Recent Results from the Harvest Experiment

Bruce Haines. Shailen Desai and Danan Dong (*Jet Propulsion Laboratory, Calif. Inst. of Technology, Pasadena, CA, USA*),
George Born (*University of Colorado, Boulder, CO, USA*) Steve Gill (*NOAA, Natl. Ocean Service, Silver Spring, MD, USA*)
Jason-1 Science Working Team Meeting, Arles, France, November 2003

Introduction

The *Arguello Inc.* Harvest Oil Platform is located about 10 km off the coast of central California near the launch site of Jason-1 at 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 can been experienced during powerful winter storms (Figure 3). Prevailing winds are from the northwest and average about 6 m/s (15 mph). 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).

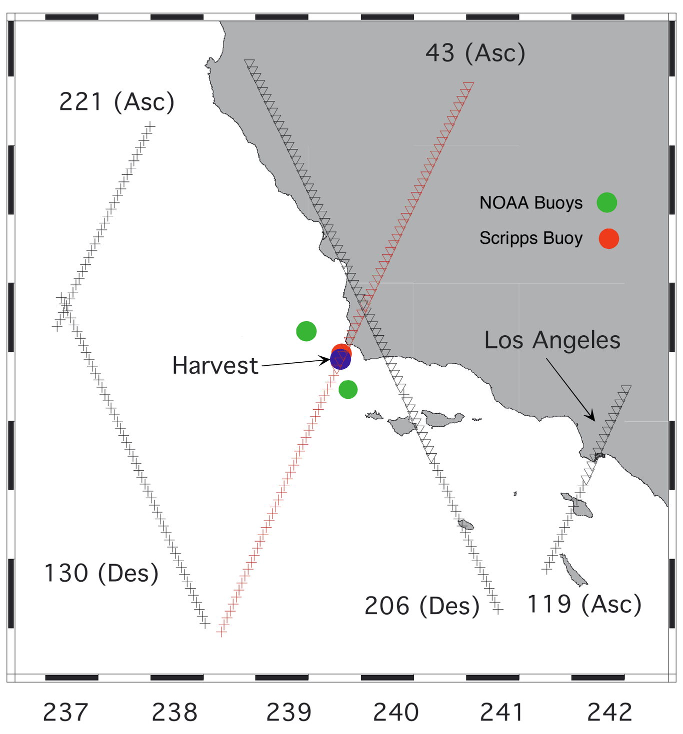


Figure 1: Map of Central California coast showing location of Platform Harvest. The red line shows the path Jason-1 traces over the ocean on approach.

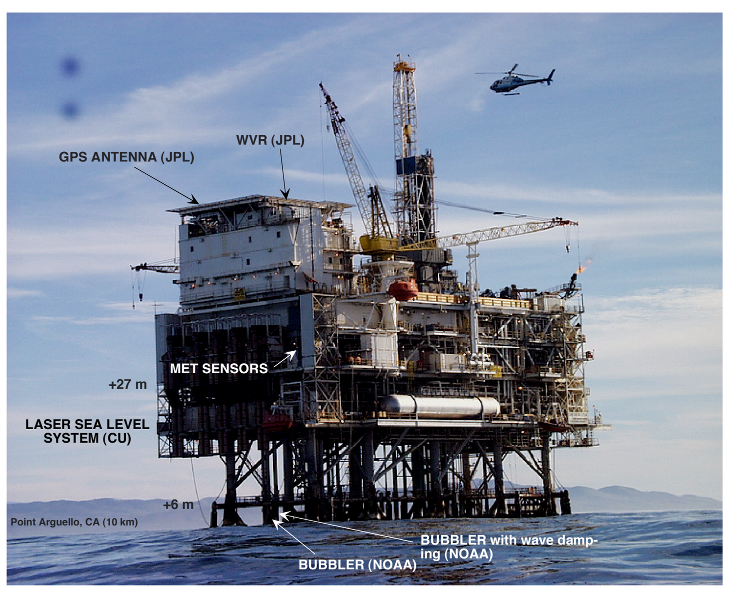


Figure 2: Arguello Inc. Platform Harvest, with locations of instruments that are being used to monitor the measurements taken by Jason-1 and TOPEX/POSEIDON.

