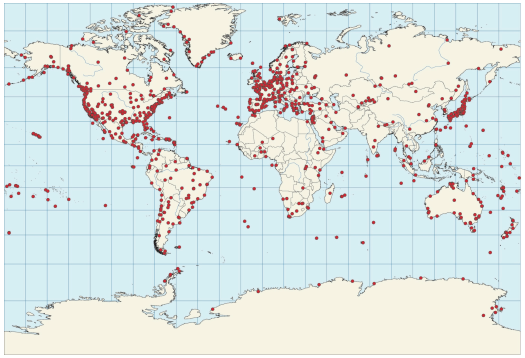
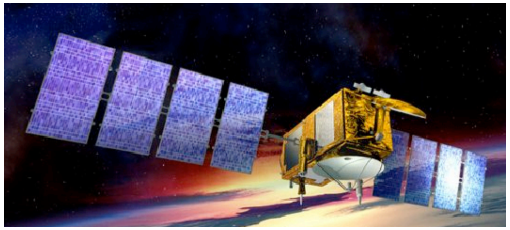
LAGEOS:
Importance to the Reference Frame, Enabled Missions, Future Outlook

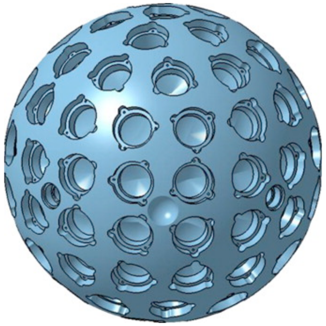
LAGEOS 1,2



(e.g.) ITRF2014



Altimeter satellites



LARES

Frank G. Lemoine

"40 Years of Reflections"

(40th Anniversary LAGEOS celebration)

Planetary Geodynamics Laboratory, Code 698

NASA Goddard Space Flight Center

May 11, 2016

Reference Frame: What is it?

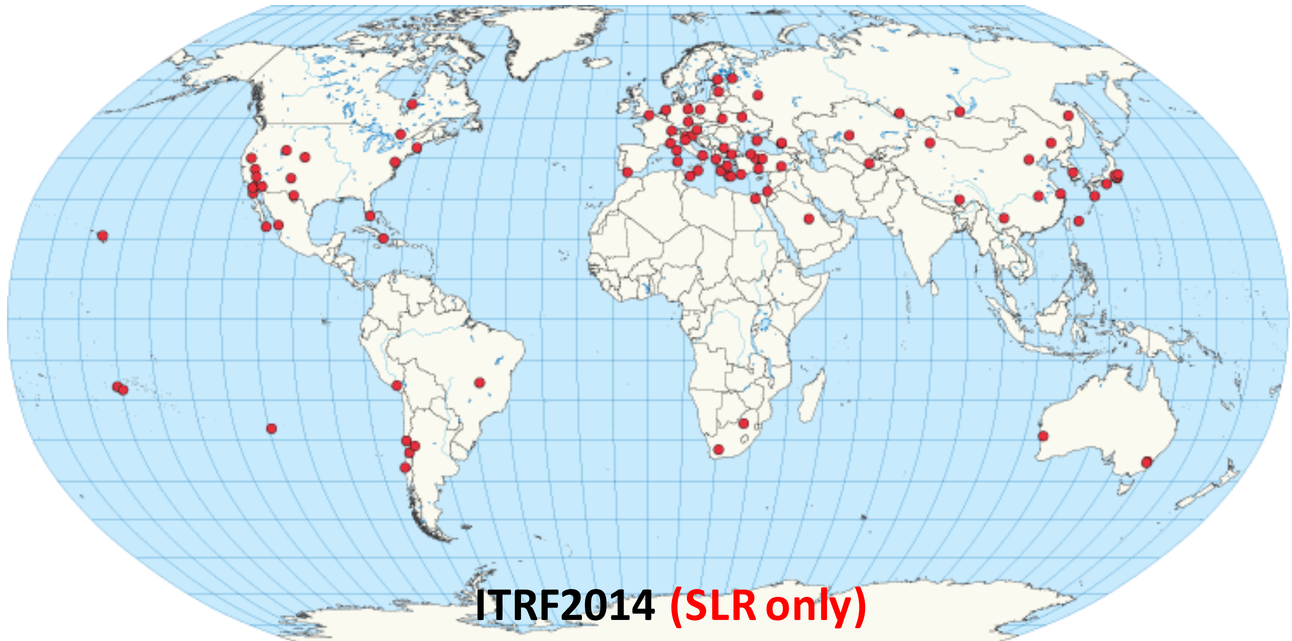
SLR

e.g. Hartebeesthoek

+

GPS

e.g. Greenbelt



+ VLBI

e.g. Greenbelt

+ DORIS

e.g. Yarragadee

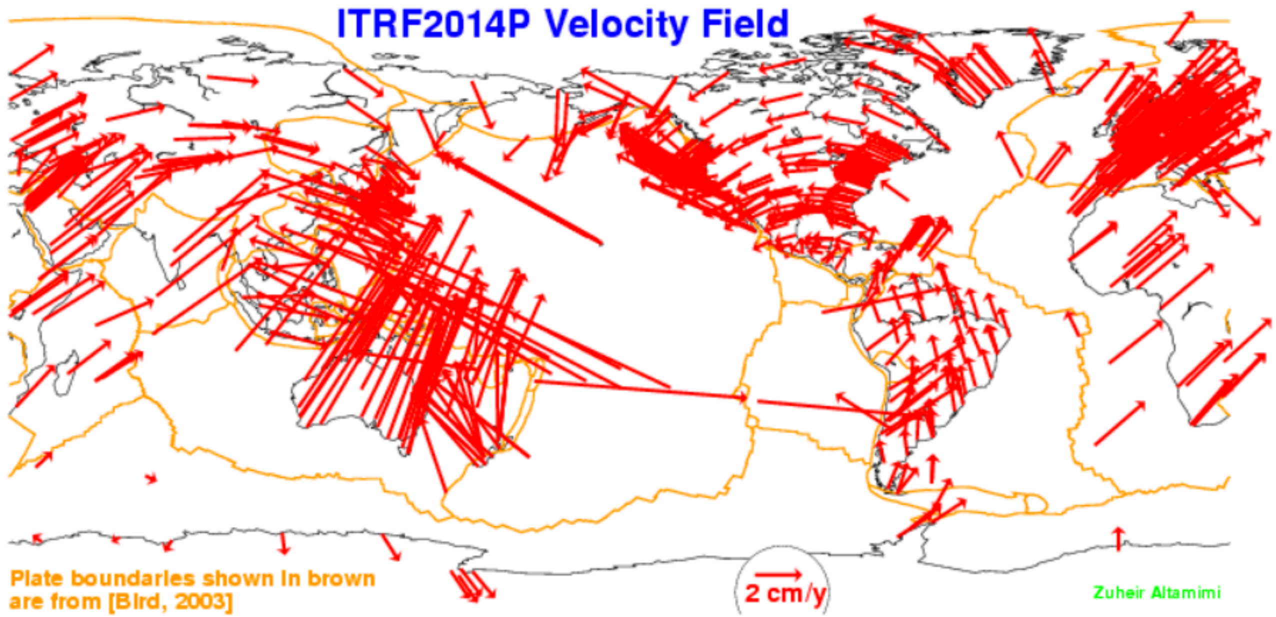
+ site ties

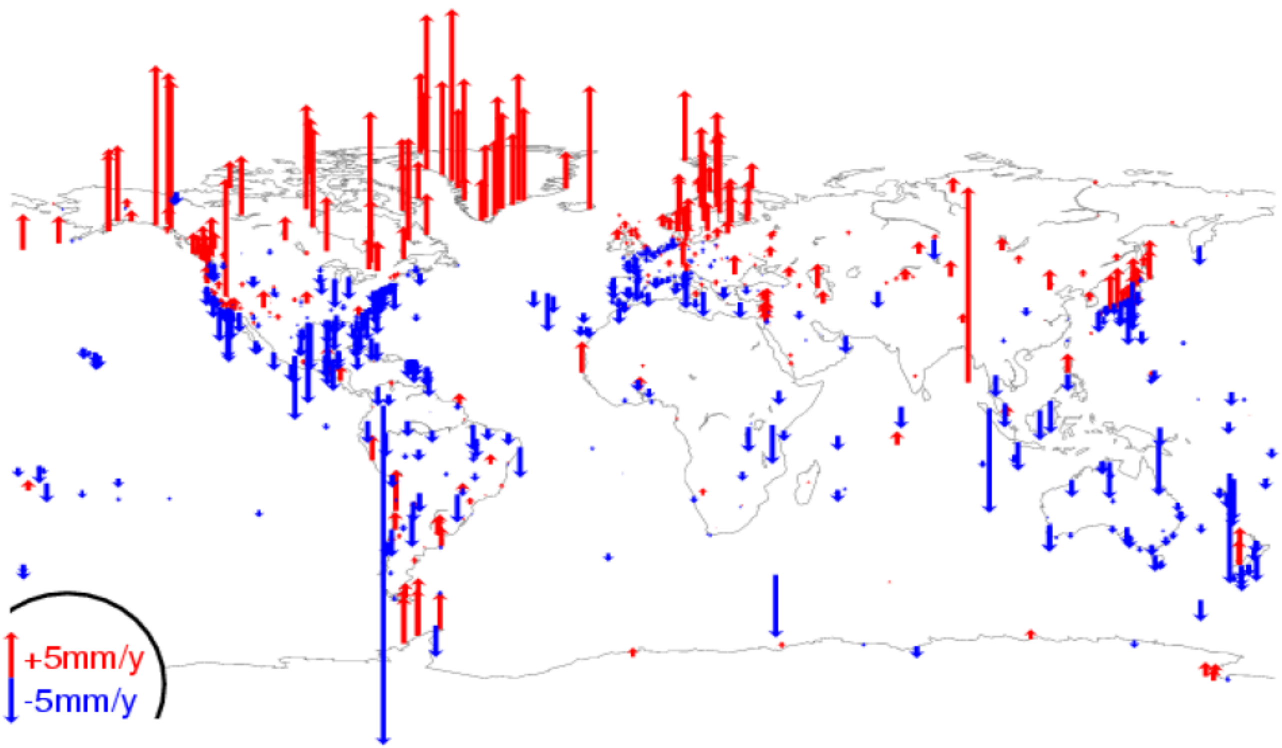
=

an ITRF Realization, e.g. ITRF2014

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

ILRS/SLR origin components wrt. ITRF2014

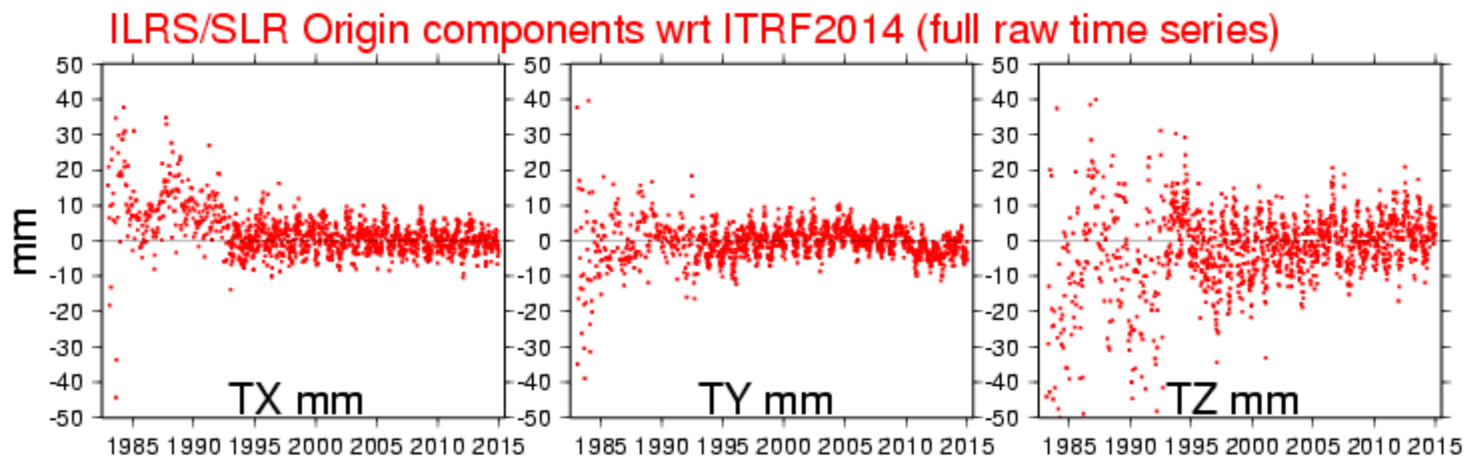


Figure from Zuheir Altamimi, IGN/France (Altamimi et al., 2016)

