Final Technical Report for NAG5-4512/6910/JPL 961462

# IMPROVEMENT OF TOPEX/POSEIDON AND JASON-1 GEOPHYSICAL DATA RECORD FOR GLOBAL CHANGE STUDIES AND COASTAL APPLICATIONS

OSURF Project #736180

Reporting Period: July 10, 1998 - September 30, 1999
Investigation Period: October 1, 1997 - September 30, 1999

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December 15, 1999

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## SUMMARY

The Earth's modern climate change has been characterized by interlinked changes in temperature, CO2, ice sheets and sea level. Global sea level change is a critical indicator for study of contemporary climate change. Sea level rise appears to have accelerated since the ice sheet retreats have stopped some 5000 years ago and it is estimated that the sea level rise has been ~15 cm over the last century. Contemporary radar altimeters represent the only technique capable of monitoring global sea level change with accuracy approaching 1 mm/yr and with a temporal scale of days and a spatial scale of 100 km or longer. This report highlights the major accomplishments of the TOPEX/POSEIDON (T/P) Extended Mission and Jason-1 science investigation (NASA Grant: NAG5-4512/6910 and JPL Grant: 961462, PI: Shum). The primary objectives of the investigation include the calibration and improvement of T/P and Jason-1 altimeter data for global sea level change and coastal tide and circulation studies. The scientific objectives of the investigation include (1) the calibration and improvement of T/P and Jason-1 data as a reference measurement system for the accurate cross-linking with other altimeter systems (Seasat, Geosat, ERS-1, ERS-2, GFO-1, and Envisat), (2) the improved determination and the associated uncertainties of the long-term (15-year) global mean sea level change using multiple altimeters, and (3) the characterization of the sea level change by analyses of independent data, including tide gauges, sea surface temperature, (4) the improvement coastal radar altimetry for studies including coastal ocean tide modeling and coastal circulation. Major accomplishments of the investigation include the development of techniques for low-cost radar altimeter absolute calibration (including the associated GPS-buoy technology), coastal ocean tide modeling, and the linking of multiple altimeter systems and the resulting determination of the 15-year (1985-1999) global mean sea level variations. The current rate of 15-year sea level rise observed by multiple satellite altimetry is +2.3±1.2 mm/yr, which is in general agreement with the analysis of sparsely distributed tide gauge measurements for the same data span, and represents the first such determination of sea level change in its kind.


## ACCOMPLISHMENTS OF CURRENT INVESTIGATION

The major accomplishments of the NASA investigations (TOPEX/POSEIDON Extended Mission and Jason-1 projects, NAG5-4512, NAG5-6910, JPL 961462) are described in this report. The accomplishments include: (1) the development of GPS-buoy technologies for sea level measurements to improve absolute calibration accuracy, and the efforts toward the establishment of low-cost absolute calibration sites in the Gulf of Mexico and Lake Erie, (2) the associated analysis of TOPEX/POSEIDON calibration time series and the calibration and validation of TOPEX-Side B altimeter in Lake Michigan and near the coast of Spain; (3) the development of techniques to improve coastal altimeter data by waveform retracking and repairing of geophysical and media corrections, (4) assessment of current tidal prediction capabilities in the coastal regions, and initial results to improve some of the regional tide models, (5) refinement of radar altimeter data and their associated geophysical and media corrections, and the improved linking of the historic and present altimeter systems, and (6) the determination of 15-year global sea level change using the resulting altimeter data and the associated error analysis and comparison with tide gauge analysis.

**Absolute Radar Altimeters Calibration Sites**

There are a number of technical issues associated with the use of GPS-buoys to measure autonomous and accurate sea level measurements for the specific application of radar altimeter calibration. They include: (1) difficulty of accurate kinematic solutions of vertical GPS (receiver) location (i.e., sea level change) using reference station longer than 30 km, (2) hardware design involving communication (radio modem capability), robust data transfer, power supply, the ability to sense water level and attitude of the buoy (tilt-meter), and (3) other typical error sources such as multi-path (when buoys are near a platform) and waves and shape of domes.

The original plan under the Jason-1 investigation is to deploy an automated GPS buoy at the triple crossover point 200 km off the coast of Gulf of Mexico near an oil platform (HI539). The assessment of the Gulf of Mexico site and its current pending negotiation with the oil company (Unical/Spirit Energy Oil Co.) caused us to consider an alternate site in Lake Erie (Fig. 1). The Ohio State University F.T. Stone Laboratory is located near a T/P or Jason descending track and near a NOAA tide gauge (Fig. 1). The collaboration has been finalized which would allow us to host instrument at the Stone Lab. and operate the GPS-buoy with the collaboration of Stone Lab (part of Ohio Sea Grant College Program) and with NOAA/NOS (Gerry Mader and Doug Martin). The objective towards building a low-cost altimeter calibration site can be achieved by establishing and operating the Stone Lab. Site within next year.

The negotiation to use the Gulf of Mexico site near oil platform HI539 owned by Unical/Spirit Energy Oil Co. is successful. However, there has been a delay in the possible technical work to be done on the platform as the oil platform was sold earlier to its present owner and we had to start the negotiation over again. The anticipated date to start instrument installations will not be until January 2000. Funds have been allocated for instrumentation (tide gauge already built by Gary Jeffrey of Texas A&M at Corpus

Christi, and GPS receiver procured). Fig. 2 shows the location of the calibration site (a "box" indicating the triple crossover point). The black dots indicate the location of offshore oil platforms in the Gulf of Mexico. This site (HI539) is about 3-5 km from the triple crossover point (Jason-1, Envisat and GFO). We anticipate the instrument to be installed and operating by next year, with GPS-buoy deployment or campaign.

Efforts have been conducted to collaborate with operational and planned absolute radar altimeter calibration sites in an attempt to have more geographical coverage for the sites, and to agree to share data towards obtaining an improved set of calibration constants for radar altimeters for the characterizations of instrument biases and biases associated with geophysical and media corrections. It is anticipated that the averaging of the various data from multiple calibration sites will yield improved calibration of the altimeters. Most of the sites will also attempt to provide calibrations of multiple altimeter systems (Jason, GFO, and Envisat). The current operational and planned sites include Harvest, Burnie, British Channel, and Baltic Sea (operating), and Corsica, Catalunya, Gulf of Mexico, Lake Erie, North Sea and New Caledonia (planned). The following Jason calibration/validation plans, which have our involvement, have been submitted to the Jason Project:

- Absolute Calibration of Multiple Radar Altimeters for Global Change and Coastal Studies
  **PIs**: C. Shum and M. Parke, Ohio State University; J. Blaha, Naval Research Laboratory; G. Jeffrey, Texas A&M Corpus Christi; D. Martin and G. Mader, NOAA/NOS; C. Morris, Jet Propulsion Laboratory; K. Schaudt, Marathon Oil.
  **Collaborating Calibration Site PIs**: J. Benjamin, Univsidad Politecnica de Catalunya: Llafrancl and San Fernando (planned); S. Calmant, ORSTOM de Noumea: New Caledonia (planned); R. Dietrich, G. Liebsch, TU Dresden: Baltic Sea (operating); M. Rentsch, A. Braun, Tilo Schoene, GeoForschungsZentrum Potsdam: North Sea (planned); N. White, Richard Coleman, CSIRO, Univ. of Tasmania: Bass Strait/Burnie (operating); P. Woodworth, P. Moore, POL and U. New Castle: English Channel (operating).

