The Contributions of Satellite Laser Ranging to Satellite Altimetry

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October 12, 2016

With contributions from N. Zelensky (SGT @ NASA GSFC), A. Couhert (CNES, Toulouse)

20th International Workshop on Laser Ranging
Potsdam, Germany
• Introduction
• The science of Satellite Altimetry.
• Role & Contribution of SLR.
  (1) POD.
  (2) ITRF.
  (3) Geocenter.
  (4) Time-Variable Gravity.
  (5) Orbit Validation.
• Some current challenges.
In order to determine the height of the sea surface, we must know the satellite position (meaning its orbital ephemerides) to a precision commensurate to or better than the accuracy of the altimeter.
Example Ground Track Coverage for TOPEX (& Jason-1, Jason-2, Jason-3)

Image from AVISO (Toulouse, France)

Altitude 1336 km. Inclin. = 66.039°;
Ground track repeat: 9.9156 days.
Cross-track separation (equator): 315 km

TOPEX/Poseidon
1992-2006

Jason-3
2016 –
Example: Ground Track Coverage for TOPEX vs. ERS/Envisat

TOPEX/Jason-1,2,3

ERS & Envisat & SARAL

Altitude ~785 km. Incl. 98.543°; (sun-synchronous)
Ground track repeat: 35 days.
Cross-track separation (equator): 80 km
• Introduction

• **The science of Satellite Altimetry.**

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• Some current challenges.
Mean displacement of the sea surface from a reference ellipsoid; follows the geoid of the Earth and includes the dynamic ocean topography. MSS are constructed from many years of satellite altimetry and data from different satellites: E.g. TOPEX/Poseidon, Jason, ERS-2, ENVISAT

With independent information on the gravity field of the Earth (e.g. GOCE) it is possible to separate out the DOT contribution to a Mean Sea Surface and image the mean shape of the oceans caused by the ocean currents ... and also compute the mean geostrophic velocities.

(a) GOCE DOT filtered with a 140 km Gaussian filter
(b) Surface geostrophic current speeds computed from the filtered GOCE DOT.

Science of Altimetry- III

Gulf Stream Mean Velocities: 
Altimetry + gravity from GOCE

Sanchez-Reales, et al., 2012, 
Marine Geodesy.

(Geodynamics and Earth Ocean 
Satellite: GEOS-3) 
Launched: Apr. 9, 1975 
Operated through July 1979.

B. Douglas et al., JGR, 1983, 
http://dx.doi.org/10.1029/JC088iC14p09595
The precise orbits for TOPEX/Poseidon, Jason-1, Jason-2, all computed in a consistent reference frame (ITRF2008, and in future ITRF2014) are used to compute the global change in mean sea level from satellite ocean radar altimeter data.
Measurement of Regional and Global Mean Sea Level Change

Regional mean sea level variations from TOPEX, Jason-1, and Jason-2 with respect to 1993-2002 mean; http://podaac.jpl.nasa.gov/Integrated_Multi-Mission_Ocean_AltimeterData
Science of Altimetry - VI

El Nino: 1997 (TOPEX/Poseidon) vs. 2015 (Jason-2)

See updates every ~10 days at
Science of Altimetry- VII

Hurricane Intensification from Passage over Warm Core Eddies

Sea Surface Height variations show the location of warm water eddies – which appear higher in absolute height. Their latent height can contribute to hurricane intensification.

Mapping of Gulf of Mexico Sea Surface Height Variations by Dr. Robert R. Leben, University of Colorado, Boulder.

## Oceanographic & Geophysical Signal Summary

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<thead>
<tr>
<th>Phenomenon</th>
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<td>± ~1.5 m</td>
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<td>aperiodic (inter-annual) phenomenon.</td>
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### Requirements for orbit accuracy:

**TOPEX/Poseidon**
- initial orbit error budget: ~13 cm (*Tapley et al., 1994, JGR-Oceans*).
- Achieved 2.5 cm by 1994 (tuned gravity model, JGM-2, JGM-3)
- Post processing ITRF2005 & ITRF2008; GRACE gravity models: 1.5-2.0 cm orbits.

