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An alternative procedure for the estimation of the altimeter bias for the Jason-1 satellite 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 since 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 additionally 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.

Up to now, altimeter calibration at Gavdos has been performed by averaging gridded sea-level anomalies as produced by the satellite altimeter measurements and then comparing the result with the tide gauge observations. The absolute altimeter bias has thus been previously estimated to be $+121 \text{ mm} \pm 10 \text{ mm}$ for Jason-1 satellite.

In this work, the absolute altimeter bias of Jason-1 has been determined using (1) approximately one year of sea-surface height observations; (2) the GDR-B altimeter record and the seasonal effects of sea level; and (3) an alternative approach for calibration by interpolating each individual altimetric correction given by the satellite at its point of closest approach over the corresponding value of the tide gauge observation.

Keywords: satellite radar altimeter, calibration, Jason

1. INTRODUCTION

The determination of mean sea level (with an accuracy below 1 cm) and its variations (to within 1 mm/yr or better) is a central question in the current debate on climate change and its impact on the environment, including oceanic circulation and the coastal regions. To help address this question, oceanography needs very accurate time series from satellite altimetry but also integration with longer series from tide gauge data.

In satellite altimetry an orbiting satellite emits electromagnetic waves to the surface of the Earth and it then records the times of arrival of the reflected signals. The vertical distance (height) of the satellite from the sea surface can be determined from these time measurements. By using the altitude measurements from the satellite altimeter in conjunction with the determination – before hand by other means as well – of its satellite orbit, it is possible to determine the instantaneous surface of the sea on global scales.

Efforts to calibrate potential biases and subtle drifts in the altimeter measurement systems from orbiting satellites have received significant attention. The effect of the altimeter bias introduces a fictitious elevation or depression of the globally averaged observations of sea-surface height, which impacts studies using in-situ and/or numerical model data. More importantly, the biases can negatively influence altimetric studies that combine data from different (successive) missions.

These aspects lead us to develop ultra-precise validation and calibration techniques, including in-situ absolute calibration experiments. The first advantage of dedicated calibration sites distributed worldwide is to enlarge a statistical base on which the altimeter calibration is dependent upon and to minimize the effect of the geographically correlated errors (systematic errors, different behaviour of the altimetric system and/or the ocean response).

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Five permanent sites exist in the world for providing absolute calibration of satellite altimeters. Three of them are located in Europe (Gavdos in Greece, Corsica in France, Ibiza in Spain), one in the USA (Harvest Oil Platform, California) and one in Australia (Bass Strait, Tasmania). On the small island Gavdos, 40 km south of Crete, Greece, a permanent calibration facility for satellite radar altimeters has established in 2001 and has been operating as of 2004. The location of the frontier land of Gavdos constitutes a strategic point for the calibration of satellite altimeters on a world level, and also for monitoring absolute sea level and climate change on a continuous and long-term basis.

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 is known 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.

