LOCAL MARINE GEOID VARIATIONS AND JASON-2 BIAS DETERMINATION USING THE GAVDOS PERMANENT CAL/VAL FACILITY

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ABSTRACT

This work outlines how changes in steep bathymetry (from 200 m to 3500 m depth over a distance of 10 km) are reflected on the determined sea surface anomalies at the Gavdos site used for satellite altimeter calibration. After almost 4 years of Jason-2 calibration activities, it has been observed that in some calibrating regions, south of Gavdos Cal/Val, and along the Passes No. 018 and No. 109, certain features in the produced bias showed a permanent characteristic that required further explanation as to its causes. Some of these features seem to be related to the general oceanographic circulation, but others are related to under-sampling of the Earth's gravity field due to the resolution of the geoid model. New reference surfaces for calibration have thus emerged. Finally, new updated values for the Jason-2 altimeter bias have been determined as 191.81 ± 2.80 mm with the geoid model and as 181.51 ± 2.73mm when using the altimetric Mean Sea Surface model.

1. INTRODUCTION

The location of Gavdos island, in the center of East Mediterranean, constitutes a strategic point for satellite calibration on a world level, and also for monitoring absolute sea level and climate change on a continuous and long-term basis [3, 4, 6].

The Gavdos facility is, the only Cal/Val site in the world, situated under a crossing point of the Jason orbits and adjacent to the orbits of Envisat and subsequently of the future SARAL/Altika (Fig. 1). It is equipped with tide gauges, permanent Global Navigation Satellite System (GNSS) receivers, meteorological instruments, a DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite; [10]) satellite beacon (Fig. 2), an electronic microwave transponder (a new one is ready to be deployed) (Fig. 3 and Fig. 11), communications systems for the transmission of data, etc.

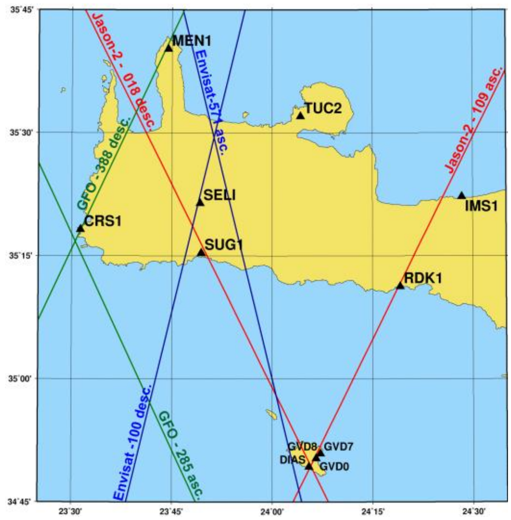

Figure 1 The ground tracks of Jason satellites, GFO, Envisat and AltiKa around Crete and Gavdos islands. The locations of the permanent GNSS sites in Gavdos (GVD7, GVD8 and GVD0) and in Crete (RDK1, SUG1, CRS1, SEL1, TUC2, IMS1) are also shown.

In this paper, the relation of the Jason-2 calibration results from the Gavdos permanent facility, with the steep bathymetry, the used marine geoid models, and the local sea level trends are investigated. Different reference surfaces have been used for this investigation. These refer to (1) a local but detailed geoid model, (2) a mean sea surface model, as determined locally by all available 20-year altimetry data in the region, and (3) the sea level height as produced by several dedicated boat and GPS buoy campaigns, taken place along the Jason-2 satellite ground tracks and south/north of Gavdos. Comparative results of calibration tests with distance from the coast and against all available models and surfaces are presented. Values for the Jason-2 altimeter bias as well as the wet troposphere delays are determined.

