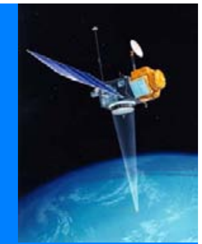


The Geodetic Networks & Space Geodesy Applications

F. G Lemoine[1], S. B Luthcke[1], D.D Rowlands[1], N. P. Zelensky[2,1], D. S. Chinn[2,1], B. D. Beckley[2,1]

[1] *NASA Goddard Space Flight Center, Greenbelt, MD, U.S.A.*

[2] *SGT-Inc., Greenbelt, MD, U.S.A.*

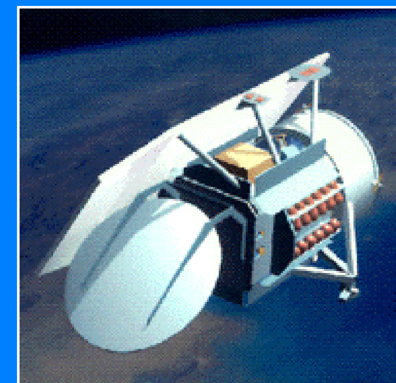
From the launch of the first spaceborne altimeters, Precision Orbit Determination (POD) has been driven by the science goals of the geodetic altimeter missions…

GEOS-3, 1975

