

Calibration of satellite radar altimeters at Gavdos Cal/Val facility using three different methodologies.

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ABSTRACT

The dedicated calibration site for satellite radar altimeters in Gavdos has been operational as of 2004. Its geographical location (crossover point for No 109 ascending and No. 18 descending passes) and the fact that altimeter's measurements are not significantly contaminated by land, make Gavdos an ideal place for calibration of satellite altimeters like Jason 1&2 missions.

This paper presents the results for the determination of Jason-2 altimeter bias, using the standard technique by comparing sea level anomalies between the satellite and the in-situ observations, an alternative technique by referring measurements to the Mean Sea Level of CLS01_MSS. A third attempt has been made to calibrate with a microwave transponder placed at an elevation of about 200m at the cross-over point on Gavdos.

1. INTRODUCTION

Satellite altimetry provides the means for studying the sea level change which is vital in global climate change studies. Today, there are several altimetric satellites in orbit, such as Jason 1&2, ERS and EnviSat, CryoSat-2, as well as the future ones of Sentinel-3, SARAL/AltiKa, HY-2, to mention a few. The expected operational period of these missions does not commonly exceed 5 years (i.e., ERS-1 from July 1991 to June 1996) even if some missions have been extremely successful providing data for more than 10 years (i.e., Topex/Poseidon from August 1992 to January 2006, Jason-1 from December 2001 to present).

In order to be able to interconnect measurements from these missions and obtain measurements of homogenous quality and rigorous reliability, the scientific community and stakeholders developed several mechanisms that ensure the fulfillment of some quality indicators. Such a mechanism is the development of dedicated facilities that provide calibration and validation of satellite altimetric missions. This is the process of quantitatively defining and comparing the altimetric system's measurements with known and controlled signal inputs, determined by independent means. The possible sources of error (the sea state bias, wet tropospheric path delay,

marine geoid, tides, geographically correlated errors, etc.) are accurately measured as well.

The dedicated Cal/Val research infrastructures have been used, to consistently and reliably determine (1) the absolute altimeter biases and drifts for each of these various satellite altimeters and (2) the relative biases among missions. The main objective is to calibrate the sea-surface height and ancillary measurements made by the satellite as it passes overhead a site, by using observations from tide gauges, GPS receivers, and other sensors directly placed under the satellite ground tracks of the earth's surface.

Today, in the world, there are four such permanent Cal/Val facilities: Gavdos, Crete in Greece, Corsica in France (operated by CNES), Harvest Oil Platform, California, USA, (operated by the Jet Propulsion Laboratory, NASA) and in the Bass Strait, Tasmania, Australia (operated by the University of Tasmania). Altimetric calibration campaigns have been also performed in Ibiza Island, Spain.

This paper presents the work conducted at the Gavdos Cal/Val facility. At first, the fundamental theory and used terms will be given. Afterwards, a description of the Gavdos infrastructure will be provided, while Section 4 describes in detail the standardized methodology for obtaining the absolute altimeter bias. The next two Sections present two alternative techniques that have been examined for Jason-2 bias estimation [1]. Finally, the calibration results and the future plans of the Gavdos facility are presented.

2. PRINCIPLES IN ALTIMETER CALIBRATION

The altimeter on board the satellite generates a signal which is reflected by the sea and recorded again on the altimeter. The time of flight is measured on the satellite altimeter. Depending on the altimetric mission objective, the wavelength of this signals emitted varies (i.e., Jason-2 is C- and Ku-bands, AltiKa is the Ka band). Giving the altitude of the satellite, the Sea Surface Height (SSH (k)) is given as:

$$SSH(k) = \text{Altitude}(k) - \text{Range}(k) \quad (1)$$

where “*Altitude*” is the satellite’s height above the reference ellipsoid and “*Range*” is the distance from the satellite to the surface of the Earth, as measured by the altimeter. This equation is effective for every satellite measurement point.

