Recent developments for the estimation of the altimeter bias for the Jason-1&2 satellites using the dedicated calibration site at Gavdos

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ABSTRACT

The dedicated calibration site for satellite radar altimeters in Gavdos has been operational as of 2004. The small island of Gavdos is located along a repeating ground track of Jason satellites (crossover point No 109 ascending and No. 18 descending pass and adjacent to Envisat), and where the altimeter and radiometer footprints do not experience significant land intrusion. The purpose of such permanent Cal/Val facility is to calibrate the sea-surface height and ancillary measurements made by the satellite as it passes overhead, by using observations from tide gauges, GPS, DORIS and other sensors directly placed under the satellite ground tracks.

The successful launch of Jason-2 satellite (20 June, 2008) initiated its calibration-validation phase. This was achieved having the two satellites flying with less than one minute difference and in the same orbit. Using the Gavdos calibration facility the following have been determined: (1) the absolute altimeter bias of Jason-1 satellite for the cycles 209-259; using GDR-C data; (2) the absolute altimeter bias of Jason-2 satellite for the cycles 2-28 using GDR-A data ; (3) the inter- mission bias for the period July 2008 – January 2009.

The expansion of the Gavdos Cal/Val facilities with the deployment of a new site in the south of Crete and along pass No. 109 is also presented in this work.

Keywords: satellite radar altimeter, calibration, Jason

1. INTRODUCTION

The study of global change, in which sea level variations play a critical role, requires that satellite altimeter measurements of homogenous quality and rigorous reliability are maintained over long periods of time. However, satellite missions have a limited lifetime of 3 to 7 years. Today, there are several altimetric satellites in orbit, such as Jason 1&2, ERS and EnviSat, as well as the future ones of CryoSat-2, Sentinel-3, SARAL/Altica, HY-2, to mention a few.

The results from each mission, such as sea surface heights and anomaly fields, need to be continuously and independently connected and calibrated on a common and long-term basis and above all in a systematic and reliable manner. The calibration and validation of altimetric missions is the process of quantitatively defining and assessing the altimetric system's responses (in other words the sea state bias, wet tropospheric path delay, marine geoid, tides, geographically correlated errors, etc.) to known and controlled signal inputs, determined by independent means. This can be achieved by using dedicated research infrastructures, together with distributed tide gauges 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.

Another approach for calibration is to use a tide gauge network, equipped with GPS receivers, in order to simultaneously measure sea surface heights and positions in the same reference frame, while the altimetric heights are recorded by the

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satellite in the ocean. While dedicated calibration sites detect absolute biases, the drift estimate of an altimeter is accurately determined by the global tide-gauge analysis. In this way the resulting drift estimate provides information that is complementary to the calibration estimates from the dedicated sites. However, cooperating tide gauges in this network are rarely found along the satellite's ground track and moreover, only a few are directly collocated with GPS or DORIS. Geodetic control by continuous and precise positioning systems is a fundamental requirement to avoid that undetected vertical tectonic motion at the tide gauges, as this could be interpreted as sea level change.

Calibration, in dedicated Cal/Val sites, is performed by combining satellite radar measurements with the computed satellite ephemerides, the geodetic position of the Cal/Val site, and the geodetic ties and sea parameters between reference points of various sensors at the facility. The objective is to calibrate the sea-surface height and ancillary measurements made by the satellite as it passes overhead, by using observations from tide gauges and other sensors directly placed under the satellite ground tracks.

In the world, there are five permanent sites for providing absolute calibration of satellite altimeters, three of which are located in Europe (Gavdos in Greece, Corsica in France-operated by CNES, Ibiza in Spain), one in the USA (Harvest Oil Platform, California-operated by JPL) and one in Australia (Bass Strait, Tasmania). These sites, of which some have been operational since early 1992, produce absolute biases and drifts for overflying satellite measurements. Nonetheless, calibration results depend on the local conditions, standards and specifications applied, duration of measurements and geographical location of the calibration sites.

Dedicated calibration sites are commonly located along a repeating ground track of altimetric satellites, and additionally where the altimeter and radiometer footprints do not experience significant land intrusion. Small islands, like Gavdos, best fulfill that role. The permanent facility in Gavdos is situated under the crossing point of the Jason satellite's orbit and adjacent to the orbits of Envisat. This fortuitous coincidence – very few islands have this advantage throughout the world – makes Gavdos an excellent and strategic position for the calibration of satellite altimeters, because: (1) The island is far from the mainland (Crete) and is situated in the open sea, (2) it disposes of medium topographic relief and has simple circulation of ocean currents; (3) The surrounding geoid has been determined from previous gravity measurements (airborne, marine and terrestrial) and the local tides are small; (4) Calibrations of the Jason satellite altimeter may thus be carried out twice every 10 days and not once every 10 days on descending and also ascending orbits, and (5) Any errors depending on the direction of the satellite's orbit may be determined and eliminated.

