Operational and Precise Orbit Determination for Geosat Follow-On Altimetry

John L. Lillibridge [1], Nikita P. Zelensky [3], Frank G. Lemoine [2], Brian D. Beckley [3], Yuchan Yi [4]

[1] *NOAA Laboratory for Satellite Altimetry, 1315 East-West Hwy. #3620, Silver Spring, MD 20910-3282*

[2] *Space Geodesy Branch, Code 926, NASA Goddard Spaceflight Center, Greenbelt, MD 20771*

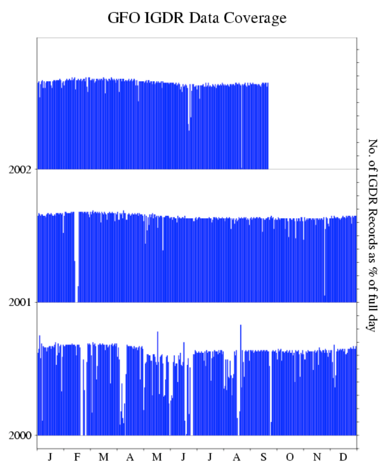
[3] *Raytheon ITSS Corporation, Greenbelt, MD 20771*

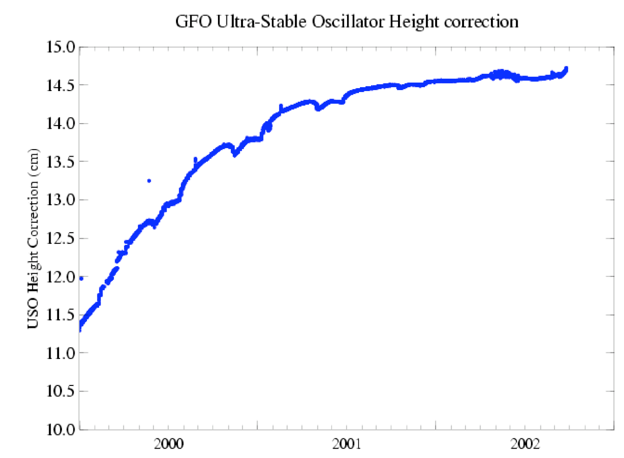
[4] *Laboratory for Space Geodesy and Remote Sensing Research, Ohio State University, Columbus, OH 43210*

ABSTRACT - The U.S. Navy's GEOSAT Follow-On spacecraft (GFO-1), launched in early 1998, began continuous radar altimeter coverage of the oceans in 2000. After an extensive series of calibration campaigns in 1999 and 2000, the satellite was accepted by the Navy on November 29, 2000. GFO supplements the altimetry data from TOPEX/POSEIDON and ERS-2 (and their successors JASON-1 and ENVISAT), by providing a different synoptic sampling of the oceans with its 17-day repeat cycle. Altimeter crossover analysis suggests that GFO is capable of "cm-class" altimetry, with orbit errors remaining the largest contributor to the sea surface height error budget. Satellite laser ranging (SLR), especially in combination with altimeter crossover data, offers the only means of high- quality precise orbit determination, due to the failure of the GPS tracking system on board GFO. SLR tracking is augmented by the operational Opnet/Tranet Doppler tracking system. These data have been used to tune the gravity field model and satellite macro-model (a 3-D representation of the spacecraft geometry and surface properties) used in the orbit determination software. Near real-time medium precision orbits (MOEs) are generated at GSFC within 72 hours and (in the absence of maneuvers) have radial orbit errors of 10 cm (1 σ) or less. These preliminary orbits are suitable for mesoscale studies where short-arc orbit error removal does not severely impact the sea surface height signals. Beginning in August, 2001 GSFC began releasing Precision Orbit Ephemeris (POE) data for use on the science-quality NOAA GDR and NASA Pathfinder Project. The POE orbits are more accurate than the MOEs, with orbit errors of 5 cm (1 σ) or less. Geophysical validation of the sea surface heights is performed by comparisons with in situ tide gauge data as well as height fields from contemporaneous altimetry missions. In this paper, recent developments will be discussed, including GFO GDR production for the year 2000 (Cycles 37-54, augmenting the existing data for Cycles 55-80), results of an improved "direct" sea state bias estimation, evaluation of a new GSFC gravity field model for orbit determination, and aspects of the ongoing GFO validation effort.