- GFZ Contribution to the Jason-1 Cal/Val in the North Sea
  **PIs**: M. Rentsch, T. Schoene, A. Braun, A. Helm, GeoForschungsZentrum Potsdam; E. Mittelstaedt, Federal Maritime and Hydrographic Agency of Germany (BSH); W. Gloeden, Deutscher Wetterdienst (DWD); R. Dietrich, G. Liebsch, Technical University Dresden; J.J. Martinez Benjamin et al., Universitat Politecnica de Catalunya; C.K. Shum, M. Parke, Ohio State University

- Contribution To Jason-1 Calibration/Validation In Llafranc And San Fernando
  **PIs**: Juan J. Martinez Benjamin, Marina Martinez Garcia, Universidad Politecnica de Cataluña, Barcelona; Jorge Garate, Jose M. Davila (Real Instituto y Observatorio

de la Armada, San Fernando; Miquel A. Ortiz, Julia Talaya, Instituto Cartografico de Cataluña, Barcelona; Jose M. Ferrandiz, M. Isabel Vigo, Universidad de Alicante; Begoña Perez, Enrique Alvarez, Clima Maritimo-Puertos del Estado, Madrid.
**International Collaborators**: G. Kruizinga, B. Haines, JPL; C.K. Shum, M. Parke, Ohio State University; P. Exertier, P. Bonnefond, F. Barlier, CERGA.

**TOPEX Side B Altimeter Calibration and Validation**

We have studied various GPS kinematic positioning solution techniques for accurate measurement of sea level using GPS buoy data collected during radar altimeter campaign field works. The campaigns were to support the calibration and verification of two new altimeters: the TOPEX Side B (TSB) and GFO-1 altimeters. The campaigns were conducted in Lake Michigan; and in Catalunya off the coast of Spain, during March, 1999 JPL [Shum et al., 1999a; Shum et al., 1999b]. The Spain campaign was conducted in collaboration with Spanish colleagues (J. Benjamin et al., UPC, ICC) and JPL.

Fig. 3 and Fig. 4 show the site and instrumentation of the Lake Michigan and Catalunya campaign respectively. In each case, fudicial GPS sites were occupied to take 1-second GPS data coincide with the GPS buoy data taking. The altimeter passes in Lake Michigan are at 1999/3/30/22:59:44 UTC for TOPEX Side B pass, and at 1999/3/24 16:18:6 UTC for the GFO pass. Fig. 5 shows the preliminary results of GPS kinematic solution closure comparing with TSB using KARS (authored by Gerry Mader) software systems. The altimeter bias estimated is 3.1 ± 10 cm [Shum et al., 1999b]. The KARS solution was compared with Trimble's GPSurvey software system. There is at present a 1.5 cm bias between the two solutions. Preliminary results indicate that the discrepancy is due to antenna modeling and it seems to be a problem of the GPSurvey solution. Fig. 6 shows the KARS solution the Catalunya calibration compared with TSB altimeter, i.e. TSB bias, is 6.8 ± 10 cm, which is in good agreement with the JPL Gipsy solution of 5.1 cm [G. Kruizinga, personal communication, 1999].

The GPS buoy was also used to "link" T/P altimeter measurement with a NOAA tide gauge, Holland West, located in Lake Michigan (Fig. 3). That is, water level measurements obtained by GPS-buoys at the tide gauge and at the altimeter track during March 1999, were used to compare with the closest T/P altimeter data for the entire mission 20 km away, by using the tide gauge historic data. Fig. 7 shows the comparison of historic time series of water level from the Holland West tide gauge and T/P measurement from 1993–1999. This preliminary analysis shows the potential of "calibrating" altimeter using existing tide gauges by "linking" the reference datums of the tide gauge and the altimeter measured surface. The link is made possible by the use of GPS water level measurements. Further studies on this subject are needed.

Further verifications of TSB altimeter measurement were conducted using global analysis and using ERS-2 altimeter measurements (sea surface height, wave height, wind speed, radiometer measured water vapor delays, ionosphere) during the same time period. Global analysis of TOPEX Side A (TSA, cycles 10-142) and Side B (cycles 236-255) altimeter sea level measurements, by excluding TSA cycles 143-235 (speculate that point target response problems in part causing an erroneous sea level rise during this time period), shows an estimated bias of $4 \pm 5$ mm based on a 7-parameter fit (Fig. 8).

**Coastal Ocean Tide Modeling**

Since the accuracy assessment of global ocean tide models in 1997 [Shum et al., 1997], a number of improved ocean tide models has become available and it is also desirable for another round of model evaluations initiated by the Jason project. We conducted an accuracy assessment of the current tide models for the prediction of coastal barotropic tides. At present, six 1999 tide models were used to focus on the coastal regions: CU (Tierney et al.), CSR4.0 (Eanes), GOT99.2b (Ray), NAO99 (Matsumoto), Delft (Smith) and JPL (Desai and Wahr) models. Fig. 9 shows the root-sum-squares of the tidal amplitude differences between the six models summed for the 8 major tidal constituents. The figure is color-coded with an intent to highlight coastal region tidal accuracy. The deep ocean tide prediction accuracy is below 2 cm rss. Fig. 10 and 11 show enlarged pictures for the South American region (Patagonian Shelf and Amazon Delta) and East and South China Seas (Indonesia Sea, Yellow Sea), showing significant predicted tidal amplitude errors exceeding 30 cm in these regions. Preliminary results for evaluations of these models using T/P, Geosat and ERS-1 Geodetic Mission Phases coastal (<1000 m depth) altimeter sea level data (altimeter sea surface topography measurement subtracting the OSU mean sea surface model) in three regions (S. America, N. America, China Seas) indicate that (1) the lowest altimeter sea level residuals are associated with the NAO99 and the GOT99.2b tide models [Yu et al., 1999] for the regions tested, and that (2) there is regional dependence associated with the performance of different models.

Preliminary test tide solutions were conducted using T/P, Geosat, and ERS-1 GDR altimeter data in the Yellow Sea region. It is intended that retracked altimeter data from ERS-1 together with the GDR data sets (T/P, ERS-1 and Geosat) will also be used to see whether the regional tide solution can be improved (higher resolution and accuracy). Analysis of the test tide solutions shows promise of improvement in this region using empirical solution techniques.

**Improvement of Radar Altimeter Data in the Coastal Ocean**

We have developed the fundamental techniques to improve coastal altimeter data by retracking of radar waveform data at 10 Hz or 20 Hz [Anzenhofer and Shum, 1999;

Anzenhofer et al., 1999]. We choose to use ERS-1 as our experimental data type, instead of TOPEX/POSEIDON, primarily because the T/P coastal data (10 Hz) are anticipated to be produced by the JPL group (Ernesto Rodriguez) in the near future. Discussions with him and other experts in the field (M. Anzenhofer, D. Wingham, F. Remy, etc.) have been conducted to choose the optimal retracker to improve coastal ocean data. Our developed technique to produce improved coastal altimeter data is to first apply a developed radar waveform tracker (using a sequence of the Offset Center of Gravity, OCOG retracker [Mullard Space Science Lab., 1987]), and then fit the waveforms using the so-called beta retracker, to estimate range, significant wave height, and $\sigma_0$ at 10 Hz (for Geosat and T/P) and at 20 Hz (for ERS-1 and ERS-2) [Anzenhofer and Shum, 1999]. It should be noted that although this procedure is suited for ERS-1 (and probably ERS-2), it might not necessarily be the best procedure for T/P, Geosat or GFO processing.

