Final Technical Report for Grants NAG5-6700, NAG5-6643

GFO-1 GEOPHYSICAL DATA RECORD AND ORBIT VERIFICATIONS FOR GLOBAL CHANGE STUDIES

OSURF Project #735414

Reporting Period: December 1, 1997 - November 30, 2000
Investigation Period: December 1, 1997 - November 30, 2000

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November 30, 2000

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SUMMARY

This final report summarizes the research work conducted under NASA's Physical Oceanography Program, Grant No. NAG5-6700 and NAG5-6643, entitled, *GFO-1 Geophysical Data Record And Orbit Verifications For Global Change Studies,* for the investigation time period from December 1, 1997 through November 30, 2000. The primary objectives of the investigation include providing verification and improvement for the precise orbit, media, geophysical, and instrument corrections to accurately reduce U.S. Navy's Geosat-Followon-1 (GFO-1) mission radar altimeter data to sea level measurements. The status of the GFO satellite (instrument and spacecraft operations, orbital tracking and altimeter) is summarized. GFO spacecraft has been accepted by the Navy from Ball Aerospace and has been declared operational since November, 2000. We have participated in four official GFO calibration/validation periods (Cal/Val I-IV), spanning from June 1999 through October 2000. Results of verification of the GFO orbit and geophysical data record measurements both from NOAA (IGDR) and from the Navy (NGDR) are reported. Our preliminary results indicate that (1) the precise orbit (GSFC and OSU) can be determined to ~5-6 cm rms radially using SLR and altimeter crossovers; (2) Estimated GFO MOE (GSFC or NRL) radial orbit accuracy is ~7-30 cm and Operational Doppler orbit accuracy is ~60-350 cm. After bias and tilt adjustment (1000 km arc), estimated Doppler orbit accuracy is ~1.2-6.5 cm rms and the MOE accuracy is ~1.0-2.3 cm; (3) the geophysical and media corrections have been validated versus in situ measurements and measurements from other operating altimeters (T/P and ERS-2). Altimeter time bias is insignificant with 0-2 ms. Sea state bias is about ~3-4.5% of SWH. Wet troposphere correction has ~1 cm bias and ~3 cm rms when compared with ERS-2 data. Use of GIM and IRI95 provide ionosphere correction accurate to 2-3 cm rms during medium to high solar activities; (4) the noise of the GFO altimeter data (uncorrected SSH) is about 15 mm, compared to 19 mm for ERS-2, and 12 mm for TOPEX. It is anticipated that the operational GFO-1 altimeter data will contribute to a number of researches in physical oceanography. A list of relevant presentations and publications is attached.

GFO STATUS

After launch on 10 February 1998 from Vandenberg Air Force Base in California, GFO radar altimeter, the main onboard instrument, has been working and altimeter is routinely tracking. Shortly after launch, the onboard Turbo-star 16-channel GPS receivers (there are four of them) failed to track more than one GPS satellite on both frequencies. Without an operational GPS receiver, there is also a problem with obtaining precise time tags for altimeter measurements.

An effort to fix and turn on onboard GPS receivers by JPL and Ball has been made since January 1999. Currently there still appears to be some problem.

NASA had paid for a laser corner cube retroreflector (LRA) for satellite laser ranging (SLR) to GFO. We have conducted efforts to keep the SLR tracking for GFO going and at an acceptable tracking priority. It is anticipated that ILRS will continue to support to track GFO. NASA/GSFC (Frank Lemoine et al.) has been computing SLR orbits to supply to NOAA to generate the NOAA GFO Interim Geophysical Data Record (IGDR, ftp://eagle.grdl.noaa.gov/igdr/slr). The ADFC is generating the Navy IGDR (NIGDR). GFO real-time data are processed by the Altimeter Data Fusion Center at NAVOCEAN at Stennis S.C. and offline data (GDR) are processed by NOAA/NESDIS for distribution to scientific community. The Ohio State University and University of Texas have been computing an alternate SLR/crossover precise orbit to provide verification. The Ohio State University is among the group who is verifying the geophysical data record. NASA/Wallops is providing support of radar altimeter instrument stability and corrections.

Four Calibration/Validation periods have been conducted on GFO. They are Cal/Val I: June 16-Aug 17, 1999, II: Dec 6 - Dec 22, 1999 and Feb 12 - Feb 28, 2000, III: May 1 - June 10, 2000 and IV: Aug 30 2000 - present. Based on these calibration results, we reported that GFO satellite is healthy and status is "green". COMSPAWARSYSCOM has considered and accepted GFO from Ball Aerospace in November 2000 and GFO has been declared fully operational.

Two data products on the GDR level are being generated. One from NOAA (IGDR) and the other from NRL (NGDR). The latter being near real-time data product and the former could evolve into a scientific data product (i.e., GDR). It is also recommended that the International Laser Ranging Service (ILRS) track GFO operationally, as SLR tracking is critical to maintain the accuracy of the GFO orbits. It is anticipated that GFO data will contribute to the ongoing physical oceanography and global climate research programs at NASA, NOAA and other agencies.

