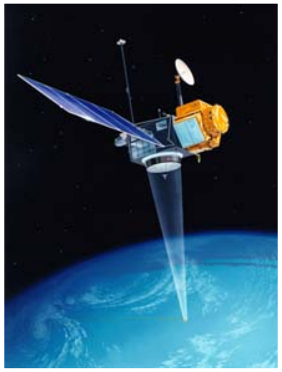
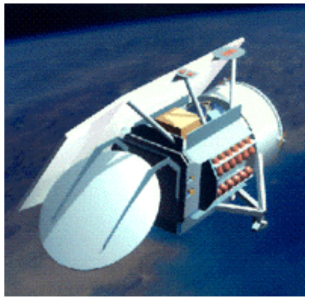
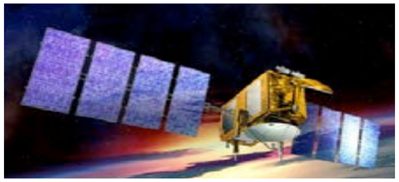
The Contributions of Satellite Laser Ranging to Satellite Altimetry

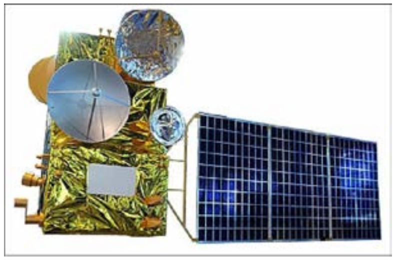
Frank G. Lemoine
NASA Goddard Space Flight Center
October 12, 2016

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

20th International Workshop on Laser Ranging
Potsdam, Germany



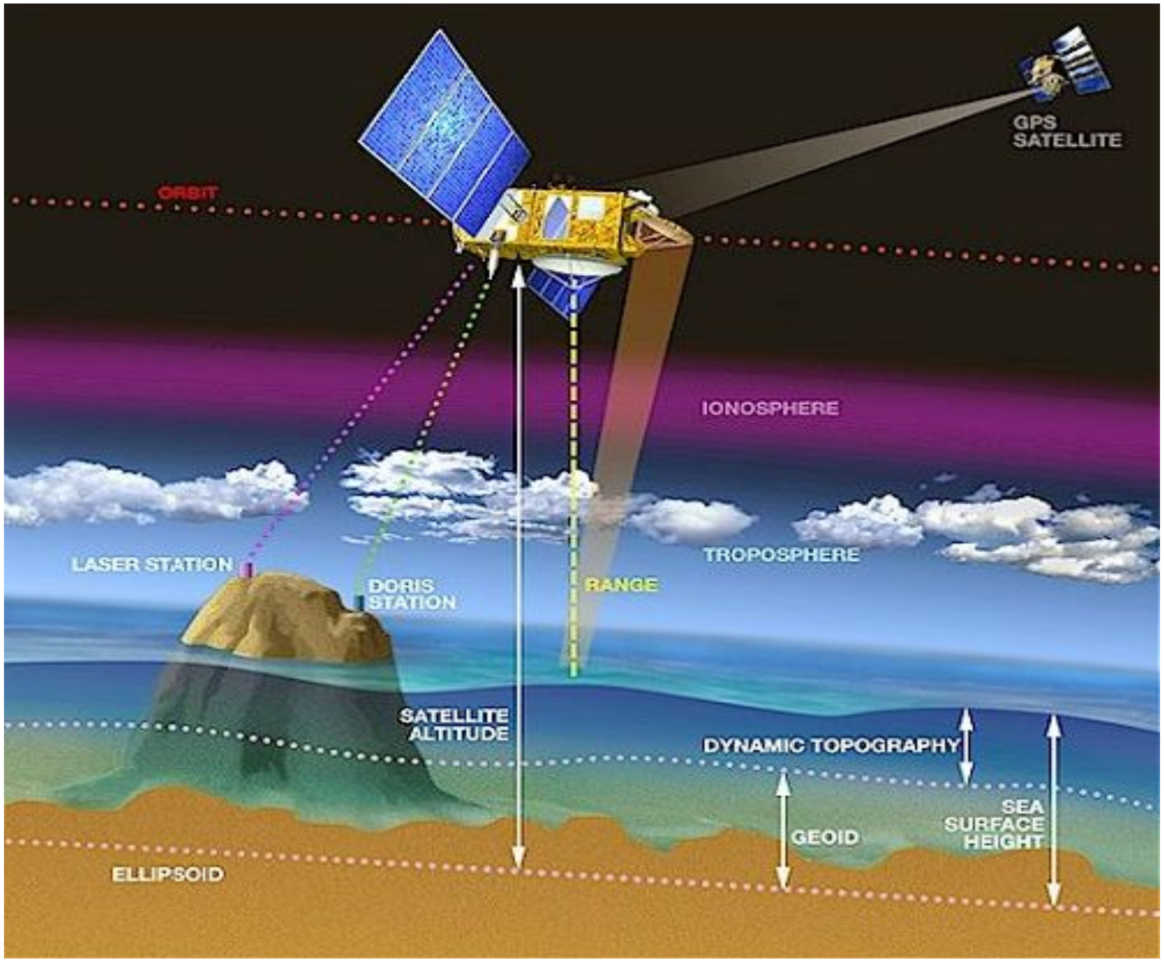




International Laser Ranging Service

- 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.

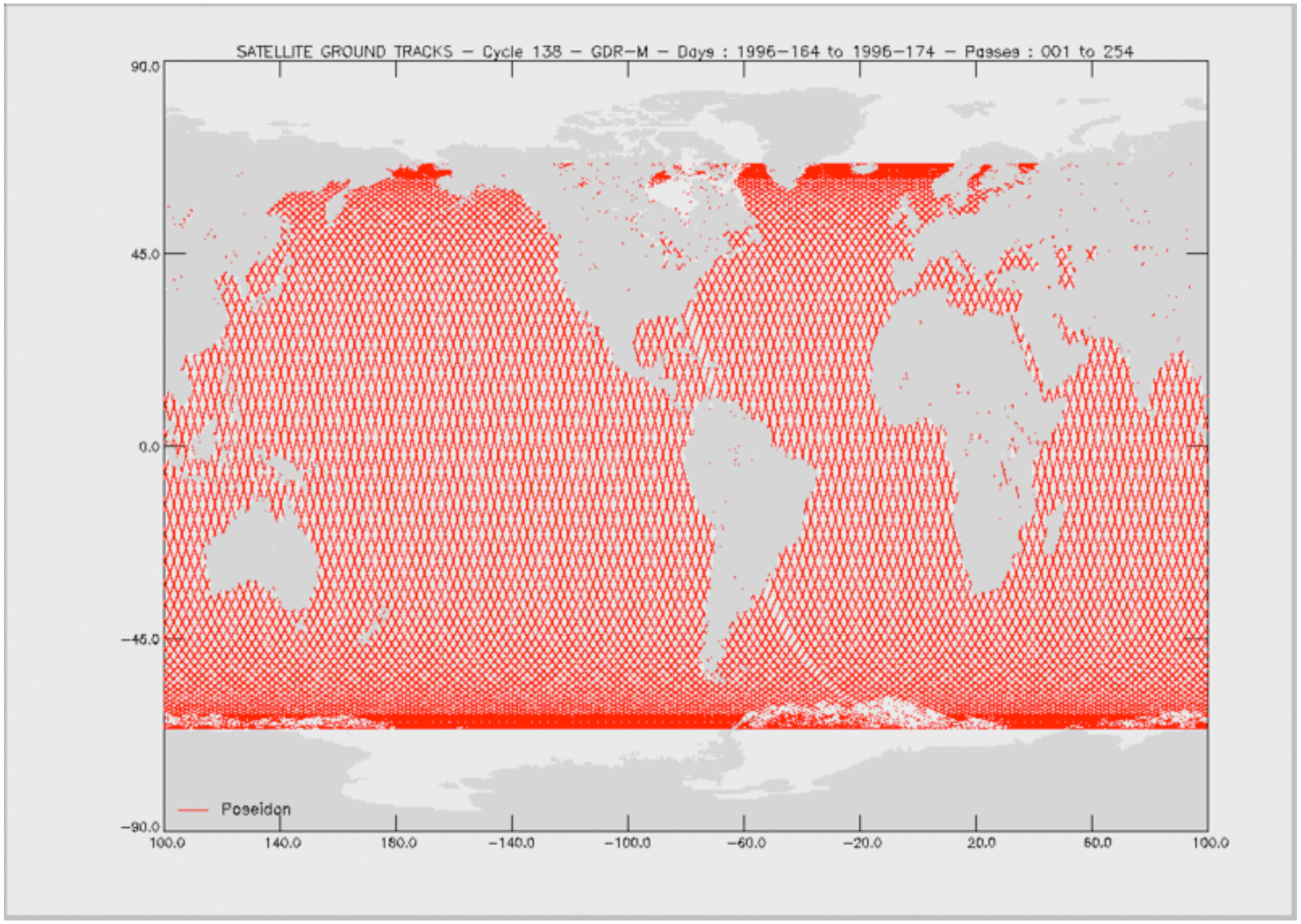
POD - Schematic

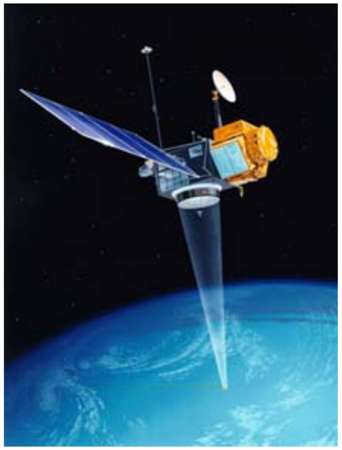


This example is for TOPEX, but the same principle applies for all altimeter satellites.

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)





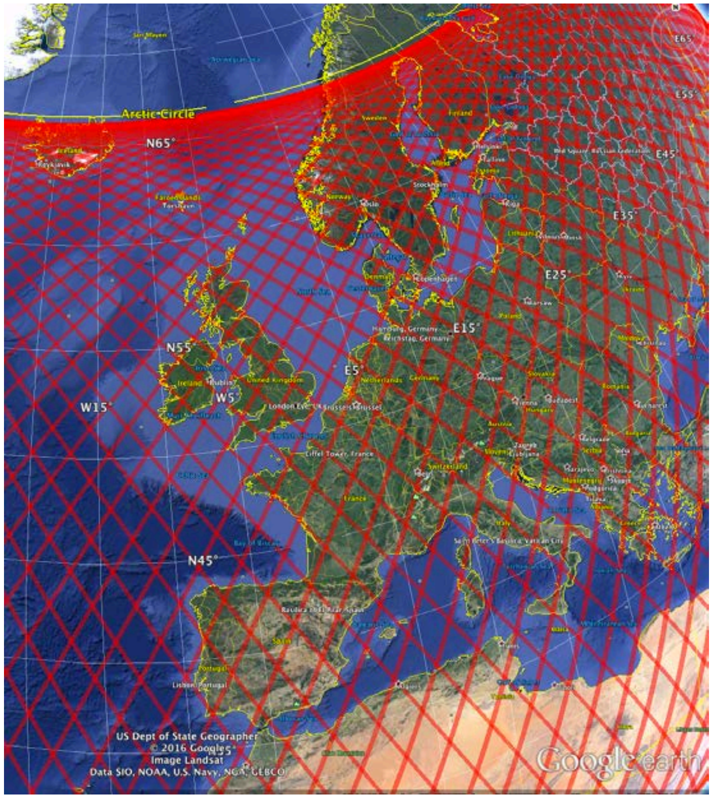
TOPEX/Poseidon
1992-2006

Jason-3
2016 –

Image from AVISO (Toulouse, France)

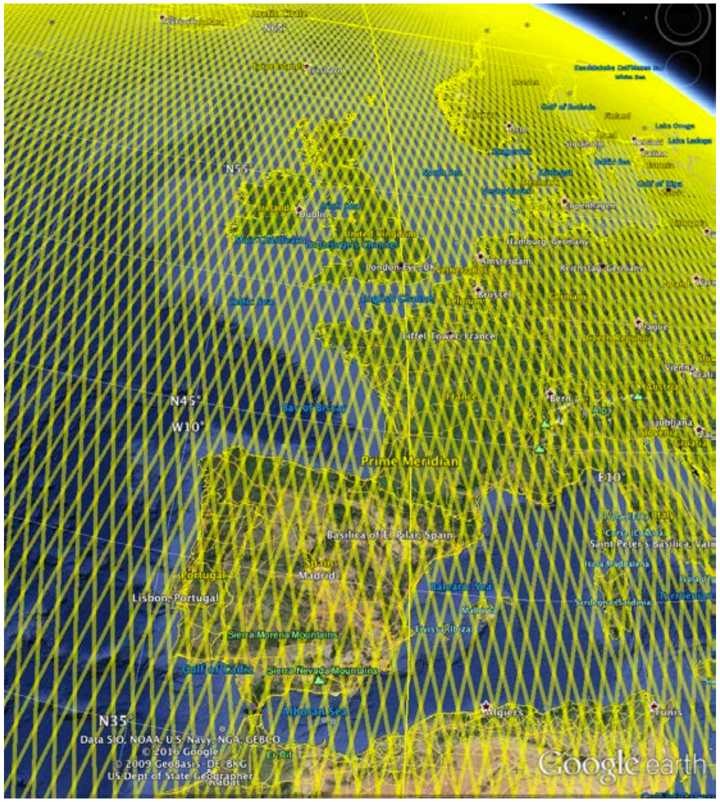
Altitude 1336 km. Inclin. = 66.039°;
Ground track repeat: 9.9156 days.
Cross-track separation (equator): 315 km

