Permanent facility for calibration/validation of satellite altimetry: GAVDOS

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ABSTRACT

An absolute sea-level monitoring and altimeter calibration permanent facility has been established on the isle of Gavdos, 50 km south of the island of Crete, Greece. This calibration/validation facility has been chosen because Gavdos is under a crossing point of the ground-tracks of Jason-1 satellites, and adjacent to an Envisat pass.

Satellite altimeter missions are evaluated at that site using external measurements from tide gauges, GPS, a DORIS beacon, meteorological sensors, wave-height sensors, airborne campaigns for gravity and sea-surface topography, water-vapour radiometry, solar atmospheric spectrometry, GPS buoys, altimeter transponder, Satellite Laser Ranging, etc. The mean sea level and the earth's tectonic deformation field in the region have also been determined accurately.

Comparison over the cycles 70 to 77 of the Jason-1 satellite indicate that its absolute mean bias for the sea-surface heights is 134 mm ±20 mm. The GAVDOS project has started in December 2001 and has been in the context of an international calibration/validation effort of the Jason-1 Science Working Team.

Keywords: Calibration/validation, Radar altimetry, Sea level, Jason-1, Envisat, Geoid, Tides, DORIS, GPS

1. OBJECTIVES

An absolute sea-level monitoring and altimeter calibration permanent facility has been established on the isle of Gavdos, 50 km south of the island of Crete, Greece. This calibration/validation facility has been chosen because Gavdos is under a crossing point of the ground-tracks of Jason-1 satellite, and adjacent to an Envisat pass. The European Union, the National Aeronautics and Space Administration and the Swiss Federal Government have jointly funded this calibration facility.

This paper describes the objectives, the instrumentation set up for in-situ measurements, the geoid models developed and the first results for the determination of absolute bias in the altimeter measurement system of the Jason-1 satellite.

GAVDOS is a research for infrastructure project. Its first objective is the establishment of an absolute sea-level monitoring and altimeter calibration facility on the isle of Gavdos, south of Crete, Greece. The calibration facility is under a crossing point of the ground-tracks of Jason-1, and adjacent to an Envisat pass. The location of the Gavdos island is shown in Fig. 1.

The site has been chosen because (1) the small island of Gavdos is far from the main land, with relatively low topography, and rather simple oceanographic circulation; (2) the surrounding geoid is known from in situ measurements and has been further improved using dedicated airborne measurements; (3) the local tides are small; (4) calibration can be made from the isle, twice per cycle of 10 days (instead of once per cycle), on ascending and descending tracks; (5) the cross-over information can be used to remove possible biases dependent on the direction of the satellite pass; and (6) the location supports the Jason-1, Envisat, and the Geosat Follow-On (GFO) missions.

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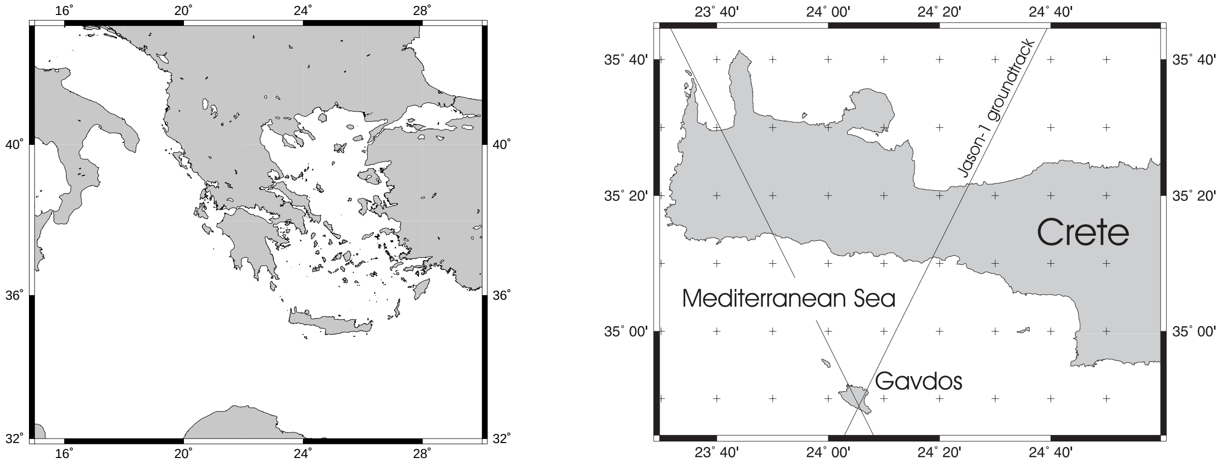

Figure 1. The location of Gavdos island and the Jason-1 ground tracks.

The purpose of such a permanent facility is (1) to conduct comparative laser distance measurements between the facility and satellite radar altimeters, such as Jason-1, Envisat, etc; (2) to ensure the unbiased establishment of the mean sea level, as realized by the globally distributed altimeter measurements; (3) to monitor consistently and reliably any radar altimeter errors (either systematic or random); and (4) to cross-calibrate different satellite altimeter missions and each one of them, on a common and long-term basis. Our challenge is to meet the 1-cm accuracy level needed for the Jason-1 data products.

The second objective is to monitor deformations of the Earth's surface at the tide gauges in the area as a contribution to the European Sea-level System (ESEAS Project). This is achieved by: (1) monitoring horizontal and vertical land deformation using GPS (Global Positioning System) permanent arrays on Gavdos (two permanent receivers), collocated with tide gauges, and on Crete (two permanent receivers); (2) determining, independently of GPS, the local tectonics by operating a DORIS beacon (Doppler Orbitography by Radio-positioning Integrated on Satellite); and (3) by monitoring local sea-level variations with a regional network of tide gauges, and with auxiliary sensors (meteorological, oceanographic, Sea Surface Topography, etc.).