However, several reductions need to be applied in eqn(1) to correct, mainly, the range measurement. Errors that influence the altimeter measurements are the atmosphere (ionosphere, wet and dry component of the troposphere) and the sea state bias (SSB). Thus, a more precise estimation of the SSH is as follows:

$$SSH(k) = Altitude(k) - Range(k) + [Iono(k) + Wet(k) + Dry(k) + SSB(k)] \quad (2)$$

Finally, the SSH has to be corrected for the tide effects as:

$$Corrected\ SSH(k) = SSH(k) + solid\ earth\ tide(k) + pole\ tide(k) + ocean\ tide(k) \quad (3)$$

All these corrections are provided in the Geophysical Data Records (GDR).

The radiometer has a footprint of about 25-30km while measurements from the altimeter are being influenced by the land as it approaches the coastline. This is another limiting factor for the quality of the measurements that can be used for Cal/Val purposes as the satellite approaches Gavdos.

The SSH is not the quantity that we use to compare satellite measurements with the independent infrastructure on the earth surface. We introduce the sea level anomaly (SLA) as:

$$SLA(k) = SSH(k) - MSS(k) \quad (4)$$

where $SSH(k)$ is the result of eqn.(3) and $MSS(k)$ is the mean sea surface at the point (k). The MSS at a given location (k) is given as the geoid undulation (N) plus the mean dynamic topography (MDT) at this point. Thus, Eqn. (5) gives the SLA at any given point (k).

$$SLA(k) = SSH(k) - N(k) - MDT(k) \quad (5)$$

Absolute calibration is performed by the estimation of the SLA at point (k) by using independent means on the ground. This requires that a water level measuring device (i.e., tide gauge or GPS buoy) is deployed exactly under the satellite’s ground-track, preferably in the open ocean. In the case of Gavdos the basic calibration principle is described in Fig. 1.

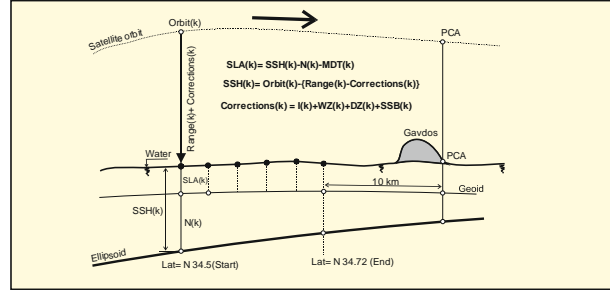


Figure 1. The principle of operation for the calibration of Jason satellites using the Gavdos facility. Black dots correspond to each satellite measurement while white dots are referred to the underlying geoid height.

The SLA at the tide gauge location is given in Eq. 6.

$$SLA(k_0) = SSH(k_0) - N(k_0) - MDT(k_0) \quad (6)$$

The estimate for the absolute bias in the altimetric measurements of Jason satellites is computed as:

$$Bias = Measurement - Truth = SLA(k_0) - SLA(k_0) \quad (7)$$

It is obvious that the accuracy of the bias estimation is strongly related to the accuracy of the determination of the various parameters that are introduced in Eqns. 1-7.

This Section presented the basic theory for the calibration of satellite altimetry missions. The following Section describes the existing infrastructure at the Gavdos Cal/Val permanent facility.

3. GAVDOS INFRASTRUCTURE

Gavdos is a small island south of Crete, characterised by medium topographic relief, and located under a cross-over point for Passes No. 018 and 109 of the Jason satellite mission and adjacent to the Envisat Pass No. 571. Fig. 2 presents the altimetric missions ground track over Gavdos and the permanent GNSS array established over western Crete. Gavdos is the only site in the world that calibration can be performed for ascending and descending passes using the same infrastructure.

The dedicated calibration facility on Gavdos includes tide gauges, permanent GPS satellite receivers, meteorological and oceanographic instruments, a DORIS satellite beacon, a microwave transponder, communications systems for the transmission of data, etc. (Fig. 3&4).

