EVOLUTION OF ALTIMETRY CALIBRATION AND FUTURE CHALLENGES

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ABSTRACT

Over the past 20 years, altimetry calibration has evolved from an engineering-oriented exercise to a multidisciplinary endeavor driving the state of the art. This evolution has been spurred by the developing promise of altimetry to capture the large-scale, but small-amplitude, changes of the ocean surface containing the expression of climate change. The scope of altimeter calibration/validation programs has expanded commensurately. Early efforts focused on determining a constant range bias and verifying basic compliance of the data products with mission requirements. Contemporary investigations capture, with increasing accuracies, the spatial and temporal characteristics of errors in all elements of the measurement system. Dedicated calibration sites still provide the fundamental service of estimating absolute bias, but also enable long-term monitoring of the sea-surface height and constituent measurements. The use of a network of island and coastal tide gauges has provided the best perspective on the measurement stability, and revealed temporal variations of altimeter measurement system drift. The cross-calibration between successive missions provided fundamentally new information on the performance of altimetry systems. Spatially and temporally correlated errors pose challenges for future missions, underscoring the importance of cross-calibration of new measurements against the established record.

1. INTRODUCTION

Satellite altimetry has come a long way since Seasat (1978) first demonstrated the feasibility of studying the variability of ocean circulation from space. One of the most significant results showed the global pattern of sea surface height (SSH) variability from only 24 days of Seasat altimeter data [1]. The sheer impact of this result on the paradigm of global ocean observation cannot be overestimated. The capability of satellite altimetry for studying the ocean was further advanced by Geosat in the 1980s. These two missions paved the way for the leaps and bounds in the advancement of satellite altimetry in the 1990s after the launch of TOPEX/Poseidon (T/P). This was the first altimeter mission specifically designed to deliver the high accuracy and precision needed for detecting large-scale, small-magnitude changes of the ocean.

The accuracy and precision of TOPEX/Poseidon were utilized to cross-calibrate other simultaneously flying satellite altimeters to minimize large-scale errors in their measurements. This approach to merging TOPEX/Poseidon and ERS-1 data increased significantly the spatial and temporal resolution of the merged data products with optimal accuracy [2]. Such efforts have led to a record of uniformly gridded global SSH products spanning the past two decades, using data from T/P and its succeeding missions of Jason-1 and Jason-2, in combination with all other altimetry missions, including ERS-1, ERS-2, Envisat, and Geosat Follow-on. With progressively improved geoid models available from the GRACE and GOCE Missions as well as modeling efforts, the absolute ocean surface topography has also become available. The two-decade long altimetry data record has fundamentally advanced global oceanography to an unprecedented level. Satellite altimetry has become a standard resource in the tool bag of both research oceanographers and practitioners needing routine oceanic information [3].

A surprising discovery from the 20-year record of altimetry observations is the pronounced spatial variability of the trend of sea level change over the span of the record [4]. Although there have been theoretical treatises of decadal variability of ocean circulation, satellite altimetry has provided the first direct evidence for the existence of geographic variability of the long-term trend of sea level change. This variability is superimposed on and overwhelms the pattern of sea level change linked to the general warming trend of Earth's climate, making it difficult to differentiate between decadal variability of the ocean and longer-term change. Anthropogenic sea-level changes are expected to occur over century-long time scales [5], of which the current altimeter record spans only a small fraction. Advances in satellite altimetry have nonetheless enabled new insights into these issues, while posing new challenges to the calibration and validation of altimeter observations. In this paper, we briefly review the evolution of altimetry calibration against the backdrop of the developing altimeter measurement system over the past 20 years. Altimetry calibration has evolved from an engineering-dominated exercise at the beginning to a multidisciplinary challenge affecting the core utility of the measurement at present and into the future [6].

2. ALTIMETRY CALIBRATION WITH TIDE GAUGES

The traditional concept of altimetry calibration focuses on the determination of an absolute bias in the altimeter measurement system—expressed in units of range or height—using data from a well-surveyed tide gauge and ancillary instruments at a dedicated site. Such sites are typically located directly in the path of the satellite repeating ground track.