Fig. 12 shows results of comparisons in the Yangtse Estuary in Southern China (the mouth of Yangtse River) between the ERS-1 OPR02 (GDR) data and the retracked data from ERS-1 using the technique described above. There are significant differences between the data: the OPR02 data (1 Hz) is not showing any corresponding variations and are probably erroneous, while the 20-Hz retracked data exhibit variations indicative of river-ocean height variations [Anzenhofer et al., 1999], indicating that the retracked data are improved. Fig. 13 shows a more detailed comparison of the ERS-1 GDR (OPR02) and retracked (20 Hz) ERS-1 altimeter data over the Yellow and South China Sea region. Some retracked data is missing primarily because of troposphere correction drop-outs [Anzenhofer et al., 1999]. However, significant more data are obtained through retracking and close examination of the significant differences between the two data sets close to the coastal region, e.g., the Yangtse Delta region, indicates that the coastal altimeter data have been improved through retracking, and further improvement is feasible by carefully implementing the appropriate media and geophysical corrections.

**Contemporary Determination of Global Sea Level**

The determination of the $21^{st}$ century sea level rise, with published rate of 2-3 mm/yr, primarily used coastal tide gauges and correcting the postglacial rebound effect [e.g., using ICE-4G model]. We have analyzed the available PSMSL and WOCE tide gauge data (a combination of daily and monthly records) using 1000+ global tide gauges. Our estimate in the regression analysis (adjusting 18.6 years, decadal, variable annual, and semiannual terms along with the sea level trend) yields substantially smaller rise in sea level for the last century: $1.1 \pm 0.1$ mm/yr (formal standard deviations) [Shum et al., 1999b] (Table 1).

Satellite radar altimeters have the potential to definitively measure the long-term (decades) global sea level change with a spatial scale of 100 km and with an accuracy approaching 1 mm/yr [e.g., Shum et al., 1999a]. The uncertainties of instrument biases and drifts and the associated biases and drifts in the geophysical and media corrections and the links of various altimeter systems represent the current limitations to fully exploit the use of radar altimeters. We have conducted improvement of the historic and present altimeter measurements and the determination of their relative biases. Fig. 14, 15, and 16 show the current validation of radar altimeter systems (Geosat, ERS-1 and TOPEX/POSEIDON Side A) with 46 WOCE island tide gauges [Shum et al., 1999b]. Different biases were also estimated for different missions phases of altimeter measurements, e.g., Geosat GM and ERM, and ERS-1 phases (A, B, C, D, E, F, G). The validation and the resulting determination of relative biases between the altimeter systems and different mission phases (Fig. 17) are considered an improvement of previous work [Guman, 1997]. Fig. 17 illustrates shows some stringent technical details needed to exploit the use of multiple mission radar altimeter measurements for the measurement of the global sea level. WOCE (and Great Lakes) tide gauges have been used to "link" or determine the relative instrument biases between different altimeter systems [Guman, 1997; Kruizinga, 1997; Urban et al., 1999; Shum et al., 1999b].

Fig. 18 shows the contemporary global sea level rise during 1985-1999 (15 years with 4 year data gap), combining three altimeter missions, is estimated at 2.3 ± 1.2 mm/yr [Shum et al., 1999b]. This represents the first such determination and illustrates the potential of using satellite measurements to measure sea level changes.

Table 1 (formal uncertainty only) shows a detailed sea level trend determination using long-term tide gauge records. It is interesting to note that the current altimeter determination of sea level using 15 years of data agrees fairly well with tide gauge determinations (2.3 to 2.5 mm/yr). However, it should be note that the vertical motions of tide gauges are still one of the largest error sources.

Table 1. Sea Level Trend Observed by Tide Gauges, Applying ICE-4G PGR Model

| Data span | Number of station | Sea Level Trend (mm/year) | Sea Level Trend (with PGR) (mm/yr) |
|---|---|---|---|
| 1858~1999 | 1077 | 1.1±0.1 | 1.1±0.1 |
| 1950~1999 | 1021 | 1.1±0.1 | 0.9±0.1 |
| 1960~1999 | 1007 | 1.2±0.1 | 1.0±0.1 |
| 1970~1999 | 907 | 1.0±0.1 | 0.8±0.1 |
| 1980~1999 | 833 | 1.6±0.1 | 1.4±0.1 |
| 1985~1999 | 791 | 2.7±0.2 | 2.5±0.2 |
| 1990~1999 | 706 | 3.1±0.3 | 2.9±0.3 |

Comparing the altimeter and the tide gauge results, we note that the radar altimeter determined sea level trend determination is probably large at 2.3 mm/yr, with interannual variations dominating, making the short data span a primary limitation. It is critically important to establish additional absolute calibration sites for radar altimeter data verification approaching an accuracy of 1-2 mm/yr, and reconcile techniques to use both data from long-term and multiple radar altimeter missions and *in situ* tide gauges for the definitive determination of global sea level change.

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## Proposed Lake Erie Altimeter Calibration Site