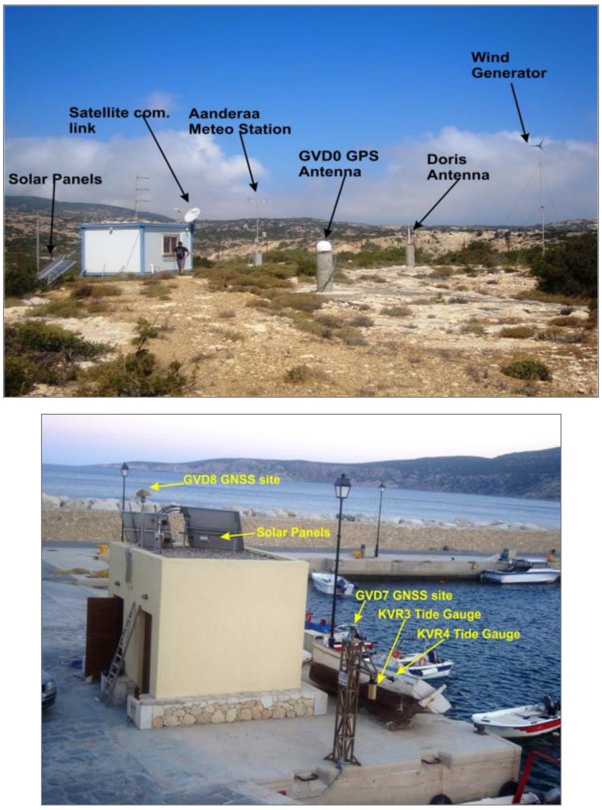

Figure 2 The main facility with its instrumentation setting, called "Theophilos" in Gavdos and the calibration site at the harbor.

2. ALTIMETRY BIAS AND BATHYMETRY

The Gavdos calibration site has determined the absolute bias for Jason-2 [5] over the ascending Pass No. 109 and the descending Pass No. 018 as of its launch. Fewer cycles have been calibrated along pass No. 18 because the altimeter was switched from sea surface to a calibration mode to track the transponder on Gavdos at 200 m elevation [2]. The absolute altimeter bias has been estimated in the Ku-band over a region south of Gavdos and along the ascending Pass No. 109 and the descending Pass 018 in the area carefully selected to avoid land contamination effects.

To investigate the relationship of steep bathymetry and their influence on the produced calibration values for Jason-2, the calibration region, south of Gavdos, has been divided into small windows of width 150m (see Fig. 3). Then, the median of altimeter biases determined for all cycles and contained in that window size has been calculated.

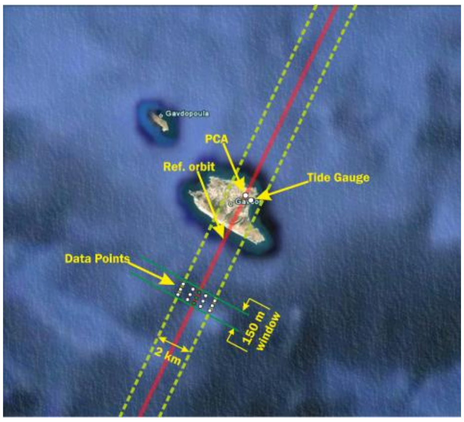

Figure 3 The median of all altimeter calibration values, contained in the data window of width 150m, shown above, has been calculated for all cycles, south of Gavdos in the open sea for Pass No. 109 & No.18.

These median values have been plotted against the distance from the point of closest approach (PCA) and compared with the bathymetry, and the geoid model as well as the MSS reference surfaces used for calibration. In that way we would like to investigate and provide answer to the following questions: (1) Is there any systematic trend in altimeter bias over all cycles? (2) Is the steep bathymetry causing any problems in calibration? (3) Is the resolution of the geoid good enough to reflect steep bathymetry changes? (4) Is there any relation of biases with bathymetry in the region? (5) Can an MSS reference surface, as the one described in Section 3.2, act better than the geoid model for calibration? (6) Are the applied altimetric reductions/corrections in the measurement causing any trends in the altimeter bias? And, finally, (7) Can we correct reference surface deficiencies (i.e., geoid model) by boat campaign, GPS buoys, as the ones outlined in the previous Section?

