The Geodetic Networks & Space Geodesy Applications

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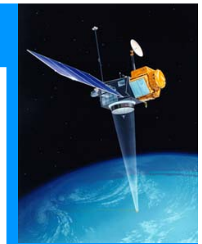
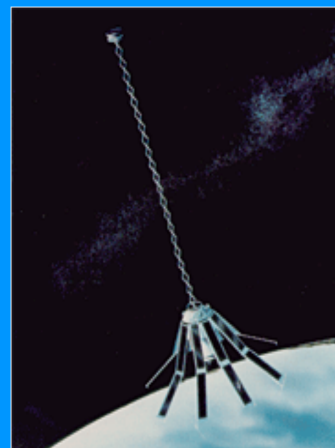
From the launch of the first spaceborne altimeters, Precision Orbit Determination (POD) has been driven by the science goals of the geodetic altimeter missions…



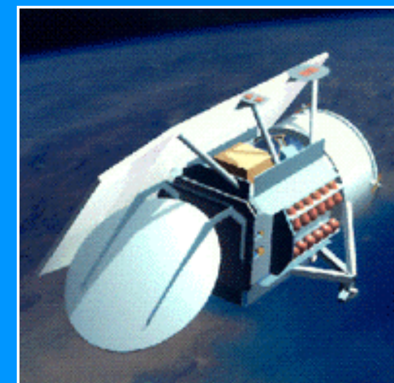
GEOS-3, 1975

SEASAT, 1978



GEOSAT, 1985

TOPEX/POSEIDON, 1992



GFO-1, 1998

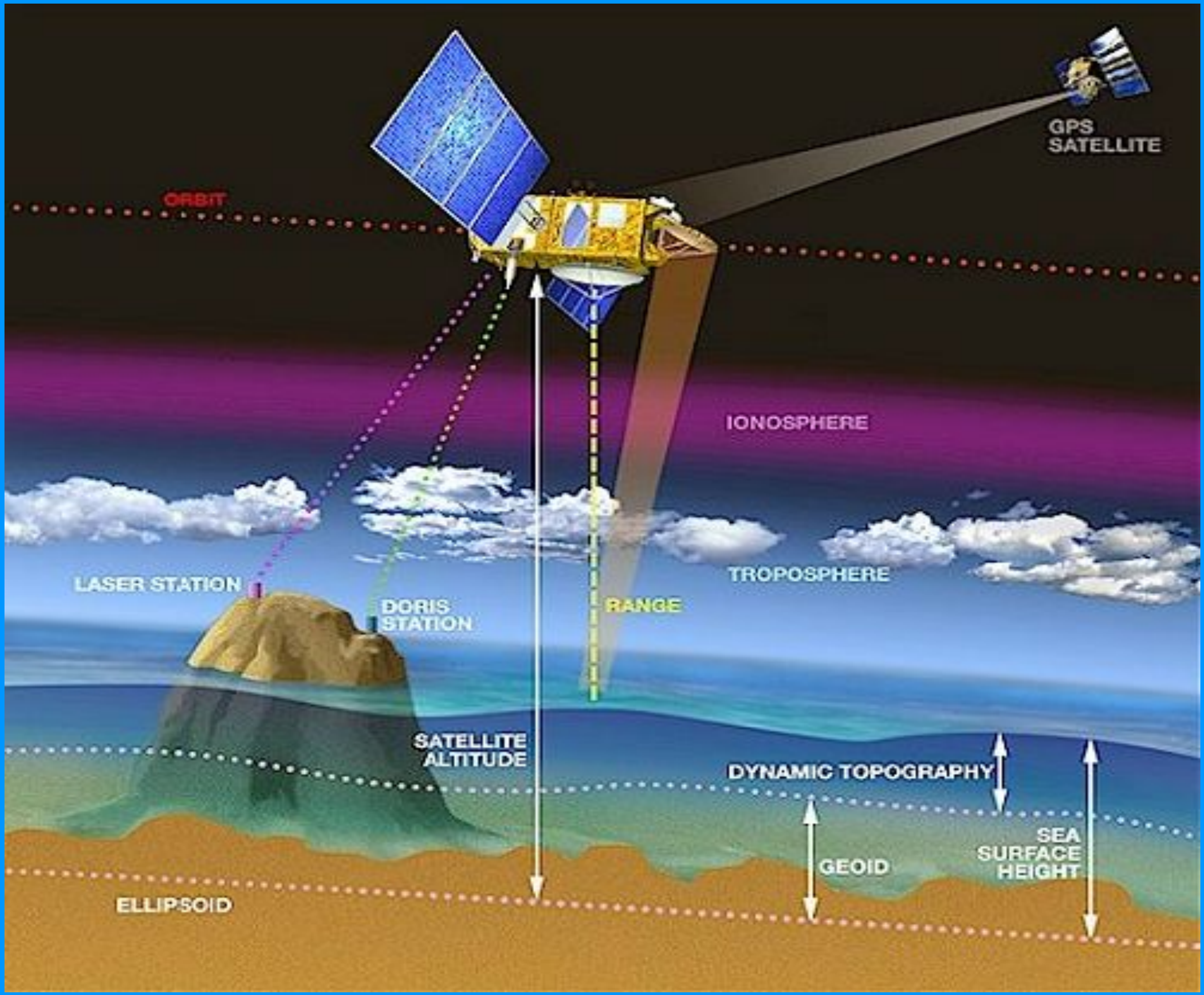
Jason-1, 2002
Jason-2, 2008

S
N

ENVISAT, 2002

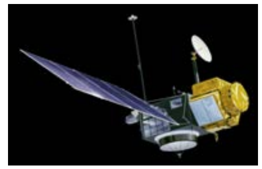
CRYOSAT-2, 2010

POD Schematic



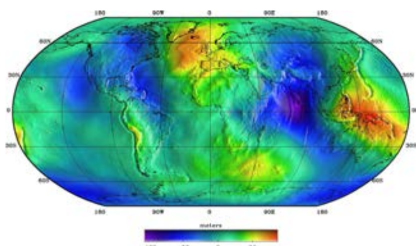
Orbit Determination Schematic

Onboard Tracking Systems
LRR
DORIS
GPS



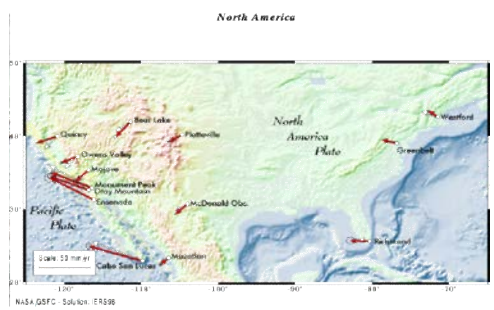
Atmospheric Modeling
Ionospheric Propagation Delay
Tropospheric Refraction
Atmospheric Density

Surface Forces
Modeling
S/C Attitude



Orbit Determination
Force Modeling
Reference Frame
Tracking Technology

Geophysical Models
Gravity Models
Tide Models
Time Variable Gravity



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

Force models

I. Gravity.

$$U = \frac{GM}{r} + \frac{GM}{r}\sum_{n=2}^{\infty}\sum_{m=0}^{n}\left(\frac{a_e}{r}\right)^n \bar{P}_{nm}(\sin\phi) \times [\bar{C}_{nm}\cos m\lambda + \bar{S}_{nm}\sin m\lambda],$$

II. Solar radiation pressure

III. Planetary radiation pressure (albedo & thermal emission).

(Cannonball, …. Macromodel, box-wing …)

IV. Atmospheric drag.

V. Earth Solid tides & Ocean Tides.

VI. Third body (Sun, Moon, Planets)

VII. Relativity.

……

Measurement modelling

I. Coordinate System
II. Tracking station coordinates.
- Earth solid tide effects.
- Ocean loading effects.

III. Earth orientation parameters.
IV. Media effects.
- Earth troposphere refraction.
- Ionosphere (radio frequencies)

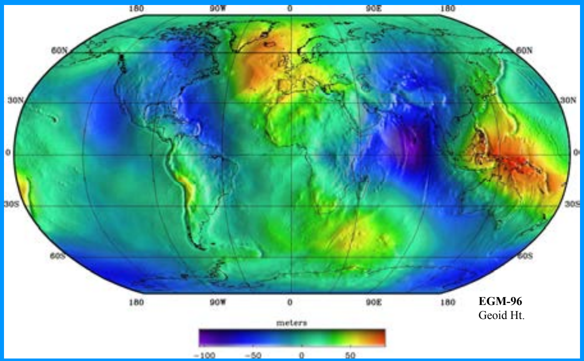
V. Relativity.
- Range delay; Light time; Coordinate-> Atomic time.

