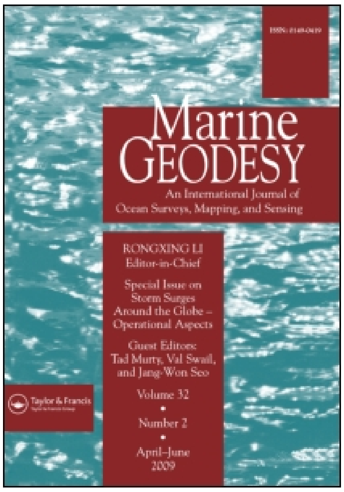

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The Harvest Experiment: Calibration of the Climate Data Record from TOPEX/Poseidon, Jason-1 and the Ocean Surface Topography Mission

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We present a 17-year calibration record of precise (Jason-class) spaceborne altimetry from a California offshore oil platform (Harvest). Our analyses indicate that the sea-surface-height (SSH) biases for all three TOPEX/Poseidon (1992–2005) measurement systems are statistically indistinguishable from zero at the 15 mm level. In contrast, the SSH bias estimates for the newer Jason-1 mission (2001–present) and the Ocean Surface Topography Mission (2008–present) are significantly positive. In orbit for over eight years, the Jason-1 measurement system yields SSH biased by +94 ± 15 mm. Its successor, OSTM/Jason-2, produces SSH measurements biased by +178 ± 16 mm.

Keywords Satellite altimetry, calibration/validation, TOPEX/Poseidon, Jason-1, Jason-2/OSTM, sea level, GPS

1. Introduction

The Plains Exploration and Production (PXP) Harvest Oil Platform is located about 10 km off the coast of central California near Vandenberg Air Force Base (Figure 1). The 30,000-ton 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: ocean swell and wind waves average 2–3 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. Built in 1985 and operational since 1991, Harvest has produced more than 74 million barrels of oil and 51 million barrels of gas as of March 2003 (http://www.mms.gov).

In addition to its primary function to drill for oil in the Santa Maria Basin, Harvest has served as a calibration site for the joint U.S./France TOPEX/Poseidon (1992–2002), Jason-1 (2001–2009), and Ocean Surface Topography (OSTM/Jason-2, 2008–pr.) missions, and as such is an important international resource for the study of sea level from space.

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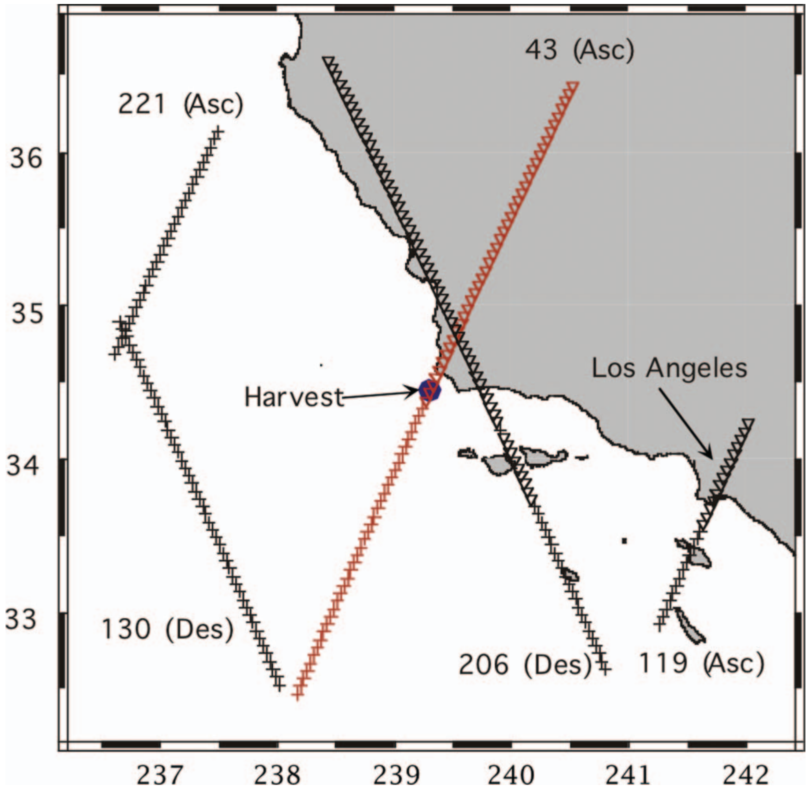

Figure 1. Map of *PXP* Harvest Platform vicinity. The facility is located in the open ocean, about 10 km from Vandenberg Air Force Base off the coast of central California.

Harvest offers a number of advantages as a calibration site for spaceborne altimeters. 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 United States, data from which contribute to measuring the geocentric positions of the altimeter satellites and platform through space-based surveying techniques. Recognizing this 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; Haines et al. 2003). A 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; Bonnefond et al. 2010). Knowledge of this

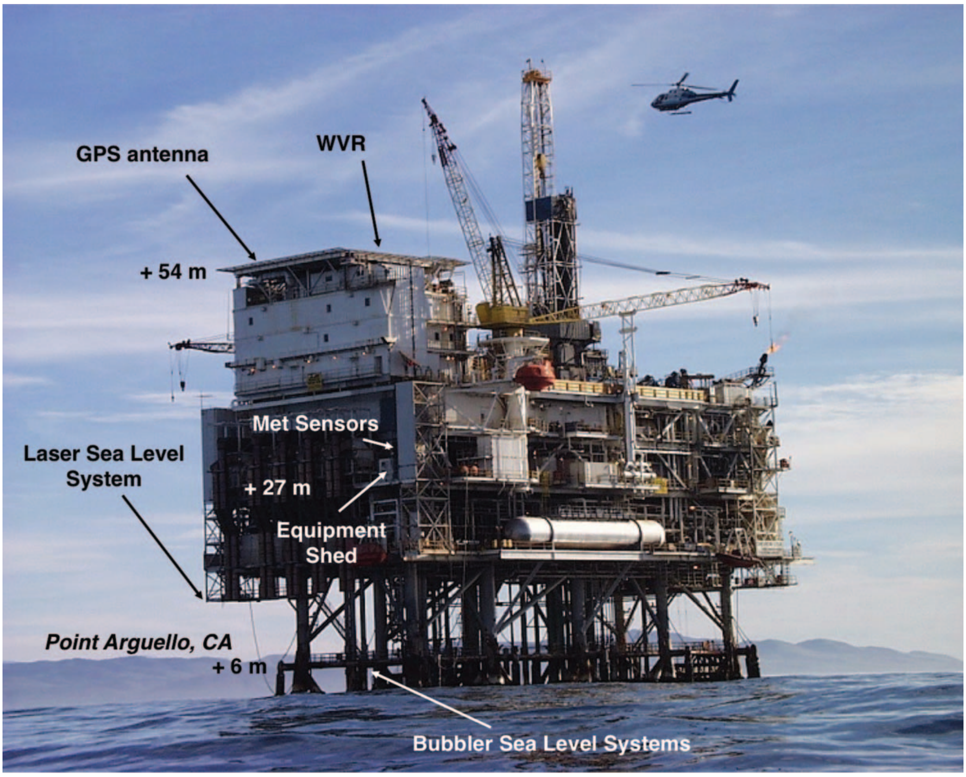

Figure 2. Photo of *PXP* Harvest Platform. The platform sits in 200 m of water, and extends approximately 50 m (excluding derrick) above the mean water level.

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 calibrate altimetric time series of global mean sea level.