The third objective is the development of a detailed regional geoid and Sea Surface Topography (SST) model. These models are required for referencing the altimeter measurements over the calibration facility and for studying the regional sea current circulation.

Finally, the fourth objective is to involve this project in other European and international programs, and in particular, the European Union Cluster on Operational Forecasting, Euro-GLOSS (Global Sea Level Observing System), WEGENER (Working Group for Earthquake Research), the IGS (International GPS Service for Geodynamics), and the TIGA (GPS Tide Gauge Benchmark Monitoring Pilot Project).

Using this calibration experiment, the influence of potential error sources resulting, e. g., from the orbital modelling, instrument malfunction, deterioration, etc., is decreased significantly. The site is designed to be used also for other altimeter missions, such as European ERS-2, and the US Geosat Follow-On (GFO) missions. The deployment of altimeter transponders at the site holds great promise in making the facility the calibration site of the European Envisat altimeter, as well.

2. THE FACILITY AND ITS INSTRUMENTATION

At the time of this presentation, the GAVDOS facility is fully operational. Three locations for installing equipment have been chosen (see Fig. 2) for the needs of the Gavdos permanent facility.

The main facility, named *Theophilos*, is located on stable ground about 2 km away from the harbour. It has been constructed on an area of more than 4000 square meters, purchased by the Technical University of Crete and for the needs of this project. There, the following instruments have been installed (Fig. 3): (1) a GPS permanent

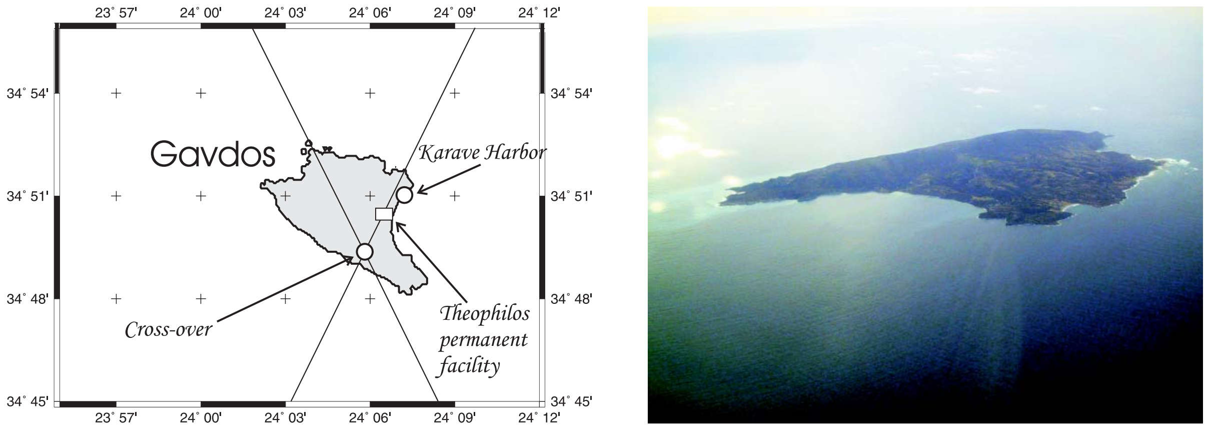

Figure 2. Location of the measurement facilities and sites on the Gavdos island and an air view of the island.

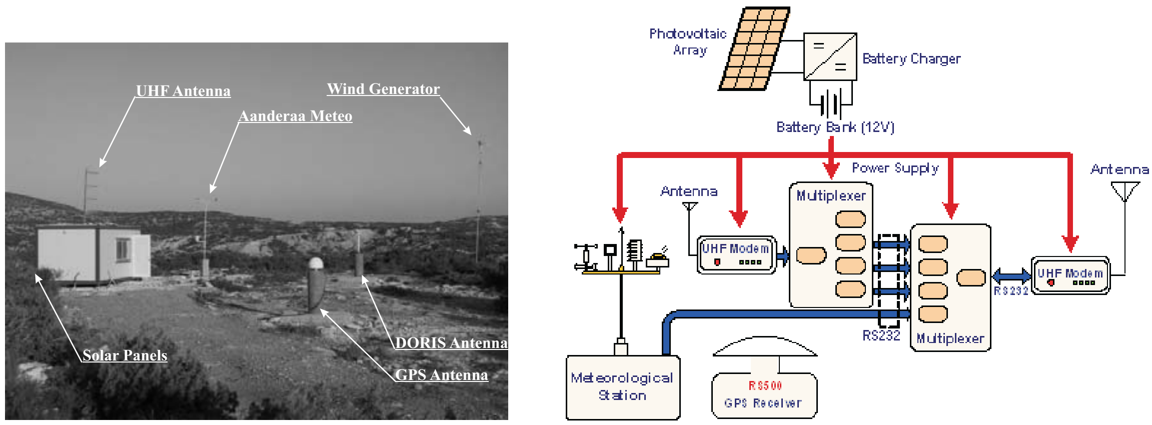

Figure 3. The GPS permanent station, the DORIS radio-beacon and the ancillary sensors and transmitters at the main facility in *Theophilos*.

station on a concrete pillar (site GVD0, established at the International GPS Service specifications) anchored on a stable limestone; (2)a DORIS radio-beacon (DOMES number 12618S001) along with its meteorological sensor; (3) a weather station, measuring wind speed and direction, solar radiation, ambient temperature and humidity and barometric pressure; and (4) the main communication and control facility. A description of the equipment network, the instrument setups and the data flows are shown in Fig. 3.