VI. Planetary ephemerides (DE403…)
VII. Spacecraft corrections to s/c center of mass.
VIII. Antenna corrections (phase center variations, motion)

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

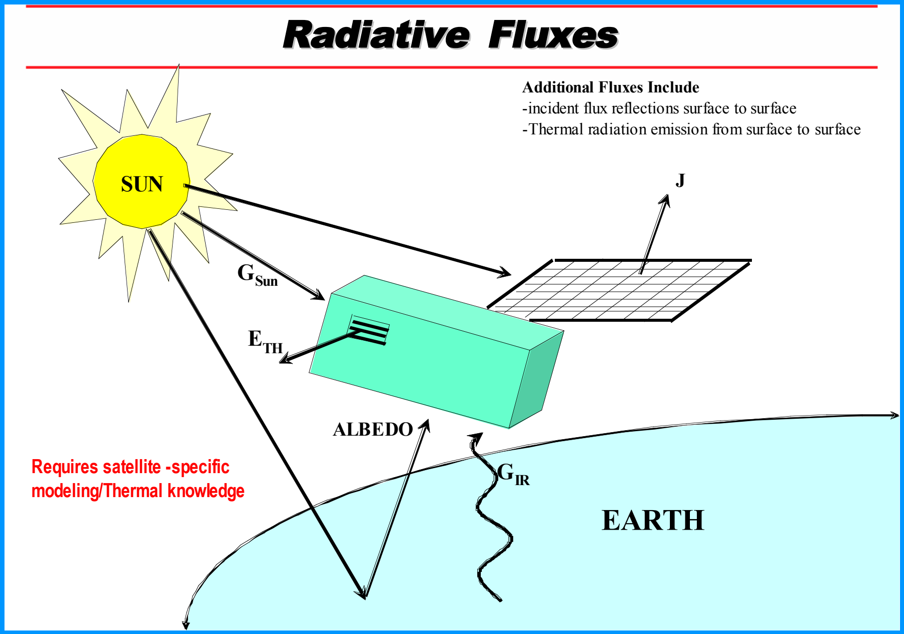
Model	Radial Calibration (cm)	SLR rms fit (cm)
GEM-L2: 1982	65.4	105.9
GEM-T1: 1988	25.0	31.4
GEM-T2: 1990	10.2	17.8
JGM-1S: 1991	6.0	7.7
JGM-2S: 1992	2.9	4.0
JGM-2: 1992	2.2	3.8
JGM-3: 1995	0.9	3.2
EGM-96 1997	0.8	2.8

GEML2: 20x20
JGM1-3: 70x70
EGM96S: 70x70; (360x360)
EIGEN-GL04S: 150x150



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



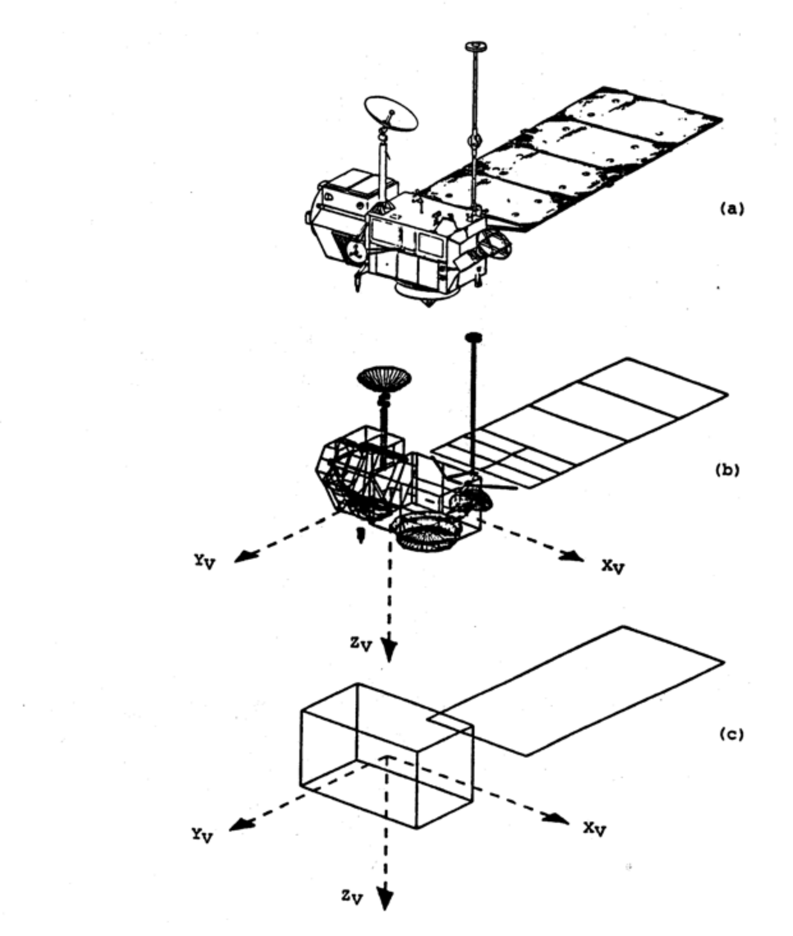


Figure 1. (a) The TOPEX/Poseidon Spacecraft, (b) Micro-Model Approximation, (c) Macro-Model Approximation

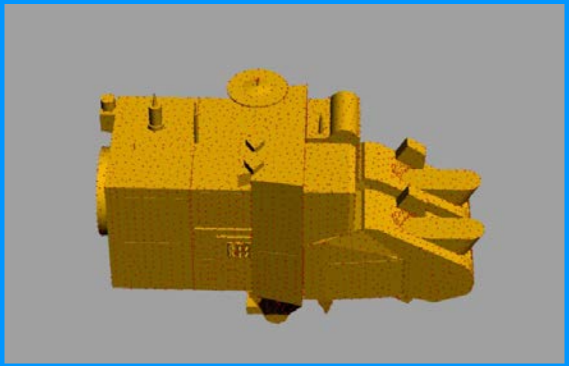
Micromodel: *(Antreasian, 1992; Antreasian & Rosborough, 1992)*

Box-Wing model

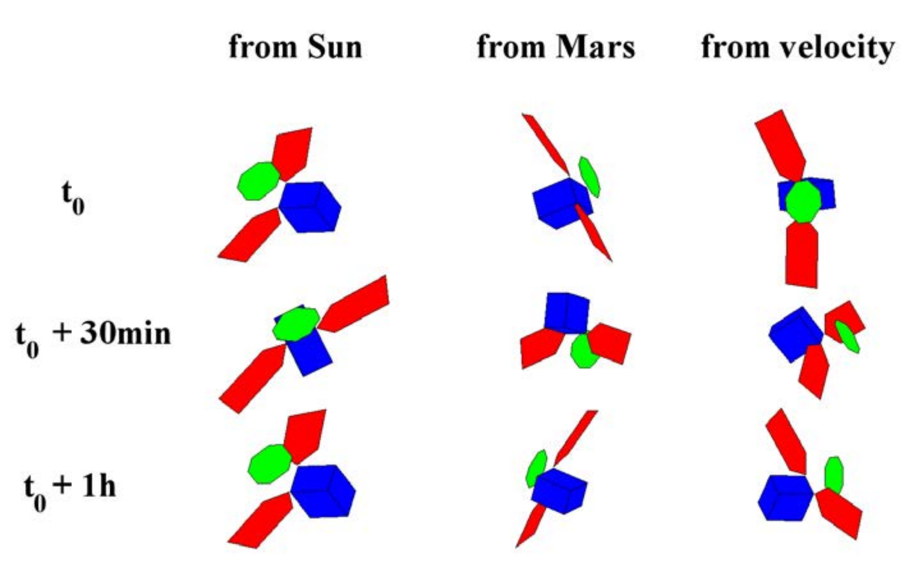
(Marshall & Luthcke. 1994)

Radiation Pressure Modelling Improvement Strategies (1)

University College London models for LEO spacecraft?



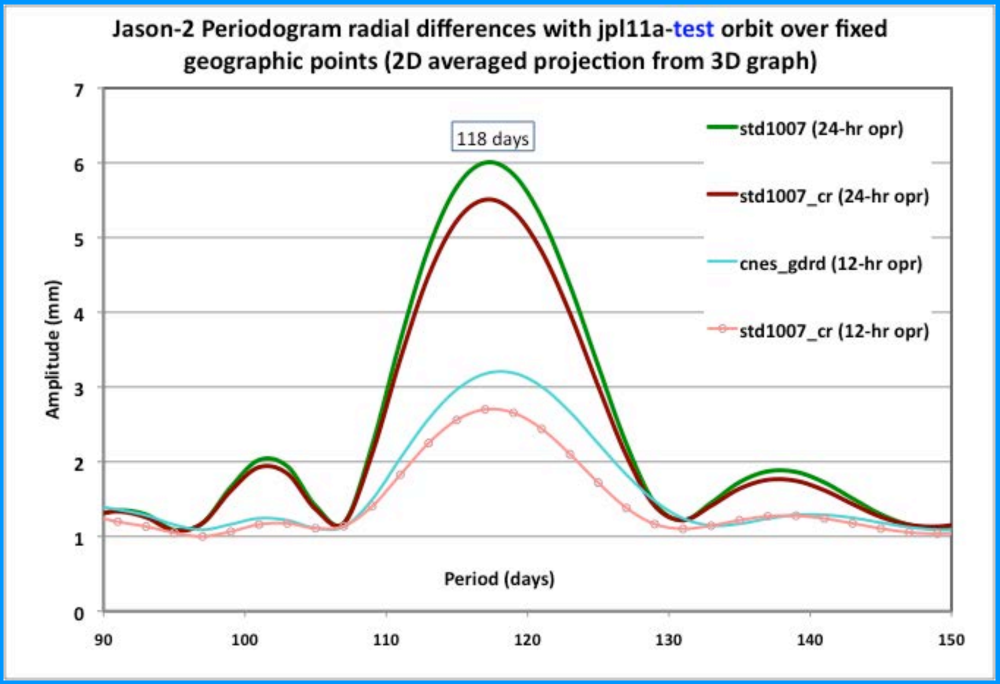
Self-shadowing as in *Mazarico et al., 2009, J. Spacecraft Rockets,* for MRO?



Spacecraft attitude at three different orbital positions - view from different directions.