Shortly after the T/P launch, results from Harvest suggested that the TOPEX 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 three-year primary mission. Also identified in early results from other dedicated calibration sites (Ménard et al. 1994; White et al. 1994; Murphy et al. 1996), the bias was determined to be the expression of an error in the software used to produce the TOPEX data for the mission scientists. (O. Zanife, P. Vincent, and P. Escudier of CNES are credited with discovering the software error.) The close agreement between the mean value of the software error (133 mm) and the bias estimates testifies to the ability of the Harvest configuration to support detection of spurious signals in the altimeter measurement and software systems. The error also introduced a spurious drift (∼7 mm/yr) in the global mean sea level (Nerem et al. 1997). This drift was first detected by Mitchum (1998) using a 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).

Far outlasting its expected lifespan of 3–5 years, 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 satellite was moved into an orbit that produced an interleaving ground track with its successor, Jason-1.

Designed to carry the T/P legacy of precision altimetry into the new millennium, Jason-1 was launched December 2001 into the same orbit as its predecessor, separated along track by only 70 s. Lasting for seven months (Ménard et al. 2003), this tandem formation-flying configuration promoted better cross calibration of the two missions owing to cancellation of common mode errors. Early results from Harvest indicated that the Jason-1 SSH measurements were high by 138 $\pm$ 18 mm (Haines et al. 2003). Data from dedicated Jason calibration sites at Corsica (Bonnefond et al. 2003) and Bass Strait (Watson et al. 2003) showed similar behavior. Ironically, these initial estimates of the Jason-1 SSH bias nearly matched early estimates of the TOPEX SSH bias (Christensen et al. 1994; Born et al. 1994; Ménard et al. 1994; White et al. 1994). More contemporary estimates of the Jason-1 SSH bias are roughly 40 mm smaller (e.g., Willis 2009; Bonnefond et al. 2010), owing primarily to evolutions in the altimetric data products. There is no evidence linking the remaining Jason-1 SSH bias to the same algorithm error underlying the early TOPEX SSH bias.

The OSTM was launched in June 2008 and relieved Jason-1 of its primary observing mission along the original T/P ground track (Neeck and Vaze 2008). Following the successful model of the T/P versus Jason-1 tandem verification phase, Jason-1 and Jason-2 flew over the platform 20 times in formation between July 2008 and January 2009. Jason-1 was then moved in order to trace out the same interleaving ground track previously defined by the T/P mission from 2002 to 2005. OSTM/Jason-2 continues to overfly the platform every 10 days. The joint U.S./France Jason-3 mission (planned 2013 launch) is expected to follow the same ground track, extending the combined calibration record into a third decade, and ensuring that Harvest will continue to serve a vital role in validating data from precise space-borne radar altimeter systems.

While the most conspicuous results from the Harvest experiment are the SSH bias determinations for the T/P and Jason series of altimeter missions, data from the long-term occupation of the platform have lent insight on many signals of geodetic, oceanographic, and environmental interest. The platform Global Positioning System (GPS) station is one of the oldest continuously operating sites in the International GPS Service (IGS) network. While early GPS 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. 2003). 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 et al. 1995; Gill and Parke 1995; Parke and Gill 1995; Kubitschek et al. 1995; Haines et al. 2003). 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 both the TOPEX and Jason microwave radiometers (Keihm et al. 2000; Haines and Bar-Sever 1998; Bonnefond et al. 2010). Calibrations of altimeter significant wave height (SWH) estimates (Parke and Morris 1995) and ionosphere delay corrections (Christensen et al. 1994; Haines et al. 2003) 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.

Table 1
Model specifics for altimeter leg in closure equation: nominal strategy

Model	TOPEX/Poseidon	Jason-1	OSTM/Jason-2
Orbital height	GSFC reprocessed (Lemoine et al., 2007)	GDR-C	T/GDR
Range	MGDR	GDR-C	T/GDR
Wet trop.	Reprocessed TMR (Brown et al., 2009)	GDR-C	T/GDR
Ionosphere	MGDR (DF for ALT, DORIS for POS)	GDR-C	T/GDR
Sea-state bias	Gaspar et al. (1994) 4-param. (MGDR)	GDR-C	T/GDR

2. Altimeter Data

Unless otherwise noted, the source of Jason-2 data for this study is the initial (test) version of the Geophysical Data Record (hereinafter T/GDR; OSTM 2009) for repeat cycles 1–50 (June 2008 through November 2009). The source of the Jason-1 data is the Version-C GDR (GDR-C; Picot et al. 2008) for cycles 1–259 (January 2002 through January 2009). The Jason-2 T/GDR is designed for consistency with the Jason-1 GDR-C. The T/P data for this study are the Merged Geophysical Data Records (MGDR; Benada 1997) for cycles 1–365 (October 1992 to August 2003). Represented in the MGDR product are three different altimeter measurement systems: sides A and B of the dual-frequency NASA Radar Altimeter (ALT-A and ALT-B, respectively), and the experimental CNES Poseidon altimeter. The primary (ALT-A) system showed signs of aging in the form of a degraded point target response (PTR), and a decision was made to switch to the second (B) side in February 1999. A precursor to the altimeters on the Jason satellites, the Poseidon instrument was an experimental single-frequency, solid-state system and was operated for about 10% of the repeat cycles. None of the T/P altimeter systems could be operated simultaneously. From the standpoint of calibration, the switch from ALT-A to ALT-B was not unlike launching a new mission with no overlap period to characterize the relative behavior.

Certain endorsed enhancements were made to the MGDR correction fields, including the use of an improved wet path delay correction for the TOPEX Microwave Radiometer (Brown et al. 2009) and an improved orbital height estimate (Lemoine et al. 2007). These enhancements were made in accordance with the Ocean Surface Topography Science Team (OST/ST) calibration/validation standards developed to promote consistency of results among the various dedicated calibration sites.

Table 1 details assumptions for the altimeter leg of the calibration exercise, for T/P as well as the Jason-1 and OSTM/Jason-2 missions. 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. The unique characteristics of the ground-track approach from ocean to land through Harvest imply that various altimeter correction terms benefit from this customized approach (Christensen et al. 1994). Unless otherwise noted, we adopt the same fitting schemes herein.

3. In Situ Data

Tide gauges provide a means of measuring water level relative to the structure to which they are attached. What is needed for the Harvest altimeter calibration exercise, however, is a precise record of the water level 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 (~50 cm RMS, to which ocean tides are the primary contributor) but also the absolute height and vertical motion of the platform itself (~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.

3.1. Platform Vertical

To support the computation of an absolute altimeter bias, the instantaneous vertical coordinates of the platform tide gauges 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, for example, 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 GPS receivers on the platform.

We must first determine the coordinates of the oil platform in the conventional terrestrial reference frame (TRF). The precise orbit (ephemeris) solution defines the TRF for the altimeter SSH measurements. Orbit computations for the T/P and Jason-1 satellites use the International Terrestrial Reference Frame 2005 (ITRF2005) or slight variants that differ at the sub-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 and 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 orbit errors (e.g., Bonnefond et al. 2010).

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.

We determined the terrestrial position of the platform GPS monument using a technique called precise point positioning (Zumberge et al. 1997). More than 5,600 daily solutions spanning nearly 17 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) archive. The daily estimated position of the platform was rotated from the fiducial-free GPS frame into the International GNSS Service (IGT05) realization of ITRF2005 using a seven-parameter Helmert transformation, values of which were also provided by the IGSAC. Additional detail on the strategy is supplied in Table 2.