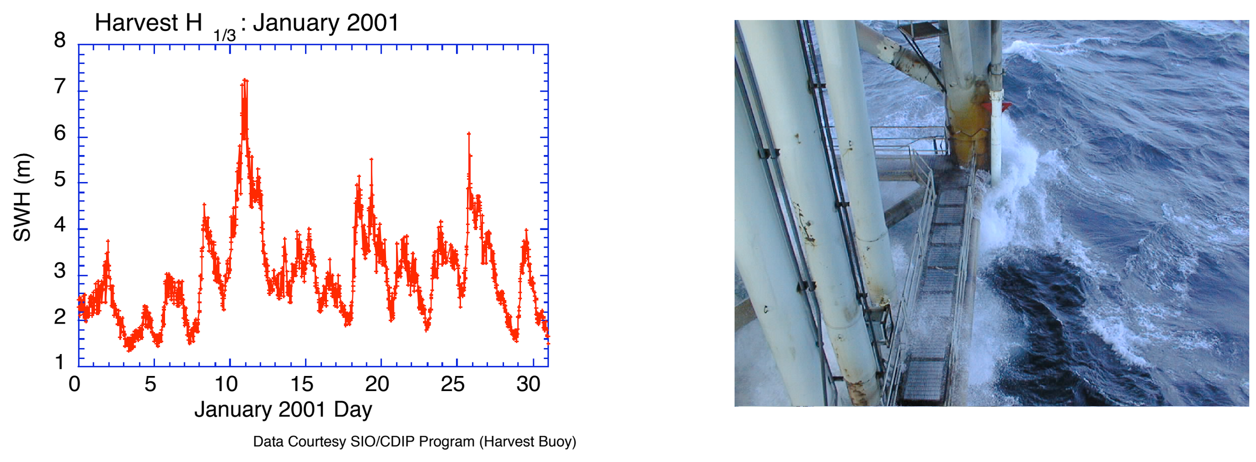


Figure 3: Wave heights at Harvest during the month of January 2001 (left). During the winter, waves can wash over the catwalk at the 20 foot level. The platform's location in the open ocean implies that the altimeter missions are monitored in conditions under which their measurement systems are designed to best operate.

In addition to its primary mission to drill for oil, Harvest is a calibration site for the Jason-1 (2001–) and TOPEX/Poseidon (1992–) missions, and as such is an important international resource for the study of sea level from space. The platform is located sufficiently far offshore so that the area illuminated by the altimeter's radar pulse 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

Jason-1 was launched into an orbit that placed it in formation flight with its predecessor for seven months (Jason-1 led T/P by about 70 s.) 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 y, 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 spaceborne radar altimeter systems.

Vertical Platform Motion

The geocentric height and rate of Harvest must be accurately measured to perform the absolute calibration of sea-surface height. To this end, the platform has been continuously occupied by a GPS station since 1992. The most conspicuous feature in the time series of the Harvest vertical (Figure 4) 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 ceased.

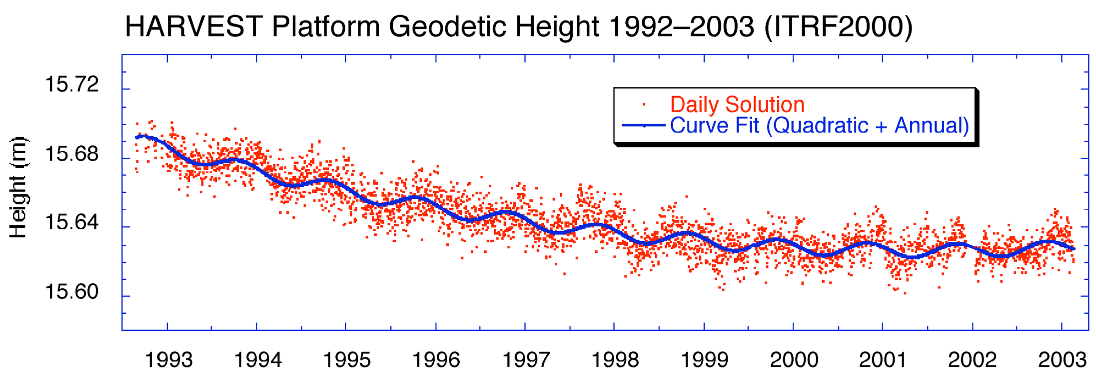


Figure 4: Conditioned time series of the platform geodetic height (ITRF2000) from 1992–2003. Subsidence from the pumping of oil and fluids from the underlying Arguello deposit has ceased.

