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The GAVDOS Mean Sea Level and Altimeter Calibration Facility: Results for Jason-1

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THE GAVDOS TEAM

(See Appendix)

The location of the GAVDOS facility is under a crossing point of the original groundtracks of TOPEX/Poseidon and the present ones for Jason-1, and adjacent to an ENVISAT pass, about 50 km south of Crete, Greece. Ground observations and altimetry comparisons over cycles 70 to 90, indicate that a preliminary estimate of the absolute measurement bias for the Jason-1 altimeter is 144.7 ± 15 mm. Comparison of Jason microwave radiometer data from cycles 37 and 62, with locally collected water vapor radiometer and solar spectrometer observations indicate a 1–2 mm agreement.

Keywords calibration, validation, radar altimetry, sea level, GPS, water vapor, Jason-1, ENVISAT

The European Union (EU), the U.S. National Aeronautics and Space Administration (NASA), and the Swiss Federal Government (SFG) have jointly funded the establishment and operation of an absolute sea level and altimeter calibration facility on the island of Gavdos, Crete, Greece. The facility is hosted by the Technical University of Crete (TUC). We describe here the objectives, first results for Jason-1, and future plans.

GAVDOS was funded as an infrastructure research project, to fill a gap in the region of southeastern Mediterranean, which was already recognized for many years (Pavlis 1999). The main objective is the establishment of an absolute sea level monitoring and altimeter calibration facility applicable to many missions. The calibration facility (Mertikas et al.

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The GAVDOS Team comprises a large number of scientists and engineers from multiple agencies and educational institutes, across Europe and the USA (Appendix). Altimeter data used here were obtained from NASA Goddard's internal Pathfinder archive and the NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC) at the Jet Propulsion Laboratory/California Institute of Technology. We thank B. Beckley for providing the Pathfinder data. The authors wish also to thank the reviewers P. Bonnefond and N. White, as well as B. Haines for valuable comments that helped improve this work. This work was funded by the U.S. National Aeronautics and Space Administration, the European Union Program *Energy, Environment & Sustainable Development* under contract EVR1-CT-2001-40019, and by the Swiss Federal Government.

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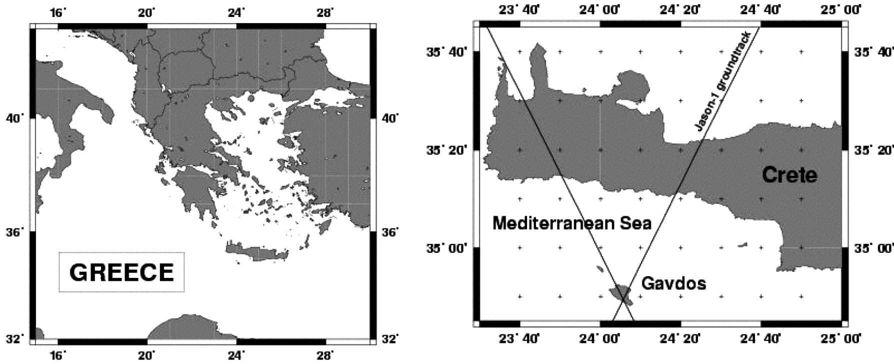

FIGURE 1 The location of Gavdos island and the Jason-1 ground-tracks.

2003) is under a crossing point of the original ground-tracks of TOPEX/Poseidon (T/P) which are also the current ones for Jason-1, and adjacent to an ENVISAT pass. The location of the island Gavdos is shown in Figure 1 with respect to mainland Greece, along with the two Jason-1 ground-tracks that cross over it (passes 018 and 109).

The particular site was chosen for the following reasons.

- The small island is far from the main land, with relatively low topography and rather simple coastal current circulation, yet close enough for easy access for logistic purposes and connection to older tide gauge facilities with a record of more than 50 years.
- The surrounding geoid is known from in situ measurements and will be further improved using airborne measurements by the project.
- The local tides are small.
- Calibration can be made from the island, twice per cycle, on ascending and descending passes.
- The crossover information can be used to remove possible biases dependent on the direction of the satellite pass.
- It was possible to locate an altimeter transponder precisely under the crossing point for an additional, independent, and innovative direct way of calibration.
- The location supports the T/P, Jason-1, ENVISAT, and Geosat Follow-On (GFO) missions.

The facility monitors local deformations near the tide gauges in the area, and it thus contributes directly to EuroGLOSS (Baker et al. 1997). We monitor horizontal and vertical land deformation using the permanently collocated with the tide gauges Global Positioning System (GPS) array on Gavdos (two receivers) and one on Crete, via dedicated campaigns. The absolute position of the main site is periodically determined with Satellite Laser Ranging (SLR). Tectonic motions on Gavdos are also monitored independently of GPS by operating a "Doppler Orbitography by Radio-positioning Integrated on Satellite (DORIS)" beacon at the facility. Local environmental variations are monitored with a regional network of auxiliary tide gauges and sensors (meteorological, oceanographic), on a daily basis, and sea surface topography (SST) with airbone lidars during planned campaigns.

Our initial challenge is to meet the 1-cm accuracy level goal set by the Jason-1 project for its scientific data products. Following that, we strive for a remotely operated, exceptionally outfitted environmental facility that will serve multiple communities and provide valuable data for oceanographic, atmospheric, geodetic, and environmental observation and forecasting for the eastern Mediterranean region.

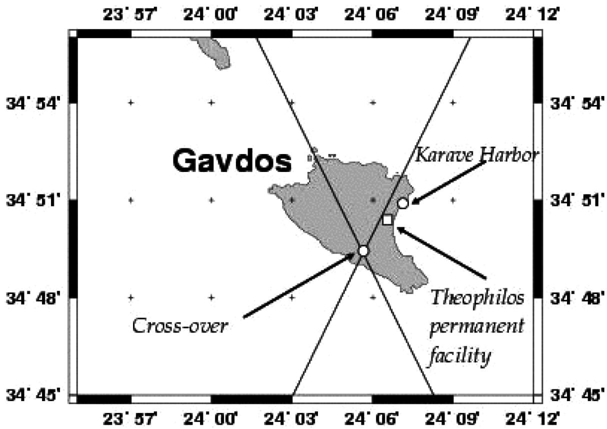

FIGURE 2 Location of instrument facilities on the island of Gavdos.

Facilities and Instrumentation

At this time, the construction of equipment facilities, the infrastructure for data transmission and processing, and preliminary analysis of geodetic, oceanographic, gravimetric, and environmental data is completed. Three locations for installing equipment were chosen (Figure 2) for the needs of the permanent facility on Gavdos:

- Theofilos (site markers GVD0 and GAVB),
- Karave (site marker GVD5), and
- Dias (site marker GJAS).

The Theophilos station, shown in Figure 3, is the central facility on Gavdos. It has been constructed on an area of approximately 4000 square meters, purchased for this project and owned by TUC. The following instruments have been installed at this site:

- A GPS receiver on a concrete pillar (site GVD0, at IGS specs) and on stable limestone bedrock,
- A 3rd generation DORIS beacon (site GAVB with DOMES number 12618S001), with its own meteorological sensor package (Vaisala PTU200), and installed at IDS specs,
- A weather station, measuring wind-speed and direction, solar radiation, ambient temperature and humidity and barometric pressure,

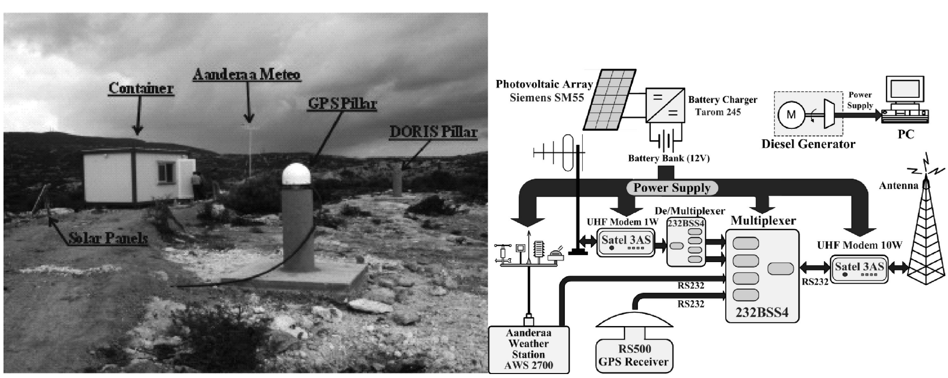

FIGURE 3 The Theophilos site and a schematic of the local installations.

- An Air-403 400 W wind generator and numerous solar panels for sufficient power generation,
- A multiplexer and demultiplexer for data fusion and transmission,
- UHF radio-modem links to Karave site and to TUC's Operations Control Center (OCC) on the TUC campus, and
- A gasoline-driven power generator as a backup and to provide additional power when operators use PCs and power tools.