Example: Ground Track Coverage for TOPEX vs. ERS/Envisat



US Dept of State Geographer
© 2016 Google
Image Landsat
Data SIO, NOAA, U.S. Navy, NGA, GEBCO

TOPEX/Jason-1,2,3



Data SIO, NOAA, U.S. Navy, NGA, GEBCO
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US Dept of State Geographer

ERS & Envisat & SARAL

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

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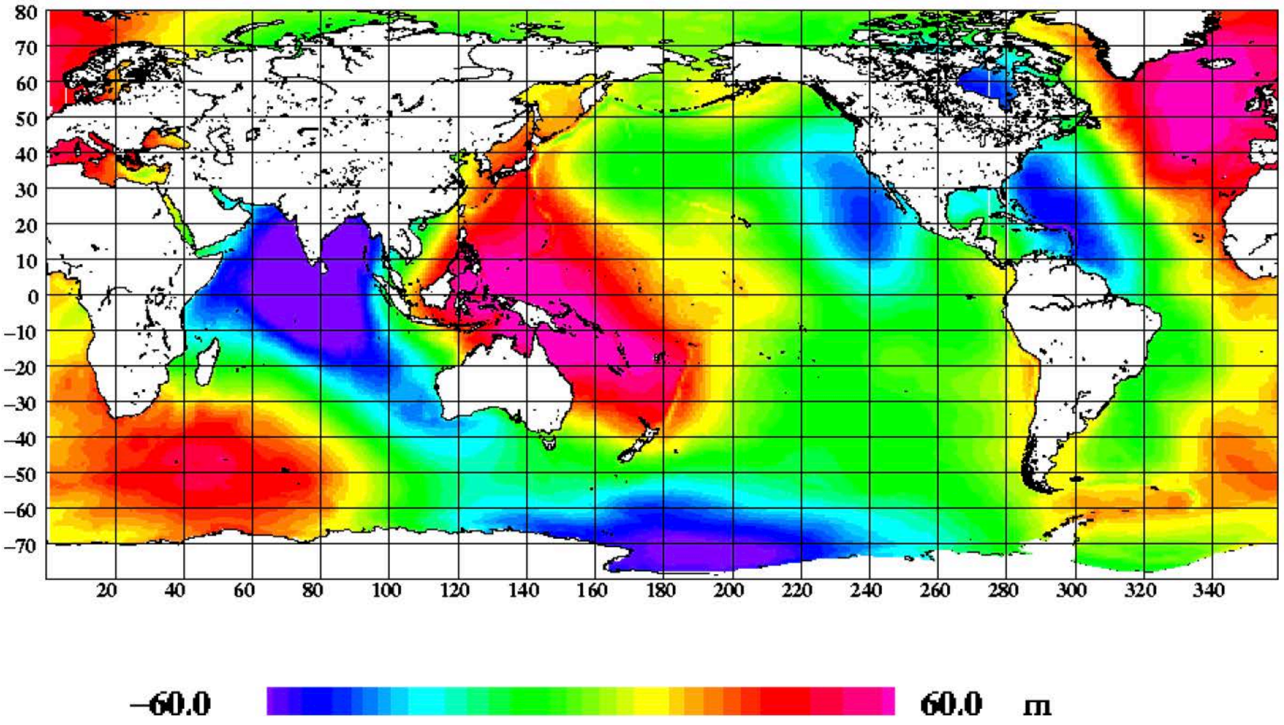
Science of Altimetry- I

Mean Sea Surface

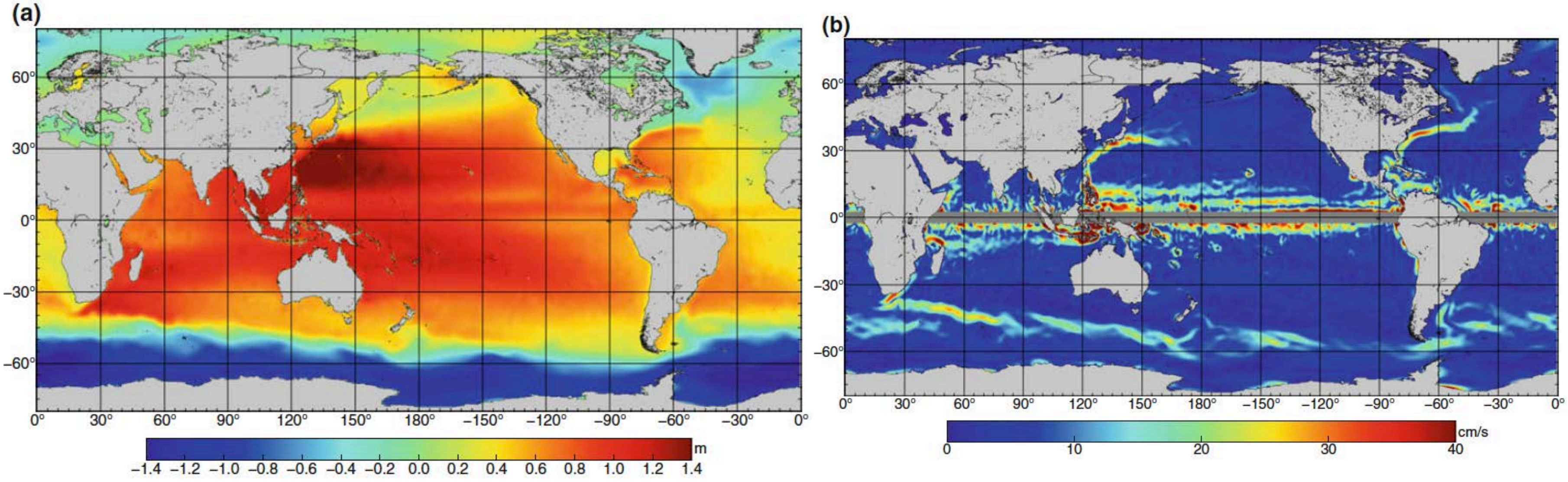


DNSC08MSS &
DTU10 (DTU Space**)**
(Andersen & Knudsen,
JGR, 2009,
doi:10.*1029/2008JC005179*)

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

Science of Altimetry- II

Dynamic Ocean Topography

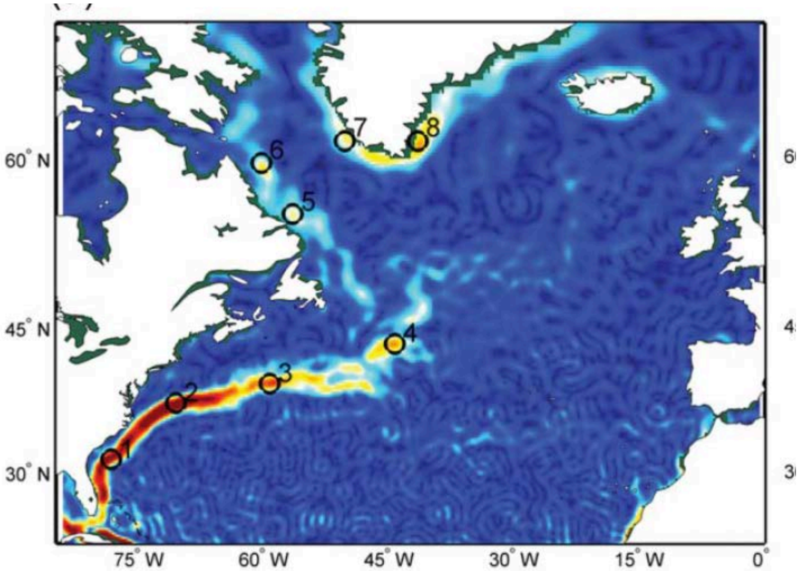


With independent information on the gravity field of the Earth (e.g. GOCE) it is possible to separate out the DOT contribution to a Mean Sea Surface and image the mean shape of the oceans caused by the ocean currents ... and also compute the mean geostropic velocities.

(a) GOCE DOT filtered with a 140 km Gaussian filter
(b) Surface geostrophic current speeds computed from the filtered GOCE DOT.
(Knudsen, P., et al., “A global mean dynamic topography and ocean circulation estimation using a preliminary GOCE gravity model”, J. Geodesy, 2011***)***

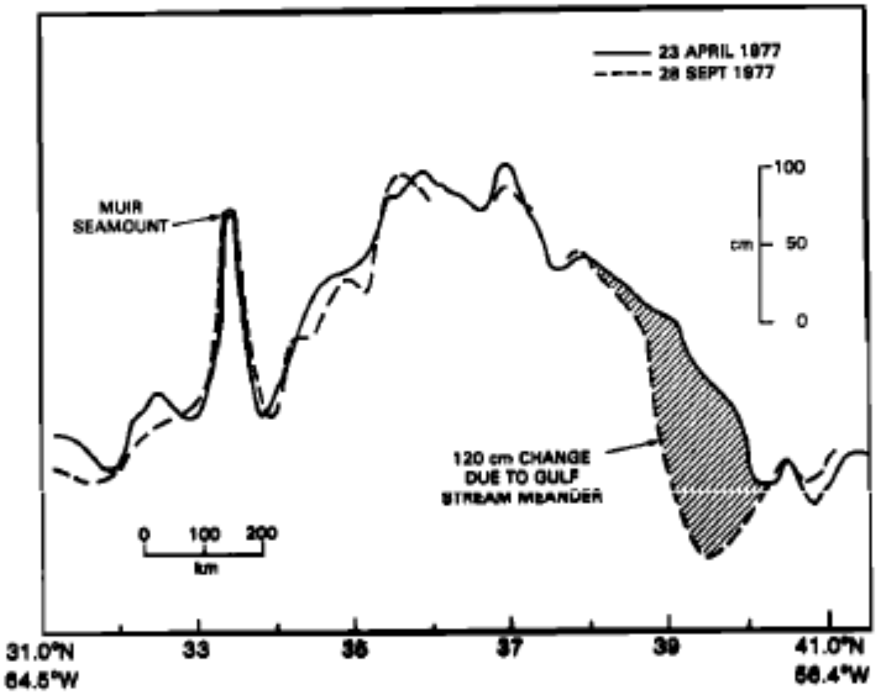
Science of Altimetry- III

Gulf Stream Mean Velocities:
Altimetry + gravity from GOCE



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

GEOS-3 COLLINEAR ALTIMETER DATA



(Geodynamics and Earth Ocean Satellite: GEOS-3)

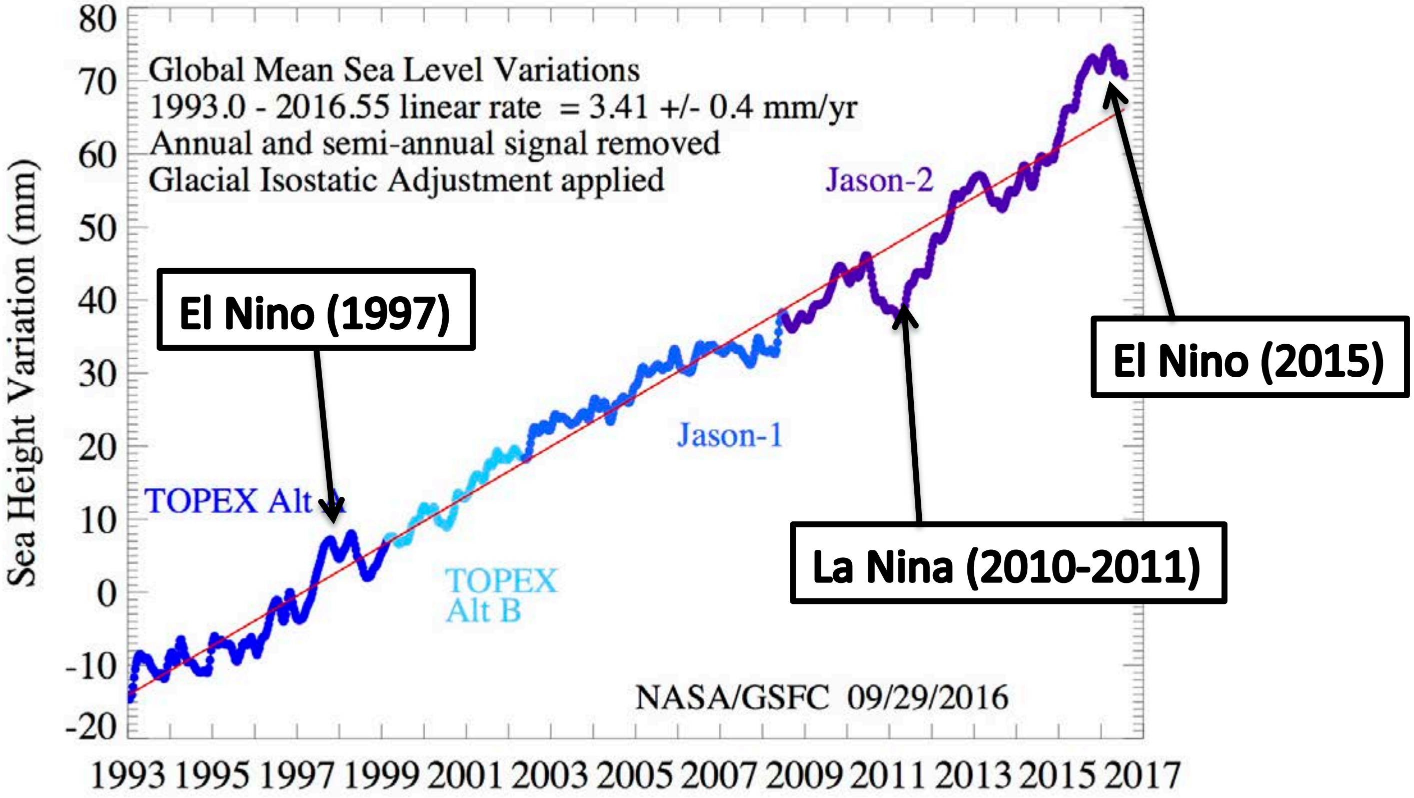
Launched: Apr. 9, 1975

Operated through July 1979.