The most prominent periodic variation in the decade-long record of platform vertical position is seasonal. Annual (seasonal) variations are commonly observed in GPS geodetic time series, and can be explained by both errors in the GPS measurement system and real ground movement, e.g. due to seasonal mass distribution within the Earth system. 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 antenna phase center variation (PCV) maps in the daily solutions (Figure 5). Developed from the postfit tracking residuals, these maps accommodate multipath and other systematic GPS measurement system errors.

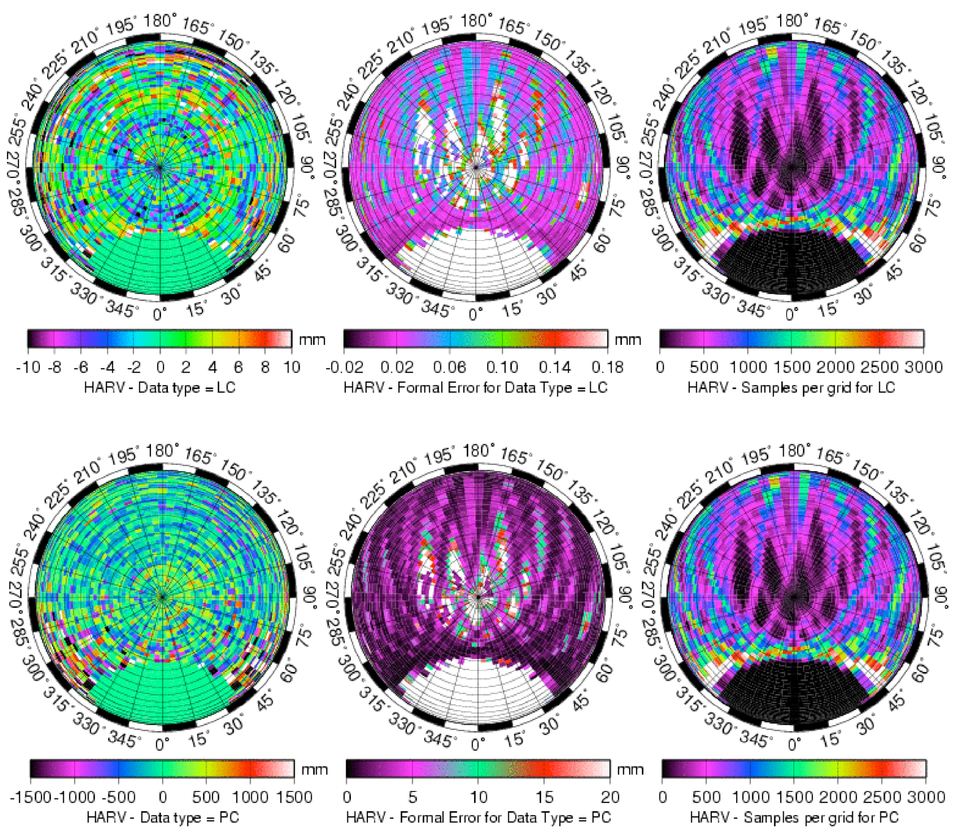


Figure 5: Maps of phase (and pseudorange) center variations for the GPS antenna at Harvest. These maps are now used in the processing of the GPS data, and have led to a reduction of systematic errors in the Harvest geodetic time series.

To lend insight on possible sources of the remaining annual signal, we modeled annual non-tidal loading effects and thermal variations due to seasonal expansion and contraction of the platform superstructure (Table 1).

Table 1 Annual loading signals modeled in time series of Harvest vertical.

