Continuous Monitoring of the Jason-1 and TOPEX/POSEIDON Ocean Altimetry Missions from Dedicated Calibration Sites

(Invited Paper)

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***Abstract*— We present calibration results from Jason-1 and TOPEX/POSEIDON overflights of the three dedicated verification sites: 1) a California offshore oil platform (Harvest); 2) the Mediterranean island of Corsica (Cape Senetosa), and 3) the Bass Strait off the coast of Tasmania. The high-accuracy of the Jason-1 measurement system is evident in the results from the dedicated calibration experiments. These experiments do indicate, however, that the Jason-1 sea-surface-height (SSH) measurements are biased high by approximately 12–15 cm. We discuss the implications of geographically correlated errors on the determination of the SSH bias.**

I. Introduction

The Jason-1 spacecraft was launched from Vandenberg Air Force Base on December 7, 2001 [1]. A joint U.S./French oceanographic mission, Jason-1 is designed to carry on the legacy of precise sea-level observation begun by the TOPEX/POSEIDON (T/P) mission in 1992 [2]. Still returning useful scientific data nearly 12 years after its August 1992 launch, the venerable T/P satellite has far exceeded expectations in terms of both mission duration and measurement-system performance [3].

The primary instrument onboard both missions is a dual-frequency (*Ku*- and *C*-band) radar altimeter for providing precise measurements of the ionosphere-corrected range between the spacecraft and nadir sea surface [4]–[6]. In order to determine the sea-surface height, these measurements must be coupled with very accurate estimates of the satellite height above the geocenter from precise orbit determination (POD) techniques [3]. Both T/P and Jason-1 carry three advanced tracking systems to support this function: 1) a French Doppler system referred to as "Doppler Orbitography and Radiopositioning Integrated by Satellite" (DORIS); 2) a laser retroreflector array (LRA) to support ranging from ground-based laser observatories; and 3) an advanced Global Positioning System (GPS) receiver. Also carried on each satellite is a three-frequency microwave radiometer to provide measurements for compensating the altimeter ranges for the delay induced by the presence of water vapor [7], [8].

The measurement systems on T/P and Jason-1 have enabled the achievement of unprecedented accuracies in the determination of sea-surface height (SSH) from Earth orbit. Chelton *et al.* [3] estimate the single-pass accuracy (1-Hz SSH averages) of T/P is 4 cm (rms), while a more recent evaluation suggests the figure may be closer to 3 cm [9]. In order to seamlessly maintain the long-term sea-level record initated by its predecessor, Jason-1 is required to match the T/P performance, and also carries an aggressive goal of 2.5 cm (rms) for SSH accuracy. Data collected during the Jason-1 calibration/validation (cal/val) phase—when the two satellites were flying in formation and separated by only 70 s—support that the 4 cm (rms) requirement is being met [1], [9].

While advances in all components of the altimeter system share responsibility for these achievements, the field of POD has been witness to conspicuous improvements in orbit accuracy over the past two decades. While the T/P mission carried a requirement for 13-cm (rms) radial orbit accuracy, the actual performance is closer to 2 cm (rms) [3]. With the improved POD systems on Jason-1, the radial orbit accuracy has now reached the 1-cm rms level [10]–[12]. This is a critical milestone on the path to achieving the 2.5 cm (rms) goal for SSH determination.

Even higher accuracies can be achieved by averaging the single-pass (1-Hz) SSH measurements over larger spatial scales. At the largest scale, global mean sea level can computed with a repeatability of 4–7 mm (10-d averages) from T/P data [13]. This unexpectedly high performance, coupled with a continuous and multifaceted calibration effort, bear the responsibility for elevating the global sea-level (GSL) problem from a research topic to major thrust of the Jason-1 mission. Indeed, measuring global sea level change with an accuracy of 1 mm/yr is an expressed goal of the Jason-1 mission [1].

II. The Role of Dedicated Calibration Sites

A central component of the Jason-1 and T/P calibration efforts is a dedicated *in situ* program that provides for continuous monitoring of the altimeter measurement systems throughout the satellites' lifetimes. Particular challenges are the characterization and monitoring of subtle bias and drift errors at the level necessary to support studies on basin- and global-scale sea-level changes.