The JPL IGSAC is undertaking a reprocessing effort that will culminate in improved GPS s/c orbit and clock products spanning 1992–present (Desai et al. 2009). These

Table 2
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 legacy estimates, e.g., Heflin et al. 2002)
Terrestrial Reference Frame	ITRF2005 as realized by rotation of fiducial-free solution (Heflin et al. 2002)
Solid Tide	IERS2000
Rotational Deformation	IERS2000
Tidal Loading	FES2004 (Lyard et al. 2006) with DTM2000.1 ocean function. (J. Saleh and N. Pavlis, personal communication, 2000)

products will provide the foundation for future Harvest positioning exercises and will support an important new capability to resolve the integer ambiguities of the GPS carrier-phase measurements from a single station (Bertiger et al. 2010a). While these products are not used for our nominal solution because of their limited availability, they provide a valuable means of estimating the vertical positioning error.

To accommodate signal multipath and other systematic local effects on the GPS observations, we also developed antenna phase variation (APV) calibration 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 choke-ring antenna at Harvest has never been replaced; so one set of APV 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. The absolute level is provided by a radome-free period in 1999, as the mounting of a new radome induced a spurious jump in the height of nearly 2 cm. For periods after the collocation of the Ashtech Z12 with the BenchMark in February 2002, it appears the data from both receivers could 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. In the current analysis, we used the Z12 data where available, and the TurboRogue/Benchmark data otherwise.

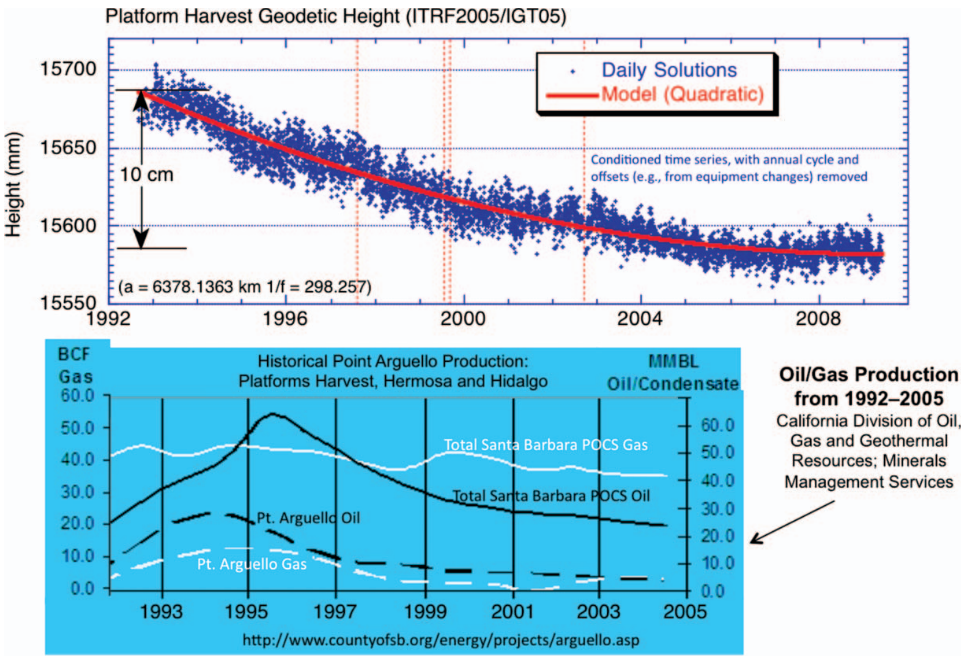

Figure 3. Conditioned time series (top) of the platform geodetic height (ITRF2005/IGT05) from 1992–2009. Subsidence from the pumping of oil and fluids from the underlying Pt. Arguello deposit has ceased. Production at Pt. Arguello peaked in 1994 (bottom) and has declined significantly (as of 2005).

The conditioned 17-year 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 two decades. 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 consequence of the extraction of oil and other fluids from the underlying Arguello deposit, the subsidence resulted in a ∼10-cm drop in the platform position from 1993 to present. The largest rate of subsidence occurred early in the record, commensurate with the peak production year (1994) at the Point Arguello Field (Figure 3). In keeping with decreased production, recent data suggest the subsidence has eased considerably.

Unraveling the real signal from the error in the GPS vertical remains one of the single greatest challenges for the Harvest calibration experiment. As indicated previously, a major reprocessing effort is underway at the JPL IGSAC. The new GPS spacecraft orbit, clock, and ancillary (e.g., phase ambiguity resolution) products will provide the framework for significant improvements to the Harvest GPS time series. While the new IGSAC products are not available for the entire 1992–2009 span represented by the Harvest time series, they can be used in selected periods to better assess the errors in the current strategy. In this spirit, we reprocessed one year's worth of Harvest GPS data (centered on January 2009) using the new products, and resolving the integer ambiguities on the GPS phase biases (Bertiger et al. 2010a). For the resulting 359 daily solutions, we then compared the height estimate to the corresponding figure from the nominal solution (Figure 3). The mean and standard deviation of the differences ($N = 359$) are 14 and 6 mm, respectively. Implied by the 14-mm mean difference is an increase in the platform geocentric height (using the reprocessed solution), which in turn would decrease the altimetric SSH bias estimates from Harvest. Since it is based on only a single year of data, this result should be considered preliminary. As reprocessed JPL IGSAC products are released for earlier years, the historical Harvest time series will be updated. In the meantime, we adopt the mean difference (14 mm) from these two competing strategies as a proxy in our error budget for the systematic (nonaveraging) error in the platform geocentric height.

The model fit (red line in Figure 3) describes the long-term platform vertical motion from GPS and provides the starting point for computing the instantaneous position for determining the altimetric SSH bias. For each overflight, we evaluate the model fit at the time of closest approach and then add instantaneous model displacements for the solid tide, rotational deformation (pole tide), and tidal loading (Table 2). Also accounted for are thermal expansion/contraction of the platform structure, and annual loading from groundwater, ice, air pressure, and nontidal ocean effects. Discussed by Haines et al. (2003), the annual loading and thermal models describe small vertical displacements (0.2–2 mm) but collectively explain the annual signal observed in the Harvest GPS time series.

3.2. 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 17 years of continuous data from collocated GPS and tide gauge systems.

Prior to the launch of T/P 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 replaced the NGWLMS with an updated system. The acoustic system—inoperative after storm damage in May 1999—was 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; 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 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/NOS 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 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 the Jason missions, CU has deployed an experimental optical (laser) system on the 47-ft sump deck. The down-looking 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.

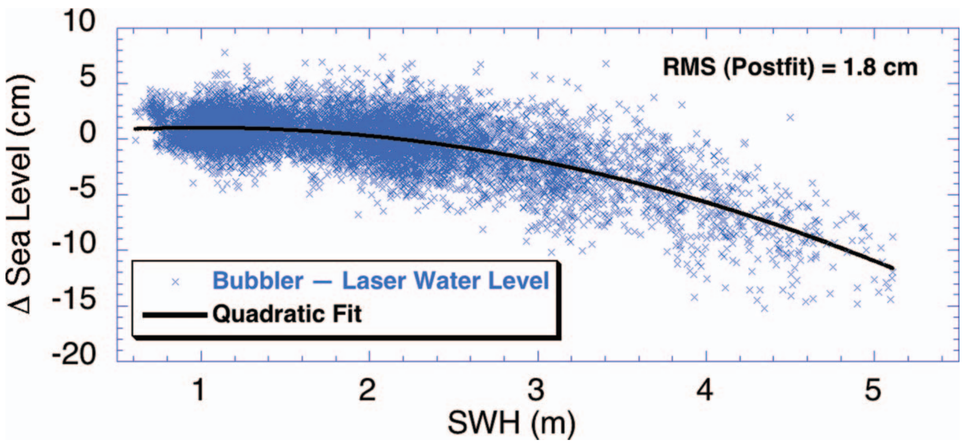

Figure 4. Difference of platform water-level observations (Bubbler minus Lidar) as a function of significant wave height. The dynamical wave conditions at the platform present special challenges for interpreting tide-gauge measurements.