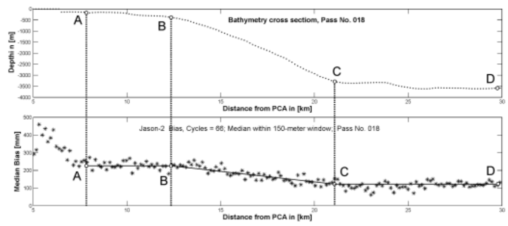

Figure 4 Comparison between the median values of produced altimeter biases and steep bathymetry changes along Pass No. 18, south of Gavdos. The distance shown is from 5-30 km from PCA.

Fig. 4 shows the median of calibration values, for all satellite cycles, with respect to distance from the point of closest approach and along Pass No. 18, south of Gavdos. Note that an instrument offset in Gavdos has been recently discovered and all altimeter bias values may not reflect the actual number, as previously published for Gavdos Cal/Val [3, 4]. So, the results of this Section are focused on the ocean floor topography and their relation to the nuances appeared on the altimeter biases as a function of distance.

It can be seen from Fig.4, that from point A (7.5 km) to point B (12.5 km), the bias values follow a horizontal line. The bathymetry over that region is not that sharp and the used geoid model has reflected this accurately. From point B to point C (a distance of ~10 km or ~6 arcmin), however, the depth changes steeply from about 300m to 3200 m. The gravity data used for the gravimetric geoid do not seem to accurately reflect this abrupt change in the bathymetry due to the resolution of the gravity data used for its development. Accordingly, the bias values indicate a slope of a few cm over that distance of 10 km, approximately. So the geoid model needs to be refined over that region and along Pass No.18, from B to C, with the inclusion of more input data. Finally, the last region from C (about 22 km) to D (30 km) seems to be horizontal for the bias values over all 66 satellite cycle calibration. So, the geoid resolution is adequate for altimeter calibration over that last region.

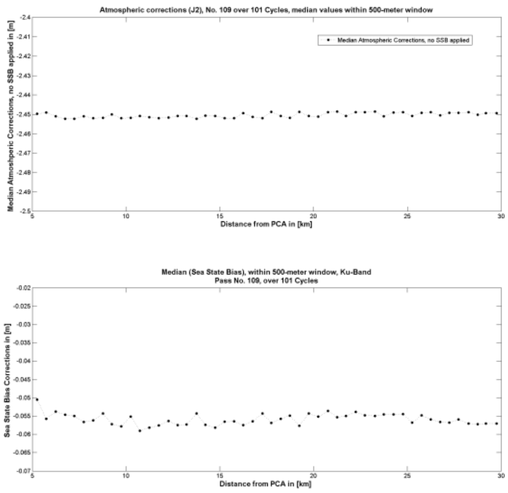

Figure 5 Comparison between the median values of the applied atmospheric corrections and SSB onto the altimeter measurements of Jason-2, over 101 cycles, along the Pass. No. 109, south of Gavdos.

All reductions in the altimeter measurements, such as the atmosphere, SSB corrections, etc., have also been examined to see whether they are producing any systematic trend in the altimeter bias. Fig. 5 shows the median values for the atmospheric corrections, the atmospheric corrections individually and in combination with the SSB, as well as the SSB corrections alone, with respect to distance from the PCA. The SSB corrections have been investigated, because this term has the largest contribution in the altimeter reductions and it is modeled empirically. All other contributions arising from atmospheric corrections have been examined, as well. No systematic trends were discovered over those 3.5 years of altimeter calibration at the Gavdos Cal/Val. Their variation was of the order of 1-2 cm and no systematic trend appeared over the cycles of Jason-2.

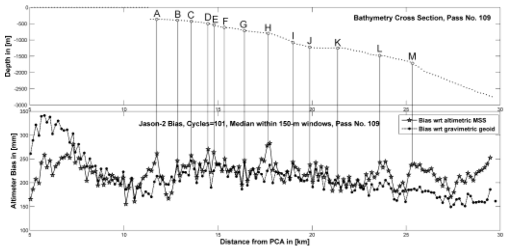

Figure 6. Comparison between the median values of determined altimeter biases and steep bathymetry changes with respect to the altimetric MSS and the geoid model along Pass No. 109, south of Gavdos.