Fig. 1 depicts the long-term time series of the SSH bias results (for T/P, Jason-1, and Jason-2) from the Harvest Platform near Point Conception, California [7]. At such dedicated calibration sites, other equipment—like water-vapor radiometers, satellite tracking sensors, meteorological sensors, etc.—provide the necessary information to validate the various corrections that are needed to derive the sea surface height estimates. The comprehensive information available at such sites allows evaluation of repeatability of the satellite measurements, and the overall uncertainty of the bias estimates. Due to systematic errors, such as those linked to the geocentric positioning of the tide gauge, the uncertainty in the absolute bias determined at each site is on the order of 1–2 cm. Results from dedicated sites can lend insight on the long-term stability of the altimeter measurement system, but tight control of systematic errors, and a long time series are needed to approach accuracy levels of 1 mm/yr.

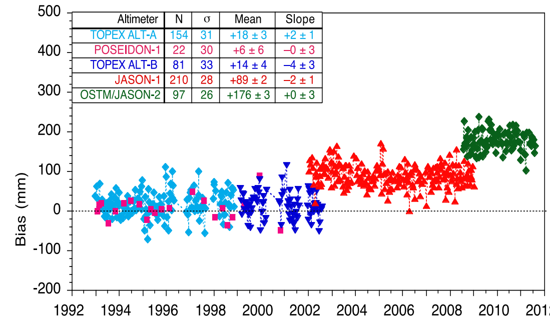


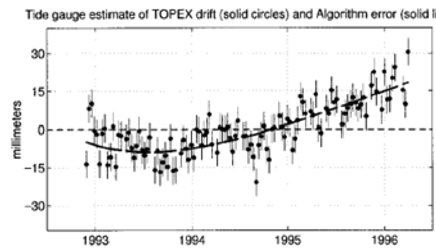
Fig. 1 Long-term SSH calibration time series from the Harvest platform [6].

In order to better monitor the stability of the altimeter measurement systems, Mitchum [8-9] used tide gauges of opportunity from the global network. At each location, a difference between the altimeter and tide gauge SSH was computed for the satellite's closest approach. All the differences computed from the global tide gauge network were then averaged to reduce errors from both measurements. Since most of the participating tide gauges were not accurately surveyed to the geocenter, the absolute bias could not be determined. Changes in the SSH bias, however, could be accurately monitored.

Shown in Fig. 2a is the first result of the global tide gauge calibration. It was surprising to note the prominent quadratic pattern of the time series of the altimeter-tide gauge difference. The much reduced error at a level about +/- 5 mm lent credence to the quadratic pattern. It was later demonstrated that this pattern was linked to an error in the data processing software, which led to erroneous estimates of the rate of global mean sea level rise [10]. The expression of the software error—in the form of a ~13-cm bias—was also seen in early results from the dedicated calibration sites. The overall experience underscored the effectiveness and importance of a multifaceted and continuous approach to altimetry calibration for detecting systematic errors in the measurement.

After the correction for the processing software error, the altimeter-tide gauge comparison still exhibited a residual quadratic pattern (Fig. 2b) of unknown origin. Such systematic differences with tide gauge measurements heightened the concerns for the complexity of the altimetry measurement system and its effect on the accuracy of estimating the rate of global mean sea level change at a level of a few mm per year. More in-depth attention was paid to the behavior of the entire measurement system after the discovery of the “altimeter drift.”

(a)



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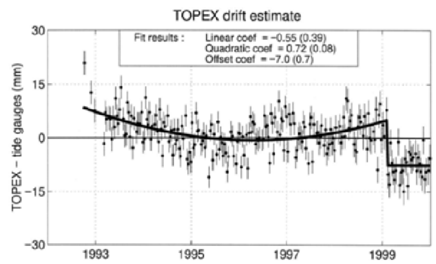