There is no electricity on the island. Therefore, the instruments had to be powered by renewable energy sources, such as photovoltaics and a wind generator. A solar charger is used to charge the battery bank from each photovoltaic source.

All devices at *Theophilos* are powered by a 12-volt battery bank, which consists of a set of three batteries. The total battery capacity is selected such that all devices are adequately powered during periods of low energy production or during service time in case of a system component failure ([10]). This configuration has a capability of producing a maximum power of 440 W (under 1 kW/m^2 solar irradiance). Solar panels have been placed at $60°$ tilt and facing south, to maximise the energy production during December; it is the month with the lowest daily irradiation ([11]). The estimated average energy production during winter is 45 Ah per day, while the energy requirements have been estimated to be approximately 25 Ah. Oversizing is required to compensate both the variable energy production and future additional energy requirements.

The solar-panel energy production is stochastic. The design for this power system has been based on monthly

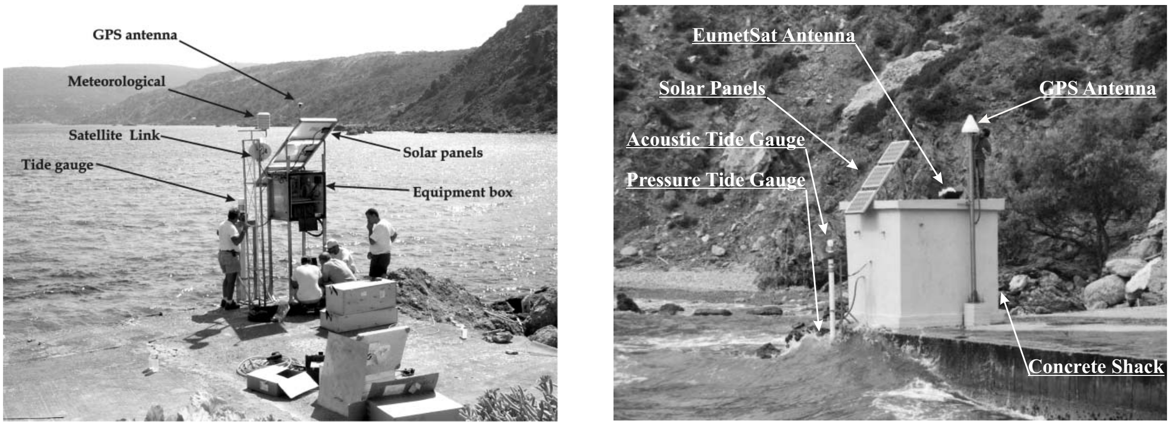

Figure 4. The *Karave* site with the two tide gauges, the meteorological station, the GPS receiver for time-tagging and the satellite link for data collection and retransmission through Meteosat. Left photo: the *Karave* site as was initially designed; Right photo: after it was protected from extreme weather conditions and also its GPS permanent station, collocated with the tide gauges, a year after initial installation.

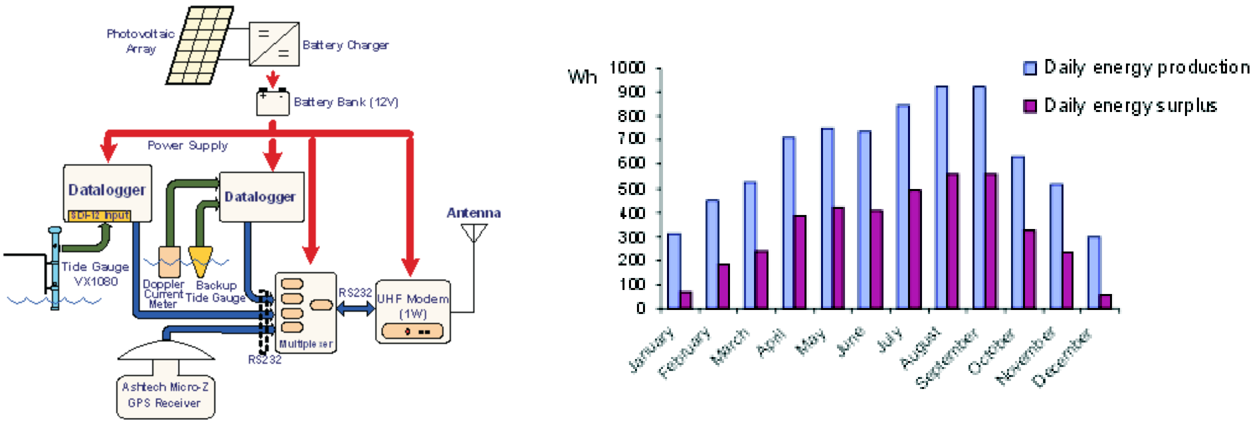

Figure 5. The *Karave* block diagram as designed for the power supply (left photo). The monthly mean photovoltaic energy production and surplus at the *Karave* site (right photo).

mean irradiation values from previous years. The battery bank has a total nominal capacity of 630 Ah. A gas generator has also been installed as a backup power supply for a personal computer, when staff is at the container.

The power consumption for the DORIS 3.0 radio-beacon is 120 W, while emitting. This required an independent power source by itself because of its relatively large consumption. For that purpose, a hybrid configuration of a wind generator along with three photovoltaic arrays, each of which consists of four photovoltaic modules, have been set up. The wind generator has been installed on an 8-meter tower.

The second site is on the *Karave* harbour of Gavdos. An acoustic tide gauge (main unit), a pressure tide gauge (back-up unit), a Doppler water current sensor, a meteorological station, a GPS receiver (site GVD5) for precise positioning and a satellite link for data collection and retransmission through Meteosat have been installed (Figs. 4, 5). Also, an additional pressure tide gauge and a wave-height sensor have been anchored at a 10 m depth in the harbour of *Karave* in May 2002.

