Towards the GEOSAT Follow-On Precise Orbit Determination Goals of High Accuracy and Near-Real-Time Processing

Frank G. Lemoine
*Planetary Geodynamics Laboratory*
NASA GSFC, Greenbelt, Maryland USA

Nikita P. Zelensky, Douglas S. Chinn, Brian D. Beckley
*SGT Inc.*
Greenbelt, Maryland USA

John L. Lillibridge
*Laboratory for Satellite Altimetry, NOAA*
Silver Spring, Maryland USA

AIAA Paper 2006-6402
AIAA/AAS Astrodynamics Conference, Keystone, Colorado
August 21-24, 2006
Outline

I. Introduction
II. Data
III. Description of GFO POD System
IV. Gravity Modelling Improvements
V. Macromodel
VI. Medium precision orbit (MOE) results
VII. Precise orbit (POE) results.
VIII. Summary
GEOSAT-FOLLOW-ON (GFO-1)

Manufactured by: Ball Aerospace for the US Navy.

Orbit:
- Altitude: 784 km
- Eccentricity: 0.0008
- Inclination: 108.04°
- Arg. of perigee: 90.5°
  (frozen orbit)

Repeat Period: 244 revs in 17 days.

Payload:
- Radar Altimeter
- Water Vapour Radiometer
- SLR Retroreflector
- Doppler Beacon
- GPS antenna (not operational)

NAVSOC: Operates s/c.
NASA: Coordinates SLR tracking with ILRS. Computes daily medium precision and precise orbits.
NOAA: Distributes altimeter data (IGDR and GDR)
Altimeter Measurement Schematic
Altimeter range measurement accuracy depends on orbit quality.

In light of the failure of GPS on GFO, can the other GFO tracking systems (SLR, Doppler, Altimeter) deliver sufficient data to meet POD requirements, especially since GFO altitude (784 km) is more challenging than Topex/Poseidon altitude (1336 km)?

Can SLR+Doppler data be used to compute operational orbits (latency of < 24 hrs)?

How do we measure orbit accuracy?
Satellite Laser Ranging

Up to 40 stations worldwide operate under the aegis of the International Laser Ranging Service (ILRS)
URL: http://ilrs.gsfc.nasa.gov/

The best stations deliver ranging accuracy of a few mm.

Greenbelt, Maryland, USA

Mt. Stromlo, Canberra, Australia
ILRS NETWORK in 2005
### Number of SLR Passes for GFO, January 2005 to March 2006

<table>
<thead>
<tr>
<th>Stations (36 total)</th>
<th>percent passes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yarragadee (YARA)</td>
<td>15 %</td>
</tr>
<tr>
<td>NASA (MNPE, GRF1, MCDO)</td>
<td>11 %</td>
</tr>
<tr>
<td>(no HOLL7210)</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>74 %</td>
</tr>
</tbody>
</table>

![Bar chart showing the number of SLR passes for various stations including Yarragadee, NASA stations, and other stations.]
SLR Tracking History: January 2005 - March 2006
Doppler Data: Three stations: Guam, Point Mugu, California; Maine. Dual-frequency 150/400 Mhz. Noise 1.5 - 2.0 cm/s.

Altimeter Data: Use data from NOAA IGDR (Intermediate Geophysical Data Record). Form altimeter crossovers.

Altimeter Range Modelling for the GFO IGDR

<table>
<thead>
<tr>
<th>Component</th>
<th>Model/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean Tide</td>
<td>GOT00.2 (Topex derived tide model)</td>
</tr>
<tr>
<td>Earth Tide</td>
<td>Cartwright &amp; Eden (updated)</td>
</tr>
<tr>
<td>Dry Troposphere</td>
<td>NCEP</td>
</tr>
<tr>
<td>Wet Troposphere</td>
<td>GFO WVR or NCEP</td>
</tr>
<tr>
<td>Ionosphere</td>
<td>IRI95</td>
</tr>
<tr>
<td>Inverse barometer</td>
<td>$f$ (dry troposphere)</td>
</tr>
<tr>
<td>EM bias</td>
<td>3.8% SWH</td>
</tr>
</tbody>
</table>
GFO Altimeter Crossover Modelling

Sea Surface Variability (TP+ERS)

Editing Criteria
Bathymetry:
(Reject depth < 500 m)
Sea surface variability:
(Reject > 20 cm)
Max Residual:
(Reject > 20 cm)

Example of Crossover Data Distribution
GFO Precision Orbit Determination System

Near Real Time SLR POD

- **SLR Tracking Data (CDDIS)** hourly
- **Earth Orientation Parameters (IERS)** daily
- **Solar/Magnetic Flux (NOAA)** daily
- **Satellite Event Information** anticipated and actual time
- **SLR Station Antenna Offset (CDDIS)** actual/change
- **SLR Station Position / Velocity (ITRF)** annual

**Data Processing using GEODYN**

- **Data Import**
- **Data Editing and Orbit Determination modeling:**
  - satellite CoM, LRA offset
  - attitude
  - reference frame
  - satellite forces