ILRS/SLR origin components wrt. ITRF2014

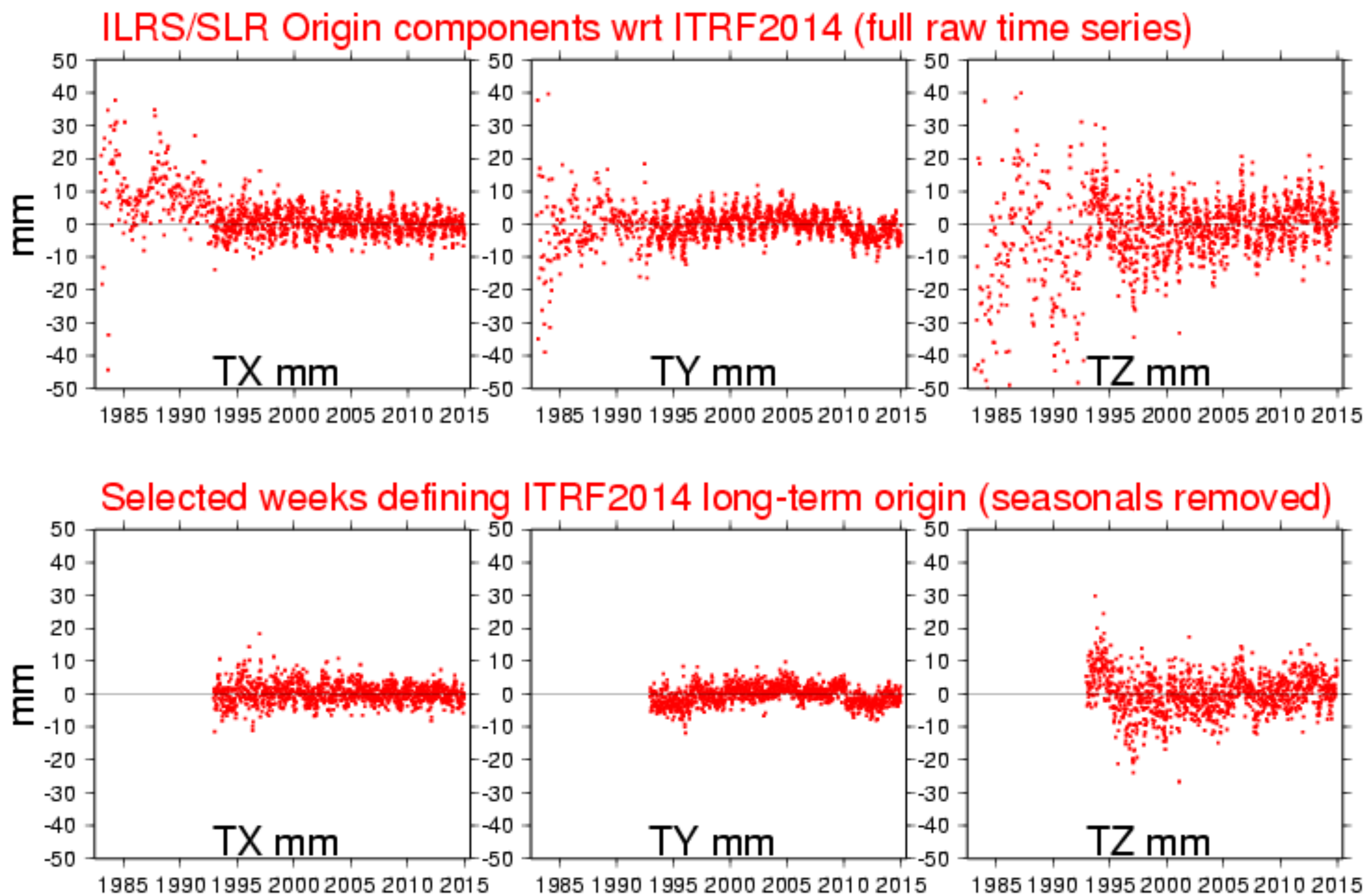


Figure from Zuheir Altamimi, IGN/France (Altamimi et al., 2016)

Annual Geocenter Motion Model

Annual amplitudes & phases fitted to the SLR translation time series

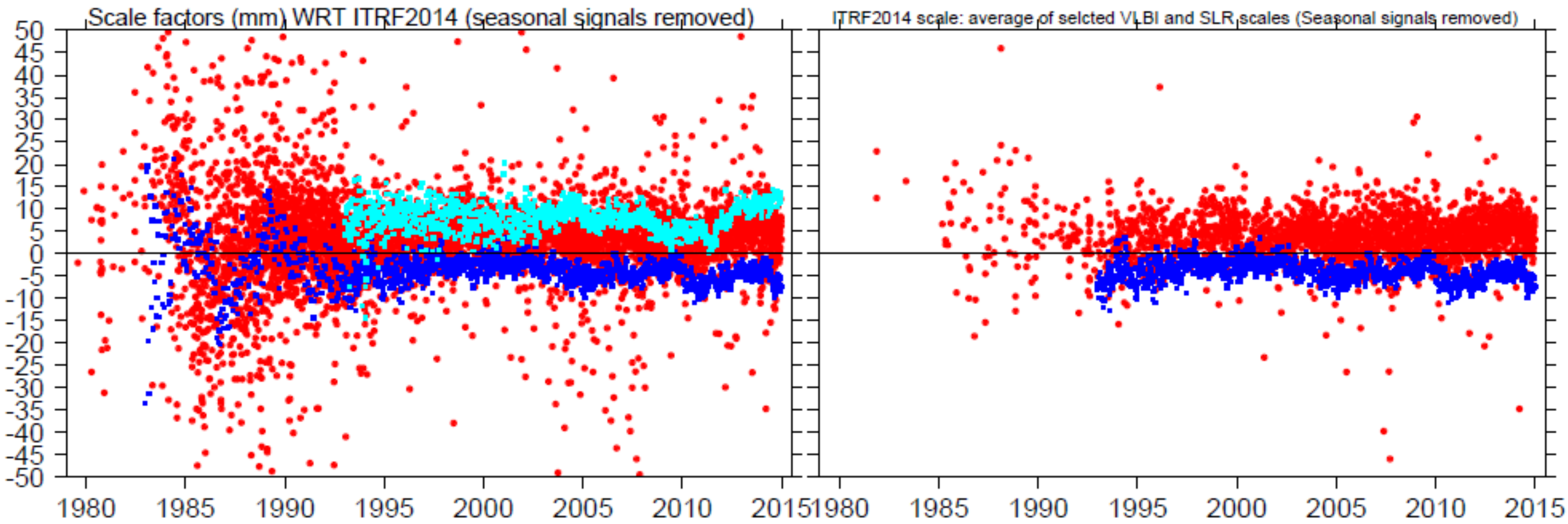
	X		Y		Z	
	A mm	φ deg	A mm	φ deg	A mm	φ deg
ITRF 2014	2.6 ±0.1	226 ±3	2.9 ±0.1	140 ±2	5.7 ±0.2	208 ±2
ITRF 2008	2.6 ±0.1	222 ±3	3.1 ±0.1	135 ±2	5.5 ±0.3	202 ±10

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

We model the geocenter explicitly in Precise Orbit Determination for Altimeter Satellites and get better agreement between SLR+DORIS & GPS Orbits on Jason-2.

(See Melachroinos et al., Adv. Space Res., 2013, doi 10.1016/j.asr.2012.06.004 for details)