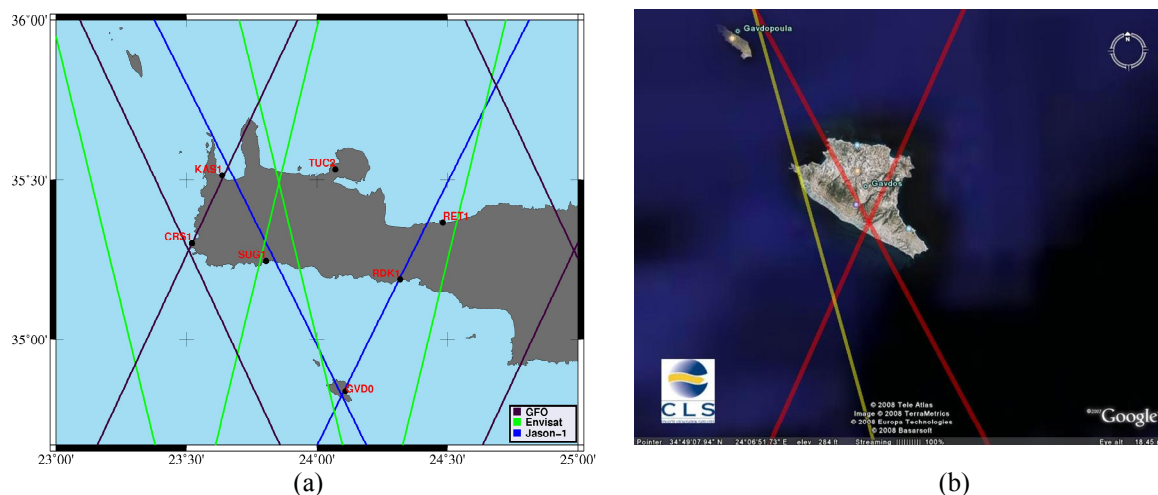


Fig. 1. (a) The locations of the continuously operating geodetic arrays over western Crete and repeating ground tracks of altimetry missions, and (b) Jason-1 (red) and Envisat (yellow) ground tracks over Gavdos.

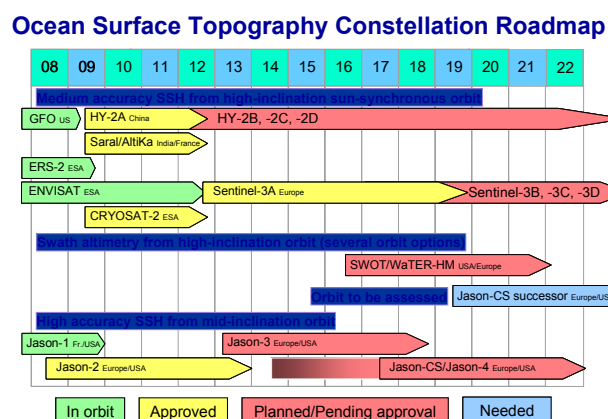


Fig. 2. Road map for the present and future altimetry mission. (OST Constellation Workshop, Assmannshausen, 2008).

The current Jason-1 orbit pattern will be preserved for the future missions of OSTM/Jason-2 (launched on 20 June 2008), Jason-3 and Jason-CS/Jason-4. These orbits will be maintained as the baseline which will serve as the groundwork for the continuity of present services. Also, the new SARAL/Altika mission will keep the same repeating orbits as ENVISAT. Hence, dedicated calibration sites, such as Gavdos, which are located on a cross-over point and exactly under their repeating orbits of Jason, will continue to provide a vital service for modern altimetry missions (OST Constellation Workshop, Assmannshausen, 2008).

In this work, the absolute altimeter bias of Jason-1 has been determined using (1) approximately one year of sea-surface height observations; (2) the GDR-B (Geophysical Data Records, Version-B) altimeter record and the seasonal effects of sea level; and (3) an alternative approach for calibration by interpolating each individual altimetric correction given by the satellite at its point of closest approach over the corresponding value of the tide gauge observation.

2. EXISTING INFRASTRUCTURE

The infrastructure is distributed in the western part of Crete, Greece, but the major installations are located on Gavdos isle (Mertikas et al., 2002, Pavlis, Mertikas et al., 2004). 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.3).



Fig. 3. The Gavdos dedicated Cal/Val site and its instrumentation (permanent GPS arrays, tide gauges, DORIS beacon, electronic transponder, communication links, etc.).

To extent and strengthen Gavdos operations similar facilities are under development at other locations, such as in Kasteli (KAS1), 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. Another two permanent GPS stations are located on the Technical University of Crete campus (TUC1, TUC2). All sites (see Fig. 4) are controlled by a local Operations Control Centre within the TUC campus. Another tide gauge is also located at Souda Bay, Crete with a history of more than 50 years of tide gauge records operated by the Hellenic Navy Hydrographic Service. This site has been used for investigations of long term sea level variations.