SEASAT, 1978

GEOSAT, 1985

TOPEX/POSEIDON, 1992



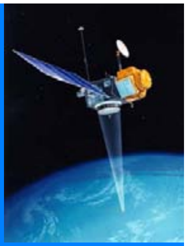
GFO-1, 1998

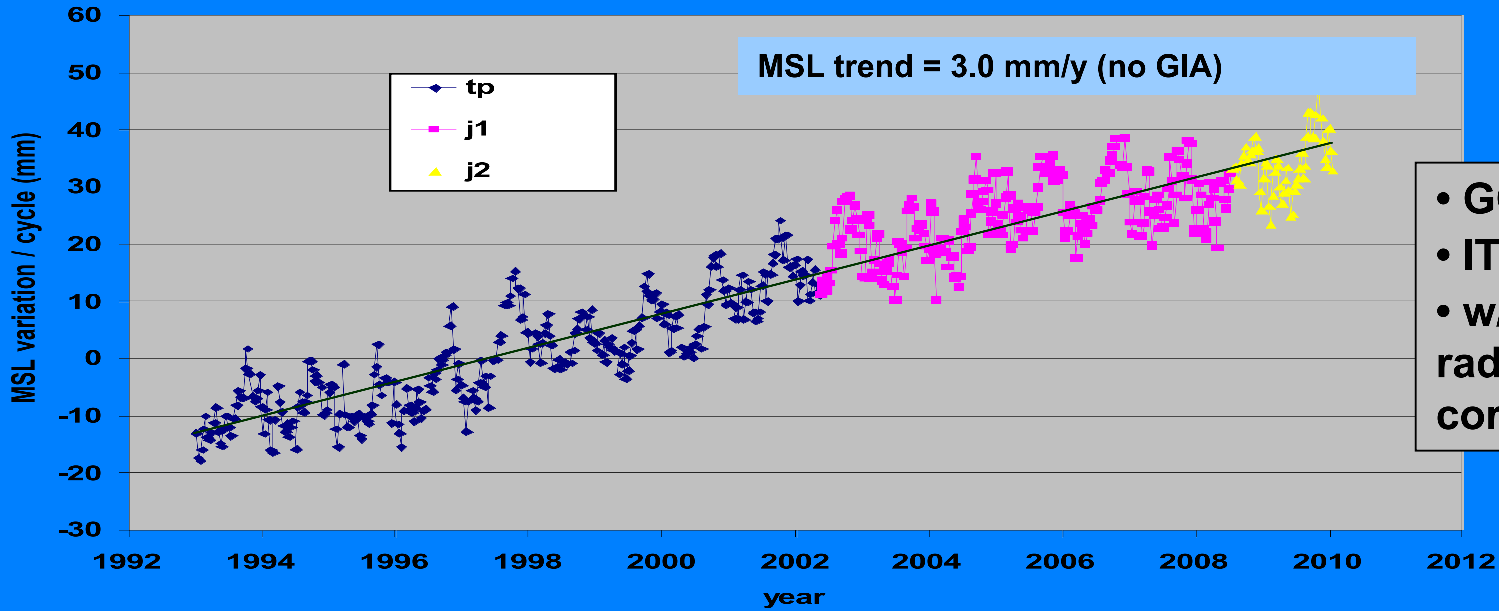
Jason-1, 2002
Jason-2, 2008

ENVISAT, 2002

CRYOSAT-2, 2010

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





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

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…

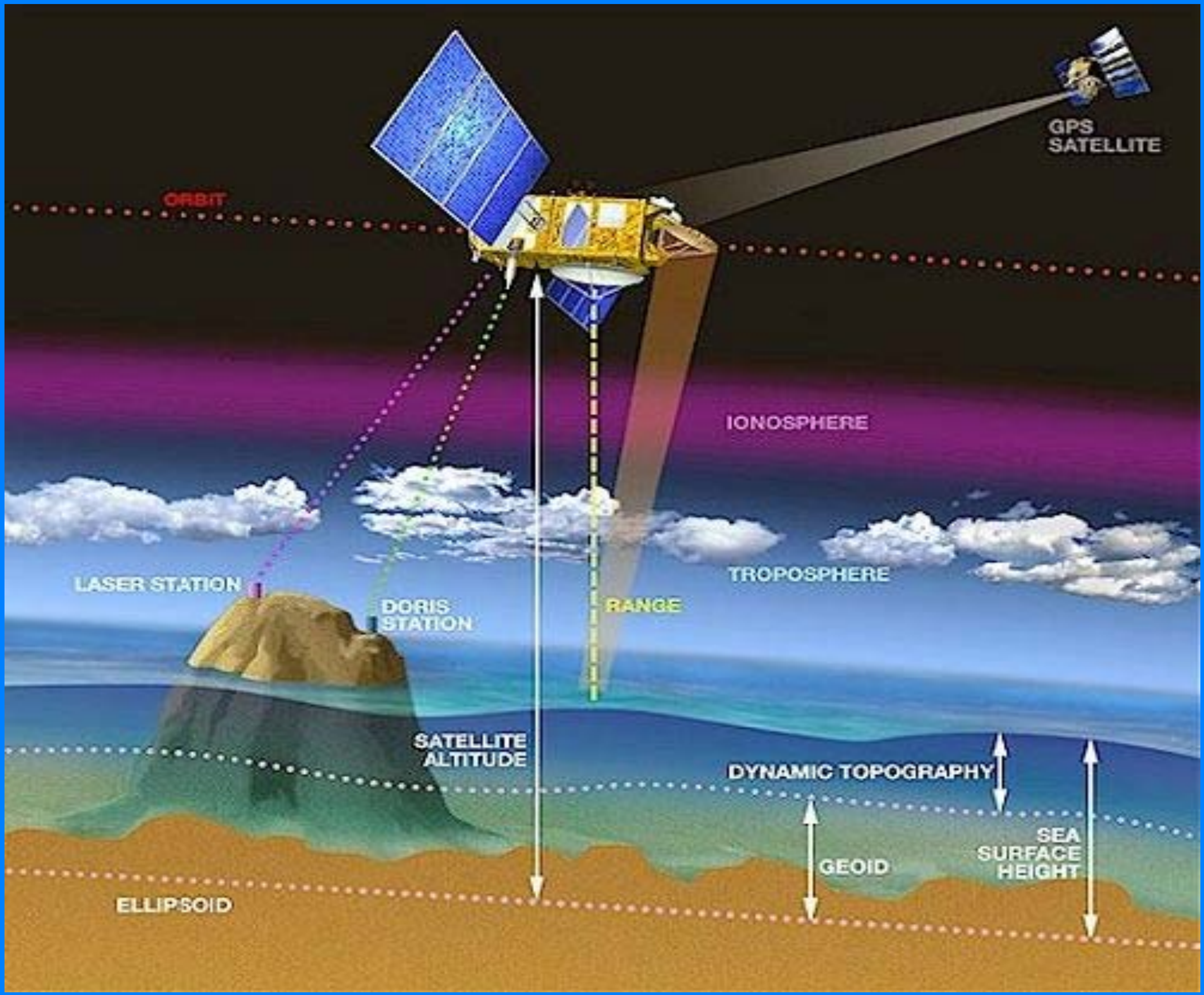
Meeting mission POD accuracy requirements has depended on advances in each of the following areas