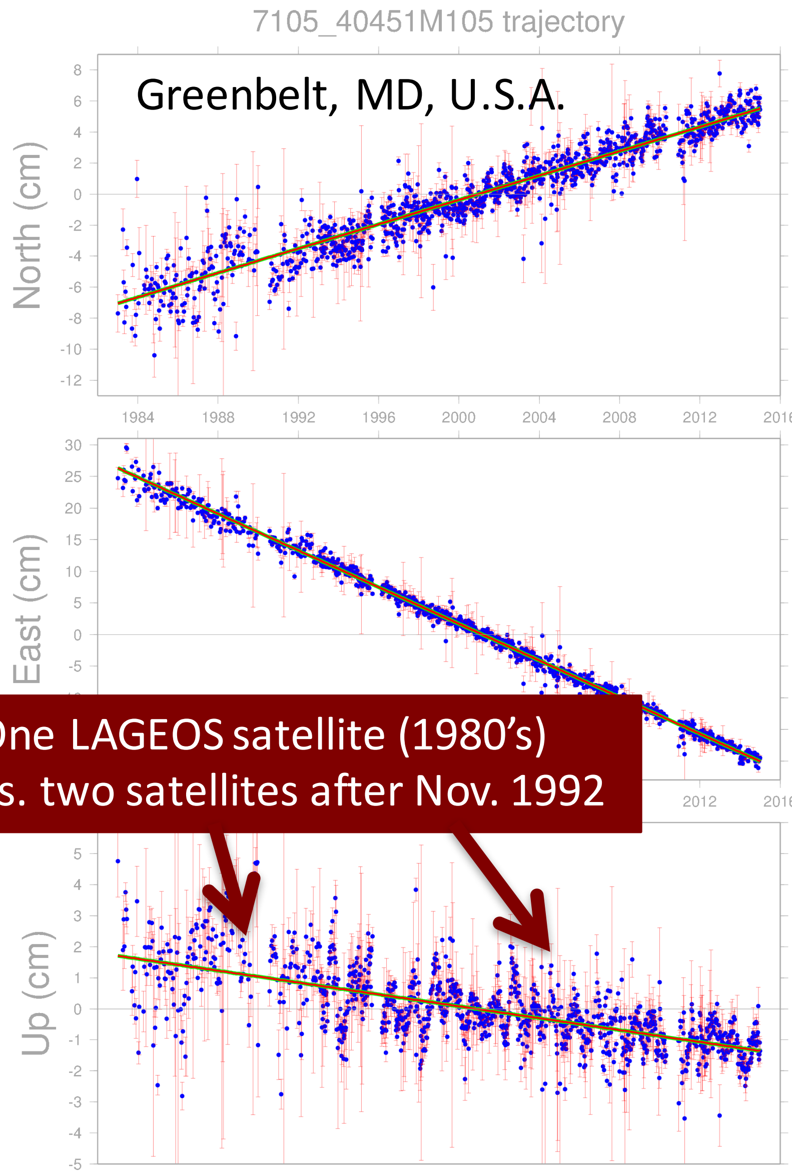
DORIS, SLR & VLBI scales wrt ITRF2014



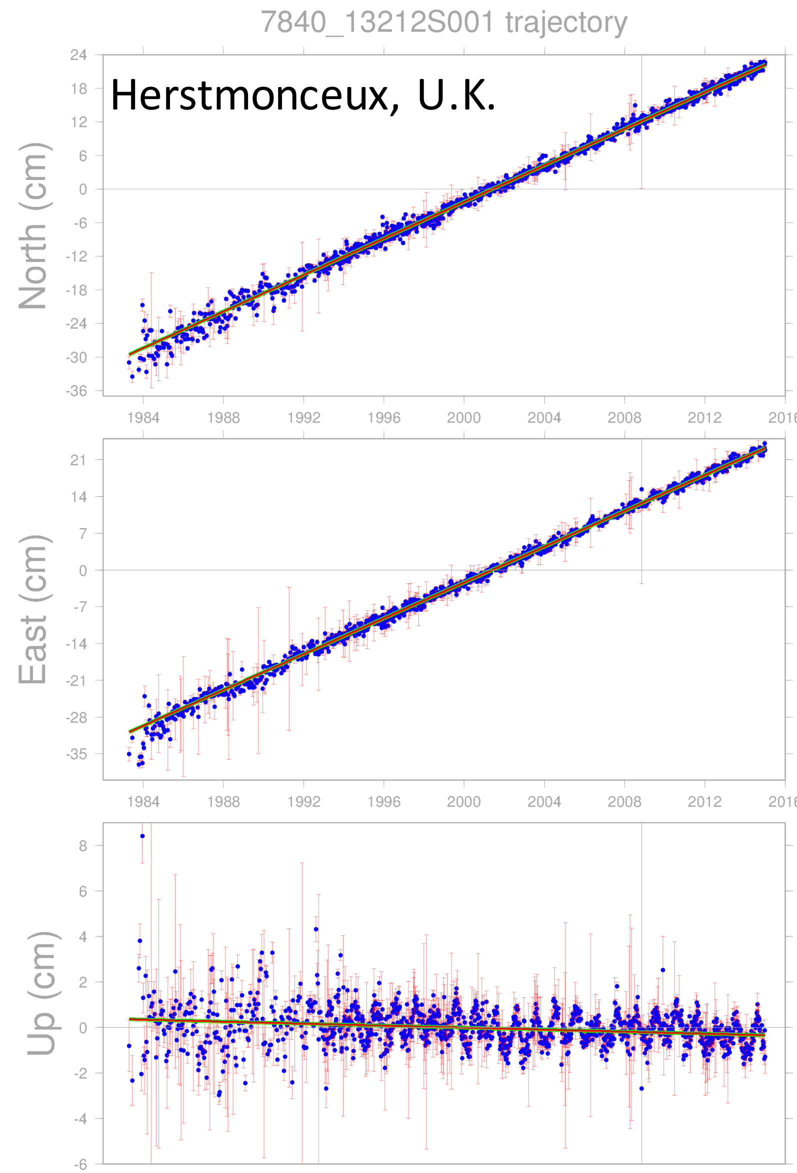
DORIS SLR VLBI

Figure from Zuheir Altamimi, IGN/France (Altamimi et al., 2016)

ITRF2014: SLR station history



Trajectory: Blue: Raw, Green: Linear, Red: PSD model
Vertical gray lines represent discontinuities



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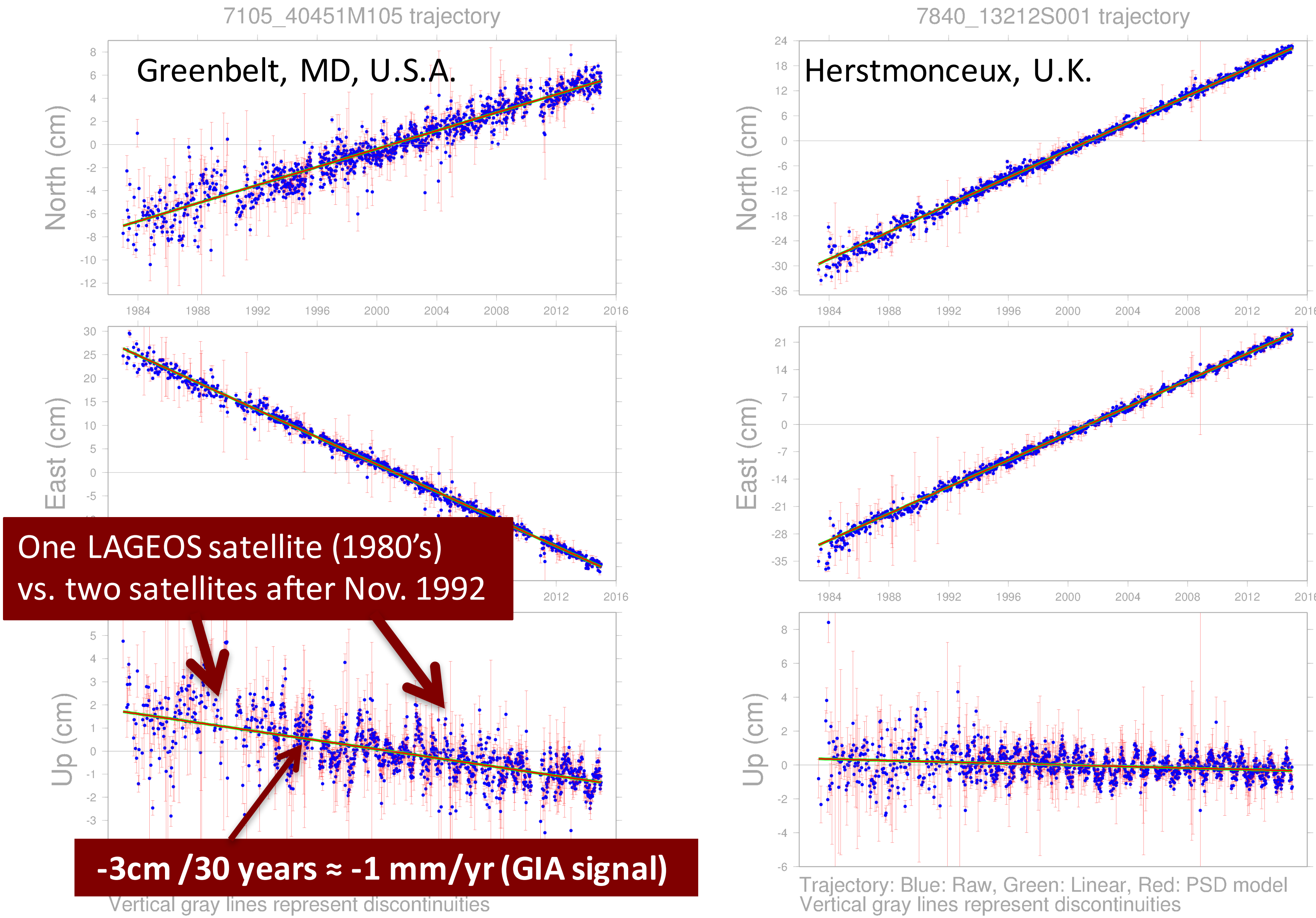
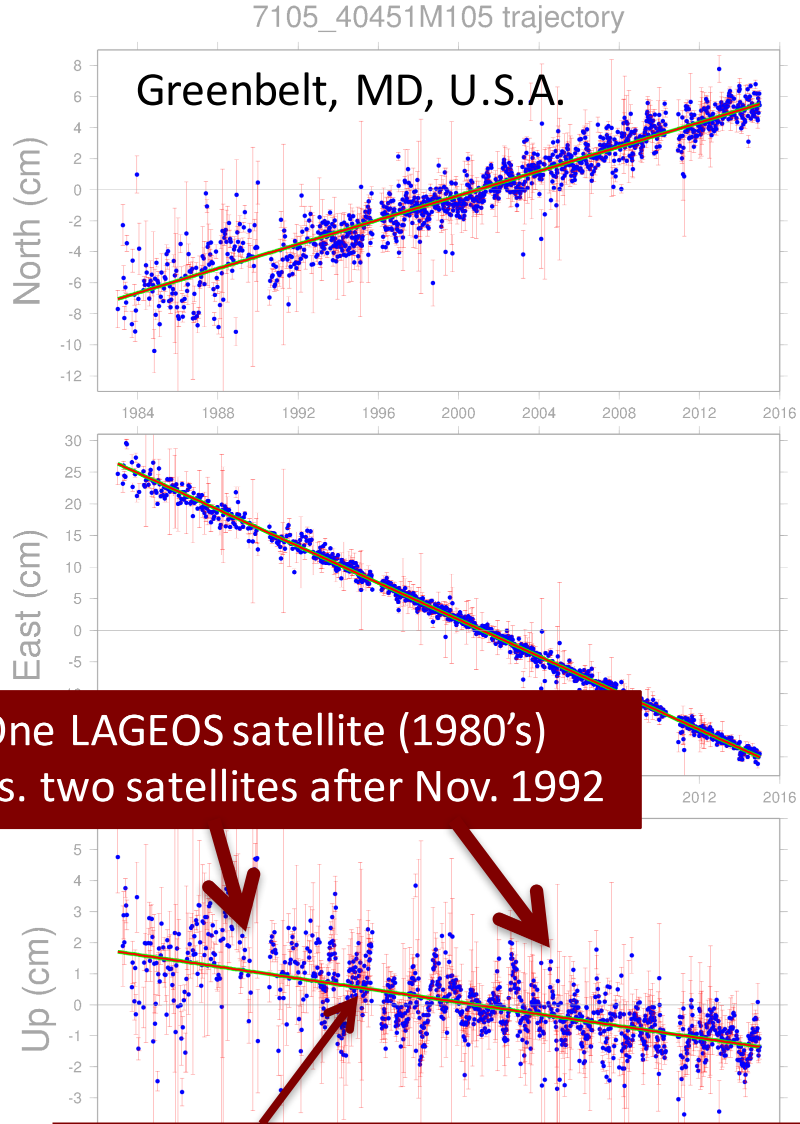
ITRF2014: SLR station history