Radiation Pressure Modelling Improvement Strategies: Adjust Empirical Accelerations (2)

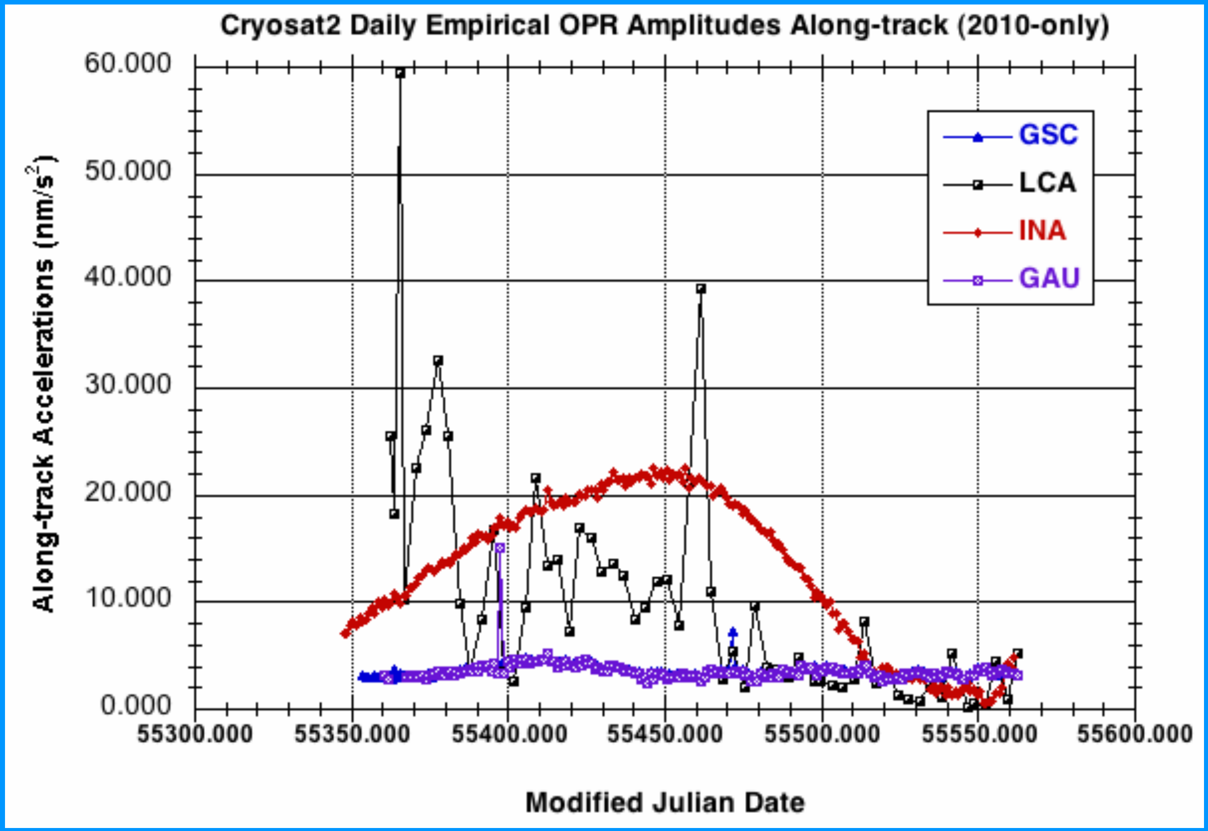
Adjust once-per-revolution empirical accelerations (along-track, cross-track to orbit)
OPR =A cos wt + B sin wt



IDS Analysis Center Comparison: Cryosat2 OPR Empirical Acceleration Amplitudes (2010 only)

Doris Center	No. of accels	Alg (avg/median) x 1e09	Crs (avg/median) x 1e09	Adjust period (days)
GSC	208	3.61 / 3.54	2.57 / 2.48	1
ESA	217	2.79 / 2.68	2.92 / 2.77	1
GAU	193	3.51 / 3.43	2.97 / 2.81	1
IGN	214	12.94 / 14.03	7.00 / 5.75	1
INA	214	13.92 / 13.86	6.93 / 4.86	1
LCA	58	9.42 / 7.61	3.41 / 2.76	3.5
CNES POD	247	4.81 / 4.83	3.01 / 2.74	1

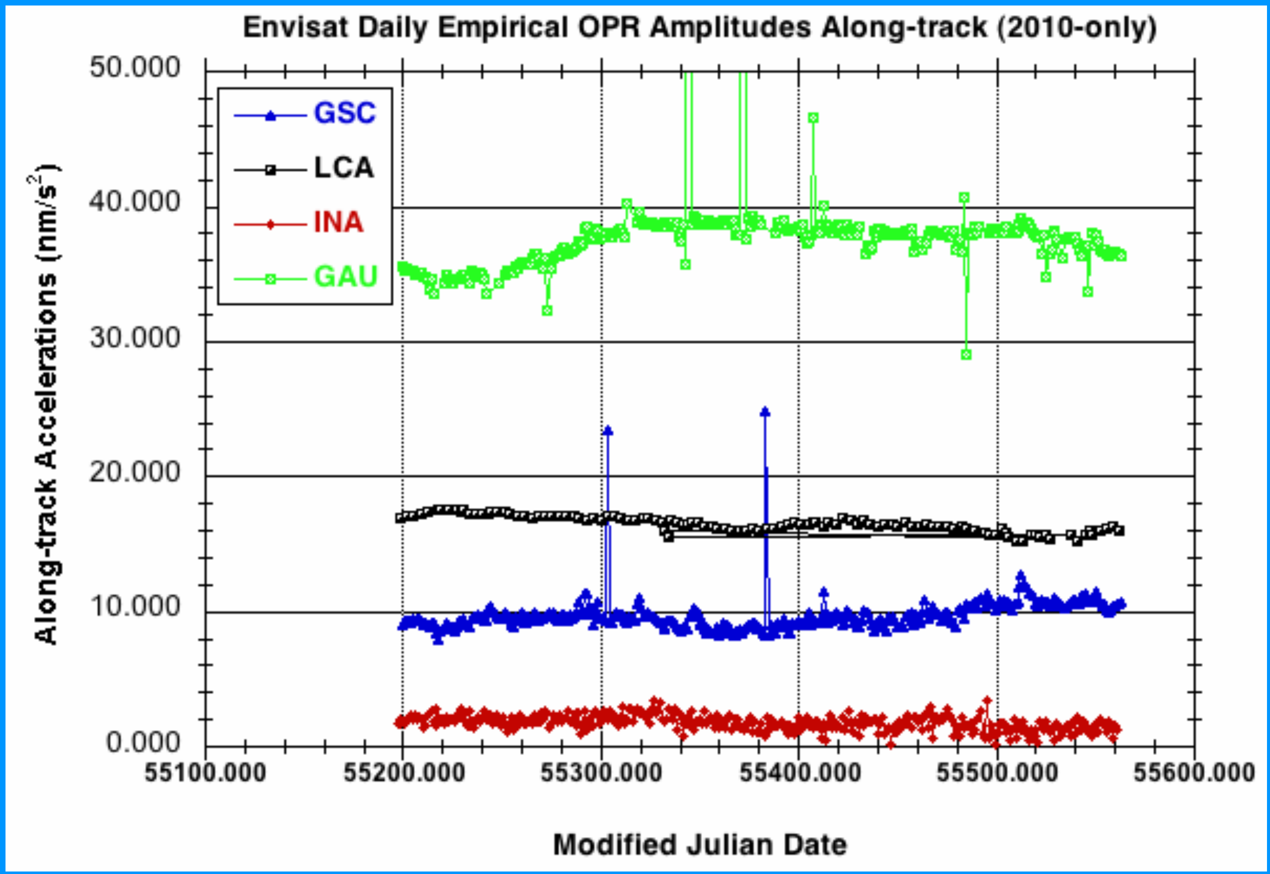
IDS Analysis Center Comparison: Cryosat2 OPR Empirical Acceleration Amplitudes (2010 only)



IDS Analysis Center Comparison: Envisat OPR Empirical Acceleration Amplitudes (2010 only)

Doris Center	No. of accels	Alg (avg/median) x 1e09	Crs (avg/median) x 1e09	Adjust period (days)
GSC	355	9.54 / 9.42	2.27 / 2.24	1
ESA	359	1.64 / 1.52	1.89 / 1.71	1
GAU	316	37.39 / 37.88	6.11 / 5.85	1
IGN	365	1.86 / 1.84	2.81 / 2.58	1
INA	364	1.79 / 1.81	23.84 / 23.95	1
LCA	117	16.52 / 16.46	5.33 / 4.98	3.5
CNES POD	416	1.54 / 1.56	1.80 / 1.71	1

IDS Analysis Center Comparison: Envisat OPR Empirical Acceleration Amplitudes (2010 only)