PRECISION ORBIT DETERMINATION AND VERIFICATION

The fact that the GPS receiver onboard of GFO is not fully operational has prompted the use of satellite laser ranging (SLR) tracking data for the computation of precise orbits (e.g., at NASA/GSFC by Frank Lemoine et al.). We have computed some alternative precise orbits using SLR and crossover data for independent accuracy verification. The average SLR residual is around 4 cm rms and crossover residual is about 8 cm rms during the calibration and validation time period (see Figure 1). GFO precise orbits (OSU orbits using the TEG3 gravity filed model and fitted using SLR and crossovers) are estimated at around 5-6 cm rms radially.

We performed 3-day crossover (not the "best" altimeter data used) analysis and geometric orbit adjustments (bias and tilt and once per rev) for the Opent Doppler orbits (OODD) and SLR MOE orbits (GSFC). Figures 2 and 3 show the results.

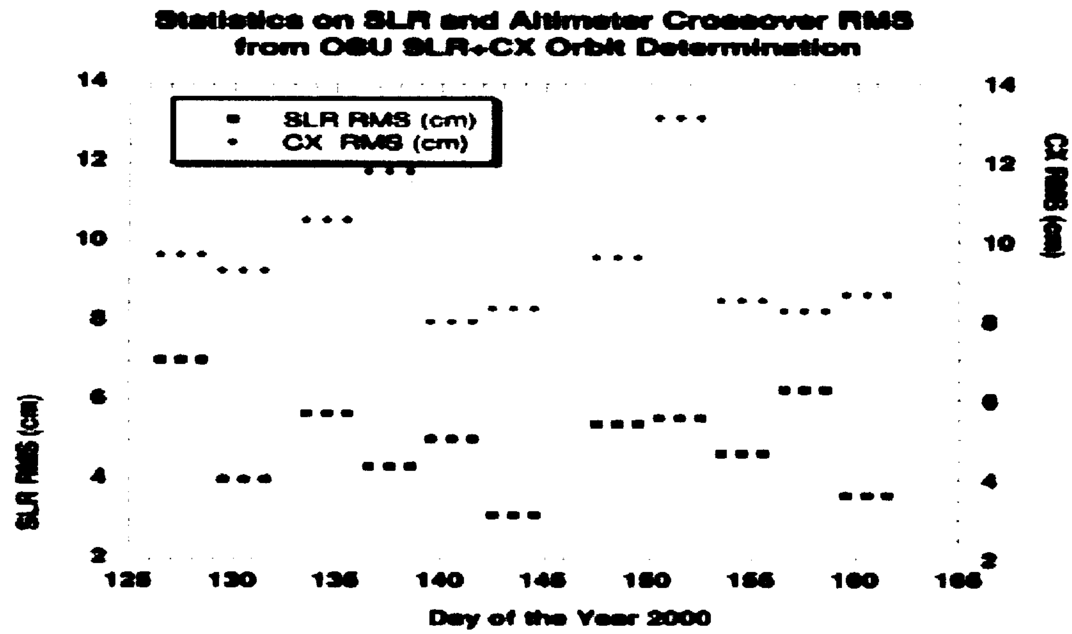

Figure 1

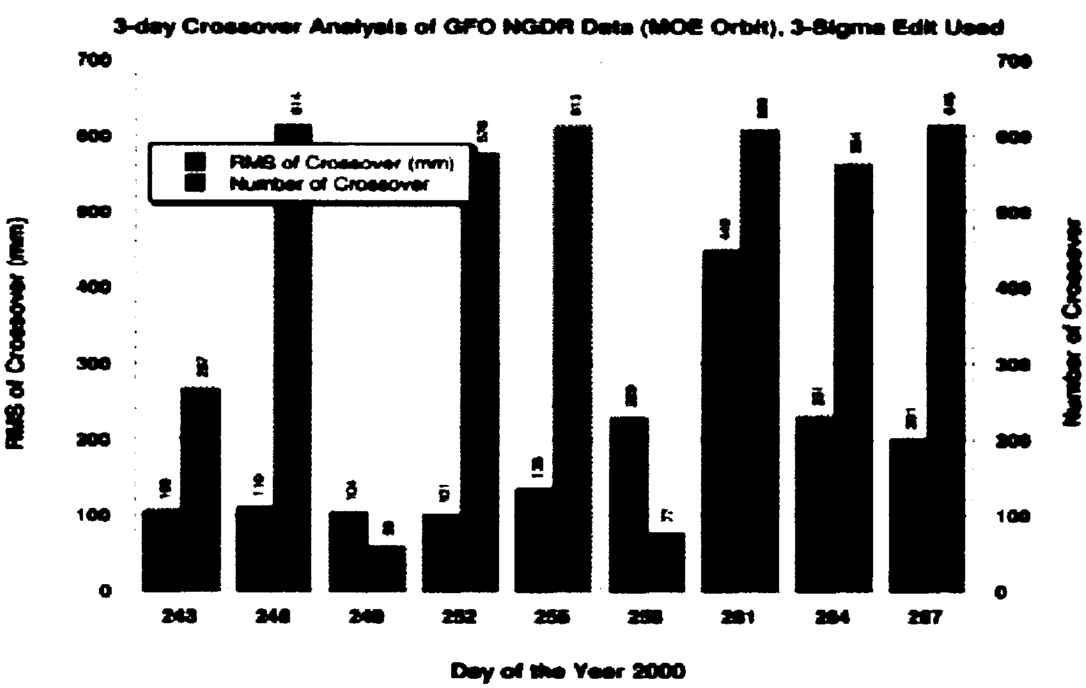

Figure 2

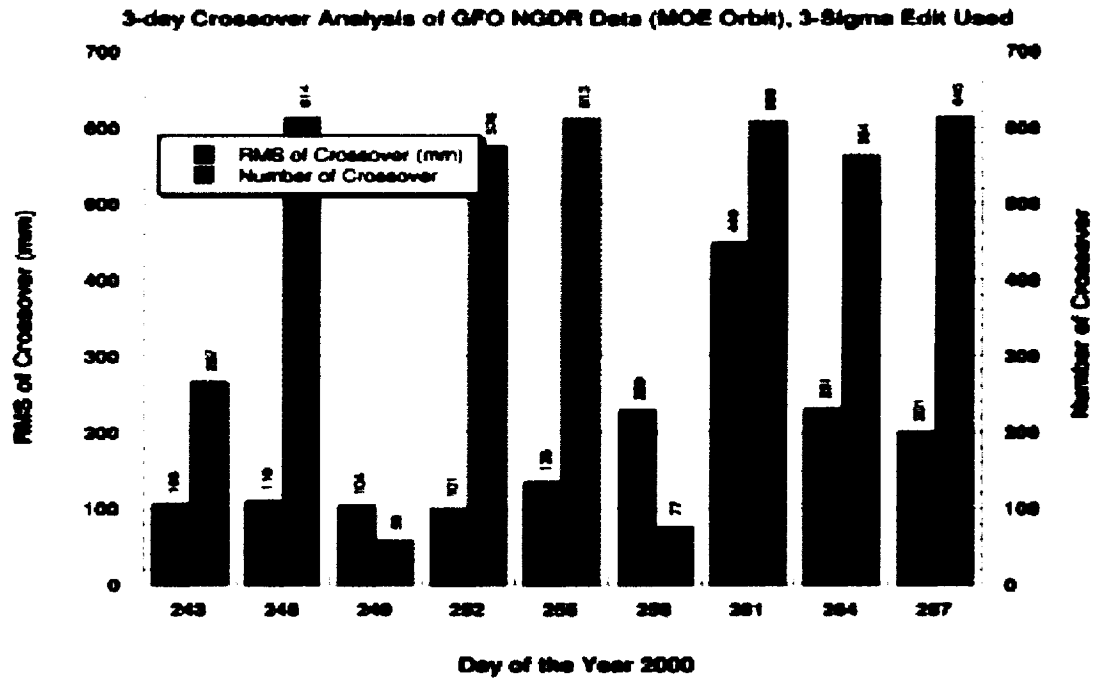

Figure 3

After adjustment of bias, tilt and 1-CPR, we estimated error for the MOE/SLR orbits. The results are as follows: ocean-wide crossovers, 8.6 cm rms for days 243-259 of year 2000, 9.7 cm rms for days 260-276, 3000 km arcs (25S-5N); 3.9 cm rms for days 243-259, 4.4 cm rms for days 260-276; 1000 km arcs (15S-5S), 1.3 cm for days 243-259, 2.3 cm for days 260-276. For OODD (Doppler) orbits, 1000 km arcs (15S-5S) adjustment gives: 1.8 cm rms for days 243-259 and 1.8 cm for days 260-276.

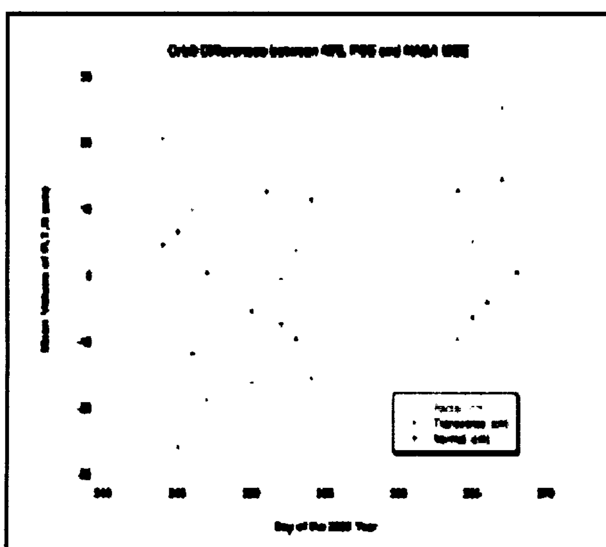

Figure 4

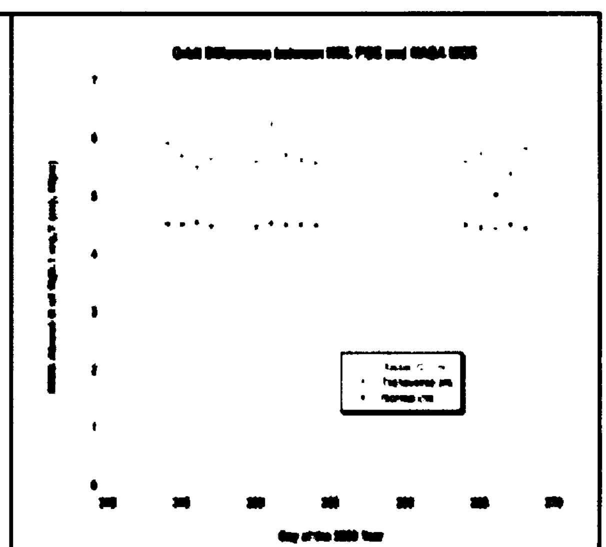

Figure 5

We did trajectory comparisons between NRL (24-hour SLR) and GSFC MOE (SLR & Doppler, delivery time uncertain) orbit. Figures 4 and 5 show the results.