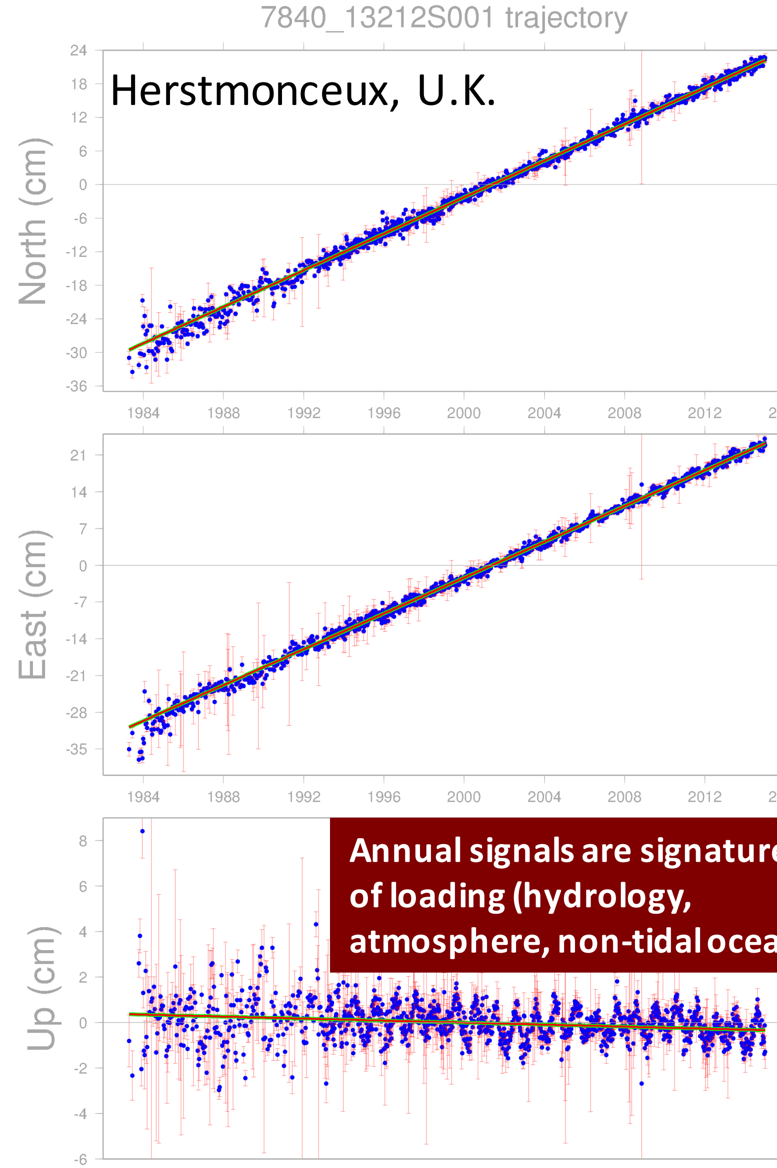
ITRF2014: SLR station history



One LAGEOS satellite (1980's) vs. two satellites after Nov. 1992

-3cm /30 years ≈ -1 mm/yr (GIA signal)

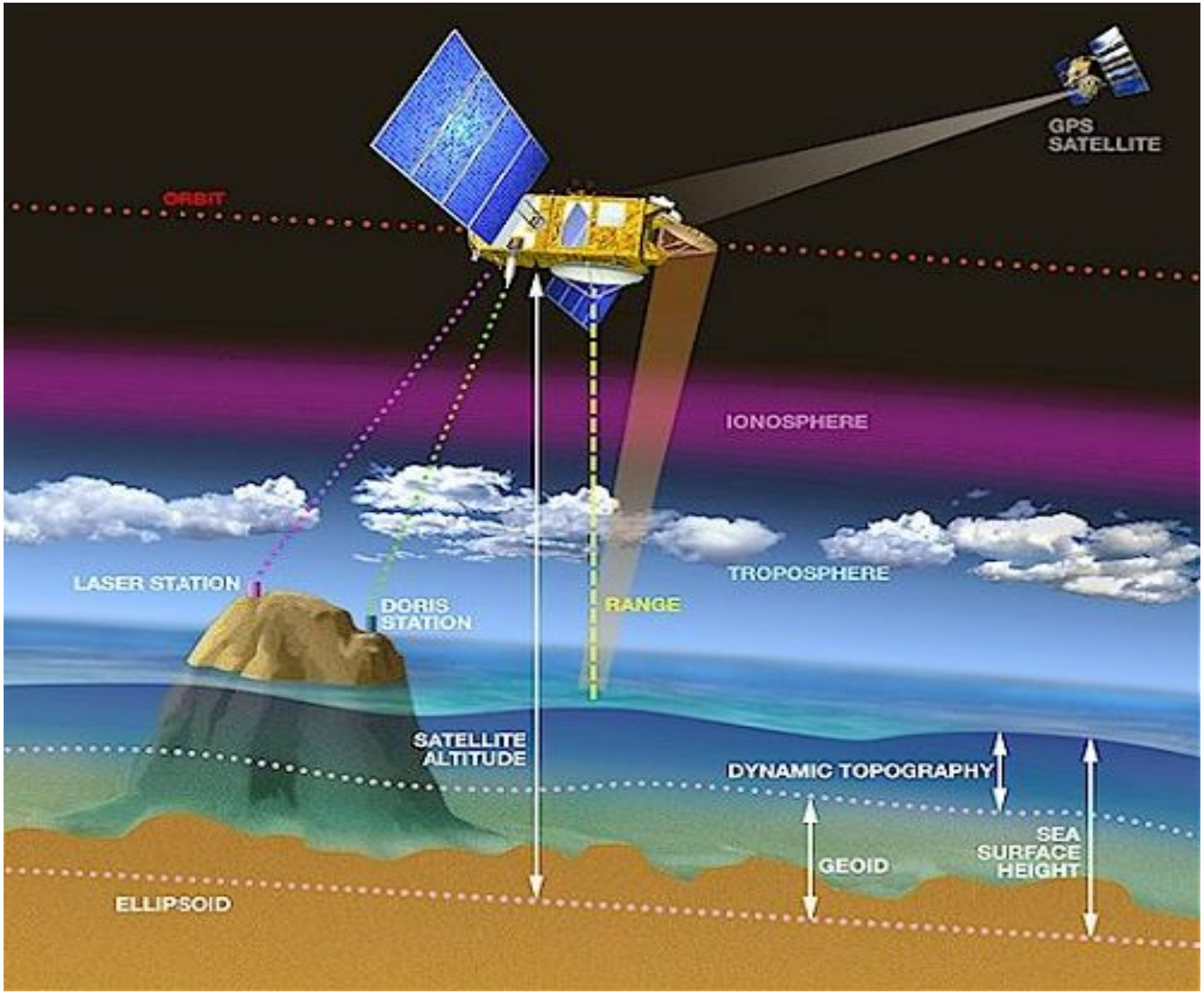
Vertical gray lines represent discontinuities



Annual signals are signatures of loading (hydrology, atmosphere, non-tidal ocean)

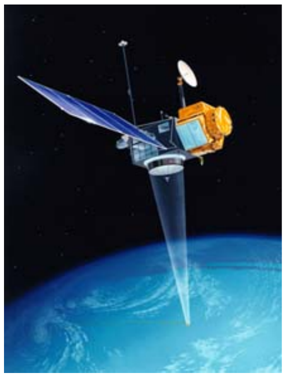
Trajectory: Blue: Raw, Green: Linear, Red: PSD model
Vertical gray lines represent discontinuities

POD - Schematic

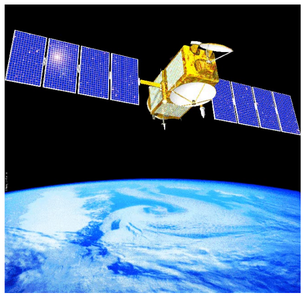


Altimeter Satellites

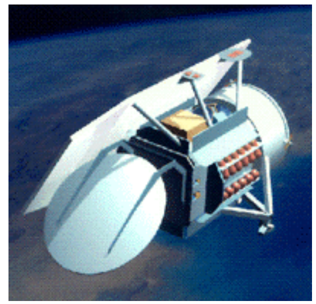
- **SLR data (**provided by stations whose positions were determined by SLR tracking of LAGEOS 1 & 2**) anchor the altimeter satellite orbits in the ITRF.**
- **SLR data are also essential for orbit validation for all missions.**