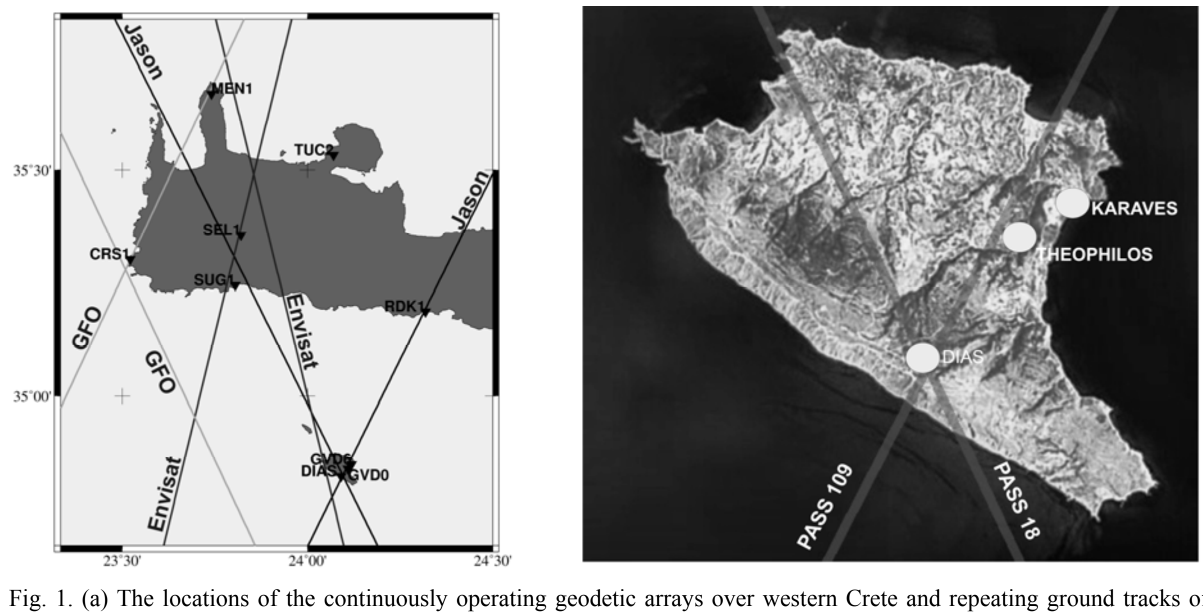

Fig. 1. (a) The locations of the continuously operating geodetic arrays over western Crete and repeating ground tracks of altimetry missions, and (b) Jason, Envisat and GFO ground tracks over Gavdos and Crete.

The Jason-1 satellite mission was launched on December 7, 2001 while the Jason-2 on June 20, 2008. The Jason-1 has been successfully operated since late January 2009 where several maneuvers have been performed in order to move it in a new orbit. After this change, Jason-2 is in Jason-1's old orbit ensuring continuation of the data time series and the usage of dedicated calibration sites, like Gavdos. During the period June 2008 – January 2009, the two satellites were flying in the same orbit with a time difference of 55 seconds. This period was the calibration and validation phase of Jason-2 and scientists were able to acquire near-simultaneous measurements of the two satellites.

In this work, we have applied the standardized methodology developed in cooperation with CNES (France) and JPL (USA) to produce: (1) the absolute altimeter bias of Jason-1 satellite for the cycles 209-259; using GDR-C data (2) the absolute altimeter bias of Jason-2 satellite for the cycles 2-28 using GDR-A data ; (3) the inter-mission bias during the Jason's-2 calibration phase June 2008–January 2009.

The latest developments on the available infrastructure, the expansion of Gavdos Cal/Val facilities with the new site at Rodakino area (south Crete) and the development of new software for satellite calibration are also presented in this work.

2. EXISTING INFRASTRUCTURE

The dedicated calibration facility on Gavdos includes tide gauges, permanent GPS satellite receivers, meteorological and oceanographic instruments, a DORIS satellite beacon, an electronic transponder, communications systems for the transmission of data, etc. (Fig.2).