Fig. 6 shows a similar to Fig.5 plot, but now along the ascending Pass No. 109, south of Gavdos. The values shown are the median values across the cycles of Jason-2, and with respect to the altimetric MSS using 20 years of altimeter data [1], as well as the gravimetric geoid model [7, 8, 9] as reference surfaces for the calibration. Bathymetry values for less than 12 km were not available, so they are shown as a horizontal line at zero depth in Fig.6. Also, bias values less than 12 km from the PCA could not be considered reliable, because the Gavdos land contaminates the Jason-2 measurements (about 5 km from the coast).

By examining the median bias in relation to bathymetry cross section as a function of distance from PCA, the following points could be observed along Pass No. 109: (1) The altimeter bias clearly reveals even small changes in bathymetry slope (see for example points B, C, D, E, F, etc.). This is more pronounced when the altimetric MSS model is used as reference surface. That indicates that the sea surface definitely maps the ocean floor topography and responds with 1-3cm changes, something expected since it is based on the original along-track data from T/P and Jason-1 in the region; (2) The bias, using the gravimetric geoid model, exhibits a systematic slope in some calibration regions (for example, see the region from 14 km to about 20km, and after Point E at 21 km till 30 km). On the other hand, the bias trend referenced on the altimetric MSS is still almost horizontal across the calibration region; (3) the change in bathymetry slope from E to F has not been reflected by the geoid model (the biases using the geoid show a slight slope in that region); (4) Biases show a resemblance in their behaviour across the distance either when using the gravimetric geoid or the local altimetric MSS as reference. That corroborates that the ocean floor topography is directly portrayed on sea surface, because in reflects what the Jason-2 altimeter measures within 101 cycles; (5) both biases show a kind of a bulge in the sea surface of a few cm at a distance of about 15 km from PCA. This ocean feature is always observed in the Jason-2 range given by the GDR in almost all cycles and may be compatible of the general ocean circulation of the Mediterranean (westward flow south of Crete with velocities of 0.4-0.5m/sec); (6) there seems to be a geoid slope from about 14km to 21km. Its slope was computed by fitting a least-squares as well as a robust regression line. That slope value was determined to be about 3.1cm over 10 km (slope = a= −3.1X10−6).

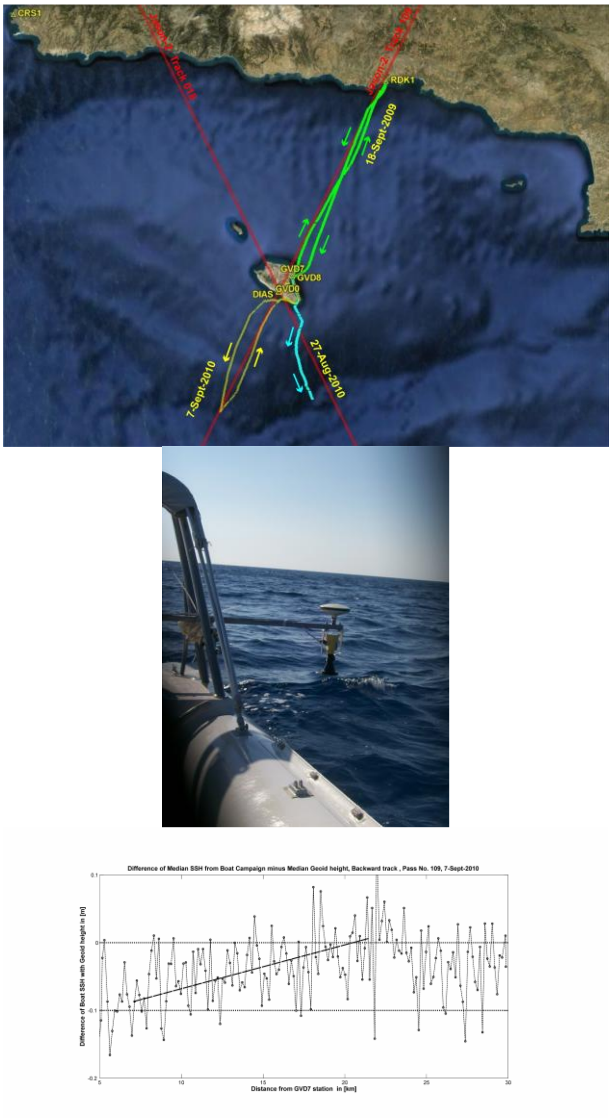

Figure 7. Comparison between the median values of determined altimeter biases and steep bathymetry changes with respect to the altimetric MSS and the geoid model along Pass No. 109, south of Gavdos.