B. Douglas et al., JGR, 1983,
http://dx.doi.org/10.1029/JC088iC14p09595

Science of Altimetry- IV

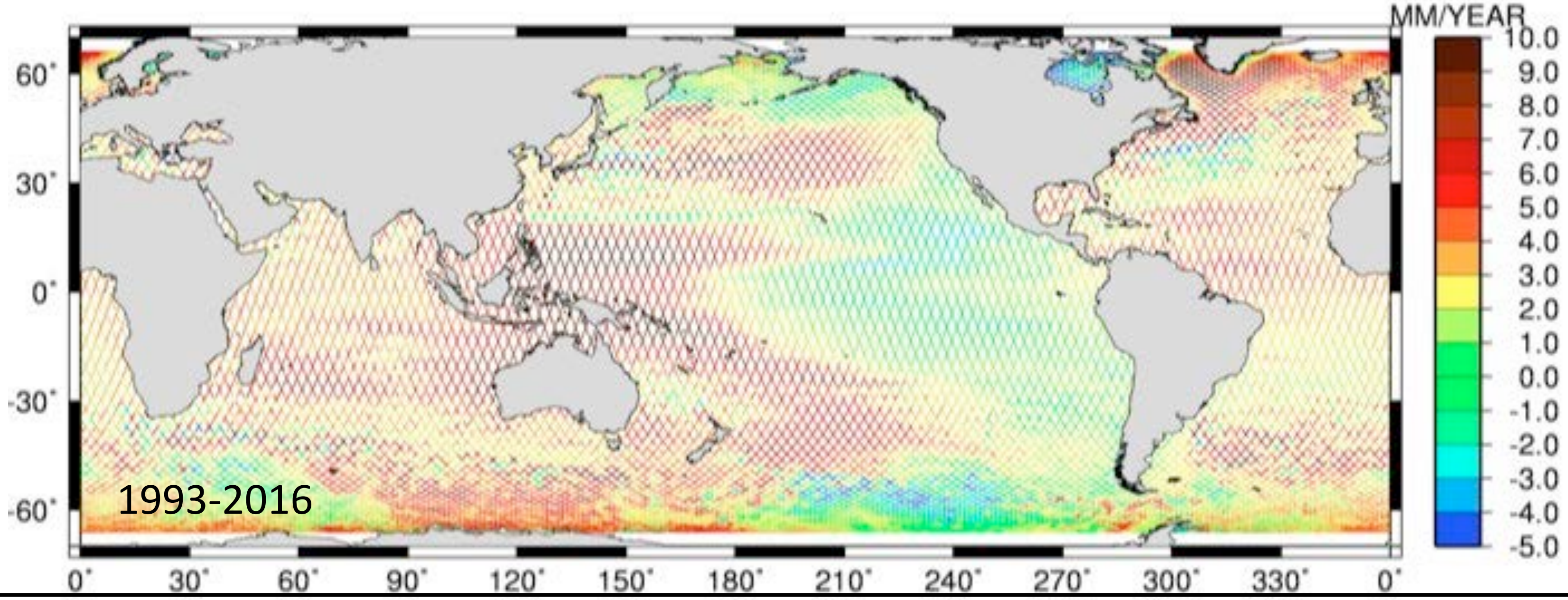
The precise orbits for TOPEX/Poseidon, Jason-1, Jason-2, all computed in a consistent reference frame (ITRF2008, and in future ITRF2014) are used to compute the global change in mean sea level from satellite ocean radar altimeter data.



http://podaac.jpl.nasa.gov/Integrated_Multi-Mission_Ocean_AltimeterData

Science of Altimetry- V

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

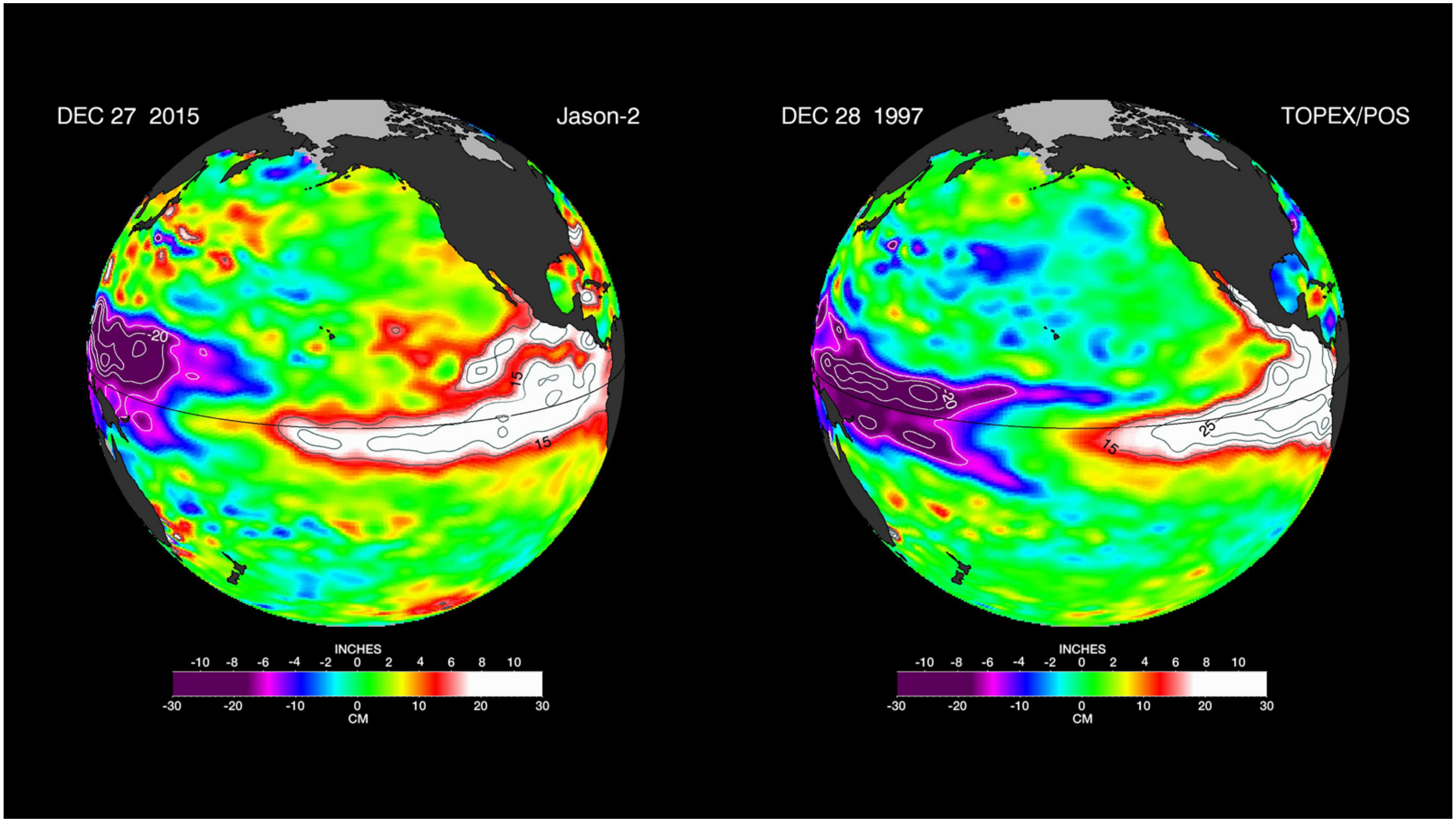
TOPEX/Poseidon
1992-2002 (-2006)

Jason-1,
2001-2009 (-2013)

Jason-2, 2008-
Jason-3, 2016-

Science of Altimetry- VI

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



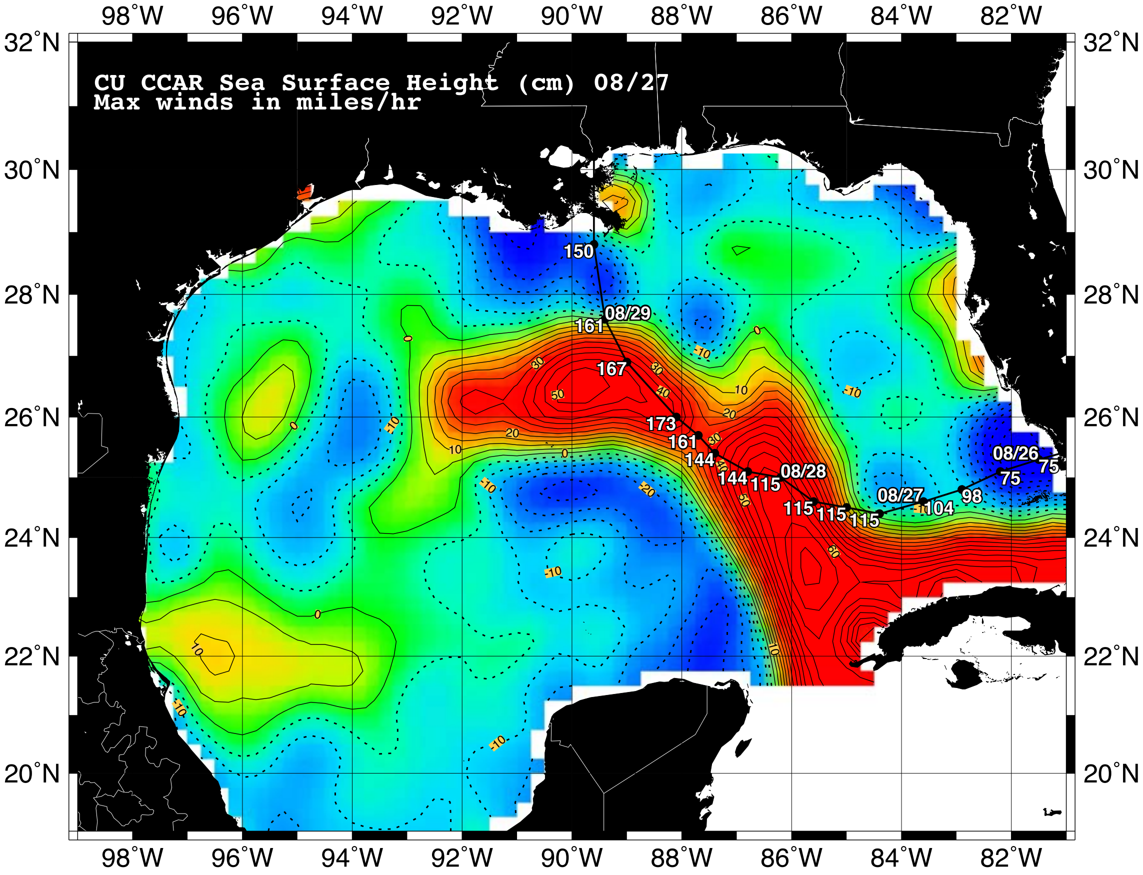
See updates every ~10 days at
http://sealevel.jpl.nasa.gov/science/elninopdo/latestdata/archive/

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.



http://oceanmotion.org/html/impact/natural-hazards.htm
http://www.nasa.gov/centers/jpl/news/ostm-20080701.html

Oceanographic & Geophysical Signal Summary

Phenomenon	Amplitude	
Mean Sea Surface	± ~100 m	Geoid + D.O.T.
Global Dynamic Ocean Topography	± ~1.5 m	Only resolvable with independent satellite gravity information
Sea Level Change	~3 mm/yr (global average)	Regional variations
Warm Core Eddies	~50 cm	e.g. Hurricane Katrina
El Nino	± ~30 cm	

Oceanographic & Geophysical Signal Summary

Phenomenon	Amplitude	
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Warm Core Eddies	~50 cm	e.g. Hurricane Katrina
El Nino/La Nina	± ~30 cm	aperiodic (inter-annual) phenomenon.