TOPEX/Poseidon 1992



Jason-1, 2002
Jason-2, 2008
Jason-3, 2016

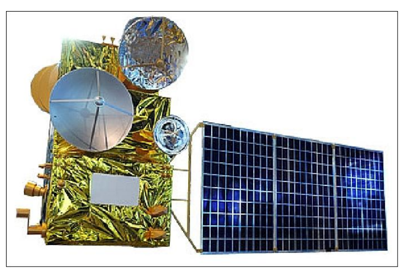


GFO, 1998

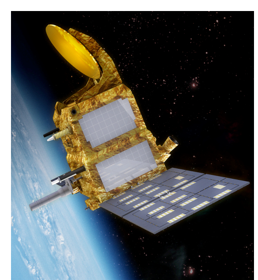
ERS-1, 1991
ERS-2, 1995

ENVISAT, 2002

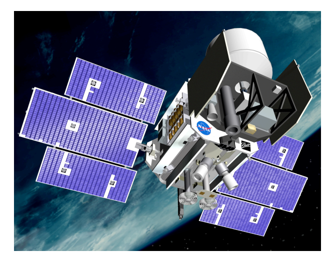
CRYOSAT-2, 2010



HY-2A, 2011

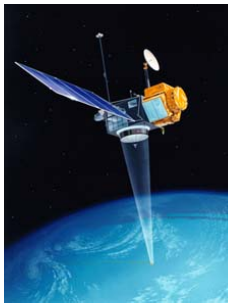


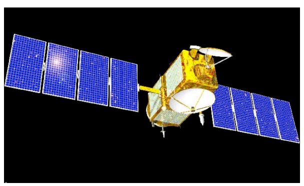
Saral, 2013

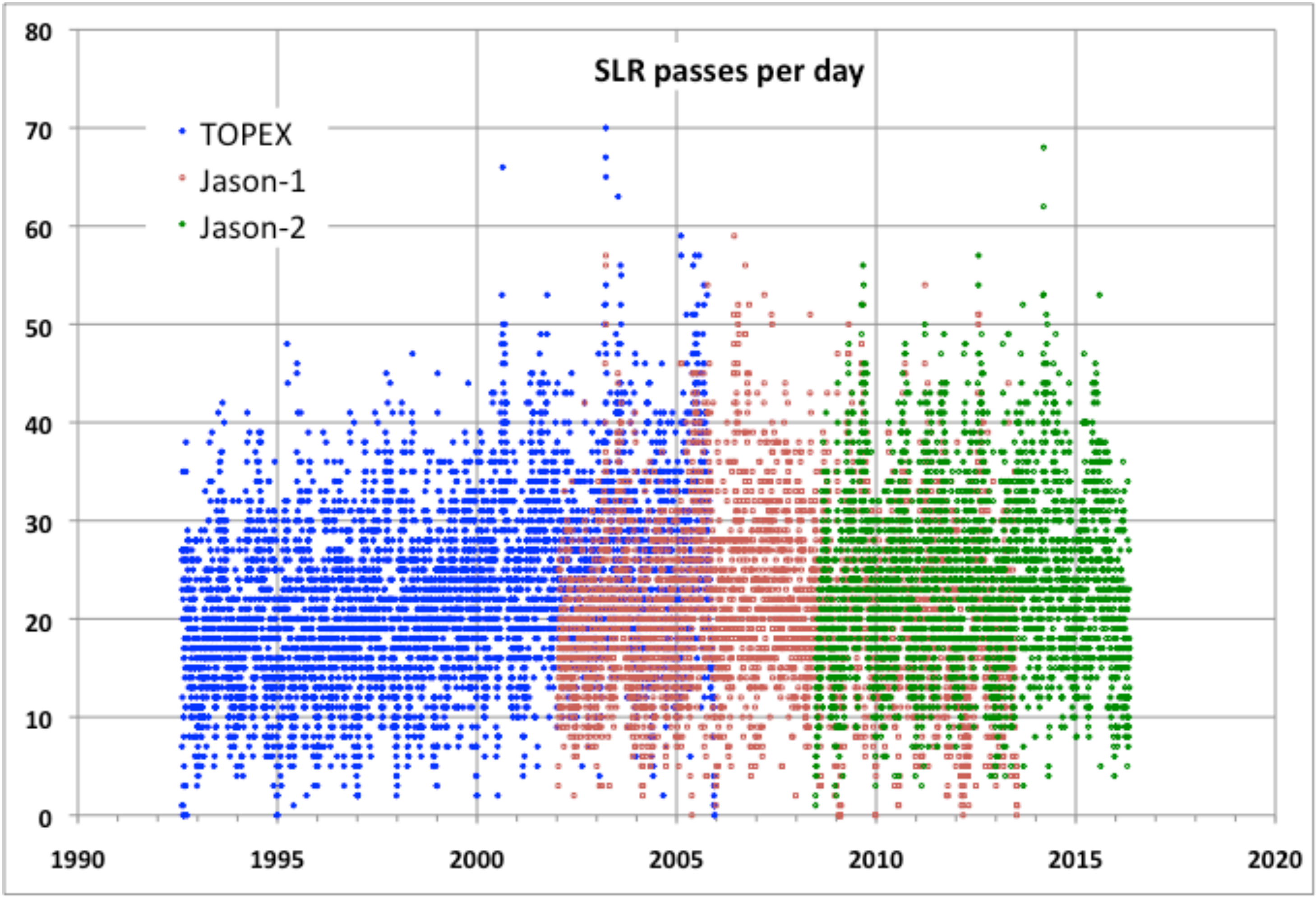


ICESAT-1, 2003

SLR – TP, J1, J2 tracking summary







SLR – RMS of fit (TP, J1, J2)

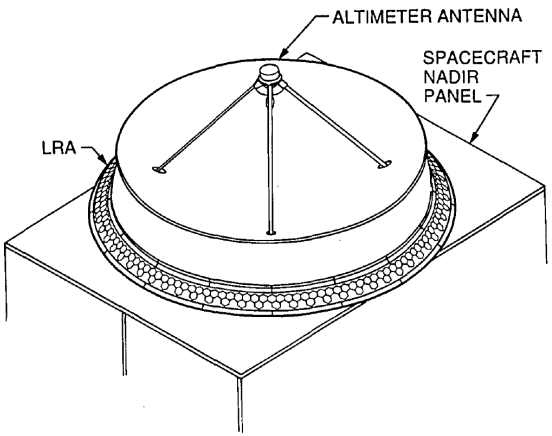
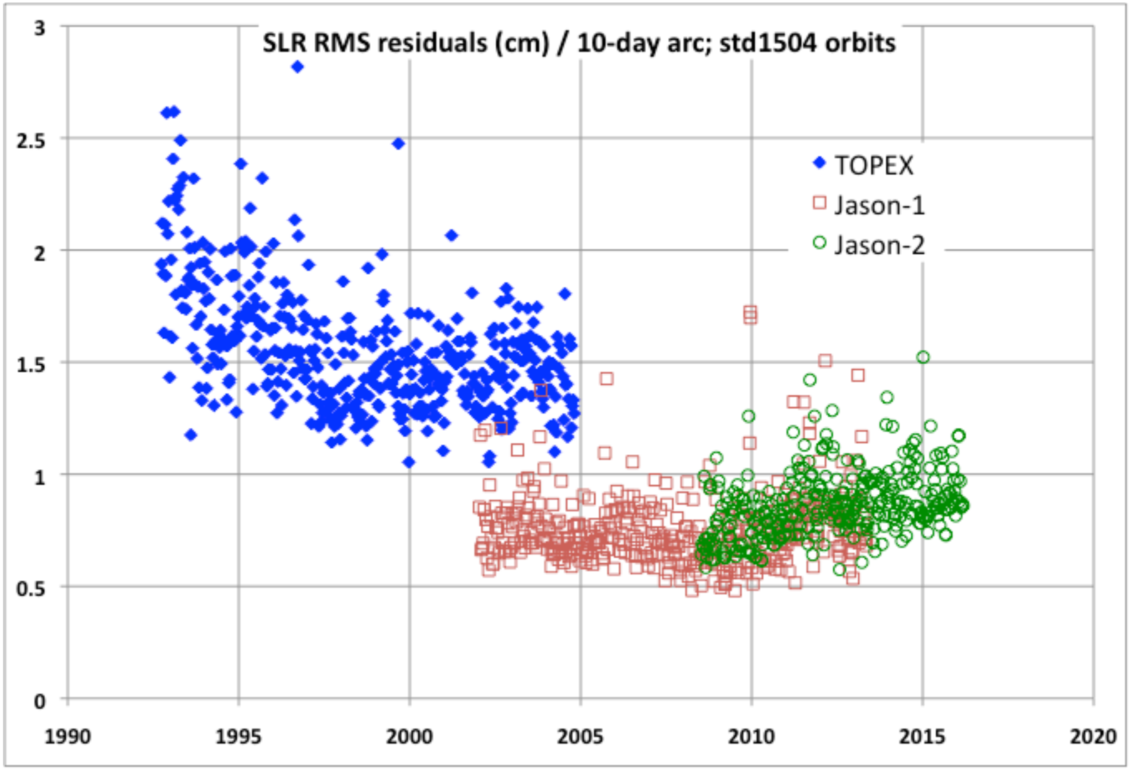
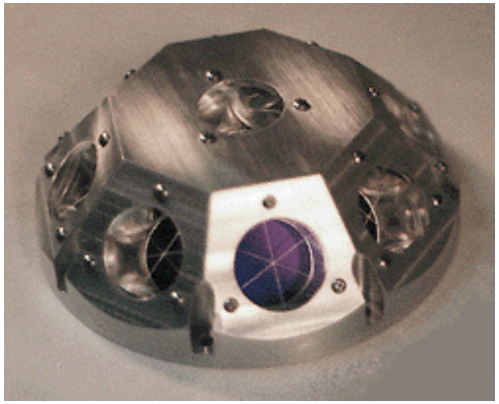


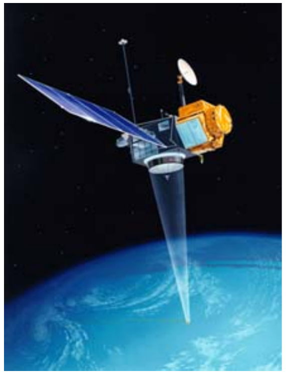
Fig. 1. TOPEX nadir panel with LRA and altimeter antenna.

TOPEX LRA.
(Schwartz, Applied Optics, 1990)

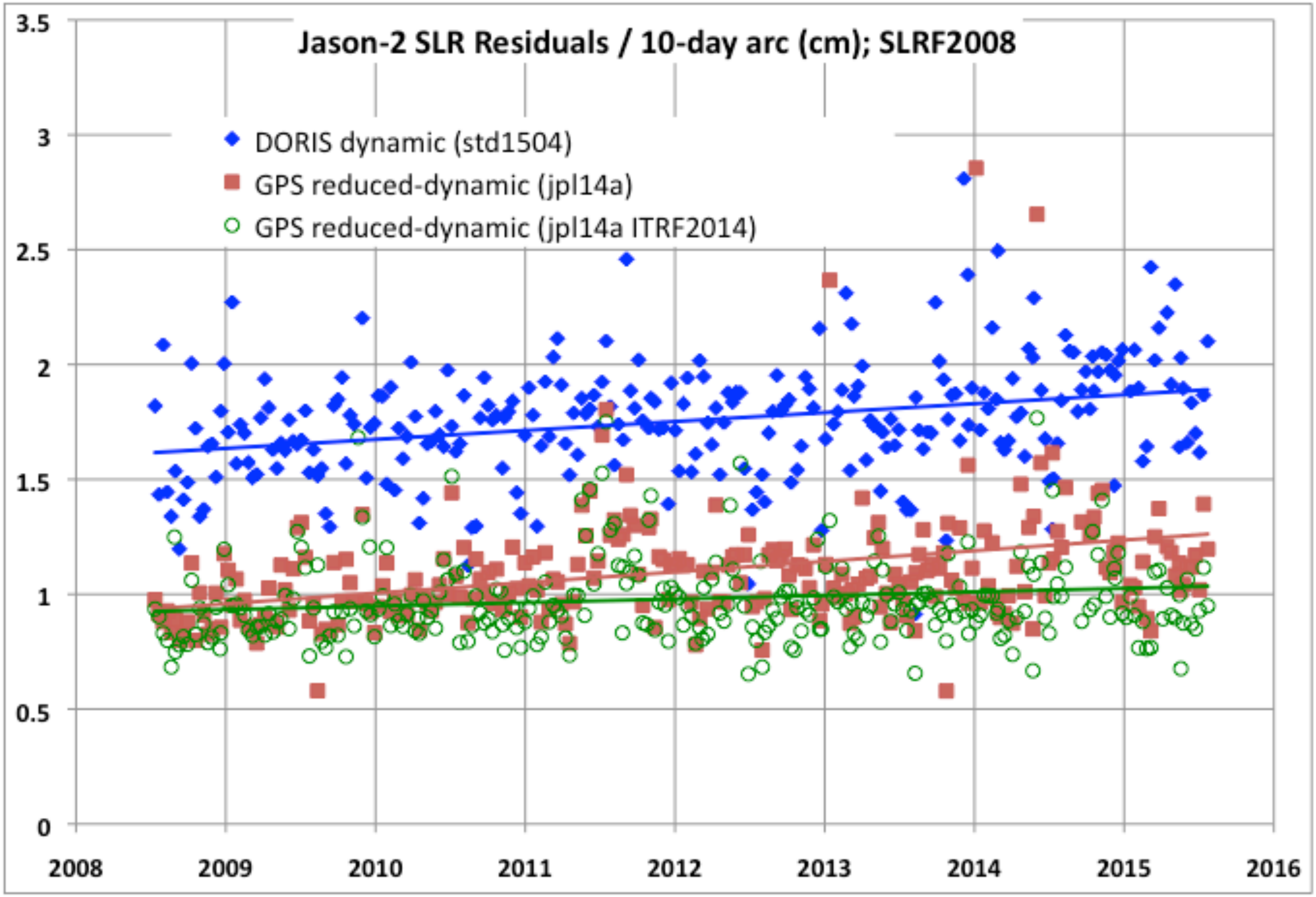




LRA for Jason-1, Jason-2, Jason-3 (courtesy of the ILRS)