**Jason-1 -> Jason-3**
- Goal is 1 cm radial orbit error accuracy!! ***REQUIRES VERIFICATION****
- We must also have an orbit that is stable enough to accurately measure global and regional changes in mean sea level.
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  (5) Orbit Validation.
  (6) (Model Validation).
• Some current challenges.
Representative SLR precision vs. time

On average we obtain 20-30 passes/day from the different stations of the global ILRS network.

On average 20-30 stations have tracked TP, J1, J2 & J3 per day.
Tracking Data for Altimeter POD

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<th>TOPEX, Jason-1, Jason-2, Jason-3</th>
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<td><strong>SLR</strong></td>
<td>(entire time span: 1993-2016)</td>
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<td><strong>DORIS</strong></td>
<td>(No DORIS on TOPEX: 2004-2006)</td>
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<td><strong>GPS</strong></td>
<td>(1993-1994 only. Demo.)</td>
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<td>Jason-1 (2001-2006)</td>
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<td>Jason-2, (July 2008-present)</td>
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<td>Jason-3: (Jan. 2016-present)</td>
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SLR – TP, J1, J2 RMS Residuals

SLR RMS Residuals to NASA GSFC std1504 orbits for TOPEX/Poseidon, Jason-1, Jason-2.

LRA for Jason-1, Jason-2, Jason-3 (courtesy of the ILRS)
SLR – J2 & J3 RMS Residuals

LRA for Jason-1, Jason-2, Jason-3 (courtesy of the ILRS)

SLR RMS Residuals to NASA GSFC std1504 orbits for Jason-2 and Jason-3 during tandem calibration period (February – September 2016)
(from N. Zelensky, SGT @ NASA GSFC)
SLR – J1 & J2 Orbit Accuracy Achieved

Jason-1 and Jason-2 Radial RMS Orbit Differences by 10-day cycle (2002-2014) (Differences by Orbit Type and by Analysis Centers)

In these tests with DORIS & GPS data, Satellite Laser Ranging Measurements of Jason-2 are independent and directly measure orbit accuracy.

The fact that these orbits from different tracking systems agree at ~1cm radial RMS, is a reason why we can have such high confidence in the determination of Mean Sea Level change from satellite altimetry.
At high elevations SLR measures directly the radial orbit error; So in this example, we can say the DORIS-only orbits on SARAL have an orbital accuracy of 10-15 mm.

A reference frame realization consists of positions and velocities of the reference points.

For ITRF2014, post-seismic relaxation is also modeled for the first time.
SLR contributes to the origin and scale of the terrestrial reference frame as well as position/velocity of key reference points (core SLR stations).

Figures from Zuheir Altamimi, IGN/France
See also Altamimi et al. (2016)
TP, J1, J2, J3. Prime data for Measure of change in global Mean Sea Level. (Key climate indicator).

- Must be determined in a stable & consistent reference frame
- ITRF2008 at present. (ITRF2014 results by OSTST In La Rochelle Nov. 2016)
- Only SLR & DORIS span entire time series!!


Errors in the Z component of the TRF can produce large regional errors in MSL rate determination.
In the **solid** Earth center of mass frame, geocenter motion of the Total Earth’s mass referenced to CF:

\[ r_c(t) = r_{cm}(t) - r_{cf}(t) \]

- \( r_{cm}(t) \): displacement of the center of mass (CM) largely due to redistribution of continental water, atmospheric and oceanic mass at the Earth’s surface.

- \( r_{cf}(t) \): displacement of the center of figure (CF) due in large part to elastic deformation of the Earth’s surface caused by loading.