The multiplexer output, containing the combined data stream (meteorological station and tide-guage data received from Karave) is interfaced to a radio modem. This radio modem transmits the collected data via a repeater to mainland Crete at TUC's OCC.

A 12 V battery bank (11 units) powers all devices at Theophilos. A solar charger is used to charge the battery bank from a photovoltaic source consisting of 16 SM55 modules (Siemens) having a maximum output power capability of 550 Watt (under 1 kWm^{-2} irradiance), eight of which are placed at 60° tilt and facing south and another eight at 40° tilt. The estimated average daily energy production during winter is 45 Ah, while the daily energy requirements have been estimated to be approximately 25 Ah. The solar panels' energy production is stochastic and the power system design has been based on monthly mean irradiation values of previous years. Power oversizing has been incorporated in the system design method in order to compensate for both the variable energy production and future additional energy requirements (Markvart 1994). The battery bank consists of 11 batteries (Gel electrolyte) with a nominal capacity of 3×210 Ah and 8×115 Ah, resulting in a total nominal capacity of 1550 Ah.

The Karave station and its instrument functionality are shown in Figure 4. The following instruments have been installed at station Karave:

- An acoustic tide guage, AQUATRAK™ VX1080,
- A data-logger to store the acoustic tide-guage sensor measurements,
- A GPS receiver on a stainless steel pole (site GVD5, at IGS specs) anchored on the concrete jetty and brace-attached to the shack,
- A backup tide guage (Aanderaa Pressure Sensor), an Aanderaa Doppler Current Meter and a data-logger for both,
- The combined data stream is transmitted via a low-power (1 Watt) UHF radio-modem to the Theophilos permanent facility,
- A solar charger to charge a 12-volt battery bank from a photovoltaic power source in order to cover the data-acquisition units' and radio modem's power requirements, and

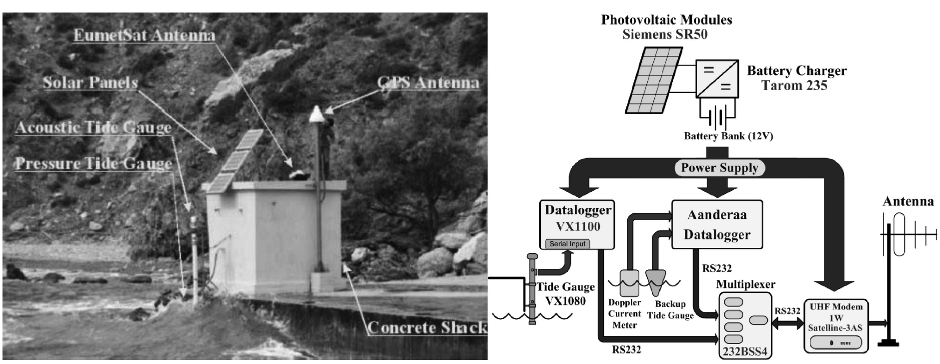

FIGURE 4 The Karave station and the local equipment diagram.

- A stand-alone wave and sea level recorder at a distance of about one mile offshore in the port at Karave and at a water depth of 10 meters.

The main acoustic tide-gauge was installed by experts who have routinely worked on similar installations for the National Oceanic and Atmospheric Administration (NOAA) and the United Nations worldwide. This gauge has a 1 mm resolution and a repeatability of $\pm 0.01\%$, and it is self-correcting each measurement by simultaneous measurement within a calibration tube with a $\pm 0.025\%$ accuracy, of the temperature variations in the measuring air-column. For our purposes, the system records "normal points" generated internally every six minutes, from 181 1-second observations (3-minute averaging time). Precision leveling of the tide gauge reference mark was carried out to several geodetic benchmarks in the surrounding area. Control levelling is repeated at least twice per year and after any changes in the system or the environment. The backup tide gauge measures differential pressure in a single channel with an accuracy of $\pm 0.2\%$ (tides in the area are of the order of 40 cm). Levelling plans for this system include implementing the method proposed by Smith et al. (1991) for its collocation.

The Dias station (site GJAS, positioned with a short GPS session) is located under the crossover point. This is about 3.5 km south of the Theophilos site. It is a concrete pad of 1.5×2.0 meters, where an altimeter signal transponder (Fu and Cazenave 2000) was installed under a plexiglass enclosure to protect it from the weather. The transponder equipment was initially tested in-house at the Space Research Institute of the Austrian Academy of Sciences, Graz (SRISG) and later, test measurements were made in the vicinity of SRISG and on the Adriatic coast to ensure that the transponder operates successfully on the altimeters of interest and to check if any modifications were required for changing-over to the Jason-1 frequencies. In September of 2003, the transponder was installed permanently at the crossover point on Gavdos. The specifications of the altimeter transponder enable us to measure direct distances to the satellite with a $\approx$5 mm precision. Unfortunately, despite many attempts and modifications, the system has been unsuccessful in acquiring Jason-1, although it has been successful on many occasions with ENVISAT. It is suspected that this is due to the difference in the way the Poseidon altimeter operates in comparison to the ERS or ENVISAT altimeters. The hypothesis is that the transponder-amplified signal is confused during the on-board filtering with noise, and thus eliminated. This has yet to be confirmed by the engineering group.

An Operations Control Center (OCC) was established at the Technical University of Crete campus in Chania (Figure 5). A radio modem at OCC links it with a repeater station on the mountain range peak, south of Chania, and the signal from that site is linked with the facility on Gavdos. A workstation (originally "COSMOS," and recently replaced by "ZEUS") and a backup computer are in continuous operation at OCC, managing data collection, archival, and dissemination. A GPS receiver with a meteorological station is also in continuous operation at OCC, since late 1997. This historical site has been connected repeatedly via short GPS campaigns with the Souda Bay tide gauge operated by the Hellenic Navy Hydrographic Service (HNHS), a system with an observational record of nearly 50 years.

Adjacent to the OCC building, a concrete pad was constructed within the TUC campus, and power, telephone, and internet connections were provided for the deployment of the French Transportable Satellite Laser Ranging System (FTLRS). The system was deployed there from March to November 2003. The results from the absolute positioning experiment and comparisons with the GPS-derived coordinates (site SLR0 with ILRS ID No. 78306901 and DOMES No. 12617M002) will be discussed later. Due to operational limitations of the system under very high ambient temperatures, it was not possible to operate during the summer months, from June to August 2003.

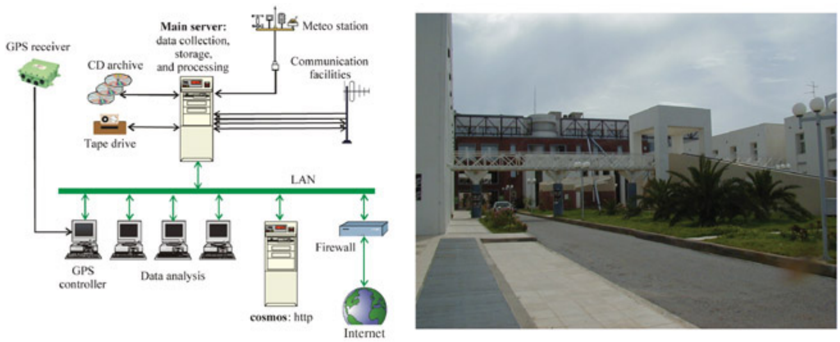

FIGURE 5 The Operations Control Center setup (left), at TUC's campus in Chania, Crete, Greece (right).

Communication of results and project data exchange is facilitated via an official, dedicated web site, which can be easily reached at ⟨http://www.gavdos.tuc.gr⟩. Project data and products are disseminated from this site through a public and a restricted area (Data Center), the latter accessible only to the Project Team. The data and products are archived at the Data Center using a Relational Database Management System (RDBMS), written in Python 2.2.2 programming language. Data will be eventually disseminated to the Permanent Service for Mean Sea Level, and MedGLOSS, on a near-real time basis. When the facility reaches full maturity, this will be accomplished by direct upload of the main and auxiliary tide gauge data records through a EUMETSAT antenna to a central facility where the data can be accessed via internet. The total amount of data transmitted from Gavdos to TUC on a daily basis is about one megabyte. An estimated 30% of that accounts for the Error Correction functions.