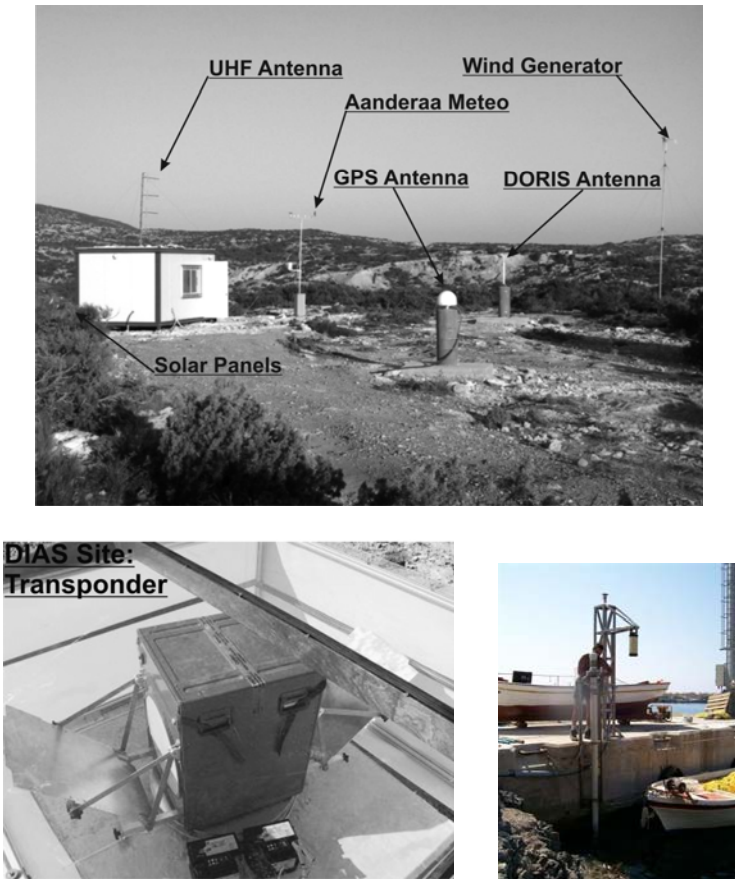

Fig. 2. The Gavdos dedicated Cal/Val site and its instrumentation (permanent GPS arrays, tide gauges, DORIS beacon, electronic transponder, communication links, etc.).

The basic infrastructure is located at the "Karave" harbor. In 2004 the construction of a new jetty was initiated by the Port Authority of Chania. In this new jetty, the Hellenic Navy Hydrographic Service (HNHS) ordered the construction of a new concrete shack in order to install its own tide gauge in the area. The Technical University of Crete made all necessary actions in order to receive permission of hosting its instruments inside the HNHS's shack. The installation of the instruments in their new location was carried out in mid-May 2009 (Fig. 3). A precise leveling was also performed to connect the “old” and the “new” instrument locations and accurately determine the height differences between instruments.

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. At these sites, tide gauges (and seismographs in some locations) are collocated with continuously operating GPS receivers. This Global Navigation Satellite System (GNSS) array is also comprised of another two sites located inside university campus (called TUC1 and TUC2), while three other GNSS sites are to be installed along the North-South axis of Crete and in cooperation with the North Carolina State University, USA.

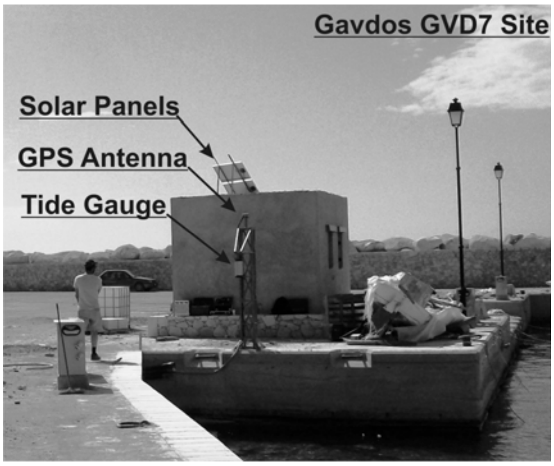

Figure 3 (a) Panoramic view of Gavdos ‘Karave’ harbour indicating the old and new location of TUC instruments (left picture), (b) TUC’s instruments at the new concrete shack (right picture).

3. ALTIMETER CALIBRATION

The instruments carried by the Jason satellites (Jason-1 and OSTM/Jason-2) make the following measurements: altimeter range, ocean significant wave height, ocean radar backscatter cross section, ionospheric electron content in the nadir direction, tropospheric water content, and position relative to the GPS satellites. Also a DORIS system onboard the satellites along with a ground based network of DORIS stations provide the precise location and speed of the satellite as it measures the ocean surface. The satellite ranges are measured in the Ku and the C bands, although the Ku band is used for most applications as being more precise. Ranges are corrected for various instrumental effects, for the path delay in the atmosphere through which the radar pulse passes and for the nature of the reflecting sea surface, using the following expression:

$$\begin{aligned}\text{Corrected Range} &= \text{Range} + \text{Wet Troposphere Correction} + \\ &+ \text{Dry Troposphere Correction} + \text{Ionosphere Correction} + \text{Sea State Bias}\end{aligned} \quad (1)$$