Fig. 7 shows the cross section of the observed sea-surface height, as determined with the GPS and the tide gauge during the boat campaign, on 7-Sept-2010, along Pass No. 109, south of Gavdos. The cross section of sea surface with respect to distance from the permanent GPS site, GVD7, on Gavdos, corresponds to the return track of the boat to Gavdos harbour (see also Fig. 7). Values of differences have been computed as median within a non-overlapping window of width 150 meters. The size of the window length of 150m is arbitrary, and various lengths tested. However, this 150m size gave detailed result for the trends. That boat campaign has followed a very close track to the mean reference orbit of Pass No. 109.

It can be seen that from 10 km to about 22 km, the geoid seems to have a systematic sloped trend with the sea surface as measured on that day of Sept 2010 (a snapshot of sea surface with the boat campaign). The slope of that trend was again computed by fitting a robust regression line to these difference values of SSH(GPS) minus the gravimetric geoid height. It was found to be 3.28cm over 10km distance (slope=a= $+3.28X10^{-6}$). This value coincides with the previous value already described in the earlier paragraph for the altimeter bias trend (i.e., 3.1 cm over 10 km). Therefore, the gravimetric geoid over that region from 10km-20km has to correct its slope by an amount of 3cm over 10km distance.

Resemblance of peak values of boat SSH with the altimeter bias, determined with the altimetric MSS reference surface, is amazing. That means that the sea surface is directly related, at cm level, with the ocean floor topography below.

The new altimetric/gravimetric geoid model, improved with the altimetric data has been applied and shown in Fig.8, for Pass No.18 and Pass No.109. Most of the deficiencies in the previous gravimetric geoid model have thus been circumvented. It is now obvious that the previous slopes in the new altimetric/gravimetric geoid have been reduced and that this outcome quantifies the geoid improvement and local altimetric MSS applied.

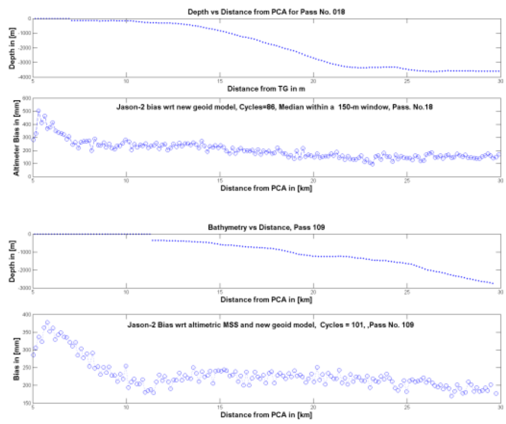

Figure 8. (a) The bias of the Jason-2 altimeter

computed over 86 cycles, using Pass. No. 18, and the new geoid with the integration of the altimetric geoid. (b) The bias of the Jason-2 altimeter computed over 101 cycles, using the Pass. No. 109, with respect to distance from PCA and the altimetric MSS as well as the new altimetric/ gravimetric geoid improved with altimetry data.

3. CONCLUDING REMARKS & ALTIMETER BIAS FOR JASON-2

Along the ascending and descending Jason-2 orbits, south of Gavdos, the weak areas and short-wavelength features in the calibrating regions, have been brought up. This led us to investigate further and analyze how these altimeter biases were correlated to bathymetry, gravimetric geoid, applied altimeter corrections /reductions, mean dynamic topography, etc. Altimeter biases, for example, as a function of distance from PCA were systematically higher (1-3 cm) at certain locations, lower at others, but also exhibiting a slight slope at other parts. Sharp variations in the topography of seafloor in the area (from 300m depth to 3200m over 10 km along Pass No. 018, and from 200m to 1500m over 12 km along Pass No. 109) had to be examined if they were reliably portrayed in the used geoid model. Also ocean dynamic features south of Crete had to be evaluated.