In addition to the above described permanent facilities and associated instruments, the project executed an airborne campaign in January of 2003 in order to (a) collect uniform and high quality gravity data over the area of interest for a precise geoid model, (b) collect a sea surface topography (SST) data set with an airborne lidar system for comparison with the radar altimetry, and (c) deploy GPS buoys under the Jason-1 ground-track during overflights for additional direct SSH comparison. The results from the lidar SST and buoy SSH comparisons will be presented in a forthcoming publication. During the same period, a Water Vapor Radiometer (WVR) and a Solar Spectrometer were also deployed under the tracks to allow for a comparison of the atmospheric delays with those observed by the Jason microwave radiometer (JMR).

Precise Positioning Results

GPS Positioning

The Theofilos site was instrumented in late 2002 with a Leica SR520 GPS receiver and an AT504 Leica antenna with a radome. At the Karave site, an Ashtech μZ GPS receiver with a choke-ring Ashtech antenna with a snow cover (cone), were installed in mid-October 2003. At secondary sites we used either Leica SR520 or Ashtech Z-12 receivers over short time periods, ranging from hours to days, depending on the case. All of the data at each site were analyzed on a daily basis.

The reduction of all GPS data collected within the project is done at least at TUC and JCET, independently, using identical software, the program suite GAMIT (King and

TABLE 1 GPS-Derived Geodetic Coordinates at Epoch 2003.0

Location	Site	Latitude	Longitude	Height [m]
FTLRS pad	SLR0	35° 31′ 58″954357 ± 0″00030	24° 04′ 13″966295 ± 0″00040	161.053 ± 0.013
FTLRS retro	SLRT	35° 31′ 54″932866 ± 0″00040	24° 04′ 10″927608 ± 0″00080	173.667 ± 0.021
Theofilos	GVD0	34° 50′ 18″583675 ± 0″00010	24° 06′ 31″904874 ± 0″00020	124.577 ± 0.007
Karave	GVD5	34° 50′ 54″352936 ± 0″00008	24° 07′ 07″047660 ± 0″00010	21.752 ± 0.006
Dias	GJAS	34° 49′ 17″297623 ± 0″00010	24° 05′ 27″663360 ± 0″00014	251.169 ± 0.019

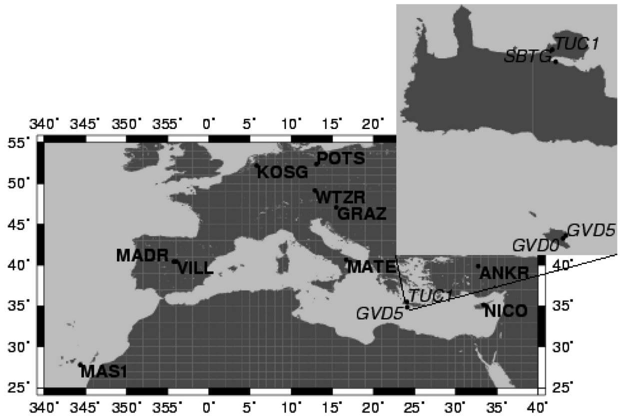

FIGURE 6 The IGS sites used as reference stations for GPS positioning.

Bock 2000). Table 1 lists the results from JCET's analysis. Geodetic coordinates are always referred to the Jason Project ellipsoid (6378136.3 m and $1/f = 298.257$). For the calibration experiment, the sites of interest are the tide gauge (GVD5), and the FTLRS pad (SLR0) and target retroreflector (SLRT).

The reduction of the GPS data was done using double differences of the observed phase, between the GAVDOS sites and a selected set of reference sites extending from as far west as Maspalomas, Spain and east as Nicosia, Cyprus. The precise IGS orbits were used unadjusted. The IGS sites used as reference stations are shown in Figure 6. OCA performed a similar reduction of the GPS data using the same s/w but a slightly different reference network, limited to Central and South European stations. Their results are included in Table 2, along with the SLR-derived positions, for easier comparisons. Positioning results

TABLE 2 FTLRS Position Vector Derived from SLR and GPS Data

Site and Epoch	X [m]	Y [m]	Z [m]
SLR0 1st part 1997.0 (JCET SLR)	4744552.665 ±0.021	2119414.416 ±0.022	3686245.086 ±0.019
SLR0 all data 1997.0 (JCET SLR)	4744552.665 ±0.006	2119414.426 ±0.006	3686245.095 ±0.006
SLR0 all data 2003.7 (JCET SLR)	4744552.558 ±0.006	2119414.553 ±0.006	3686245.158 ±0.006
SLR0 2003.7 (JCET GPS)	4744552.558 ±0.005	2119414.553 ±0.005	3686245.135 ±0.008
SLR0 4 S/C 2003.7 (OCA SLR)	4744552.564 ±0.006	2119414.553 ±0.006	3686245.139 ±0.006
SLR0 2003.7 (OCA GPS)	4744552.561 ±0.005	2119414.555 ±0.005	3686245.138 ±0.008

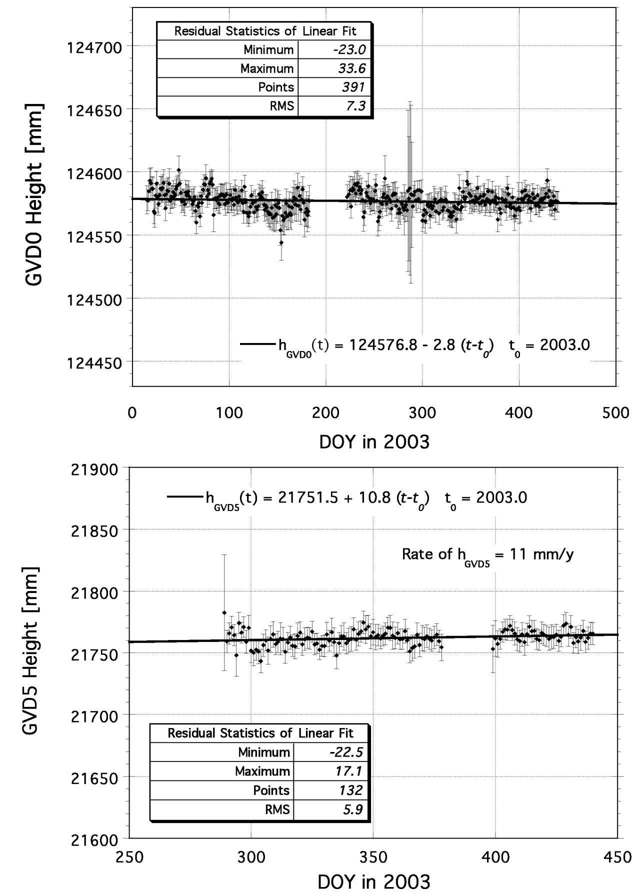

FIGURE 7 Time series of daily geodetic height estimates from GPS observations at the GAVDOS sites Theofilos (top) and Karave (bottom).

for the GPS buoy deployed during the January 2003 campaign will be discussed in a separate forthcoming paper along with comparisons of the deduced SSH data to that from Jason-1 altimetry along the buoy trajectories.

For the primary objective of GAVDOS, the robust and unbiased estimation of the height components is essential. This is assured here with the use of continuous tracking GPS with appropriately designed antenna pillars, and using high-end receivers with geodetic precision. The results for the two sites of highest importance on Gavdos, Karave (GVD5) and Theofilos (GVD0), are shown in Figure 7. From these, the adopted height for GVD5 used in the calibration process was 21.762 m. Leveling by TUC between the GVD5 antenna reference point (ARP) and main tide gauge Sensor Leveling Point (SLP), connected the two systems and effected a geometric height transfer. The result for SLP is 19.263 m at an epoch 2004.0.

SLR Positioning at OCC

Reference frame consistency, especially in the vertical, is of primary importance for this project. Local orbital improvement over the calibration area, is also highly recommended for these experiments. Since Gavdos site is fairly far away from permanent SLR tracking sites Matera, Italy, and Graz, Austria, are the closest two), our project decided include a

FIGURE 8 FTLRS at the TUC campus, the system and the facility.

short-term campaign with a transportable system visiting the oldest site of the GAVDOS network, the OCC at TUC. This established a SLR collocation with one of the GPS network sites. The deployment of FTLRS (Figure 8) lasted from March to October 2003, with data primarily collected during two periods, April–June and September–October, avoiding the high temperature midsummer months. The data, promptly submitted to the ILRS data centers, were analyzed by various analysis centers, including OCA/CERGA and JCET/NASA. The system tracked a number of SLR target satellites, with emphasis placed on the two altimeter-carrying missions, T/P and Jason-1. The distribution of the acquired passes and Normal Point (NP) data is shown in Figure 9.