Finally, a sea surface height (SSH) is produced above the reference ellipsoid after subtracting the corrected range from the satellite altitude:

$$SSH = \text{altitude} - \text{Corrected Range} \quad (2)$$

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

$$Bias = Measurement - Truth = \mathrm{SLA}_{sat} - \mathrm{SLA}_{TG} \quad (3)$$

where SLA_{sat} is the sea level anomaly as measured by the satellite altimeter and SLA_{TG} is the sea level anomaly at the tide gauge location. The sea level anomaly is the sea surface height above the ellipsoid minus the mean sea surface and minus several geophysical effects. Those geophysical effects include the height originating from solid earth tide, the geocentric ocean tide the pole tide as well as atmospheric effects such as the inverted barometer effects. More details can be found in the OSTN/Jason-2 Products Handbook (2008).

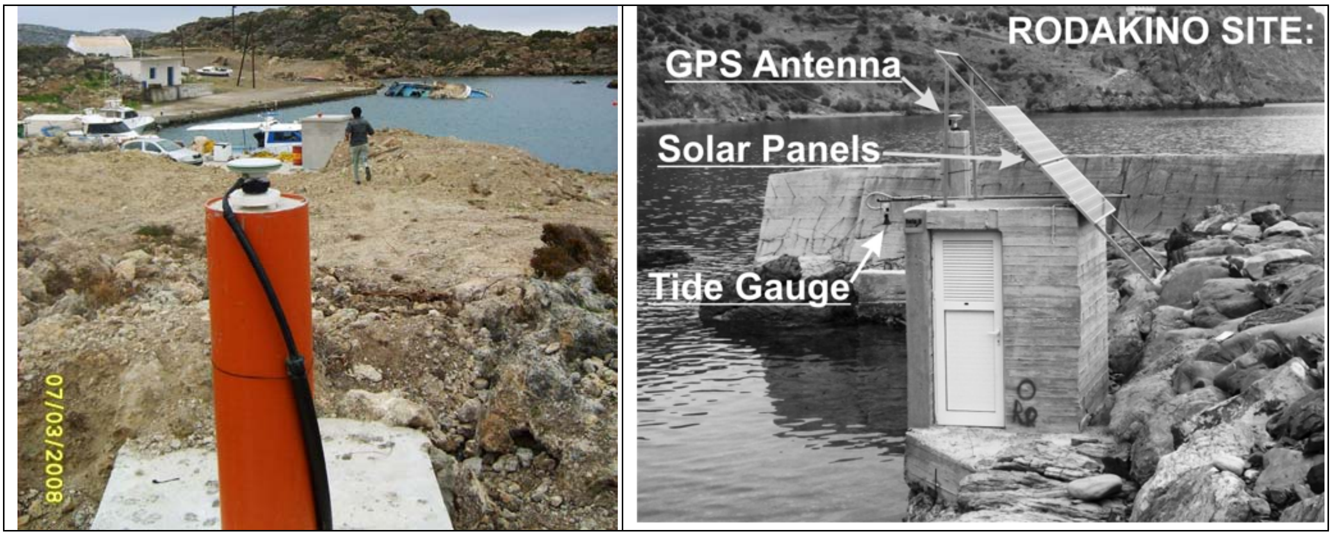

Figure 4.The new infrastructures in (a) Chrisoskalitissa : CRS1 site, and (b) Rodakino: RDK1 site.

3.1 GPS positioning and reference geoids in the region

Three locations for installing equipment have been chosen for the needs of the Gavdos permanent facility. The main facility, named GVD0, is located on stable ground about 3 km away from the Gavdos harbor. There, the GPS permanent stations, the DORIS beacon along with the principal weather station and the main communication and control facility have been built. The GVD0 station there was installed on 6 October 2002.

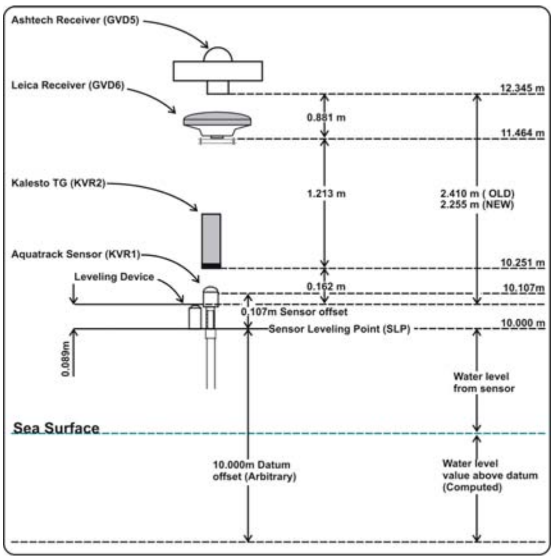

Fig. 5. Height differences as established between the various GPS and tide gauges at the Karave harbor in Gavdos permanent facility.