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 SWH derived from buoy data. We use SWH data from the Scripps Institution of Oceanography Harvest buoy for current comparisons. Differences in the sea-level readings from the laser (CU) system and NOAA bubbler show important wave-height dependencies (Figure 4), and 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 bubbler system.

In a final step, the corrected water level measurements are combined with the local survey information, GPS vertical estimates and associated model information to develop a precise estimate of geocentric SSH at satellite overflight times.

4. Altimeter Measurement System Calibration Results

At this writing, OSTM (Jason-2) has passed over the platform 52 times since the mission began its observational phase in July 2008. During the first seven months (until January 2009), the overflights occurred in tandem with Jason-1 (Jason-2 trailing its predecessor by ∼55 s.). We focus herein on calibration results from the Jason-2 mission. We also update the TOPEX/Poseidon and Jason-1 calibration results, including those from their own formation-flying phase in 2002, and present overall (17-year) calibration time series for all missions.

4.1. Sea Surface Height

The 17-year calibration record of SSH (altimeter minus in situ) from Harvest is depicted in Figure 5. Represented in the plot are three missions (T/P, Jason-1, and OSTM/Jason-2) and five different altimeter measurements systems (ALT-A, ALT-B and Poseidon on T/P, as well as Poseidon-2 and -3 on Jason-1 and OSTM/Jason-2, respectively). Each point corresponds to the instantaneous difference of the in situ and altimetric SSH for a single overflight. The repeatability of the SSH bias estimates is at the 3-cm level, which is consistent with

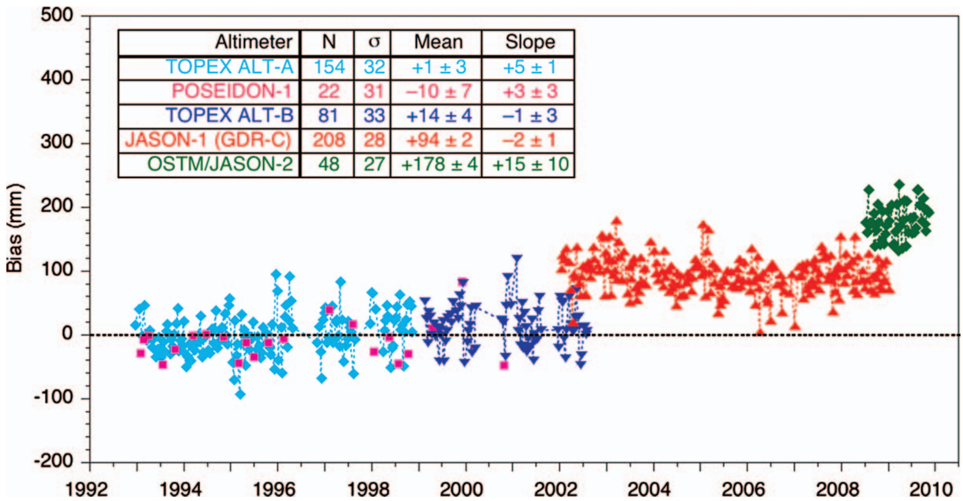

Figure 5. Historical (17-yr.) time series of Harvest SSH calibration. Each point represents the instantaneous difference between in situ and altimeter SSH for a single overflight. Five altimeter measurement systems on three different satellite platforms are represented.

historical performance at Harvest (Christensen et al. 1994; Haines et al. 2003) and other dedicated calibration sites monitoring the T/P and Jason systems (e.g., Bonnefond et al. 2003; Watson et al. 2003). Also provided for each of the five measurements systems is the mean SSH bias and the corresponding standard deviation of the mean. A more rigorous error budget—embracing the contribution of systematic errors—is provided later.

4.1.1. Absolute Bias. Consistent with prior studies (e.g., Haines et al. 2003; Bonnefond et al. 2010), the Harvest results indicate that the SSH measurements for the three legacy measurement systems on T/P are unbiased at the ∼15-mm level. In contrast, the Jason-1 and OSTM/Jason-2 data sets are significantly biased, by +94 and +178 mm, respectively. This implies that both Jason measurement systems are measuring short and the SSH readings are accordingly high. The Jason-1 value is about 30% smaller than the figure (138 mm) reported by Haines et al. (2003), due almost exclusively to evolutions of the nonparametric sea-state bias (SSB) correction on the GDR product (Labroue et al. 2004).

Representing a convolution of the traditional electromagnetic bias (EMB) as well as tracker and skewness biases (Chelton et al. 2001), alternative SSB models for the same instrument system can affect the SSH bias estimates systematically by several cm (e.g., Christensen et al. 1994; Haines et al. 2003). Indeed, the SSB correction used in the original (A) version of the Jason-1 GDR is 5-cm larger, on average at Harvest, than its counterpart on the latest (C) version. Due to its large potential influence on the SSH bias computation, the SSB correction has a conspicuous ability to confound comparisons of SSH bias estimates from different missions and calibration programs. The dedicated calibration sites have adopted calibration standards to ensure ready comparison of SSH bias estimates and to maintain consistency with the processing procedures used by the overall OST/ST.

To assign more realistic errors to our SSH bias estimates, we include the systematic in situ measurement errors shown in Table 3 (using OSTM/Jason-2 as an example). Adapted from Haines et al. (2003), with updated numbers, the table indicates that the largest contributor is the uncertainty in the platform vertical height from GPS (cf. section 3.1). We

Table 3
Error budget for OSTM/Jason-2 SSH bias estimate at Harvest

Error source	Magnitude (Standard Error)	Reference
GPS survey of platform in terrestrial reference frame	14 mm	This study (see text)
Local survey of GPS benchmark to tide-gauge benchmark	4 mm	Morris et al. (1995)
Tide gauge error (non-averaging)	5 mm	Parke and Gill (1995)
Random error	4 mm	1 standard error (N = 48, $\sigma = 27$ mm)
TOTAL	16 mm	Root-sum-square

note that the error budget applies to the skill of the Harvest experiment at producing an SSH bias estimate for that location. It does not reflect geographically correlated errors in the altimeter measurements that could render the Harvest result different from a global one. These errors can be quantified by comparisons among the results from different dedicated calibration sites (e.g., Bonnefond et al. 2010).

The total estimated error on the mean SSH bias estimates is in the range of 15–17 mm, depending on the particular altimeter measurement system (e.g., Jason-1 vs. T/P). The total error is dominated by the systematic in situ contributions (Table 3), and the slight variations are due to the different sample sizes (overflight counts) and commensurate effect on the random component of the error. In view of this error budget, the T/P SSH bias estimates are indistinguishable from zero, while the Jason estimates are significantly positive, with the newer Jason-2 measurement system yielding an SSH bias roughly two times larger than the legacy Jason-1 system. The T/P, Jason-1, and Jason-2 SSH bias estimates are generally quite consistent among the dedicated calibration sites (Willis 2009; Bonnefond et al. 2010), reinforcing these results. While the primary sources of the biases are known to be the radar altimeter ranges, as discussed in section 4.2, the exact causes remain subjects of ongoing investigation.