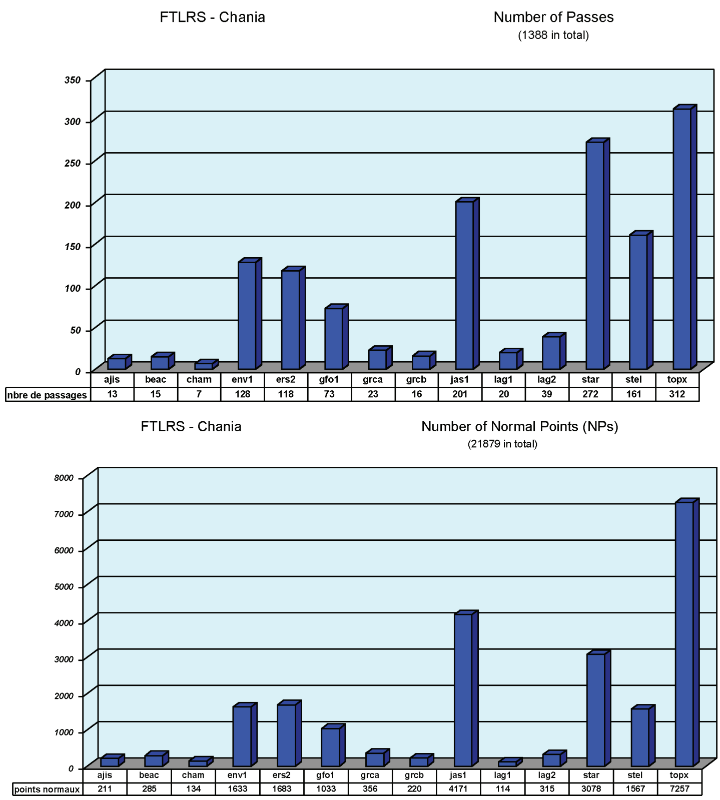

FIGURE 9 FTLRS-acquired SLR data during 2003: number of passes (top) and normal point data (bottom), at TUC, Chania, Crete, Greece.

For precise positioning of the system, two different approaches were used by OCA and JCET, both leading to essentially the same results, given the differences in the amount and distribution of the data used.

At JCET we used a dynamic technique and data taken only on the two geodetic targets, LAGEOS 1 and 2 (Pavlis 2002, 2003). Separate solutions were done for the small data set of Spring 2003, as well as the entire set of data, using a fixed velocity vector relative to stable Europe, derived from many years of GPS observations at TUC1: 35.7 mm/yr at an azimuth of 226° (Pavlis et al. 2002). The position of FTLRS was determined in a quasi-ITRF2000 frame, realized by constraining the rest of the SLR sites' positions and velocities to their ITRF2000 values.

At OCA, the technique of SLR data reduction was based on their short-arc methodology with end-arc-overlaps (Bonnefond et al. 1995), using data taken on the two LAGEOS spacecraft (s/c) and additionally, on the low altitude geodetic satellites *Starlette* and *Stella*. The OCA analysis allowed for the estimation of measurement biases for each target satellite, assuming the biases stable over the entire campaign, with a strategy that minimized the correlation between the height component and the estimated biases. The JCET analysis made no use of low altitude satellites and since JCET's preliminary analysis did not indicate the existence of biases, we did not allow for such parameters in the final solution. The bias recovered from the OCA analysis is at the level of 10 mm, as opposed to an expected level of about 5 mm. The Cartesian positions from SLR, along with those obtained by GPS, are shown in Table 2 for both, the JCET and the OCA analyses. The results are in excellent agreement within techniques as well as across techniques, with only exception the Z-component values between the JCET and OCA SLR solutions and the corresponding GPS estimates.

The discrepancy with GPS of some 20 mm may be due to the fact that the GPS values are simply averaged between the daily estimates from pre- and postdeployment solutions, while for the JCET SLR reductions, the GPS-derived velocity vector was used in the analysis. OCA also averaged their position estimates over the campaign period, making no use of an underlying velocity vector as JCET did. These issues are being investigated now, as the SLR data taken on the other targets during the campaign are analyzed and alternative estimates at JCET, allowing for biases are explored. For this reason, the results presented here do not incorporate the systematic 2-cm Z-shift reported above, but rather accept the GPS-established frame as correct for now.

Local Reference Surface—Regional Geoid

The fact that comparison of distances measured along the local vertical is central to a calibration procedure, requires that we pay special attention in determining as accurately as possible the reference surfaces to which all vertical measurements are referred. Two such surfaces are of interest here: the geoid, to which leveling heights are referred, and the mean sea surface (MSS), which is used by oceanographers to reference sea level anomalies (SLA) obtained from satellite altimetry. The two surfaces differ only by the mean dynamic topography (MDT). The MSS provided on the Jason Project Geophysical Data Records (GDRs) was used in our analysis to remain consistent.

The local geoid mainly reflects the tectonics and geomorphology, as indicated by the detailed, 1-km resolution, topographic and bathymetric digital terrain model (DTM) that we compiled for the area (Figure 10). The new model is based on a 500-m resolution DTM data set obtained from the Greek Military Mapping Service and the Smith and Sandwell DDM. This data set was used to compute accurate topographic corrections for the surface gravity data during the development of the regional geoid model. With Gavdos only a few

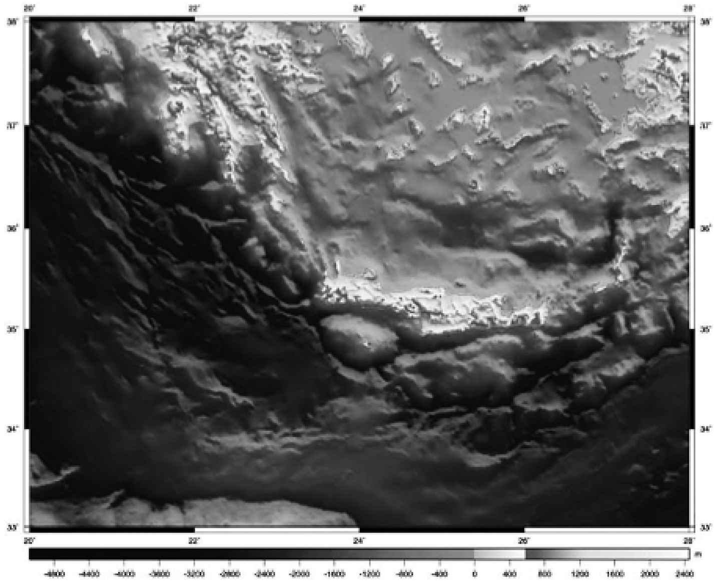

FIGURE 10 The newly developed 1-km DTM for the GAVDOS region of interest and surrounding area.

kilometers north of the Hellenic Trench that runs south of Crete and nearly parallel to it, the regional geoid is fairly rough and with rapidly varying gradients that are very much direction-dependent. Although the area was covered by shipborne gravity measurements, the quality and distribution of that data was deemed insufficient for the purposes of this project. We therefore planned two airborne campaigns to collect high quality and uniformly distributed gravity data over the region of western Crete.

Because another project, CAATER (Olesen et al. 2002), with similar requirements over the same area was executed one year prior to ours, we finally reduced our campaigns to one, while increasing the number of overflights (Figure 11) and adding an expanded suite of height-measuring devices, a lidar, and a scanning lidar for SSH measurements.

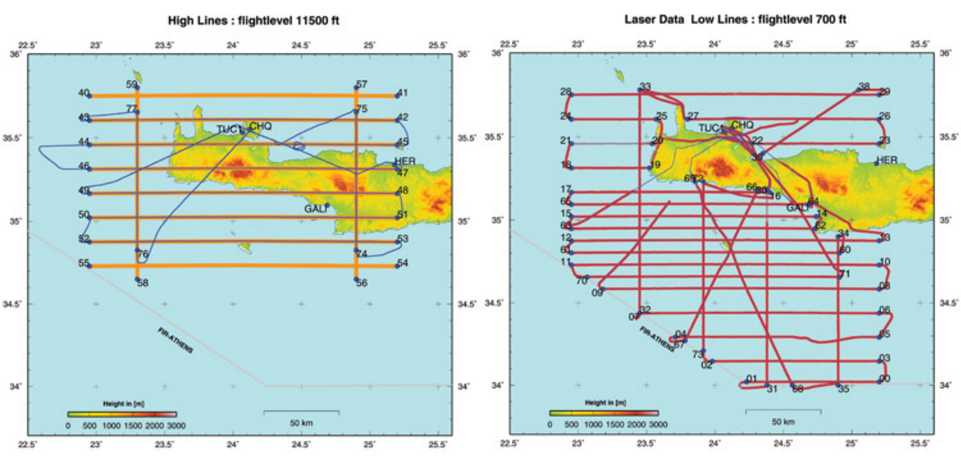

FIGURE 11 Flight-paths for airborne gravity measurement campaign. On the left, high (3 km) and on the right, low (300 m) altitude flight paths. The red lines indicate lidar data taken during the low flights.