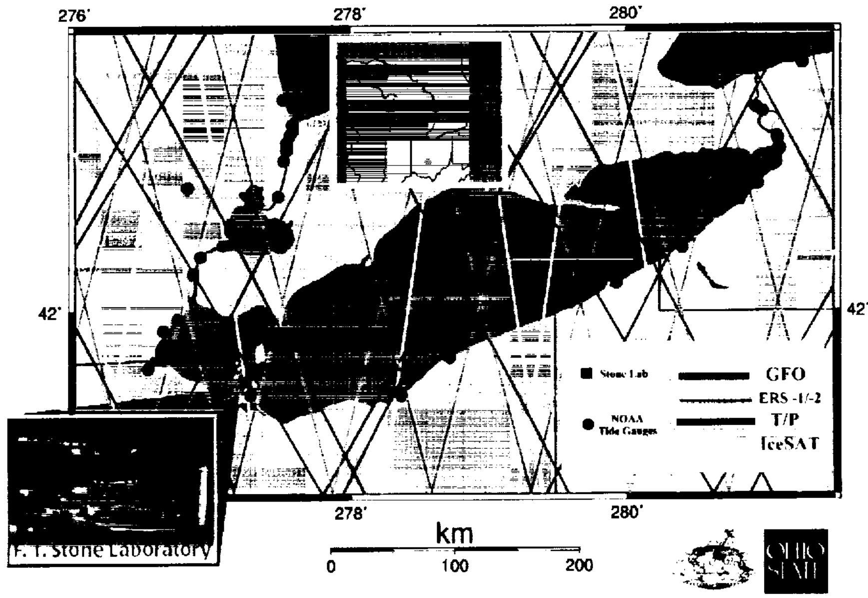


Figure 1. Proposed Lake Erie Radar Altimeter Calibration Site

## Gulf of Mexico Radar Altimeter Calibration

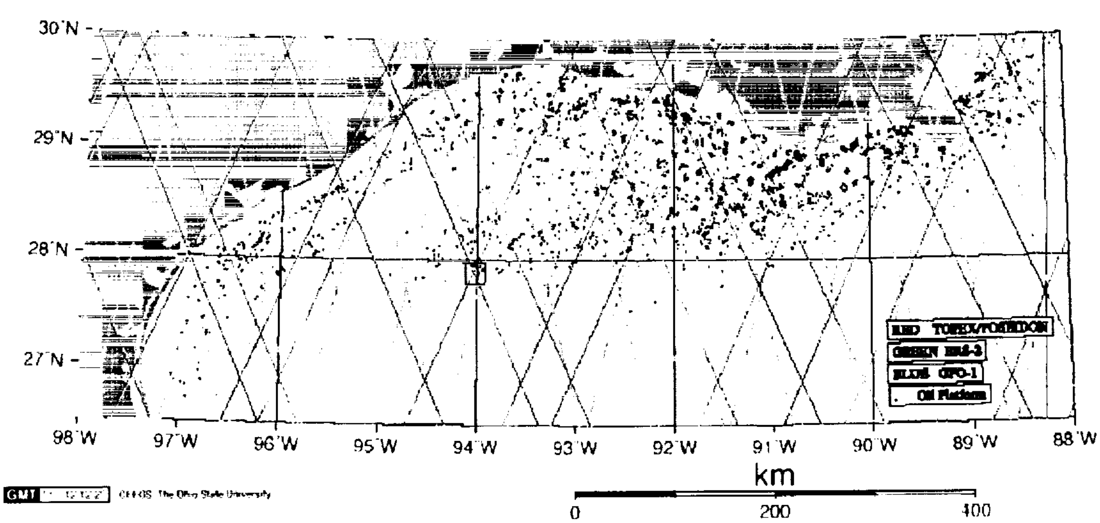


Figure 2. Proposed Gulf of Mexico Radar Altimeter Calibration Site

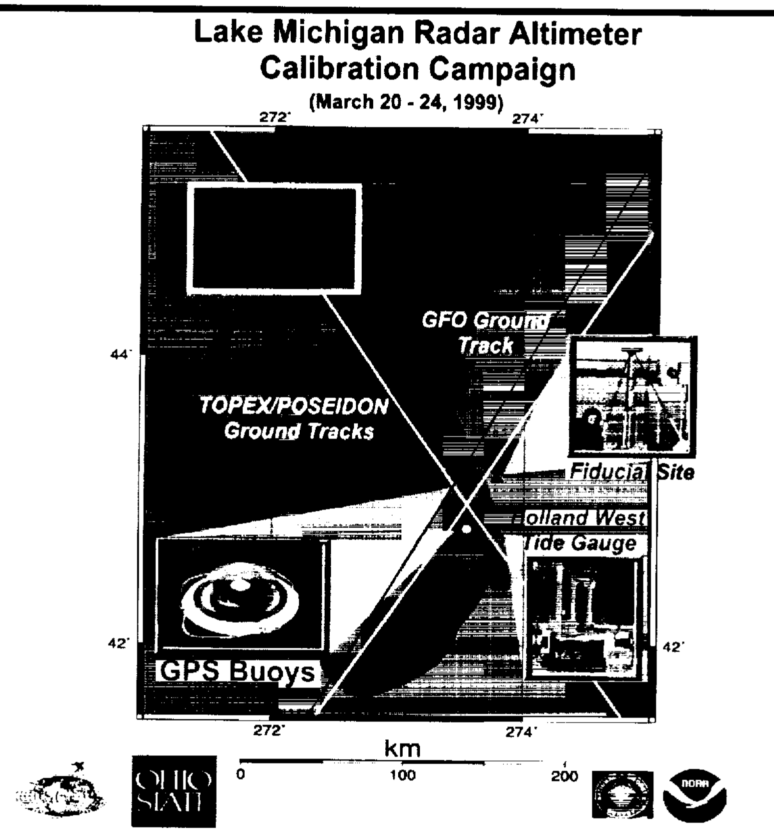


Figure 3. Lake Michigan Radar Altimeter Calibration Campaign

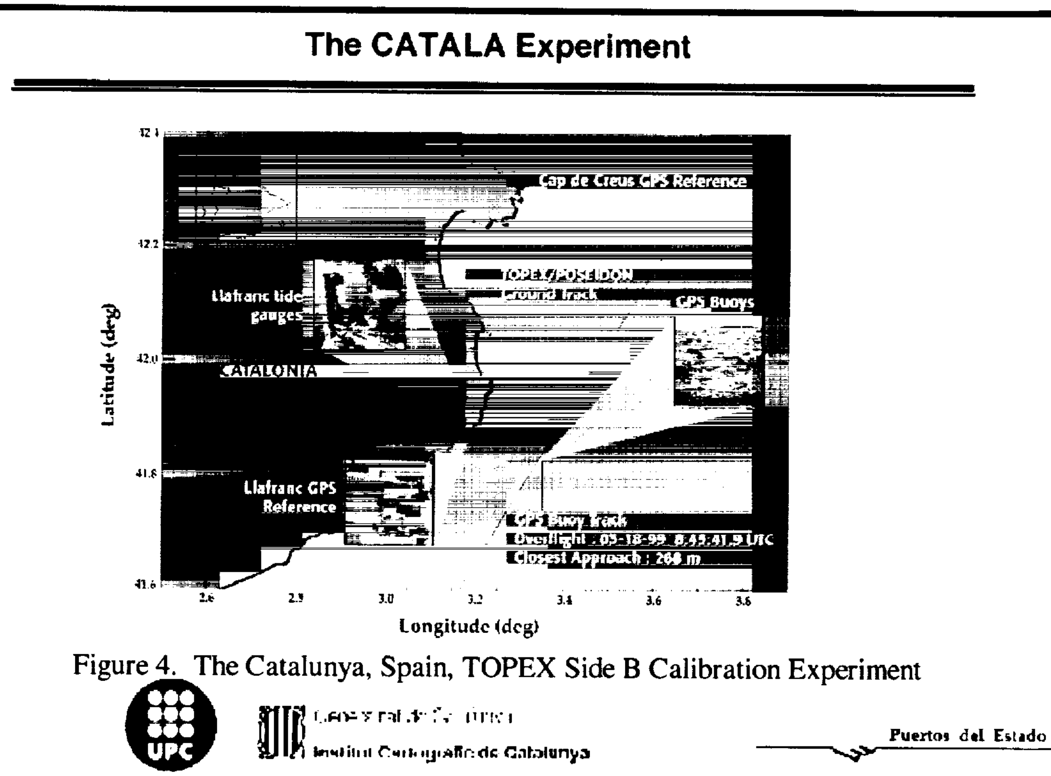


Figure 4. The Catalunya, Spain, TOPEX Side B Calibration Experiment