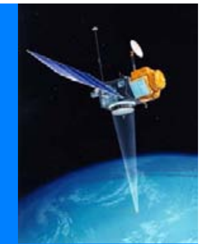
1) Accurately modelling the forces acting on the satellite… Force Modelling

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.

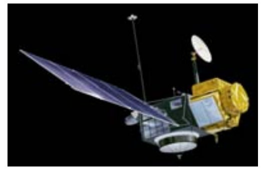
POD Schematic





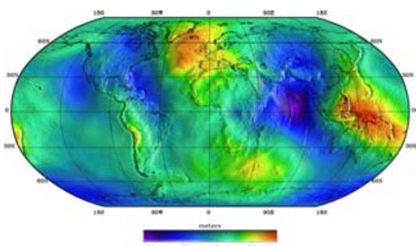
Orbit Determination

Onboard Tracking Systems
LRR
DORIS
GPS



Atmospheric Modeling
Ionospheric Propagation Delay
Tropospheric Refraction
Atmospheric Density

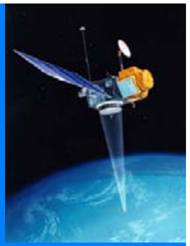
Surface Forces
Modeling
S/C Attitude



Orbit Determination
Force Modeling
Reference Frame
Tracking Technology

Geophysical Models
Gravity Models
Tide Models
Time Variable Gravity

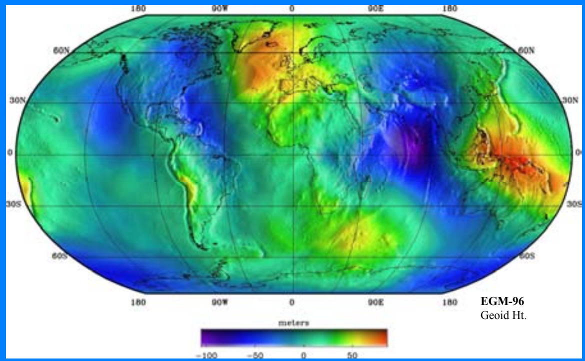
Reference Frame
International Terrestrial Reference Frame
Horizontal plate and vertical site motion
Geocenter motion
Polar Motion and Earth Orientation



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

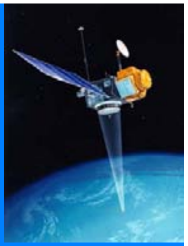
Model	Radial Calibration (cm)	SLR rms fit (cm)
GEM-L2: 1982	65.4	105.9
GEM-T1: 1988	25.0	31.4
GEM-T2: 1990	10.2	17.8
JGM-1S: 1991	6.0	7.7
JGM-2S: 1992	2.9	4.0
JGM-2: 1992	2.2	3.8
JGM-3: 1995	0.9	3.2
EGM-96 1997	0.8	2.8