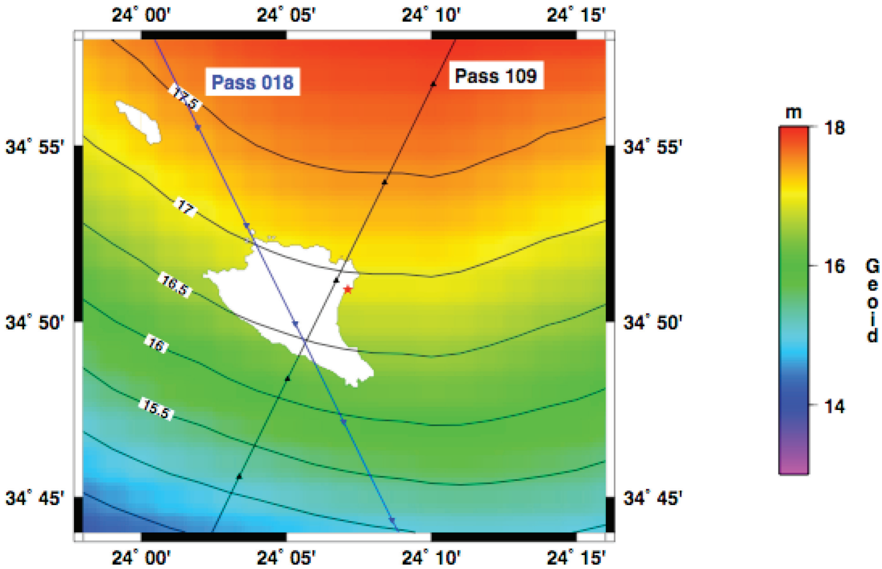

FIGURE 12 The final $1' \times 1'$ resolution geoid model around Gavdos, Greece, with Jason-1 mean-track locations for descending pass 018 and ascending pass 109. The red star indicates the Karave tide gauge.

The data collected from our campaign along with that from the CAATER campaign and the shipborne and surface gravimetry, were all used to generate, through optimal combination procedures, a set of geoid models for the region (Vergos et al. 2003).

The model used here is shown in Figure 12 for the area immediately around Gavdos. The formal accuracy estimate produced during the generation of the model indicates a subcentimeter accuracy. Validation with ground-truth though suggests that a more realistic value is 1–2 cm at best. Interpolation of the local geoid and the MSS at the 1 Hz Jason-1 sub-satellite points (referenced to the mean track), show good agreement, since the mean dynamic topography (MDT) in the area has a relatively small range centered at -14 cm (Rio et al. 2004). The predicted geoid undulation N from our $1' \times 1'$ geoid at the tide gauge is 16.733 ± 0.012 m. Combining this with Rio's MDT for the tide gauge location (-12 cm), we arrived at a MSS ($= \text{N} + \text{MDT}$) value of 16.613 m. Interpolation of the GSFC00.1 MSS, which is the reference for the altimeter sea level anomalies (SLAs), results in a value of 16.820 m, the two estimates differing by 20.7 cm. This is not unreasonable for this area and indicates that the regional geoid development was indeed required. In order to remain consistent with the new geoid and MDT, both of which are more accurate over our region, we have referenced the GDR SLAs to the new geoid and MDT, applying at each point the difference between the two surfaces. On the basis of this final geoid and MDT combination, the adopted MSS value at the tide gauge is 16.613 m. This is the reference value subtracted from the tide gauge sea level heights to generate the ground-truth SLAs at Karave.

Tide Gauge Measurements

The main (acoustic) tide gauge on Gavdos was initially installed in late August of 2002. A subsequent storm, only less than a month later, damaged the sensor and the recording data-logger, which led to several delays until the problems were understood, the installation improved and protected from the high seas, and a new system installed. Unfortunately, by

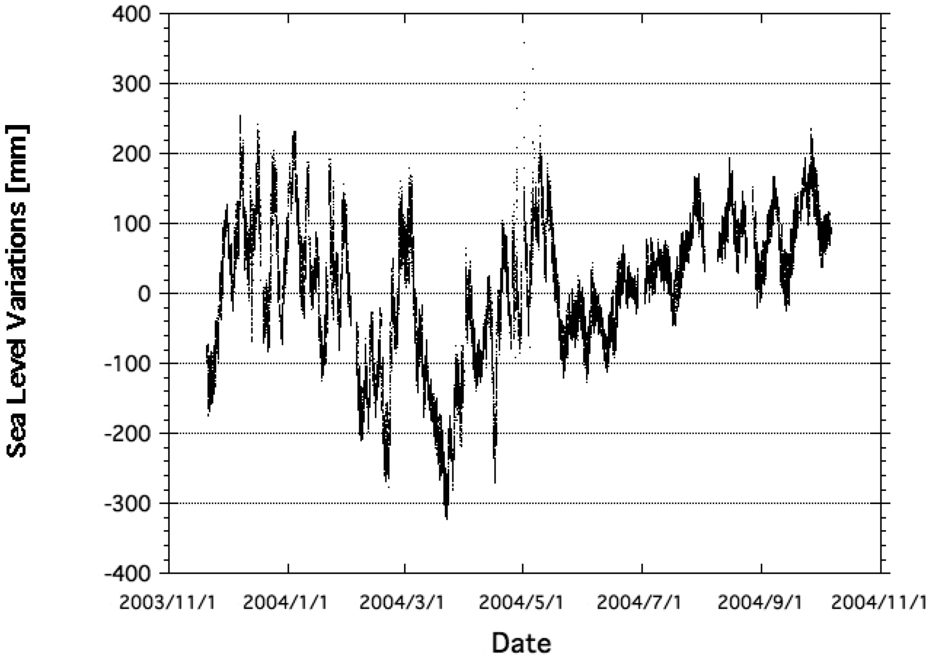

FIGURE 13 Sea level variation observed by the main tide gauge at Karave, Gavdos, Greece, with respect to adopted reference MSS = 16.613 m. Ocean tides are fully present.

the time the new system was operational again, the formation flight phase was completed and despite all our efforts, our plans to crosscalibrate both Jason-1 and T/P at the same facility, fell through. The current system works very well and produces high-resolution accurate sea level observations (3-minute normal points) at 6-min intervals and with a 0.1-mm resolution (Figure 13). After editing, the raw tide gauge measurements are stored in the project database.

The raw sea level observations are subsequently converted to SLA-equivalent values for direct comparison with the Jason-1 observations. This step comprises several corrections. Firstly the observation time-tags are converted to the UTC from the GPS timescale, since our timing is obtained from GPS. We then apply corrections specific to our system to convert the raw water level values to actual height variations with respect to the ellipsoid and then to reference them to the MSS. These include the engineering corrections to account for the offset between the sensor "zero" and the leveling benchmark, and the offset between the same benchmark and the antenna reference point (ARP) of the GPS receiver which is the point of reference of our position estimates (Figure 14). One further correction applied is that of the ocean tides. This is done using the exact same models used in the case of the altimetry data set, and it is applied so that our SLAs are compatible with the altimetry counterparts, which in our case have all but the IB corrections applied. This will be explained further in the calibration section.

Altimetry Data

The altimetry observations used in the calibration process are based on the official 1 Hz GDRs, they are obtained though from the Pathfinder database (Koblinsky et al. 1999a, 1999b). These data will be replaced by the reconstructed 20 Hz data, once our new database