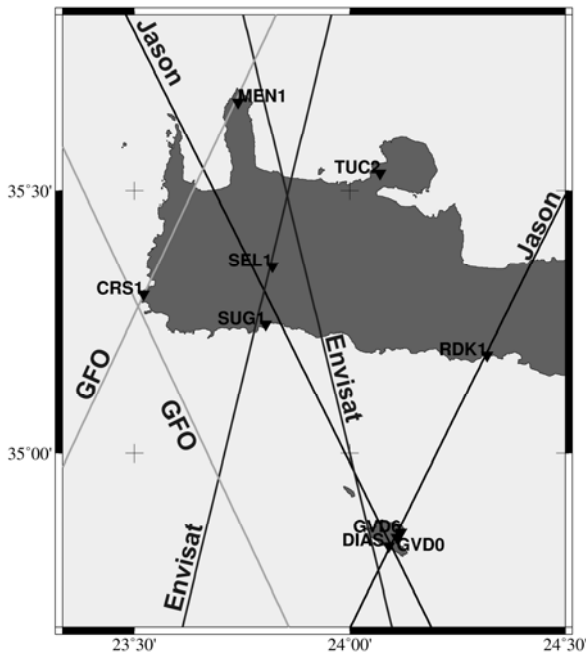


Figure 2. The locations of the continuously operating geodetic arrays (GVD0, GVD6, RDK1, CRS1, TUC2, SUG1, SEL1, MEN1) over western Crete and repeating ground tracks of altimetry missions.



Figure 3. The basic infrastructure of Gavdos dedicated Cal/Val site at the "Karave" port.

To extent and strengthen Gavdos operations, similar facilities have been developed in Crysoskalitissa (CRS1) and Rodakino (RDK1), all on the mainland of west Crete, Greece (Fig. 5). At these sites, tide gauges are collocated with continuously operating GNSS receivers. The array is also comprised of two other GNSS sites located inside the university campus (TUC1 and TUC2), while another three additional GNSS sites are to be installed in the North-South axis of Crete in cooperation with the North Carolina State University, USA (Fig. 2).



Figure 4. the DORIS beacon at the "THEOPHILOS" site (left) and the microwave transponder at the "DIAS" crossover point (right).



Figure 5. The RDK1 (left) and the CRS1(right) sites.

Using this infrastructure, the calibration procedure described in the following section has been used to estimate the Jason-2 absolute bias using sea surface heights.

4. THE CONVENTIONAL CALIBRATION

A standardized technique for the estimation of the Jason-2 altimeter has been developed between Gavdos, Corsica and Harvest platform calibration sites. Certainly, each site has its local characteristics that do not appear to the others. For example at the Harvest platform tide gauge measurements are made exactly under the Jason-2 ground track, while this is not the case for the Gavdos facility. This is why we have to introduce the terms Point of Closest Approach (PCA) and the relative Time of Closest Approach (TCA) which refer to the point (and time) that the satellite is closest to the tide gauge location. Common modeling procedures for the altimetric and radiometric measurements have been adopted in the three Cal/Val sites.

For Gavdos, the ionosphere correction applied for the calibration, is the average of the values given by the GDR and corresponding from $t_1 = -21\text{sec}$ up to $t_2 = -1\text{sec}$ with respect to the TCA. For the dry troposphere, the corrections used is an interpolated value at the point of TCA using a linear fit from $t_1 = -5\text{sec}$ up to $t_2 = +2\text{sec}$. To avoid land contamination to the satellite radiometer, with a footprint for Jason-2 at the order of 25-30 km, we have chosen to apply a linear fit of the produced values

for the wet troposphere from GDR covering a region from $t_1 = -15\text{sec}$ up to $t_2 = -5\text{sec}$.

Finally for the sea state bias, a cubic polynomial has been applied in the area between $t_1 = -10\text{sec}$ up to $t_2 = -1\text{sec}$. All these times are referenced with respect to the TCA where we consider that $t = 0\text{ sec}$.

Based on these fitting models, we calculate the SSH at any point (k) of satellite measurement. For the determination of the SLA at any point (k) we need accurate determination of the geoid and the MDT at the point of interest (Eq. 5). The geoid in the area surrounding Gavdos has been established in 2003 using a variety of sensors and techniques. The application of different geoid models revealed that only a certain area, between 12 and 21 km, south of Gavdos and under pass No.109 can be used, at the moment, for calibration.

The geoid heights above ellipsoid have been recalculated and correspond exactly under the satellite pass. Calculations have been based on a newly compiled gravity database, refined topography and bathymetry models for the evaluation of terrain effects [2] and considering the EGM2008 geopotential model [3] as reference.

The “remove-compute-restore” method has been employed for the evaluation of the final geoid heights along the ground track of Jason-2. The prediction of residual geoid heights has been based on the least-squares collocation optimal estimation method [4, 5]. This resulted in new geoid heights being estimated for the sub-satellite points of Jason-2 south of Gavdos.