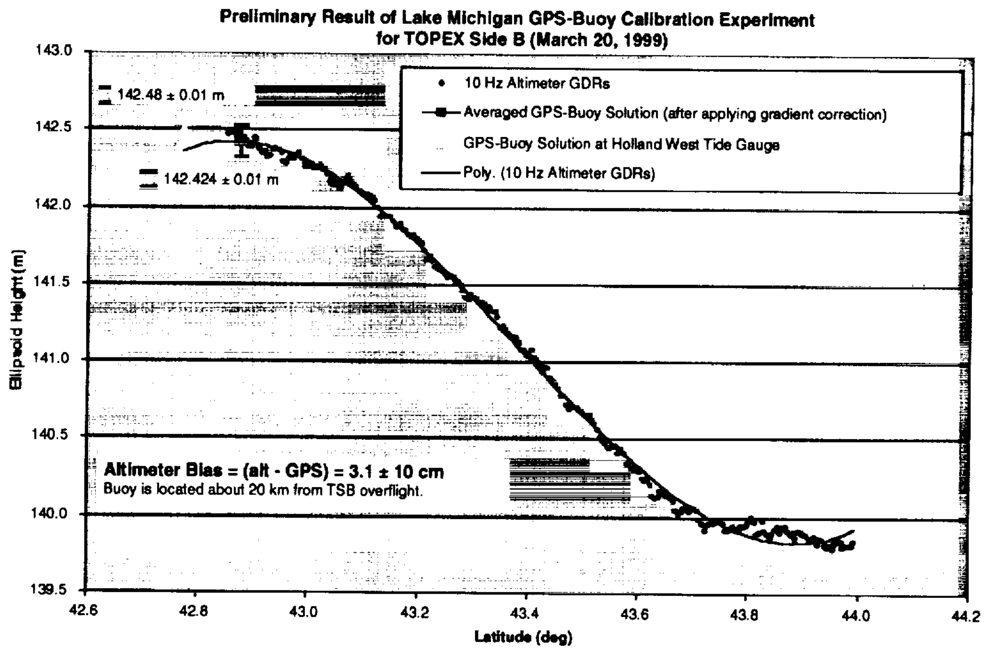


Figure 5. Preliminary Result of Lake Michigan GPS-Buoy Calibration for TOPEX Side B Altimeter

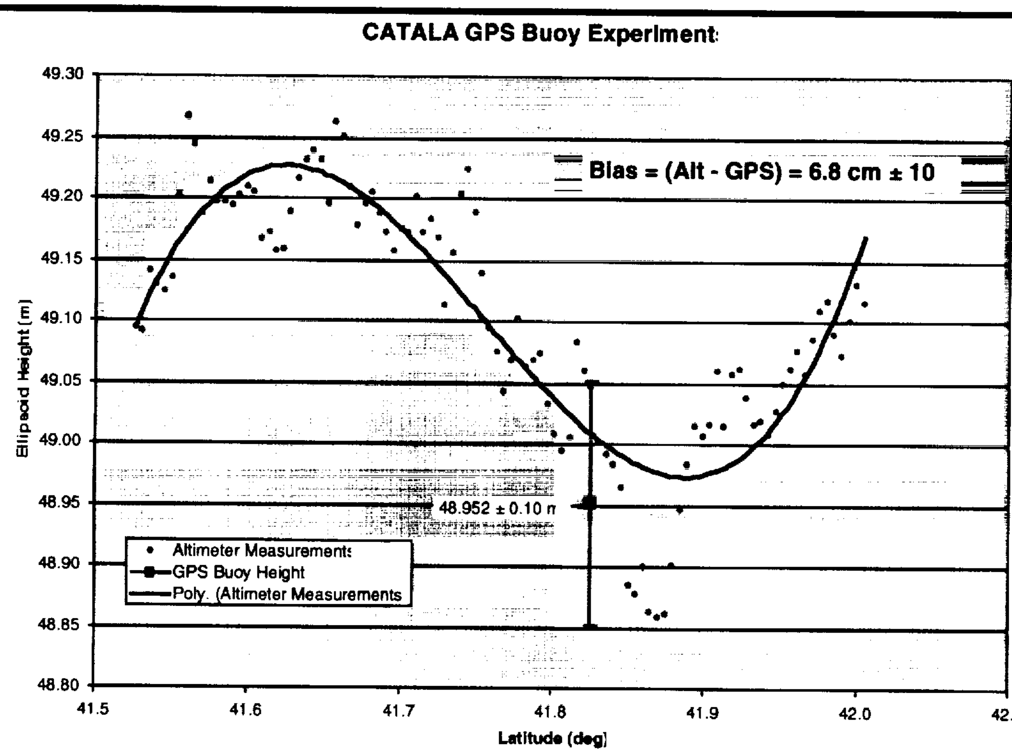


Figure 6. Preliminary Result of Catalunya GPS-Buoy Calibration of TSB Altimeter

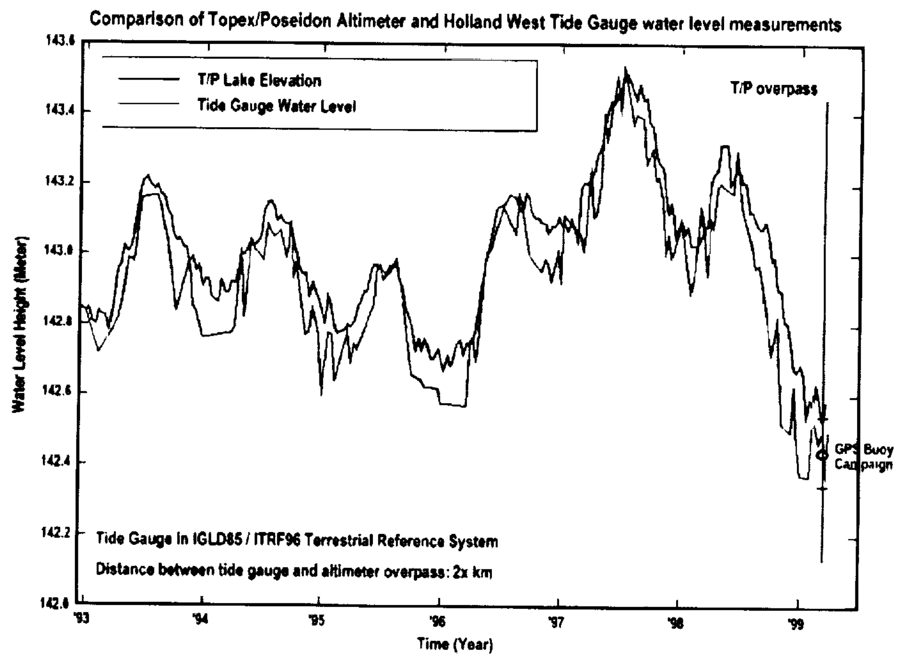


Figure 7. Calibration of T/P Mission Altimeter Measurements Linking Tide Gauge (Holland West) Using GPS-Buoys in Lake Michigan