**Orbit Verification**

- **Data Archival and Export**

**ORBIT**
Typical Processing Scenario

=> Import SLR Data and Doppler data by early afternoon (local time, or 17:00-18:00 UT). (SLR data delivered hourly to ILRS data centers)
=> Import IGDR altimetry data from NOAA (Lag of 48 hrs in data delivery).
⇒ Import updated Earth orientation parameter info (IERS) and solar flux/geomagnetic index info (NOAA/NGDC)
⇒ Process data with GEODYN Orbit Processor and Geodetic Parameter Estimation Program. Medium precision orbits (MOE’s) have five day sliding window.
⇒ By COB, or 21:00 to 23:00 UT, deliver MOE orbit to users at NOAA and the US Navy.
=> Send new ephemeris predict based on daily MOE orbit to SLR stations.
⇒ Precise orbits have a latency of ~3 weeks. (6-day arcs with 1-day overlaps).
=> Maneuvers introduce complications!!
## GFO Processing Standards

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity</td>
<td>PGS7727 (70x70)</td>
<td>PGS7777b (110x110)</td>
<td>GGM02C (120x120)</td>
</tr>
<tr>
<td>Time-variable Gravity</td>
<td>C20dot, C21dot S21dot</td>
<td>Same +zonal annuals</td>
<td>20x20 annuals from GRACE</td>
</tr>
<tr>
<td>Ocean Tides</td>
<td>Ray99 + pgs7727 resonant</td>
<td>Ray99 + pgs7777b resonant</td>
<td>GOT00.2 (20x20)</td>
</tr>
<tr>
<td>Solid Earth tides</td>
<td>k₂, k₃, + FCN</td>
<td>Same</td>
<td>IERS2003</td>
</tr>
<tr>
<td>Albedo/IR</td>
<td>Knocke/Ries, 1988</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>Drag</td>
<td>MSIS86</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>Parameterization</td>
<td>C_d/ 8hrs, opr along+cross/day</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>SLR coordinates</td>
<td>ITRF2000</td>
<td>ITRF2000</td>
<td>ITRF2000</td>
</tr>
<tr>
<td>Doppler coordinates</td>
<td>Tuned with CSR95L02</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>LRA offset</td>
<td>Estimated with CSR95L02</td>
<td>Same</td>
<td>Same</td>
</tr>
</tbody>
</table>
## GEOSAT Gravity Model Error

<table>
<thead>
<tr>
<th>Gravity model</th>
<th>projected radial orbit error (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JGM-3 (1995) Update to JGM-2 with TOPEX/GPS, Stella and other satellite data</td>
<td>49.8</td>
</tr>
<tr>
<td>EGM96 (1996) Model with new-satellite tracking data, altimetry, and surface gravity</td>
<td>26.2</td>
</tr>
<tr>
<td>PGS7727 (2001) computed from post-EGM96 pgs7609g using GFO SLR, Doppler, GFO and TOPEX-GFO altimeter crossover data</td>
<td>13.2</td>
</tr>
<tr>
<td>PGS7777b (2003) computed from pgs7727 using 87 days of Champ data and tracking data from GFO (SLR/Crossovers), TOPEX (SLR/DORIS), Jason (GPS), Envisat (SLR/DORIS), and other SLR data</td>
<td>10.0</td>
</tr>
<tr>
<td>GGM02C (2004) GRACE-based combination model</td>
<td>4.0 (Ries 2006)</td>
</tr>
</tbody>
</table>
GEOSAT Gravity Model
Radial Orbit Error

Radial Orbit Error, mm

Spherical Harmonic Order
GFO Macromodel
(Nonconservative Force Modelling)

Acceleration due to radiation pressure on a flat plate:

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

where
\( \Gamma \) = acceleration (m/s\(^2\))
\( \Phi \) = radiation flux from source
\( A \) = surface area of flat plate (m\(^2\))
\( \theta \) = incidence angle (surface normal to source)
\( M \) = satellite mass (m)
\( c \) = speed of light (m/s)
\( \delta \) = diffuse reflectivity
\( \rho \) = specular reflectivity
\( \mathbf{n} \) = surface normal unit vector
\( \mathbf{s} \) = source incidence unit vector

* are the adjustable macro model parameters
GFO LRA Offset Modelling
Estimate GFO LRA Offset using June ’98 SLR Data

<table>
<thead>
<tr>
<th>Description</th>
<th>Spacecraft body-fixed coordinates (cm)</th>
<th>SLR residuals (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>A priori CoM</td>
<td>89.7</td>
<td>0.8</td>
</tr>
<tr>
<td>A priori LRA offset</td>
<td>114.2</td>
<td>77.2</td>
</tr>
<tr>
<td>Estimated LRA offset</td>
<td>107.9</td>
<td>76.1</td>
</tr>
</tbody>
</table>

![Graph showing GFO Mean SLR Residuals and the LRA Offset](image)
SLR avg. RMS = 6.1 cm
Crossover avg. RMS = 7.3 cm

Due to latency issues, MOE arcs, have altimeter crossovers for first three days of each arc only.
GFO MOE Orbit Overlaps