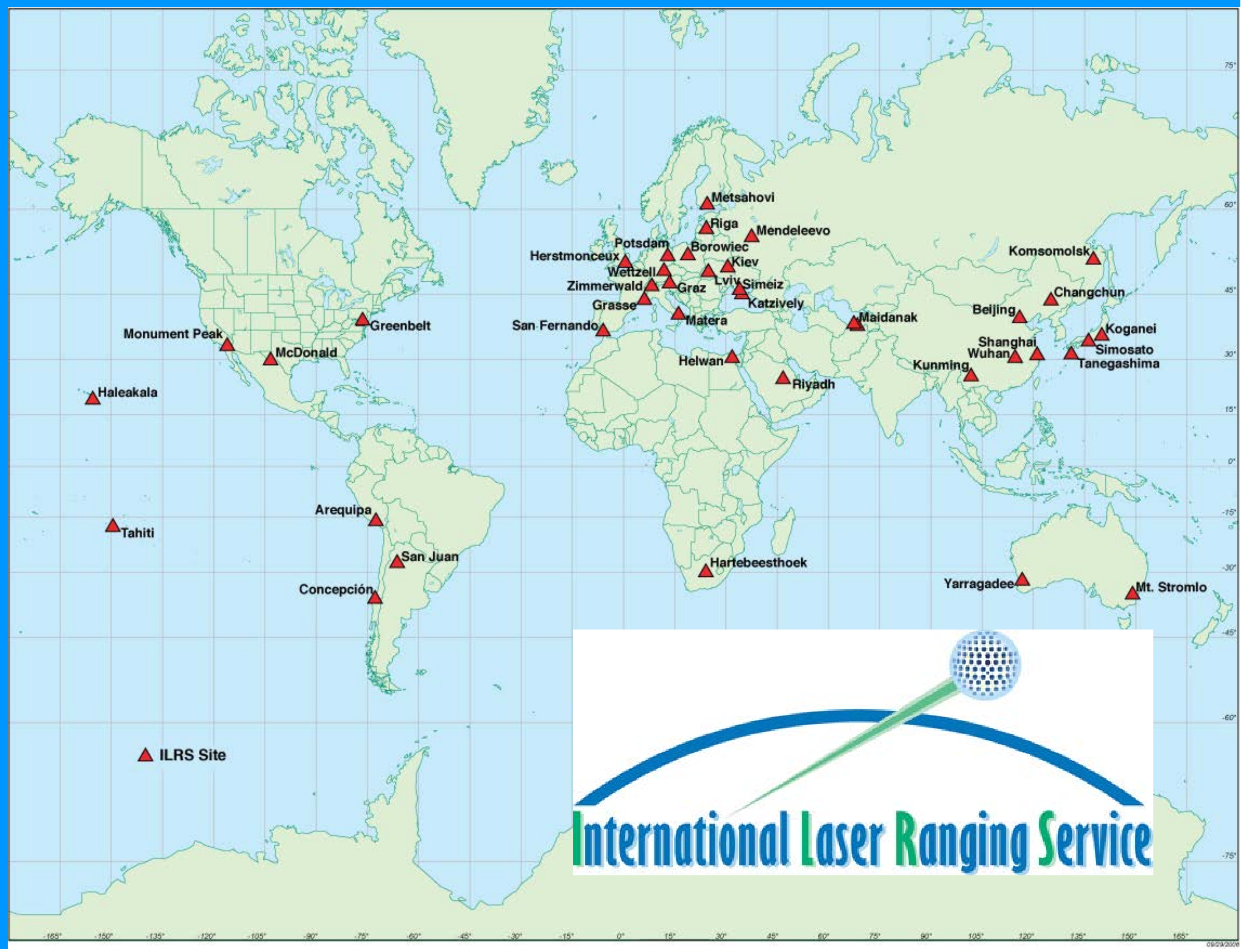


The Geodetic Networks are the Key to Altimeter Satellite Mission Success

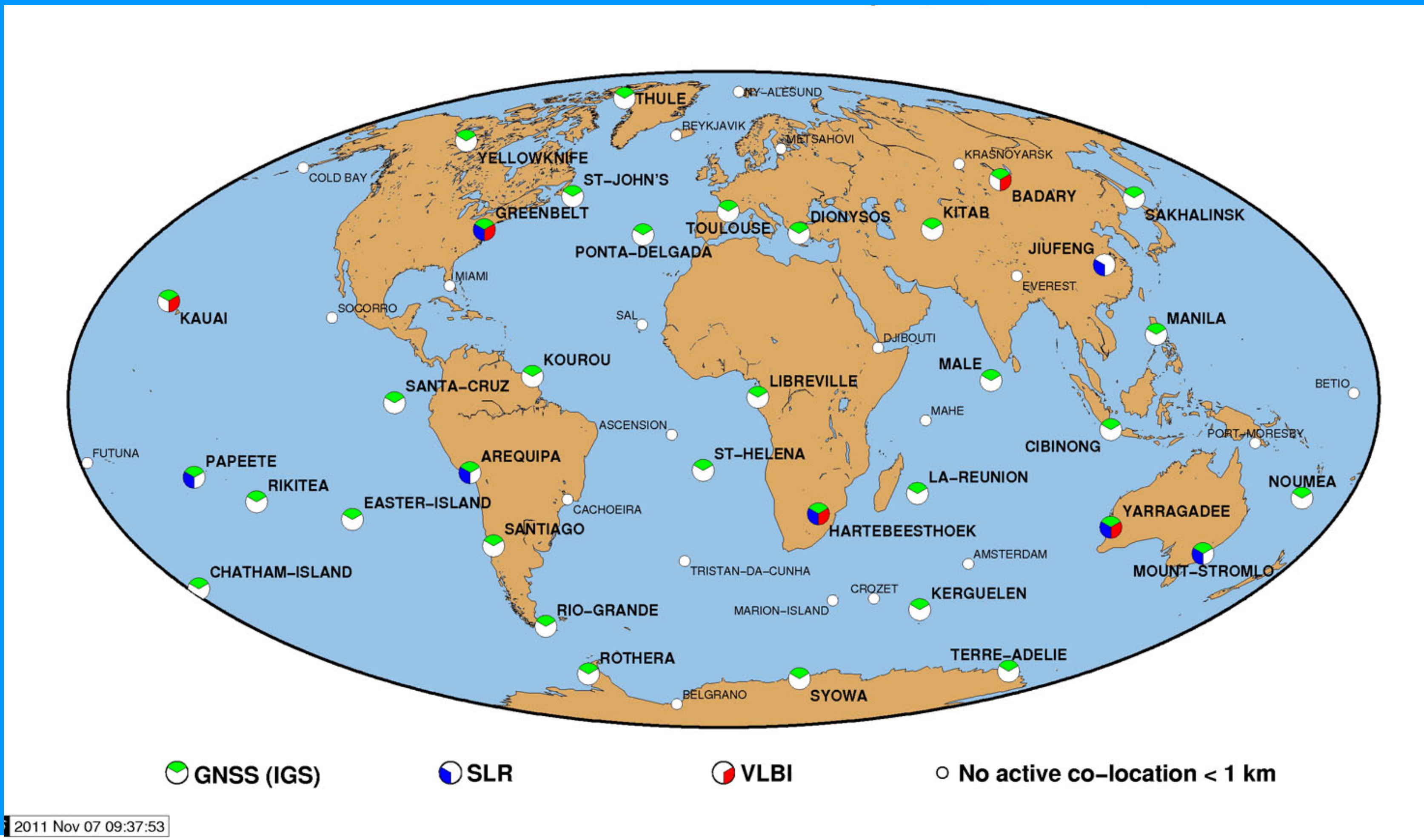
Satellite Laser Ranging (SLR)

SLR, Maui

SLR, Graz, Austria



DORIS (Ground Network) (Sept. 2011)



IDS

International DORIS Service

DORIS Station Examples

Rothera, *Antarctica*

- **ROTA 1993-2005**

ª **ROTB 2005-2007**

- **ROUB 2007-present**

Thule, *Greenland*

- **THUB 2002-present**

Arequipa, *Peru*

- **AREA 1988-2001**
- **AREB 2001-2006**
- **ARFB 2006-present**

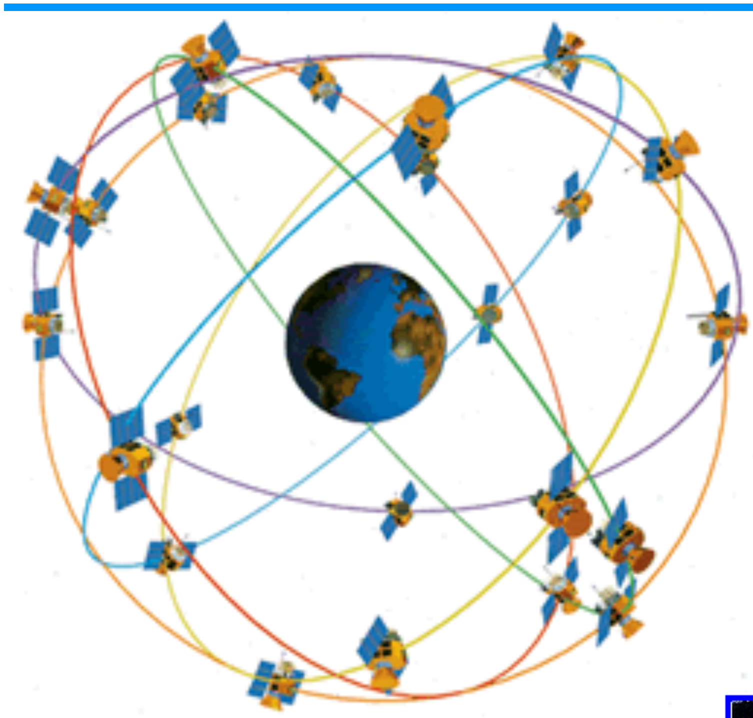
IDS

International DORIS Service

GPS Tracking System for OSTM

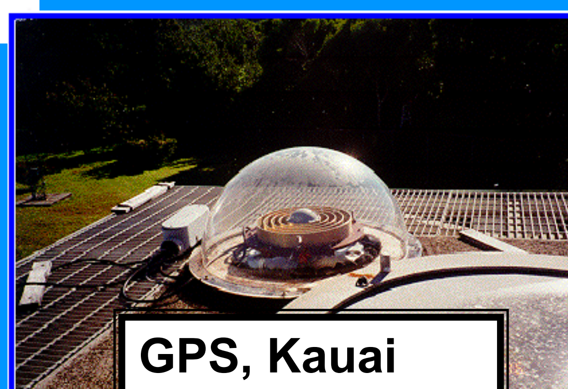
International GNSS Service
Formerly the International GPS Service