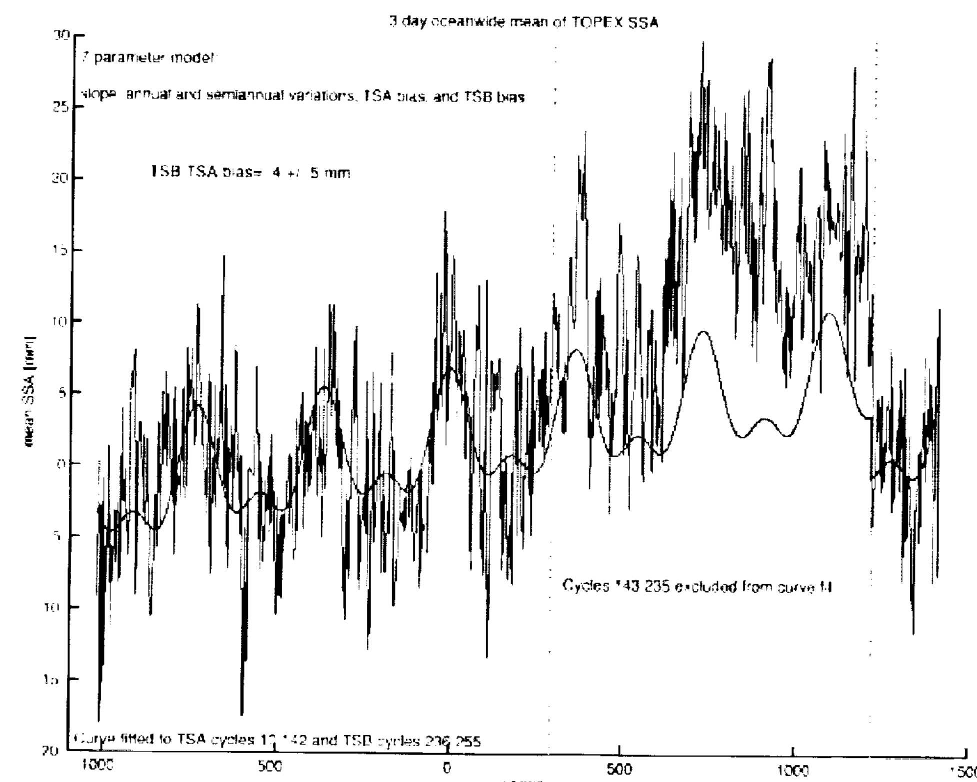


Figure 8. Global Analysis to Determine TOPEX Side A and Side A Altimeter Bias

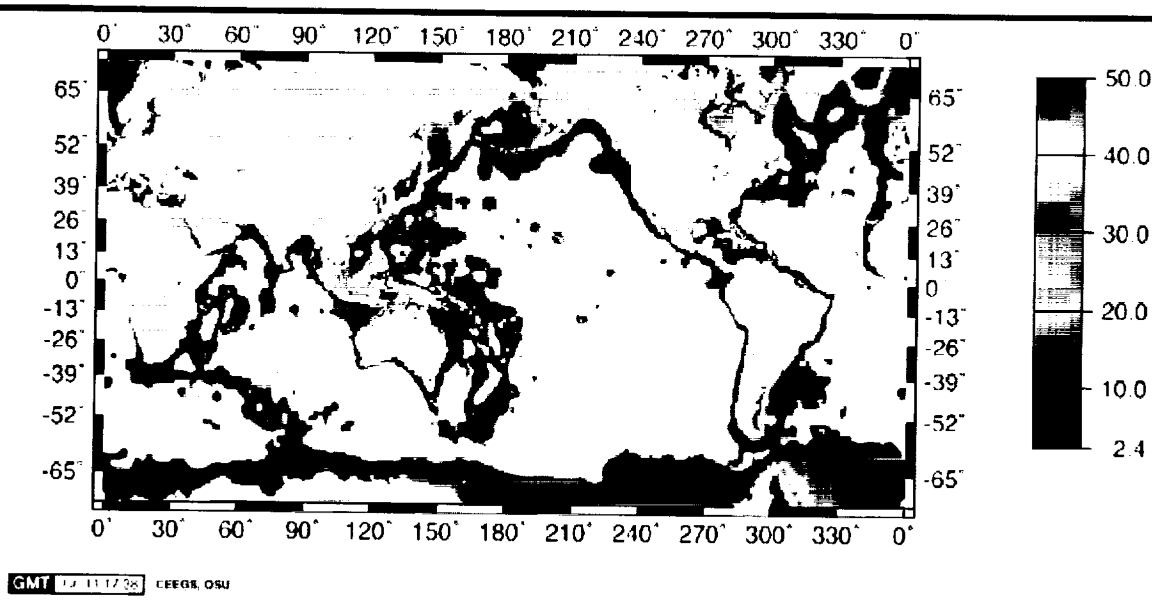


Figure 9. Assessment of Coastal Ocean Tide Error Using 6 Current Tide Models (Standard Deviation of 8 Constituents for CSR4, D&W, GOT99, NAO99, CU, Delft Models)