The traditional "overhead' concept of altimeter in-situ calibration invokes direct satellite overflights of a thoroughly instrumented experiment site [3]. Site essentials are accurate systems for measuring the local sea level (e.g., tide gauges), and a means of tying this sea level to the geocenter (e.g., using nearby GPS receivers). We discuss herein calibration results from Jason-1 and TOPEX/POSEIDON overflights of the three dedicated verification sites: 1) a California offshore oil platform (Harvest); 2) the Mediterranean island of Corsica (Cape Senetosa), and 3) the Bass Strait off the coast of Tasmania. All three feature carefully designed collocations of space-geodetic and local sea-level systems. They also have a variety of ancillary sensors for measuring the environmental conditions that underlie the formation of the fully corrected sea-surface height, thus permitting a useful segregation of the various potential error sources.

The *Arguello Inc.* Harvest Oil Platform is located about 10 km off the coast of central California near Point Conception. Attached to the sea floor, the platform sits in about 200 m of water near the western entrance to the Santa Barbara Channel. Harvest served for a decade (1992–2002) as a calibration site for the T/P mission, and is serving in a similar capacity for Jason-1 [14], [15]. Initiated in 1996, the Corsica experiment features a fiducial reference point near Aspretto, and a primary sub-satellite tide-gauge site 40 km south at Cape Senetosa where the Jason-1 ascending ground track reaches landfall [16]. Innovative pelagic GPS techniques have been applied to measure the geoid slope between the locations of the open-ocean altimeter measurements and the coastal tide gauges [17]. The only calibration site in the southern hemisphere, the Bass Strait experiment features an oceanographic mooring array, coastal tide gauges monitored by GPS and episodic GPS buoy deployments [18], [19]. Like Harvest, this site has a heritage dating back to the launch of T/P in 1992 [20].

The most prominent role of these dedicated calibration sites has been the determination of the absolute bias in the altimeter measurement system. While it is common to refer to this simply as an "altimeter bias", it is more aptly named "SSH bias" because it embraces mean errors from all the sensors and accompanying corrections that contribute to the measurement of SSH. Both the SSH bias and its stability are important elements of the altimeter system error budget [3]. Knowledge of the SSH bias is essential for specialized studies that rely on accurate determination of the Earth's mean radius, such as defining the terrestrial reference frame. More important, estimates of the biases are needed to merge data from different missions, or from different measurement systems on the same

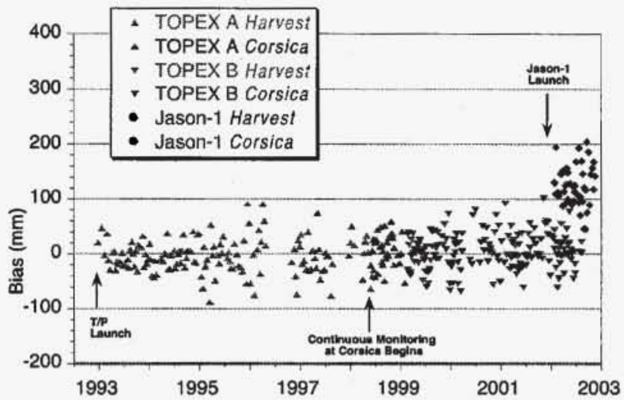

Fig. 1. Ten-year time series of T/P and Jason-1 SSH bias estimates from the Harvest and Corsica verification sites. Both Sides A and B of the TOPEX altimeter systems, as well as the Jason-1 altimeter system, are represented.

mission, in order to condition altimetric time series of global mean sea level [21]

The importance of the absolute calibration exercise was amply demonstrated by the T/P experience. Shortly after the T/P launch, results from calibration sites were unanimous in indicating the TOPEX (SSH) measurements were erroneously high [14], [20], [22], [23]. The estimate from Harvest, for example, was $+145\pm29$ mm [14]. This estimate was refined to $+125\pm20$ mm at the conclusion of the 3-year primary mission [24]. Also identified in results from other dedicated calibration sites [25], the bias is now recognized as a consequence of an error is the software used to produce the mission's sensor data records [13]. The close agreement between the mean value of the software error (133 mm) and the bias estimates testifies to the ability of a dedicated calibration site to support detection of spurious signals in the altimeter measurement systems. The software error also introduced a spurious drift (~ 7 mm/yr) in the global mean sea level [13]. This drift was first detected by Mitchum [26] using an innovative technique that relies on proximate overflights of tide gauges in the global network. In restrospect, the combined calibration results had provided a remarkably accurate portrayal of the expression of this software error. The overall experience underscored the essential role of continuous calibration and validation for any altimeter mission [3].