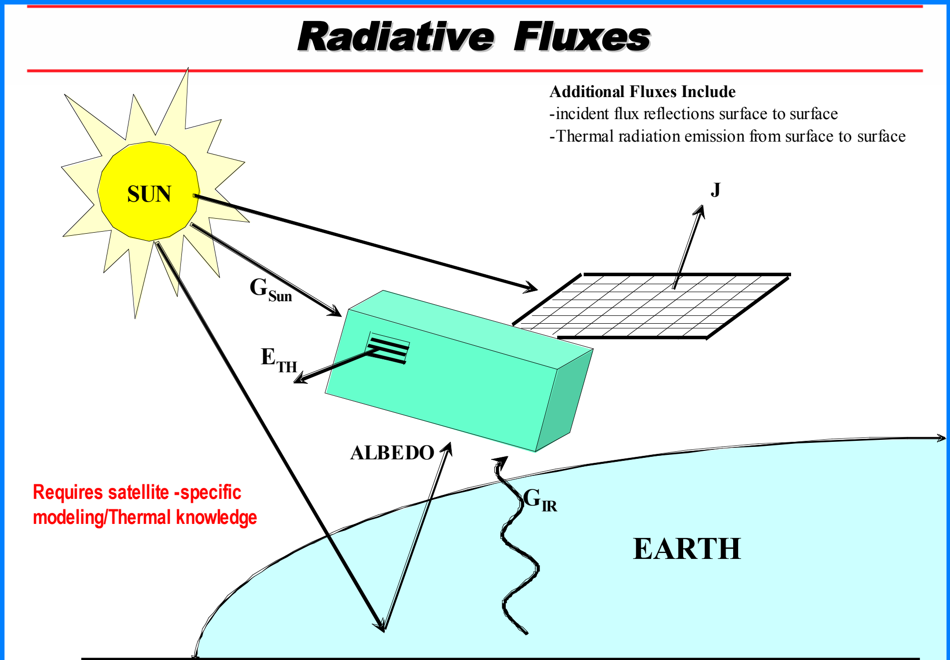
GEML2: 20x20
JGM1-3: 70x70
EGM96S: 70x70; (360x360)
EIGEN-GL04S: 150x150



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





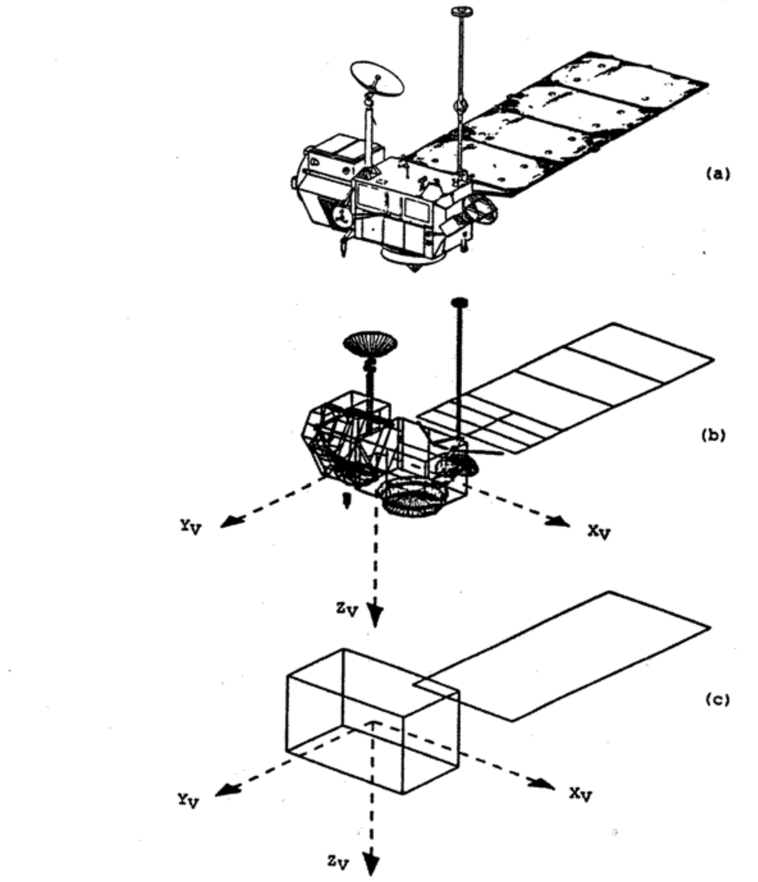


Figure 1. (a) The TOPEX/Poseidon Spacecraft, (b) Micro-Model Approximation, (c) Macro-Model Approximation