The University of Texas has been working on verification of GFO yaw model and center of mass corrections of GFO SLR tracking. We have also assessed the orbit accuracy using different gravity field models. Preliminary results indicate that the TEG-3 model is better than EGM96 for GFO orbit determination and altimeter data analysis. More detailed analysis is continuing.

ALTIMETER DATA VERIFICATIONS

We conducted an effort in the verification of the available GFO-1 radar altimeter data from the NOAA Interim Geophysical Data Record (IGDR) and NAVY NGDR. We have verified media and geophysical corrections for the GFO IGDR and NGDR (ionosphere, dry and wet troposphere, significant wave height, automatic gain control, attitude, attitude SWH correction, solid Earth and ocean tides, timing, and USO drifts). We provided preliminary estimates of the GFO absolute bias, time bias, and sea state bias, and an assessment of the radiometer delay computed using the GFO microwave radiometer.

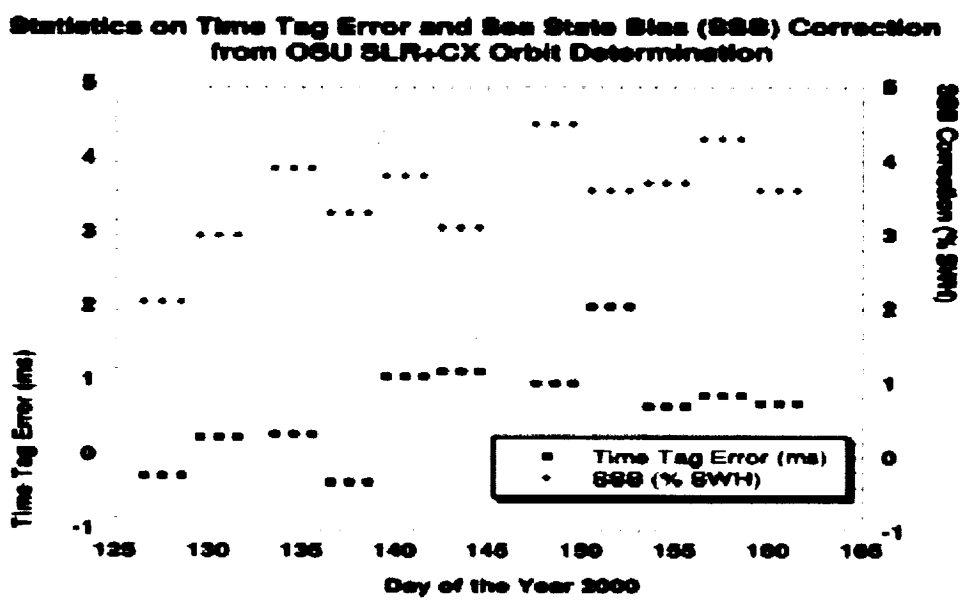

Figure 6

Using SLR tracking data and altimeter crossover data, we estimated and assessed the accuracy of the NOAA IGDR and NAVY NGDR time tag. For most of the IGDR and NGDR data, the preliminary time bias estimated is less than 2 ms (Figure 6). The sea state bias estimate is about 3.5% (3.0% to 4.3%) of SWH (Figure 6). Preliminary study indicates that GFO-1 altimeter range bias is approximately zero relatives to the T/P mean sea surface after sea state biases were corrected. Due in part to the analysis by John Lillibridge, David Hancock and others at Ball, the USO drift correction algorithm is believes to have been implemented correctly. USO drift range correction is 15 cm since launch, which seem large and is perhaps a concern. Preliminary results indicate GFO offsets with the TOPEX SWH and σ_0 values (Figure 7).