GPS Satellite Constellation



JASON GPS Receiver

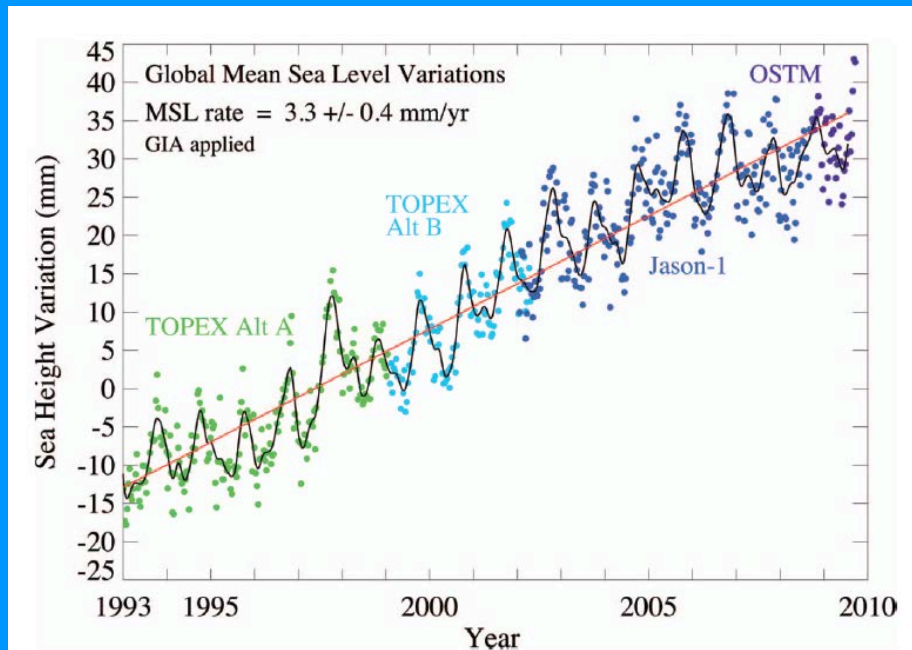
Examples: Ground Receivers



GPS, Kauai

GPS, Thule

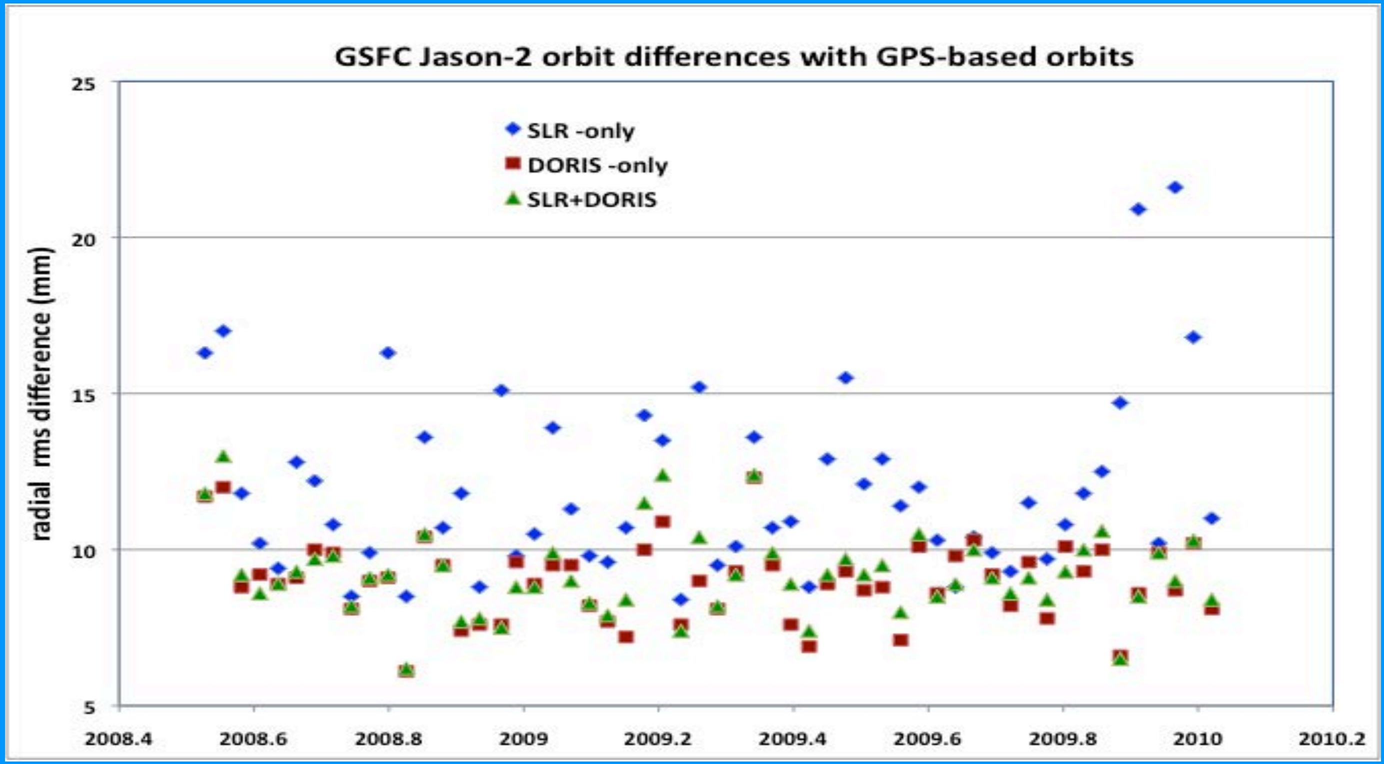
Measurements of Global Mean Sea Level from Satellite Altimetry (TOPEX, Jason1, Jason2)



- GOT4.7 (tides)
- ITRF2005
- w/ TP & Jason radiometer corrections.

The determination of change in global mean sea level in the altimetry era (after 1993) is done with **SLR+DORIS** orbits in a consistent reference frame (ITRF2005). (*Beckley et al., Marine Geodesy, 2010; Lemoine et al., Adv. Space. Res., 2010*)

For POD on the TOPEX/J1/J2 satellites, the Geodetic tracking from SLR, DORIS & GPS are Complementary & Synergistic



SLR + DORIS and DORIS-only orbits are superior to SLR-only orbits (*above example for Jason-2, but the same is true for Jason-1 and TOPEX*).

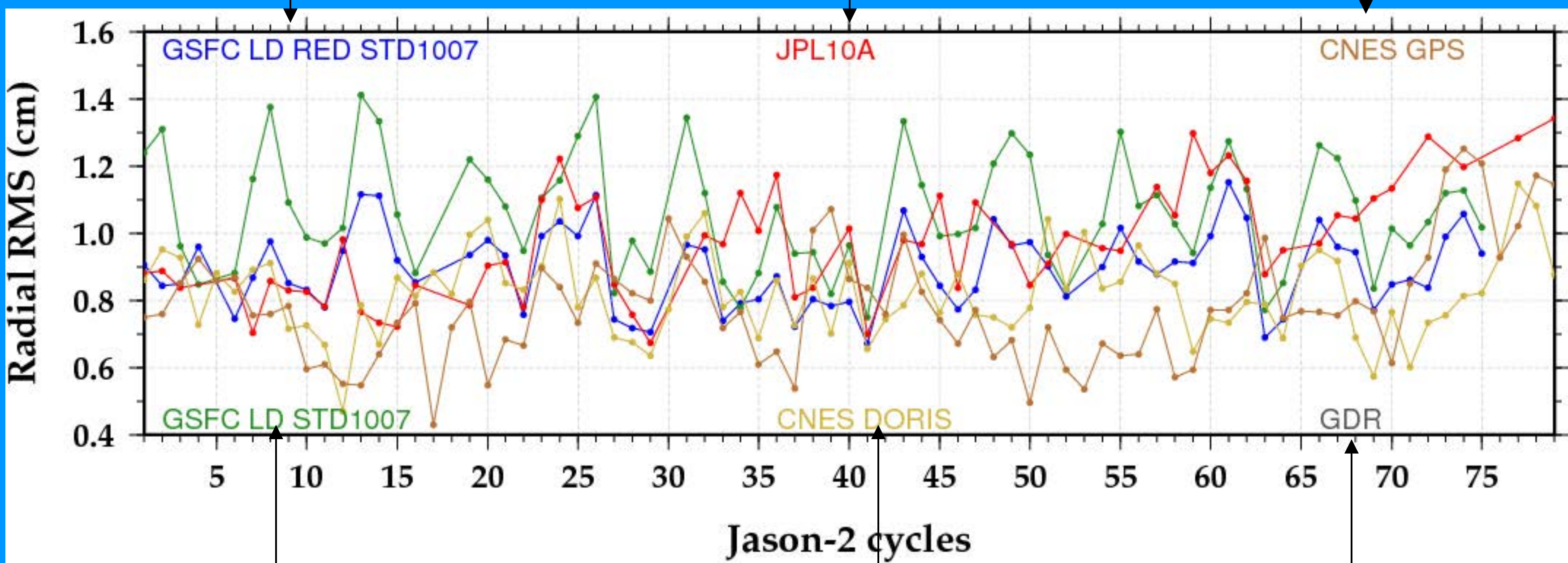
Jason-2 Orbit Accuracy Validation

Jason-2 Orbit Intercomparisons using orbits computed with different geodetic data and based on different referece frame realizations) Allow Validation of Radial Orbit Accuracy. **HERE ALL ORBITS AGREE TO 1 cm radially.**

SLR+DORIS red-dyn (GSFC)

GPS-only red-dyn (JPL)

GPS-only (CNES)



SLR DORIS dyn. (GSFC)

