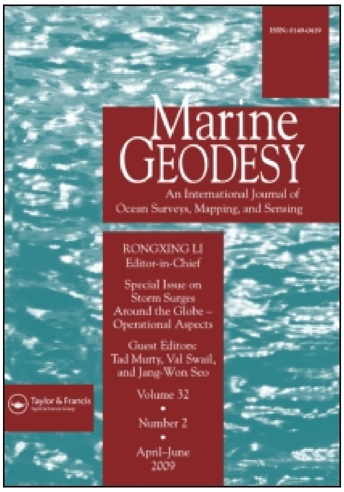

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Bruce J. Haines; Danan Dong; George H. Born; Stephen K. Gill

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The Harvest Experiment: Monitoring Jason-1 and TOPEX/POSEIDON from a California Offshore Platform

BRUCE J. HAINES
DANAN DONG

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California, USA

GEORGE H. BORN

Colorado Center for Astrodynamics Research
University of Colorado
Boulder, Colorado, USA

STEPHEN K. GILL

National Oceanic and Atmospheric Administration
National Ocean Service
Silver Spring, Maryland, USA

We present calibration results from Jason-1 (2001–) and TOPEX/POSEIDON (1992–) overflights of a California offshore oil platform (Harvest). Data from Harvest indicate that current Jason-1 sea-surface height (SSH) measurements are high by 138 ± 18 mm. Excepting the bias, the high accuracy of the Jason-1 measurements is in evidence from the overflights. In orbit for over 10 years, the T/P measurement system is well calibrated, and the SSH bias is statistically indistinguishable from zero. Also reviewed are over 10 years of geodetic results from the Harvest experiment.

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This article is dedicated to Edward "Chris" Christensen, whose Harvest Platform experiment continues to return useful scientific data 10 years beyond the end of the T/P verification phase for which is was designed. We are indebted to Plains Resources, and their subsidiary Arguello Inc., for hosting our experiment on platform Harvest. We also thank the Torch Operating Company, especially John Turner, Jim Chapman, Bob Ryan, and Geary Olivera for accommodating our trips to the facility and assisting with the experiments whenever possible. The Harvest experiment is a multiagency effort, and we are indebted to numerous individuals for engaging in design, installation, operation, and maintenance of the sensors, as well as interpretation of the data. They include: Dan Kubitschek, Dave Stowers, Kevin Miller, Steve Dinardo, and Charles Morris (JPL); Razmik Khachikyan (Raytheon); Joel Nyquist and Keith Morris (CU); Mickey Moss, Eddie Shih, Jim Russell, Clyde Kakazu, and Mark Bailey (NOAA); K. C. Rockwell (Arguello). The Harvest research activities of authors B.H. and D.D. are funded by the NASA Physical Oceanography Program. We are grateful to Eric Lindstrom and Lee Fu for advancing the Harvest experiment and for assisting with the renewal of interagency cooperations needed for experiment upgrades prior to Jason-1 launch. A portion of this work was conducted by the Jet Propulsion Laboratory, California Institute of Technology under contract with NASA.

Address correspondence to Bruce Haines, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA. E-mail: bruce.j.haines@jpl.nasa.gov

Keywords calibration, GPS, Jason-1, satellite altimetry, sea level, TOPEX/POSEIDON, validation

The Arguello Inc. Harvest Oil Platform is located about 10 km off the coast of central California near Vandenberg Air Force Base (Figure 1). An impressive structure, the platform is anchored to the sea floor and sits in about 200 m of water near the western entrance to the Santa Barbara Channel (Figure 2). Conditions at Harvest are typical of the open ocean, and the seas can be quite heavy. Ocean swell and wind waves average about 2 m, though waves over 7 m have been experienced during powerful winter storms. Prevailing winds are from the northwest and average about 6 m/s. The platform is served by helicopters from the Santa Maria, California, airport, and is regularly visited by supply boats. Built in 1985 and operational since 1991, Harvest has produced over 68 million barrels of oil as of April 2001.[1]

In addition to its primary mission to drill for oil, Harvest has served as a calibration site for the joint U.S./France TOPEX/POSEIDON (1992–) and Jason-1 (2001–) missions, and thus is an important international resource for the study of sea level from space. Harvest offers a number of advantages as a spaceborne altimeter calibration site. The platform is located sufficiently far offshore so that the area illuminated by the altimeter's radar pulses is covered entirely by ocean when the satellite is directly overhead. At the same time, the platform itself is small enough so that it cannot influence the reflected radar signal. Equally important, the open-ocean environment implies that the spacecraft measurement systems are monitored in the conditions under which they are designed to best operate. Finally, the platform is located in proximity to important tracking stations in California and the western U.S., data from which contribute to measuring the geocentric positions of the altimeter satellites and platform through space-based surveying techniques. Recognizing the potential, the Jet Propulsion Laboratory (JPL) reached an agreement in March 1991 to use Harvest, owned then by Texaco U.S.A., as the primary NASA calibration site for the TOPEX/Poseidon (T/P) mission (Christensen et al. 1994; Morris et al. 1995). A

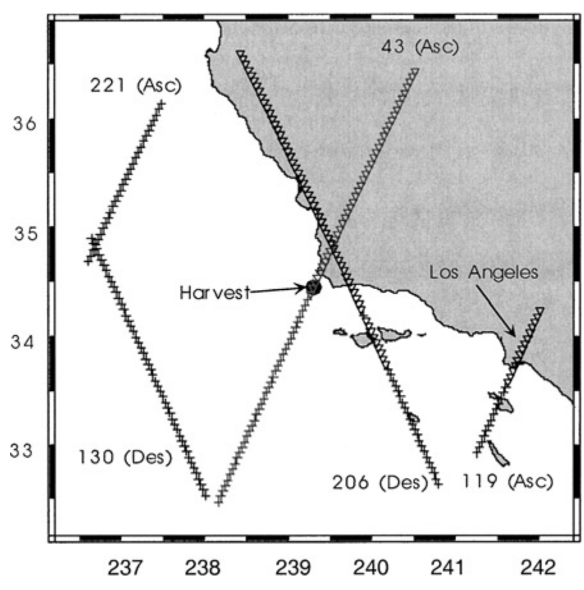

FIGURE 1 Map of Arguello Harvest Platform vicinity. The facility is located in the open ocean, about 10 km from Vandenberg Air Force Base off the coast of central California.