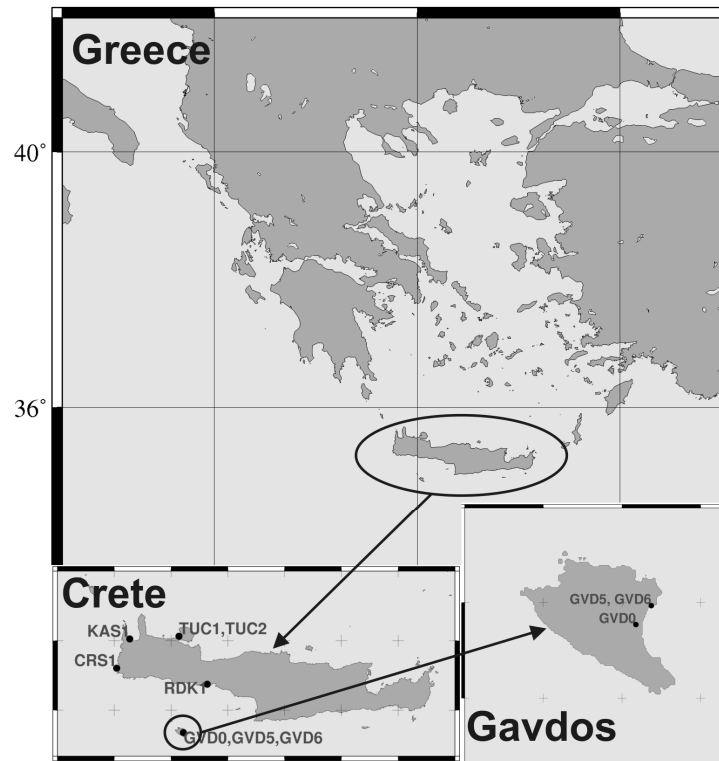


Fig. 4. The locations of the continuously operating geodetic arrays over Crete and Gavdos.

A competitive advantage of Gavdos infrastructure is that its location and some of the instruments already installed there, such as an electronic transponder, are unique on a global scale. For example, there are only few (2-3) transponders dedicated to satellite altimetry calibration around the world. Transponders, collocated with tide gauges, provide an independent way to determine the altimeter absolute bias other than tide gauges. Before Gavdos, this method had only been used marginally during the calibration phase of ERS-2 satellite. Only in one experiment, the height of an oil platform in the North Sea was determined with a transponder while all other experiments had been carried out on mainland. The same situation now exists on Gavdos Island and the transponder has been employed routinely for the calibration of Envisat. A DORIS radio beacon has also been operating since 2003 on the facility and is one of the 17 European stations of the International Doris Service network.

3. ALTIMETER CALIBRATION

Today, there are several altimetric satellites in orbit, such as Jason-1, OSTM/Jason-2, ERS, EnviSat, and GFO, as well as the future ones of the European CryoSat-2, Sentinel-3, the Indian SARAL/Altica, the Chinese HY-2, to mention a few. 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 surface height, atmospheric measurements with on-board microwave radiometers, significant wave heights, sea state, etc.) to known and controlled signal inputs, determined by independent means, such as dedicated Cal/Val sites.

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 purpose of such permanent Cal/Val facilities is firstly to ensure unbiased sea-surface height monitoring, as realized by the globally distributed altimeter measurements and secondly to monitor and comprehensively characterize any altimeter errors (e.g., sea state bias, wet tropospheric path delay, marine geoid, tides, geographically correlated errors, etc.).

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

$$Bias = Measurement - Truth = SLA_{sat} - SLA_{TG} \quad (3)$$

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).

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 Theophilos, is located on stable ground about 3 km away from the harbor. There, the GPS permanent station, the DORIS beacon along with the principal weather station and the main communication and control facility are built. The GPS station there (named GVD0) was installed on 6 October 2002.

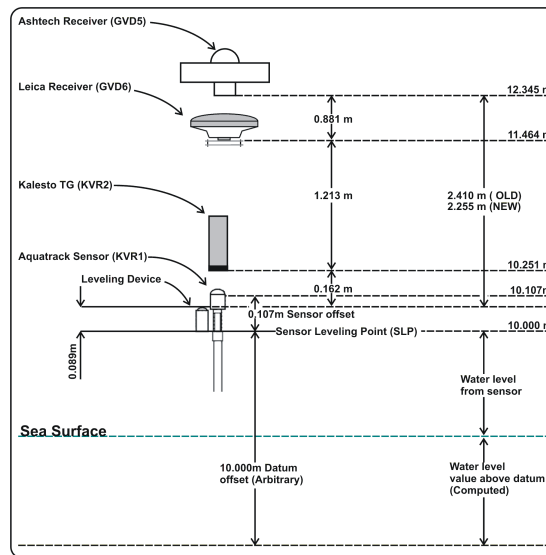


Fig. 5. Height differences as established between the various GPS and tide gauges at the Karave harbor in Gavdos permanent facility.