The second site is on the Karave harbor of Gavdos. A radar tide gauge (named KVR3: an OTT Kalesto Radar tide gauge) was installed in September, 2007, collocated with a permanent GPS/GLONASS receiver (GVD6: Leica GRX1200PRO with a Leica 1202GG antenna). High precision leveling of the tide gauge bench marks has been carried out to several bench marks in the area around the Karave harbor. The established height differences are shown in Fig. 5.

The reduction of GPS observations was carried out using double differences of the measured phase, between the three Gavdos sites and a selected set of IGS core sites extending from Bahrain to Italy, Poland Finland, Sweden, Spain, etc. The results for the GVD6 station are presented in Table 1 and in Fig. 6 (time series) and cover the period from September 2007 till May 2009.

Table 1. Position vector for the GVD6 site derived from GPS data processing using GAMIT and computed at epoch 2009.0.

GVD6 Position vector at 2009.0	
Geocentric Cartesian coordinates	
X(m)	4782622.81490
Y(m)	2141233.15995
Z(m)	3624087.86088
Geodetic Coordinates	
Latitude (DMS)	N 34 50 54.198506
Longitude(DMS)	E 24 7 6.926257
Ellipsoidal Height (m)	20.22701
Velocities	
Ve (mm/year)	6.1
Vn (mm/year)	-15.9
Vu (mm/year)	-5.8

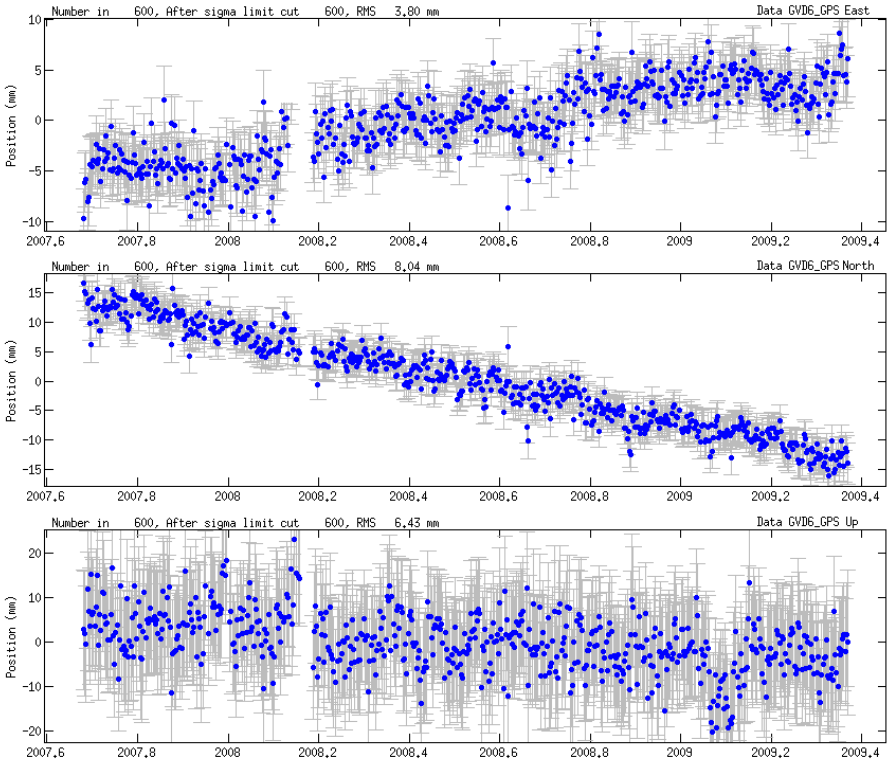

Fig. 6. The GPS time series for the station GVD6 in Gavdos, Greece.

The local geoid was determined using airborne, satellite altimetry, land and marine gravity data as well as digital topography and bathymetry terrain models for the accurate determination of residual terrain effects to gravity data and altimetric sea surface heights. The Gavdos Island (with an average height about 250 m above sea level) lies over the

Eurasia-African subduction zone moving along with the Aegean microplate at 36 mm/yr (Reilinger et al., 2006). Therefore the local geoid is fairly rough and with rapidly varying gradients. To this extent, space- as well as frequency-domain combination methods (least squares collocation and the multiple-input multiple-output system theory respectively) have been employed for the optimal estimation of the final geoid in the area (Vergos, et al., 2005). A final map for the geoid around Gavdos is given in Fig 7 (Adritsanos et al., 2001). Also, the Mean Dynamic Topography is relative small with a value MDT= −14 cm (Rio, et al., 2005).