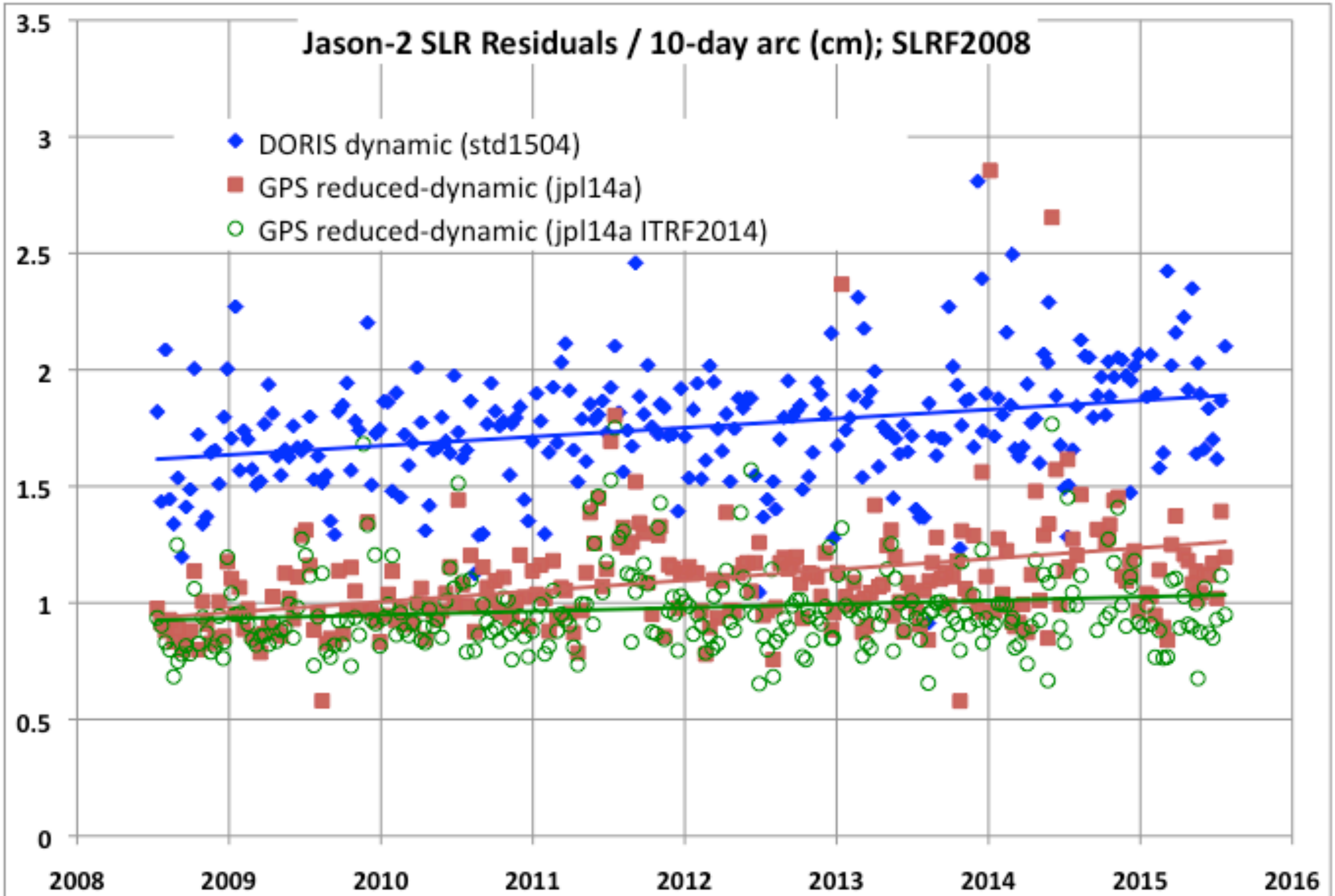


SLR – Validation of Jason-2 GPS & DORIS orbits



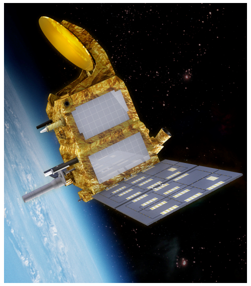
RMS of SLR fit per Jason-2 10-day cycle for DORIS-only (NASA GSFC) and GPS-only (JPL) Jason-2 orbits

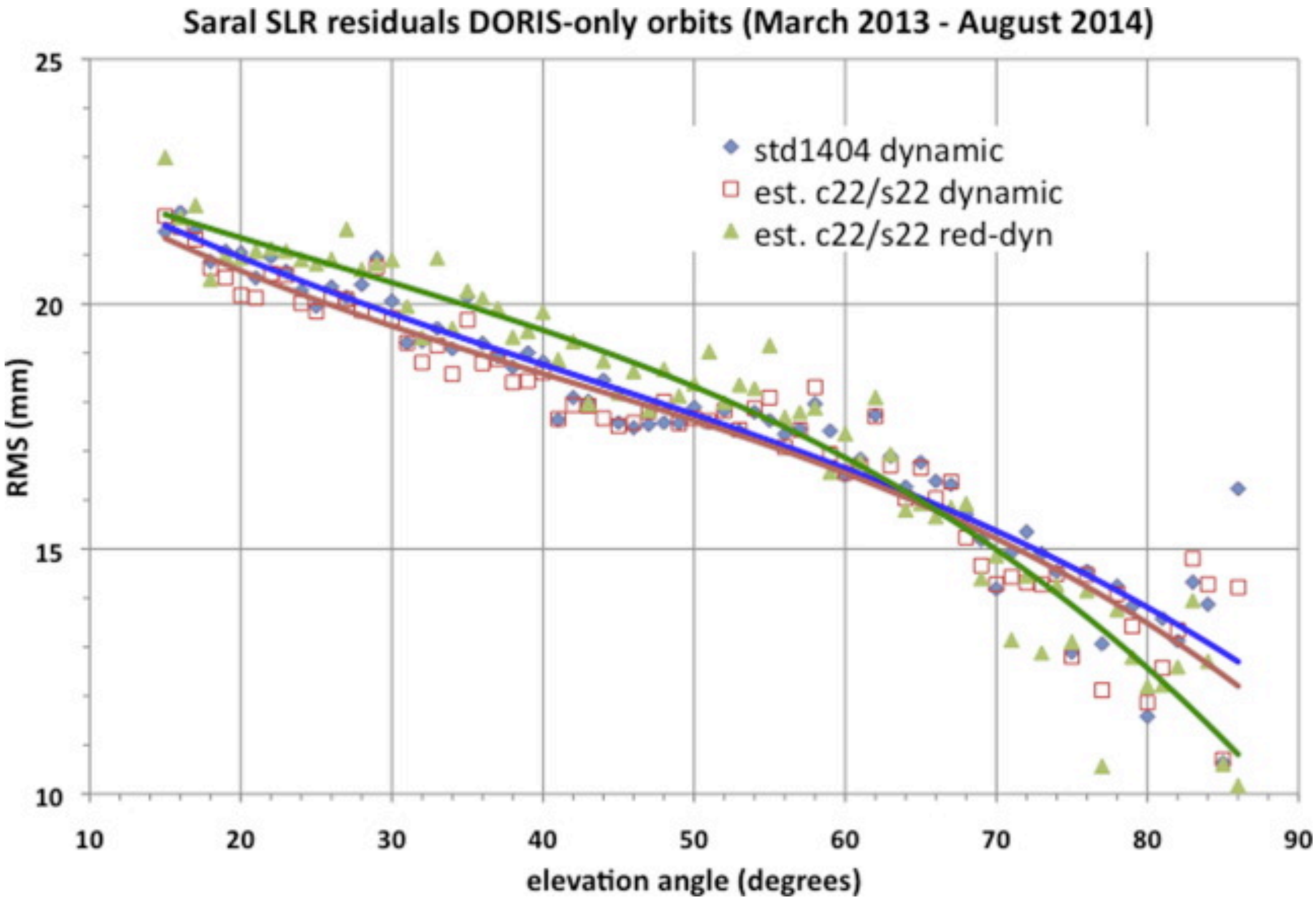
SLR – Validation of Jason-2 GPS & DORIS orbits



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)

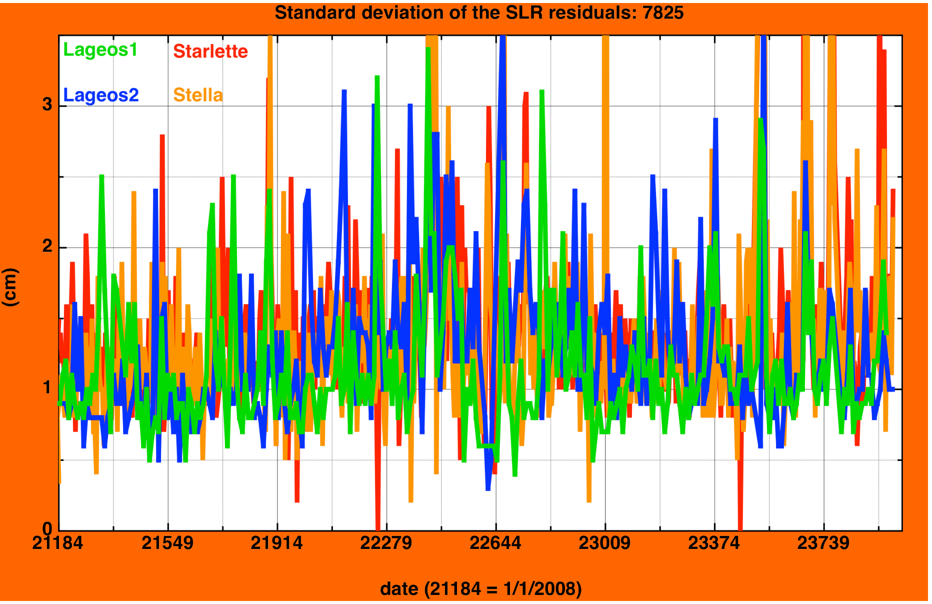


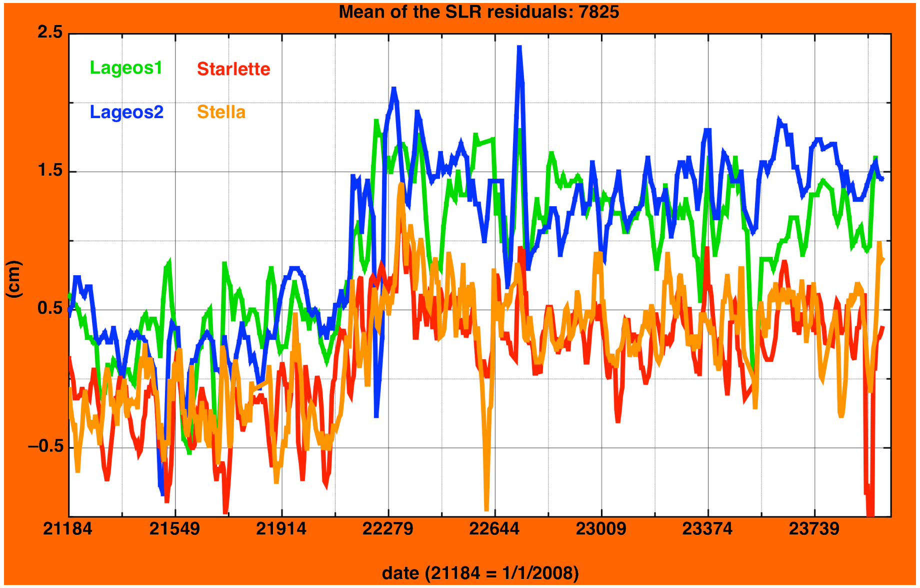


(Zelensky et al., 2016, "Towards the 1-cm SARAL orbit", Adv. Space Res, doi: 10.1016/j.asr.2015.12.011)

Monitor SLR station Performance for Altimeter Satellites

- **Use Data From L1, L2, Starlette, Stella.**
- **Monitor RMS of Fit, & Mean of Residuals.**
- **Bruinsma et al.** (OSTST, Reston, 2015) **reported results on analyses with ITRF2008; 5 day arcs (St/SL), 10-day arcs (L1,L2) – Example below is Mt. Stromlo.**





Is there an event timer issue with Mt. Stromlo starting in 2011? We need to repeat this evaluation with ITRF2014.