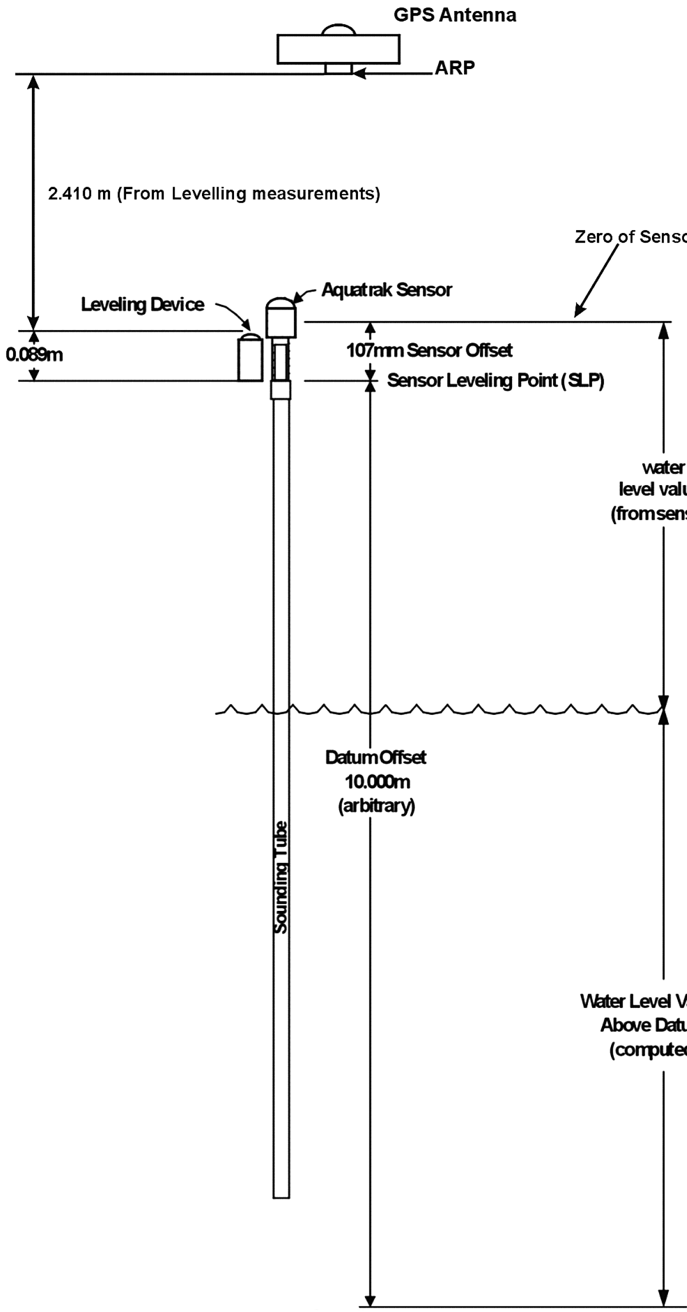

FIGURE 14 The primary tide gauge setup at Karave.

with the higher rate data becomes available (late 2004). It is expected that the denser data set will allow for better data editing and a better comparison with observations closer to the ground-truth data. The Pathfinder database is fully compatible with the Jason GDRs, these data however are referenced to a set of standard geographic locations (latitude, longitude) identified by the standard Pathfinder location numbers. These are unique and correspond sequentially to locations on a mean T/P track rather than the actual track for each revolution of Jason-1. They also have the corrections that appear on the GDRs applied already, with the exception of the IB correction. This necessitates that we also must remove the ocean tides signal from the tide gauge observations. We do so using the same model that is on the GDRs. In doing so, we also remove the small but not negligible differences between the tidal signal at the tide gauge versus the one at each altimeter observation, due to the difference in geographic location. The tracks for the passes of relevance to GAVDOS were shown in Figure 12, descending pass 18 and ascending pass 109. The Pathfinder SLAs that we have used here are also available at the PO.DAAC database, including documentation and software to access them. The availability of this product simplifies comparisons since there are no additional interpolations involved. The required cross-track corrections between the mean and actual tracks are applied during the generation of the Pathfinder product.

The altimeter data indicate higher noise and systematic biases as the altimeter approaches land and when the system starts tracking again over water after being over land. It is thus required that data close to the shoreline be edited, otherwise the calibration results will be contaminated by artifacts. After testing several schemes to automate this process, we have concluded that the simple approach to delete any observations within an adopted interval covering the area over the landmasses of Gavdos and Crete, works best. The selected data points for cycles 70–90 are shown in Figure 15.

Calibration Results

Altimeter Calibration

The very first, preliminary absolute bias estimates from GAVDOS were presented at the November 2003 Science Working Team meeting. Although, at the time, we had only results from two cycles (52 and 53) and the preprocessing did not follow entirely the methodology used here, the difference of the estimated value of 128 ± 78 mm was well within the error bar of the estimate and the commonly accepted value of the bias.

By early 2004, our data processing was improved, and we had also acquired a more robust set of tide gauge measurements that allowed us to perform a reasonable number of comparisons (16) over eight consecutive cycles (70–77). At the 2004 COSPAR we reported a more accurate bias estimate of 134 ± 20 mm, (Pavlis et al. 2004). This value however was still based on a preliminary geoid model with a $3' \times 3'$ resolution, which did not incorporate regional information from the airborne campaigns.

The results presented here are based on an extended observational record that covers all Jason-1 cycles from 70 up to 90 inclusive. They benefit from the improved GDR data editing procedures, the higher resolution regional geoid, and nearly quadruple the number of observations: 41 comparisons in 21 cycles for the two passes 18 and 109 (cycle 78 data

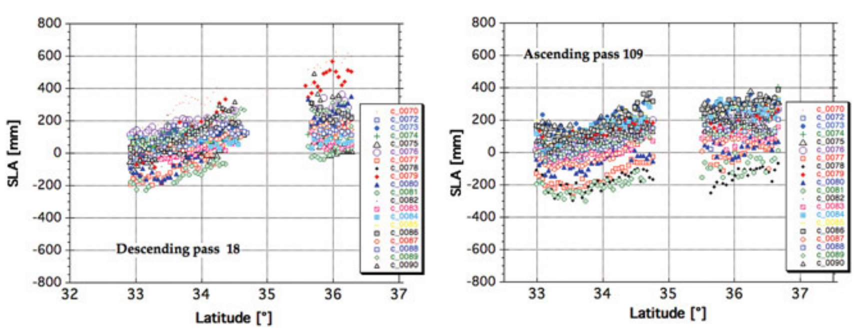

FIGURE 15 Jason-1 1-Hz SLA data in the Gavdos area from the Pathfinder database for passes 18 and 109, and during cycles 70–90.

for pass 18 are flagged unusable). The calibration concept is based on the comparison of sea surface heights obtained from the altimeter and the tide gauge, over an area surrounding the tide gauge, and after both data sets are reduced to sea level anomalies with respect to a common reference surface. This is encapsulated in the following set of equations:

$$
\begin{aligned}
\text{Altimeter bias} &= \text{SLA}^*_{\text{Alt}} - \text{SLA}^*_{\text{TG}} \\
&= [\text{SSH}_{\text{Alt}} - \text{MSS}_{\text{Alt}}] - [\text{SSH}_{\text{TG}} - \text{MSS}_{\text{TG}}] \\
&= \left[\text{SLA}^{\text{P}}_{\text{Alt}} + \text{MSS}^{\text{GDR}}_{\text{Alt}} - \text{MSS}^{\text{L}}_{\text{Alt}}\right] \\
&\quad - [\text{SLA}_{\text{TG}} - (\text{Ocean tides})_{\text{TG}}]
\end{aligned}
$$

In the above equation, the first line states the concept, while the relationship of the SLA*s to the SSHs. The third version details the corrections applied to the Pathfinder product ($\text{SLA}^{\text{P}}_{\text{Alt}}$), correcting it for the difference between the GSFC00.1 reference surface which appears on the GDRs, $\text{MSS}^{\text{GDR}}_{\text{Alt}}$, using the locally determined surface $\text{MSS}^{\text{L}}_{\text{Alt}}$.

In this last version of the closure equation we also show how the spatial difference in ocean tide signal is handled, eliminating the signal from both SLAs (at the tide gauge and the altimeter observation), using identical models evaluated at the appropriate locations and epochs. This scheme is applied on each pass separately, and an average bias is estimated along with a set of formal statistics for each pass. Since formal statistics convey only internal consistency, we have attempted to develop a more realistic error budget for the estimated bias, using the known or realistically expected systematic and random errors associated with each of the measured components entering the closure equation. This error budget is listed in Table 3.

The inclusion of a possible systematic bias from the Jason microwave radiometer (JMR) correction was prompted by the reports that such a bias seems likely near coastal areas and closed seas, like the Mediterranean (Desai and Haines 2004; Scharroo et al. 2004). During the calibration process, we determine the mean, the median, the RMS scatter and the standard deviation of the mean for each pass and each cycle (Figure 16). The scatter for each pass is subsequently used to determine relative weights, when we combine all the mean and median estimates to determine the best overall estimate of the bias and its formal statistics.

It is worth noting that the overall scatter for descending pass 18 estimates is significantly larger than for the ascending pass 109 estimates. This is probably due, among other reasons, to some remaining land contamination and further investigation of our editing limits is required. Mean and median estimates of the altimeter bias based on different weighting schemes are given in Table 4, for each pass separately and in combination.

TABLE 3 Calibration Process Error Budget for the Jason-1 GAVDOS Tide Gauge Results and the Period Spanning Cycles 70–90, (41 Cases)

Component	Systematic	Random
GPS position (Karave)	10 mm	6 mm
Levelling, (TG to GPS antenna)	3 mm	1 mm
Jason altimetry	—	30 mm
Local geoid	10 mm	4 mm
JMR bias	−5 to −10 mm	—
Uncertainty without JMR bias		15 mm
Uncertainty with JMR bias		16–18 mm

— Not defined.