High precision levelling of the tide gauge marks has been carried out to several benchmarks in the area around the Karave harbour.

Direct distance measurements to the satellite have to be verified by a signal transponder placed at the cross-

Figure 6. The transponder and the deployment of GPS buoys.

over point on Gavdos. So, a third site has also been established on Gavdos at the cross-over point of the ground tracks of the Jason-1 satellite. This site was named *Dias* and is located 3.5 km south of the *Theophilos* site. It consists of a concrete pad of 1.5×2.0 m, where the transponder has been placed on top of it in a plexiglass enclosure to protect it from the weather (Fig. 6).

The transponder was initially tested in-house at the Space Research Institute of the Austrian Academy of Sciences, Graz, Austria (One of the GAVDOS Partners). Later on, measurements to the Jason-1 and Envisat satellites have been made in the vicinity of Graz and on the Adriatic coast to ensure that the transponder operates properly, before it was finally deployed in Gavdos. On September 2003, the tans ponder was installed permanently at the *Dias* site.

An *Operations Control Center* has also been established at the Technical University of Crete. There, a main computer has been used for data archiving, processing and equipment control via a UHF radio tele-communication links [12]. A radio-modem at the *Operations Control Center* links all facilities in Gavdos with repeater stations established on the main island of Crete. A workstation and a back-up computer are in continuous operation at the *Operations Control Center*.

Communication of results and data exchange is facilitated via an official and dedicated web site. This can be reached at `http://www.gavdos.tuc.gr`. Project data and results are disseminated from this site through a public and a restricted area. Data will be eventually disseminated to the Permanent Service for Mean Sea Level and MedGLOSS, on a near real-time basis.

The data and results are archived at the Project Data Center using a specially designed database.

3. PRECISE POSITIONING

Four permanent GPS sites have been established thus far. The original station was TUC1 (DOMES number 12617S001). It is located on the roof of the Geodesy and Geomatics Engineering Laboratory in the TUC Campus, Crete. The second station TUC2 (DOMES number 12617M003) also on Campus has recently been established in June 2004. It is a concrete pillar on stable limestone at IGS specifications. This TUC2 station is to become part of the EUREF Permanent Network. The two other permanent sites are on Gavdos (i. e., GVD0 and GVD5).

An analysis of the data for the permanent GPS stations has been carried out using using double differences of the observed GPS phase and the GAMIT [7] software from the Massachusetts Institute of Technology. Data have been processed together with the set of global IGS stations, extending as west as Maspalomas, Spain and as east as Nicosia, Cyprus. Coordinates of the sites in the International Terrestrial Reference Frame (ITRF 2000) are presented in the Table 1 for the epoch 2003.0.

Figure 7. The map of the GPS sites and the newly established station TUC2.

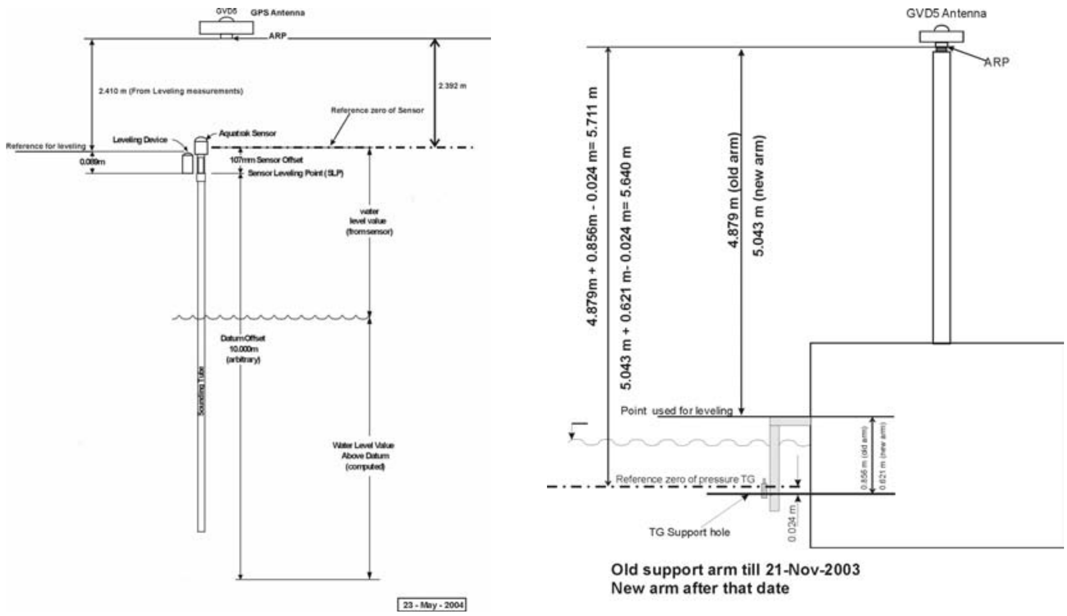

Figure 8. Precise leveling results and height differences between the GPS station GVD5 and the tide gauges at the *Karave* site.

For the needs of the calibration process, care has been taken to determine heights as accurately as possible. Levelling difference between the antenna reference point of GVD5 and the main tide-gauge reference point was 19.299 m (see Fig. 8). The adopted height for the GVD5 and for the satellite calibration process was 21.762 m for the main tide gauge. The position variations as determined for the the main GPS site at *Theophilos* (GVD0) are shown in Fig. 9.

