The Geodetic Networks & Space Geodesy Applications

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From the launch of the first spaceborne altimeters, Precision Orbit Determination (POD) has been driven by the science goals of the geodetic altimeter missions...

GEOS-3, 1975
SEASAT, 1978
GEOSAT, 1985
TOPEX/POSEIDON, 1992
GFO-1, 1998

Jason-1, 2002
Jason-2, 2008
ENVISAT, 2002
CRYOSAT-2, 2010
The accurate knowledge of the spacecraft ephemeris in an accurate common reference frame is essential to the successful science derived from radar altimetry, particularly for global circulation and MSL studies...
Meeting mission POD accuracy requirements has depended on advances in each of the following areas:

1) Accurately modelling the forces acting on the satellite… **Force Modelling**

2) Accuracy and consistency of the reference frame as realized through the ground and space based tracking network … **Reference Frame**

3) Observing the satellite motion with high temporal sampling and accuracy … **Tracking Technology** and **Measurement Modelling**.
Orbit Determination

Onboard Tracking Systems
- LRR
- DORIS
- GPS

Surface Forces Modeling
- S/C Attitude

Atmospheric Modeling
- Ionospheric Propagation Delay
- Tropospheric Refraction
- Atmospheric Density

Orbit Determination
- Force Modeling
- Reference Frame
- Tracking Technology

Reference Frame
- International Terrestrial Reference Frame
- Horizontal plate and vertical site motion
- Geocenter motion
- Polar Motion and Earth Orientation

Geophysical Models
- Gravity Models
- Tide Models
- Time Variable Gravity
Errors in Models of the Earth’s Gravity Field were the largest source of orbit error for altimeter missions … Until the launch of TOPEX/Poseidon

<table>
<thead>
<tr>
<th>Model</th>
<th>Radial Calibration (cm)</th>
<th>SLR rms fit (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEM-L2: 1982</td>
<td>65.4</td>
<td>105.9</td>
</tr>
<tr>
<td>GEM-T1: 1988</td>
<td>25.0</td>
<td>31.4</td>
</tr>
<tr>
<td>GEM-T2: 1990</td>
<td>10.2</td>
<td>17.8</td>
</tr>
<tr>
<td>JGM-1S: 1991</td>
<td>6.0</td>
<td>7.7</td>
</tr>
<tr>
<td>JGM-2S: 1992</td>
<td>2.9</td>
<td>4.0</td>
</tr>
<tr>
<td>JGM-2: 1992</td>
<td>2.2</td>
<td>3.8</td>
</tr>
<tr>
<td>JGM-3: 1995</td>
<td>0.9</td>
<td>3.2</td>
</tr>
<tr>
<td>EGM-96 1997</td>
<td>0.8</td>
<td>2.8</td>
</tr>
</tbody>
</table>

The latest gravity models (e.g. GGM03S, EIGEN-GL04S) derived from GRACE data eliminate static gravity error on the TP orbit and allow us to model in detail the temporal gravity variations ….
Radiation Pressure Modelling is the largest source of orbit error after gravity model error … And remains a challenge.

**Radiative Fluxes**

Additional Fluxes Include:
- Incident flux reflections surface to surface
- Thermal radiation emission from surface to surface

**Micromodel**

- (Antreasian, 1992; Antreasian & Rosborough, 1992)

**Box-Wing model**

- (Marshall & Luthcke. 1994)
Impact of the Terrestrial Reference Frame on Mean Sea Level Determination

Regional TOPEX (1993-2002) Sea Surface Height Trend differences from direct impact of the ITRF2005 (GGM02C) minus CSR95 (JGM3) orbit differences. (from Beckley et al., 2007)

Space Geodesy Applications
September 26, 2011
The Geodetic Networks are the Key to Altimeter Satellite Mission Success

Satellite Laser Ranging (SLR)
DORIS Station Examples

Rothera, Antarctica
- ROTA 1993-2005
- ROTB 2005-2007
- ROUB 2007-present

Thule, Greenland
- THUB 2002-present

Arequipa, Peru
- AREA 1988-2001
- AREB 2001-2006
- ARFB 2006-present
GPS Satellite Constellation

JASON GPS Receiver

Examples: Ground Receivers

GPS, Kauai

GPS, Thule
TOPEX/POSEIDON (1992)...A giant leap forward in orbit accuracy ....... 2.5 cm orbit accuracy achieved early in the mission (c.f. Marshall et al., 1995)

SIGNIFICANT ADVANCEMENTS WERE DUE TO:

**Force modelling improvements:**
- Tide model (Ray et al. 1994)
- Improvements in the reduction of surface forces errors:
  - Box-wing model (Marshall and Luthcke, 1994)
  - Reduced dynamic solution from GPS (Bertiger et al., 1994)

**Advanced tracking technology:** SLR, DORIS, GPS, (TDRSS)
- GPS and DORIS near-continuous orbit observability is a significant advancement
- Ability to characterize orbit error through the comparison of high accuracy orbits determined from independent data (SLR/DORIS vs. GPS)

*Tracking network, reference frame and measurement modeling improvements*

**Diverse and cooperative POD Team:** NASA GSFC, CNES, JPL, UT/CSR, CU, ... with contributions by many others e.g. The Ohio State University.
Jason-1 (2001); Jason-2 (2008)

The 1-cm orbit …

1 cm radial orbit accuracy demonstrated (Luthcke et al. 2003, Haines et al. 2004, Choi et al., 2004; Lemoine et al., 2010; Cerri et al., 2010; Bertiger et al., 2010).