[1]http://www.mms.gov/omm/pacific/offshore/platforms/arguelloplatform.htm

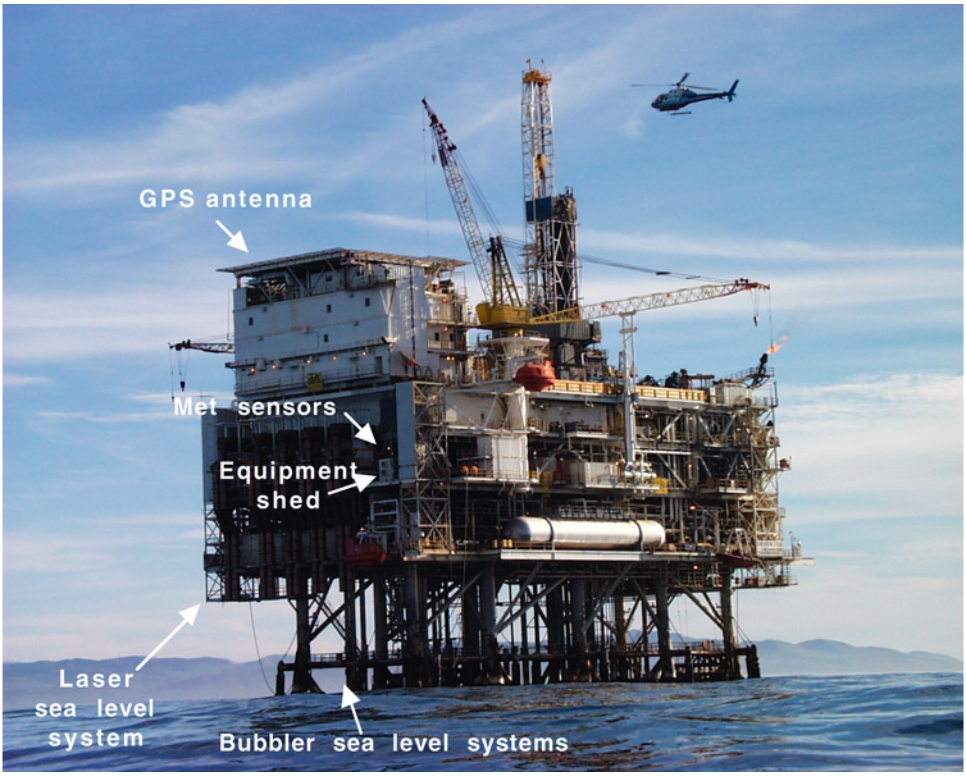

FIGURE 2 Photo of Arguello Harvest Platform. The platform sits in 200 m of water, and extends approximately 50 m (excluding derrick) above the mean water level.

companion site was identified by the French Centre National d'Etudes Spatiales (CNES) on the Mediterranean islet of Lampione (Ménard et al. 1994), and the 10-d repeating T/P orbit was designed to bring the satellite directly over both locations.

The Harvest experiment features carefully designed collocations of space-geodetic and tide-gauge systems to support the absolute calibration of the altimetric sea surface height (SSH). The SSH bias and its stability are important elements of the altimeter system error budget (Chelton et al. 2001). Knowledge of this bias is essential for specialized studies that rely on accurate determination of scale, such as determination of the Earth's mean radius. More important, estimates of the biases are needed to merge data from different missions, or from different measurement systems on the same mission, in order to condition altimetric time series of global mean sea level.

Shortly after the T/P launch, results from Harvest suggested that the TOPEX sea surface height (SSH) measurements were erroneously high by 145 ± 29 mm (Christensen et al. 1994). With data from additional overflights and improved GPS-based determinations of the platform geocentric height and velocity, Haines et al. (1996) reported a TOPEX bias of 125 ± 20 mm at the conclusion of the 3-year primary mission. Also identified in early results from other dedicated calibration sites (Ménard et al. 1994; Murphy et al. 1996; White et al. 1994), the bias is now recognized as a consequence of an error in the software used to produce the TOPEX data for the mission scientists (Neram et al. 1997).[2] The close agreement between the mean value of the software error (133 mm) and the bias estimates

[2]O. Zanifé, P. Escudier, and P. Vincent are credited with discovering the software error.

testifies to the ability of the Harvest configuration to support detection of spurious signals in the T/P altimeter measurement systems. The software error also introduced a spurious drift ($\sim$7 mm/yr) in the global mean sea level (Nerem et al. 1997). This drift was first detected by Mitchum (1998) using an innovative technique that relies on proximate overflights of tide gauges in the global network. The overall experience underscored the essential role of continuous calibration and validation for any altimeter mission (Chelton et al. 2001).

While the most conspicuous results from the Harvest experiment are the SSH bias determinations, data from the long-term occupation of the platform have lent insight on many signals of geodetic, oceanographic, and environmental interest. The platform GPS station is one of the oldest continuously operating sites in the International GPS Service (IGS) network. While early data yielded no signs of systematic changes in the platform height (Purcell et al. 1995), longer time series have exposed significant ($\sim$1 cm/yr) subsidence and periodic variations due to various loading and thermal effects (Haines et al. 2001). Data from the platform sea-level systems have shed new light on the performance of competing tide-gauge technologies in dynamic sea-state environments (Gill and Parke 1995; Gill et al. 1995; Kubitschek et al. 1995; Parke and Gill 1995). Measurements of vertical wet path delay from the GPS and an up-looking water vapor radiometer were valuable in detecting a small but important drift in the readings from the TOPEX microwave radiometer (Haines and Bar-Sever 1998; Keihm et al. 2000). Calibrations of altimeter significant wave height (SWH) estimates (Parke and Morris 1995) and ionosphere delay corrections (Christensen et al. 1994) have also been performed. The wealth of information from the Harvest experiment underscores the unique contributions of a dedicated, well-instrumented, and continuously maintained calibration site. In addition to providing information on the SSH bias and stability, data from dedicated sites can be used to segregate the various potential sources of error.

Designed to carry the T/P legacy of precision altimetry into the new millennium, Jason-1 was launched December 2001 into an orbit that placed it in formation flight with its predecessor for seven months (Ménard et al. this issue). This tandem configuration enabled better cross calibration of the two missions owing to cancellation of common mode errors. Far outlasting its expected lifespan of 3–5 yrs, the T/P satellite flew over the platform 365 times (every 10 days) from 1992–2002. The final overflight occurred on August 13, 2002, after which the venerable satellite was moved into an orbit that produced an interleaving ground track with its younger counterpart. Jason-1 will continue to pass over Harvest, enabling long-term monitoring of the measurement system stability. The joint U.S./France Ocean Surface Topography Mission (planned 2007 launch) will follow the same ground track, implying that Harvest will continue to serve a vital role in validating data from precise space-borne radar altimeter systems.

Altimeter Data

The source of Jason-1 data for this study is the Interim Geophysical Data Record (IGDR; Picot et al. 2001) for repeat cycles 1–50 (January 2002 through May 2003). Where possible, improvements to the IGDR were made to reflect the corrections on the definitive Geophysical Data Record (GDR). (The first GDRs were released in July 2003, too late to support the Harvest analysis described in this article.) Individual enhancements to the IGDR are discussed in the appropriate sections that follow. The source of T/P data for this study is the Merged Geophysical Data Record (MGDR; Benada 1997) for Cycles 1–365 (October 1992 to August 2003). Again, certain accepted enhancements were made to the MGDR correction fields. As with the improvements to the Jason-1 IGDR, these were made in accordance with the Jason-1 calibration/validation (cal/val) standards developed to promote consistency of results among the various dedicated calibration sites (Ménard and Haines 2001).

We note that the unique characteristics of the land approach to Harvest imply that various altimeter correction terms benefit from different approaches to polynomial fitting and smoothing the data. Christensen et al. (1994) provide a comprehensive discussion of this. Unless otherwise noted, we adopt the same fitting schemes herein.

In Situ Data

Tide gauges provide a means of measuring water level relative to the surface to which they are attached. What is needed for the Harvest altimeter calibration exercise, however, is a precise record of the SSH relative to the center of mass (CM) of the Earth system. This must reflect not only the changing height of water relative to the platform ($\sim$50 cm RMS, to which ocean tides are the primary contributor), but also the absolute height and vertical motion of the platform itself ($\sim$10 cm RMS, to which solid tides are the primary contributor). This implies that the tide-gauge record must be complemented with information from a space geodetic survey, as well as model information on the platform motions at a variety of frequencies.

Platform Vertical Height and Velocity

To support the computation of an absolute altimeter bias, the instantaneous coordinates of the Harvest platform at the overflight times must be tied as closely as possible to the Earth's CM. Proper determination of this measurement demands a detailed consideration of vertical motions on a variety of time scales (e.g., tectonics, subsidence, tidal and loading effects, and platform sway). Underlying the measurement of these time-varying effects is absolute position information determined from a local platform survey and data from geodetic-quality Global Positioning System (GPS) receivers on the platform.