TABLE 4 Jason-1 Mean and Median Absolute Bias Estimates, Based on Two Different Weighting Schemes

Units are mm	Pass no.	Weight factors (WF)		Absolute bias	
Weights based on:		Mean WF	Median WF	Mean	Median
Standard	18	63	56	134.7 ± 5.4	134.4 ± 5.5
Deviation	109	55	46	157.1 ± 5.2	155.9 ± 5.1
	18 + 109	47	45	145.9 ± 5.3	145.1 ± 5.2
Standard	18	12	10	131.6 ± 5.7	131.5 ± 5.8
Error	109	11	10	156.8 ± 5.3	155.6 ± 5.2
	18 + 109	10	9	144.2 ± 5.5	143.6 ± 5.4

The range of estimates for each pass separately and the combination of the two are:

Pass	18	131.5 to 134.7 mm	Δbias = 2.2 mm
Pass	109	155.6 to 157.1 mm	Δbias = 1.5 mm
Combined		143.6 to 145.9 mm	Δbias = 2.3 mm

This indicates that the choice of weighting and the use of the mean versus the median, only insignificantly affects the end result, at the 2-mm level. On the other hand, the choice between one pass or the other, results in a range of values spanning 131.5 to 157.1 (i.e., 25.6 mm), 4 to 5 times the average standard error in Table 4. This systematic difference points to still existing errors at that level, resulting from a combination of the data editing scheme, the local geoid, and the positioning estimates. Averaging the four combined estimates we arrive at a bias of 144.7 ± 5.4 mm. Based on the above comments about the formal statistics and the error budget from Table 3 though, we consider that a more realistic bias and error estimate is 144.7 ± 15 mm based on our 41 calibration events.

The absolute bias result is consistent within the quoted accuracy estimate with the results reported from the Harvest Platform (Haines et al. 2003), Corsica (Bonnefond et al. 2003), Bass Strait (Watson et al. 2004) facilities and the results from the UK group (Woodworth et al. 2004). We have plotted in Figure 17 our individual estimates along those from Harvest and

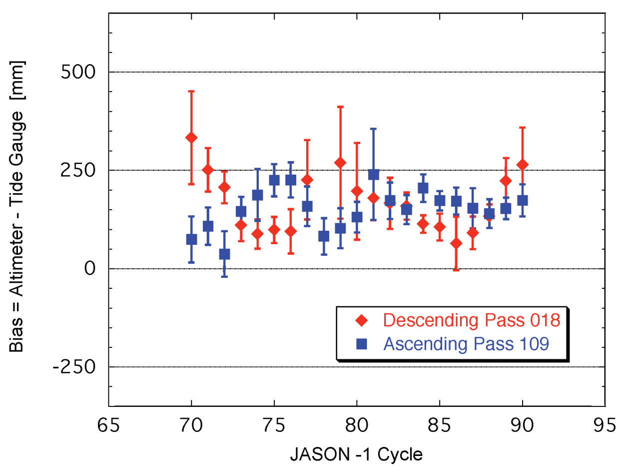

FIGURE 16 Absolute bias estimates for Jason-1, obtained at the GAVDOS facility during cycles 70–90, for descending pass 18 and ascending pass 109. Error bars indicate scatter about the mean.

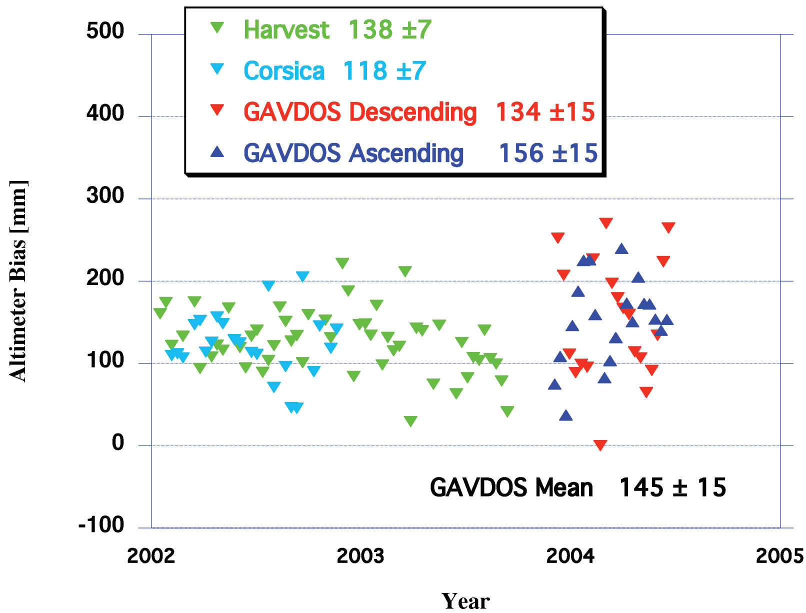

FIGURE 17 Absolute bias values for Jason-1 obtained at the GAVDOS facility for cycles 70–90 and for pass 18 and 109, along with Jason-1 results from the Harvest and Corsica calibration facilities.

Corsica, kindly made available to us by B. Haines (private communication). Additionally, Table 5 summarizes the current results at all above sites, along with the quoted accuracy estimates and the number of events on which these results are based. A quick review of the evolution history of calibration results from the above sites, reveals a systematic increase

TABLE 5 Jason-1 Absolute Bias Estimates from Various Calibration Experiments and for Different Standards (Orbit, SSB Model, Cases, etc.)

Facility	Orbit	Events	Mean ± std. error [mm]	σ [mm]
Harvest	CNES POE	31	+138 ± 7	41
Harvest	JPL GPS	31	+132 ± 6	34
Corsica	CNES POE	29	+118 ± 7	35
Corsica	JPL GPS	29	+124 ± 7	36
Bass strait	CNES POE	47	+148 ± 6	42
Bass strait	JPL GPS	47	+131 ± 6	40
UK group	CNES MOE	387*	+137 ± 30	80
UK group	CNES POE	610†	+143 ± 30	71
GAVDOS[1]	CNES POE	16	+134 ± 20	80
GAVDOS[2]	CNES POE	41	+145 ± 15	47

Note: In all cases the sea state bias (SSB) model of Labroue and Gaspar (2002) was used (on GDRs).

*Two events (ascending/descending) at five locations over 43 cycles, except for one site with only one event/cycle.

†Two events (ascending/descending) at five locations over 61 cycles.

[1]COSPAR 2004 results.

[2]Present analysis.

in the mean estimates, from the early 9–10 cm levels during the formation flight phase, to the more recent results reaching the 15 cm level. This upward trend is likely tied to the previously discussed issues with the Jason microwave radiometer (JMR) performance over this period. Through our parallel investigation for the calibration of the JMR, we hoped to shed some light on this systematic behavior, however, the limited number of experiments (2), and the specific period covered did not produce any conclusive evidence for or against this theory so far.

JMR Calibration

The GAVDOS project plan incorporates a number of experiments to calibrate in addition to the altimeter radar; these include a number of other observables, one of which is the atmospheric delay obtained from the on-board microwave radiometer (JMR). These measurements are extremely important in deriving unbiased sea level estimates from satellite altimetry, since any bias, drift or other systematic error here, will translate directly into a comparable SLA error and corrupt them. Furthermore, drifts over time, will alias as sea level change with obvious repercussions. The project has, on a limited time basis, two instruments with which independent estimates of the atmospheric delay can be obtained. A Water Vapor Radiometer (WVR2000) and a GEodetic MObile Solar Spectrometer (GEMOSS), both of which belong to the Geodesy and Geodynamics Laboratory of ETH Zurich, one of the GAVDOS Project partners. A detailed description of the experiments carried out with these instruments will appear in a forthcoming paper (Somieski et al. 2004). In this section, we summarize the results and complement them with additional comparisons from an independent space-borne system utilized by JCET.

GEMOSS and WVR Results

Two campaigns with the WVR2000 and GEMOSS instruments were carried out in 2003. The first one in January of 2003 took place as part of the airborne campaign over Crete, with the two instruments and a GPS reveiver deployed near Rethimnon, Crete, under the ascending pass 109. The second deployment was in September 2003, as part of another campaign separate ETHZ project, with the same instruments deployed at Fiskardo, Kefalonia, under the Jason-1 pass 211 (Figure 18).