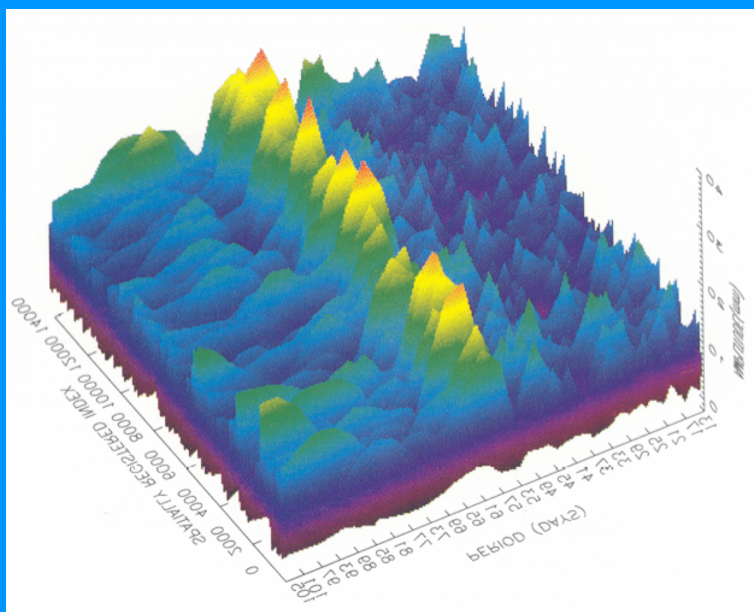
DORIS-only (CNES)

SLR+DORIS+GPS (CNES)

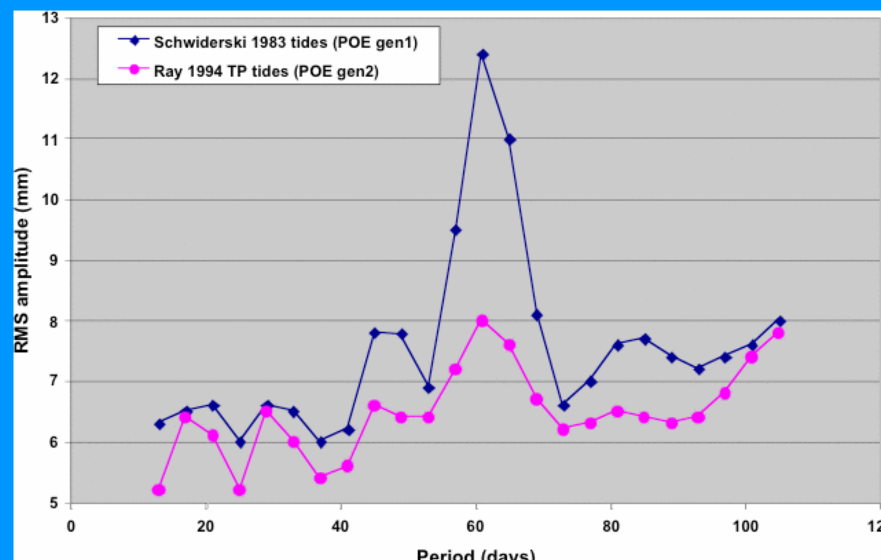
Cerri et al. (2010)

Intercomparison of Independent Orbits Produced by SLR/DORIS & GPS (Reduced Dynamic) allows insights into model and geodetic technique error ….. And helps to validate improvements ….

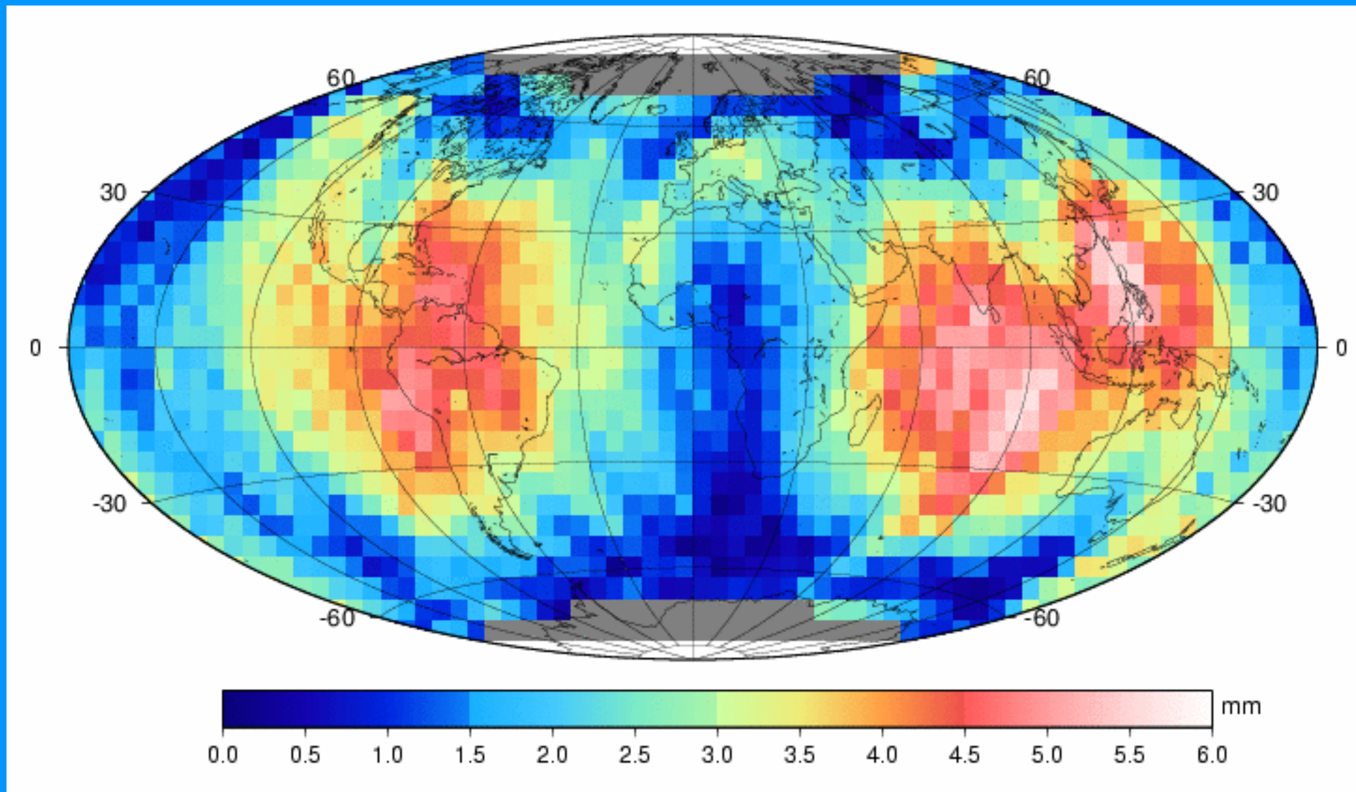
A priori **(Schwiderski) Tide model produced orbit error at the M2 alias period (~60 days) for TOPEX**



Tide model improvement using TOPEX altimeter data

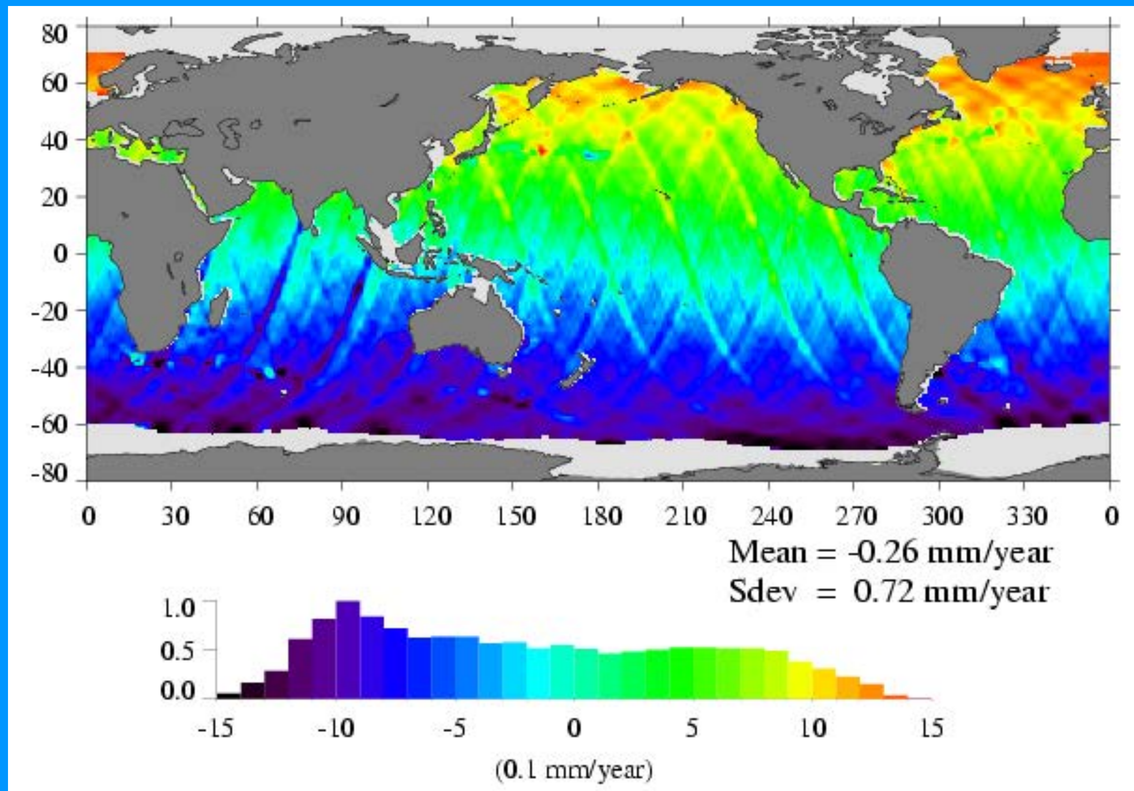


Jason radial orbit 5-mm annual amplitude due to time varying gravity (*operational model from ECMWF + 20x20 annual from GRACE*)