At the recent OST/ST meeting, Picot et al. (Willis 2009) reported the discovery of errors in the truncation of the pulse repetition frequency (PRF) and in the *Ku*-band characterization files used in processing the measurements from both the Jason radar altimeters. If confirmed, the errors would collectively explain 120 and 25 mm of excess range in the Jason-1 and Jason-2 altimeter measurements, respectively. Correcting for the error would shorten the ranges, further increasing the respective (Harvest) SSH biases (from +94 to +214 mm for Jason-1, and from +178 to +203 mm for Jason-2). While this would improve the agreement between the two Jason missions, it would also move them both further from the current T/P standard that yields no significant bias at the calibration sites. Pending further confirmation of these findings, our nominal estimates apply the standardized GDR-C (Jason-1) and T/GDR (Jason-2) data with no additional adjustments of the altimeter range data.

4.1.2. Relative Bias. The two tandem verification phases provide a unique perspective on the relative SSH bias between missions. In the first phase (2002), Jason-1 flew in formation with T/P, passing over the platform 22 times together, separated by approximately 70 s. In the second phase (2008), OSTM/Jason-2 and Jason-1 overflew the platform 20 times with a separation of about 55 s. These tandem verification phases have proven invaluable for connecting data from the three missions as seamlessly as possible. Excepting

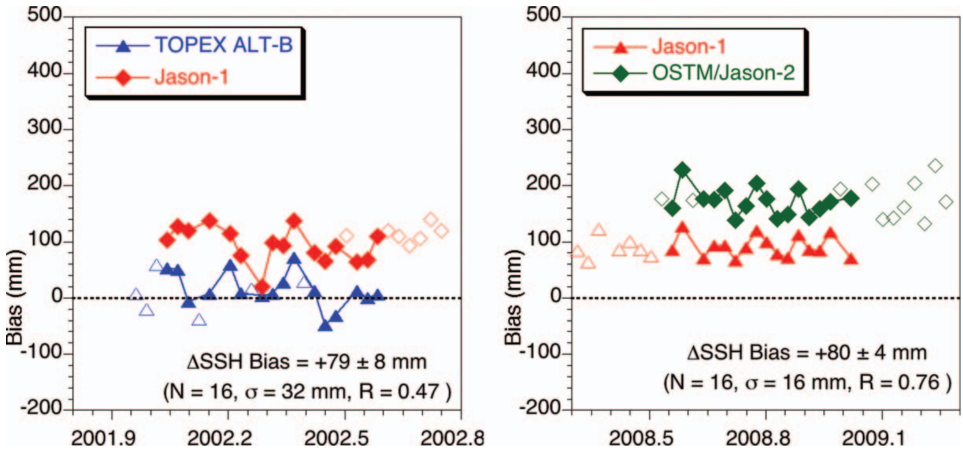

Figure 6. Closeups of the Harvest SSH calibration time series corresponding to the 2002 (T/P vs. Jason-2) and 2008 (Jason-1 vs Jason-2) tandem verification phases. Solid symbols represent the common overflights used in generating the statistics. Open symbols depict other overflights.

the propagation of wind waves and swell, the ocean environment within the radar scene surrounding the platform changes negligibly over 1 min. Any differences in the altimetric data can be attributed almost entirely to errors in the respective measurement systems.

Shown in Figure 6 are closeups of the calibration time series framing the 2002 (T/P vs. Jason-1) and 2008 (Jason-1 vs. Jason-2) tandem verification phases. The individual SSH bias estimates for T/P (ALT-B) and Jason-1 are only mildly correlated ($R = 0.47$, N = 16), suggesting that the two altimeter systems respond somewhat differently to near-identical radar scenes. In contrast, the cycle-by-cycle variations of the Jason-1 and Jason-2 biases are more significantly correlated ($R = 0.76$, N = 16), reflecting perhaps the similar Poseidon heritage in the radar altimeter designs. The mean ΔSSH biases are +79 and +80 mm, respectively, for Jason-1–T/P (2002) and Jason-2–Jason-1 (2008), implying consecutive ∼8-cm spurious increases in the apparent SSH for the data from each follow-on mission. At this writing, these successive 8-cm steps are considered coincidental.

The +80 mm ΔSSH bias (Jason-2–Jason-1) is in excellent agreement with our own global analysis, which reveals a ΔSSH of +77 mm (cf. +75 mm from deCarvalho et al. 2009; Ablain et al. 2009). For the 2002 tandem verification phase (Jason-1–T/P), the ΔSSH from our global analysis (close to 100 mm) is somewhat larger than the corresponding number from Harvest (+79 mm). This suggests that the geographically correlated errors in the T/P versus Jason-1 differences are larger than those in the Jason-1 versus Jason-2 differences. This is not surprising in view of the similar heritage of the two Jason systems. For further information, the reader is referred to Bonnefond et al. (2010), who provide a summary of results from different dedicated calibration sites in the context of geographically correlated errors.

4.2. Correction Terms

To lend further insight on potential causes of the SSH biases, we show in Figure 7 differences of the various correction terms underlying the formation of the altimetric SSH. The time series again correspond to closeups of the tandem verification phases (for T/P and Jason-1 in 2002 and Jason-1 and -2 in 2008), allowing us to better express the behavior of the newly launched missions with respect to their predecessors. Also of interest during these