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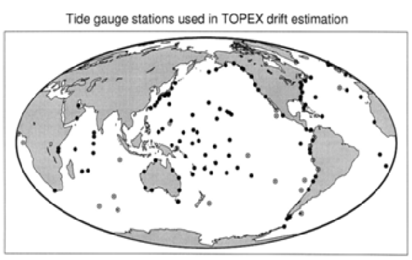


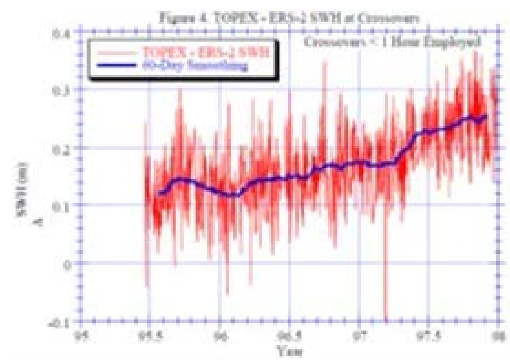
Fig. 2 (a) The solid circles are estimates of the TOPEX altimeter drift from comparisons to tide gauge data before the correction for processing errors [8]. (b) the same as (a) after the correction [9]. (c) The locations of the tide gauges used in the analysis [9].

Shortly after the episode of the altimeter “drift correction”, investigators spotted an anomalous increase in the altimeter measurement of the significant wave height (SWH). Mission engineers attributed this to aging of the altimeter, which led to the decision to switch the operation of the T/P altimeter to its redundant channel, from the so-called Side A to Side B. The tide gauge comparison clearly showed the transition as a jump in the altimeter-tide gauge difference time series in 1999 (Fig. 2b).

3. CALIBRATION OF THE MEASUREMENT SYSTEM

Displayed in Fig. 3a are differences of SWH measured by T/P and ERS-2 at locations where the two satellites’ ground tracks crossed one another within one hour [11]. Similar findings on the anomalous increase of T/P SWH were obtained from comparisons to buoy measurements. Shown in Fig. 3b is the effect of the SWH error on the estimate of the global mean sea level change via the sea-state bias correction. This warning sign triggered the decision to switch the operation of the TOPEX altimeter from Side A to Side B. This switch in fact dictated a new calibration effort to determine the new bias revealed by the jump in Fig. 2b and ensure a seamless transition of the altimeter measurement.

(a)



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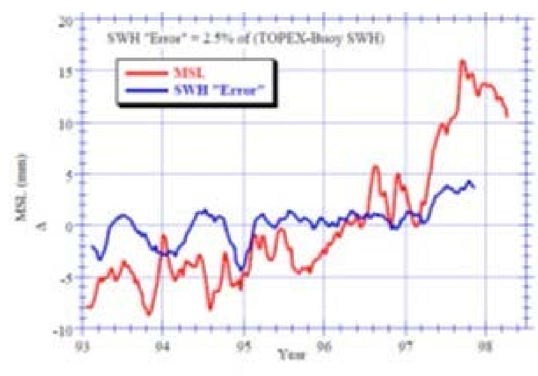

Fig. 3 (a) Crossover differences in the SWH between T/P and ERS-2 measurements when the time difference of the two was less than 1 hour [11]. (b) The effect of the SWH error (blue) on the estimate of the global mean sea level change (red) via the sea-state bias correction [11].

While measuring the small change in global mean sea level becomes a goal of satellite altimetry, it becomes imperative that we must ensure there is no systematic drift in the measurement system with a rate more than

1 mm/yr. The stability of the water vapor radiometer for correcting the effects of tropospheric water vapor becomes a leading concern. A drift at a rate of 1–1.5 mm/yr was discovered in the water vapor correction in the T/P data [12]. Extensive inter-comparison of the Jason water vapor correction with other radiometer measurements and model results led to the finding of two jumps in the Jason radiometer data [13] (Fig. 4). The 5–8 mm jumps would cause 6 mm/yr errors in the estimate of global mean sea level change rate. Using vicarious calibrations from terrestrial cold and hot targets has reduced the drift on the current geophysical data records to less than 1 mm/yr. However, it remains a challenge to maintain stable long-term calibration for spaceborne