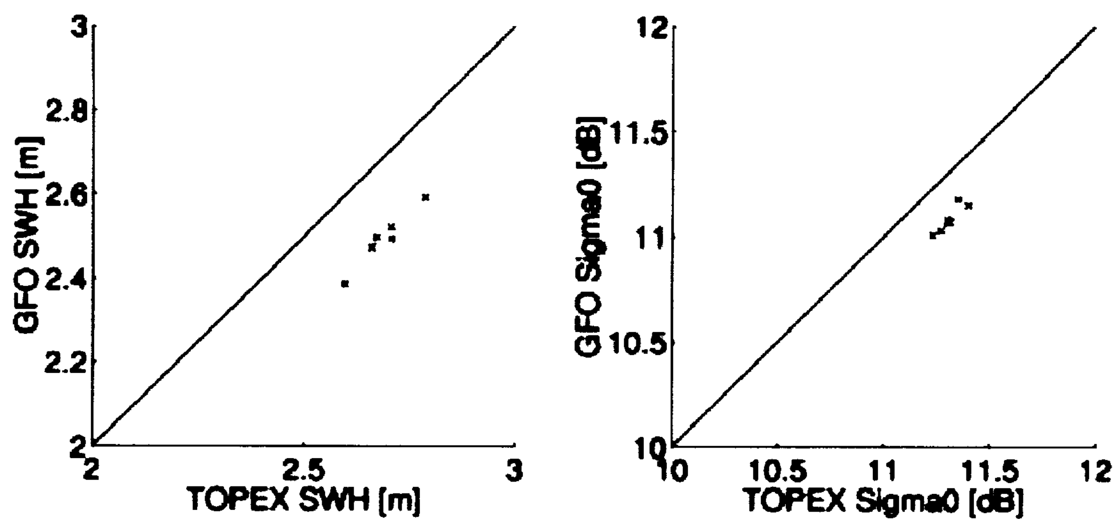

Figure 7

GFO Microwave Radiometer measured water vapor delays were compared with atmospheric model delays (i.e., NCEP and NVAP) and TOPEX and ERS-2 Radiometer data. An offset of ~3 to 5 cm exists between GFO MWR and models and ERS-2 and TOPEX data before the algorithm fix by C. Ruf at Univ. of Michigan. After the algorithm fix, GMR-ERS2 gives -11±31 mm differences and NCEP-GFO gives -4±31 mm differences (Figures 8, 9 and 10).