We must first determine the coordinates of the oil platform in the conventional terrestrial reference frame (TRF). More exactly, our interest is the precise geodetic height of the platform relative to the reference ellipsoid ($a = 6378.1363$ m, $l/f = 298.257$) used for expressing the satellite orbital height on the GDRs. The precise orbit (ephemeris) solution for the altimeter satellite dictates how the TRF is realized on the altimeter SSH measurements. Orbit computations for contemporary altimeter systems, such as TOPEX/POSEIDON and Jason-1, use the International Terrestrial Reference Frame 2000 (ITRF2000), or slight variants that are indistinguishable at the 1-cm level. It is important to recognize, however, that the origin of a TRF realized through a satellite orbit determination process can depart slightly from the center of figure (CF) realized by a global network of tracking stations on the Earth's crust. Underlying these departures are the expressions of a variety of signals, including seasonal geocenter motions from mass redistribution within the Earth system, as well as systematic orbit errors. The overall effect is difficult to characterize in the present case, but the departures probably emerge as potential error sources at the 1-cm level. This level is consistent with contemporary estimates of geocenter motion (Dong et al. 2003) and correlated Jason-1 orbit errors (Bonnefond et al. this issue; Haines et al. 2003).

Data from the platform GPS system have been collected continuously (with a few short interruptions) since 1992. The original receiver (8-channel TurboRogue) served from 1992–1999. Its replacement, a 12-channel BenchMark from Allen Osborne Associates, was joined in February 2002 by an Ashtech Z12 to provide competing measurements from the same antenna. The antenna is a Dorne-Margolin choke ring, and is protected from the harsh marine environment by a custom-built clear spherical radome. A custom-designed monument on the sloping roof of the heliport stairwell (at nearly the highest point of the platform superstructure) hosts the antenna mount.

TABLE 1 GIPSY Solution Strategy for Estimating the Harvest Position in a Terrestrial Reference Frame

Model or parameter	Selection
Observation types	5-min ionosphere-free carrier phase (LC) and pseudorange (PC)
Observation weights	LC 1 cm; PC 100 cm
Elevation cutoff	7°
Troposphere mapping function	Niell (1996)
Wet troposphere	Zenith and gradient terms estimated as random walk (Bar-Sever et al. 1998)
GPS receiver clock	Estimated as unconstrained (white-noise) process
GPS spacecraft orbits/clocks	JPL IGSAC (definitive fiducial-free estimates; e.g., Heflin et al. 2002)
Terrestrial Reference Frame	ITRF2000 as realized by rotation of fiducial-free solution (Heflin et al. 2002)
Solid tide	IERS2000
Rotational deformation	IERS2000
Tidal loading	FES2002 (LeProvost et al. 2002) with DTM2000.1 ocean function. (J. Saleh and N. Pavlis, personal communication 2000)

We determined the terrestrial position of the platform GPS monument using a technique called precise point positioning (Zumberge et al. 1997). Over 3400 daily solutions spanning nearly 11 years were derived from the GIPSY/OASIS II (GIPSY) software (Webb and Zumberge 1995) using fiducial-free GPS orbit and clock estimates from the JPL International GPS Service Analysis Center (IGSAC). The daily estimated position of the platform was rotated from the fiducial-free GPS frame into ITRF2000 using a seven-parameter Helmert transformation (Heflin et al. 2002), values of which are also provided by the IGSAC. Additional details on the GIPSY solution strategy are provided in Table 1. It is important to note that the fiducial-free IGSAC products are intended to provide the foundation for a consistent and stable GPS framework, to the extent practical, over long periods of time. As such, they are well suited for use in generating geodetic time series spanning a decade or more (e.g., Heflin et al. 2002). Products from the early 1990s have been regenerated using contemporary solution strategies for the GPS orbital states and clock offsets. The adoption of the fiducial-free technique ensures that the products are not linked to historical realizations of the ITRF, and can be readily transformed into new frame realizations (e.g., ITRF2000) as they are published.

In order to accommodate signal multipath and other systematic local effects on the GPS observations, we also developed antenna phase-center variation (PCV) maps (e.g., Hurst and Bar-Sever 1998) from the postfit residuals for both the GPS carrier and pseudorange data types. These maps, which characterize signal delays as a function of azimuth and elevation, were iterated and fed back into the GIPSY solutions until converged. The chokering antenna at Harvest has never been replaced; so one set of PCV maps was used for the duration of the time series.

To condition the time series of the daily vertical positions, we estimated height offsets to account for spurious jumps introduced by equipment changes. For example, an offset was estimated to accommodate the discontinuity caused by the 1999 replacement of the TurboRogue with its modern counterpart, the BenchMark. For periods after the collocation

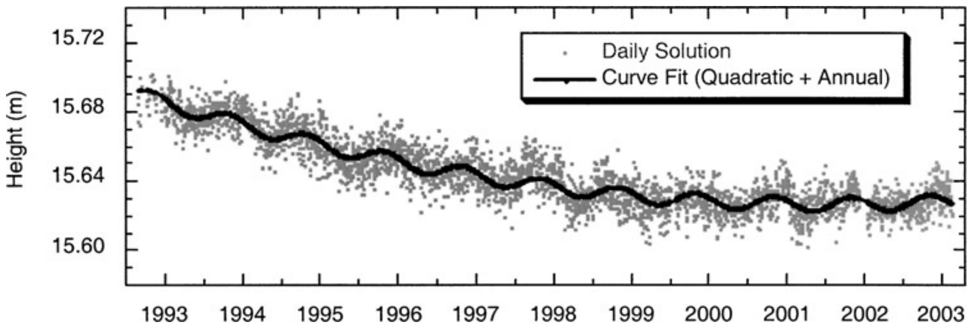

FIGURE 3 Conditioned time series of the platform geodetic height (ITRF2000) from 1992–2003. Subsidence from the pumping of oil and fluids from the underlying Arguello deposit has ceased.

of Ashtech Z12 with the BenchMark in February 2002, it appears the data from both receivers can be used interchangeably with no statistically significant effect on the long-term characteristics of the time series. Both are state-of-the-art geodetic receivers that use advanced codeless tracking techniques to track GPS signals from up to 12 spacecraft simultaneously. We used the Z12 data in the current analysis, as the Benchmark was offline for a short time in 2002 to undergo some troubleshooting.

The conditioned decade-long time series of the platform geodetic height is given in Figure 3. The repeatability of the daily solutions is at the level of 8 mm (RMS). There is no appreciable long-term variation in the scatter, testifying to the robustness of the solution strategy in the face of evolutionary changes to the GPS system over the past decade. The most conspicuous feature in the time series of the Harvest vertical (Figure 3) is the downward trend signifying the subsidence of the platform. A likely consequence of the extraction of oil and other fluids from the underlying Arguello deposit, the sinking resulted in a ~6-cm drop in the platform position from 1993 to 2001. Recent data suggest the subsidence has eased. We do not believe this long-term behavior is a symptom of some insidious systematic GPS error, as disparate strategies for computing the platform vertical rate yield estimates that agree at the ~1 mm/yr level. More important, time series from neighboring southern California GPS stations do not exhibit a similar subsidence. Finally, a spurious 6-cm drop in the modeled platform position from 1993–2001 would have manifest as an unrealistically large drift (nearly 1 cm/yr) in the T/P SSH calibration time series. Results from studies directed at measuring the stability of the T/P system using the global tide-gauge network (e.g., Mitchum 1998) indicate that residual drifts are much smaller (order 1 mm/yr).