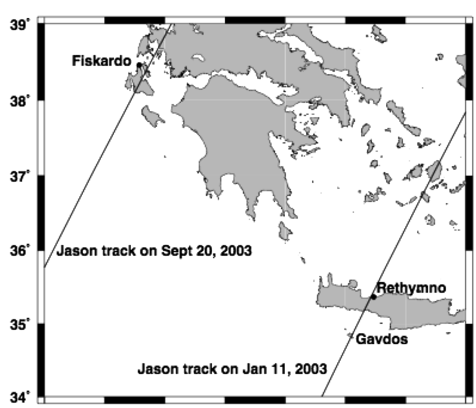

FIGURE 18 The Jason-1 passes 109 and 211 over Rethimnon and Fiskardo, Greece, for cycles 37 (Jan. 2003) and 62 (Sept. 2003), respectively, during calibration measurements for the JMR instrument.

TABLE 6 Jason-1 Zenith Wet Path Delay from JMR Compared to Ground Observations from WVR2000 and GEMOSS

System(s)	Fiskardo, Kefalonia	Rethimnon, Crete
Jason-1 GDR Model	*131.2 mm*	*85.5 mm*
JMR	132.4 mm	71.6 mm
GEMOSS	134.0	70.4
WVR2000	138.9	—
JMR—GEMOSS	−1.6 mm	1.2 mm
JMR—WVR2000	−6.5	—

— Not defined.

The zenith wet path delay measurements from WVR and GEMOSS were also compared to radiosonde measurements at Fiskardo. The agreement of all different means of measuring the wet path delay is excellent, at the 1–2 mm level, and the results are summarized in Table 6. These measurements fall in a period during which the JMR instrument shows no significantly irregular behavior in terms of jumps, drifts, and so on, which has indeed been observed in previous and subsequent periods. The Fiskardo comparisons are of higher quality as Jason-1 is approaching from open seas, while in the case of Rethimnon, the system has been over land (Crete) and the JMR measurements show increased noise and systematic behavior.

AIRS Comparison Results

The Atmospheric Infra-Red Sounder (AIRS) aboard NASA's satellite mission AQUA, is able to measure twice daily a number of environmental parameters of Earth's atmosphere in the form of atmospheric profiles (Aumann et al. 2003). AIRS data comes in the form of a granule, which contains 30 cross-track points in each of 45 along-track scan-lines. Each measurement point has a spatial resolution of approximately 50 km and there are a total of 1350 ($= 45 \times 30$) such points per granule. The vertical resolution is 28 pressure levels extending from the surface up to 0.01 mb, pressure being ancillary data from ECMWF fields. AIRS granules that were chosen here cover the appropriate JMR track spatially and temporally. In addition to AIRS data, we also have available from another AQUA instrument, the Advanced Microwave Sounding Unit (AMSU), brightness temperatures to be compared with those from JMR measurements. The spectral range includes 13 channels from 50–90 GHz and 2 channels from 23–32 GHz. We have looked at channel 1 (23.8 GHz) and channel 2 (31.4 GHz), the two closest to those used by JMR. JMR measures sea surface microwave brightness temperatures at three frequencies, 18.7 GHz, 23.8 GHz and 34.0 GHz. The 23.8 GHz channel is used for water-vapor measurement, the 18.7 GHz channel provides corrections for wind-induced effects in the sea surface background emissions, and the 34.0 GHz channel provides a correction for cloud liquid water. All these measurements are combined to provide the range correction for the wet path delay due to water vapor in the atmosphere. We are currently extending our comparison between the two systems to global comparisons, focusing on regions that are exclusively open seas, as well as areas that are close to the coast, so that we can discriminate between the variable performance of JMR as it was discussed during the November 2003 Science Working Team meeting and in (Scharroo et al. 2004). At this time, the comparisons we present here are limited to the two Mediterranean campaigns as described in the previous section. The wet zenith path delay comparison between JMR and AIRS/AMSU are summarized in Table 7. As was the case with WVR2000 and GEMOSS, the two systems agree very well and within their observational error uncertainty, at about the 2 mm level.

TABLE 7 Jason-1 Zenith Wet Path Delay from JMR Compared to AIRS/AMSU Equivalent Product

System	Fiskardo (cyc 62/pass 211)	Rethimnon (cyc 37/pass 109)
JMR	132.40 mm	71.60 mm
AIRS/AMSU	130.28	72.64

In addition to comparing the wet zenith delay at the over-flight locations, we have also compared the total precipitable water vapor at locations prior to and following these two, and for the two tracks that we examined here. Regression plots for each case are shown in Figure 19.

We note the order of magnitude difference in the observable between the two cases, as the one (Rethimnon) occurred during winter (January 2003) and the other (Fiskardo), during autumn (September 2003). Although the correlation is fairly strong in both cases, the scatter about the regression line is one order higher in the second case (0.12 vs. 1.2 kg/m^2), indicating a strong dependence on the magnitude of the measured quantity. This, however, is more likely due to the fact that, in the case of the winter observation, the range of measurements is 8–12 kg/m^2 vs. a range of 20–48 kg/m^2 for the autumnal measurement. In the first case, the signal level and the range of the observed signal is much smaller than in the second case, and it is certainly a much more uncertain estimation of the regression coefficient and the correlation between the two systems. The fact that the slope of the regression lines are not equal to one means that there is a bias between the two systems, however, we cannot make a definitive statement for its value, based on two observations. It should also be noted that in neither case, are the AIRS and JMR observations simultaneous in time. Although this can happen at times, in these two cases, there is a 1-hour difference between the two. While the atmosphere is dryer and more stable over an hour in the winter, things can change considerably over an hour during the humid, warm months of early autumn. For these reasons we view these experiments as a "proof of concept," rather than as a definitive result. A lot more work remains to be done until this method can pass the test as a truly operational calibration procedure. To this extent, comparison of the two systems is already underway on a global scale, and for all periods of significant JMR performance changes.

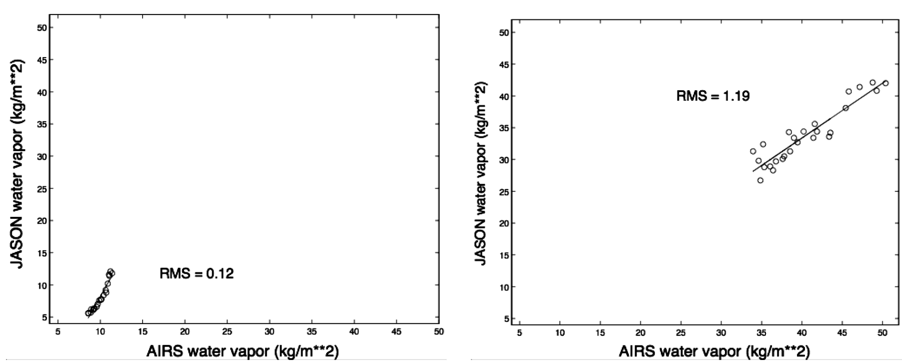

FIGURE 19 Total precipitable water vapor comparison for passes 109 and 211 (cycles 37 and 62, respectively) over Rethimnon and Fiskardo between Jason-1 JMR and AIRS observations.

Summary and Future Plans

Full deployment and regular operation of the GAVDOS project facility by the fall of 2003, produced a wealthy collection of in situ observations that allowed us to carry several comparisons with observations made on-board Jason-1 with its altimeter radar and the JMR instruments. The current sample is now comparable to what is reported from other similar facilities, and the continued regular operation of the facility will soon deliver in near-real time calibration and validation results of equal and higher quality. As for the Poseidon altimeter absolute measurements bias, our 41 observations during cycles 70–90 and the earlier two cycles 52 and 53, indicate that a best estimate is 145 ± 15 mm, consistent with the results obtained at other calibration/validation sites. Comparison of JMR measurements with ground observations and equivalent products from the AQUA mission's AIRS and AMSU instruments, indicate an agreement in the total wet zenith path delay at the 2 mm level, for the two specific cycles 37 and 62.

Future plans of the project include the reevaluation of the altimeter calibration using a better-edited 20 Hza data set, which we are now regularly reconstructing and archiving in a local database. We will start delivery of our comparisons in near-real time, following the release of GDR products, and extend the processing to include IGDR evaluations. We are expanding our JMR cal/val activity with a broader focus on global rather than local scale comparisons. In particular, we will be discriminating between closed seas/coastal areas, and open ocean, looking at the total precipitate water vapor, the wet zenith path delay, and brightness temperatures at 23.8 GHz and 31.4 GHz. These comparisons will be supplemented with comparisons to the total zenith wet tropospheric delay derived from our daily GPS observations at Karave. In terms of ground collected data, we will attempt again to resolve issues that prohibit acquisition of Jason-1 observations with the transponder unit deployed on Gavdos, and expand our cal/val activities to include other oceanographic missions, in particular, ENVISAT and GFO. We plan to deploy an additional tide gauge on Crete, so that we can increase redundancy in the existing infrastructure, and to also allow us to calibrate T/P in its present orbit.

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