Problematic locations in the reference calibrating surfaces have been corrected by improving the used geoid models with the inclusion of additional input data in the processing. New improved altimetric/gravimetric geoid models, as well as a local altimetric MSS model, have thus emerged.

Based on these updated reference surfaces, new updated values for the Jason-2 altimeter bias have been determined (Fig. 9) using 144 cycles. The mean value for the bias when using the marine gravimetric geoid has been determined as 191.81 ± 2.80 mm. On the other hand, when using the altimetric Mean Sea Surface the bias was computed as 181.51 ± 2.73 mm. Also, the wet troposphere delays as determined by the satellite radiometer have been compared against these values as determined by the dedicated GPS network established on Gavdos. The values have been estimated to be: -7.48 ± 4.5 mm (satellite radiometer-GPS) along Pass No. 18, and -6.27 ± 4.7 mm using Pass No. 109.

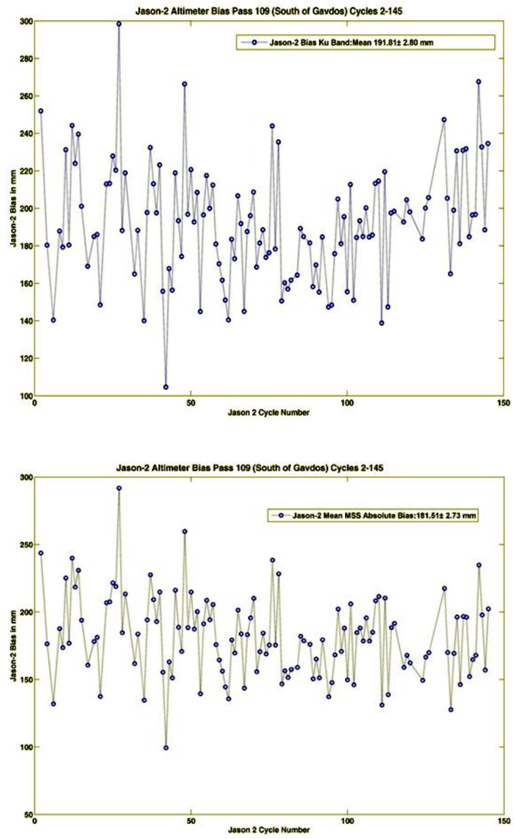

Figure 9. The bias (mean value 191.81 ± 2.80mm) of the Jason-2 altimeter computed over 144 cycles along Pass No. 109 and using the improved marine gravimetric geoid (upper diagram). (b) The bias values (mean value 181.51 ± 2.73mm) for the same cycles, but now based on the Mean Sea Surface as produced by 20 years of altimeter data on the region (lower diagram).

Regarding future work, preparations are under way, at the moment, for the calibration of the Chinese satellite HY-2 using the CRS1 site on the west Crete (Fig.10). Also, a new microwave transponder has been constructed by the Technical University of Crete under the guidance and specifications of ESA. Full calibration and characterisation of this transponder has been completed during March-June 2012 at ESTEC/ESA In the Netherlands. The operating frequency of this transponder is 13.575 GHz and its bandwidth is 350 MHz. The transponder has now returned from ESA to Crete and is ready for calibration measurements of the altimetric satellites Cryosat-2, Jason-2, Sentinel-3 and HY-2.

Figure 10. The descending Pass No. 280 of the Chinese altimetric satellite HY-2 in west Crete. The calibration site CRS1 has been prepared for the calibration of this satellite. The IGDR data have already received for Cycles No. 19-22; (19 June-14 Aug, 2012) have been received and preparations are under way for providing the first HY-2 altimeter bias results.

Figure 11. The newly developed transponder of the Technical University of Crete at the European Space Agency, where it is tested and calibrated in the Compact Payload Test Range facilities in ESTEC/ESA, the Netherlands

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