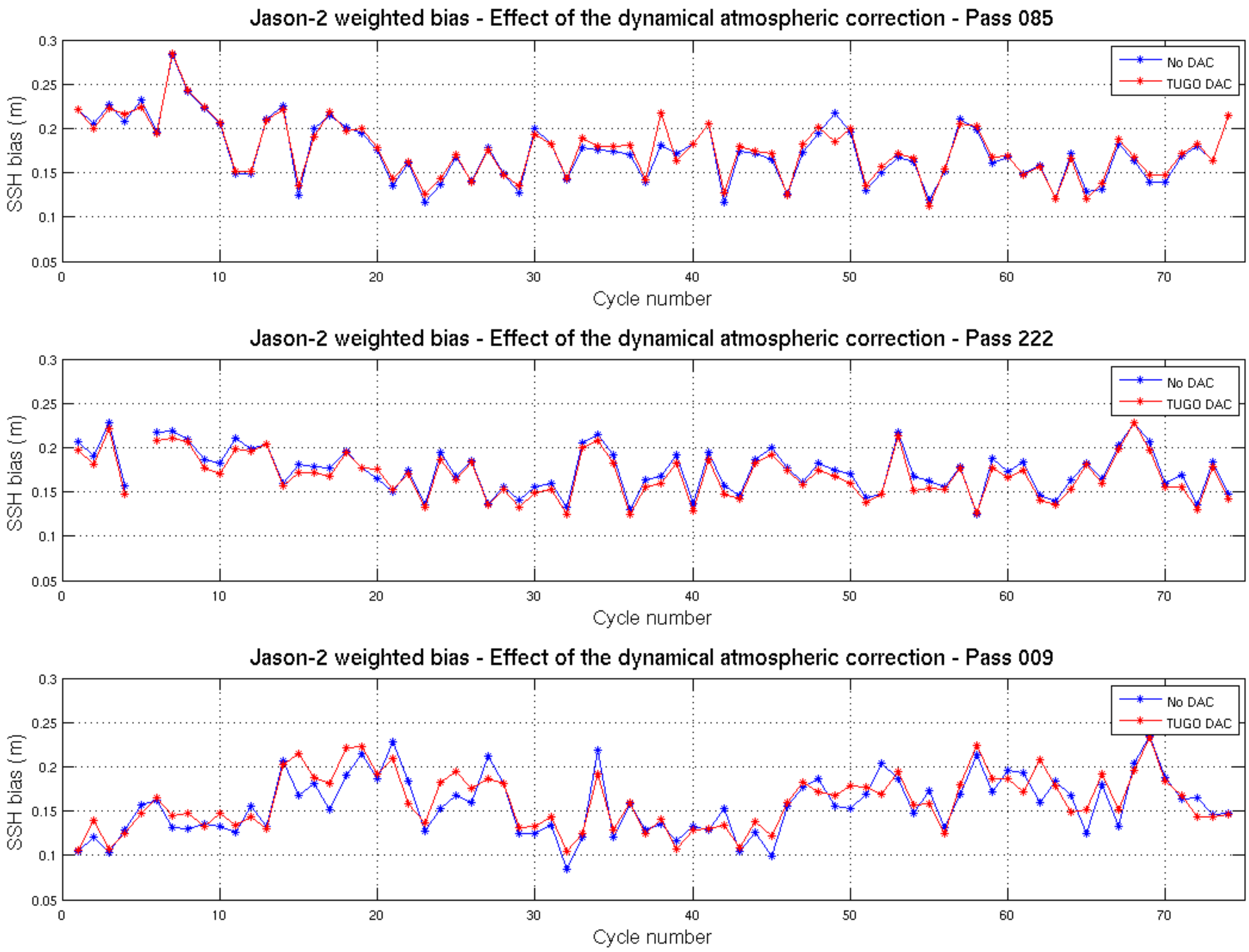

Figure 24: Jason-2 bias using the TUGO dynamical atmospheric correction or not, for the passes 085, 222 and 009

The wind and pressure effects on the sea surface height partially explain the lower bias on the pass 009. It should also be kept in mind that the sum of the MSS differences at the crossover points used to compute the bias on the pass 009 reaches 0.8cm. Finally, part of this discrepancy between the pass 085 and the others may be due to the fact that the altimetry data are of lower quality near the coast, which may induce a higher bias estimation.

It is also interesting to notice that the regional mean bias is not impacted by the application of the DAC. More precisely, the scattering of the bias estimates computed on the various passes using the DAC is smaller (0.7cm) than when no DAC is applied (1.0cm). This result is consistent with the conclusions of Jan *et al.* ([DR1]) who showed that within 200km from the calibration site, the ocean dynamics was not very different for periods up to 20 days (what is seen by Jason-2 as "aliased"). The fact that they could not see any difference in the bias for pass 009 can be explained by the higher spatial and temporal resolutions of the TUGO model, compared to the MOG2D version in 2003. The ocean dynamics phenomena are probably better resolved with this new configuration of the model.

Both the tide and the dynamical atmosphere corrections have impacts of a few millimeters on the bias estimates at Senetosa. Neither of them totally explains the discrepancy in the bias between the offshore pass 009 and the coastal passes 085 and 222. Nevertheless, these corrections should be applied when computing the bias, especially when considering remote passes or more dynamic regions.

5. Conclusions and recommendations

The main conclusions and recommendations resulting from this NOVELTIS study are:

1. **CALVAL site: in situ data**

The redundancy of tide gauge data, the investment in the instrument maintenance, and the data quality checking are of prime importance in order to obtain valuable measurements for the altimeter calibration, since we reach a sub-centimeter accuracy. The fact of maintaining instruments at sea is challenging.

2. **Bias estimates**

The NOVELTIS Jason-1 and Jason-2 bias estimates are coherent when using either the absolute or the regional calibration methods, even if some differences between the coastal and the offshore passes still remain unexplained for the moment. Moreover, they are consistent with the bias results obtained by the various groups involved in absolute calibration. All these bias estimates present a maximum difference of 3cm. Though, a rigorous statistic test may help on concluding whether the results obtained at the various sites by different methods are statistically equivalent, given their respective dispersions. The variety of calibration sites provides robustness to the absolute CALVAL approach, by mitigating the impact of local systematic errors (e.g. tide gauge leveling, geographically correlated error).

3. **Advantages of the NOVELTIS regional method**

The regional method has three main advantages compared to the purely local approach:

- It increases the precision of the bias estimation;
- It enables to estimate the altimeter bias far from the calibration site;
- It allows the assessment of interleaved orbits and, more generally, of other missions flying on orbits for which the calibration site has not been designed.

It should also be noted that this method can be adapted to exploit the times series of the other in situ CalVal sites (Harvest, Bass Strait, Gavdos).

4. **Sensitivity studies**

The sensitivity studies provide recommendations concerning the choice of corrections or parameters when several are available. The protocol applied can be exploited also for other corrections (e.g. wet troposphere corrections, ionosphere correction, MSS in coastal zones, tide models).