MOE Orbit Statistics (cm) (Avg. RMS Overlaps)

<table>
<thead>
<tr>
<th>Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial</td>
<td>5.11</td>
</tr>
<tr>
<td>Cross-track</td>
<td>11.89</td>
</tr>
<tr>
<td>Along-track</td>
<td>23.82</td>
</tr>
</tbody>
</table>

(Only show statistics since we started routinely including crossovers in MOE orbits in February 2004)
SLR avg. RMS = 4.37 cm  
Crossover avg. RMS = 7.51 cm
## GFO POE RMS of Fit Summary

<table>
<thead>
<tr>
<th>Year</th>
<th>No. of Arcs</th>
<th>SLR (cm)</th>
<th>Crossovers (cm)</th>
<th>Doppler (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>67</td>
<td>4.68</td>
<td>8.41</td>
<td>1.74</td>
</tr>
<tr>
<td>2001</td>
<td>60</td>
<td>4.70</td>
<td>8.64</td>
<td>1.93</td>
</tr>
<tr>
<td>2002</td>
<td>66</td>
<td>5.39</td>
<td>8.12</td>
<td>2.10</td>
</tr>
<tr>
<td>2003</td>
<td>63</td>
<td>4.45</td>
<td>7.12</td>
<td>1.93</td>
</tr>
<tr>
<td>2004</td>
<td>62</td>
<td>4.49</td>
<td>6.80</td>
<td>1.75</td>
</tr>
<tr>
<td>2005</td>
<td>71</td>
<td>3.26</td>
<td>6.57</td>
<td>1.90</td>
</tr>
<tr>
<td>2006</td>
<td>34</td>
<td>3.18</td>
<td>6.58</td>
<td>1.54</td>
</tr>
<tr>
<td><strong>ALL</strong></td>
<td><strong>423</strong></td>
<td><strong>4.37</strong></td>
<td><strong>7.51</strong></td>
<td><strong>1.89</strong></td>
</tr>
</tbody>
</table>
GFO POE Orbit Overlaps

POE Orbit Statistics (cm) (Avg. RMS Overlaps)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial</td>
<td>1.84</td>
</tr>
<tr>
<td>Cross-track</td>
<td>11.56</td>
</tr>
<tr>
<td>Along-track</td>
<td>13.50</td>
</tr>
</tbody>
</table>
GFO Orbit Error Assessment from analysis of mean of the GFO sea surface variability

Before Empirical Correction

![Map showing orbit variability without correction with Mean RMS = 9.5 cm.]

After Empirical Correction with Topex/POSEIDON

![Map showing orbit variability after correction with Mean RMS = 8.3 cm.]

Orbit Error (relative to Topex) from RSS difference = 4.62 cm. Including Topex error (2.5 cm) => GFO orbit error = 5.25 cm. This assessment done with PGS7727 orbits early in mission.
Applications: Mapping of Ocean eddies
(Courtesy Anthony Liu & Brian Beckley, NASA GSFC)

Chlorophyll-a concentration from SeaWifs: May 8, 2000

Sea Surface Height anomaly map (Topex-only)

Sea Surface Height anomaly map (Topex+ERS2)

Sea Surface Height anomaly map (Topex+ERS2+GFO)
Applications: Lake level monitoring
(Courtesy Charon Birkett & Brian Beckley,
UMD & NASA GSFC;
Lake level monitoring funded by the USDA)

Lake Nasser Height Variations
TOPEX 10 Year Geo-referenced 10Hz Along Track Reference

Height variations (meters)

*** TOPEX/Poseidon historical archive
*** Jason-1 Interim GDR 20hz altimetry
Summary

• The GFO mission was rescued by the laser retroreflector and the demonstration of near-real-time POD using SLR, Doppler, and altimeter crossover data.
• MOE (medium precision) orbits are exported daily, with a probable radial accuracy of 15 to 20 cm.
• POE (precise) orbits are exported with a ~3-week latency with a radial accuracy of about 5 cm.
• GFO altimeter data have many scientific applications, especially in combination with data from other missions such as Jason-1, Envisat, ERS: mapping of eddies; near-real-time monitoring for hurricane forecasts; inland lake monitoring; detection (ex post facto) of the Indian Ocean tsunami.
• Further orbit modelling improvements are planned using GRACE gravity models, better CG modelling, improved drag and radiation pressure modelling.
GFO orbit and altimetry data availability

**Orbits**

**MOE**
1-day latency
anonymous ftp
dirac.gsfc.nasa.gov
cd pub/earth/gfo/moe

**POE**
3-week latency
anonymous ftp
dirac.gsfc.nasa.gov
cd pub/earth/gfo/poe

**Altimeter Data**

**IGDR**
2-day latency
authorized ftp (NOAA)

**GDR**
4-week latency
authorized ftp, and CDs (NOAA)

---

1 Frank Lemoine (NASA GSFC)
Frank.G.Lemoine@nasa.gov

2 John Lillibridge (NOAA)
John.Lillibridge@noaa.gov