The most prominent periodic variation in the decade-long record of platform vertical position is seasonal (Figure 4). Annual (seasonal) variations are commonly observed in GPS geodetic time series, and can be explained by errors in both the GPS measurement system and real ground movement, e.g., due to seasonal mass distribution within the Earth system (Dong et al. 2002). For the Harvest time series, an important reduction in the amplitude of the annual variation (from 5.5 mm to 3.6 mm) was realized through application of the PCV maps. To lend insight on possible sources of the remaining annual signal, we modeled annual nontidal loading effects and thermal variations due to seasonal expansion and contraction of the platform superstructure (Table 2). By applying these models to the conditioned time series, the amplitude of the annual signal is further reduced to 1.3 mm. As revealed in the periodogram, the peak associated with the remaining annual signal is not readily distinguished from neighboring peaks (Figure 4). Properly explaining and reducing

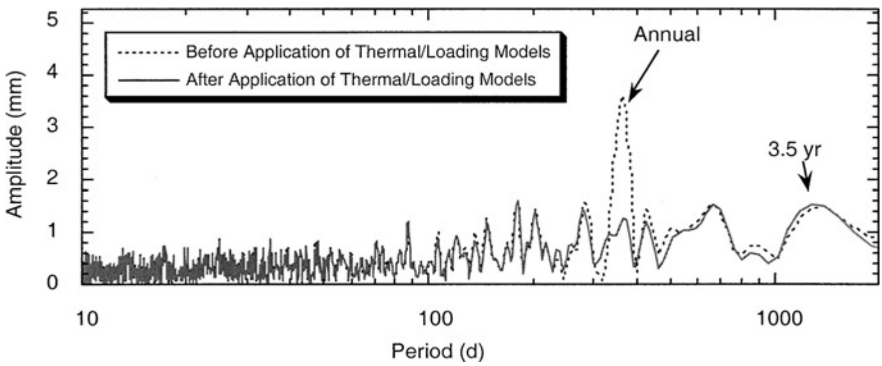

FIGURE 4 Periodogram of the platform vertical variations in the terrestrial reference frame (ITRF2000). The annual signal is largely explained by nontidal loading effects and seasonal thermal expansion of the platform superstructure.

annual signals in this manner has important implications for improved determination of vertical rates at all tide gauge/GPS collocations.

Water Level from Tide Gauges

Data from the platform tide gauges have been collected continuously (with a few short interruptions) since 1992. Viewed together with the GPS observation record, this implies the Harvest experience has produced more than 10 years of continuous data from collocated GPS and tide gauge systems. During most of the T/P mission, three independent sea-level systems provided measurements to support the calibration exercise.

In 1992, NOAA personnel installed a Next Generation Water Level Measurement System (NGWLMS) on risers serviced from the 20-ft boat-landing deck. The system consisted of a self-calibrating acoustic sensor and a secondary digital "bubbler" (Gill et al. 1995). To support the Jason-1 mission, NOAA personnel recently replaced the NGWLMS with an updated system. The acoustic system–inoperative after storm damage in May 1999–was

TABLE 2 Annual Loading Signals Modeled in the Harvest Time Series

Annual signal	Amp. (mm)	Peak	Source
Thermal (below water)	1.8	Nov.	200 m steel ($\lambda = 1.2 \times 10^{-5}/°C$), Temperature climatology from hydrographic station 80.55 (http://www.calcofi.org)
Thermal (above water)	1.3	Sep.	52 m steel ($\lambda = 1.2 \times 10^{-5}/°C$) Temperature variations from platform thermometer
Soil moisture load	1.2	Sep.	NCEP/DOE AMIP II reanalysis (Dong et al. 2002)
Nontidal ocean load	0.8	Mar.	T/P altimeter–WOA-94 steric (Dong et al. 2002)
Snow/ice load	0.3	Apr.	NCEP/DOE AMIP II reanalysis (Dong et al. 2002)
Atmosphere load	0.2	Feb.	NCEP reanalysis (Dong et al. 2002)

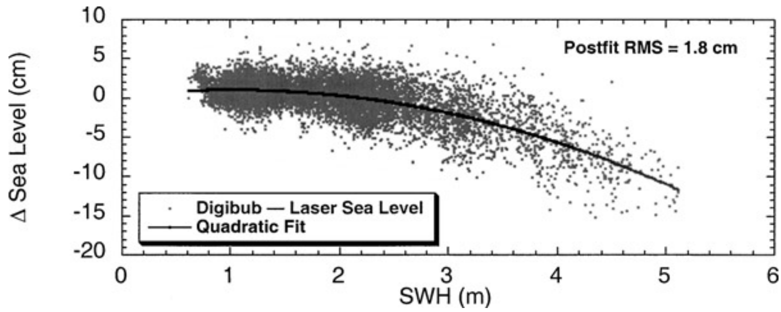

FIGURE 5 Difference of platform sea-level observations (bubbler minus laser) as a function of significant wave height. The dynamical wave conditions at the platform present special challenges for interpreting tide-gauge measurements.

converted to a bubbler in October 2002, and the original bubbler was refurbished in April 2003. Bubbler technology was selected for both NOAA systems for logistical and safety reasons, as no power is needed at the 20-ft deck (The boat-landing deck is commonly subjected to wave action during winter storms.) The new bubbler systems have been designed to mitigate the systematic sea-state errors observed with the original bubbler design (Parke and Gill 1995). Both are equipped with two Paroscientific pressure transducers, enabling two water level measurements on each system. NOAA personnel performed repeated local surveys to measure the height (46.041 m) of the GPS marker above the NGWLMS leveling points (Gill et al. 1995). Undertaking differential leveling at the platform is a formidable challenge, as the measurements must be taken along various narrow stairwells and decks exposed to the wind. The platform itself is swaying[3] and can expand and contract in response to temperature changes. Despite these difficulties, NOAA surveyed the vertical distance with an estimated accuracy of 4 mm (Morris et al. 1995).

The University of Colorado (CU) maintained submerged pressure transducers from 1992–1999 (Kubitschek et al. 1995). To support Jason-1, they have deployed an experimental optical (laser) system on the 47-ft sump deck. The down-looking Optech laser system has no submerged parts, and is readily accessed from the sump deck regardless of sea conditions. NOAA/NOS personnel performed a local survey to level the new CU system to the platform tide-gauge benchmark.

The dynamic wave conditions at Harvest present special challenges for interpreting tide gauge measurements. Following Parke and Gill (1995), we have developed empirical corrections to mitigate systematic effects of sea-state biases in the platform sea level data. These corrections are based on regressions of tide-gauge differences against significant wave height (SWH) derived from buoy data. We use SWH data from the Scripps Institute of Oceanography Harvest buoy[4] for current comparisons. Differences in the sea-level readings from laser (CU) system and NOAA bubbler (prior to redesign) show important wave-height dependencies (Figure 5). The pattern is very similar to the bubbler SWH dependence described by Parke and Gill (1995). The model correction derived from the comparison is thus being used to mitigate the wave-induced errors in the measurements from the original bubbler system. At this writing, data from the new bubbler system have not been sufficiently analyzed to characterize the SWH dependence.

[3]Under normal conditions, the vertical motion of the platform from sway is less than 5 mm (Morris et al. 1995)

[4]http://cdip.ucsd.edu/

Altimeter Measurement System Calibration Results

At this writing, Jason-1 has passed over the platform 57 times since the mission began its observational phase in January 2002. During the first seven months (until August 2002), the overflights occurred in tandem with TOPEX/POSEIDON (Jason-1 leading its predecessor by 70 s). We focus herein on calibration results from the Jason-1 mission. In addition to the SSH, we carefully examine two of the constituent measurements: the path delays to account for wet troposphere and ionosphere. We also update the TOPEX/POSEIDON calibration results, and present decade-long calibration time series for both missions.