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)
Non-tidal 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)

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 6). Properly explaining and reducing annual signals in this manner has important implications for improved determination of vertical rates at all tide gauge/GPS collocations.

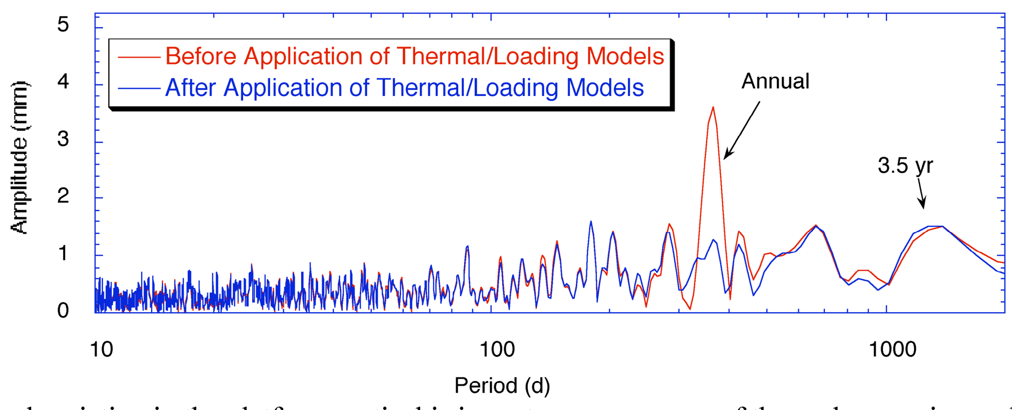


Figure 6: The annual variation in the platform vertical is in part a consequence of thermal expansion and contraction, as well as various mass loading effects.

Jason-1 Microwave Radiometer

We have compared columnar wet path delay measurements from the platform GPS data and both the TOPEX and Jason-1 Microwave Radiometer (TMR and JMR respectively) at the overflight times have been compared (Figure 7). .

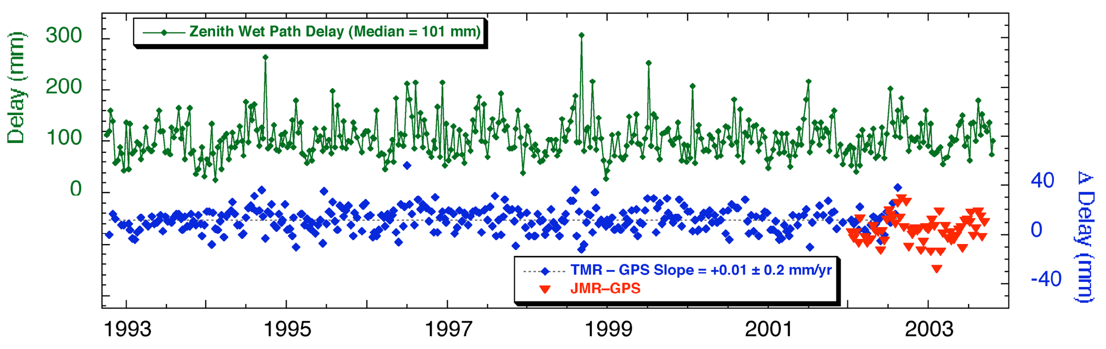


Figure 7: Decade-long time series of GPS vs. radiometer wet path delay calibrations. The top curve gives the overall delay at the overflight times. The bottom curves depict the excellent long-term stability of the GPS vs. radiometer differences. (The TMR data have been corrected for the drift of the 18 GHz brightness temperatures.)

Direct comparisons of the radiometer data for dual overflights indicate that JMR measures about 1 cm drier than TMR at Harvest (Figure 8). This is consistent with the geographic patterns observed in global comparisons (Figure 9), which suggest JMR yields drier readings than TMR in coastal regions. It is not uncommon to encounter biases of ~1 cm in PD recoveries from terrestrial GPS stations, so we do not consider the GPS results at Harvest to favor one radiometer over the other in terms of absolute PD calibration. More comprehensive information on the JMR/TMR vs. GPS comparisons can be found in the poster by Desai and Haines.