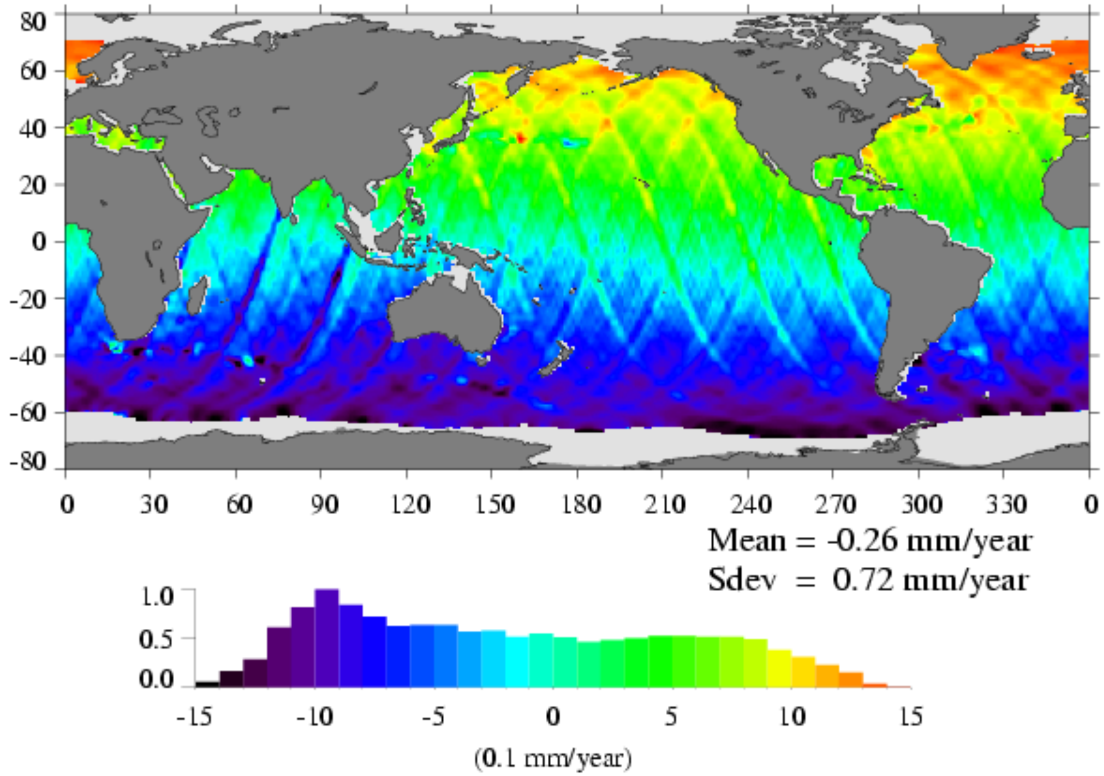
Comment: No aberrant residuals observed in development of ITRF2014 (ZA, le 10 mai 2016)

Altimeter satellites & TRF error

Reference Frame Realizations used in Altimeter Satellite POD.

- **CSR95**
- **ITRF2000**
- **ITRF2005**
- **ITRF2008**

Next. **ITRF2014.**

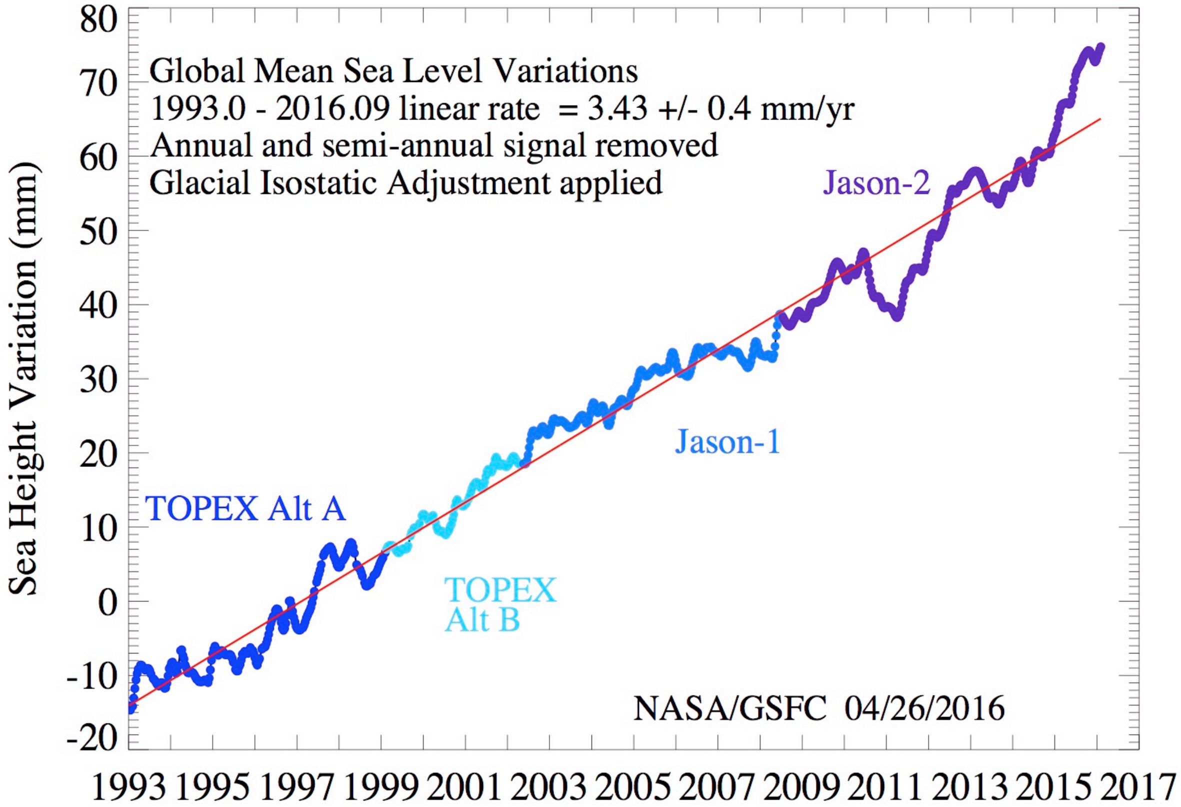


Regional **TOPEX** (**1993-2002**) Sea Surface Height Trend differences from direct impact of the **ITRF2005** (GGM02C) minus **CSR95** (JGM3) orbit differences. **(from Beckley et al.,** *Geophys. Res. Lett*.**, 2007).**

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

Altimeter satellites – MSL determination

The precise orbits for TOPEX/Poseidon, Jason-1, Jason-2, all computed in a consistent reference frame (ITRF2008) 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

I-What about LAGEOS “constellations”?

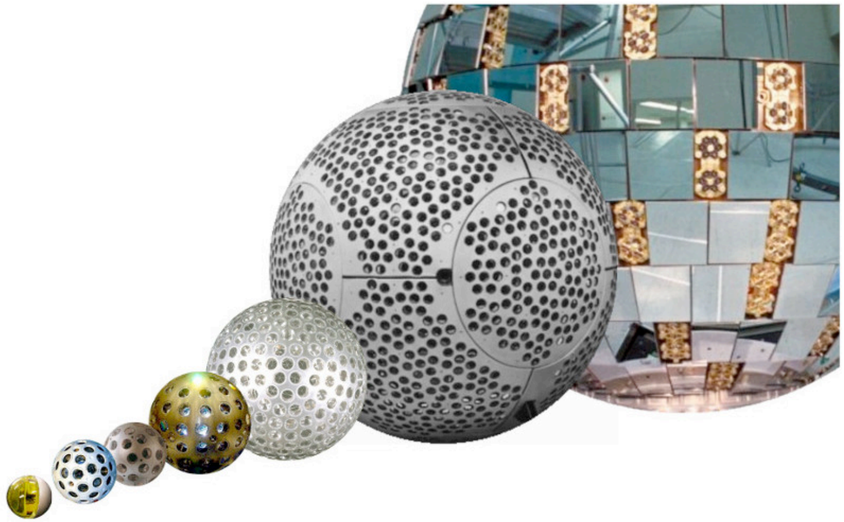


Figure courtesy of SGF/Herstmonceux

We have a suite of passive ‘geodetic’ satellites that orbit the Earth and are precisely tracked by Satellite Laser Ranging.

We have a “de facto” constellation, and these satellites have contributed to estimations of time-variable gravity as well as drag studies.

Can they also contribute to the TRF?

II-What about LAGEOS "constellations"?

Altitude (km)	Satellite	1985	1990	1995	2000	2005	2010	2015
5850	**Lageos1**							
5625	**Lageos2**							
1472	**Ajisai**							
1450	Lares							
958*	**Starlette**							
832	Blits							
780	**Stella**							
691	Larets							
		1985	1990	1995	2000	2005	2010	2015

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

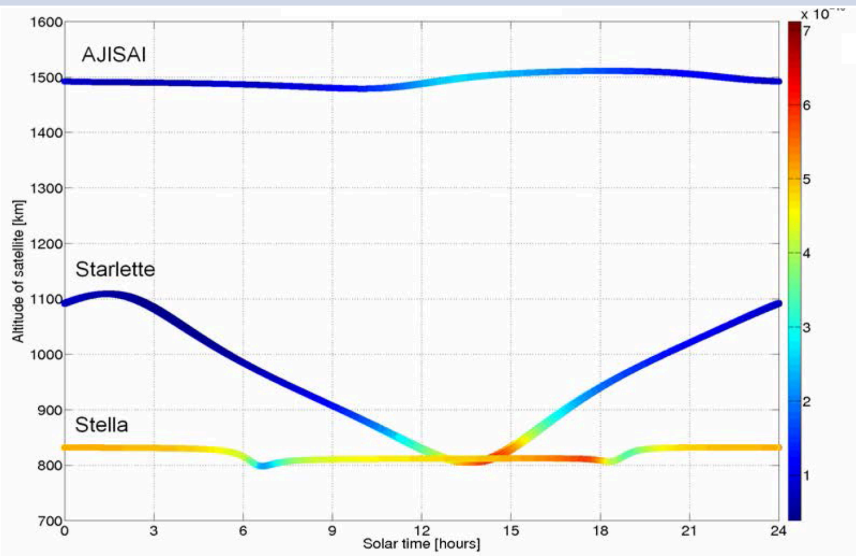
アジサイ
(Ajisai)
hydrangea
318 mirrors, 1436 CCRs

Starlette:
Satellite de Taille Adaptée avec Réflecteurs Laser pour les Etudes de la Terre

Starlette & Stella:
noyau. U-238
+ 1,5% Mb (Starlette),
+ 0.2% V (Stella);
Surface: Al (20 facettes, 3 CCRs each)

III-What about LAGEOS "constellations"?