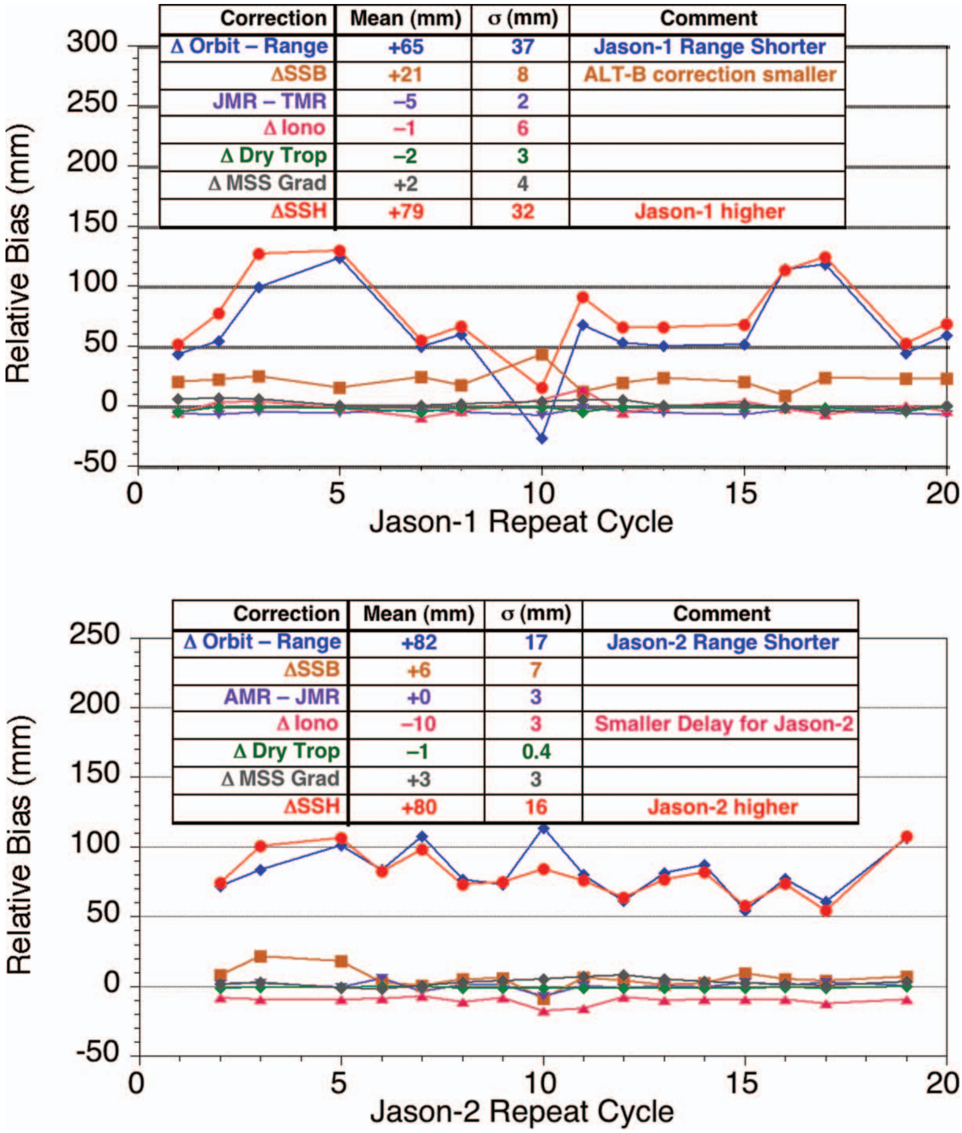

Figure 7. Time series of altimetric correction term differences for (top) the T/P vs. Jason-1 tandem verification phase in 2002, and (bottom) the Jason-1 vs. Jason-2 tandem verification phase in 2008.

periods is the ability to form ΔSSH biases (between missions) without any of the traditional correction terms for atmospheric delays and sea state. The uncorrected SSH is simply the orbital altitude—from precise orbit determination—minus the altimeter range (hereinafter OMR for "Orbit Minus Range"). Common-mode errors, due, for example, to atmospheric delays, cancel out in the ΔOMR (between missions), since the satellites pass over the platform with a lag between them of only 1 min (cf. section 4.1.2).

The results for both 2002 and 2008 tandem verification phases implicate the OMR as the primary source of the ΔSSH biases between missions. Competing orbit solutions based on GPS tracking data (Bertiger et al. 2010b) can be used to detect potential biases in the orbit altitude over the platform. For the legacy missions, such orbit comparisons have generally supported the idea that the correlated (nonaveraging) error is less than 1 cm over Harvest (e.g., Christensen et al. 1994; Haines et al. 2003). Likewise for Jason-2, the average difference of the GDR-C and independent GPS orbit over Harvest is small (average of 2 mm, with $N = 45$ and $\sigma = 6$ mm). Consistent with prior studies (Bonnefond et al. 2010), this demonstrates that the altimeter range measurements themselves bear the primary responsibility for the ΔSSH biases. The correction terms for atmospheric delays and sea-state remain of course important to evaluate, especially insofar as their long-term stability is concerned. Due to their thorough instrumentation directly along the satellite ground tracks, dedicated calibration sites such as Harvest are well suited to this task.

4.2.1. Ionosphere. Since the ionosphere is linearly dispersive, the associated delay can be removed to first order using radio signals on two frequencies. With the exception of the experimental Poseidon system on T/P, all altimeter measurement systems considered herein broadcast on two frequencies (in the *C* and *Ku* bands). The dual-frequency (DF) ionosphere correction for the primary (*Ku*) band of the altimeter is expressed as:

$$\Delta R_{ION} = \frac{f_C^2}{f_{Ku}^2 - f_C^2}(R_{Ku} - R_C) = 0.1798 \cdot (R_{Ku} - R_C) \tag{1}$$

where R_{Ku} and R_C are the *Ku*- and *C*-band ranges, with frequencies f_{Ku} (13.575 GHz) and f_C (5.3 GHz), respectively.

An independent measure of the columnar ionosphere delay at Harvest can be obtained using the GPS Ionosphere Maps (GIM) based on DF (*L*-band) GPS signals from a global network (Mannucci et al. 1998). We note that the GIM estimates represent the total columnar delay, while the altimeters observe the portion of the ionosphere below the 1330 km altitude of the T/P and Jason 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 8 provides a time series (1997–2009) of the GIM versus altimeter dual-frequency (DF) ionosphere corrections at Harvest, expressed in units of delay (mm) for the primary *Ku*-band frequency of the altimeter. The DF measurements from all four altimeters

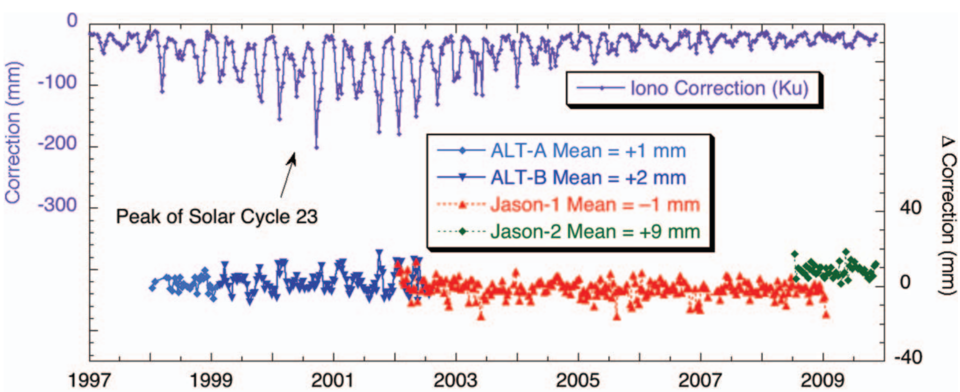

Figure 8. 17-yr. calibration record of GPS (GIM) vs. dual-frequency (DF) altimeter ionosphere corrections (Ku Band). The top curve gives the overall correction at the overflight times and depicts solar cycle 23 as well as a high-frequency (every 120 d) aliasing due to sampling. The bottom curves depict the excellent long-term stability of the GPS vs. altimeter differences. A bias of ∼1 cm is observed in the GIM vs. Jason-2 differences.

Table 4
Summary of Ku- Cu-band SSH and SSB biases for Jason-1 and Jason-2/OSTM

	Jason-1 Ku Band	Jason-1 C Band	Jason-2 Ku Band	Jason-2 C Band
SSH Bias	+81 ± 6 mm	+90 ± 11 mm	+169 ± 10 mm	+209 ± 15 mm
Local SSB	3.4 ± 0.2%	4.6 ± 0.4%	3.5 ± 0.4%	4.6 ± 0.6%
Number of Overflights	217	216	48	43
Postfit σ	35 mm	63 mm	27 mm	39 mm

(TOPEX A/B and Jason 1/2) agree with the GIM estimates at the sub-cm level in terms of repeatability. There is no evidence of important long-term instabilities and no apparent correlation with the overall level of ionospheric activity. However, a bias of $\sim$1 cm is observed in the Jason-2 DF ionosphere correction at Harvest with respect to both GIM and Jason-1. A similar 1-cm bias is observed in globally averaged differences of the Jason-2 and Jason-1 DF ionosphere corrections and is consistent with +8 and +13 cm ΔOMR averages obtained using *Ku* and *C* band ranges, respectively (Desai et al. 2008; Bonnefond et al. 2010). The global differential analysis, however, cannot be used to arbitrate how the underlying errors should be allocated to each mission and each frequency band. To address this, we developed a technique for estimating the absolute SSH biases at Harvest on each of the altimeter frequencies (13.575 and 5.3 GHz, respectively, for *Ku* and *C* bands).