Also, the satellite orbit has precisely determined locally using the French Transportable Satellite Laser Ranging at the TUC campus. For that purpose, adjacent to the building of the *Operations Control Center*, a concrete pad was constructed within the TUC campus. Power, telephone, and Internet connections were provided for the deployment of the Satellite Laser Ranging campaign. The Satellite Laser Ranging measurements have been made by the *Observatoire de la Cote d'Azur*, France (One of the GAVDOS Partners). Measurements lasted from March to October 2003. To avoid the high temperatures of July and August, no measurements were made during these months. Absolute results have been derived for the main point on the laser pad (SLR0 with ILRS

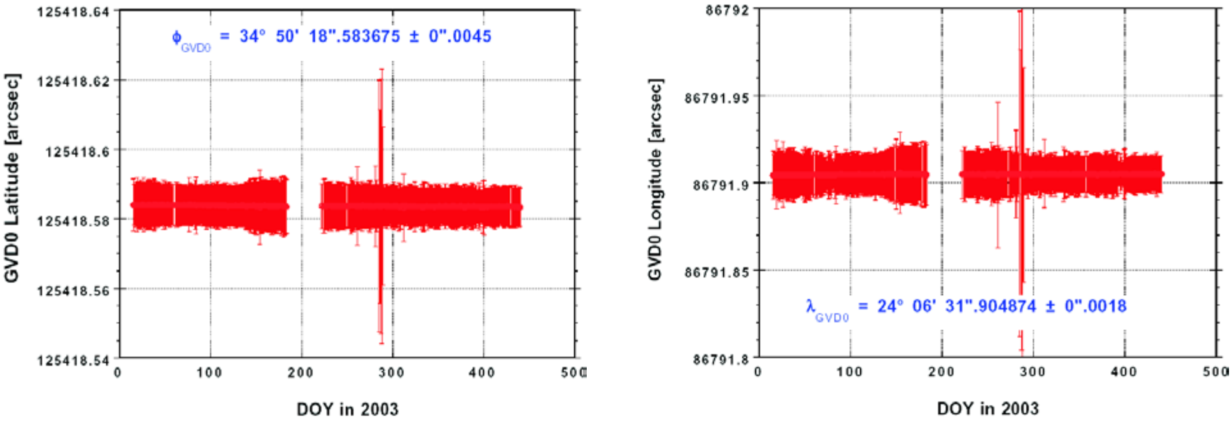

Figure 9. Latitude and longitude variations of the GPS station GVD0 at the *Theophilos* site.

Table 1. ITRF2003.0 Coordinates of primary geodetic marks of the GAVDOS Project.

Mark name	Latitude (deg/min/sec)	Longitude (deg/min/sec)	height (m)
GJAS (Dias)	34 49 17.297623 ± 0.00010	24 05 27.663360± 0.00014	251.169± 0.019
GVD0 (Theophilos)	34 50 18.583675± 0.00010	24 06 31.904874± 0.00020	124.577± 0.007
GVD5 (Karave)	34 50 54.352936 ± 0.00008	24 07 07.047660 ± 0.00010	21.752 ± 0.006
SLR0 (Laser Pad, Crete)	35 31 58.954357± 0.00030	24 04 13.966295± 0.00040	161.053± 0.013

ID No. 78306901 and DOMES No. 12617M002).

Several satellites were tracked but mainly the target was the two altimeter missions of TOPEX/Poseidon and Jason-1. Part of the distribution of the acquired data from the above Satellite Laser Ranging campaign are presented in Fig. 10.

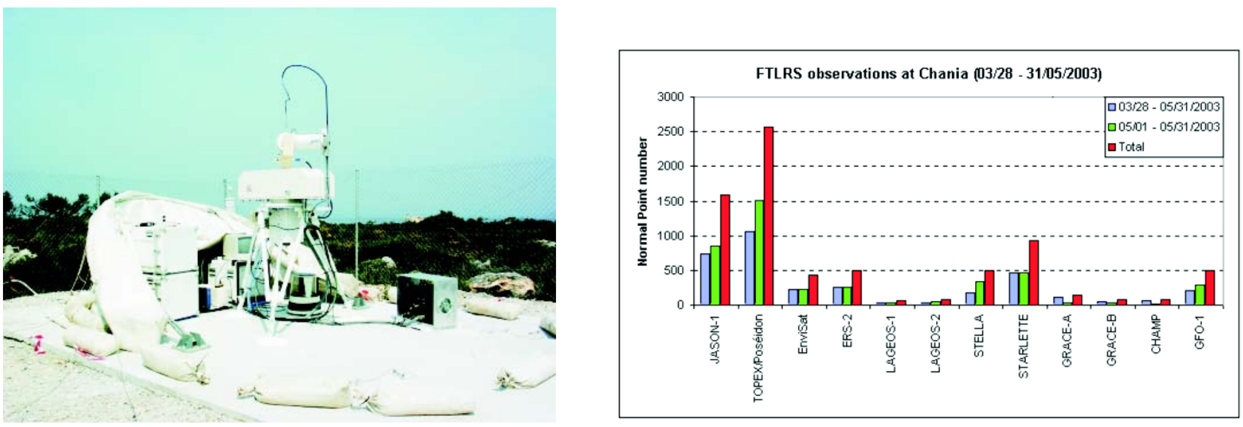

Figure 10. The distribution of data from the Satellite Laser Ranging campaign as measured by the French Transportable Satellite Laser Ranging System at TUC Campus.

Figure 11. The Twin Otter aircraft and the airborne campaign with laser and gravity measurements over the west Crete.

4. PRECISE GEOID MODELS AND REFERENCE SURFACES

Because the facility is to measure absolute heights for satellite calibration, care has been taken to determine height reference surfaces accurately. The geoid is an equipotential surface of the Earth's gravity field that is used as reference for levelling heights. The Mean Sea Surface is a reference used by oceanographers for the Sea Level Anomalies as obtained from data using satellite altimetry. The geoid and the Mean Sea Surface differ by the Mean Dynamic Topography.

