Calibration Results of GFO

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Abstract. GFO has been operational since November 2000 and it's data products are available to the scientific community. This paper provides a summary of the GFO calibration and sensor validation results, and presents results of sensor performance evaluations and accuracy of both the near-real time and offline Geophysical Data Record data products.

Keywords. GFO, altimetry, orbit, media corrections, bias

1 Introduction

The first U.S. Navy GEOSAT Follow on (GFO) mission was launched on 10 February 1998 from Vandenberg AFB, and has been operational since November 2000. With an anticipated 8-year or more life, GFO is a DoD satellite mission managed by the Space and Naval Warfare Systems Command's (SPAWAR's) Meteorology and Oceanography (METOC) Systems Program Office (PMW 155) located in San Diego, California. The primary objective for the GFO Program is to develop an operational series of radar altimeter satellites to maintain continuous ocean observation for accurate global measurements of both mesoscale and basin-scale oceanography (GFO web site). GFO has undertaken extensive calibration and validation activities (Cal/Val I-IV) from June 1999–October 2000. Precise and near-real time orbit determination relies on satellite laser ranging and Opnet Doppler tracking, and GFO is now one of the operational tracking targets for the International Laser Ranging Service (ILRS) network. The IGDR and precise orbits are computed by NASA/GSFC. This paper provides a summary of the GFO calibration and sensor validation results, including verification and improvement for the precise orbit, and media, geophysical, and instrument corrections. These data products are produced at the U.S. Navy's NAVOCEANO Altimetry Data Fusion Center and NOAA's Laboratory for Satellite Altimetry. GFO's data products are available to the scientific community and are distributed by NOAA's Laboratory for Satellite Altimetry.

2 Precise Orbit Determination and Verification

2.1 Precise Orbit Determination

Shortly after launch, the onboard Turbo-star 16-channel GPS receivers failed to track more than one GPS satellite on both frequencies. NASA had paid for a laser corner cube retroreflector (LRA) for satellite laser ranging (SLR) to GFO. 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 alternative precise orbits using SLR and crossover data primarily for independent accuracy verification purposes. The average SLR residual is around 4 cm rms and crossover residual is about 8 cm rms during the calibration, validation and operational time periods. Figure 1 and 2 present two examples of the results. 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, which agrees with the independent GSFC orbit accuracy assessment using tuned gravity field models.

2.2 Verification of GFO Orbit Accuracy

We performed 3-day crossover analysis routinely and geometric orbit adjustments (bias and tilt and once per rev) for the Opnet Doppler orbits (OODD) and SLR MOE orbits (GSFC). Fig. 3 and 4 show some of the orbit accuracy assessment results.

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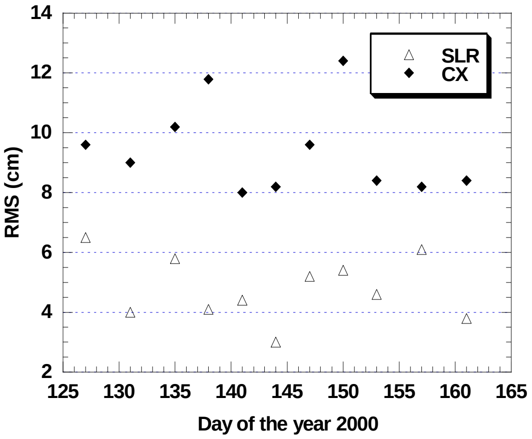

Fig. 1 Statistics on SLR and altimeter crossover RMS from OSU SLR+CX orbit determination, TEG3 gravity model used.

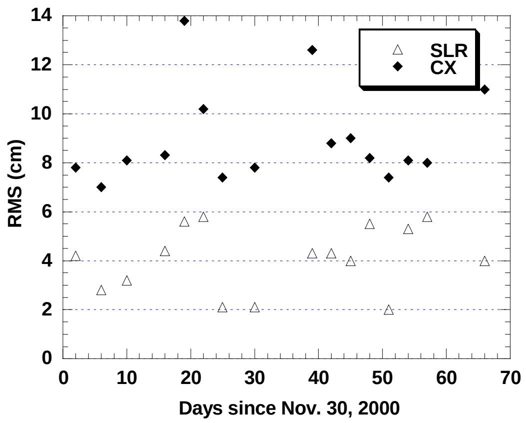

Fig. 2 Same as Fig.1 but for different time period

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.

We have also assessed the orbit accuracy using different gravity field models. Preliminary results indicate that the latest TEG-4 model is marginally better than others for GFO orbit determination and altimeter data analysis. Table 1 lists detail results.

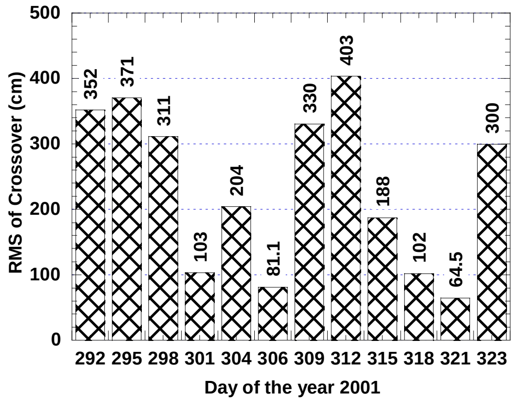

Fig. 3 3-day crossover analysis of GFO NGDR data (Doppler orbit), GFO operational cycle 19 and 20, 3 σ edit used.