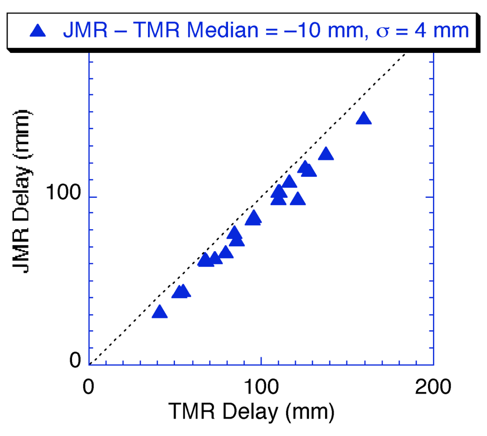


Figure 8: Scatter plot of JMR and TMR path-delays overflight times from dual Jason-1 and T/P overflights.

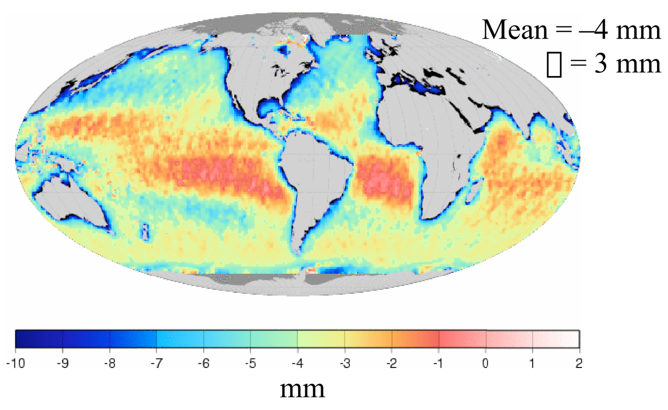


Figure 9: Global map of JMR–TMR path delays from the formation flying phase of the Jason-1 mission (Cycles 1–22). A constant value of 8 mm has been used to compensate for the cumulative effect of the TMR 18-GHz channel drift.

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 were compared with those from the TOPEX (Sides A and B) and Poseidon-2 (Jason-1) altimeters at Harvest. Figure 10 provides a time series (1997–2003) of the GIM vs. 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. 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 3–4 mm on average. The sense of the bias is corroborated by our global comparisons.

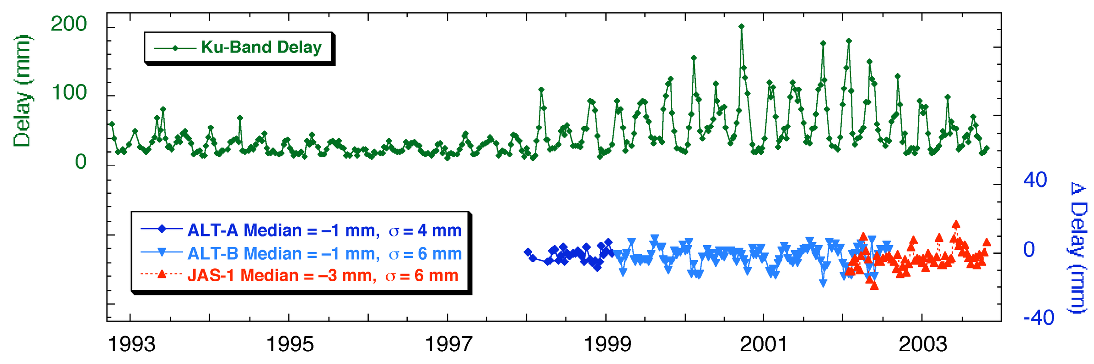


Figure 10: Decade-long time series of GPS vs. dual-frequency altimeter ionosphere calibrations (Ku Band). The top curve gives the overall delay at the overflight times. The bottom curves depict the excellent long-term stability of the GPS vs. altimeter differences.

Jason-1 Sea-Surface Height

Shown in Figure (11) is a decade-long time series of the Harvest SSH bias determinations, including results from all four altimeter measurements systems (ALT-A/B and POS-1 on T/P, and Jason-1). Table (2) provides an accounting of the assumptions for the altimeter leg of the closure equation.