Mission History and Status

- Launched February 10, 1998 - nominal 8-year lifetime.
- GPS system failure necessitated laser tracking for precise orbit determination and external time-tagging unit
- Precision timing provided by ground-based unit, installed at NAVSOC in June, 1999
- CPU resets of both on board processors hampered operations until software patched in November, 1999
- Navy accepted GFO on November 29, 2000 - good data return during 2000 and excellent return in 2001-2002
- Large initial drift in Ultra-Stable-Oscillator has stabilized since 2001
- NOAA GDR's based on NASA POE orbits available on DVD-ROM: Jan. 2000 - Jan. 2002 and beyond...
- GFO collinear data now available on NASA/GSFC Ocean Pathfinder web site: http://iliad.gsfc.nasa.gov.

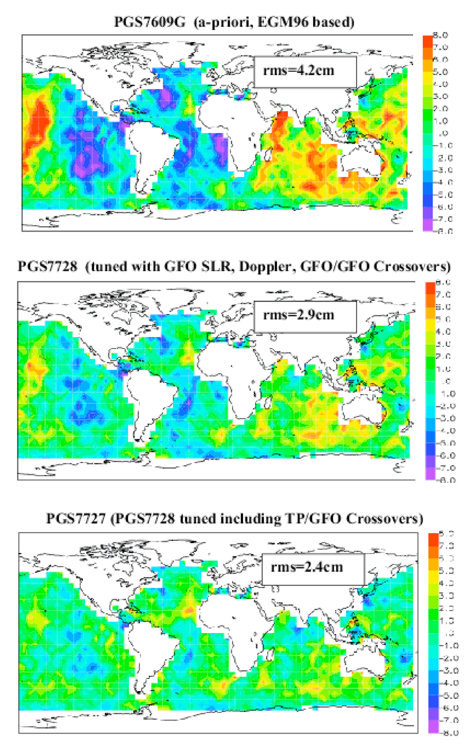




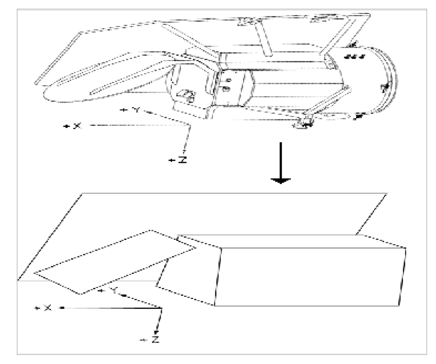
Gravity Field & Satellite Macro Modeling

gravity field	radial orbit error projected from 70x70 gravity covariance (cm)	data RMS (cm) combined results over five 10-day arcs			
		TP crossover	TP/GFO crossover	GFO crossover	GFO SLR
JGM3	4.97	6.17	8.45	8.51	7.42
EGM96	2.61	6.14	7.71	8.27	6.97
PGS7609G [1]	2.61	6.16	7.74	8.26	6.75
PGS7728 [2]	1.66	6.14	7.17	7.68	5.64
PGS7727 [3]	1.31	6.13	7.02	7.59	5.53

1. PGS7609G = EGM96 + TDRSS tracking of GRO, XTE, TRMM, ERBS
2. PGS7728 = PGS7609G + GFO SLR/Doppler + GFO/GFO crossover
3. PGS7727 = PGS7728 + TOPEX/GFO crossover



- NASA/GSFC has developed tuned GFO gravity models
- Geographically correlated orbit error is reduced as tuned models are improved
- Macro modeling is constrained to realistic surface properties values, but still aids precise orbit determination
- Remaining orbit errors mainly due to unmodeled non-conservative forces (solar radiation pressure and drag)
- Recent analyses reveal correlation between residual force model errors and the orbit's beta-prime value
- Reduced Dynamic orbit solutions (next panel) use additional empirical parameters to better model forces