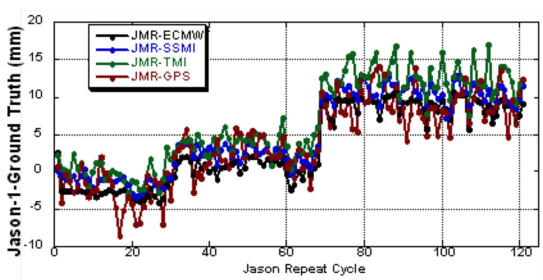

Fig. 4. The differences between the path delay derived from the JMR measurements and various other measurements (ECMWF-black, SSMI (blue), TMI (green), and GPS (red)) [13].

radiometers. One approach, proposed for Jason-3, is to periodically flip the satellite to point the radiometer antenna to open space for "cold sky" calibration. This should further improve the stability of radiometer calibration for achieving climate quality data record.

4. ALTIMETER CROSS-CALIBRATION

During the first 7 months of the operation of Jason-1, it flew over the same ground tracks as T/P with over-flight time difference of about only one minute. During this short period of time, the conditions of the atmosphere and ocean surface can be considered almost identical for the measurements of the two altimeters. This provided an unprecedented opportunity for cross-calibration of the two altimeters.

Shown in Fig. 5 are maps of the sea surface height differences between T/P and Jason-1 during the 7-month "cross-calibration" phase [6]. Superimposed on the overall 16-cm bias are prominent geographic patterns of variability. These patterns reveal effects of orbit errors. There are also indications of large variability at the southern latitudes, suggesting wave-related effects. There has been a wide range of efforts on examining all elements of the altimeter measurement system, leading to significant reduction of the differences [14].

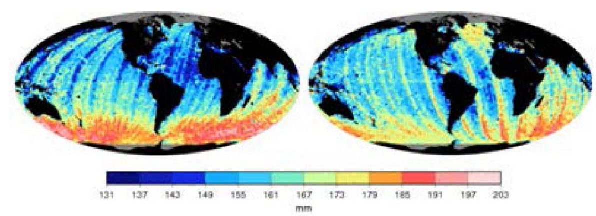

Fig. 5 Global differences (in mm) of Jason-1 and T/P sea-surface height from 2002 tandem verification phase for ascending (left) and descending (right) tracks. [6]

Displayed in Fig. 6 are scatter diagrams of the differences in altimeter height measurements versus SWH. There is significant correlation with SWH in the differences between T/P and Jason-1. Because the wave conditions should be nearly identical over a period of only 1 minute, the EM (electromagnetic) should be nearly the same between the two altimeter measurements. The correlation suggests that the altimeter instrument algorithm (such as the range-tracking scheme) must have SWH-dependent errors. Because Jason-1 and Jason-2 have similar instrument algorithms, there is significantly less correlation with SWH in their differences during a similar cross-calibration phase (the right panel of Fig. 6).

The large number of coincident observations from the cross-calibration phase has significantly reduced the error in the determination of the relative bias between successive missions. The relative SSH bias between Jason-1/Jason-2, for example, was determined with variability of only 2 mm [15]. Therefore overlapping missions with cross-calibrations are an efficient and effective approach for determining relative biases between successive missions in building a climate data record.

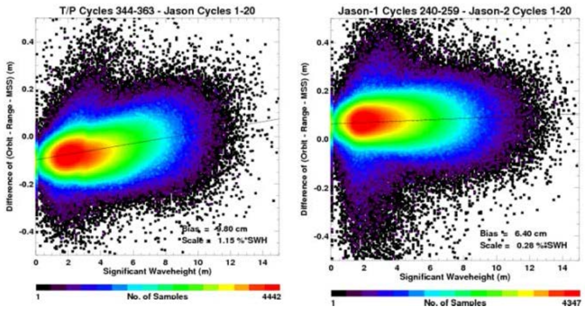

Fig. 6. Scatter diagrams of the differences in altimeter height measurements (calculated as orbit altitude – altimeter range- mean sea surface) versus SWH during the cross-calibration phase. Left: T/P minus Jason-1. Right: Jason-1 minus Jason-2 (courtesy of Shailen Desai of JPL)