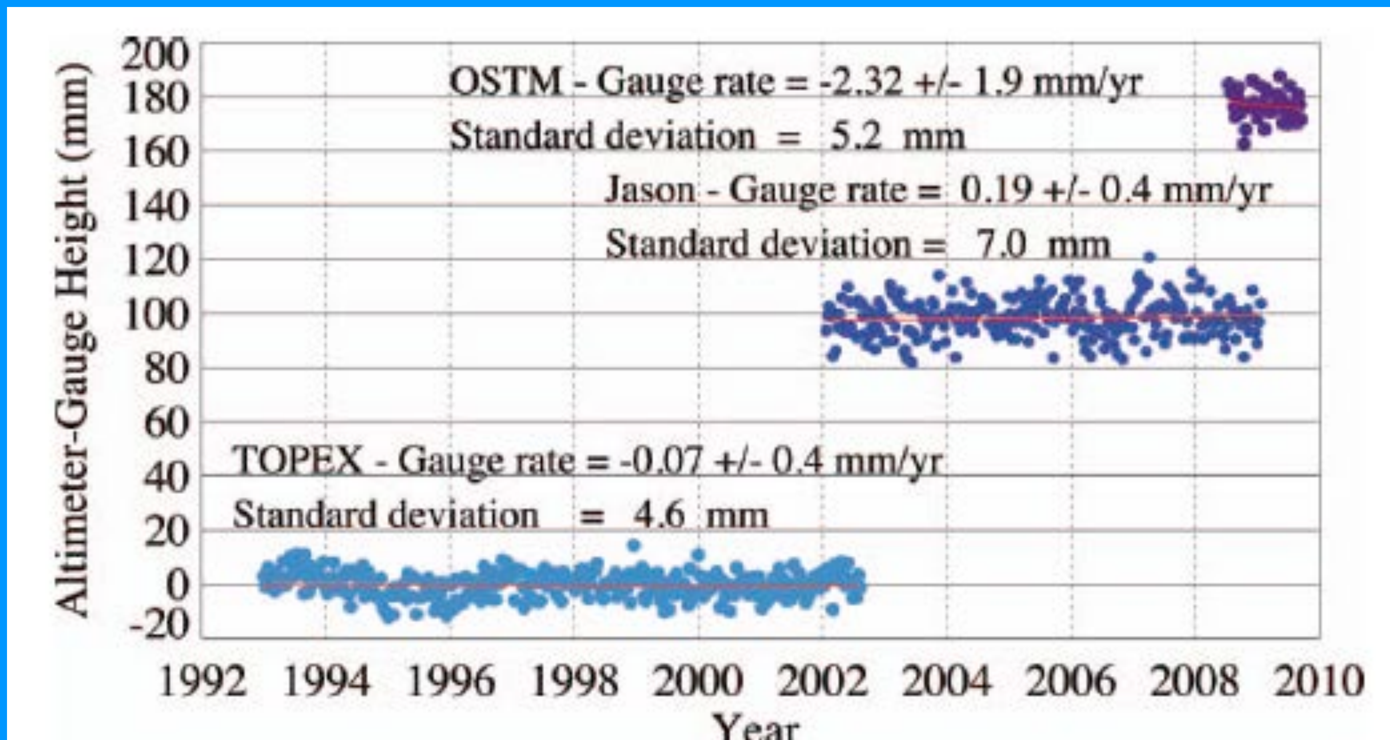
By applying the time-varying gravity field of the atmosphere (to 50x50 every six hrs), and using annual variations in the geopotential to 20x20 derived from GRACE, we can improve POD on altimeter satellites such as Jason. SLR/DORIS orbits with/without this TVG model induce a radial annual variation in the orbits with an amplitude of 5 mm … that would map into the altimetry or into station positioning (for DORIS).

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

Application (example): Altimeter vs. tide-gauge calibration



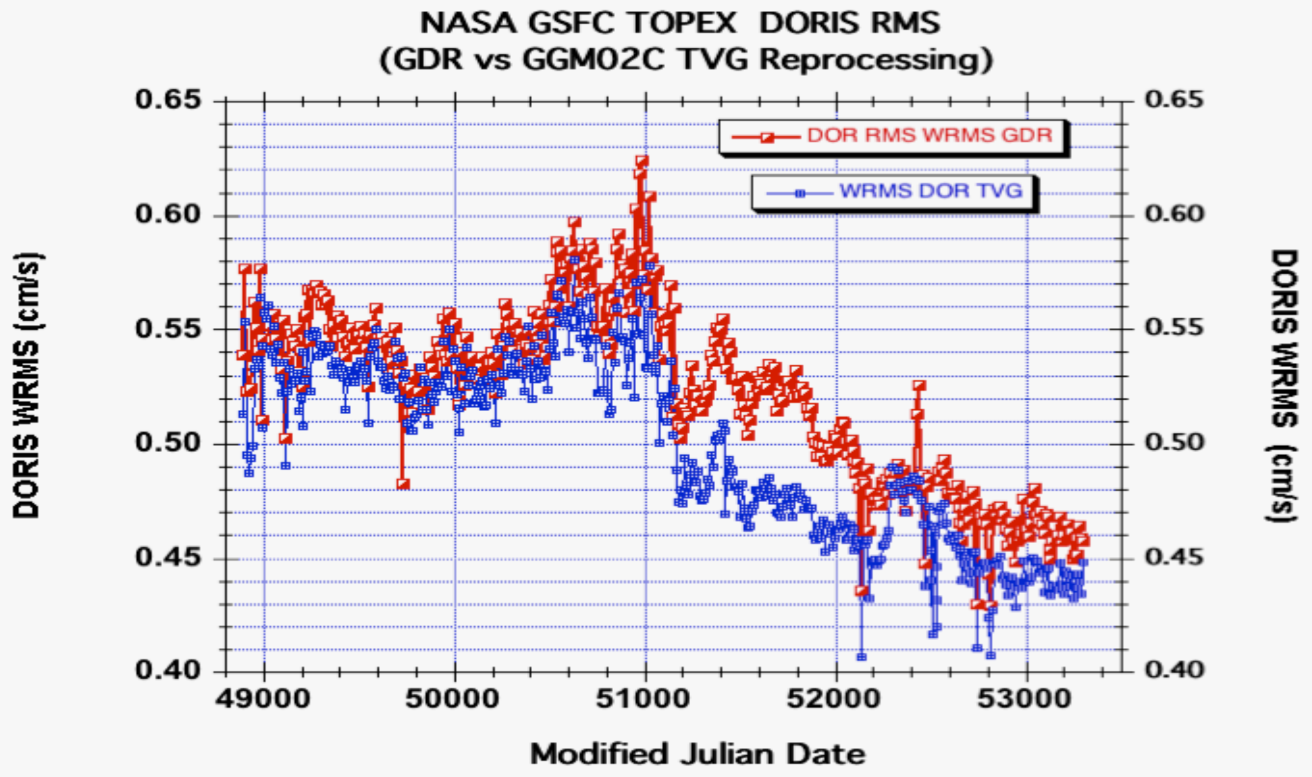
GPS/DORIS/SLR enter into the determination of mean sea level in two ways:

1. (Directly) The orbit determination for the altimeter satellites (**TOPEX**, **Jason1**, **Jason2**)
2. (Indirectly) Determination of the vertical rates at some of the tide gauge sites.

Monitoring the global average of the differences between sea level between altimetry data and the tide gauges allows us to monitor the performance of the altimeter system and guard against any instrumental drifts.

Synopsis of Some Recent Improvements … Tracking System & Model Improvements (e.g.)