The average MDT difference between the calibration site and the satellite pass has been determined by several measurement campaigns to be, on average, at the order of 1cm and is in agreement with the most widely accepted MDT model [6].

After the calculation of the SLA at the satellite location, we have to determine the SLA at the tide gauge location. There, following Eqn. 6, the geoid is known with high accuracy and the SSH is established by the tide gauge measurements. In order to be able to compare the SLA between the satellite measurement and the tide gauge location both SSH's must be referred to the same reference frame.

The SSH at the tide gauge location is determined by processing of the co-located GPS receiver measurements and by applying the corresponding offsets (distance between tide gauge and the GPS antenna reference point) and the water level measurements. The GPS height determination is considered as the most critical element

in Eqn. 6, thus the following Section describes the way that GPS processing was done.

4.1. GPS processing

For the precise determination of the ellipsoidal height at the calibration site, GPS observations have been reduced using double-difference phase measurements. In this study, we have used two different software: GAMIT [7] and Bernese [8]. The processing results are loosely constrained Cartesian coordinates for stations, satellite orbit parameters, as well as their mutual dependencies.

The GAMIT results, from the processed sub-networks, are then combined using QOCA (designed and developed at Jet Propulsion Laboratory, California Institute of Technology, USA), where the reference frame is also realized. This procedure results in daily estimates of positions for all sites, included in the analysis, in a well-defined reference frame.

The GAMIT processing included all the stations installed by the Technical University of Crete on the island of Crete (TUC2 EUREF site, CRS1, GVD0, GVD6, RDK1), all the other EUREF stations in Greece and 14 other EUREF and IGS stations located in Europe and western Asia. Finally, daily solutions (h-files) obtained through GAMIT were combined with the h-files from 8 IGS sub-networks (igs1, igs2, igs3, igs4, igs5, igs6, emed, eura) using the QOCA package, to obtain station positions and velocities in the ITRF2005 reference frame. The same procedure has been applied in the Bernese processing.

The coordinates of the GPS array and the corresponding uncertainties are given in Tables 1 & 2 while the site velocities in the ITRF2005 frame are given in Table 3.

Table 1. The ITRF2005 Geodetic Coordinates of the TUC-Net sites (Reference Epoch 2009.0).

Site	Latitude (N)			Longitude (E)			Ell. Height (m)
CRS1	35	18	12.650626	23	31	17.262681	21.2044
GVD0	34	50	18.580122	24	6	31.906601	123.8775
GVD6	34	50	54.198510	24	7	6.926229	20.2237
GVD7	34	50	52.746275	24	7	11.204109	20.1467
RDK1	35	11	15.377346	24	19	6.538132	25.5530
TUC2	35	31	59.484441	24	4	14.013629	160.8997

Table 2. The position uncertainties of the TUC-Net sites.

Site	East Bias (mm)	North Bias (mm)	Vert. Bias (mm)
CRS1	0.085	0.080	0.336
GVD0	0.057	0.054	0.220
GVD6	0.167	0.173	0.784
GVD7	0.376	0.368	1.640
RDK1	0.446	0.429	1.978
TUC2	0.057	0.053	0.213

Table 3. The XYZ (ITRF2005) Velocities of the TUC-Net sites (Reference Epoch 2009.0)

Site	Vx (mm/yr)	Vy (mm/yr)	Vz (mm/yr)
CRS1	4.249±0.569	9.821±0.310	-7.776±0.440
GVD0	3.790±0.178	10.588±0.099	-9.943±0.137
GVD6	3.039±0.850	8.548±0.450	-14.053±0.658
GVD7	0.491±1.818	5.237±0.940	-7.578±1.367
RDK1	1.050±2.999	11.701±1.655	-14.892±2.308
TUC2	3.804±0.166	10.144±0.093	-9.607±0.130

Giving the SSH at the tide gauge location and the precise geoid height above ellipsoid for this point, the SLA can be determined and compared with the $SLA(k)$, resulting the absolute altimeter bias.

Detailed description on the conventional technique can be also found in [9].