The second site is on the Karave harbor of Gavdos. An acoustic tide gauge (named: KVR1) has been installed as of August 2002 (owned by JCET, USA), collocated with an Ashtech μ Z GPS receiver (named: GVD5) with a choke-ring antenna were installed in mid-October 2003. Another radar tide gauge (named KVR2: an OTT Kalesto Radar tide gauge) was also installed in September, 2007, collocated with a permanent GPS/GLONASS receiver (GVD6: Leica GRX1200PRO with a LEIAX1202GGLeica 1200X antenna). The measurements from station KVR1 and GVD5 have been interrupted from 25 November 2005 till 24 September 2006 because of construction works taken place at the harbor for the construction of a new jetty. High precision leveling of the tide gauge 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 reference stations extending from Bahrain to Italy, Poland Finland, Sweden, Spain, etc. The results for the GVD6 station are presented in Table 1, below and in Fig. 6 (time series) and cover the period from September 2007 till February 2008.

Table 1. Position vector for the GVD6 site derived from GPS data processing using GAMIT and computed at time 2008.2445.

| GVD6 Position vector at 2008.2445 | |
|---|----------------|
| <u>Geocentric Cartesian coordinates</u> | |
| X(m) | 4782622.79508 |
| Y(m) | 2141233.15349 |
| Z(m) | 3624087.86256 |
| <u>Geodetic Coordinates</u> | |
| Latitude (DMS) | 34 50 54.19894 |
| Longitude(DMS) | 24 7 6.92634 |
| Ellipsoidal Height (m) | 20.211 |
| <u>Velocities</u> | |
| Ve (mm/year) | 8.94 |
| Vn (mm/year) | -12.30318 |
| Vu (mm/year) | -12.4 |

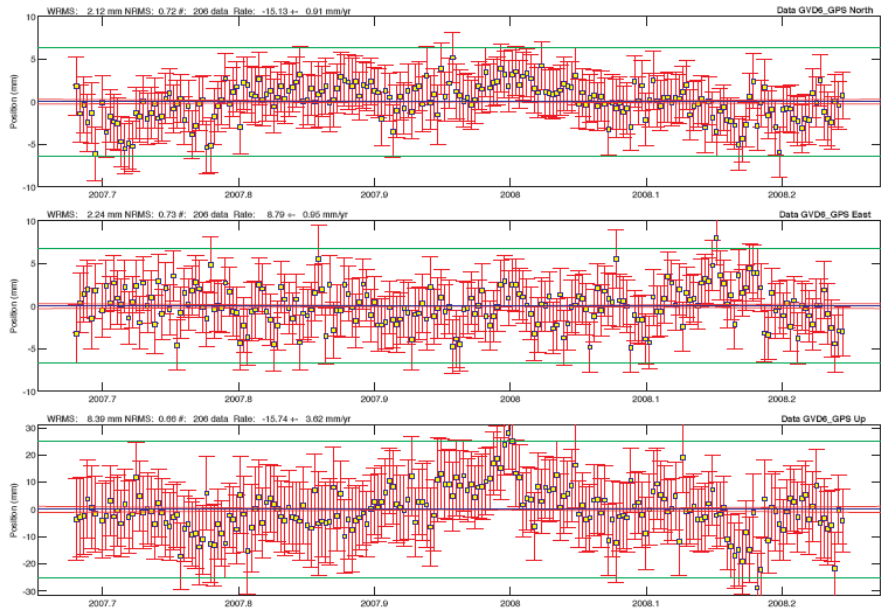


Fig. 6. The time series of the GPS coordinate components for the station GVD6 in Gavdos, Greece.