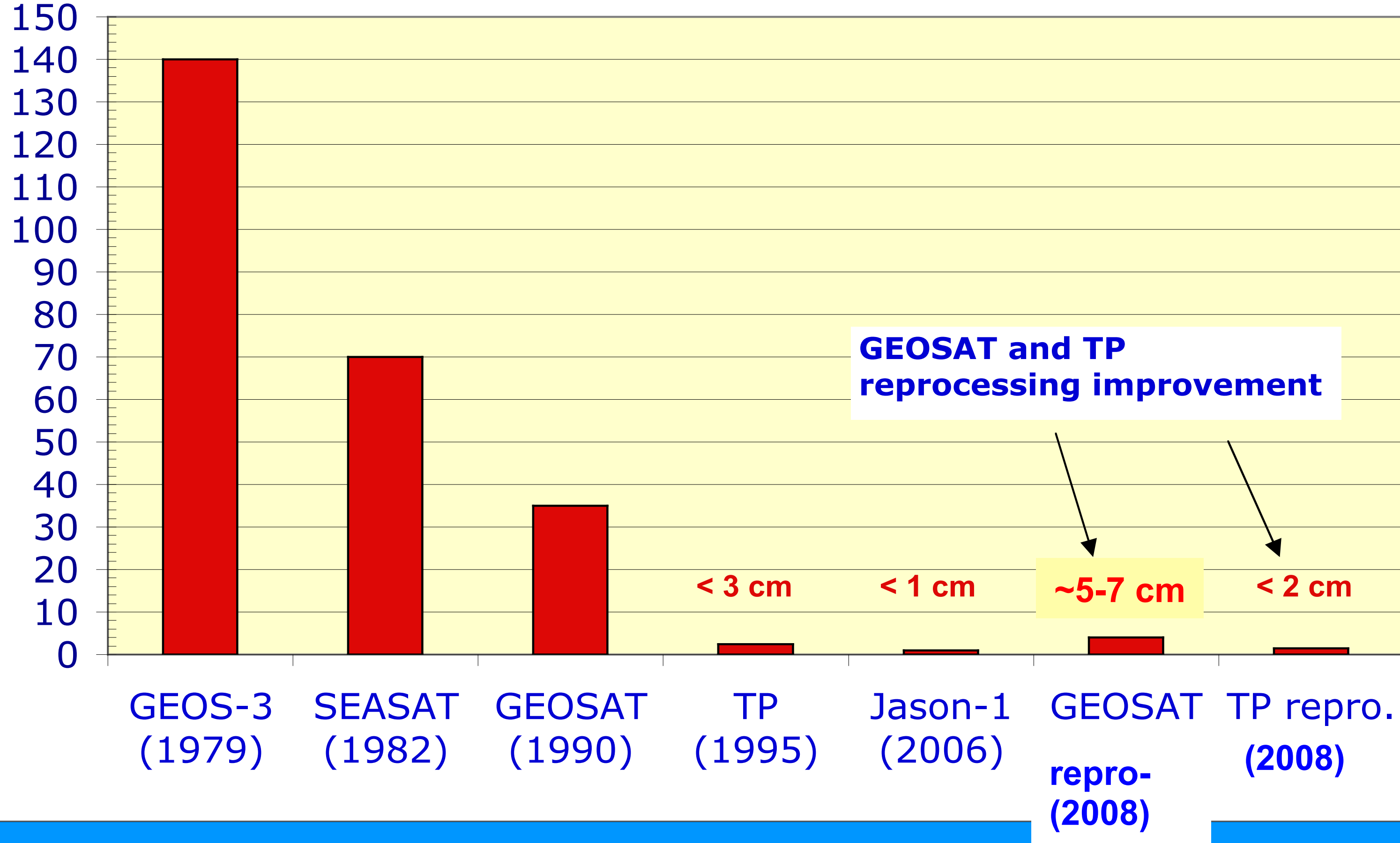
DORIS Evolution from TOPEX re-analysis



DORIS monument improvement and systematic application of site quality criteria significantly improved system performance (*cf. Fagard, J. Geodesy, 2006*). ***Stable & precise monumentation is essential.***

Altimeter Satellite POD Summary

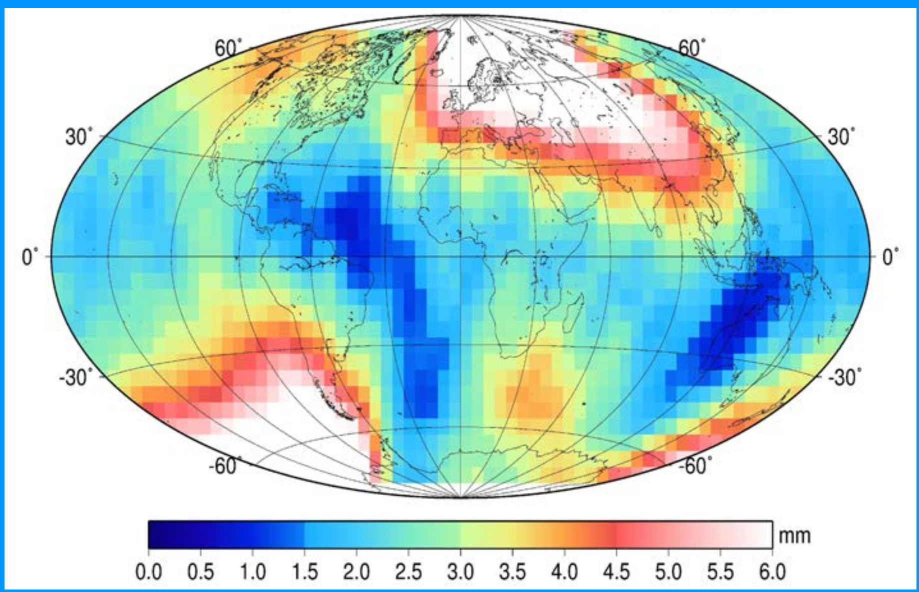
Radial Orbit Accuracy Achievement



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.**
6. **Deployment of Next Generation Geodetic Stations (SLR, GPS).**

Altimeter Satellite Status & Future Missions

JASON-1 (*CNES, NASA*), *2002*	**1336 km, 66°**	**D2G + SLR +GPS**
JASON-2 (*NASA, CNES*), *2008*	**1336 km, 66°**	**DGXX+SLR+GPS**
CRYOSAT-2 (*ESA*), *April 2010*	**717 km, 92°**	**DGXX+SLR**
ENVISAT (*ESA*), *2002*	**~800 km, 98.5°**	**D2G +SLR**
HY2A (*CNSA*),	**963 km, 99.3°**	**DGXX+SLR+GPS**
(Launched August 2011; Then HY2B, HY2C ….)		

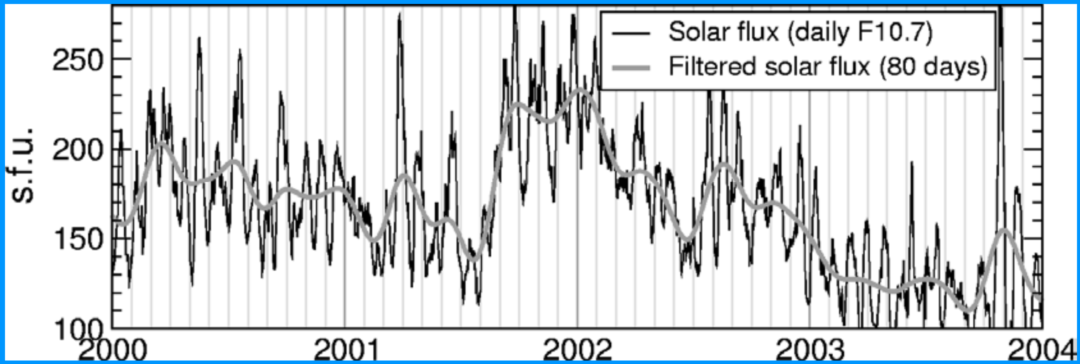
SARAL/ALTIKA (*ISRO/CNES*)	**880 km, 98.5°**	**DGXX+SLR**
(Launch: 2012)		
SENTINAL 3A (*GMES*)	**814 km, 98.6°**	**DGXX+SLR+GPS**
(Launch: April 2013)		
JASON-3	**1336 km, 66°**	**DGXX+SLR+ GPS**
(*NASA/NOAA/CNES/EUMETSAT/***)***(2014; Follow-on to TOPEX, Jason-1, Jason-2)*		
ICESAT-2 (*NASA, Laser altimeter*)		**GPS+(**SLR)
(*Launch ~2015***)**		
SWOT (*CNES, NASA*)	**970 km, 78°**	**DGXX+SLR+GPS**
(Surface Water Ocean Topography; Launch 2018-2020)		

Obrigado. Thank you for your attention.

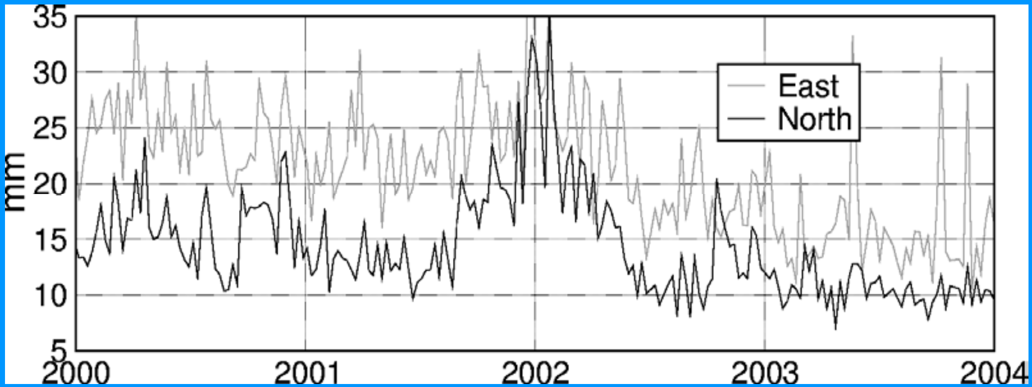
(Some) Reference Frame Issues (3)

DORIS Station Determination affected by Atmospheric Drag Increase near Solar maximum

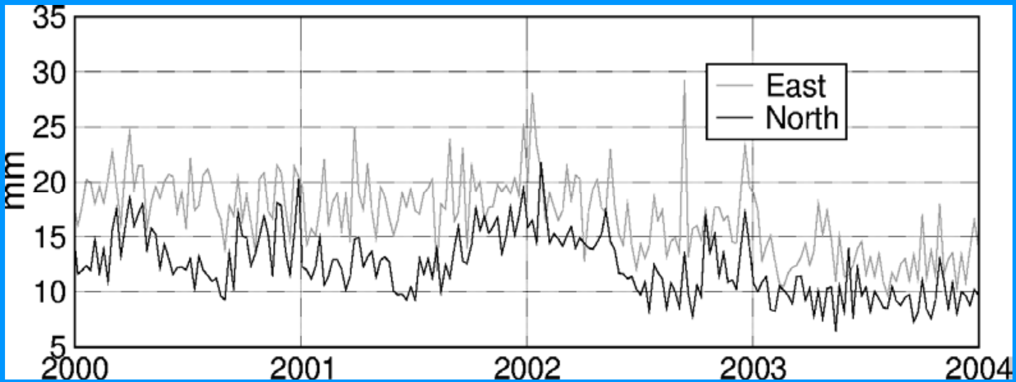
Solar Flux



IDS-1
Horizontal Residuals



IDS-3
Horizontal Residuals



Valette et al., 2010.