Wet Troposphere

Essential components of the altimeter measurement systems are the down-looking Jason-1 and TOPEX microwave radiometers (JMR and TMR, respectively) to passively measure water vapor abundance along the altimeter path (e.g., Chelton et al. 2001). The information is used to correct the altimeter range for the retarding effects of tropospheric water vapor and cloud liquid water droplets. Data from the platform GPS receivers can be used to compute an independent estimate of the columnar wet path-delay (PD) measurements, which can be used in turn to calibrate JMR and TMR. Using the strategy described by Haines and Bar-Sever (1998), GPS-based PD measurements were recovered at the overflight times and compared with the corresponding JMR/TMR measurements. We note that the JMR/TMR observations collected as the satellite passes over the platform are not trustworthy owing to contamination of the radiometer footprints by nearby coastal lands. To obtain the JMR/TMR measurement for these comparisons, we thus follow the procedure adopted by Christensen et al. (1994). In particular, we perform a linear least-squares fit to along-track (1-Hz) PD measurements over a 10-s window ending 5 s prior to the overflight. The value of the linear fit at the end of the window—approximately 30 km southwest of Harvest—is considered representative of the JMR/TMR PD at the platform.

For this comparison exercise, we corrected the TMR PD measurements for the spurious drift of the 18-Ghz channel (Ruf 2002). For TMR readings that are contemporaneous with Jason-1, this implies a nearly constant correction of 6–7 mm. Also noteworthy, we applied a small correction to the TMR PDs to account for the yaw state of the satellite. There are only two values for the correction: -2.4 mm if the T/P satellite is in sinusoidal (“yaw steering”) mode, and $+1.4$ mm if the satellite is in fixed yaw mode (S. Brown, C. Ruf, and S. Keihm, private communication 2002).

The JMR PD data used in this exercise are from dual Jason-1 and T/P overflights only (repeat cycles 1–22 for Jason-1). These data were reprocessed by S. Brown and C. Ruf (private communication 2002) at the University of Michigan (UM) to ensure that the JMR PD data used at Harvest reflected updated calibration coefficients. The UM data set also corrects a JMR interpolation error that manifests itself on currently available IGDRs as a constant PD for $\sim$8 s on approach to land (S. Desai, private communication 2003). It should be noted that an additional calibration exercise has been recently completed and a newer set of calibration coefficients are being used for the production of the GDRs. Improvements realized by the latest coefficients are not reflected in the UM data set; thus, a more definitive JMR calibration awaits the evaluation of the GDRs.

Shown in Figure 6 is a scatter plot of the JMR/TMR versus GPS wet PDs at Harvest. The agreement between both the JMR and TMR PDs and corresponding GPS PDs is at the 1-cm level in terms of point-to-point scatter. It is not uncommon to encounter biases of 5–15 mm in PD recoveries from terrestrial GPS stations, so we do not consider the median statistics (11 mm and 2 mm, respectively) to favor one radiometer over the other in terms of absolute PD calibration. Represented as a 10-yr time series (Figure 7), the TMR–GPS

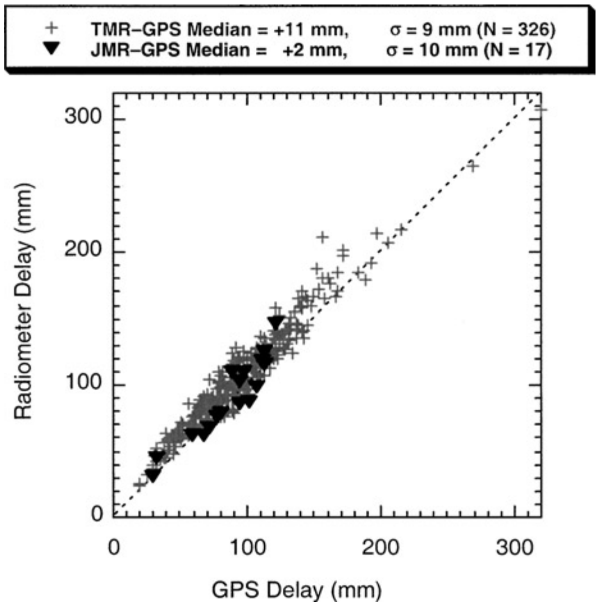

FIGURE 6 Scatter plot of GPS vs. radiometer (JMR and TMR) wet path delay readings at overflight times. The agreement is at the 1-cm level.

PD differences show good long-term stability. The estimated drift is indistinguishable from the null result at the level of 0.2 mm/yr (1 standard error).

Additional insight on the radiometer calibrations is gained from direct comparisons of the TMR and JMR PD values for near-identical conditions, namely during 17 dual overflights of the platform (Figure 8). The scatter of the differences (JMR–TMR) is only 3 mm, and the median is –6 mm. The sign of the difference is such that JMR PDs are systematically drier than those from TMR, consistent with the inferred result from the GPS comparisons. Interestingly, the relative bias is reduced to insignificance if we elect not to apply the correction for the 18-GHz channel drift in TMR. The relative bias, however, could be symptomatic of a small residual calibration error in the JMR PDs that manifests itself for the typical dry conditions at the platform (median wet PD of 10 cm). We will test this hypothesis when we examine the GDR-based JMR data, which will be based on the next-generation calibration coefficients.

Ionosphere

The TOPEX and Jason-1 altimeters use two frequencies (Ku- and C-band) to measure the delay induced by the presence of free electrons in the signal path. Ionosphere delays (Ku) determined independently from the JPL GPS ionosphere maps (Mannucci et al. 1998) were compared with those from the TOPEX (Sides A and B[5]) and POSEIDON-2 (Jason-1) altimeters at Harvest. To reduce the along-track noise of the dual-frequency altimeter (DF) ionosphere corrections on the IGDRs, we averaged the data over 140 km on approach to the platform (Imel 1994). It must be remembered that the GPS ionosphere maps (GIM) represent the columnar delay of the entire ionosphere, while the altimeters

[5]The primary (A) side of the TOPEX altimeter was switched off in February 1999 in response to signs of aging.

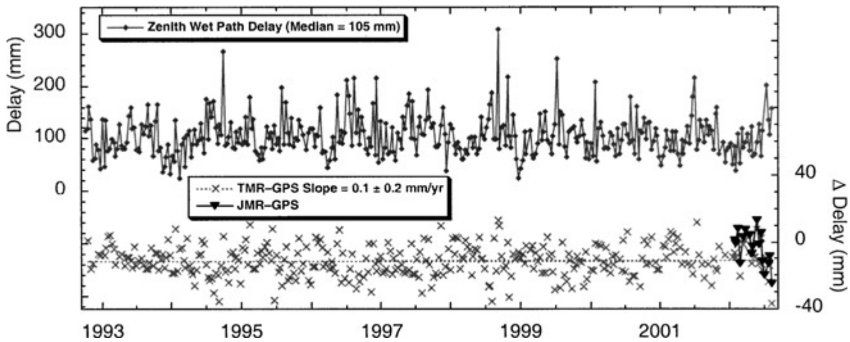

FIGURE 7 Decade-long time series of GPS vs. radiometer wet path delay calibrations. The top curve gives the overall delay at the overflight times. The bottom curves depict the excellent long-term stability of the GPS vs. radiometer differences.

observe the portion of the ionosphere below the 1330 km altitude of the Jason-1 and T/P orbits. Only a small percentage of the ionosphere can be found above this altitude, but it could induce an additional 2–10 mm of path delay at Ku-band (Christensen et al. 1994).