The local geoid was determined using airborne, terrestrial and marine gravity data as well as topographic and bathymetric digital terrain models for accurate topographic corrections for the surface gravity data. 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. A final geoid map is given in Fig 7 around Gavdos are shown (Adritsanos et al., 2001). Also, the Mean Dynamic Topography is relative small with a value $MDT = -14$ cm (Rio, et al., 2005).

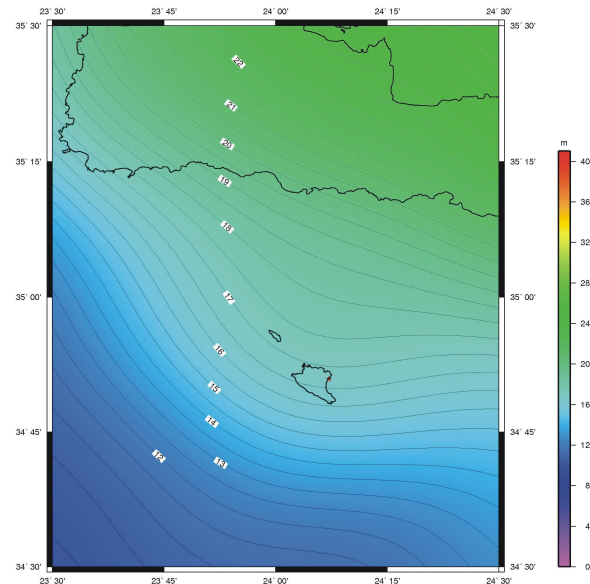


Fig. 7. The geoid model at a resolution (1arcmin X 1arcmin) around Gavdos, Greece (after Andritsanos et al., 2001).

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 (indicated by M1 in Fig. 9). 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. 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 $v = 6$ km/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.

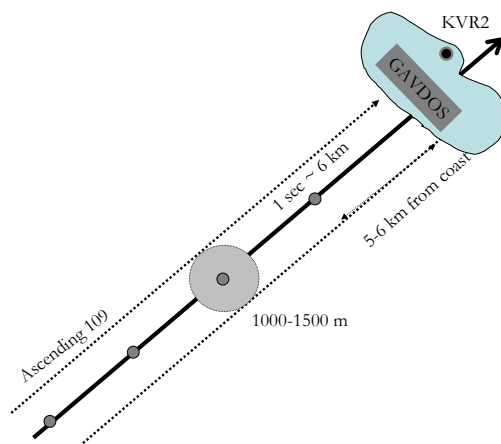


Fig. 8. The applied scheme for the calibration procedures, as an example, in the ascending Pass No. 109 over Gavdos, Greece.

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 $t_1 = -21$ sec up to $t_2 = -1$ sec before the TCA (see Fig. 9). For the dry troposphere the corrections used for calibration is an interpolate value at the point of TCA using a linear fit from $t_1 = -5$ sec up to $t_2 = +2$ 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 $t_1 = -15$ sec up to $t_2 = -5$ sec.