- **Applied Upgraded tracking technology:** GPS, SLR, DORIS (Especially JPL GPS BlackJack codeless receiver).
- **Improved tracking network positions and measurement modelling** (e.g. GPS antenna phase center modeling)
- **Improved application of the reduced dynamic solutions** in GPS, GPS+SLR and even SLR+DORIS based solutions
- **The challenge is to assess and characterize the remaining orbit errors**
- **Necessary to exploit all available tracking data in various combination solutions**
Intercomparison of Independent Orbits Produced by SLR/DORIS & GPS (Reduced Dynamic) allows insights into model and geodetic technique error ..... And helps to validate improvements ....

A priori (Schwiderski) Tide model produced orbit error at the M2 alias period (~60 days) for T/P

Tide model improvement using TOPEX altimeter data
Jason GPS Reduced Dynamic POD Achieved the 1-cm radial orbit accuracy goal...

Independent high elevation SLR performance demonstrated the 1 cm radial orbit accuracy (Luthcke et al. 2003).

Other error sources are included beyond radial orbit error.
Jason-2 Orbit Intercomparisons Allow Validation of Radial Orbit Accuracy

- SLR DORIS red-dyn (GSFC)
- GPS-only red-dyn (JPL)
- GPS-only (CNES)
- SLR DORIS dyn. (GSFC)
- DORIS-only (CNES)
- SLR+DORIS+GPS (CNES)

Cerri et al. (2010)
Synopsis of Some Recent Improvements (1) Tracking System & Model Improvements (e.g.)

DORIS Evolution from TOPEX re-analysis

DORIS monument improvement and systematic application of site quality criteria significantly improved system performance (cf. Fagard, 2006)
Synopsis of Recent Improvements ... (2)

**Improved gravity modelling using products from the GRACE mission**

Model Time-Variable Gravity due to the Atmosphere & Land Hydrology

Geographically correlated error removed (GGM02C vs. JGM3)
Radial Orbit Accuracy Achievement

- GEOS-3 (1979)
- SEASAT (1982)
- GEOSAT (1990)
- TP (1995)
- Jason-1 (2006)
- GEOSAT repro. (2008)
- TP repro. (2008)

Improvement:
- GEOSAT and TP reprocessing improvement

Accuracy:
- < 3 cm
- < 1 cm
- ~5-7 cm
- < 2 cm
Continued Challenges

Radiation Pressure Modelling:
e.g., SLR/DORIS ($C_R=1$) – JPL GPS6b orbits, 120-day amplitude for Jason-1

1. Providing a consistent orbit time series for altimeter data over 16+ years, spanning three missions, and four altimeters - to better resolve interdecadal signals & MSL change.

2. Radiation Modelling Improvements.

3. Reference Frame Stability.

4. Measurement model improvements for SLR, GPS & DORIS.

5. Geocenter.

(Some) Reference Frame Issues (1)

TOPEX SLR+DORIS Orbit Differences (ITRF2005 - ITRF2008)

Network effect in differences, centered ~1996?

From Beckley et al., 2007; Morel & Willis, 2005, change in sea level rate will be ~0.06 mm/yr.
DORIS Station Performance: ITRF2005 vs. ITRF2008

Predominantly SAA stations show degradation for Jason-2
(Some) Reference Frame Issues (3)

DORIS Station Determination affected by Atmospheric Drag Increase near Solar maximum

Solar Flux

IDS-1
Horizontal Residuals

IDS-3
Horizontal Residuals

Valette et al., 2010.
<table>
<thead>
<tr>
<th>Satellite</th>
<th>Agency(s)</th>
<th>Launch Year</th>
<th>Orbit Height</th>
<th>Orbit Inclination</th>
<th>Instrumentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>JASON-1</td>
<td>CNES, NASA</td>
<td>2002</td>
<td>1336 km</td>
<td>66°</td>
<td>D2G + SLR + GPS</td>
</tr>
<tr>
<td>JASON-2</td>
<td>NASA, CNES</td>
<td>2008</td>
<td>1336 km</td>
<td>66°</td>
<td>DGXX + SLR + GPS</td>
</tr>
<tr>
<td>CRYOSAT-2</td>
<td>ESA</td>
<td>April 2010</td>
<td>717 km</td>
<td>92°</td>
<td>DGXX + SLR</td>
</tr>
<tr>
<td>ENVISAT</td>
<td>ESA</td>
<td>2002</td>
<td>~800 km</td>
<td>98.5°</td>
<td>D2G + SLR</td>
</tr>
<tr>
<td>HY2A</td>
<td>CNSA</td>
<td></td>
<td>963 km</td>
<td>99.3°</td>
<td>DGXX + SLR + GPS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Launched August 2011; Then HY2B, HY2C ....)</td>
</tr>
<tr>
<td>SARAL/ALTIKA</td>
<td>ISRO/CNES</td>
<td>2012</td>
<td>880 km</td>
<td>98.5°</td>
<td>DGXX + SLR</td>
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<tr>
<td>SENTINAL 3A</td>
<td>GMES</td>
<td>April 2013</td>
<td>814 km</td>
<td>98.6°</td>
<td>DGXX + SLR + GPS</td>
</tr>
<tr>
<td>JASON-3</td>
<td>NOAA/EUMETSAT/CNES/NASA</td>
<td>2013; Follow-on to TOPEX, Jason-1, Jason-2</td>
<td>1336 km</td>
<td>66°</td>
<td>DGXX + SLR + GPS</td>
</tr>
<tr>
<td>ICESAT-2</td>
<td>NASA, Laser altimeter</td>
<td>~2015</td>
<td>~600 km</td>
<td>94°</td>
<td>GPS + (SLR)</td>
</tr>
<tr>
<td>SWOT</td>
<td>CNES, NASA</td>
<td></td>
<td>970 km</td>
<td>78°</td>
<td>DGXX + SLR + GPS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>(Surface Water Ocean Topography; Launch 2018-2020)</td>
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