Region II –60-30, 270-320

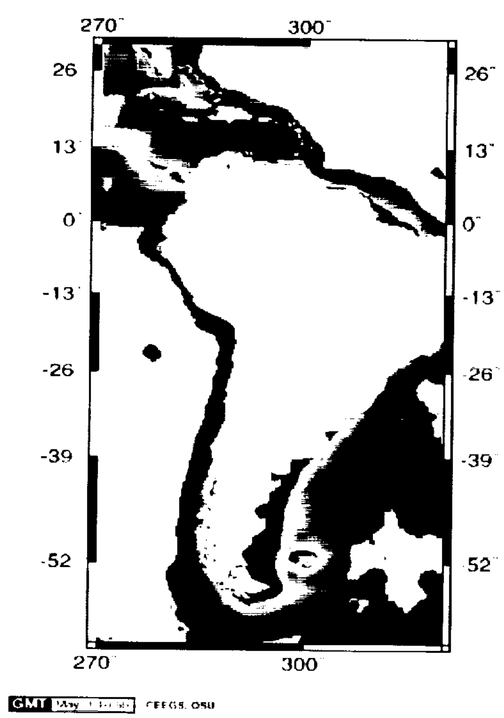


Figure 10. Tide Error for South America Coastal Seas

Region IV –40-60, 100-1700

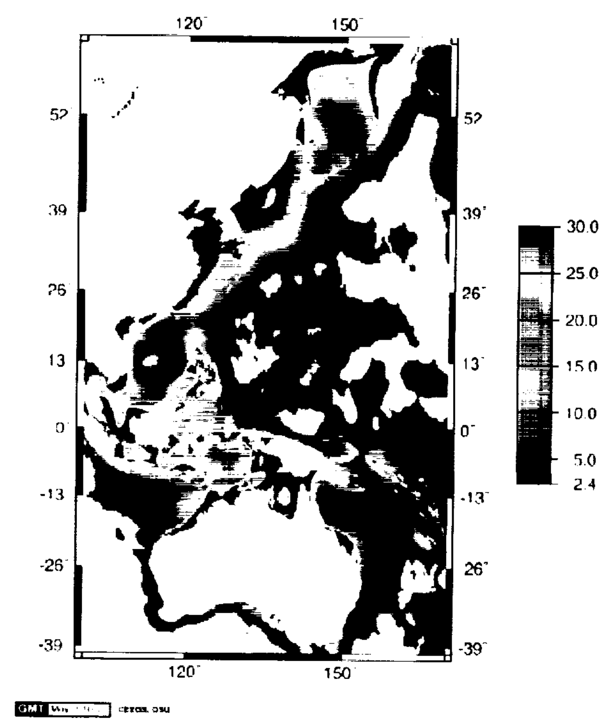


Figure 11. Tide Error for Coastal Regions in China Seas and Indonesia Sea

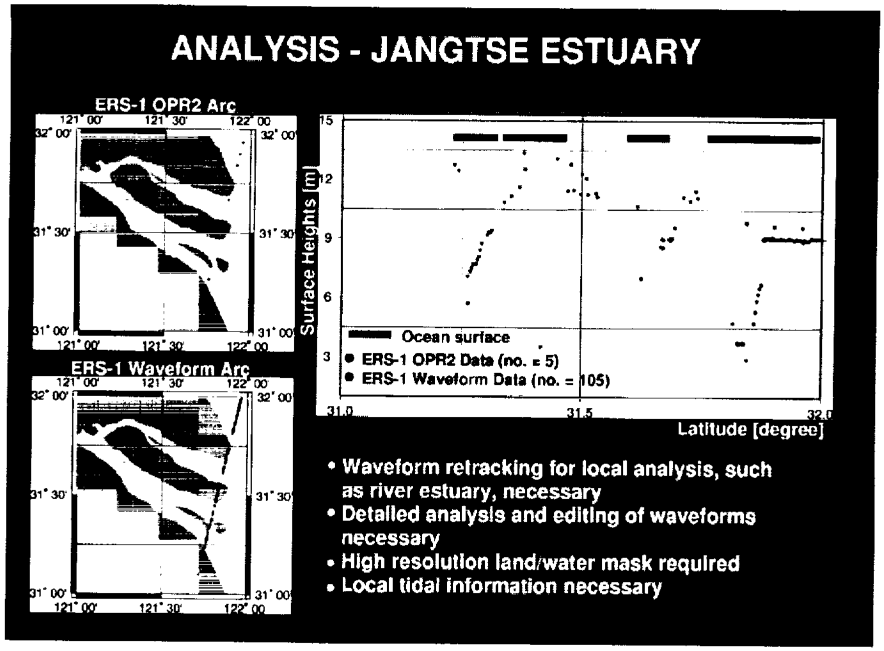


Figure 12. Comparison of OPR02 and ERS-1 altimeter data over the Jangtse Estuary in Southern China. Significant difference is found and implying that retracking of waveform data helped to recover data [Anzenhofer et al., 1999].

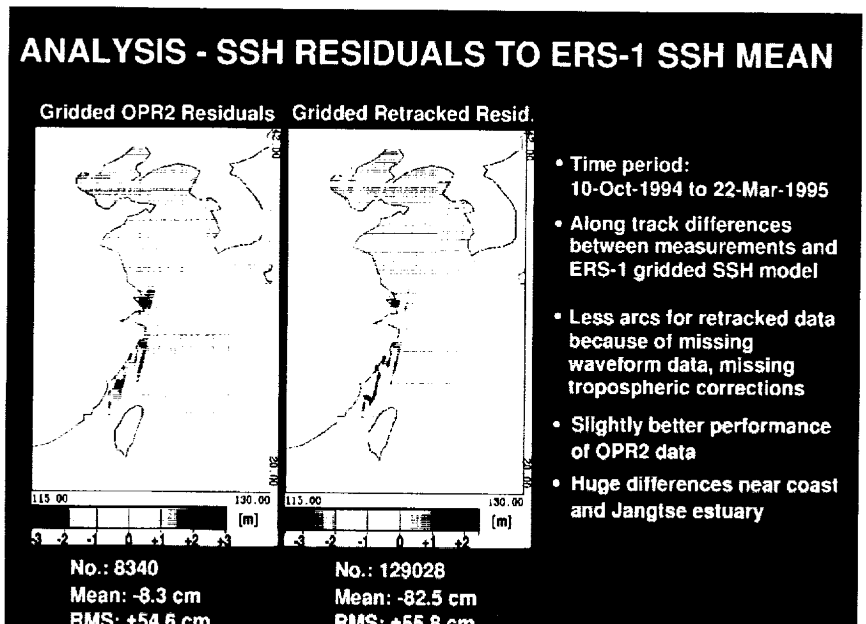


Figure 13. Comparison of OPR02 and retracked (20 Hz) ERS-1 altimeter data over the Yellow and South China Sea region. Significantly more data can be recovered by waveform retracking of the 20 Hz data. [Anzenhofer et al., 1999].