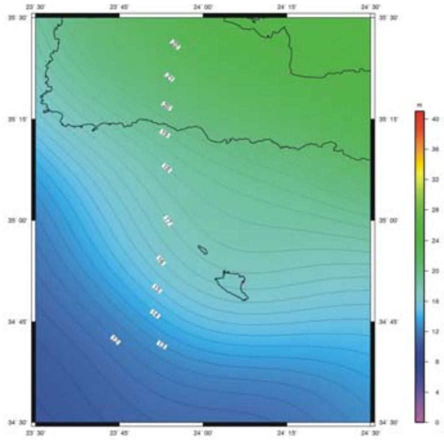

Fig. 7. The geoid model at a resolution (1arcmin×1arcmin) around Gavdos, Greece (after Andritsanos et al., 2001).

3.2 Calibration methodology and results

Calibration reduction requires that all corrections are applied to the satellite measurements in an area where the land does not interfere with the observing capabilities of the satellite sensors. For example, the altimeter foot print has a diameter of about 1.5 km when the significant wave height is about SWH = 2 m in the region of Gavdos. So, one has to start measuring at least 3 km away from the coastline to get reasonable results with the satellite altimeter. Finally, the calibration area is to be in either the ascending or descending pass of Jason satellites from 30 km to about 10 km before or after the point of closest approach (see Fig. 8). The point of closest approach is that satellite point which is closest to the tide gauge location in Gavdos. The corresponding time at PCA is referred to as Time of Closest Approach (TCA).

The orthometric height for the KVR2 tide gauge was determined to be N(KVR2)=16.7187 m and referenced to the GRS80 ellipsoid. The tide gauge measurements which correspond to the TCA is determined after applying a linear fit model to the 6-min sampling of tide gauge observations and the predicted value is the one centered on TCA.

The altimetric satellite is approaching the Point of Closet Approach in Gavdos at a speed of about v=6km/sec. Therefore, 1sec of time corresponds roughly to 6 km in distance for the satellite motion. Based on that we can calculate what models and at what locations the corrections will take place for the wet and dry troposphere, the ionosphere and the sea state bias.

The ionosphere correction which is applied for the calibration is the one produced as the average value between the value given by the GDR corresponding from t1= −21sec up to t2=−1 sec before the TCA (see Fig. 8). For the dry troposphere the corrections used for calibration is an interpolate value at the point of TCA using a linear fit from t1= −5sec up to t2=+2 sec. To avoid land contamination to the satellite radiometer, with a footprint for Jason-1 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 t1= −15sec up to t2=−5 sec. The previous established thresholds as well as the model applied for the estimation for the determination and reduction of effects have been based on the behavior of the onboard satellite equipment as well on the nature of data behavior (i.e., troposphere, ionosphere, winds, etc.). Certainly all these models are under investigation and exhaustive review by in-house scientific tools.

Finally for the sea state bias, a cubic polynomial has been applied in the area between t1= −10sec up to t2=−1sec. All these times are referenced with respect to the TCA where we consider that t=0sec at TCA. All the other corrections have been applied to for the solid earth tide, the geocentric ocean tide, the Pole tide and the inverted barometric height correction have been applied to reduce the measured satellite ranges.

The above mentioned methodology for calibration of Jason satellites has been standardized between Gavdos, Corsica and harvest platform dedicated calibration sites. GeoMatLab has developed a specialized software, called **TUCalibrit** (Ioannides at al., 2009), for the routine calculation of the satellite altimeter bias using the Gavdos facility. This developed and in-house software will be also used to improve the accuracy of the estimated parameters that deteriorate the actual sea surface heights measured by the satellite.

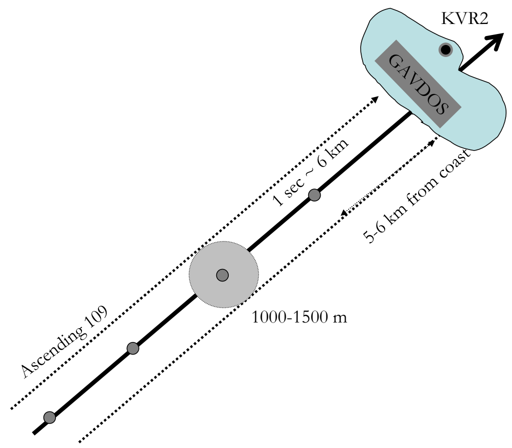

Fig. 8. The applied scheme for the calibration procedures, as an example, in the ascending Pass No. 109 over Gavdos, Greece.