A detailed gravity database for the area of Crete-Gavdos has been constructed using land and marine gravity data. Data from previous campaigns for airborne gravity (Project CAATER, [14]) have also been used in the geoid determination. In addition, an airborne campaign with laser scanners and lidar and airborne gravimeters was carried out, in January 2003, over the region of western Crete. The Swiss Federal Office of Topography provided the Twin Otter aircraft for these airborne surveys. The airborne gravimeter was provided by the University of Bergen, Norway (Fig.11).

Radar satellite altimeter measurements were verified with GPS buoy experiments that took place during the airborne campaign. The GPS buoys were placed under the satellite ground tracks to provide in situ Sea Surface Topography data.

For the determination of an accurate geoid model an effort has been made to collect all available gravity data for the area of GAVDOS, i. e., ship-borne, land and airborne free-air gravity anomalies. Upon the collection of these data an editing and blunder-detection and -removal procedure was carried out using both empirical (visual inspection) and statistically rigorous (least squares collocation—LSC) methods. The final grid of gravity anomalies, which constitutes the project gravity database, presents an accuracy at the 5 mGal level while the prediction errors from the LSC method are at the 0.2–0.4 mGal. The error level of 5 mGal is considered as very pessimistic, but is a safe one, since no information about the input errors of the data was available. The resolution of the gravity data base is $1' \times 1'$ (1.7 km×1.7 km) in both latitude and longitude and was subsequently used for a gravimetric determination of the geoid in the area.

For the gravimetric geoid determination, the remove-compute-restore method was employed using spectral methods for the estimation of geoid heights from gravity anomalies with Stokes' function. The final gravimetric geoid (see Fig. 12) was also accompanied by an altimetric and combined, i. e., gravimetric and altimetric, models so as to exploit the advantages of both the gravimetric and altimetric data.

The determination of the altimetric geoid was based on sea-surface height data from the geodetic missions of ERS1 ([2]) and GEOSAT ([13]) employing once again the remove-compute-restore method. For the determination of the combined models the traditional LSC method was used together with the Fast Fourier Transform based Input-Output System Theory (IOST) method ([1]). The final gravimetric, altimetric and combined models where compared against a 9-year stacked TOPEX/Poseidon data set for validation purposes.

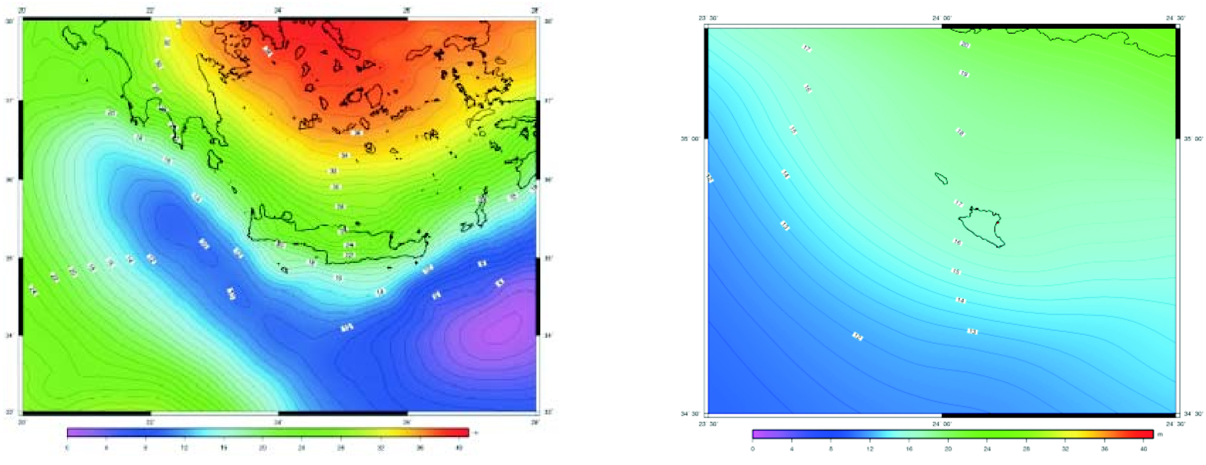

Figure 12. Geoid models at $1' \times 1'$ resolution, computed using land, marine, airborne and satellite altimetry data.

From the analysis of the comparisons it was found that the gravimetric geoid is accurate to the ±14.5 cm level, while the altimetric and combined ones to ±8.60 cm and ±12.5 cm. These results are expected since the altimetric observations are more homogeneous and precise than the gravimetric ones, but an altimetric geoid is much better close to the coastline and of course in land areas where altimetric sea surface heights are unavailable. The combined solution possesses the advantages of the other two models, since it is a combination of the two data sets. The achieved accuracy of ±12.5 cm signals a major improvement (by about 6–8 cm) compared to the previous geoid models for the area.

In support of the geoid determination carried out, new Digital-Terrain and -Depth Models (DTDMs) were generated. The new DTDM was estimated by combining all available data sources, i. e., the DBDV2, GEODAS and Smith&Sandwell Ver. 8 (S&SV8) DDMs. For the estimation of the new model a multi-step procedure was followed, whose first step refers to the detection and elimination of any blunders in all datasets. The blunders can be either land points in the DDM or ocean points with positive depths. To remove such points, the GMT 3.4 ([18]) coastline was used and applied a land-mask on each dataset to separate dry-land from wet regions. Then, and since only wet points have been selected, we merged them in one single dataset and proceeded to the prediction of the final DDM with 500 m (16.36″) spatial resolution.