Requirements for orbit accuracy:

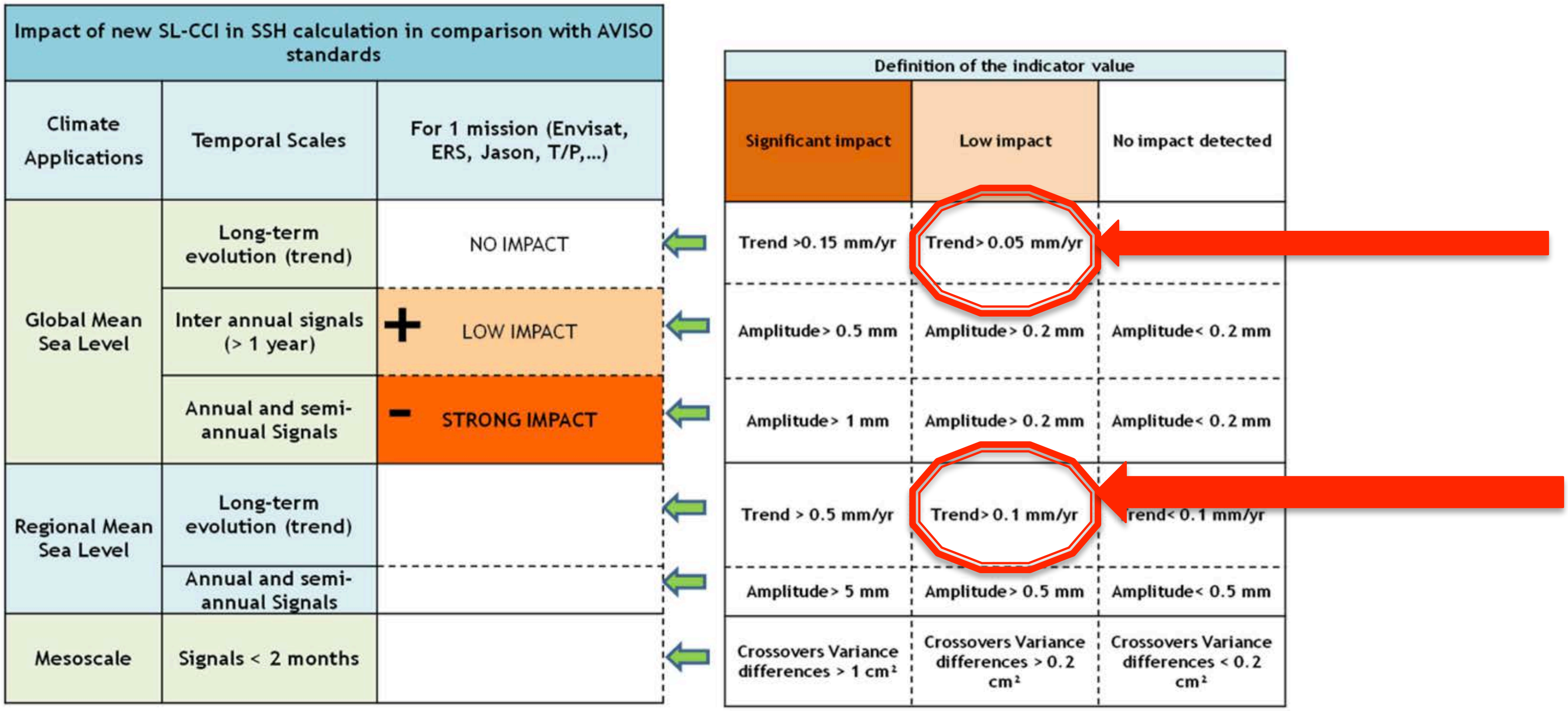
TOPEX/Poseidon

- 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**

Orbit Stability requirement (global & regional mean sea level)



Impact of new SL-CCI in SSH calculation in comparison with AVISO standards		
Climate Applications	Temporal Scales	For 1 mission (Envisat, ERS, Jason, T/P,…)
Global Mean Sea Level	Long-term evolution (trend)	NO IMPACT
	Inter annual signals (> 1 year)	+ LOW IMPACT
	Annual and semi-annual Signals	- STRONG IMPACT
Regional Mean Sea Level	Long-term evolution (trend)	
	Annual and semi-annual Signals	
Mesoscale	Signals < 2 months	

Definition of the indicator value		
Significant impact	Low impact	No impact detected
Trend >0.15 mm/yr	Trend> 0.05 mm/yr	
Amplitude> 0.5 mm	Amplitude> 0.2 mm	Amplitude< 0.2 mm
Amplitude> 1 mm	Amplitude> 0.2 mm	Amplitude< 0.2 mm
Trend > 0.5 mm/yr	Trend> 0.1 mm/yr	rend< 0.1 mm/yr
Amplitude> 5 mm	Amplitude> 0.5 mm	Amplitude< 0.5 mm
Crossovers Variance differences > 1 cm^2	Crossovers Variance differences > 0.2 cm^2	Crossovers Variance differences < 0.2 cm^2

Ablain M. et al., “Improved sea level record over the satellite altimetry era (1993–2010) from the Climate Change Initiative project”
Ocean Sci., 11, 67–82, 2015

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  (6) (Model Validation).
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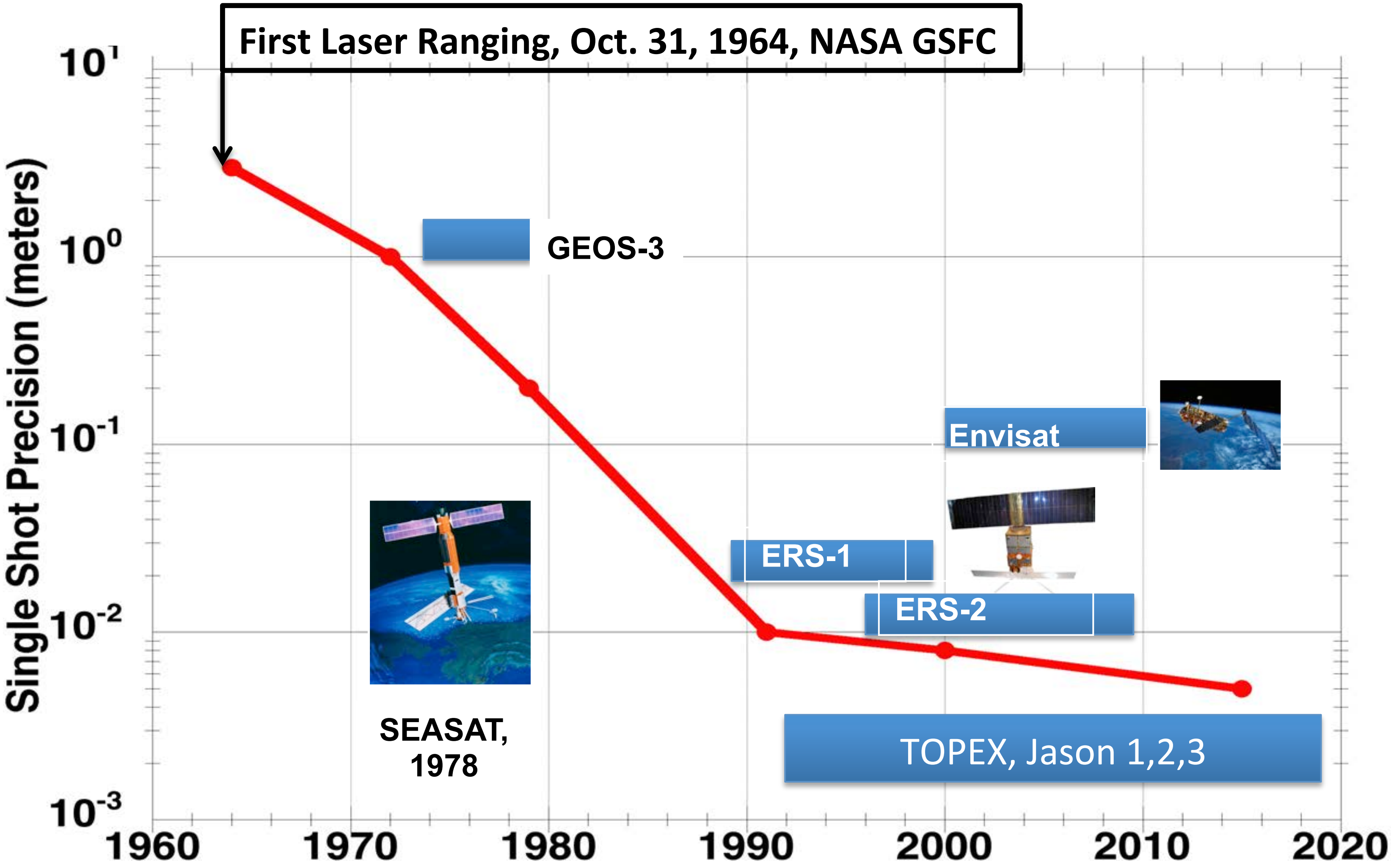
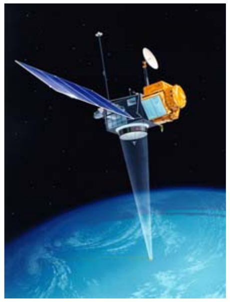
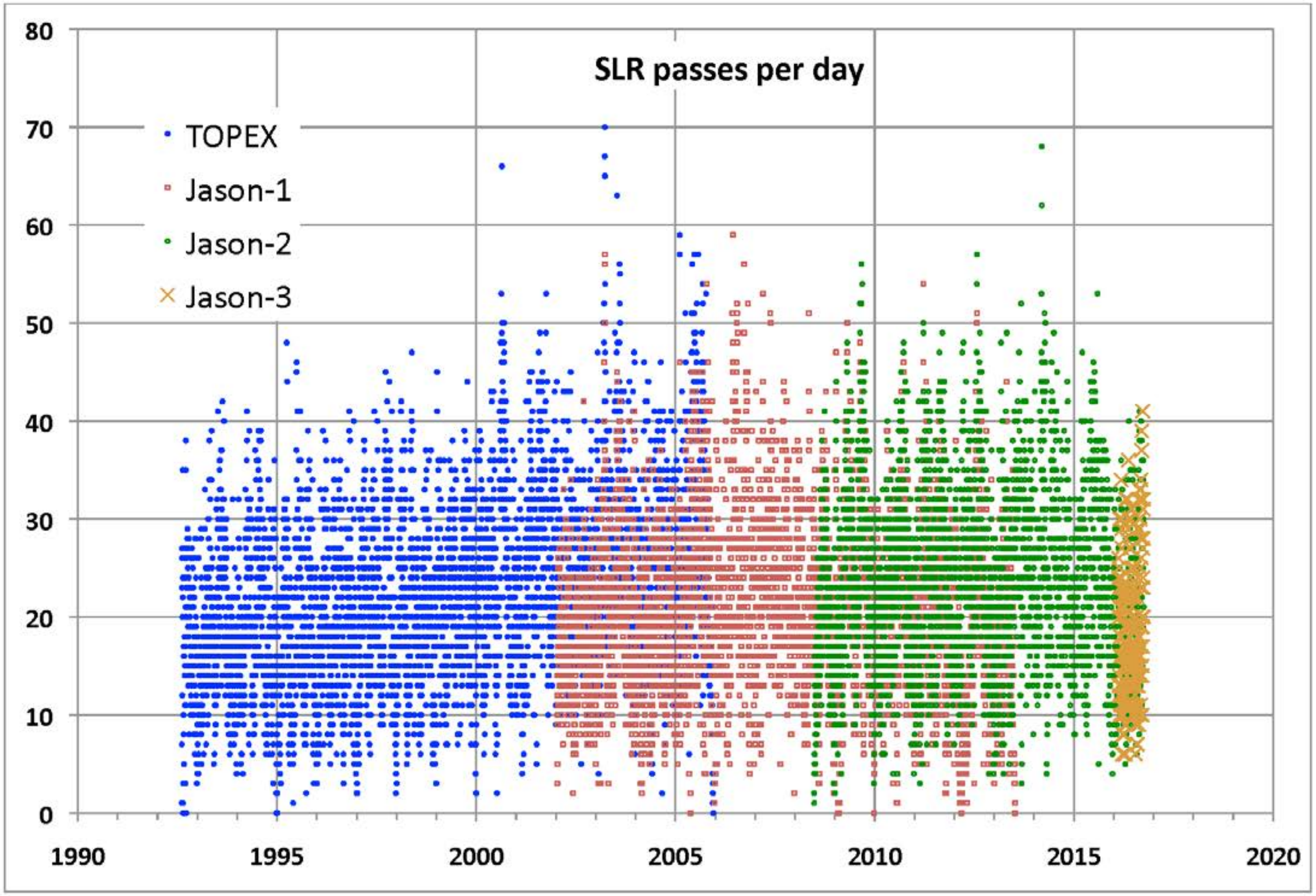
Representative SLR precision vs. time



Adapted from J. Degnan. “Impact of SLR Technology Innovations on Modern Science”, 18th ILRS Workshop, Fujiyoshida, Japan, Nov. 11, 2013. http://cddis.gsfc.nasa.gov/lw18/docs/presentations/Session0/13-0001-Degnan_2.pdf

SLR – TP, J1, J2, J3 tracking summary





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

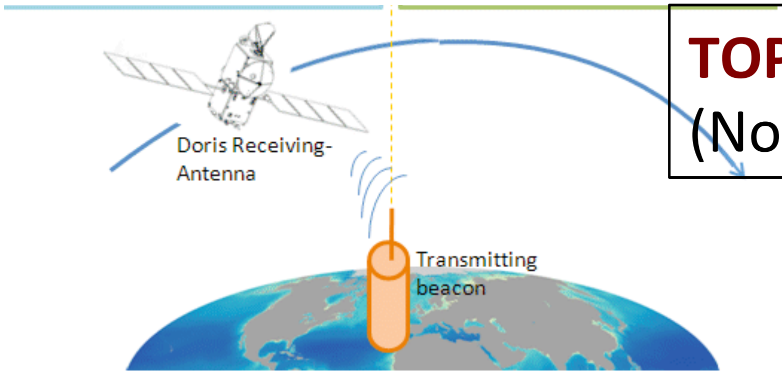
On average 20-30 stations have tracked TP, J1, J2 & J3 per day

Tracking Data for Altimeter POD

SLR

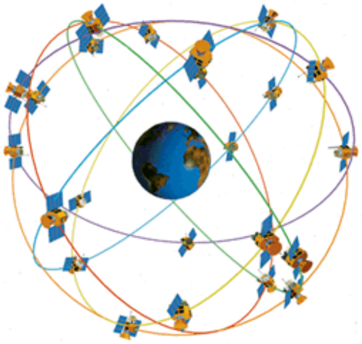
TOPEX, Jason-1, Jason-2, Jason-3
(entire time span: 1993-2016)

DORIS



TOPEX, Jason-1, Jason-2, Jason-3
(No DORIS on TOPEX: 2004-2006)

GPS



TOPEX (1993-1994 only. Demo.)
Jason-1 (2001-2006)
Jason-2, (July 2008-present)
Jason-3: (Jan. 2016-present)