Table 2 Model assumptions for altimeter leg in closure equation: nominal strategy

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

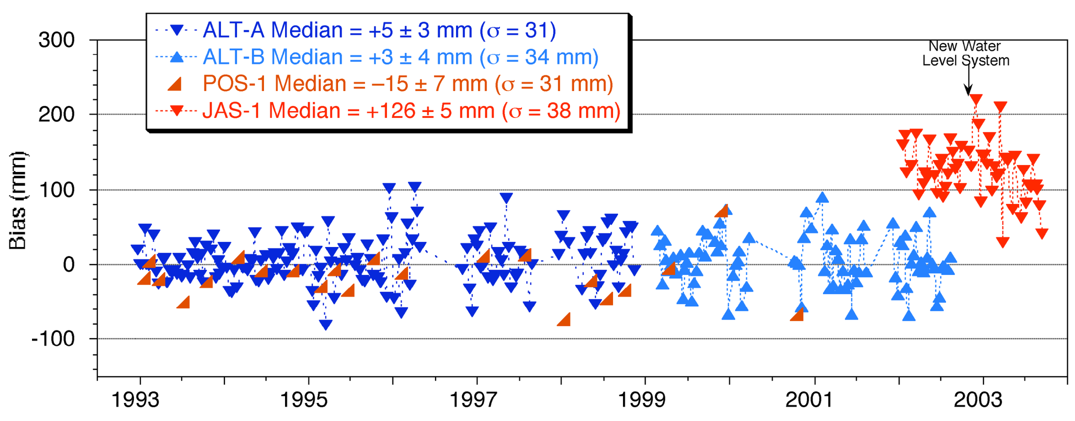


Figure 11 Decade-long time series of Harvest SSH calibrations. Each point represents the instantaneous difference between in-situ and altimeter SSH for a single overflight. Four altimeter measurement systems are represented.

Our nominal strategy leads to a Jason-1 SSH bias estimate of +126 + 5 mm (1 standard error). The most recent data yield lower bias estimates, consistent with the trend observed at the CNES calibration site (Bonnefond et al. poster). It should also be noted, however, that the Harvest sea level systems (NOAA) were updated beginning in November 2002. We will be carefully evaluating the new system's response to dynamic sea-state conditions by comparing against data from the new laser system deployed by the University of Colorado.

The SSH biases for the TOPEX measurement systems are statistically indistinguishable from zero. New sea-state bias (SSB) models have been issued as candidates for the ALT-B data. Our evaluation of the Labroue et al. (2002) model for ALT–B indicates that it will raise the ALT-B SSH bias estimates by 10–20 mm.

<u>ERROR BUDGET</u>: Developing a realistic error budget for the Jason-1 SSH bias estimates is challenging, particularly for the systematic (non-averaging) error sources. Despite the many advances in GPS positioning, the largest contributor likely remains the GPS survey of the platform in the TRF (Table 3).