The interpolation was based on three methods, i. e., a) weighted means with prediction power 2 (weight= $1/\lambda^2$), b) weighted means with prediction power 3 (weight= $1/\lambda^3$), and c) krigging using least-squares collocation. In cases a) and b), λ denotes the distance of each irregular point to the grid node to be predicted. From the tests carried out it was found that when employing the weighted means methods, then the resulting DDM presented some noisy characteristics which do not conform to a bathymetric chart/dataset. Thus, we decided to use the LSC-based interpolation to estimate the 500 m DDM. A major concern in such an approach refers to the selection of the proper variance and correlation length for the estimation to be carried out. The selection of the variance was based on the errors characteristics of all available data sources (at least for the ones that were accompanied by some information of that kind). Thus, the DBDBV2 data were accompanied by an error estimate between 16 and 300 m, the S&SV8 data with as error worse that 100 m and the GEOADAS soundings with an error between 10 and 100 m. We should mention at this point that the data for each DDM were not related to some error estimates for each individual data point, but with an error range for the entire dataset. That is why we finally selected an error of 100 m to represent the entire merged DDM. The correlation length was selected after some trial and error tests based on a signal to noise criterion, i. e., the resulting field should not be noisy or too smooth either. To derive the final combined DDM and DTM for the area of Gavdos we combined the aforementioned 500 DDM with the 500 DTM that we had available from the GLOBE Project ([8]).

Finally, a detailed model of the Quasi-stationary Sea-Surface Topography (QSST) over Gavdos has been determined (see Fig. 13) as well as the geostrophic current velocities in the same area. The approach followed

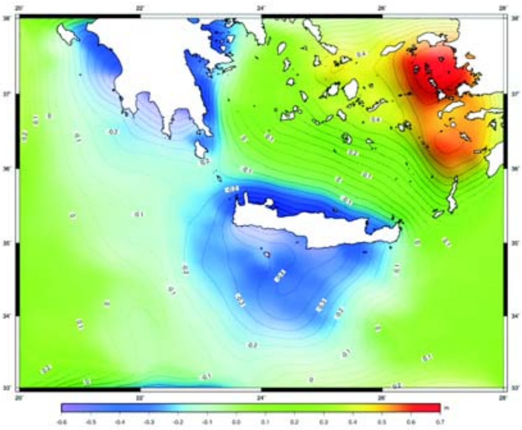

Figure 13. The Sea Surface Topography in the region of investigation.

utilises the previously determined altimetric and gravimetric geoid models and a low-pass filtering procedure. From the results obtained, we have managed to identify many known currents in the area which proves the appropriateness of the methodology employed. The QSST over GAVDOS is estimated at about −35 cm and the geostrophic velocities at the 18 cm/s level.

5. RESULTS

A record on sea-tide measurements has been collected. The number of observations analysed was 17,554. After a quality check the number of good observations used in the tidal analysis was 16,827. This record corresponds to 731 days and the start time of observations was 24 August 2002. A graphical representation of this record is shown in Fig. 14. Analysis of two years of tide-gauge data obtained from the GAVDOS tide gauges indicates that the maximum amplitude of diurnal and semi-diurnal tides does not exceed 5 cm.

Using tide-gauge data from the most proximate tide gauge (SOUDA, Crete) for the period 1982–2003, the impact of North Atlantic Oscillation (NAO) on sea level was investigated. Annual mean sea levels exhibit a correlation coefficient of about −0.45 during this period. After 1992, the phase of the annual (PSA) and semi-annual (PSSA) components of the seasonal cycle is also controlled by NAO. During 1992–2003, the correlation coefficient between NAO and PSA is −0.74 and between NAO and PSSA 0.73. Before 1992 no relation was found between NAO and the seasonal cycle.

In the region, most of the sea-level decadal variability is associated with the nodal tide and its first harmonic (period 18.6 and 9.3 years respectively). At these frequencies, sea level changes are larger than the ones predicted by gravitational theory of tides ([6]). Moreover, the predicted amplitude of the nodal tide is less than 1 cm, while the observed is larger than 3 cm. Slow changes in NAO are in phase with the two components of the nodal tide indicating that NAO drives sea-level changes also at decadal scales.

The geoid model constructed was compared with the Mean-Sea-Surface value, as produced from the altimetry data at its footprints and along the descending pass No. 018 and the ascending pass No. 109 of the Jason-1 satellite. Based on the computed geoid model and the value for Mean-Dynamic-Topography ([16]) at the location of the tide gauges in Karave, the MSS was determined. Over eight consecutive satellite cycles (70–77), sixteen comparisons of ground-truth and satellite data were performed to estimate the absolute satellite bias using the Gavdos facility. Theses results, although preliminary, indicate an average absolute bias of 134 mm ±20 mm. A detailed description of these experiments will appear in a forthcoming article ([15]).

Within the context of the GAVDOS project, another experiment with a Water Vapour Radiometer (WVR2000) and a GEodetic MObile Solar Spectrometer (GEMOSS) took place. Both instruments belong to the Geodesy and Geodynamics Laboratory of ETH Zurich (One of the GAVDOS Partners). These experiments were carried out