SLR – TP, J1, J2 RMS Residuals

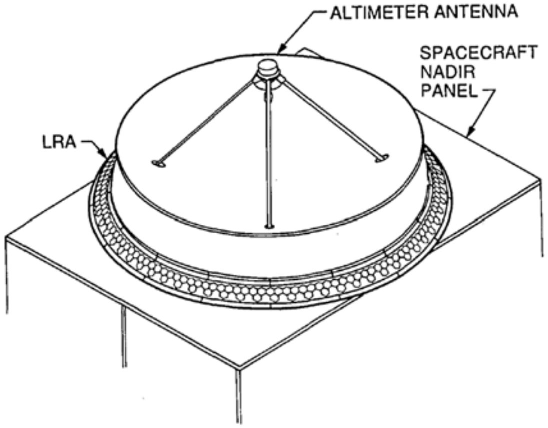
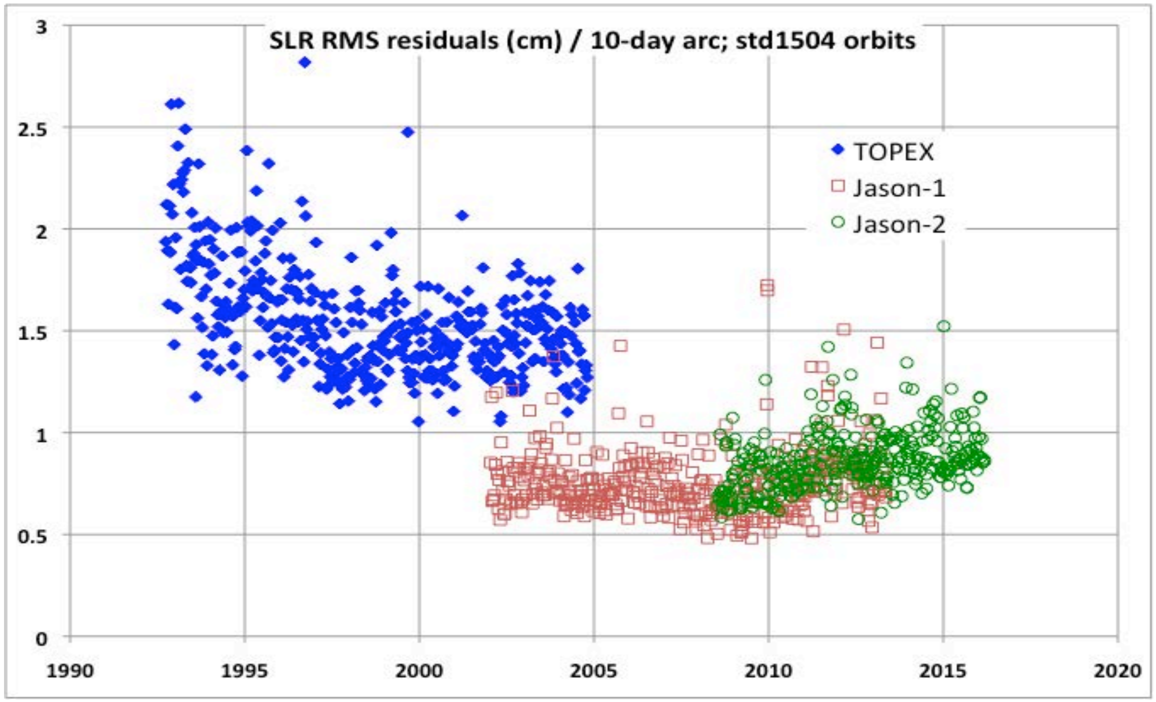
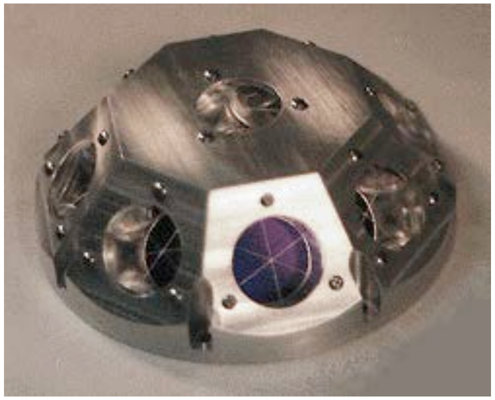


Fig. 1. TOPEX nadir panel with LRA and altimeter antenna.

TOPEX LRA.
(Schwartz, Applied Optics, 1990)

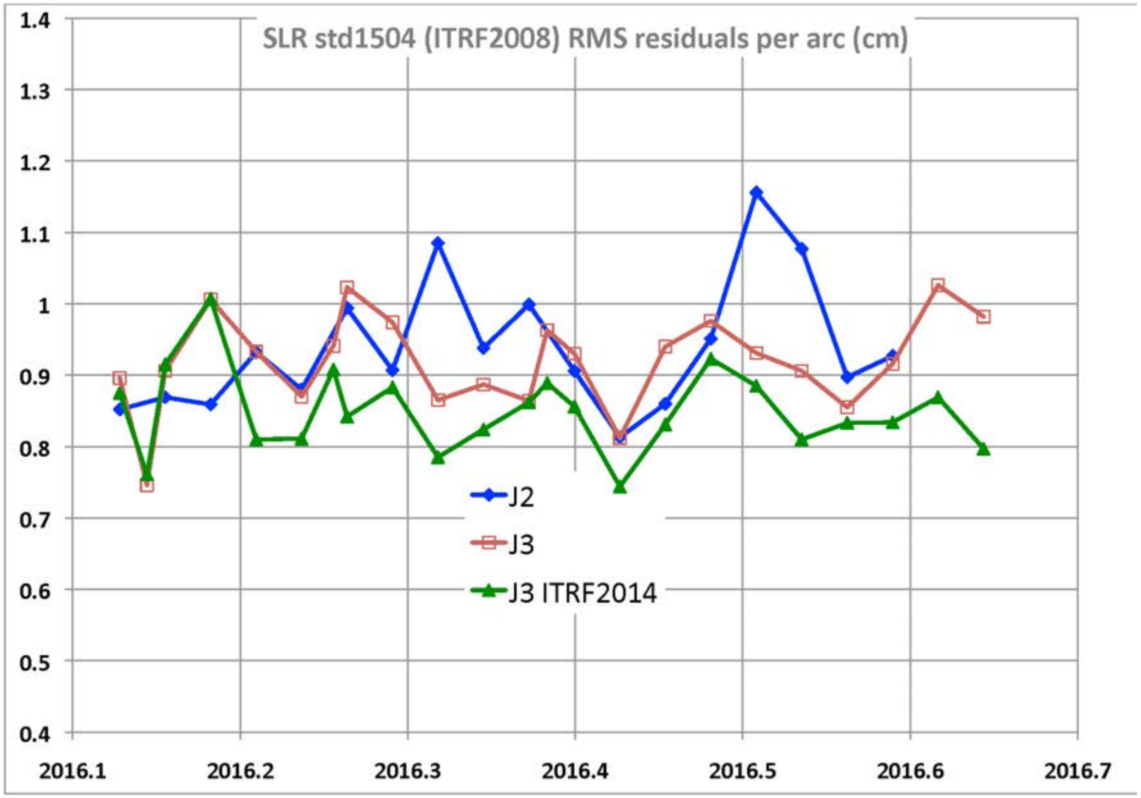


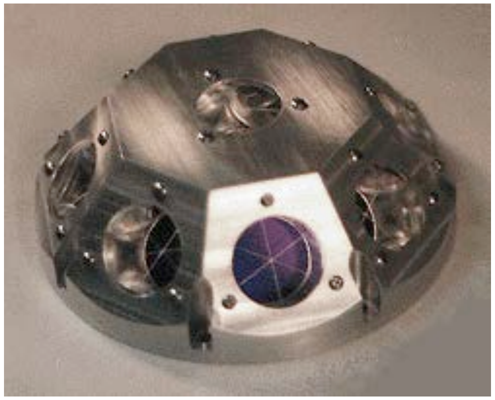
SLR RMS Residuals to NASA GSFC std1504 orbits for TOPEX/Poseidon, Jason-1, Jason-2.



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

SLR – J2 & J3 RMS Residuals



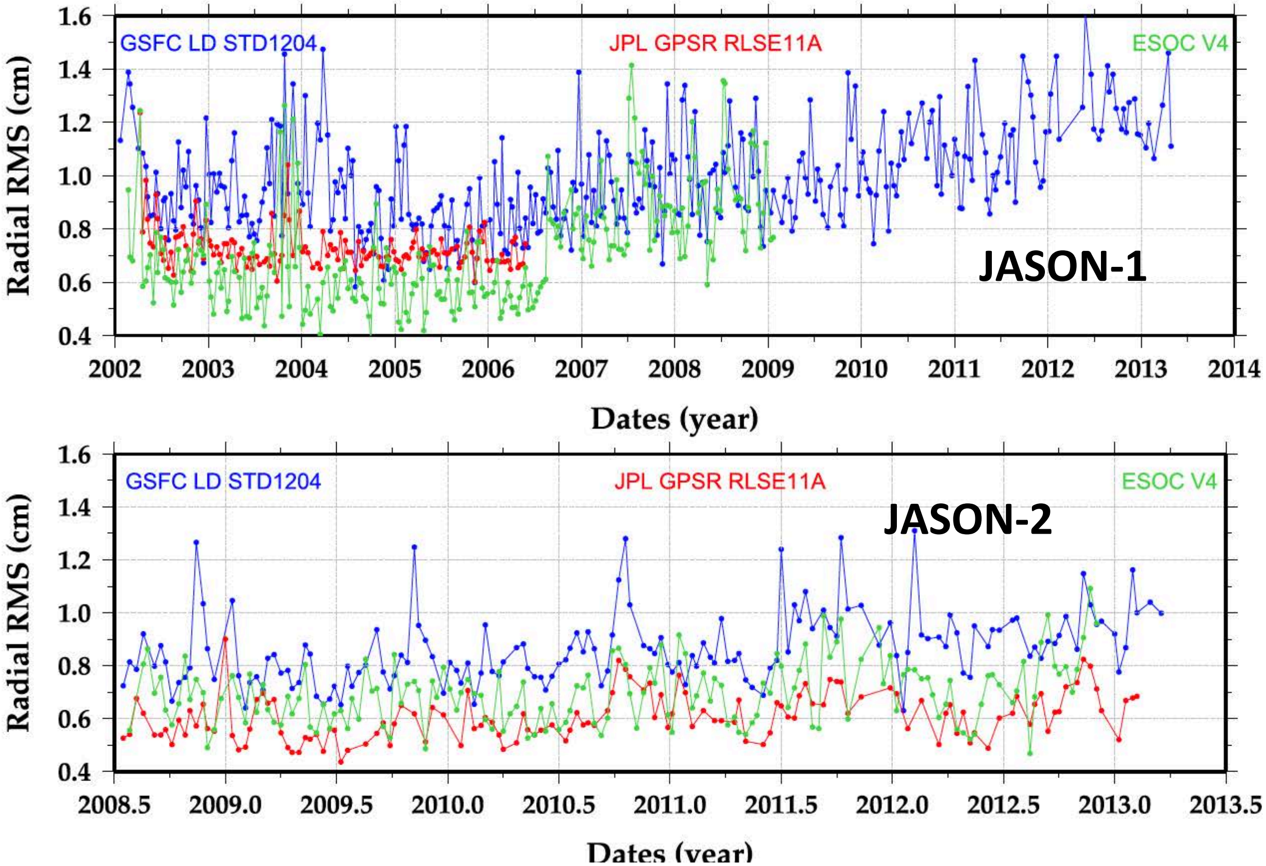


LRA for Jason-1, Jason-2, Jason-3
(courtesy of the ILRS)

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)



NASA GSFC
vs. JPL
vs. CNES
vs. ESOC

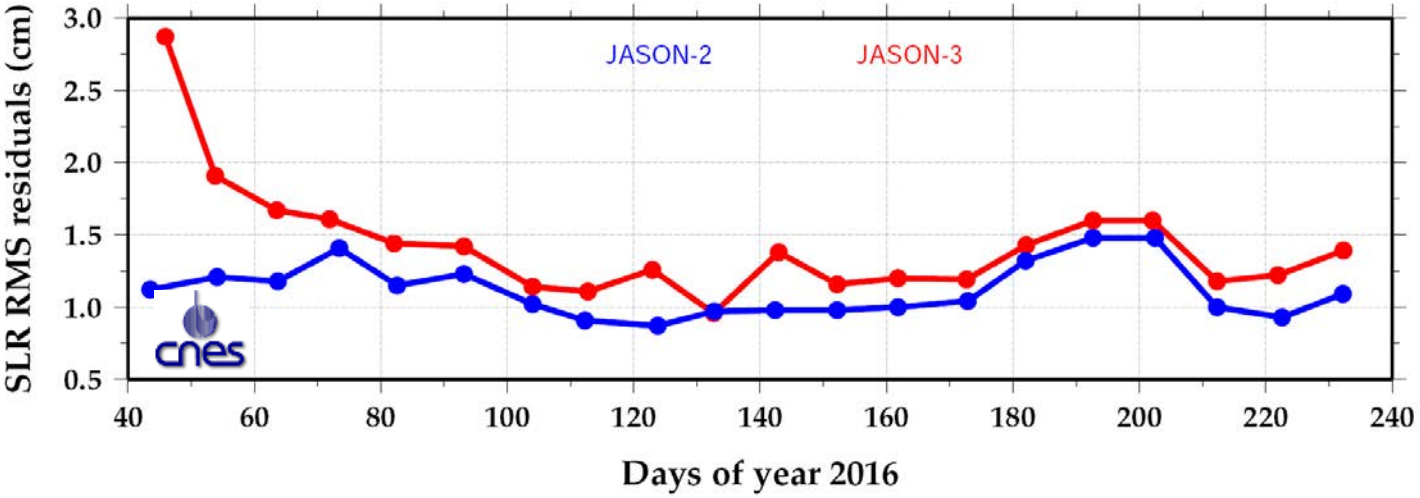
SLR/DORIS (NASA GSFC)
vs
GPS-only (JPL)
vs.
GPS+DORIS+SLR (ESOC)
vs.
GPS + DORIS + SLR
(CNES-GDR-D)

Couhert, A., et al., "Towards the 1 mm/y stability of the radial orbit error at regional scales", *Adv. Space Res.*, 2015, doi:10.1016/j.asr.2014.06.041.