5. THE CLS01_MSS CALIBRATION TECHNIQUE

For a given satellite pass, each cycle has different latitude - longitude measuring points because the satellite is allowed to drift by ± 1 km. This introduces a cross-track geoid gradient on different cycles.

The pass No. 018 ground track, south of Gavdos, is characterised by major underwater tectonic feature at the subduction zone, as shown is Figure 6. In order to be able to cross-check the given geoid height over that area, GeoMatLab followed the procedure given at the OSTST/Jason-2 Product Handbook, 2009 for the determination of the SSH difference between two dates (Fig. 7)

Initially, we have applied this MSS calibration technique for the Pass No 109 and compared the results determined by the previous conventional technique. For that reason, a reference track has been established as the average of the satellite measurement points over the 58 cycles of this study.

For every cycle and for every measurement point, (k), the $SLA(k)$ is calculated as the difference between the corrected $SSH(k)$ (Eqn. 4) and the $MSS(k)$ as provided by the CLS01 MSS model. Similarly, we have estimated the $SLA(k_0)$ at the tide gauge using, again, the CLS01_MSS model. Thus, the altimeter bias for every measuring point (k) on the sea surface has been determined. Then, we have interpolated these biases to the reference track using a 3rd order polynomial. The Jason-2 altimeter bias for cycles 2-60 has been determined using the same area (12 to 21 km south of Gavdos) for Pass 109.

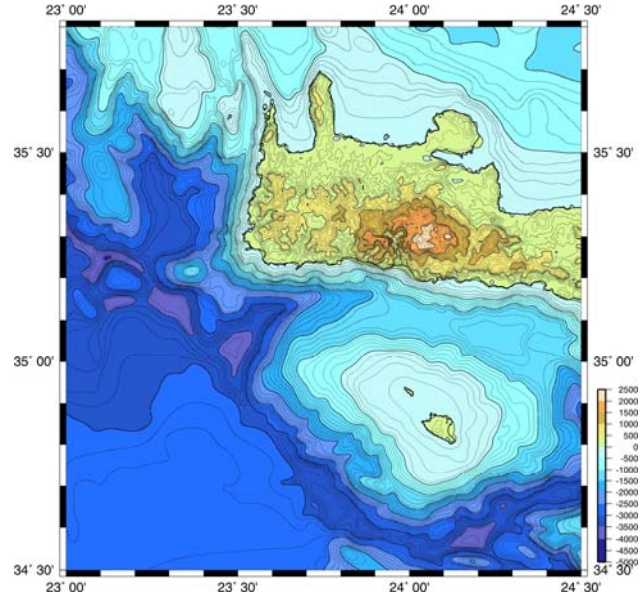


Figure 6. Gavdos bathymetric map. Source:(personal communication Dr. S. Alexandri, Hellenic Centre for Marine Research).

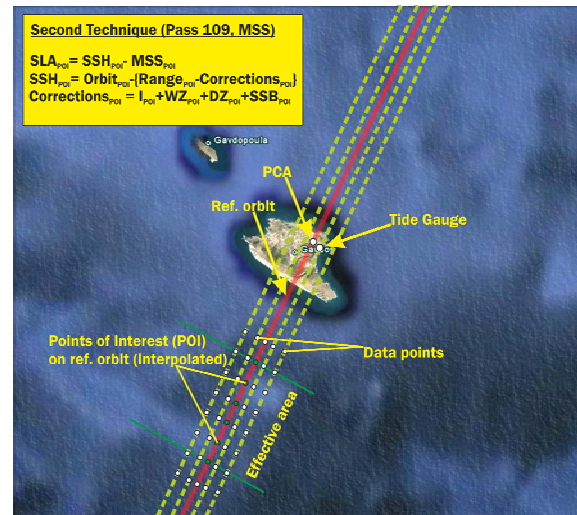


Figure 7. The CLS01_MSS alternative technique for Jason-2 bias estimation.

5.1. Field campaign for geoid values validation

A kinematic GPS field survey has been performed on the 18th September, 2009, for the determination of the SSH under Pass No. 109, north of Gavdos. For that reason GeoMatLab hired a boat and installed there a GPS receiver and a device to measure the water level with respect to the GPS antenna reference point. Thus, the sea surface height above the reference ellipsoid could be determined since all offsets had been determined with mm accuracy (Fig. 8). Both instruments logged data at the same sampling rate (2 seconds).