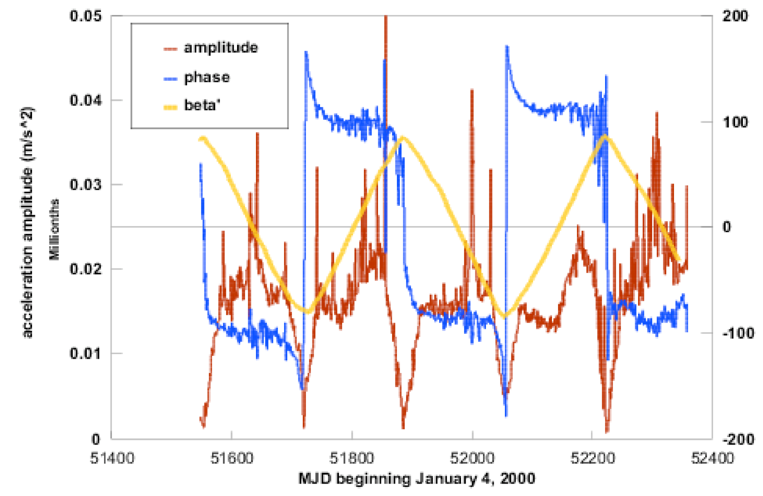


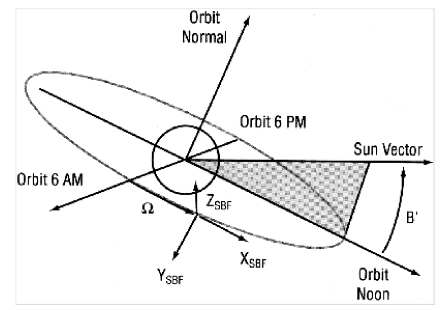
Acceleration due to radiation pressure on a flat plate:

$$\Gamma = -\frac{\Phi A \cos\theta}{Mc}\left[2(\delta/3 + \rho\cos\theta)\mathbf{n} + (1-\rho)\mathbf{s}\right]$$

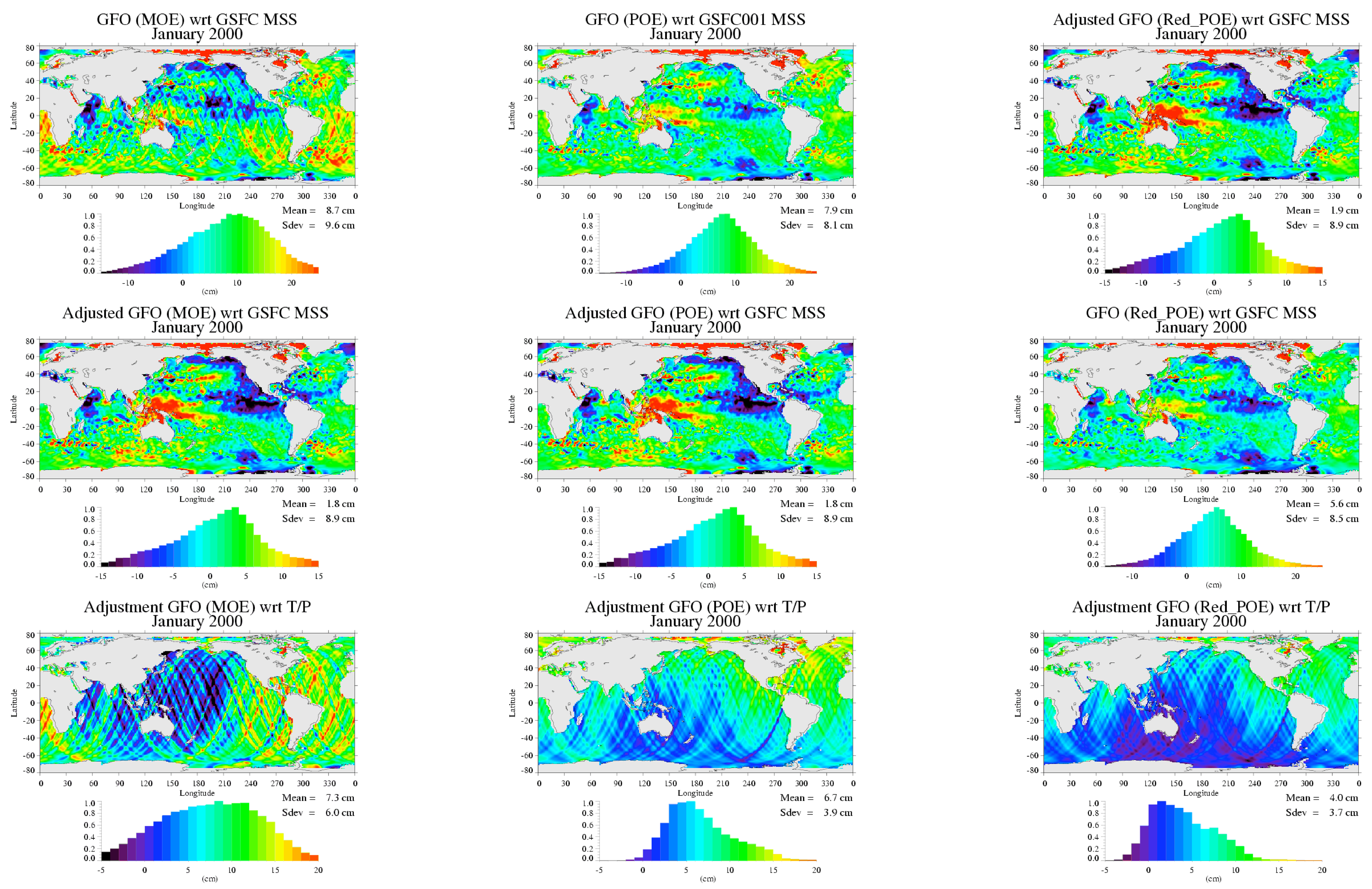
where
- Γ = acceleration (m/s²)
- Φ = radiation flux from source
- A = surface area of flat plate (m²)
- θ = incidence angle (surface normal to source)
- M = satellite mass (m)
- c = speed of light (m/s)
- δ = diffuse reflectivity
- ρ = specular reflectivity
- **n** = surface normal unit vector
- **s** = source incidence unit vector