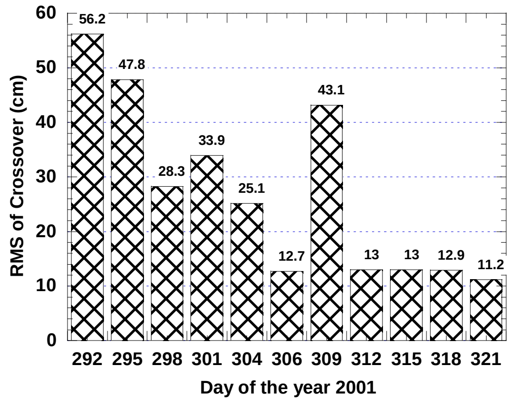

Fig. 4 Same as Fig.3 but for SLR MOE orbit

3 Altimeter Data Product 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 estimated the GFO altimeter absolute bias, time bias, and sea state bias, and made an assessment of the radiometer delay computed using the GFO microwave radiometer.

Table 1. Results of GFO orbit determination using different gravity models

Gravity Model	CX RMS (cm)	SLR RMS (cm)
JGM3	13.5	6.0
EGM96	12.7	5.6
TEG3	12.1	4.3
TEG4	12.2	3.3
PGM2000A	12.7	5.4
PGS7727	11.5	4.5
GRIM5C1	15.2	6.2

3.1 GFO Altimeter Bias

Using SLR tracking data and altimeter crossover data, we estimated and assessed the accuracy of the NOAA IGDR and NAVY NGDR time tag, sea state bias and altimeter absolute bias. For most of the IGDR and NGDR data, the preliminary time bias estimated is less than 2 ms (Figure 5 and 6). The sea state bias is estimated using one parameter model (dependence on SWH) and some of results are shown in Figure 5 and 6. Preliminary study indicates that GFO-1 altimeter range bias is approximately –3cm relative to the T/P mean sea surface after sea state biases were corrected (see Figure 5 and 6 for some of results).

3.2 USO Drift and SWH Offset

Due in part to the analysis by John Lillibridge, David Hancock and others at Ball Aerospace, the USO drift correction algorithm is believed to have been implemented correctly. USO drift range correction is 15 cm since launch, which seem very large and is perhaps a concern (Lillibridge et al. 2000). Preliminary results indicate GFO offsets with the TOPEX SWH and σ_0 values (Figure 7).

3.3 Media and Geophysics Corrections

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. Detail results of GFO-NCEP are listed in the Table 2.

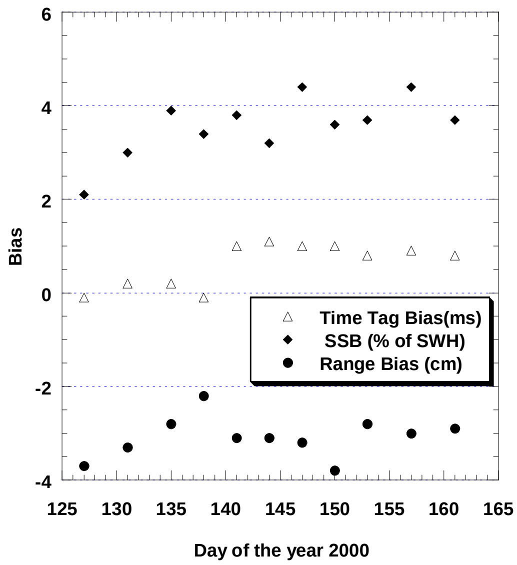

Fig. 5 Statistics of GFO altimeter data time tag error, sea state bias (SSB, % of SWH) and absolute range bias relative to TOPEX mean sea surface