To determine the SSH biases for both frequency bands independently, we must first find a means of computing the SSH without the aid of the altimetric DF ionosphere and SSB corrections. Both are inextricably linked to the altimeter ranges in the ground processing, and independent estimates are needed to properly unravel the *Ku*- and *C*-band contributions to the SSH bias. For this exercise, we thus use GIM to provide an ionospheric correction for both the *C*- and *Ku*-band ranges. We use the standard GDR corrections for the dry and wet troposphere as they are derived, respectively, from a model and on-board radiometer (cf. section 4.2.2), implying they are already independent of the radar altimeter data. For each overflight, we then compute *Ku*- and *C*-band SSH measurements corrected for the atmospheric delays according to the above prescription and form the difference with the in situ SSH. The residual is regressed against SWH from nearby buoys, and the intercept of the linear fit with SWH = 0 is considered the SSH bias. A byproduct of the technique is a local SSB model—expressed as a simple percentage of SWH—for each frequency band.

Summarized in Table 4 are the results of this exercise. For Jason-1, both the *Ku*- and *C*-band SSH bias estimates (+81 and +90 mm, respectively) agree reasonably well with the estimate from the traditional closure exercise (+94 mm). This is not the case for Jason-2, where the *C*-band SSH bias (+209 mm) is significantly larger than its *Ku* counterpart (+169 mm) and the figure from traditional closure (+178 mm). Expressing the Jason-2 bias results in terms of range rather than SSH (by changing signs) and substituting the respective values (–169 mm for R_{Ku} and –209 mm for R_C) into Eq. (1) yield a bias of +7.2 mm for the Jason-2 DF ionosphere correction. This is consistent with the results depicted in Figure 8, and provides further evidence that Jason-2 is the source of the ionosphere bias.

It is not possible to ascertain which of the two Jason-2 ranges (*Ku* or *C*) is responsible, as they are both measuring significantly short (by 169 and 209 mm, respectively). Not accounted for in this analysis are the apparent errors in the *Ku*-band ranges from the altimeter characterization data and PRF truncation (cf. section 4.1.1). Application of the correction for Jason-2 would shorten the *Ku*-band range by an additional 25 mm (from 169 to 194 mm), leading to better agreement with the current *C*-band range and significantly reducing the Jason-2 ionosphere bias. At the same time, however, the Jason-1 results (*C* vs. *Ku*) would become more disparate since the *Ku*-band ranges would decrease by an additional 120 mm with no accompanying decrease in *C* band. Analysis of the *C*-band altimeter data for errors due to altimeter characterization information and PRF truncation is underway (Willis 2009). A more definitive explanation of these results awaits the outcome of this investigation.

4.2.2. Wet Troposphere. Essential components of the altimeter measurement systems are the down-looking TOPEX, Jason-1, and OSTM/Jason-2 microwave radiometers (TMR, JMR, and AMR, respectively) which passively measure water-vapor abundance along the altimeter path (e.g., Chelton et al. 2001). This 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 could be used to compute an independent estimate of the columnar wet path-delay (WPD) measurements, which in turn could be used to calibrate the spaceborne microwave radiometer (MR) data. Using the strategy described by Haines and Bar-Sever (1998), GPS-based WPD measurements were recovered at the overflight times and compared with the corresponding MR measurements. We note that the MR observations collected as the satellite passes over the platform are typically not trustworthy owing to contamination of the radiometer footprints by nearby coastal lands. (An enhanced MR product, described later, has been developed to combat this problem.) To obtain the MR measurements for our nominal 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) WPD 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 MRWPD at the platform. For this comparison exercise, we used reprocessed TMR WPD data to account for the spurious drift of the 18-Ghz channel (Brown et al. 2009). The JMR and AMR measurements are taken directly off the GDR-C and T/GDR.

Shown in Figure 9 is the 17-year calibration time series of the MR–GPS WPD differences. The repeatability of the differences is at the 1-cm level for all three systems, and the overall MR–WPD biases are indistinguishable from zero. (Due to the influence of the radome and other systematic errors, the GPS WPD measurements cannot be used to discern potential biases in the MR data at the few-mm level.) The data from the two legacy systems (TMR, JMR) show good long-term stability at Harvest ($<$ 0.5 mm/yr). The time series of the AMR–GPS WPD (July 2008 to August 2009) is too short to evaluate long-term drift, and monitoring will continue.

To extend the utility of the MR data closer to the coast, Brown (2010) has developed a novel WPD retrieval algorithm for the AMR data from OSTM/Jason-2. The resulting enhanced path delay (EPD) product can be used to replace the AMR correction on the GDR for coastal applications. (The GDR-C and EPD versions of the AMR WPD corrections are identical for distances greater than 25 m from the coast.) The EPD product is of obvious value to the in situ calibration program, owing to the proximity of the dedicated sites and other tide gauges to the coast. In Figure 10, we show a scatter plot of the GPS versus AMR WPD at Harvest, using for the latter both the GDR and EPD corrections. We note that the GPS WPD solution in this limited test is based on reprocessed data products from the JPL IGSAC (cf. section 3.1), so the GPS WPD estimates will not agree exactly

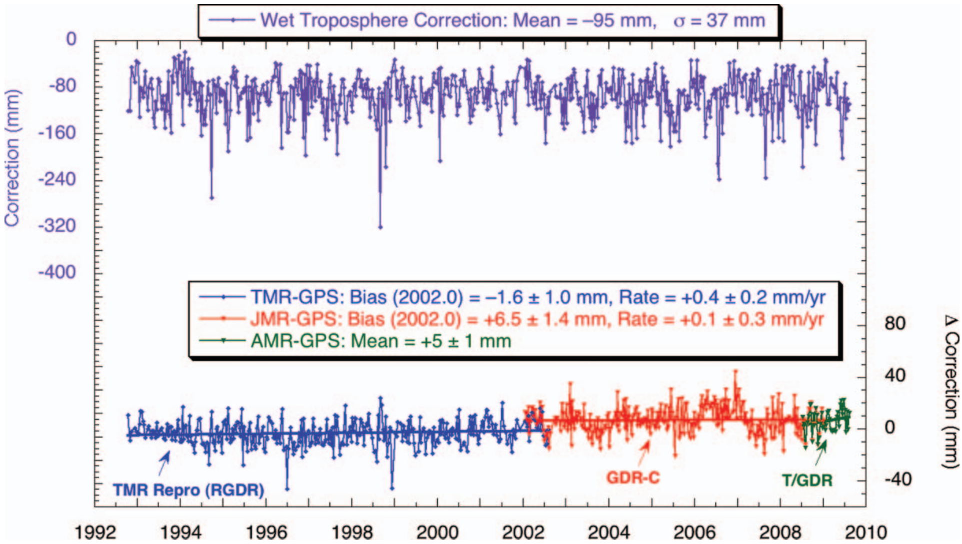

Figure 9. 17-yr. calibration record of GPS vs. microwave radiometer (MR) wet path delay corrections. The top curve gives the overall correction at the overflight times, showing the typical dry conditions at the platform (median delay of 95 mm). The bottom curves depict the excellent long-term stability of the GPS vs. MR differences. A slight bias between JMR and TMR (< 1 cm) is symptomatic of JMR measuring slightly drier than TMR for typical Harvest conditions.