* are the adjustable macro model parameters

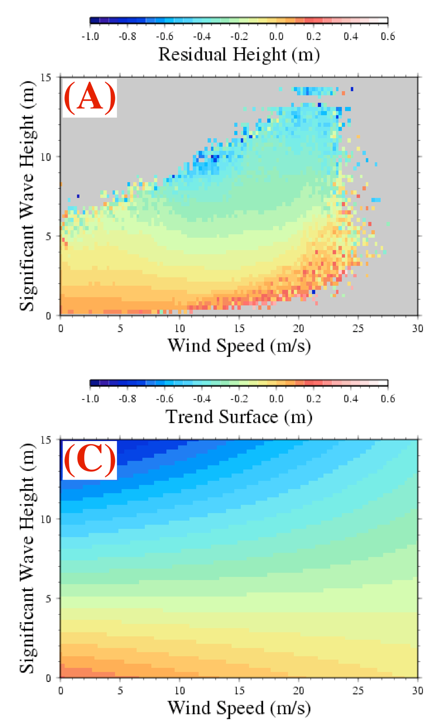




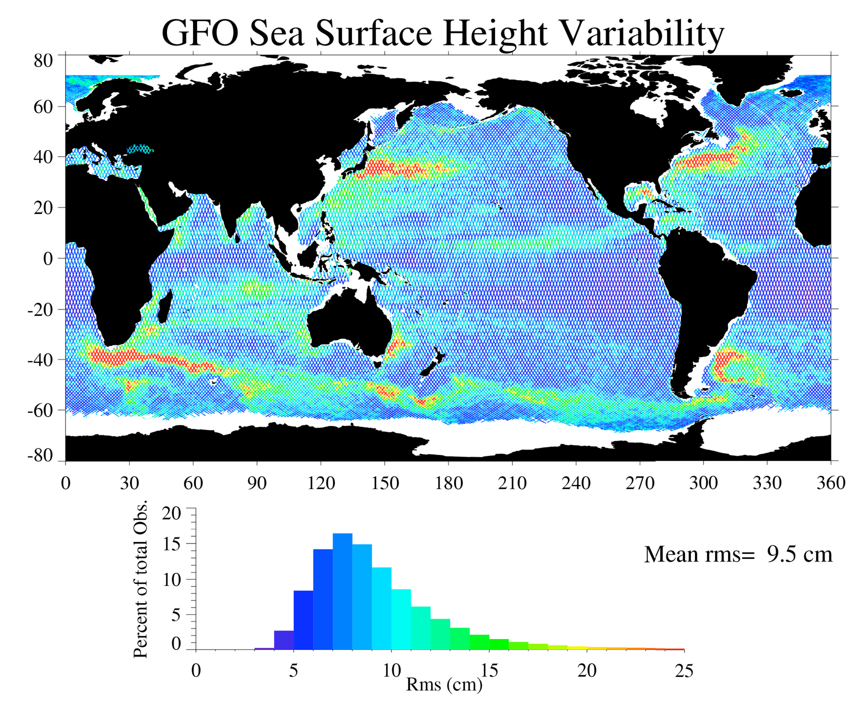
GFO Orbit Improvement: MOE > POE > Reduced Dynamic