The along-track differences between two altimeter measurements made with only 1 minute time difference also provide information on the measurement errors over various scales. Displayed in Fig. 7 is wavenumber spectrum of such differences between Jason-1 and Jason-2 over a long pass in the eastern Pacific. It is quite surprising to find that only the portion at wavelengths shorter than 100 km exhibits a white noise spectrum. At longer wavelengths, the spectrum reveals spatially correlated errors, which reflect errors in media corrections (primarily ionospheric and wet tropospheric), sea-state bias, and orbit errors. Such a spectrum is a good measure of the limit of the repeatability of altimeter measurement, representing a lower limit of the measurement errors because the common errors are not represented.

5. SYSTEMATIC ORBIT ERRORS

Orbit errors are able to introduce low-frequency errors in altimetry observations of sea surface height. Errors in the centering of the terrestrial reference frame adopted in an orbit solution could lead to spurious trends in the estimate of sea level change. Displayed in Fig. 8 are the geographic patterns of such trends in the T/P data (1993-2002) introduced by the application of different reference frames [16]. Another issue in orbit solutions is the treatment of the time-varying gravity field. The difference between two orbit solutions for Jason-2 was performed to evaluate this effect. One of them is the GPS reduced-dynamic solution that is less sensitive to the errors in

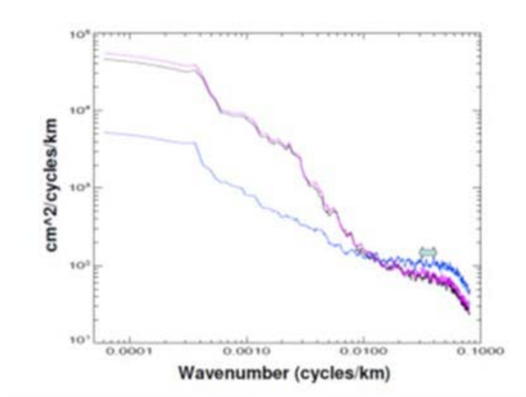

Fig. 7 SSH spectrum from Jason-1 (black) and Jason-2 (red) altimeter observations along a pass in the eastern Pacific during the cross-calibration phase. Superimposed is the spectrum of the difference between the two observations (blue)

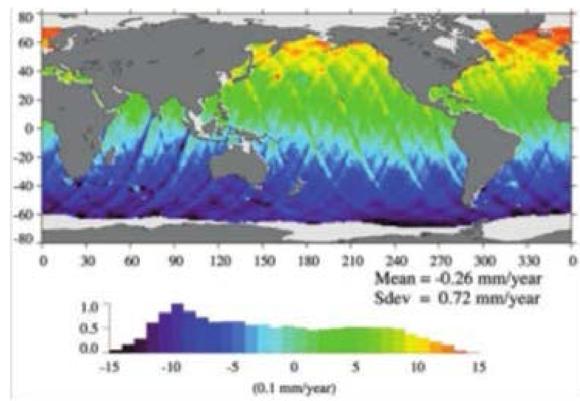

Fig. 8 Spurious TOPEX (1993–2002) sea-level trends introduced by the application of different reference frames (ITRF2005 vs. CSR95L01) in the POD process [16].

gravity models, while the other is the solution used to generate the Jason-2 official geophysical data records (GDR). Depicted in Fig. 9 are the geographic patterns of the trends of the orbit differences over 2008-2011. While the global standard deviation of the rate differences is only 1 mm/yr, there are large-scale hemispheric patterns with peak-to-peak amplitudes exceeding 5 mm/yr. Errors from the gravity models underlying the GDR solutions probably contribute, as do possible differences in how the terrestrial reference frame is realized and how surface forces are modeled. We expect the patterns also reflect contributions from measurement model errors, particularly from the GPS-based orbit since it is based on a reduced-dynamic technique.