Figure 8. The kinematic GPS field survey, north of Gavdos and on Pass No. 109 ground track.

The GVD7 site was also set to record data at 2-sec rates and used as the reference station for the kinematic processing. The results were then cleaned from outliers (both GPS heights and water level measurements). We then compared the SSH as produced by the GPS processing with the geoid heights for the same points. Figure 9 shows the compatibility between the SSH and the geoid model. A comparison between the GPS-derived height during the field campaign and the geoid model gave an average discrepancy of about 1.38 cm (Fig. 10).

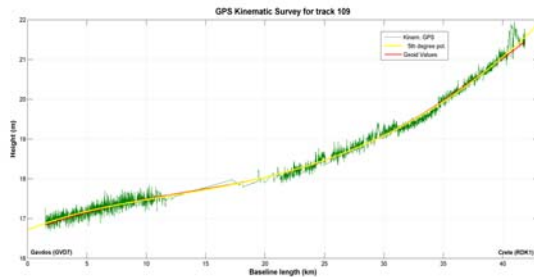


Figure 9. The SSH vs Geoid model heights for Pass No.109, north of Gavdos.

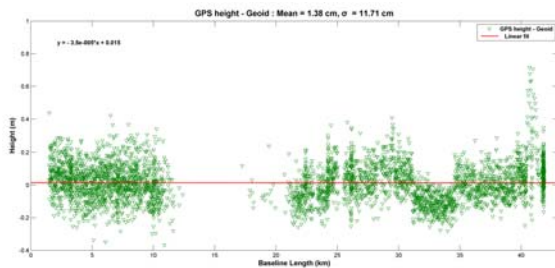


Figure 10. The SSH - Geoid values for Pass No. 109 north of Gavdos.

6. THE TRANSPONDER EXPERIMENT

An alternative and independent technique of altimeter calibration can be performed by means of dedicated microwave transponders. The principle of a transponder is to receive, amplify and retransmit with minimal distortion a satellite radar altimeter pulse which is emitted and recorded again on-board the satellite. A transponder deployed accurately beneath a satellite's pass mirrors the radar echo. It can thus serve as a well-defined point of reflection. The measure of the pulse's two-way travel-time yields the range between satellite and transponder. The Space Research Institute of the Austrian Academy of Sciences (SRISG) and GeoMatLab established a transponder site at DIAS, the crossing point of the Jason satellite's ground tracks on Gavdos.

Fig. 11 shows 1 Hz-calibration data of Jason-2 for both C-band and Ku-band measured on Nov. 12, 2009. This campaign has been in coordination with CNES, France.

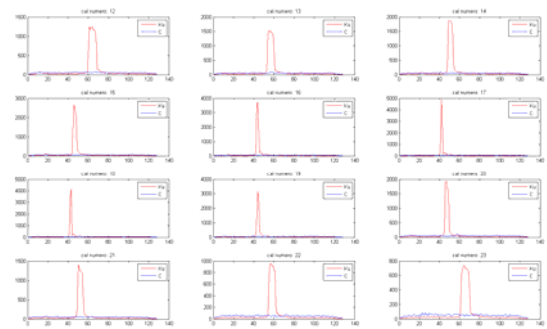


Figure 11. Series of 1-Hz calibration data of Jason-2 for C-band (blue), Ku-band (red); calibration performed on Nov. 12., 2009.

Fig. 12 shows the Ku-band calibration data of the above mentioned pass both as 2D- and 3D plots. The transponder signature can easily be identified and analyzed. The actual distance between the satellite and the transponder deduced from the radar pulse's travel time is then corrected for the propagation effects from the dry and wet part of the troposphere and of the ionosphere. Geophysical corrections, e.g., solid Earth and tides affecting the range have to be applied as well. The horizontal offset of the satellite's ground track from the transponder position can be determined from the satellite orbit.

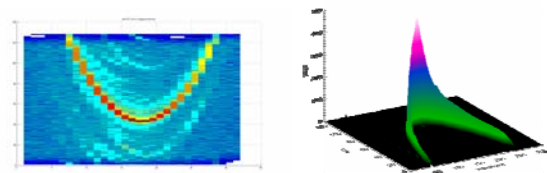


Figure 12. Ku-band calibration data showing the strong transponder signals in 2D (left) and 3D (right) calibration.