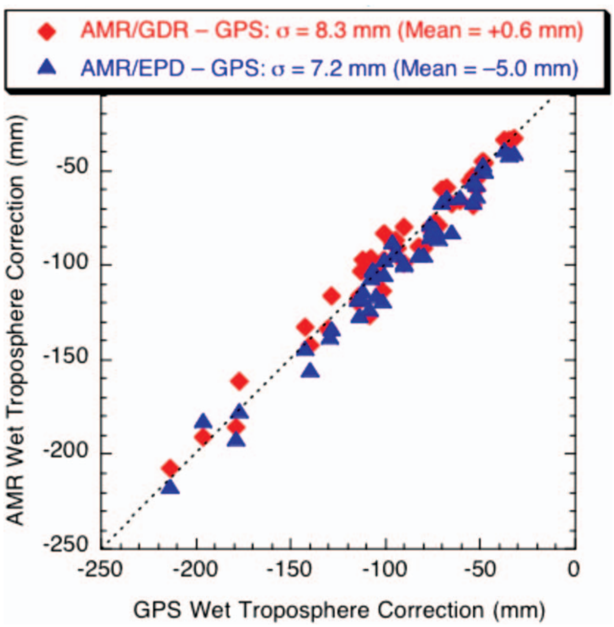

Figure 10. Scatter plot showing agreement of competing OSTM/Jason-2 AMR wet path delay corrections with values from GPS. The new enhanced path delay (EPD) product shows better agreement with GPS (minus a bias), even though the EPD product is evaluated directly over the platform (vs. 30 km offshore for the conventional AMR correction on the GDR).

with those underlying the historical calibration record shown in Figure 9. In particular, the reprocessed GPS solutions yield WPD estimates that are about 4 mm drier (on average) than the corresponding values from the legacy GPS processing. This result, however, applies to a short period (less than one year), and it is not yet known if a similar pattern will persist for the entire historical calibration record.

The AMR/EPD correction is evaluated directly over the platform and still outperforms the GDR correction, which is evaluated 30 km out. (The scatter of the AMR vs. GPS differences is reduced with the EPD product. In view of systematic errors in the GPS measurements, e.g., from radome effects, the change in the bias is of questionable significance and merits additional investigation.) The AMR/EPD product suggests the troposphere over the platform is slightly wetter (on average) versus 30 km offshore, and its use would increase the Jason-2 SSH bias by about 5 mm. The land-contamination correction is more important at other dedicated sites, such as Corsica (Bonnefond et al. 2010), and its application improves agreement among the sites. We will use it in our nominal solutions when it is more widely available for JMR and TMR (in addition to AMR).

4.3. Outlook on Monitoring Stability

Measuring global sea level change with accuracy significantly better than 1 mm yr^{-1} is an expressed goal for the climate record from the combined T/P, Jason-1, and OSTM/Jason-2 data. The unexpectedly high performance of the T/P mission and the 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 and OSTM missions. Also provided in the 17-year SSH calibration time series (Figure 5) are estimates—using a simple linear regression—of the SSH drifts for each of the five altimeter measurements systems: ALT-A (1992–1998), ALT-B (1999–2002), Poseidon (1992–2002), Jason-1 (2002–2009), and Jason-2 (2009–pr.) The uncertainties correspond to one standard error from the regression, and are undoubtedly optimistic since they do not include systematic error sources. With the possible exception of ALT-A, none of the drift estimates is statistically compelling. The sense of the estimated drift on ALT-A (+5 mm yr^{-1}) is consistent with effects of the degrading point target response (PTR) on the primary side of the altimeter (Hayne and Hancock 1998), but the magnitude is too large. The other four systems appear stable within the limits of the present abilities of Harvest to support accurate determination of the drift.

While the formal (standard) errors are optimistic, they do demonstrate that a minimum of 5–7 years of data, and near-perfect control of systematic errors are needed under present circumstances to approach the 1-mm yr^{-1} level. This situation can be improved in two ways. One is to improve the repeatability—currently at the 3-cm level—of the individual (cycle-by-cycle) SSH bias estimates. In this context, it is important to bear in mind that the altimetric SSH represents an average over a footprint width of several km surrounding the platform, while the in situ SSH represents a pinpoint measurement taken at the tide-gauge location. In addition to the intrinsic random errors in each measurement leg (in situ and altimetric), this fundamental difference in the measurement impacts the repeatability of the bias estimates. The discrepancies between the point (tide gauge) and footprint (altimetric) measurements are not well understood and are sensitive to varied local conditions (e.g., circulation, wind speed, wave heights). These effects need to be better characterized and are particularly important at Harvest due to its open-ocean location, where tide-gauge behaviors are not as well known.

A parallel effort is being directed at reducing the systematic errors, the most important of which is the uncertainty in the vertical rate of the platform from GPS. Successive realizations of the ITRF have impacted the platform vertical rate at the 1-mm yr^{-1} level. Effects of long-term changes in the GPS receiver performance, as well as "jumps" from equipment changes (e.g., radomes) must also be carefully considered. We plan to undertake a comprehensive reprocessing of the Harvest GPS data for the entire 1992–2009 time series, relying on novel new positioning techniques (Bertiger et al. 2010a) and new GPS s/c orbit and clock products (Desai et al. 2009).

Discriminating drift at the 1-mm yr^{-1} level clearly remains a significant challenge for a single calibration site and will be contingent on extremely tight control of potential systematic errors and the development of a long observing record. This is not to say, however, that the calibration sites have not contributed to the characterization of important drifts in the altimetric measurement systems. By 2004, the calibration time series from Harvest pointed to a significant drift ($\sim$1 cm/yr) in the Jason-1 SSH height measurements (Haines et al. 2004). Originating in the first (A) version of the GDR, the drift was attributed to a combination of the wet path delay correction from the Jason microwave radiometer (Brown et al. 2007), and the precise orbit ephemeris (POE). With the release of the B version of the GDR, the estimated drift at Harvest was reduced dramatically (from -10 ± 3 mm yr^{-1} to $+0.3 \pm 2$ mm yr^{-1}). Together with similar experiences at Corsica and Bass Strait, this episode provided the strongest evidence yet that dedicated calibration sites are capable of providing insight on not only the bias of the altimetric SSH but also the stability (Bonnefond et al. 2010). The collocation of instruments at the dedicated sites also proved crucial in diagnosing the underlying causes of the drift. Finally, the revelation that some of the instability was due to the POE led to the eventual discovery of long-term, geographically correlated radial drifts in the computed orbit (Bertiger et al. 2004; Bonnefond et al. 2010), with varying effects on the calibration sites depending on location.

5. Summary

Established in 1992 along the T/P ground track, the Harvest experiment has provided for continuous and accurate monitoring of precise (Jason-class) spaceborne altimeter measurement systems for nearly two decades. The Harvest in situ record continues to indicate that SSH biases for all three T/P (1992–2005) measurement systems (ALT-A, ALT-B, and Poseidon) are statistically indistinguishable from zero at the 15-mm level. In contrast, the SSH bias estimates for the newer Jason-1 mission (2001–present) and the Ocean Surface Topography Mission (2008–present) are significantly positive. In orbit for over eight years, the Jason-1 measurement system yields SSH biased by $+94 \pm 15$ mm. Its successor, OSTM/Jason-2, produces SSH measurements biased by $+178 \pm 16$ mm. While the primary sources of the biases are known to be the radar altimeter ranges (see section 4.2), the exact causes remain subjects of ongoing investigation.

In evidence from the OSTM/Jason-2 tandem verification phase (2008) data is a significant correlation between the two Jason altimeter systems. The relative SSH bias (Jason-2 –Jason-1) from 16 tandem overflights is +80 mm and is consistent with the +77 mm figure from global analysis. A new technique for computing SSH biases independently on the Ku- and C-band channels is described and points to an additional 4-cm bias on the secondary Jason-2 (C) band.

Based on the standardized GDR products adopted for the study, none of the altimeter measurement systems shows signs of significant drift. This is also true of the constituent measurements (e.g., ionosphere and wet path delays). Further research is needed, however, to demonstrate that the measurement system stabilities can be monitored from Harvest at the level (1 mm yr^{-1}) necessary to support calibration of the emerging altimetric sea level record. This necessitates combining results from different calibration sites (e.g., Bonnefond et al. 2010) and applying complementary techniques based on data from the global tide-gauge network (e.g., Mitchum 1998).

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