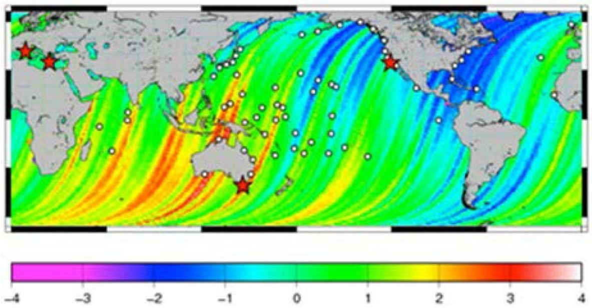

Fig. 9 Jason-2 orbit errors expressed as sea-level rate (mm yr^{-1}) over 2008–2011, based on differences between GPS reduced-dynamic solutions and (GDR) orbits [6].

6. SUMMARY AND FUTURE CHALLENGES

Altimetry calibration has evolved from an engineering-oriented discipline in the early 1990s to a multidisciplinary scientific endeavor at present. Early efforts focused on the determination of constant measurement bias at a few dedicated sites equipped with multiple sensors including a tide gauge. Evaluations of the geophysical data products were undertaken, but mainly with the intent of verifying compliance with mission requirements. With the launch of TOPEX/Poseidon, calibration efforts grew significantly more diverse and rigorous as they attempted to address the most scientifically challenging problems. One important advance was the use of globally distributed tide gauge of opportunity to reduce errors in monitoring the stability of the altimeter measurement system. This development provided a robust verification on the capability of altimetry to measure the global mean sea level change. This new objective has motivated more thorough studies of the entire measurement system, including errors in altimeter, radiometer, orbit determination, etc. The challenges include the need for more robust radiometer calibration by perhaps flipping the instrument periodically for "cold-sky" calibration in future missions.

The cross-calibration between T/P and Jason-1 and between Jason-1 and Jason-2 has created an unprecedented opportunity for evaluation of the uncertainty of altimetry measurements globally and over various spatial scales. The comparison of measurements over the same ground tracks with time separation about 1 minute reveals the relative measurement errors from all sources. This is an ideal way to cross-calibrate successive missions. The results shown in Fig. 7 are representative of the lower bound of measurement errors of the Jason class of altimeters. In the future, it would be desirable to calibrate new type of altimeters against this standard.

In the case of the proposed SWOT mission, which is based on radar interferometry for wide-swath altimetry instead of conventional pulse-limited nadir altimetry, a new strategy for calibration needs to be developed. Over a domain size of the swath width (~120 km), new high-resolution two-dimensional "ground truth" is required for calibration of the measurement at scales not accessible by conventional altimeters. An airborne radar interferometer has been developed for fulfilling this role. At scales larger than 120 km, we will need to calibrate the new measurement against a Jason-class altimeter so that SWOT observations can be properly calibrated for (1) studying the interaction between large scales and the newly measured small scales; (2) continuing the climate data record built by the previous conventional altimeters. Depicted in Fig. 10 is the calibration strategy for SWOT.

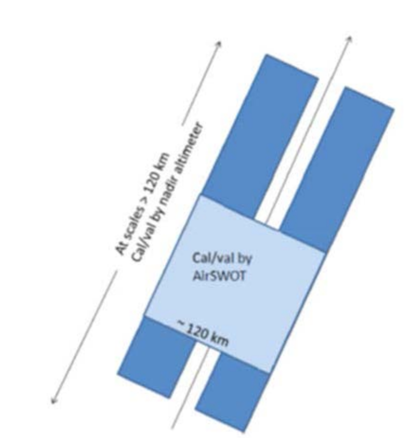

Fig. 10. Calibration strategy for the proposed SWOT Mission.

Orbit errors remain an important source of geographically correlated, low-frequency errors in the determination of the patterns of long-term change of sea level. Part of the errors is caused by the lack of an optimal approach to the time-varying gravity field. More research is needed in this subject. Another issue is the uncertainty in the terrestrial reference frame, causing instability of 1 mm/yr. It is highly desired to reduce the instability significantly. Flying a spaceborne geodetic satellite like the concept of GRASP would be a viable approach.

7. ACKNOWLEDGEMENTS

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