Figure 9 provides a time series (1997–2003) of the GIM versus DF ionosphere delays (Ku) at Harvest. The DF measurements from all three altimeters (TOPEX A/B and POSEIDON-2) agree with the GIM data at the sub-cm level, in terms of both bias and repeatability. There is no apparent correlation of the differences with the overall level of ionospheric activity (Figure 10). Direct comparisons of the altimeter DF corrections for 18 dual overflights suggest that the POSEIDON-2 delays are smaller than the TOPEX-B delays by 4 mm on average. The sense of the bias is corroborated by our global comparisons. At this small level, however, GIM is unable to distinguish which of the competing DF altimeter measurements is more accurate.

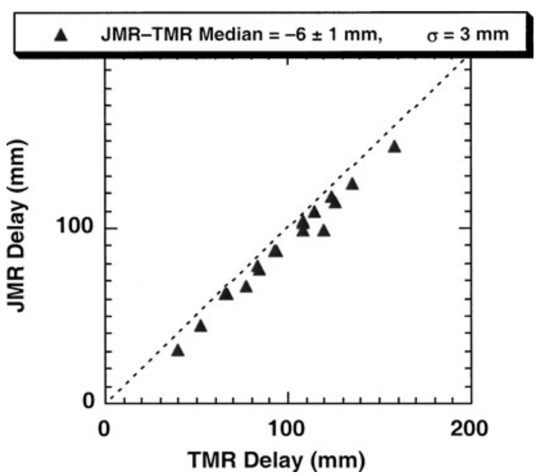

FIGURE 8 Scatter plot of JMR and TMR path-delays overflight times from dual Jason-1 and T/P overflights. A slight bias between the two is symptomatic of JMR measuring slightly drier than TMR for typical Harvest conditions.

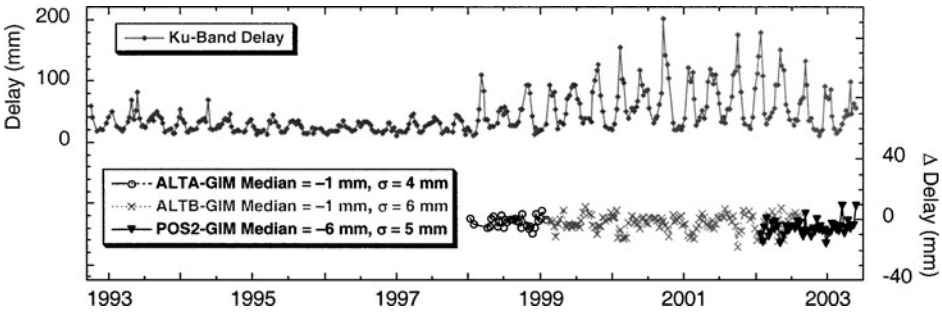

FIGURE 9 Decade-long time series of GPS vs. dual-frequency altimeter ionosphere calibrations (Ku-Band). The top curve gives the overall delay at the overflight times. The bottom curves depict the excellent long-term stability of the GPS vs. altimeter differences.

Sea Surface Height

The tide-gauge measurements are combined with local survey information, GPS vertical estimates, and associated model information to develop a precise estimate of geocentric SSH at satellite overflight times. In what has been dubbed a "closure" exercise, this in situ reading is compared with the altimetric SSH to monitor potential biases and instabilities in the spaceborne measurements. Additional details on both the in situ and altimeter components of this closure analysis follow.

To obtain our in situ SSH, we begin with a quadratic model for the long-term variation of the geodetic height of the platform (ITRF2000) from GPS, as depicted in Figure 3. A more conventional linear model is unable to capture the recent easing of the platform subsidence. For the overflight time of interest, we evaluate the quadratic and superimpose the instantaneous vertical displacements from the solid tide, rotational deformation (pole

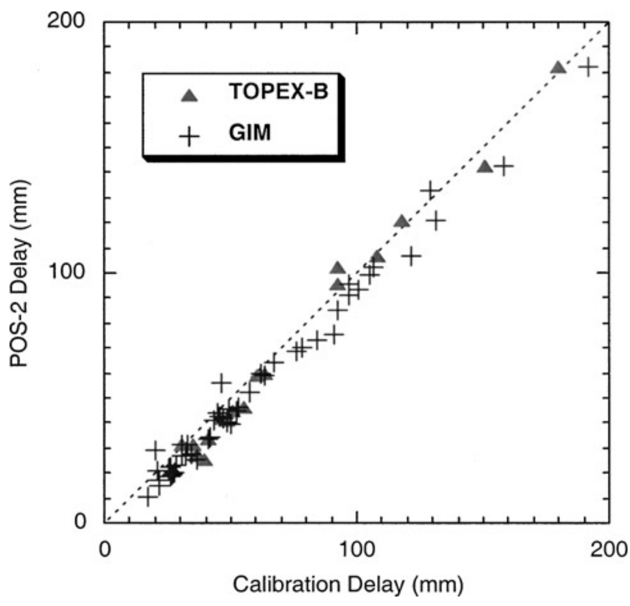

FIGURE 10 Scatter plot showing agreement of Jason-1 dual-frequency ionosphere delay with corresponding TOPEX- and GPS-based delays.

TABLE 3 Model Specifics for Altimeter Leg in Closure Equation: Nominal Strategy

Model	Jason-1	TOPEX/POSEIDON
Orbital height	CNES POE (SLR + Doris)	NASA POE (SLR + Doris)
Range	Ku-Band (IGDR)	Ku-Band (MGDR)
Wet troposphere	Reprocessed JMR (see text)	TMR w/18-GHz drift + yaw correction
Ionosphere	Ku-Band (IGDR)	Ku-Band (MGDR) except DORIS for POSEIDON
Sea-state bias	Tuned nonparametric (Gaspar et al. 2002)	Gaspar et al. (1994) 4-param. (MGDR)

tide), and tidal loading (Table 1). Also accounted for are vertical models for the thermal[6] and mass loading effects as described in Table 2. Discussed previously, these models of vertical displacements were used to correct the platform GPS data in order to unveil the long-term subsidence. Here, we simply reverse the exercise by beginning with the long-term platform motion and adding—rather than subtracting—the model displacements to obtain an estimate of the instantaneous height of the platform GPS mark as the satellite flies overhead. This is combined with the local survey information and water-level measurements from the platform tide gauges to obtain the in situ SSH in ITRF200, against which the satellite altimeter measurements can be directly compared. In this exercise, the NOAA NGWLMS serves as the source of platform tide-gauge data. As described previously, the data are first corrected for systematic sea-state effects.

Table 3 details assumptions for the altimeter leg of the closure exercise, for T/P as well as Jason-1. Each of the constituent measurements underlying the formation of the altimetric SSH (e.g., range, orbital height, wet-tropospheric path delay) is separately smoothed and interpolated to a specific time—generally the time of closest approach (TCA) to the platform. In particular, the along-track data are fit to a least-squares polynomial, with the order, time span, and evaluation point defined uniquely by Christensen et al. (1994) for each constituent. This approach was selected because the along-track profiles of each constituent exhibit distinct behaviors on approach to the platform and nearby coast. As indicated previously, radiometer data collected directly over the platform suffer from land contamination, and PD readings collected 30 km up-track of Harvest must be used. In contrast, the radar altimeter data collected over the platform are generally of high quality, enabling us to fit along-track range data over a time interval framing the overflight (i.e., from -10 s to $+1$ s relative to TCA).