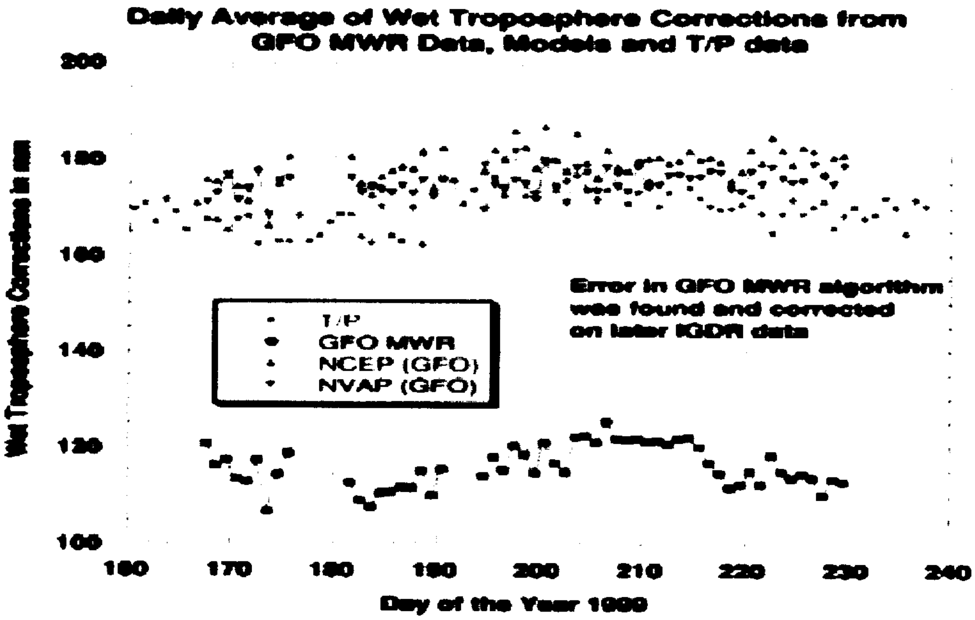

Figure 8

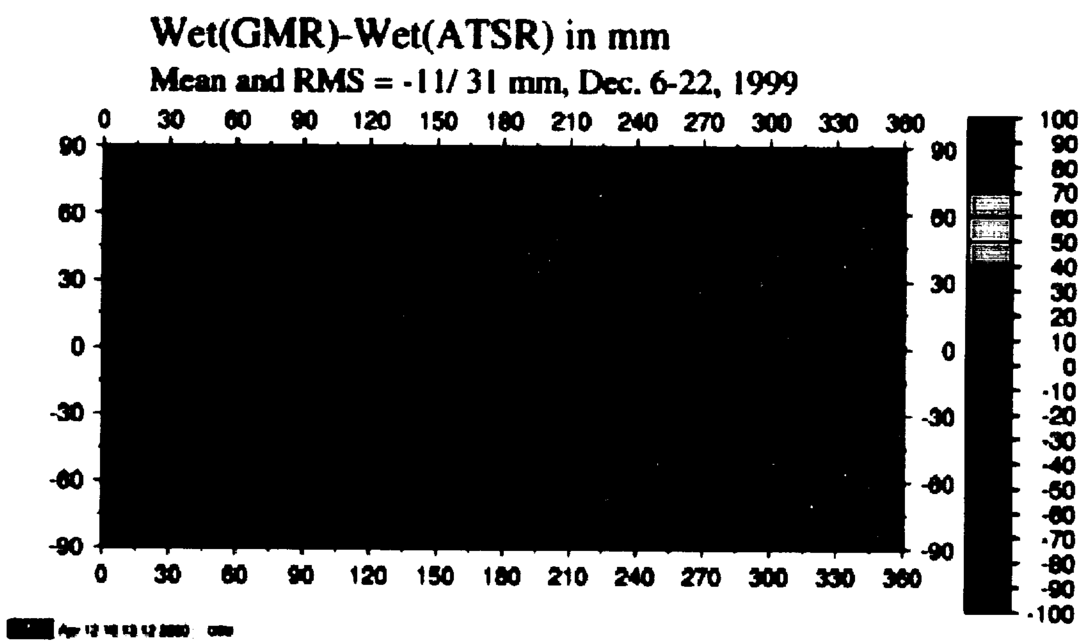

Figure 9

John Lillibridge and others (including our group) have uncovered a unrealistic sea level rise observed by the GFO data on the order of 3 cm over 60 days. We have provided an analysis, which indicated that GFO ionosphere model, IRI95, was the source of the problem. There is also a jump at the year 2000 (Y2K problem), uncovered by John Lillibridge.

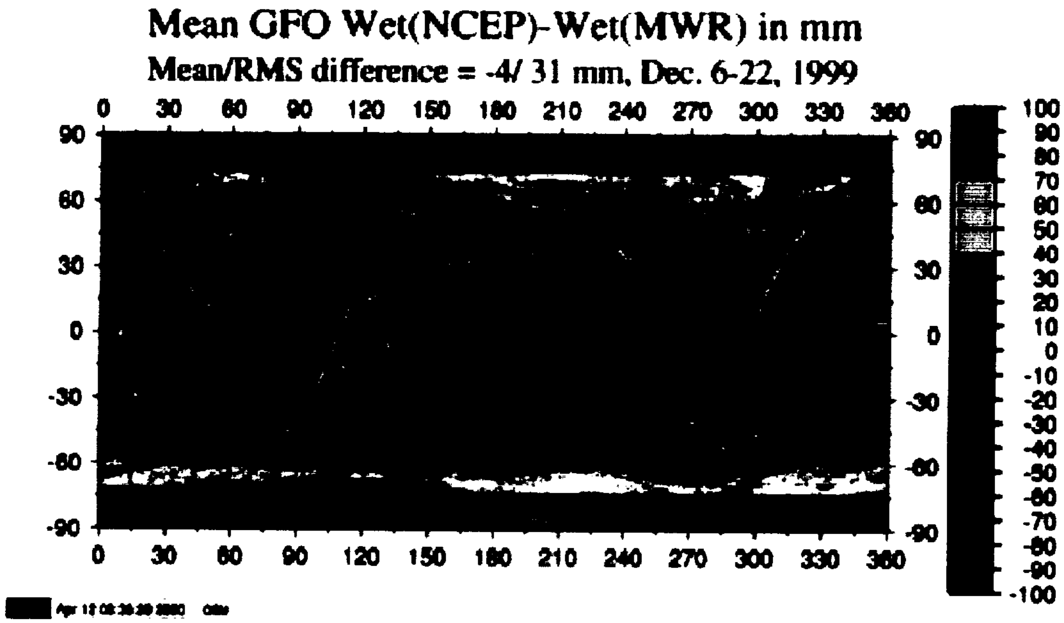

Figure 10

The GFO ionosphere correction is further studied by comparing with the TOPEX (ground truth) observed average ionosphere delay. Preliminary analysis indicates that the IRI95 is in part responsible for the apparent (unrealistic) global sea level rise of 3 cm per 2 months. The correlation coefficient between sea level change and ionosphere correction is 0.6. Comparison of IRI95 and CODE GIM (Global Ionosphere Map) gives ~2-4 cm rms during Cal/Val II time period and ~2 cm rms and <1 cm bias during the Cal/Val III time period (Figure 11).