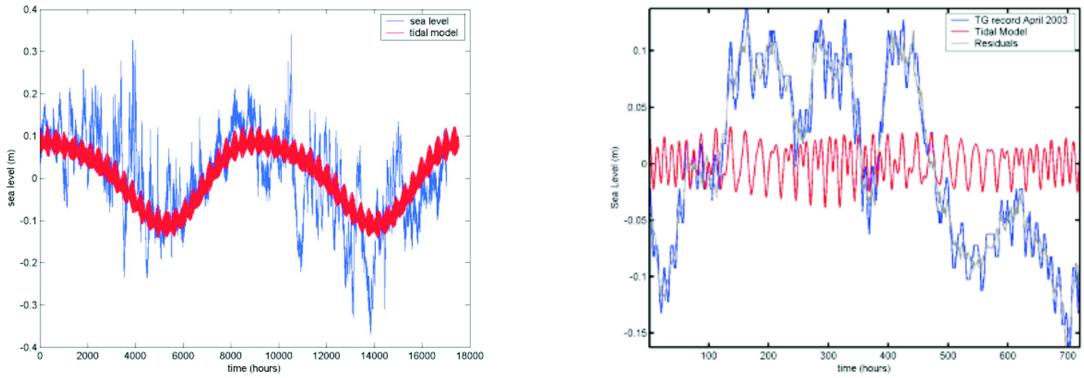

Figure 14. A record of sea tides as measured by one of the tide gauges at the *Karave* site (731 days with the tidal model) and an example of the record analysis for the SOUDA tide gauge (April, 2003).

to calibrate the on-board Jason-1 Microwave Radiometer (JMR) by determining independently the atmospheric signal delay. Two campaigns took place. The first one in January 2003 took place as part of the GAVDOS airborne campaign in the city of Rethymnon, Crete and under the ascending pass 109. The second campaign was carried out in September 2003 at Fiskardo, Kefalonia island, Greece. Measurements for the wet-path delay were made using the WVR2000 and the GEMOSS. The results indicate an agreement within the 1–2 mm level. A detailed description of these experiments will appear in a forthcoming article ([17]).

6. FUTURE PLANS

The GAVDOS calibration facility has been fully operational as of fall 2003. The facility produces *in situ* observations not only for the Jason-1 satellite but also for the Envisat. Along the lines of this research project, the transponder equipment has been tested using the Envisat data and stated a satisfactory operation. Later, the transponder is to be moved at another location on Gavdos to observe permanently the Envisat satellite. It is expected that with the deployment of altimeter transponder will enable us to measure direct distances to the satellite with a ≈5 mm precision.

The *Operations Control Center* already collects automatically the data from the tide gauges, the meteorological sensors, etc., as measured on Gavdos. It is anticipated that the GPS data will be soon downloaded in real time as well.

Finally, the GAVDOS Project is developing software for automated data analysis and quality control checks of all data. This permanent facility will not only create a dedicated observatory on the fringes of the Hellenic trench, it will also expand its utility to sea-level monitoring and altimeter calibration of a number of current and future oceanographic missions, such as Envisat, US GFO, etc.

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REFERENCES

1. V. D. Andritsanos, Sideris M. G., Tziavos I. N., A survey of gravity field modeling applications of the Input-Output System Theory (IOST). *International Geoid Service Bulletin*, Vol. 10, pp. 1–17, 2001.
2. AVISO User Handbook, Corrected Sea Surface Heights (CORSSHs), Publication AVI-NT-011-311-CN, Edition 3.1, 1998.
3. Y. Menard and B. Haines, “Jason-1 CALVAL plan”, CNES, JPL, April 2, 2001. Ref: TP2-J0-PL-974-CN.
4. Y. Menard, “Jason-1 & TOPEX/POSEIDON Science Working Team Meeting”, Minutes, CNES and NASA, 10–12 June 2002, Biarritz, France, Ref: TP2-J0-CR-2156-CNES.
5. Digital Bathymetry Data Base Version 1.0—DBDBV1.0, Internet resources: `http://idbms.navo.navy.mil/dbdbv/dbdbv.html`, 2002.
6. A. Doodson, The harmonic development of the tide generating potential, *Proceedings of the Royal Society*, Vol. 100, pp. 305–329, 1921.
7. “Documentation for the GAMIT GPS analysis software”, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Scripps Institution of Oceanography, University of California at San Diego, Release 10.0. 6 December 2000.
8. Global Land One-km Base Elevation (GLOBE) Project, Internet resources: `http://www.ngdc.noaa.gov/seg/topo/globe.shtml`, 2002.
9. L.-L. Fu and A. Cazenave, Editors, *Satellite Altimetry and Earth Sciences: A Handbook of Techniques and Applications*, International Geophysics Series, Volume 69, Academic Press, New York, 2001.
10. IEEE Std 1013-2000, *IEEE Recommended Practice for Sizing Lead-Acid Batteries for Photovoltaic Systems*, 2001.
11. T. Markvart, *Solar Electricity*, Wiley, New York, 1994.
12. C. L. Nachtigal, *Instrumentation and Control: Fundamentals and Applications*, Wiley, New York, 1990.
13. National Oceanographic and Atmospheric Administration, The GEOSAT-Gravity Mission Altimeter JGM-3 Geophysical Data Records, 1997.
14. A. V. Olesen, I. N. Tziavos, R. Forsberg, New Airborne Gravity Dta Around Crete: First Results from the CAATER Campaign, *Proceedings of the 3rd Meeting on Gravity and Geoid 2002*, I. N. Tziavos, ed., Ziti Editions, Thessaloniki, 2002.
15. E. C. Pavlis, S. P. Mertikas, and the GAVDOS Team, The GAVDOS Mean Sea Level and Altimeter Calibration Facility: Results for Jason-1, accepted for publication in *Marine Geodesy*, 2004.
16. M. H. Rio, *Personal Communication*, 2004.
17. A. Somieski, B. Buerki, A. Geiger, H.-G. Kahle, E. C. Pavlis, H. Becker-Ross, S. Florek and M. Orkuss, Geodetic Mobile Solar Spectrometer for JASON altimeter Calibration, submitted to IEEE *Transactions on Geoscience and Remote Sensing*, 2004.
18. P. Wessel, Smith W. H. F., New improved version of Generic Mapping Tools released. EOS *Transactions of the American Geophysical Union*, Vol. 79 (47), pp. 579, 1998.