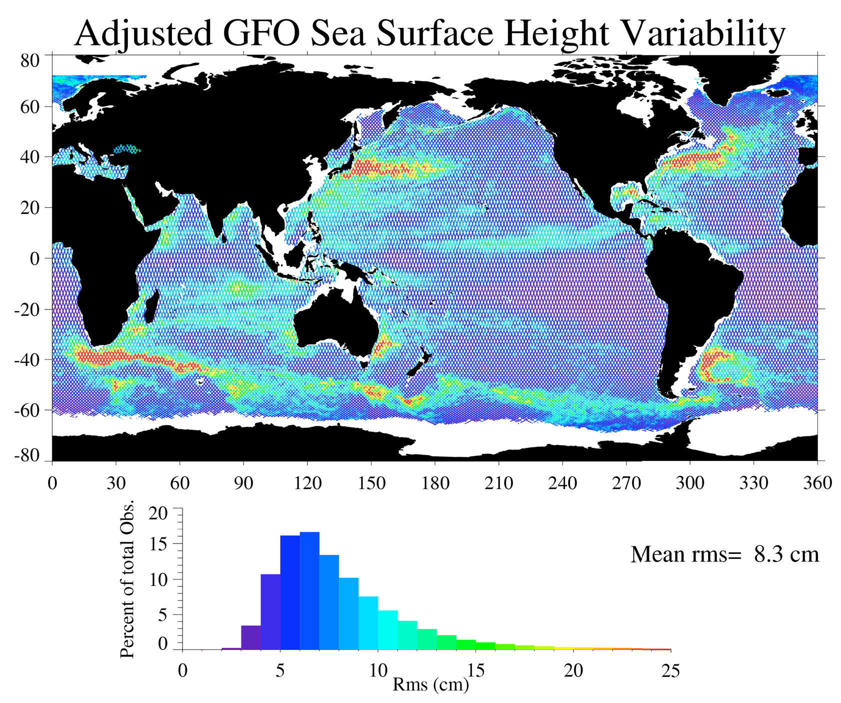


Hybrid Sea State Bias Model for GFO



- Sea State Bias is one of the largest remaining error sources
- Utilize Vandemark et al.'s Direct Estimation Technique:
  - Compute SSH residuals relative to mean sea surface
  - All corrections *except* SSB are applied
  - Average in .25 m/s x .25 m bins in wind/wave space
  - Height residuals reveal true SSB correction **(A)**
- Extend model using a new hybrid method:
  - Fit low order polynomials in wind/wave to residuals
  - Weighting based on number of observations in bins **(B)**
  - Polynomial fit covers the entire wind/wave domain **(C)**
  - A blend of residuals **(A)** and polynomial **(C)** yields the final hybrid model **(D)**





Summary

- Geosat Follow-On altimetry data are now available on NOAA DVD's and from NASA Ocean Pathfinder web site
- Improved gravity and satellite macro models, combined with Reduced Dynamic orbit determination, greatly reduces residual orbit error
- GFO/TOPEX crossovers are used to adjust GFO into TOPEX frame - RSS differences in variability maps consistent with 5 cm GFO orbit error
- A new hybrid sea state bias model is being developed for GFO, which will further improve sea surface height accuracy