Once the constituent measurements are obtained, the altimetric SSH is then computed using a straightforward summation. We note that the resulting SSH observation refers to a footprint centered on the point-of-closest approach to the platform. Due to the inexact nature of the ground-track repeat, the center of this footprint may fall up to 1 km (cross track) from Harvest. We apply a gradient correction to compensate for a slight slope (<1 cm/km) of the sea surface against the satellite path. This cross-track geoid gradient correction is based on the GSFC00 mean sea-surface model (Wang 2001).

It is important to recognize that the SSH bias estimate is highly sensitive to the selections made for the underlying altimetric correction terms. The sea-state bias (SSB) correction, in particular, has a conspicuous ability to confound comparisons of SSH bias estimates from different investigations. Representing a convolution of the traditional electromagnetic

[6]The model for above-water thermal variations is not applied, since this has negligible impact on the motion of the tide-gauge benchmark near the water line.

bias (EMB), as well as tracker and skewness biases (Chelton et al. 2001), alternative SSB models for the same instrument system can impact the SSH bias estimates systematically at the few-cm level (e.g., Christensen et al. 1994).

For Jason-1, we adopt the SSB model chosen for GDR production. The entries in the lookup table underlying this nonparametric Ku-band SSB model (Gaspar et al. 2002) have been tuned by Labroue and Gaspar (2002) using Jason-1 collinear repeat-track data. Replacing the prelaunch SSB model with the tuned model significantly improves the repeatability of the Harvest SSH bias estimates. At the same time, the overall SSH bias (already positive) is increased by $\sim$6 cm owing to a higher median value for the new SSB corrections.

For T/P, we adopt as nominal the 4-parameter SSB model (Gaspar et al. 1994) from the MGDR. The coefficients of the model were recovered by fitting data from side A of the TOPEX altimeter, which was turned off in February 1999 after showing signs of aging. Chambers et al. (this issue) provide evidence that these coefficients are not well suited for the currently active (B) side of the TOPEX altimeter. Until a new model is selected for representing the SSB on T/P geophysical data products, however, the vast majority of applications will continue to rely on the current MGDR correction. As an alternative, however, we provide TOPEX-B results using a nonparametric model developed by Labroue and Gaspar (2002) in much the same way as the Jason-1 GDR model.

Our strategy for forming the Jason-1 altimeter SSH uses two competing estimates for the spacecraft orbital height. The orbital height data being impressed on the first release of the GDRs are based on the CNES precise orbit ephemeris (POE). The current CNES POE strategy uses a combination of DORIS Doppler and satellite laser ranging (SLR) data (e.g., Berthias et al. 2002). Also represented are GPS-based precise orbit solutions from JPL (Haines et al. 2003). Capitalizing on the observing strength afforded by GPS, these orbit solutions use a reduced-dynamic (RD) strategy to partially liberate the POD process from models of the forces underlying the satellite motion. For the overflight sample represented in the calibration exercise, the overall SSH bias estimates for the two orbit solutions agree to 5 mm. We note that regional biases are present in the differences of the two orbit solutions at the 1-cm level, which can bear on interpreting and combining results from the dedicated calibration sites (Bonnefond et al. this issue). In terms of repeatability, the GPS RD orbits yield the best consistency on an overflight-to-overflight basis at Harvest. In keeping with our goal to stay as true to the GDR data product as possible, we select the POE as nominal and arrive at the estimate of $+138 \pm 7$ mm (one standard error) for the Jason-1 SSH bias at Harvest based on 31 overflights[7] (Table 4).

For comparison, our current nominal estimate for the T/P SSH bias is $+2 \pm 4$ mm (one standard error), based on 84 overflights. This estimate applies to the active (B) side of the primary TOPEX altimeter, which has been in operation since February 1999. Preliminary analyses suggest that use of a SSB model tuned with TOPEX-B data will increase the bias, evidence of which is provided in Table 4. Also included in the table is a comprehensive tabulation of the SSH bias estimates for both T/P and Jason-1, including results from POSEIDON, as well as the primary (A) side of TOPEX.

Error Budget

Developing a realistic error budget for the SSH bias estimates is challenging, particularly for the systematic (nonaveraging) error sources. The accuracy of the in situ SSH at Harvest has undoubtedly improved since Christensen et al. (1994) published their error budget

[7]Based on repeat cycles 1–42. Eight overflight samples were excluded on account of altimeter data problems due to unusually calm winds (Ku-band backscatter >14 dB). Three overflights had missing Jason-1 IGDR pass files.

TABLE 4 Jason-1 and T/P SSH Bias Estimates. (The Jason-1 and TOPEX-B Results are Given with Competing Orbit and SSB Solutions)

System	Year	Orbit soln.	SSB model	N	Median ± std. err.	σ
Jason-1	2001–	CNES POE	Labroue et al. (2002)	31	+138 ± 7 mm	41 mm
Jason-1	2001–	JPL GPS	Labroue et al. (2002)	31	+132 ± 6 mm	34 mm
TOPEX-B	1999–	NASA POE	Gaspar et al. (1994)	84	+2 ± 4 mm	35 mm
TOPEX-B	1999–	NASA POE	Labroue et al. (2002)	84	+19 ± 4 mm	35 mm
TOPEX-A (early)	1992–1996	NASA POE	Gaspar et al. (1994)	103	+2 ± 3 mm	31 mm
TOPEX-A (aging)	1996–1999	NASA POE	Gaspar et al. (1994)	52	+12 ± 5 mm	33 mm
POSEIDON	1992–	NASA POE	Gaspar et al. (1994)	22	−14 ± 7 mm	31 mm

based on the early T/P experience. Advances in the determination of the platform height from GPS have been significant, as have the improvements in modeling of the platform vertical motions at a variety of frequencies. In terms of the fixed error, however, the largest contributor likely remains the GPS survey of the platform in the TRF (Table 5). Competing GPS solution strategies yield discrepancies at the 1-cm level. For example, the JPL IGSAC model (ITRF2000) of the Harvest geodetic height from 1992–2003[8] departs from our own estimate by an average of 13 mm. This appears to be due primarily to systematic effects of the radome, the presence of which induces a 12 mm jump in the estimated height. In the present study, we use the estimated height bias from two years of radome-free data from 1997–1999 in leveling our time series. The absolute level of the IGSAC time series, in contrast, is not adjusted in this manner. While we are inclined to place more confidence in the radome-free data, we have no direct evidence to support that this approach should be preferred over other strategies. In recognition of this, and of other potential systematic effects in the GPS processing—such as seasonal geocenter motion—we adopt a value of 15 mm for the systematic error in the GPS survey. Onto this must be added estimates of the constant (bias) error in the tide-gauge sea level and local platform survey (Table 5).

To gain insight on the variable error component of the in situ SSH, we turn first to results from the 22 dual overflights of the platform, wherein T/P and Jason-1 passed over the platform within 70 s of one another. From the standpoint of the in situ measurement systems, the errors at lag intervals of only 70 s should be highly correlated. As such, the in situ errors would largely cancel in forming the relative Jason-1 and T/P SSH bias estimates dual overflights. Examination of the results from these 22 overflights, however, indicates that the scatter of the relative biases (37 mm) is larger than the scatter of the underlying absolute (single-satellite) biases (33 mm and 27 mm, respectively, for Jason-1 and T/P). This tends to absolve the in situ component as the primary contributor to scatter in the bias determinations. A more likely candidate is the noise of the

[8]http://sideshow.jpl.nasa.gov/mbh/series.html; see also Heflin et al. (2002).