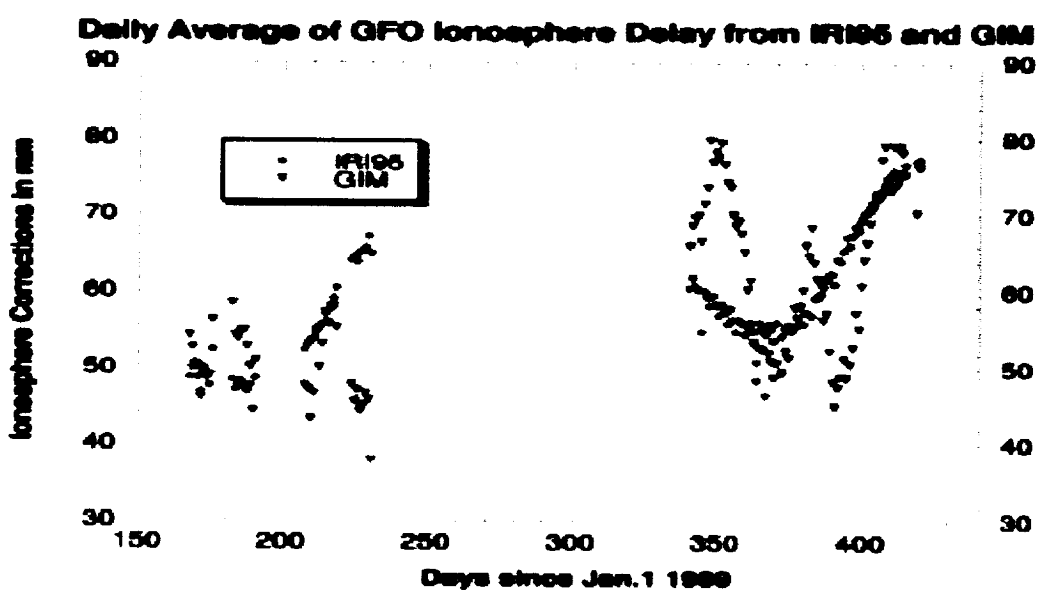

Figure 11

ESTIMATED NOISE OF GFO ALTIMETER DATA

The estimated noise of the uncorrected 1 Hz GFO data in the form of sea surface height measurements (orbital height subtracting the uncorrected altimeter measurement) over two regions of the ocean (Atlantic: 330^0E to 360^0E and 20^0S to 3^0N; and Pacific: 240^0E to 270^0E and 20^0S to 3^0N) is approximately 19 mm rms (Figure 12). The corresponding estimated ERS-2 SSH noise is 28 mm rms, and TOPEX SSH noise is 10 mm.

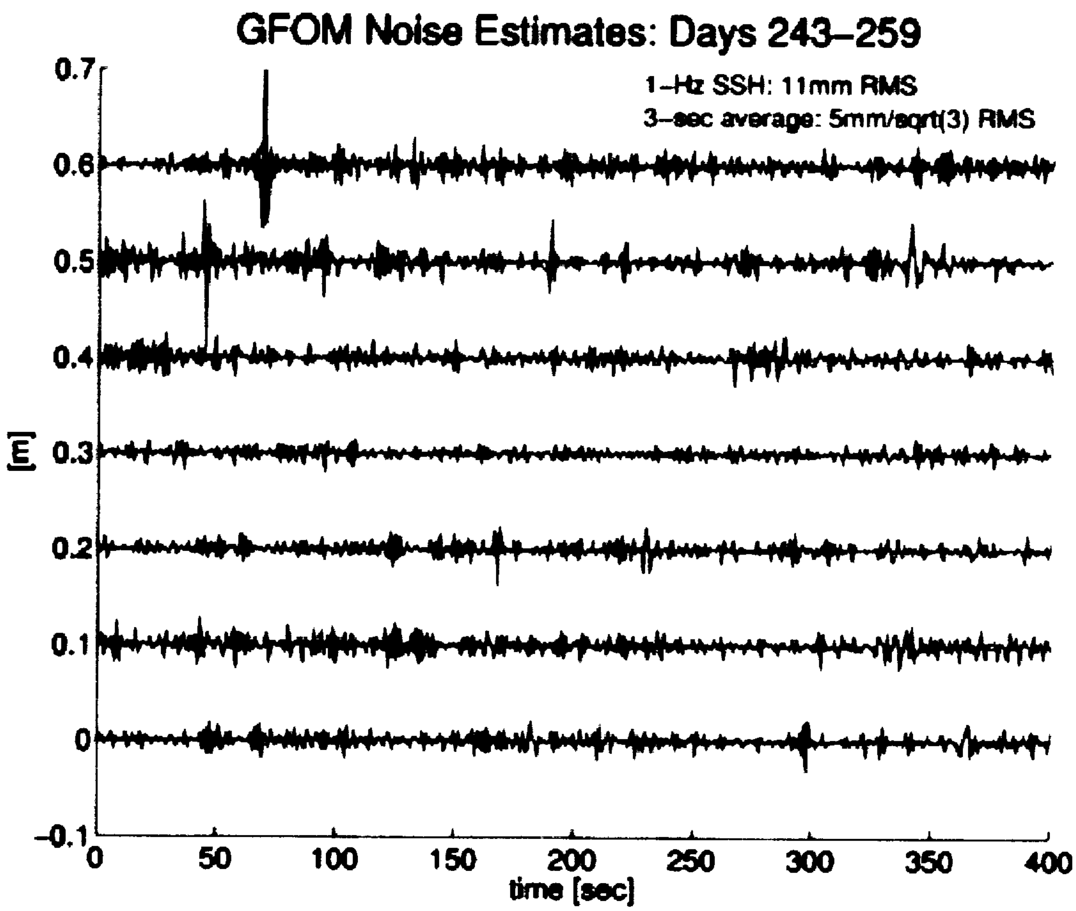

Figure 12

GPS BUOY CAMPAIGN AND ALTIMETER DATA VERIFICATION USING WOCE TIDE GAUGE DATA

On March 24 and 25, 1999, we made a GPS buoy campaign on Lake Michigan for GFO absolute calibration and verification on a March 24 GFO descending track. Unfortunately, because of the satellite drift, we were some 30 km away from actual GFO overpass.

With the cooperation of ILRS and the global SLR network, we have 13 stations tracking and 241 observations within 3 days from March 23 to March 25 for precise orbit determination. After correcting more than 2 seconds time tag error on IGDR data in that time period and using SLR and crossover data, we obtained a good orbit with 3.7 cm SLR rms and 7.7 cm crossover rms. We improved radar altimeter data, which is being used to calibrate with GPS buoy measurements. Preliminary kinematic GPS solution and GFO data analysis over Lake Michigan give a GFO range bias of 30 ± 42cm.