III. Calibration Results

Shown in Fig.1 is a decade-long time series of SSH bias estimates from the Harvest and Corsica sites. Adapted from Bonnefond *et al.* [27], the plot depicts results for three different altimeter systems: sides A and B of the NASA radar altimeter (TOPEX), and the CNES altimeter (Posedion-2) on Jason-1. The primary (A) side of the NASA altimeter was switched off in February 1999 in response to signs of aging [3]. The B side was activated soon thereafter and remains operational at this writing.

Each point in Fig.1 represents an SSH comparison (*in situ* vs. satellite) at the instant of an overflight event. Detials of

TABLE I

JASON-1 MEDIAN SSH BIAS USING GDR ORBIT

Site	Estimate	Source
Bass Strait	$+146 \pm 6$ mm	Fig. 13 of Watson *et al.* [19]
Corsica	$+121 \pm 7$ mm	Table 11 of Bonnefond *et al.* [16]
Harvest	$+138 \pm 7$ mm	Table 4 of Haines *et al.* [15]

this SSH "closure" computation are given by Bonnefond *et al.* [16] and Haines *et al.* [15]. Every attempt was made to use consistent standards and procedures in processing the data from each of the locations. Typical repeatabilities of the individual bias estimates are in the range of 2 to 4 cm, depending on the altimeter system and time period in question.

Inasmuch as both Jason-1 and T/P are in exact repeating orbits, the overflights occur every 10 days for each satellite. After Jason-1 launch in 2001, the satellite was placed in close formation with T/P (70-s separation) to allow a rigorous cross-calibration of the two systems. At the conclusion of the Jason-1 cal/val phase in August 2002, the T/P satellite was moved to a different repeat ground-track. The T/P orbit was shifted to produce an interleaving with the Jason-1 ground tracks, thus doubling the spatial and temporal coverage of the combined missions. This implies, however, that the T/P satellite no longer passes over the Harvest and Corsica sites.

The time series (Fig. 1) testifies to the excellent overall agreement between results from the two verification sites. The T/P SSH biases from both Harvest and Corsica are statistically indistinguishable from zero. In contrast, the Jason-1 SSH bias is anomalously high. For the data used in this exercise, the value from the combined Harvest and Corsica experiment data is $+122 \pm 5$ mm (one standard error) [27].

These estimates have since been refined using data from additional overflights, as well as results from the Bass Strait verification site (Table I). [1] Results in Table I are based on the orbit solution used in generating the Jason-1 geophysical data records (GDR). Based on DORIS and SLR measurements, this orbit is estimated to be accurate to 15 mm (rms) [1]. Despite its high accuracy, the GDR orbit solution shows evidence of geographically correlated errors (GCE) that are large enough to explain a significant fraction of the discrepancy among the SSH bias estimates in Table I [11], [16], [19]. To further illustrate this, we provide results in Table II based on GPS-based orbit solutions that are less susceptible to GCE [11]. The range of the median SSH bias estimates decreases from 25 mm (using the GDR orbit) to 6 mm (using the GPS orbit).

We arrive at a unified estimate for the Jason-1 SSH bias by taking the weighted average of the individual estimates in Table II, yielding $+128 \pm 4$ mm (one standard error). Results from other absolute calibration programs provide corroboration that Jason-1 SSH measurements are spuriously high [28], [29]. Current estimates of the Jason-1 SSH bias bear an ironic resemblance to early estimates of the T/P (side A) SSH bias [14], [20], [22], [23]. As discussed previously, it was eventually determined that the TOPEX bias was symptomatic of a software error. The error appeared 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 source of the Jason-1 bias is related.