TABLE 5 Error Budget for Jason-1 SSH Bias Estimate at Harvest

Error source	Magnitude	Reference
GPS survey of platform in terrrestrial reference frame	15 mm	This study (see text)
Local survey of GPS benchmark to tide-gauge benchmark	4 mm	Morris et al. (1995)
Tide gauge error (nonaveraging)	5 mm	Parke and Gill (1995)
Random error	7 mm	1 standard error ($N = 31, \sigma = 41$ mm)
Total	18 mm	Root-sum-square

along-track altimeter SSH measurements. Of course, it remains important to reduce the variable component of the in situ measurement errors to the extent possible. In this context, we believe a careful evaluation of the tide-gauge data offers the best prospects for reducing this component of the error budget. Parke and Gill (1995) reported that water-level measurements from completing platform tide gauges differ by 1.5 cm RMS, even after empirical accommodation of the sea-state errors. We continue to observe discrepancies of similar size, but expect the CU laser system to continue lending new insight on these differences.

Finally, it must be remembered that the in situ SSH refers to a “pinpoint” location underneath the platform, while the altimeter measures SSH over a footprint with typical diameter of 3–5 km. The spatial variability of the SSH within the footprint is probably the least understood of the error-budget components. Christensen et al. (1994) assumed a variable error of 2 cm (RMS) to account for the effects of local SSH variability on reconciling the tide-gauge and altimeter measurements at Harvest.

Accounting for the systematic errors in the in situ observing system (Table 5), we estimate the overall uncertainty in the present Jason-1 SSH bias estimate from Harvest to be 18 mm (1σ). We note that this error figure addresses the skill of the Harvest experiment in determining the Jason-1 SSH bias at this particular location. It does not reflect the impact of geographically correlated errors in the altimeter system that would render a local result (e.g., off the coast of California) different than a global result. A review of results from other dedicated calibration sites, however, gives cause for optimism that the overall errors are indeed contained at the 10–20 mm level. Bonnefond et al. (this issue) report an SSH bias of +120 mm based on overflights of the CNES dedicated calibration site on the island of Corsica. Using data from overflights of a “waverider” GPS buoy deployed in Bass Strait off the coast of Tasmania, Watson et al. (this issue) report a Jason-1 SSH bias of +139 mm. Because of the potential geographic correlations of altimetric SSH errors, consistency among results from globally dispersed calibration sites is essential for establishing whether the SSH bias estimates are representative of global results. In view of the small number of dedicated calibration sites, the ensemble result from the calibration sites will still depart from an idealized global result.

One cannot escape the irony that current estimates of the Jason-1 SSH bias nearly match the early estimates of the TOPEX SSH bias (Born et al. 1994; Christensen et al. 1994; Ménard et al. 1994; White et al. 1994). As discussed previously, it was eventually determined that the TOPEX bias was symptomatic of an error in an algorithm used to account for the drift of the onboard oscillator. We are not aware of any current evidence to support that the explanation for the Jason-1 bias is in any way related.

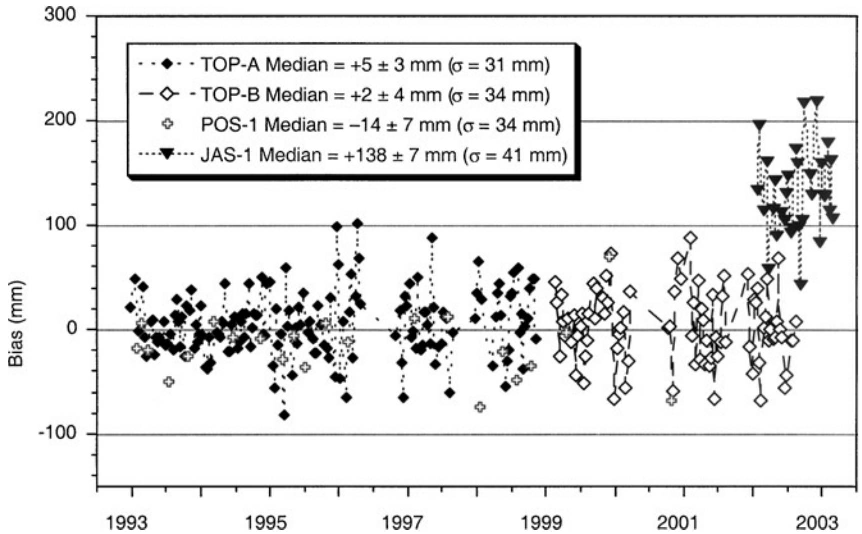

FIGURE 11 Decade-long time series of Harvest SSH calibration. Each point represents the instantaneous difference between in situ and altimeter SSH for a single overflight. Four altimeter systems are represented: TOPEX Sides A and B, POSEIDON, and Jason-1. The Jason-1 SSH measurements are spuriously high (by 138 ± 7 mm). The TOPEX biases are indistinguishable from zero.

Outlook on Monitoring Stability

Measuring global sea level change with an accuracy of 1 mm/yr is an expressed goal of the Jason-1 mission. The unexpectedly high performance of the T/P mission, coupled with a continuous and multifaceted calibration effort, bear the responsibility for elevating the global sea level problem from a research topic to major thrust of the Jason-1 mission. In terms of characterizing the stability of the Jason-1 measurement system at Harvest, it is premature to draw any firm conclusions on account of the small number of overflight samples. More important, a consistent GDR-quality data set spanning the comparison period is needed. By drawing on the T/P experience, however, we gain some insight on the adeptness of the Harvest experiment for monitoring potential instabilities in the altimeter measurement system.

Shown in Figure 11 is a decade-long time series of the Harvest SSH bias determinations, including results from four altimeter measurements systems: TOPEX-A (1992–1998), TOPEX-B (1999–Present), POSEIDON-1 (1992–Present) and Jason-1 (2002–Present). A linear regression to the TOPEX-A time series yields a slope of $+2.6 \pm 1.4$ mm/yr (one standard error). This positive rate is also illustrated in the 1-cm difference between the bias estimates from early and aging TOPEX-A data (Table 4). On first impression, the result appears to corroborate the spurious increase ($\sim$1 cm) in TOPEX SSH associated with the gradual degradation of the point target response (PTR) of the primary (A) side of the altimeter[9] (Hayne and Hancock 1998). The error figure on the rate estimate is undoubtedly optimistic, however, as it does not account for potential serial correlations of the fit residuals. More important, uncertainty in GPS-based measurements of the platform subsidence and slight potential drifts in the tide-gauge data will influence the result. Discriminating drift at the 1 mm/yr level remains a significant challenge for a single calibration site, and

[9]The PTR degradation prompted the switch to the secondary or "B" side in February 1999.

will be contingent on extremely tight control of potential systematic errors, as well as the development of a long observing record.

Summary

Based on 31 overflights of the Harvest platform, we estimate that current Jason-1 sea-surface height (SSH) measurements are high by 138 ± 18 mm. Excepting the bias, the high accuracy of the Jason-1 measurements is in evidence from the overflights. Based on comparisons with T/P and GPS, the Jason-1 constituent measurements of path delay (ionosphere and wet troposphere) are accurate to better than 1 cm. There is early evidence of a small (6 mm) bias in the JMR measurements over Harvest, but the result is based on data that predate the final JMR calibration update for the recent GDR release. In orbit for over 10 years, the T/P measurement systems appear stable and well calibrated. The current SSH bias estimates for both Sides A and B of the TOPEX measurement systems are not statistically distinguishable from zero. A slight spurious increase in the TOPEX-A SSH calibration curve may be symptomatic of the PTR degradation that prompted the 1999 switch to TOPEX-B, but the signal is at the edge of the experiment's present ability to detect it.

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