SLR – Validation of Jason-2 GPS & DORIS orbits

SLR RMS of fit (Core stations, All elevations) for CNES GDR-E orbits (based on DORIS + GNSS, reduced-dynamic orbits)

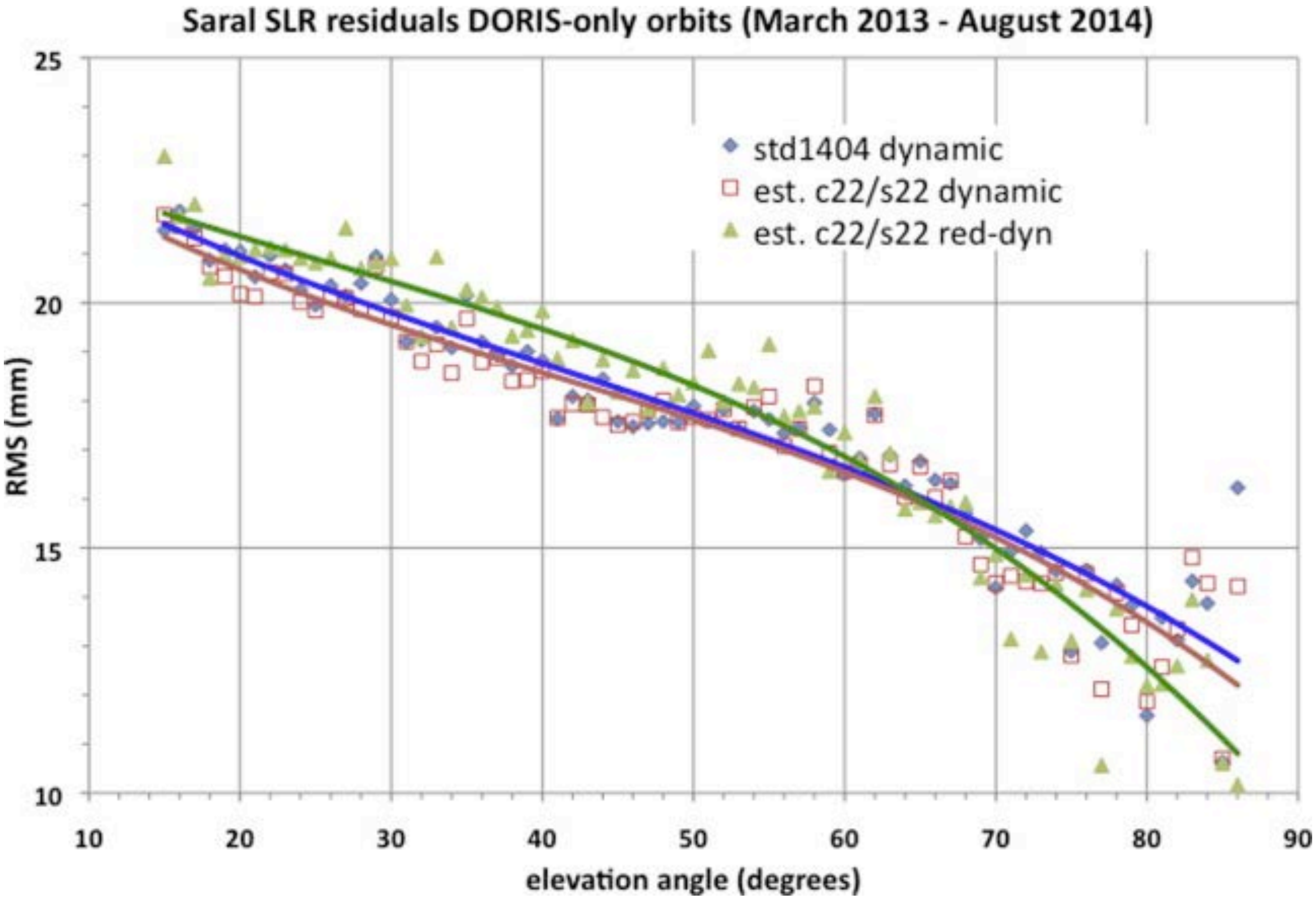
(from Alexandre Couhert, CNES)



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.

SLR – Evaluation of DORIS-only orbits (Saral)

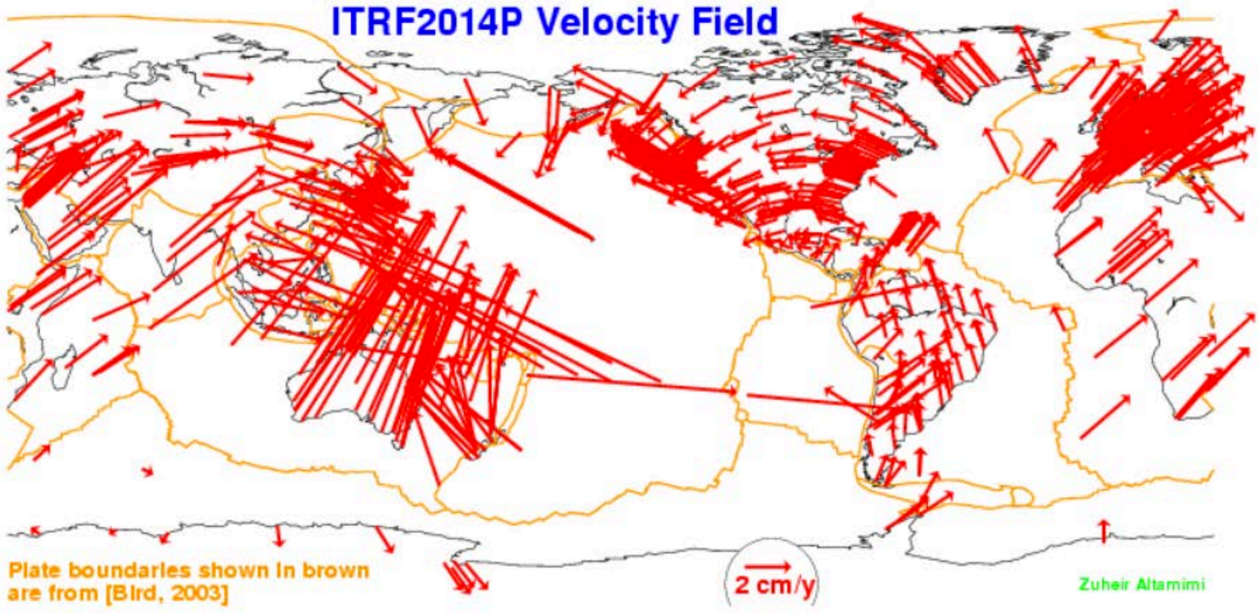


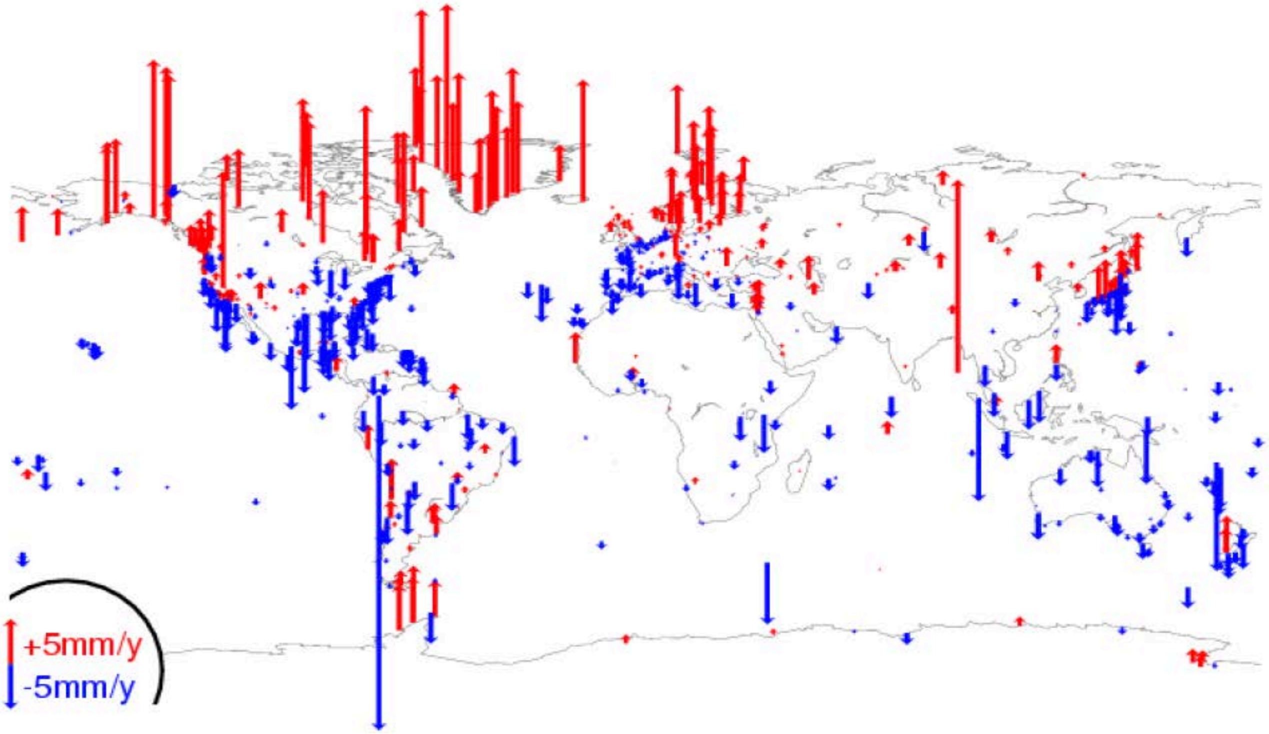
At high elevations SLR measures directly the radial orbit error; So in this example, we can say the DORIS-only orbits on SARAL have an orbital accuracy of 10-15 mm.

(Zelensky et al., 2016, "Towards the 1-cm SARAL orbit", *Adv. Space Res*, doi: 10.1016/j.asr.2015.12.011)

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.



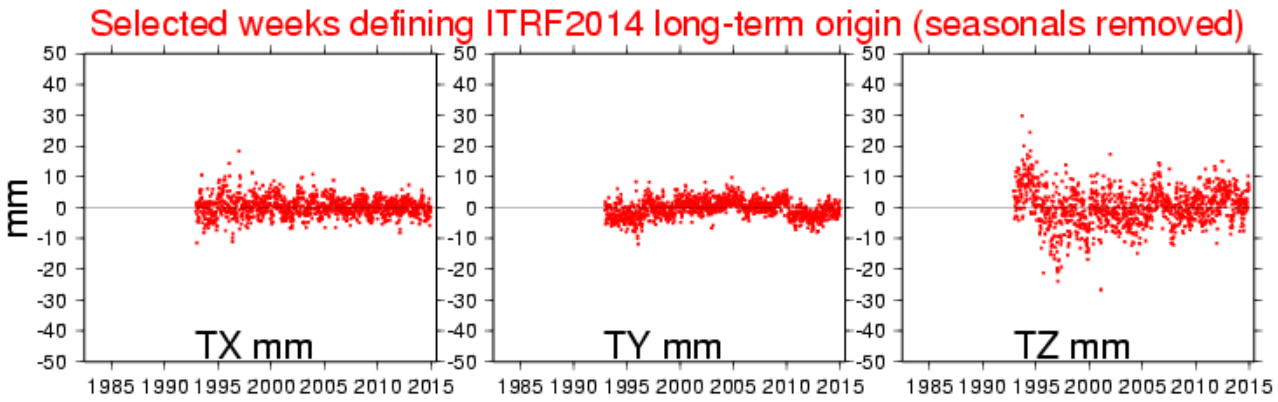


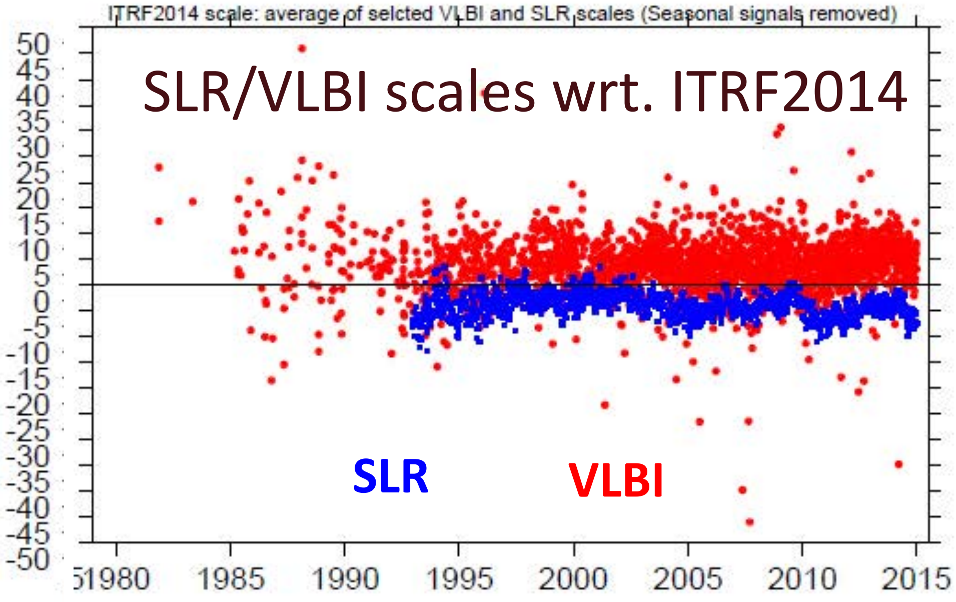
Figures from Zuheir Altamimi, IGN/France

SLR – Contribution to ITRF

SLR contributes to the origin and scale of the terrestrial reference frame as well as position/velocity of key reference points (core SLR stations).