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

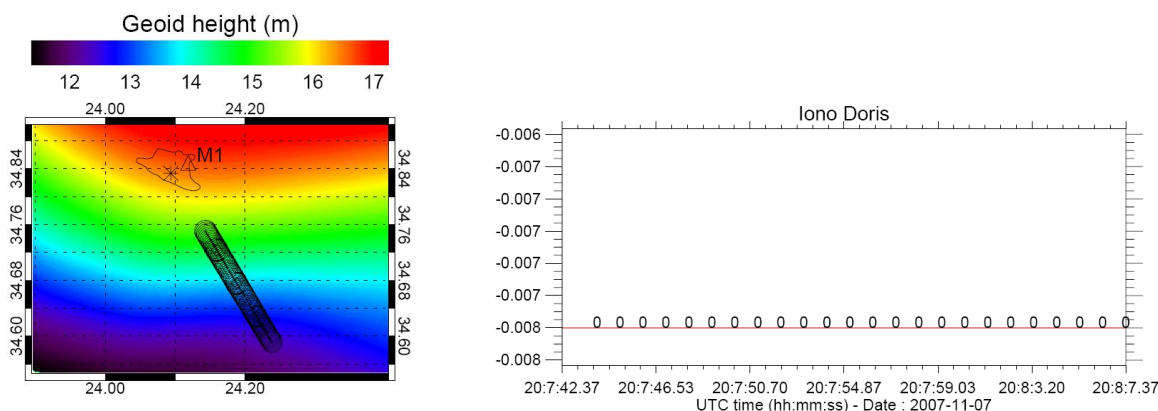


Fig. 9. The geoid model and the region where calibration takes place in the descending pass No. 18 of Jason satellites, as an example. The calibration region is 10 km away from the Point of Closet Approach (indicated by a star on the island) and reaches a distance of 30 km away from it. The right diagram shows the ionosphere behavior for Cycle No. 215 and Pass No. 18 (7 November, 2007). The y-axis is given in meters and the x-axis is time in UTC. The point of closest approach is the origin of the diagram.

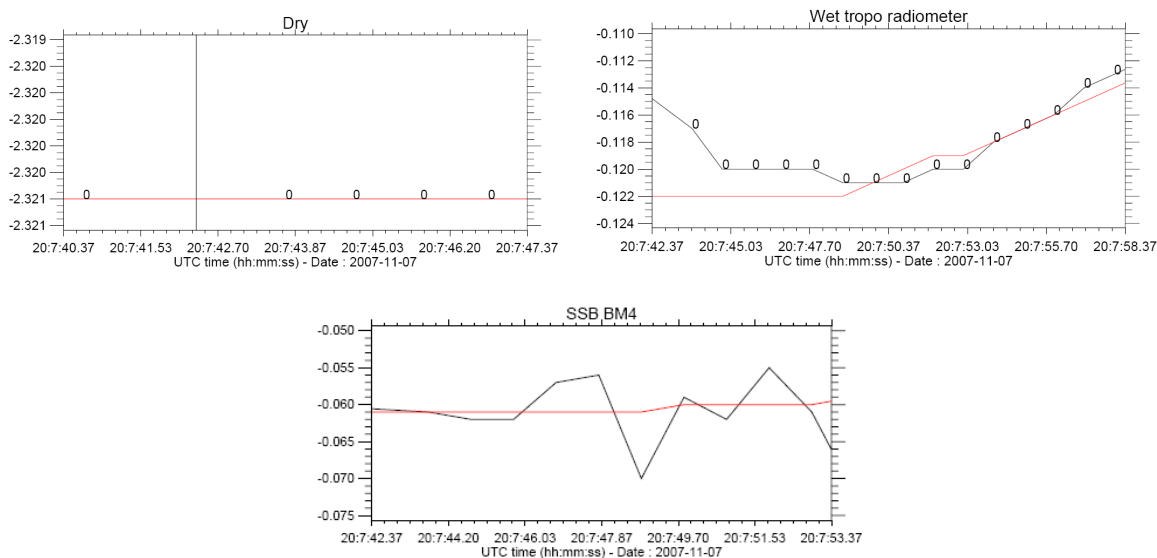


Fig. 10. The dry and wet troposphere behavior and their prediction model used for determining the corresponding value at the point of closest approach (shown as a vertical line in the dry model). The bottom diagram shows the Sea State Bias and the cubic polynomial applied for Cycle No. 215 and Pass No. 18 (7 November, 2007).

Finally the altimeter bias for Jason-1 was determined to be +74.7 mm (with a bias error of 23.4 mm) using 18 cycles using the GDR-B data. This value comes to be in close agreement with the results reported from the Harvest Platform (USA) and Corsica (France). As more data are being accumulated at the Gavdos facility, the value for the altimeter bias is going to be determined with improved accuracy and in particular during the period when Jason-1 and Jason-2 are in tandem orbit after 20 June 2008.

4. CONCLUDING REMARKS

In this work, the absolute altimeter bias of Jason-1 has been determined and found to be +74.7 mm (with a bias error of 23.4 mm) using an alternative approach for satellite calibration by interpolating each individual altimetric correction given by the satellite at its point of closest approach over the corresponding value of the tide gauge observation.

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