7. RESULTS

Through GPS processing, it is possible to calculate the ionosphere delay as well as the wet and dry troposphere component during altimeter calibration. Fig. 13 gives the differences of the ionosphere and wet troposphere corrections as produced by the GDR's and the GPS data processing.

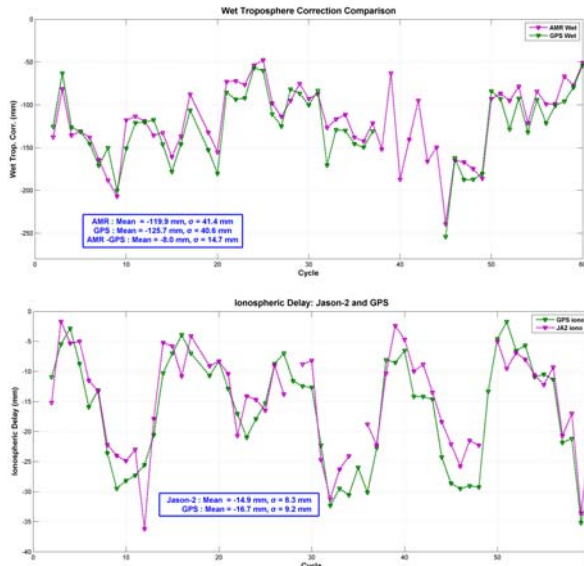


Figure 13. Ionosphere (bottom) and wet troposphere (top) corrections as produced by GPS processing and the GDR.

The Jason-2 absolute bias using the conventional technique has been determined for Pass No. 109 and cycles: 2-60. Fig. 14 gives this altimeter bias for every cycle. This results to a mean altimeter bias of $+18.67 \pm 5$ cm in the Ku-Band and $+17.99 \pm 7$ cm for the C-Band respectively. Using the alternative CLS01_MSS technique and for the same GDR data, the altimeter bias has been estimated to be 15.98 ± 0.2 cm

The results of the transponder experiment for Pass 018 are currently being analyzed in cooperation with CNES and will further be processed.

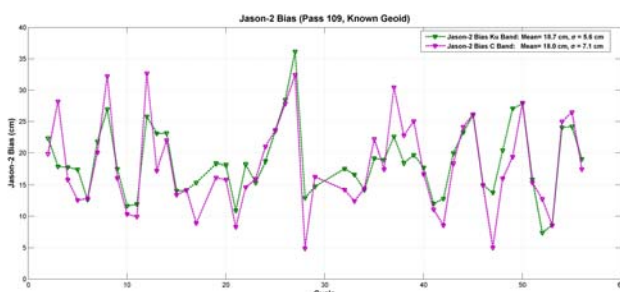


Figure 14. Jason-2 absolute bias for Pass No. 109, Cycles 2-60.

8. CONCLUSIONS

The analysis conducted so far at Gavdos Cal/Val facility gives that the conventional technique gives the most accurate and reliable results for Pass 109. Additionally, the preliminary results for the CLS01_MSS technique indicate the results obtained give a comparison of Jason-2 with the Topex/Poseidon. By the time of this writing a new model for the MSS, i.e., MSS_CNES_CLS_10, has been released.

Future plans include the following activities:

- Ionosphere and wet troposphere corrections delivered by the GPS data analysis will be introduced and incorporated to the applied Cal/Val methodology;
- The MDT between the tide gauge location and the satellite measuring area will be determined with dedicated field oceanographic campaigns;
- The SSH along pass No. 018, south of Gavdos, will be determined using kinematic GPS surveys;
- The SSH along Pass No. 018, south of Gavdos will be determined with GPS buoy campaigns simultaneously with the satellite measurements;
- Inclusion of the north part of Pass No 109 and use of RDK1 tide gauge data in the standardized methodology will be performed.

Acknowledgements. This work has been supported by the FP7-REGPOT-2008-1, Project No. 229885 (SOFIA), sponsored by the European Commission. Dr. Nicolas Picot and Dr. Jean-Damien Desjonqueres of CNES, France are thanked for their help and support.

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