We also analyzed GFO altimeter data using 53 WOCE island tide gauge measurements. After improving altimeter data, we computed sea level change difference between GFO data and tide gauge data. The observed relative drift was inconclusive, as longer data span is needed. See Figure 13.

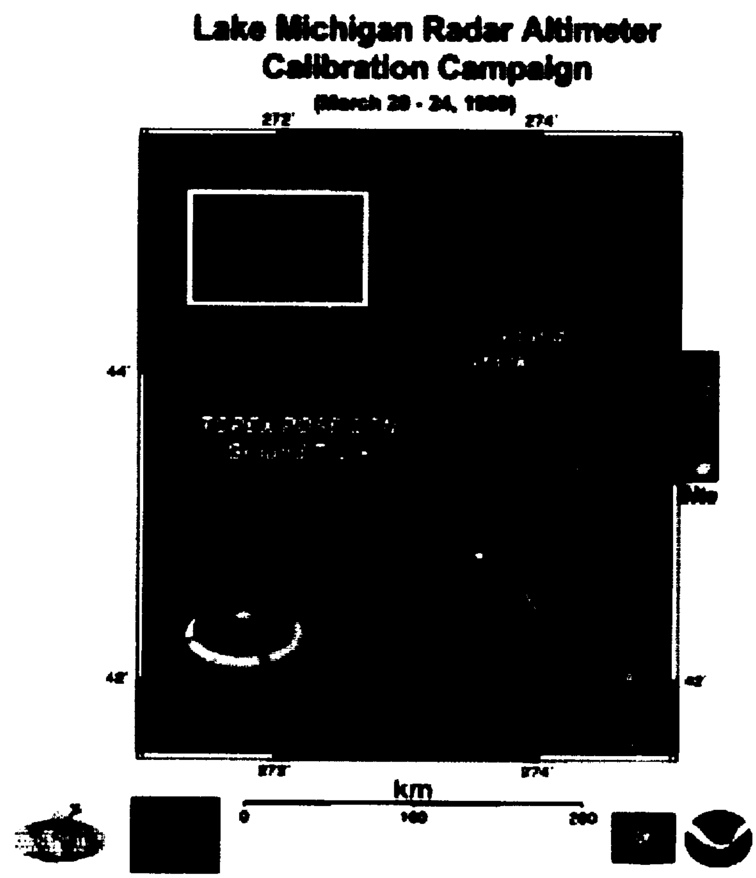

Figure 13

RELEVANT PRESENTATIONS/PUBLICATIONS

A list of relevant presentations to the investigation is provided as follows.

Lillibridge, J., C. Shum, R. Cheney, C. Zhao, Calibration/Validation results for Geosat follow-on, Spring AGU Meeting, Washington D.C. May 30-June 3, 2000.

Parke, M., C. Shum, K. Cheng, H. Tseng, P. Abusali, T. Urban, K. Key, J. Bodi, J. Ries, and J. Lillibridge, Preliminary verification of GFO sea surface height measurements, GFO Mission Data Validation Meeting, Penn State University, July 16, 1998.

Shum, C., C. Zhao and Y. Yi, GFO-1 sensor and data product verifications, GFO Calibration and Validation Report, The Ohio State University, November, 2000.

Shum, C., and C. Zhao, GFO-1 radar altimeter data product verifications, GFO Operational Evaluation meeting. U.S. Naval Observatory, Washington, D.C., July 20, 2000.

Shum, C., J. Finkelstein , C.Y. Zhao, J. Lillibridge, Y. Yi, and P.A. M. Abusali, Initial analysis of GFO-1 radar altimeter data, 25th General Assembly of the EGS in Nice, France, April 24-29, 2000.

Shum. C., Y. Yi, C. Zhao, M. Parke, K. Cheng, H. Tseng, D. Martin, and G. Mader, Preliminary results: TOPEX side B altimeter calibration campaigns, Jason SWT Meeting, St. Raphael, France, October 25-27, 1999.

Shum, C., Y. Yi, C. Zhao, M. Parke, K. Cheng, J. Lin, K. Snow, H. Tseng, D. Martin and G. Mader, TOPEX Side B Altimeter Calibration/Validation, First Calibration (Validation) Workshop on Topex Side B Altimeter, NASA/GSFC, April, 1999.

Shum, C., M. Parke, and P. Abusali, Preliminary assessment of GFO orbit and measurement accuracy, PORSEC 98, Qingdao, China, August 1998.

Zhao, C., C. Shum, Y. Yi, P. Abusali and J. Ries, Preliminary Verification Results of GFO Radar Altimeter Data, Report for GFO CAL/VAL Meeting, November 1999.

Zhao, C., D. Bilitza, C. Shum, S. Schaer, G. Beutler, and S. Ge, Evaluation of ionosphere models using dual-frequency radar altimeter measurements, Proc. COSPAR meeting, Warsaw, Poland, July 16-23, 2000.

Zhao, C., D. Bilitza, C. Shum, S. Schaer, G. Beutler and S. Ge, Evaluation of ionosphere models for radar altimeter applications, Adv. Space Res., in review, 2000.