Satellite	Altitude	Diameter	A/m (10^{-4} m^2/kg)	Mass (kg)
LAGEOS 1,2	**5850, 5625**	**60 cm**	**7.0**	**407; 405**
Ajisai	**1472**	**2.15 m**	**53.0**	**685**
LARES	1450	36 cm	2.7	386.8
Starlette/Stella	**958, 780**	**24 cm**	**~9.6**	**47.5; 48**
Blits	832	17 cm	30.1	7.5
Larets	691	21 cm	14.9	23.3
[see Bloßfeld (2015, J. Geodesy, Table 2) & Sosnica (2014, J. Geodesy) & ILRS web site (http://ilrs.gsfc.nasa.gov) for a more detailed list.]				



Drag Accelerations on Starlette, Stella and Ajisai
(from Sosnica, Ph.D Thesis, AIUB, 2014)

IV-What about LAGEOS "constellations"?

Satellite	Altitude	Diameter	A/m (10^{-4} m^2/kg)	Mass (kg)
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Three issues:

(1) Nonconservative forces.

(Drag, Solar Radiation, Planetary Radiation Pressure)

(2) Pass Length (Amount of data).

(3) Target Signature effects.

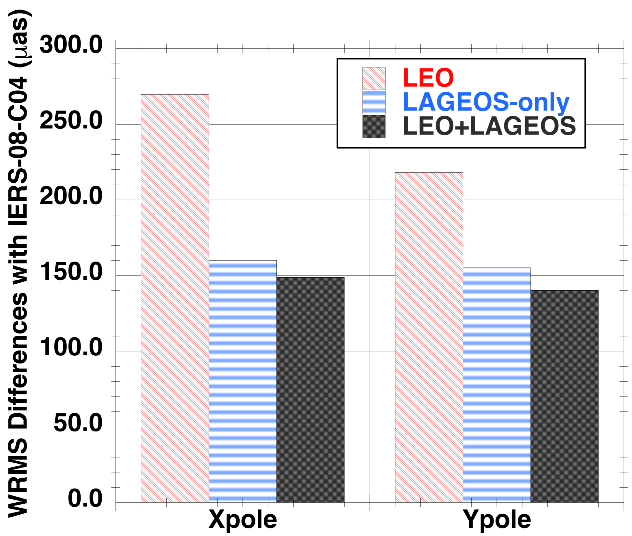
-> cannot be ignored for mm geodesy!!

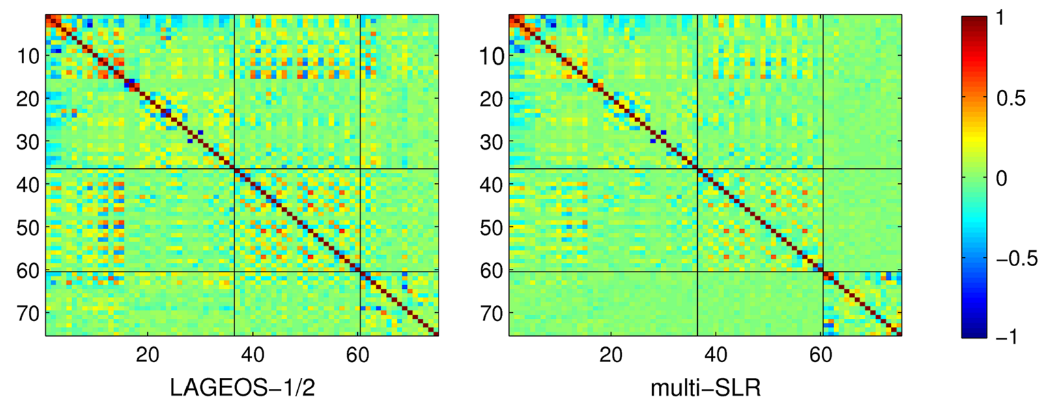
- Otsubo & Appleby, *JGR*, 2003; LAGEOS & Ajisai.
- Otsubo et al., *J. Geodesy*, 2015

Starlette, Stella, LARES.

V-What about LAGEOS "constellations"?

• Sosnica (J. Geodesy, 2014) looked at the contribution of adding Starlette, Stella + Ajisai to the TRF weekly solutions.





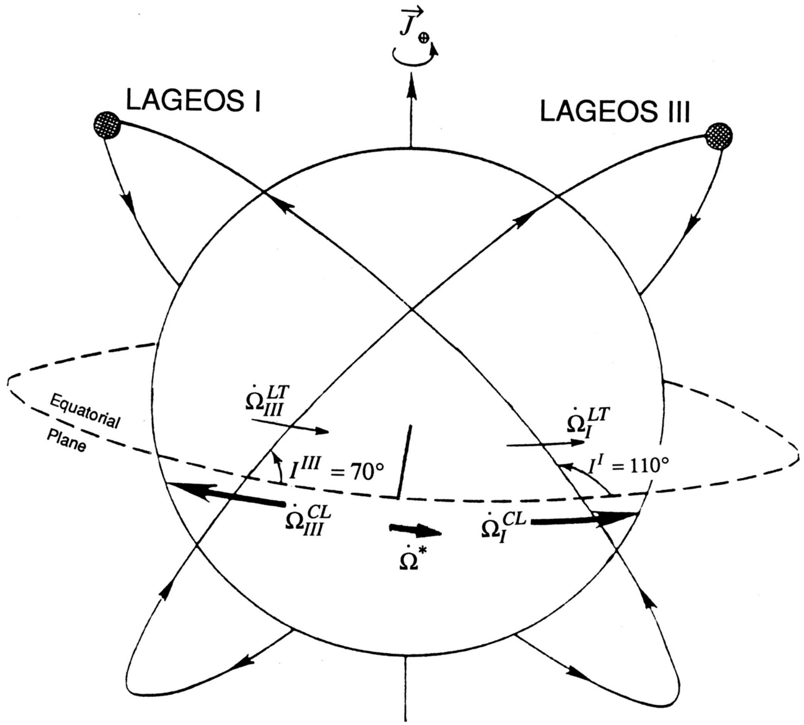
• Only a small improvement for EOP.

Fig 12. Sosnica (J. Geodesy, 2014). Correlation matrix of weekly solutions, ordered by station coordinates, EOP, gravity.

• Correlations reduced for 'combination solution'.

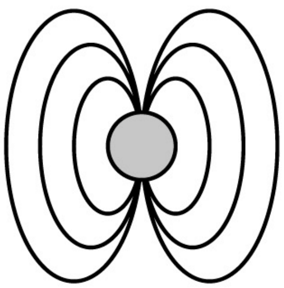
• Position determination for stations that have limited SLR data from LAGEOS, are improved.

What about LAGEOS-3?



Object of measurement:

$$\dot{\Omega}^{*} = \tfrac{1}{2}(\dot{\Omega}^{I} + \dot{\Omega}^{III})$$



$$\bar{F}_{LT} = m_0 \bar{v} \times \left[\nabla \times \left(\left(-(1+\gamma) \frac{G}{c^2} \frac{\bar{J}_{cb} \times \bar{r}}{r^3} \right) \right] \right.$$

Spinning Mass

Just as a spinning charge produces a magnetic field, a spinning mass produces a "gravitomagnetic" field.

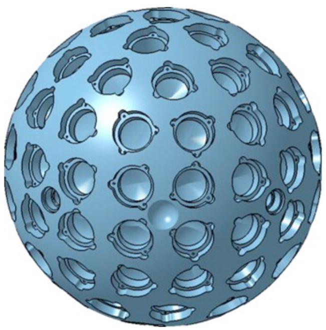
- The most observable effect on the satellite orbit is the Lense-Thirring precession of the ascending node.

- Ciufolini (1986) proposed a LAGEOS-3 satellite to measure LT.
- A NASA study (1989), Ph.D theses (Ries, 1992; Petersen 1997) & other studies explored this idea.

$$\dot{\Omega} = \frac{2G}{c^2 a^3} \frac{J}{(1-e^2)^{\frac{3}{2}}}$$

~31 milli-arcsec/yr for LAGEOS

What is LARES?



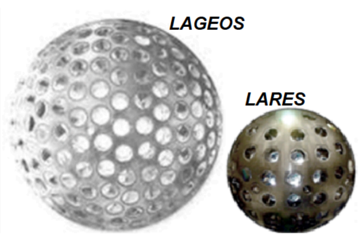
LARES

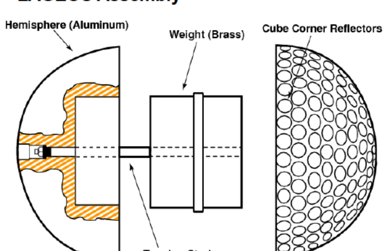
- Launched in 2012 (Italy).
- Main objective – measure Lense-Thirring effect.
- Built with a high-density, tungsten alloy (18 gm/cm^3).
- Launched on a VEGA qualification flight;

Target altitude & inclination were a combination of what the launch vehicle could reach, and minimization of error in Lense-Thirring measurement.

LARES Mission: engineering aspects

Design: LARES vs LAGEOS





	LAGEOS	LARES
Launch:	• 1976 (1) • 1992 (2)	2012
Mass:	• 406.9 kg (1) • 405.3 kg (2)	386.8 kg
Diameter:	60 cm	36.4 cm
Body:	Assembly.	Single piece.
No. of CCR:	426	92
Eccentricity:	• 0.0045 • 0.0135	0.0002
Altitude:	• 5860 km (1) • 5620 km (2)	1450 km

Figure from Pavlis et al., 2015

Impact of LARES on TRF
(ie. LARES + LAGEOS-1,2)

Stations: Improve by 17-20%.
EOP: Improve by 20-23%.

(Preliminary results from E. Pavlis)

Summary

- The LAGEOS satellites are of immense importance for the ITRF since they are the means by which the origin of the reference frame is determined.

- The SLR stations – whose positions are determined by LAGEOS data – anchor all radar and laser altimeter data in the ITRF; Their data is also used for orbit validation.

- The determination of mean sea level on a global and regional basis have depended on the SLR contribution to the ITRF and hence directly on LAGEOS data.

- The addition of a "LAGEOS-2" had a profound impact on the determination of the station coordinates and the geocenter.

- Studies have proposed (e.g. Ciufolini et al., IAF, 2015) to launch a LARES-2 s/c to low altitude (1450 km), or to a LAGEOS-type altitude (but a supplementary inclination).
The benefit for the TRF should be seriously evaluated.
(For DORIS the addition of new LEO satellites at new inclinations has each time improved the determination of the TRF parameters – see Moreaux et al., Adv Space Res, 2016).

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