ILRS/SLR origin components wrt. ITRF2014

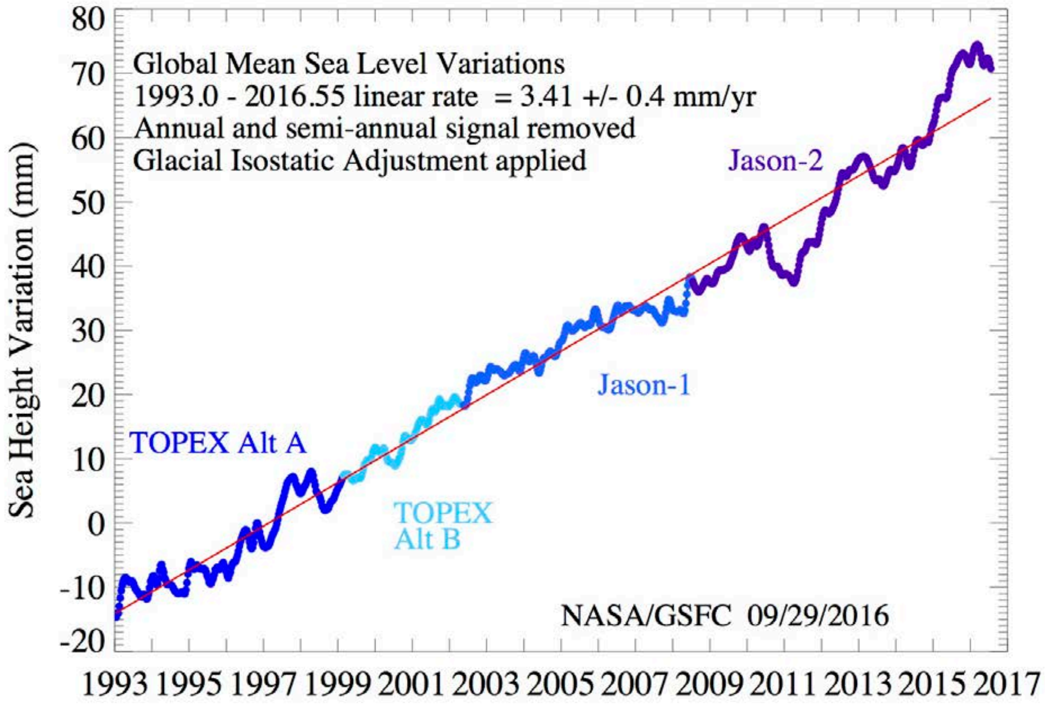




SLR/VLBI scales wrt. ITRF2014

Figures from Zuheir Altamimi, IGN/France
See also
Altamimi et al. (2016)

ITRF & Mean Sea Level

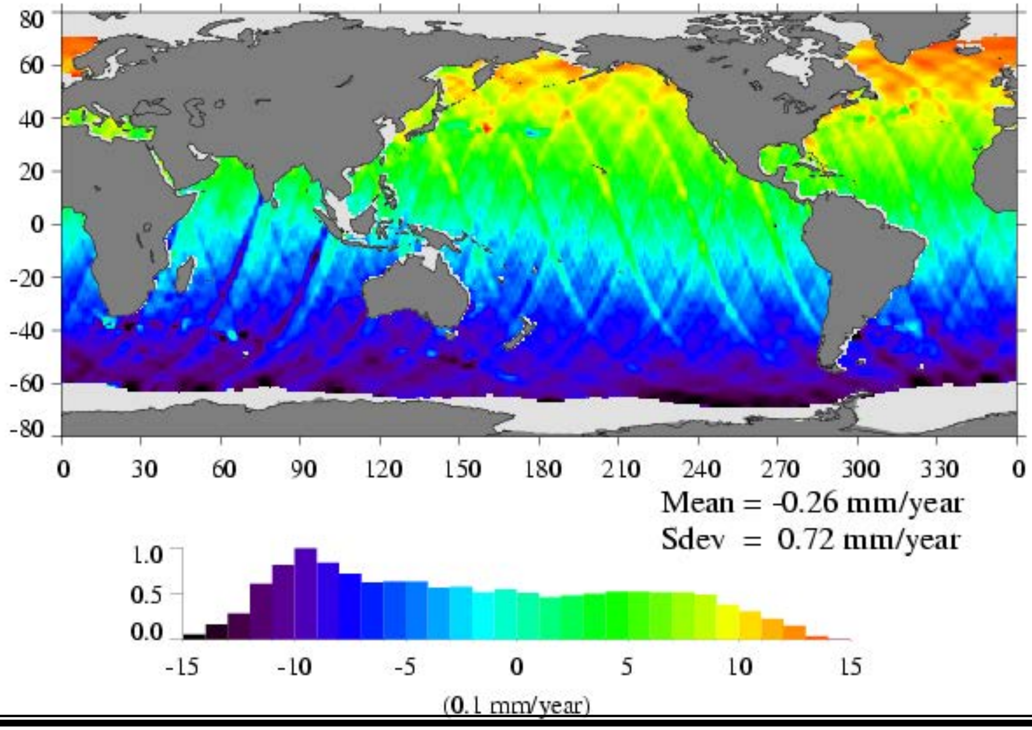


TP, J1, J2 ,J3. Prime data for Measure of change in global Mean Sea Level. (Key climate indicator).

- 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!!**

(GPS on TOPEX: 1993-1994 only; GPS on Jason-1: 2001-2006; GPS on Jason-2: 2008- present).

Mean Sea Level: Impact of TRF error



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.,** *Geophys. Res. Lett*.**, 2007).**

Errors in the Z component of the TRF can produce large regional errors in MSL rate determination.

SLR – Geocenter & Altimetry POD (I)

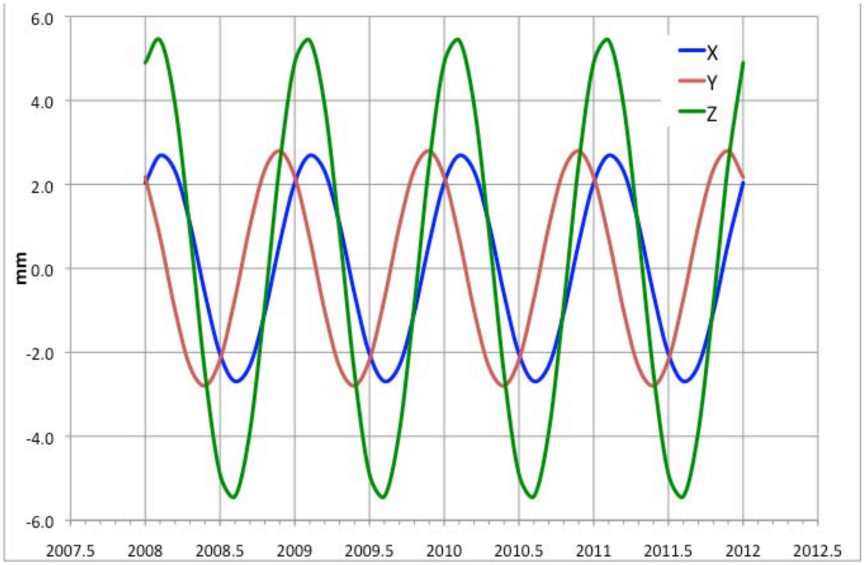
In the **solid** Earth center of mass frame, geocenter motion of the Total Earth's mass referenced to CF:

$$r_c\,(t) \;=\; r_{cm}\,(t) - r_{cf}\,(t)$$

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.

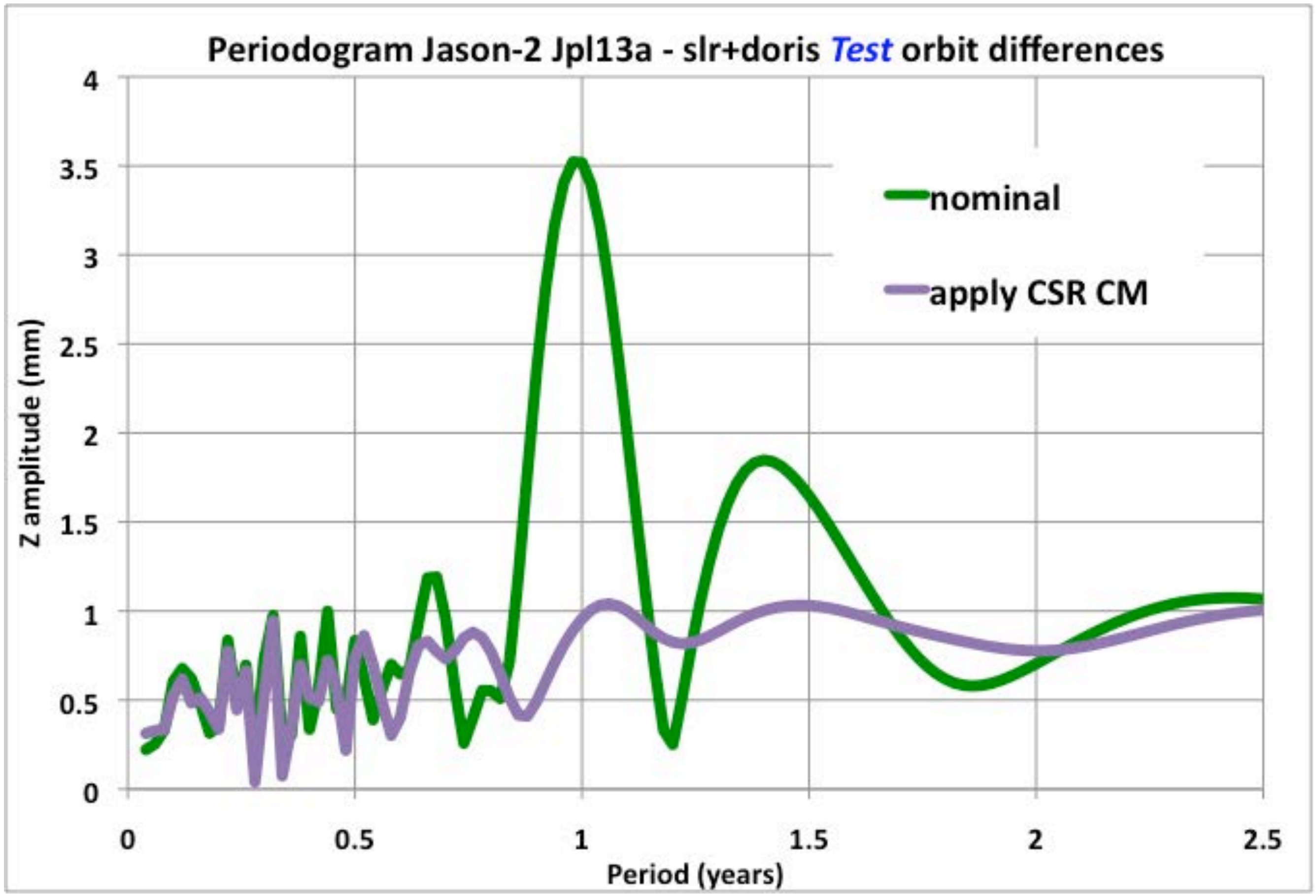
L1/L2 Geocenter Solution from Ries (2013)



Note. The SLR center of network (CN) becomes the center of figure (CF) origin in the SLR geocenter estimate.