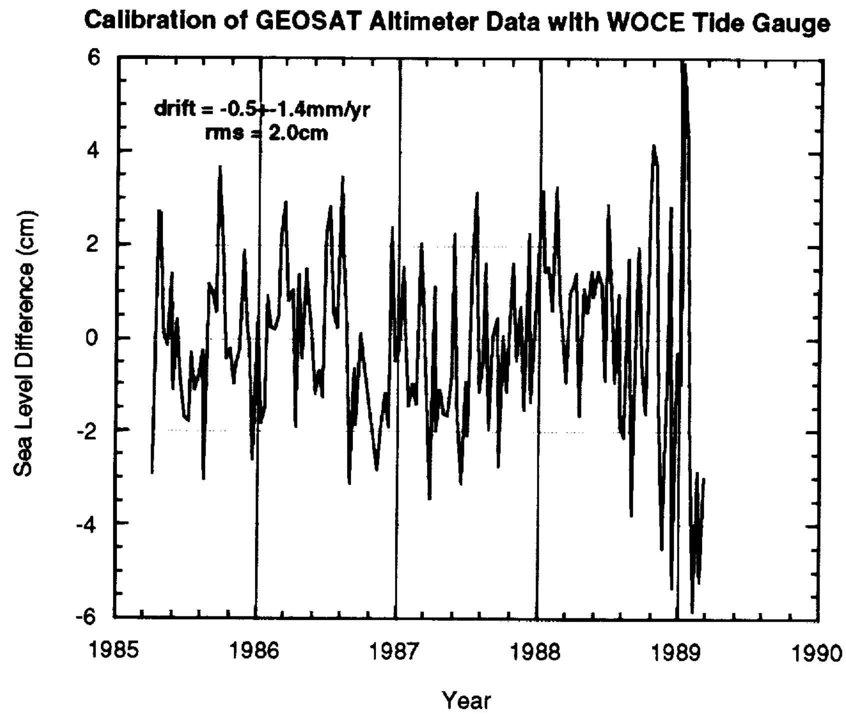


Figure 14. Verification of Geosat altimeter Data UsingWOCE Tide Gauge

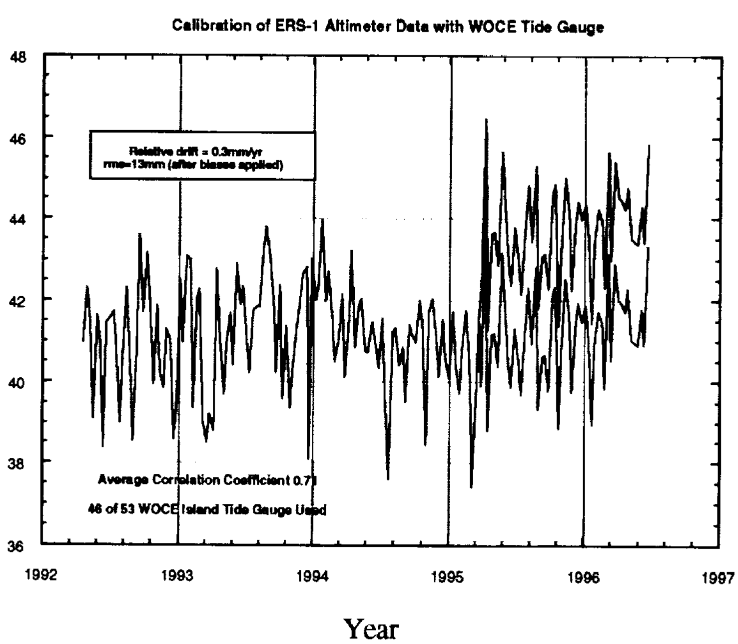


Figure 15. Verifications of ERS-1 Altimeter Data Using WOCE Tide Gauge

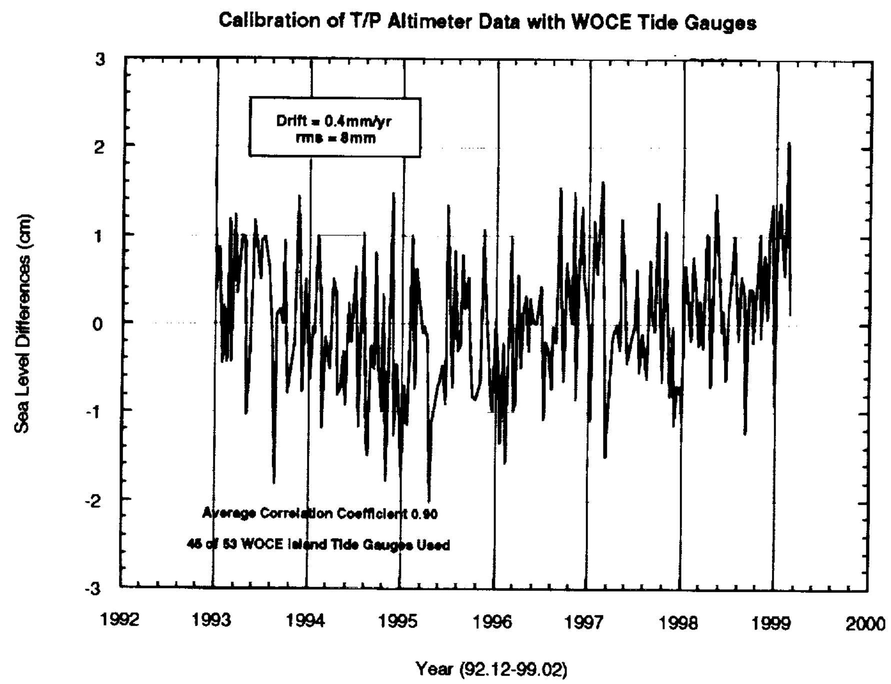


Figure 16. Verification of T/P altimeter Data UsingWOCE Tide Gauge

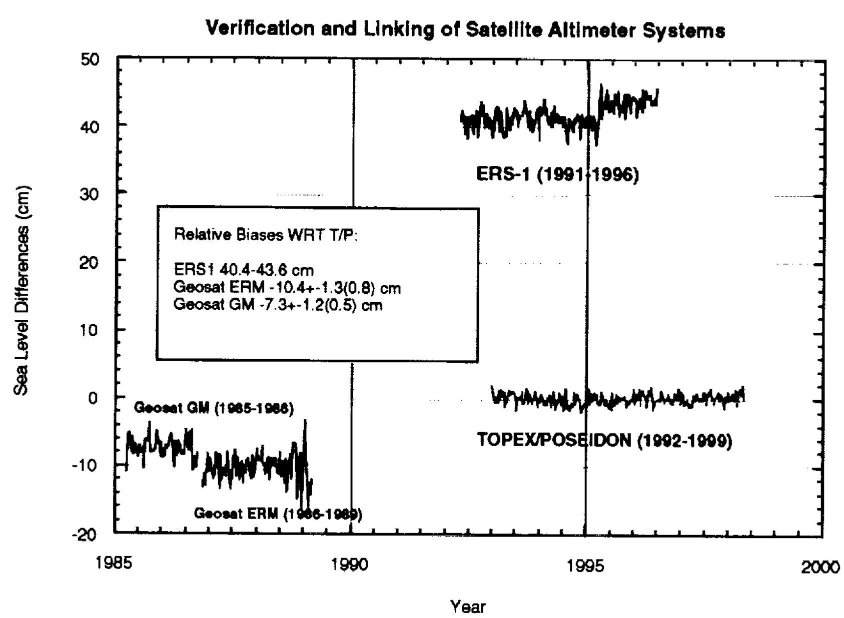


Figure 17. Verification and Linking of Radar Altimeter Systems

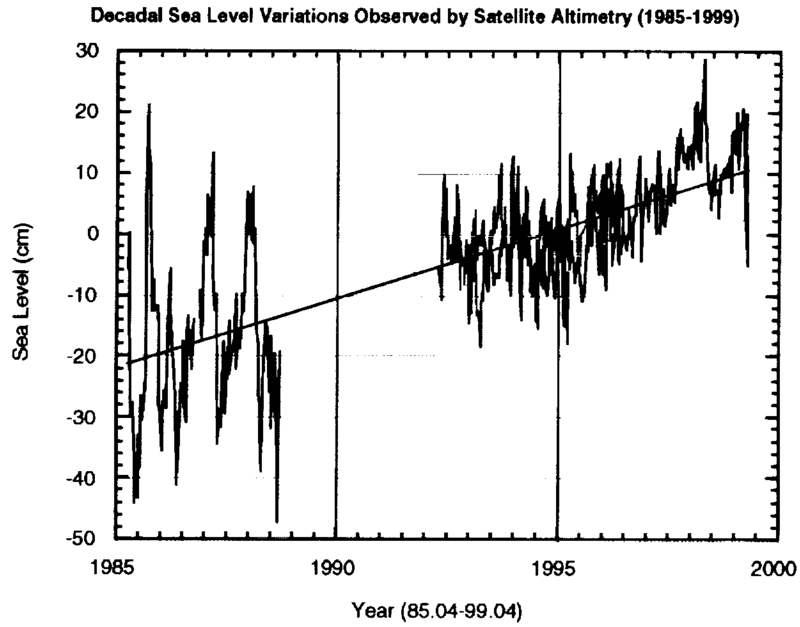


Figure 18. 15 year (1985-1999) global mean sea level change observed by radar altimeters (Geosat GM/ERM, ERS-1 and TOPEX/POSEIDON) [Shum et al.,1999]. Shown for the inverted-barometer corrected sea level and seasonal variations not removed. The observed rise in sea level in either case is 2.3 +/- 1.2 mm/yr. The uncertainty is estimated considering many modeled and unmodeled error sources.