**Note.** The SLR center of network (CN) becomes the center of figure (CF) origin in the SLR geocenter estimate.
CSR CM model largely removes annual Z difference signature between SLR/DORIS & JPL13a/GPS Reduced-dynamic orbits.
SLR – Time-Variable Gravity (1)

- SLR contributes to determination of the time-variable gravity variations of the Earth.
- Pre-GRACE – it is the primary source of information for low degree terms.
- In era of GRACE --- determination of zonal terms ($C_{20}$, $C_{40}$) – to which GRACE data are relatively insensitive or strongly aliased with S2-like signal.

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* Starlette: Elliptical orbit (~800 x ~1100 km)
SLR – Time-Variable Gravity (1)

4x4 & 5x5 time series developed @ NASA GSFC for altimetry satellite POD, and for DORIS reprocessing associated with ITRF2014.

**NASA GSFC SLR+DORIS-derived TVG time series vs. CSR/SLR/RL05 series.**

(Lemoine et al., 2014, OSTST)
Current Ocean-radar mapping altimeter satellites (Oct. 2016)

These satellites form a “virtual” constellation that monitors the ocean surface topography.

Golden Age of Satellite Altimetry!!
We need multiple tracking systems
(a) to ensure and establish orbit accuracy;

This is especially important for the demanding application of measurement of the change in global mean sea level & to demonstrate orbit accuracy.

(b) to ensure redundancy; in the event one tracking system has “problems”, or even fails.

(I) GFO. Failure of GPS. SLR + altimeter crossovers only reliable tracking system.
(II) Jason-1. DORIS Oscillator not hardened before launch – perturbed by passage through S. Atlantic anomaly, Apply a “correction” model.
1. Improvements in Time-variable gravity modeling, and in the ITRF.

2. Improvement in Non-conservative force modelling.

3. Tuning of phase maps for GPS-satellite receivers:
   Luthcke S. et al. (2003), Marine Geodesy, “The 1-cm Orbit:....”
   Haines Br. et al. (2004), Marine Geodesy, “One cm POD for Jason-1 ...”
   Mercier Fl. et al. (2009), OSTST meeting, Seattle Washington June 2009.

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• **Some current challenges.**
**SLR – Current Challenges: SLR biases**

**Challenge:** We use SLR data to validate the performance of DORIS-only and GPS-only or GPS+DORIS orbits (e.g. CNES GDR-E). We also wish to use the SLR data to monitor long-term drifts in the orbits. SLR biases interfere with and complicate this direct orbit accuracy validation.

This is confounded by (possible) reference frame issues (GPS vs. SLR) and possible velocity errors of stations.

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**Fig. 6.** Mean SLR Graz L7839 reference station residuals by cycle above 70° elevation from 2002 to 2013 for the Jason-1 and Jason-2 independent DORIS-only, GPS-based GDR-D-like dynamic orbits and JPL GPS-Reduced-dynamic counterparts. The solid curves are the results of the least squares fit to the mean SLR residuals of a bias, drift and annual periods.

SLR – Current Challenges: Target Signature

Jason-1: SLR Residuals to GPS orbit vs. boresight angle

Cerri et al., 2010, Marine Geodesy (Figure 5)

SARAL: Arnold LRA model vs. mean correction & data distribution vs elevation

Zelensky et al., 2016, Adv. Space Res. (Figure 3.2)
Summary

• TOPEX, Jason-1, Jason-2, Jason-3 form a series of satellites that provide essential key “climate data records” to measure global & regional sea level change.

• These satellites are part of a virtual constellation of altimeter satellites to monitor the global ocean topography.

• All the altimeter satellites use SLR directly for POD, indirectly for validation, or to establish improvement in underlying models.

• Challenges:
  (1) Maintaining stability and accuracy of SLR data – as well as minimizing biases – orbit RMS radial accuracy goal is 1 cm radial RMS.
  (2) Target signatures on altimeter satellites.
  (3) Continuing to Improving models for Geocenter, Non-conservative force modelling and coherence between the different techniques as manifested in the orbits computed with the different geodetic data types for any given altimeter satellite.