Figure 9 illustrates the determined bias of Jason-1 during the study period (September 2007-January 2009) that is before the change of its orbit. Figure 10 is the bias calculated for Jason-2 for the period July 2008 – April 2009 while figure 11 is the bias between the two satellites during the calibration phase of Jason-2.

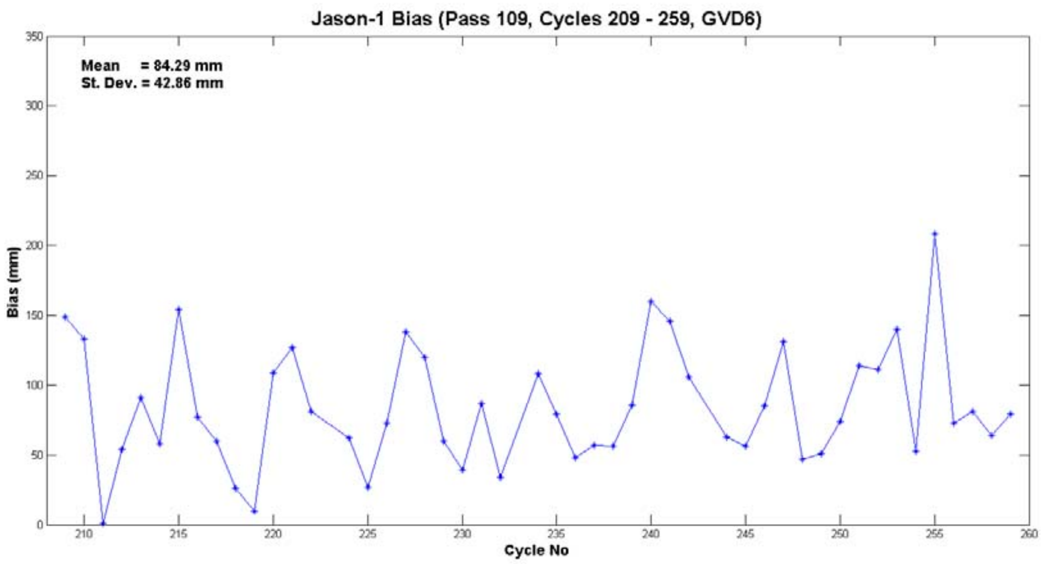

Fig. 9. The altimeter bias for Jason-1 using GDR-C data and for cycles 209-259.

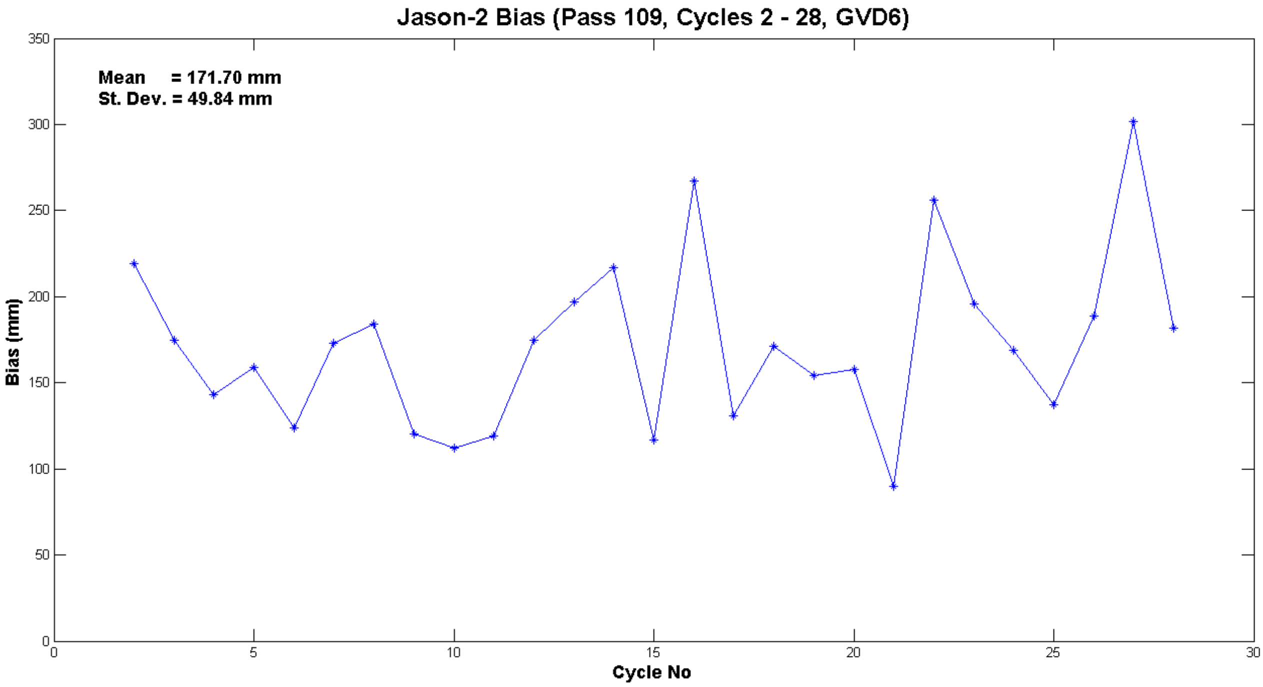

Fig. 10. The altimeter bias for Jason-2 using GDR data and for cycles 2-28.