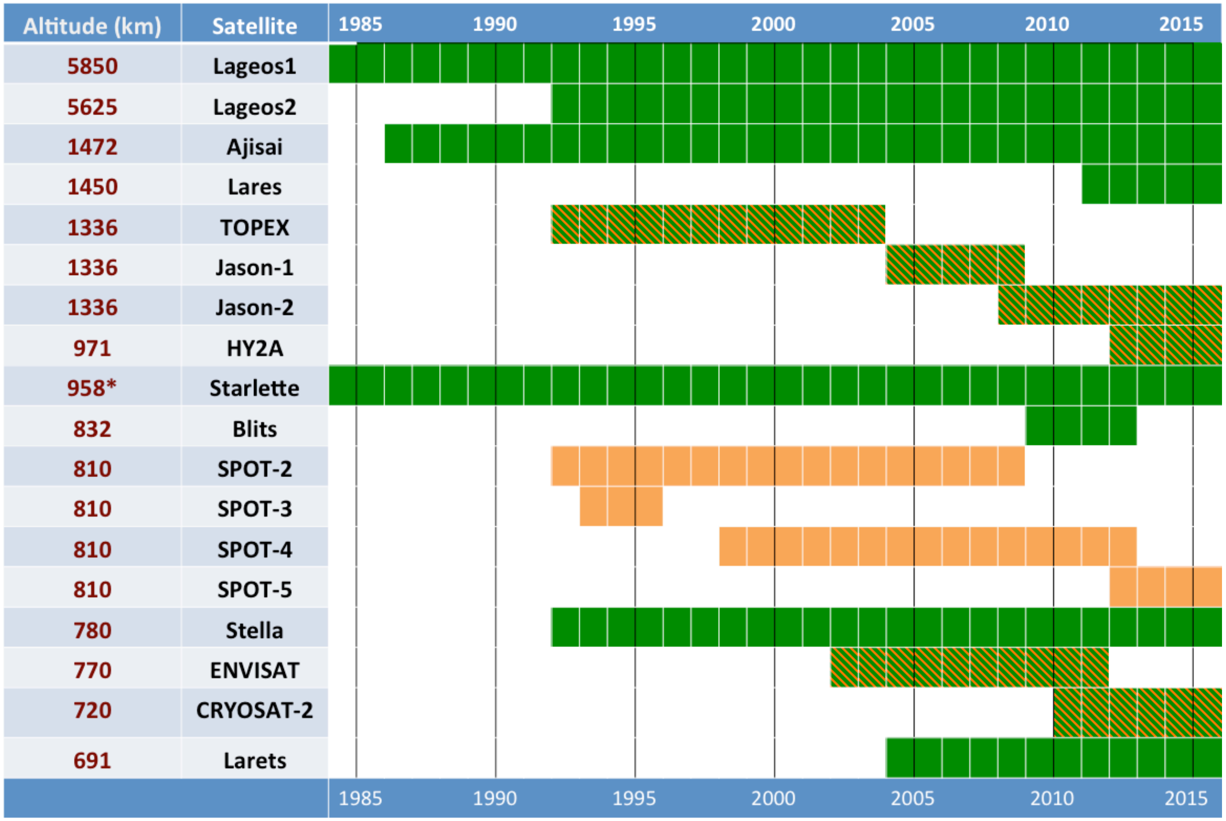
SLR – Geocenter & Altimetry POD (II)

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.

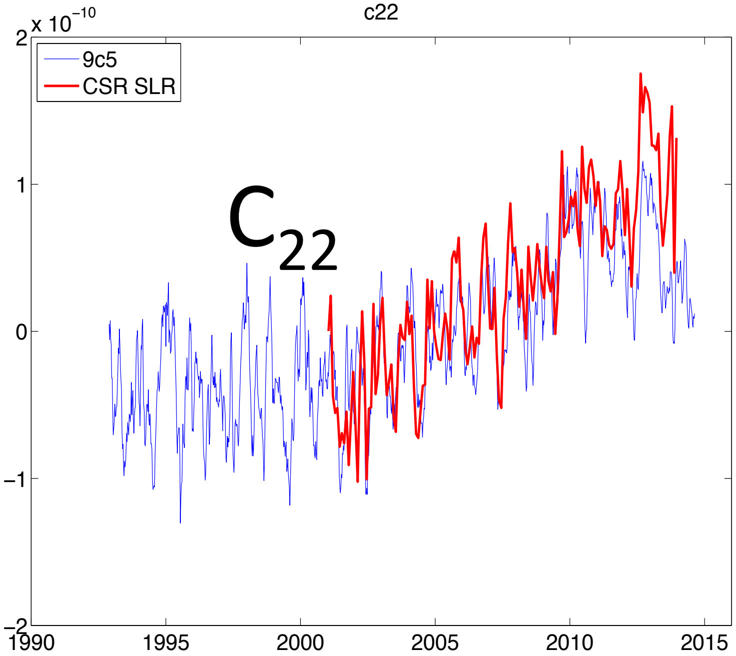


Altitude (km)	Satellite
5850	Lageos1
5625	Lageos2
1472	Ajisai
1450	Lares
1336	TOPEX
1336	Jason-1
1336	Jason-2
971	HY2A
958*	Starlette
832	Blits
810	SPOT-2
810	SPOT-3
810	SPOT-4
810	SPOT-5
780	Stella
770	ENVISAT
720	CRYOSAT-2
691	Larets

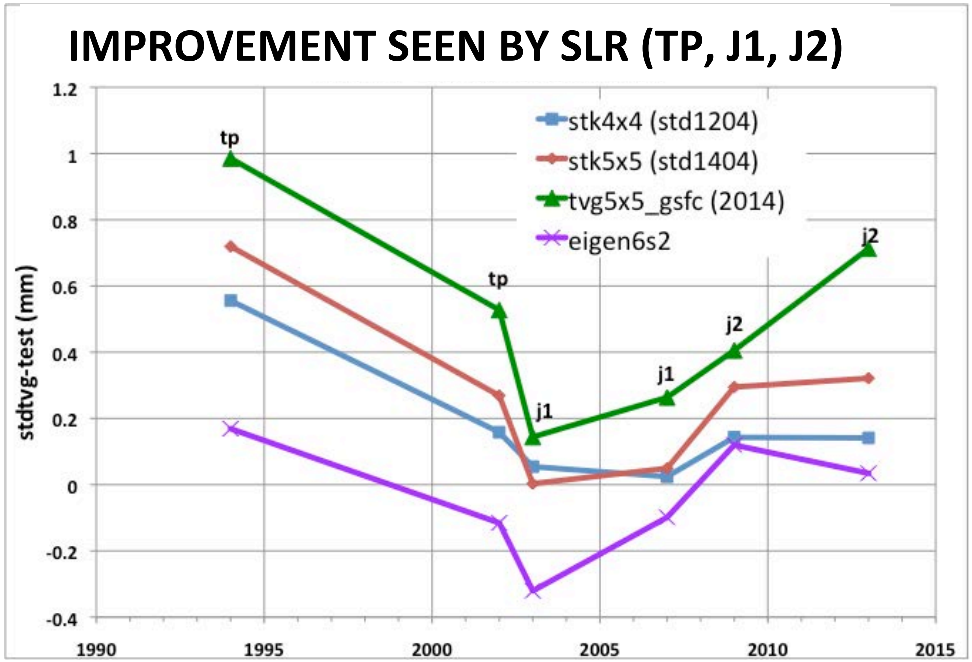
* Starlette: Elliptical orbit (~800 x ~1100 km)

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)

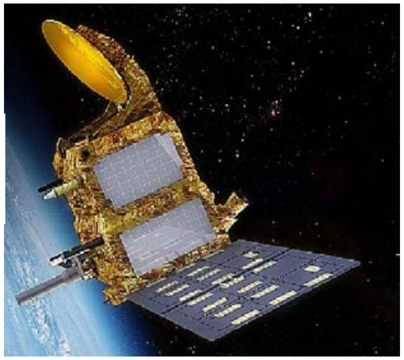

Jason-2, 2008-
Jason-3, 2016-

SLR+DORIS+GNSS

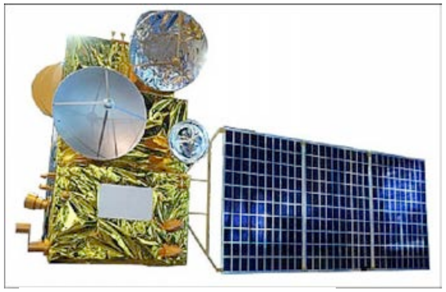

CRYOSAT-2, 2010-

SLR+DORIS

ISRO
(India)


SARAL, 2013-

SLR+DORIS


Haiyang
(HY)-2A, 2011
(CNSA)

SLR+DORIS+ … (GNSS*)


Sentinel-3A
2016

(SLR)+DORIS+GNSS

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

Golden Age of Satellite Altimetry!!

Summary: Why do we need multiple tracking systems?

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.

SLR – Model Improvement & Validation for Altimeter Satellites (Examples)

1. Improvements in Time-variable gravity modeling, and in the ITRF.

Couhert A et al. (2015) "Towards the 1 mm/y stability of the radial orbit error at regional scales", *Adv. Space Res*., *doi:10.1016/j.asr.2014.06.041.*

2. Improvement in Non-conservative force modelling.

Zelensky et al., (2010). "DORIS/SLR POD modeling improvements for Jason-1 and Jason-2", *Adv. Space Res.,* *doi:10.1016/j.asr.2010.05.008*

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.

4. Monitoring Performance of DORIS/USO on Jason-2 using T2L2 instrument.

Belli A. **et al ., in press (2016). "Temperature, radiation and aging analysis of the DORIS Ultra Stable Oscillator by means of the Time Transfer by Laser Link experiment on Jason-2"**, ***Adv. Space Res***., *doi: 10.1016/ j.asr.2015.11.025.*

- Introduction
- The science of Satellite Altimetry.
- Role & Contribution of SLR.
  (1) POD.
  (2) ITRF.
  (3) Geocenter.
  (4) Time-Variable Gravity.
  (5) Orbit Validation.
  (6) Model Validation.
- **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.

Graz

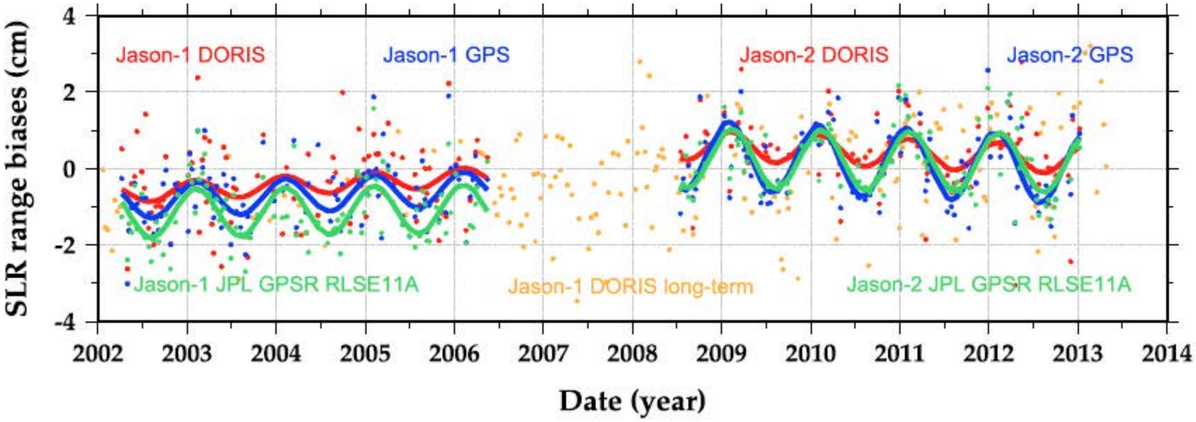
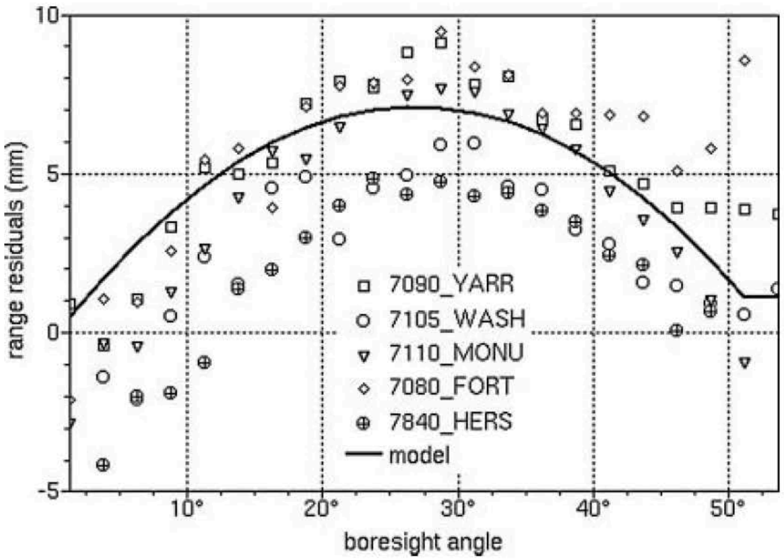


Fig. 6. Mean SLR Graz L7839 reference station residuals by cycle above 70° elevation from 2002 to 2013 for the Jason-1 and Jason-2 independent DORIS-only, GPS-based GDR-D-like dynamic orbits and JPL GPS-Reduced-dynamic counterparts. The solid curves are the results of the least squares fit to the mean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

Couhert, A., et al., "Towards the 1 mm/y stability of the radial orbit error at regional scales", *Adv. Space Res.*, 2015, doi:10.1016/j.asr.2014.06.041.

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

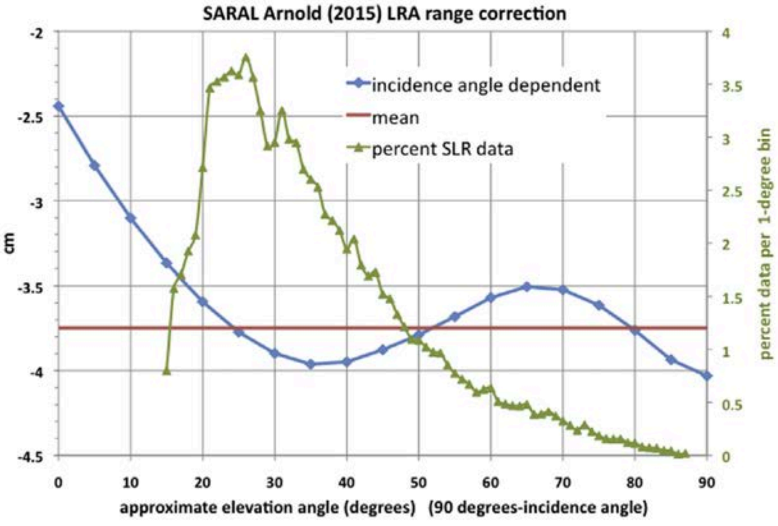


Fig. 3.2. Arnold LRA (2015) models and percent SLR data used in SARAL POD.

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.