[1]Note that the median is used to uniformly report the SSH bias estimate, and that the error figure is "one standard error", reflecting only the random component of the error budget.

TABLE II

JASON-1 MEDIAN SSH BIAS USING GPS ORBIT

Site	Estimate	Source
Bass Strait	$+126 \pm 6$ mm	Fig. 13 of Watson *et al.* [19]
Corsica	$+127 \pm 7$ mm	Table 11 of Bonnefond *et al.* [16]
Harvest	$+132 \pm 6$ mm	Table 4 of Haines *et al.* [15]

TABLE III

T/P ALT SIDE-B MEDIAN SSH BIAS

Site	Estimate	Source
Bass Strait	$+6 \pm 2$ mm	Fig. 14 of Watson *et al.* [19]
Corsica	$+5 \pm 3$ mm	Table 7 of Bonnefond *et al.* [16]
Harvest	$+2 \pm 4$ mm	Table 4 of Haines *et al.* [15]

The T/P satellite continues to operate after nearly 12 years, and recent estimates of the side-B SSH biases are given in Table III. The side-B SSH bias is indistinguishable from zero. For the Jason-1 vs. T/P relative SSH bias, we thus infer values of 120–140 mm from the calibraton sites (Jason-1 higher than T/P). This range is somewhat lower than typical estimates from global analysis [9], [21].

Figs. 2 and 3 underscore the challenge of reconciling results from global analysis with those from individual calibration sites. They show maps of global SSH differences (Jason-1 − T/P) from over 200 days of data collected while the two satellite were flying in formation (separated by 70 s). Ascending and descending tracks are depicted separately. Expressed in the maps are the convolution of GCEs from a variety of sources, including sea-state, troposphere, and other altimeter corrections, in addition to the orbit solution. Understanding and reducing these errors represent important steps toward a more effective exploitation of the calibration site results in Jason-1 science investigations. More important, the reduction of the GCEs has direct implications for Jason-1 science, owing to the conspicuous ability of these errors to confound estimates of ocean circulation [3].

IV. CONCLUSION

Based on direct overflights of three dedicated calibration sites, we estimate the current Jason-1 SSH measurements are high by $+128 \pm 4$ mm (one standard error). Excepting the bias, the high accuracy of the Jason-1 measurements is in evidence from the overflights. In orbit for nearly 12 years, the T/P measurement system appears stable and well calibrated. The SSH bias (side B) is indistinguishable from zero. The excellent agreement among the SSH bias estimates from the three experiments testifies to the important role of dedicated, well-

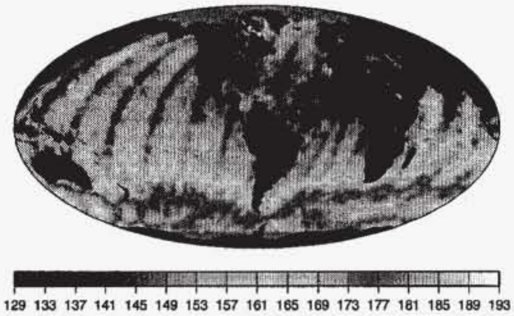

Fig. 2. Ascending geographically correlated errors in global Jason-1 minus T/P SSH differences. Median = 158 mm; $\sigma = 16$ mm ($2^\circ \times 2^\circ$ bins).

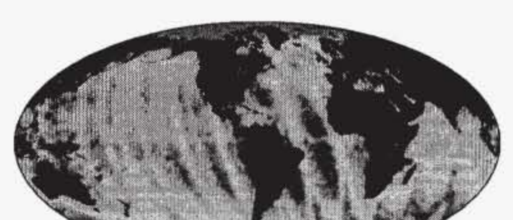

Fig. 3. Descending geographically correlated errors in global Jason-1 minus T/P SSH differences. Median = 159 mm; $\sigma = 12$ mm ($2^\circ \times 2^\circ$ bins).

instrumented verification sites in satellite altimeter calibration programs. Future work will focus on better characterizing and reducing the geographically correlated errors, and on monitoring the long-term stability of the measurement systems at the level required to support studies of global sea-level change.

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