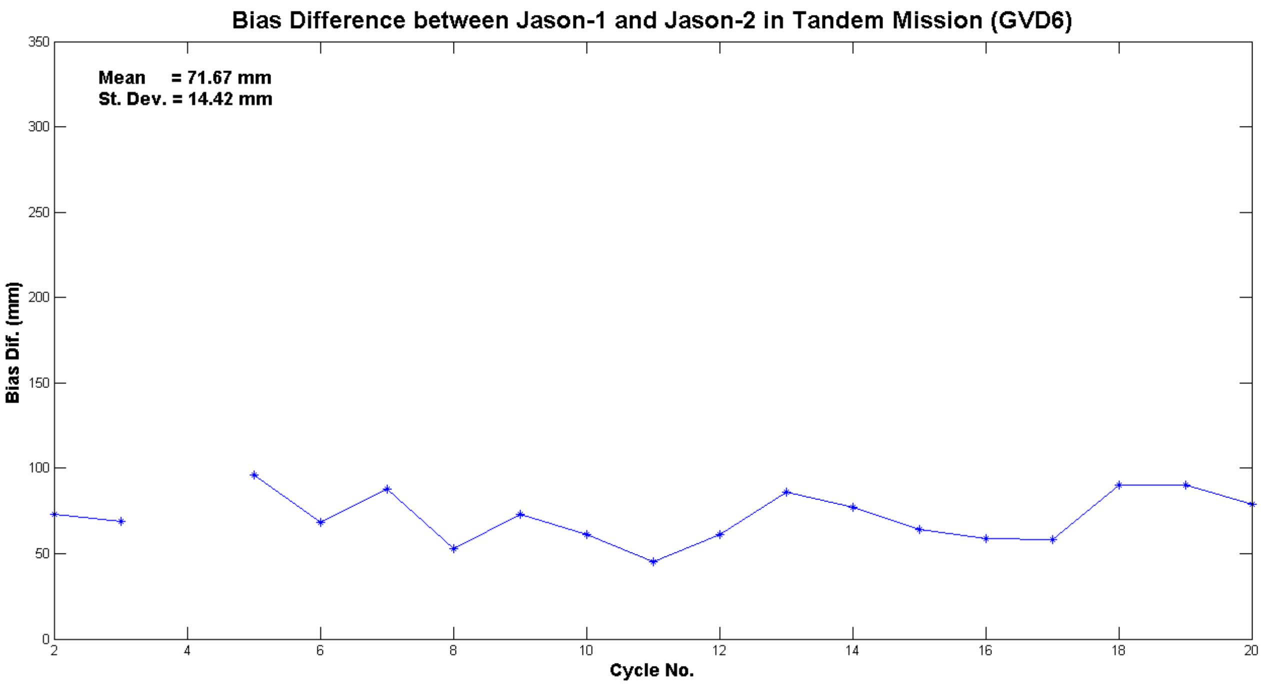

Fig. 11. The bias difference between Jason-1 and Jason-2 in tandem mission.

4. CONCLUDING REMARKS

The altimeter bias for Jason-1 was determined to be +84.29 mm (with a bias error of ±42.4 mm) using 50 cycles using the GDR-C data. The altimeter bias for Jason-2 was determined to be +171,70 with a bias error of ±49.00mm using 20Hz GDR data resulting a bias difference between the two satellites of 71.67mm with a bias error of ±14.42 mm.

The results obtained are in close relation with the ones presented by the operators of the other Cal/Val sites as indicating by the following table:

Cal/Val site	**Jason 1 Bias**	**Jason-2 bias**	**Bias difference(J2-J1)**
Gavdos	+84.29mm±42.40mm (50 cycles)	+171,70±49.00mm (20 cycles)	71.67mm±14 mm
Corsica	102.00mm±9.00mm (259 cycles)	+189±9.00mm (20 cycles)	87.00mm±8 mm
Harvest platform	+94±2.00mm (208 cycles)	+174±27.00mm (27 cycles)	80.00mm±4.00mm

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