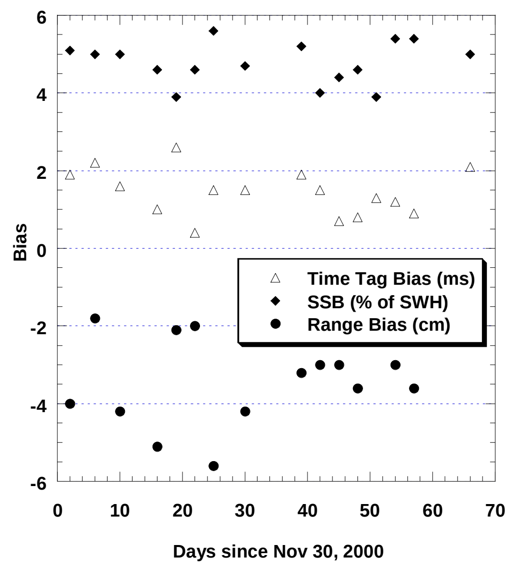

Fig. 6 Same as Fig.5 but for different time period

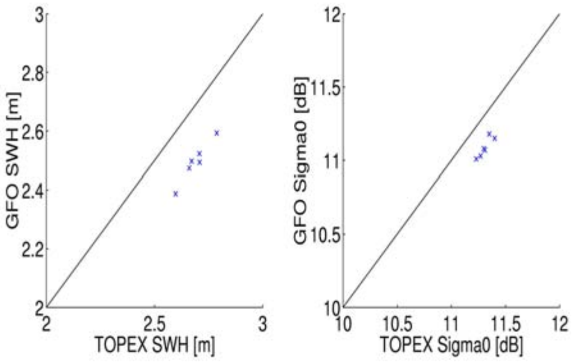

Fig. 7 GFO SWH and σ_0 offset with TOPEX

Table 2. GFO wet troposphere correction differences between GFO MWR (measured water vapor) and NCEP model

GFO operational cycle	MWR-NCEP (mm)	
	mean	rms
2(Jan 3-19,2001)	1.6	25.7
6(Mar 12-28, 2001)	3.5	24.2
8(April 15-may 1, 2001)	3.6	25.3
9(May 2-18, 2001)	2.1	24.8
13(July 9-25, 2001)	2.3	25.0
15(Aug 12-28, 2001)	2.0	25.4
17(Sept 15-Oct 1, 2001)	0.10	24.7
20 (Nov 5-21,2001)	-0.45	24.8

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 in the summer of 1999 (Lillibridge et al. 2000). We have provided an analysis, which indicated that GFO IGDR ionosphere model, IRI95, was the source of the problem. 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. Table 3 gives a comparison result of IRI95 and other models, including CODE GIM (Global Ionosphere Map).

Table 3. Comparison results of different ionosphere models for GFO (Data: Dec 1999-May 2001)

Unit: mm, mm/year	JPL GIM-CODE GIM	IRI95-CODE GIM	IRI2001-CODE GIM	IRI95-IRI2001
Data percentage of differences within ±30	95.8	79.1	78.7	98.0 within ±10
Mean	-2.5	-11.5	-13.3	1.8
RMS about 0	14.8	34.8	31.0	3.8
Relative drift	-1.1	-1.9	-1.4	-0.4

3.4 GFO Altimeter Noise

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. The corresponding estimated ERS-2 SSH noise is 28 mm rms, and TOPEX SSH noise is 10 mm.

3.5 GFO Absolute Calibration with GPS Buoy

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.

3.6 GFO Ground Track

GFO mission was designed to retrace the Geosat Exact Repeat Mission (ERM) ground track to +/-1 km. We made a ground track comparison between GFO and Geosat ERM over Lake Michigan and in the equatorial region. We found that the GFO ground track repeat control is within ±1 km at the equator. However, the GFO ground track offsets more with the Geosat ERM ground track away from the equator, due primarily to variations of the Geosat orbit inclination. In other words, GFO tracks are not exactly overlaying on Geosat ERM tracks primarily because of inclination differences between the two orbits.

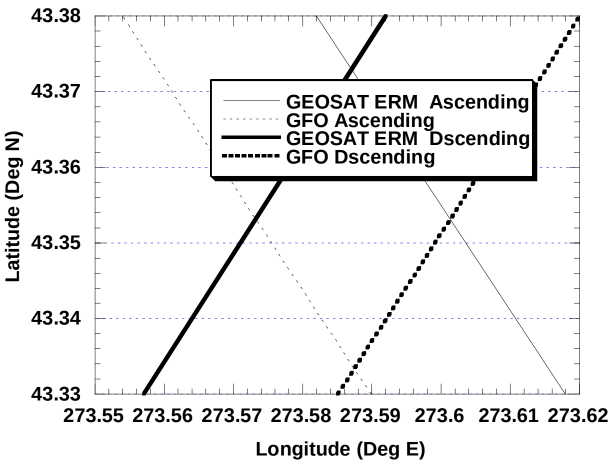

Fig. 8 GFO ground track offset GEOSAT ERM track over Lake Michigan

4 Conclusions

We have gone through four times GFO calibration/validation cycle and are working on GFO products. Extensive work of verification of the GFO orbit and geophysical data record measurements are done. Our preliminary results indicate that (1) the 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 ~7-40 cm and Operational Doppler orbit accuracy is ~40-300 cm. After bias and tilt adjustment (1000 km arc), estimated Doppler orbit accuracy is ~1.2-6.5 cm rms and MOE accuracy ~1.0-2.3 cm; (3) Time bias is insignificant with 0-2 ms. Sea state bias is ~3.5-4.7% of SWH. Estimated GFO absolute range is 3 cm short w.r.t. TOPEX mean sea surface. (4) The geophysical and media corrections are in general fine. Wet troposphere correction has less than 1cm bias and ~3 cm rms compared with NCEP model and ERS-2 data. Use of GIM and IRI95 provide ionosphere correction accurate to 2-3 cm rms during medium to high solar activities; (5) 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. (6) GFO ground track offsets GEOSAT ERM track.

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