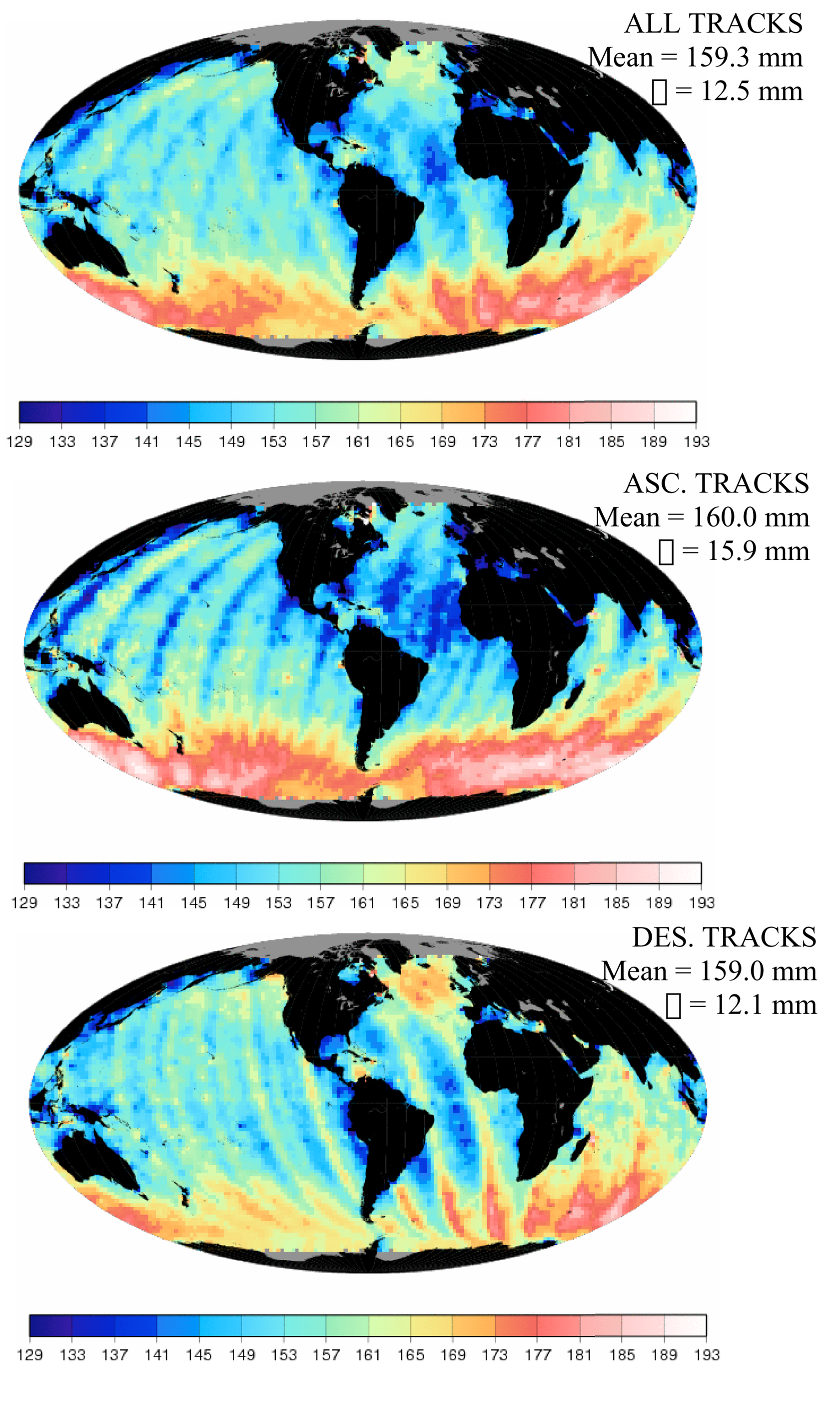
Table 3 Error budget for Jason-1 SSH bias estimate at Harvest.

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 (non-averaging)	5 mm	Parke and Gill (1995)
Random error	5 mm	1 standard error (N=52, σ = 38 mm)
TOTAL	17 mm	Root-sum-square

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 (GCEs) in the altimeter system that would render a local result (e.g., off the coast of California) different than a global result.

The maps at the right depict average SSH differences (Jason-1 – T/P) for the formation flying phase of the missions (Jason-1 repeat cycles 1–22). They illustrate the potential influence of GCEs in contributing to discrepancies in bias estimates at distributed calibration sites. Errors in the orbit, sea-state bias and wet path delay corrections are all known contributors to the GCE. For example, during the formation flying phase, the cumulative atmospheric delay corrections for Jason-1 (JMR, Ku-band ionosphere and dry troposphere) were 15 mm smaller (closer to zero) at Harvest than their T/P counterparts. This is not consistent with the global result. If we were to consider the 15 mm as a "GCE correction" to the Jason-1 SSH at Harvest, the bias estimate would be raised from +126 mm to +141 mm.

Characterizing the GCEs and identifying their sources are important prerequisites for reconciling estimates from distributed calibration sites at the 1–2 cm level.



ACKNOWLEDGMENTS: We are indebted to Plains Resources, their subsidiary Arguello Inc., and the Torch Operating Company for hosting our experiment on Platform Harvest. A portion of this work was conducted by the Jet Propulsion Laboratory, California Institute of Technology under contract with NASA.