Micromodel

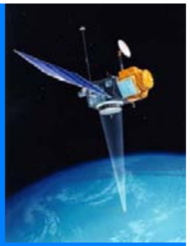
- ***(Antreasian, 1992; Antreasian & Rosborough, 1992)***

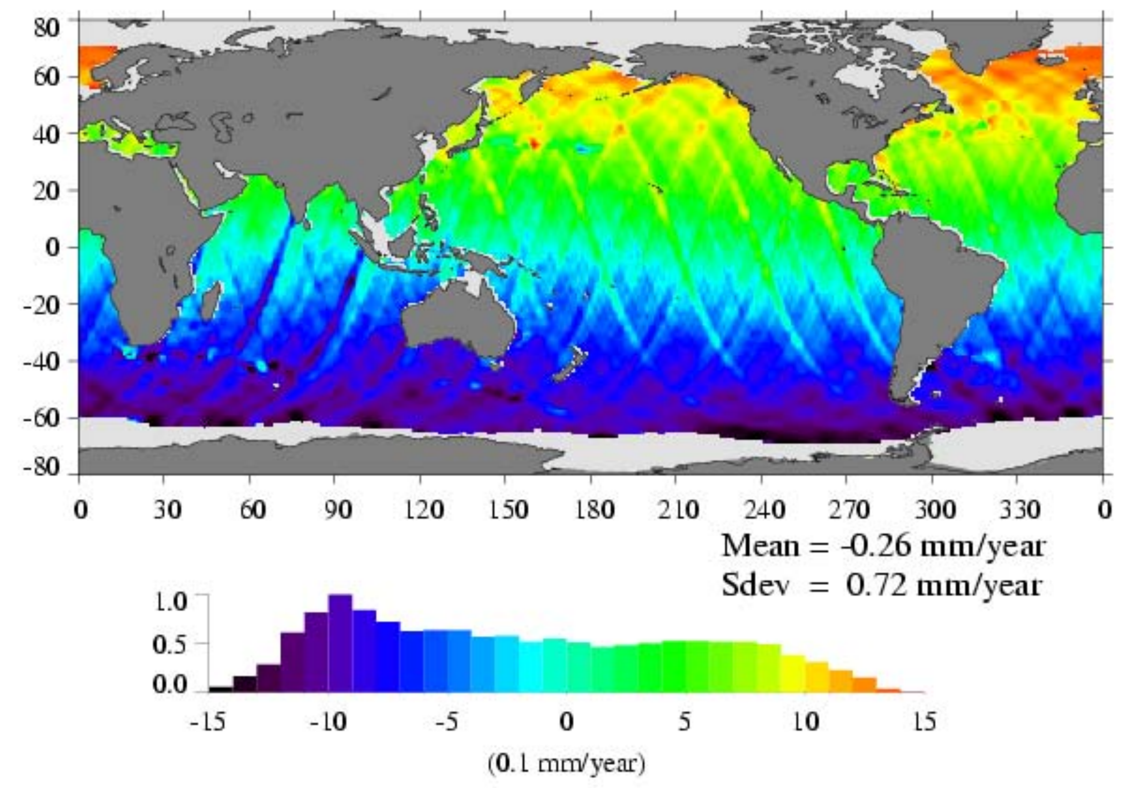
Box-Wing model

- ***(Marshall & Luthcke. 1994)***

y Ap
r 26, 2011

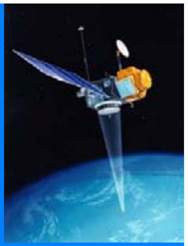
Impact of the Terrestrial Reference Frame on Mean Sea Level Determination





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)**

The Geodetic Networks are the Key to Altimeter Satellite Mission Success



Satellite Laser Ranging (SLR)

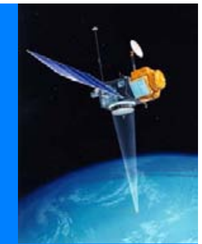
SLR, Maui

SLR, Graz, Austria

DORIS (Ground Network) (Sept. 2011)

Space Geodesy Applications
September 26, 2011

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**

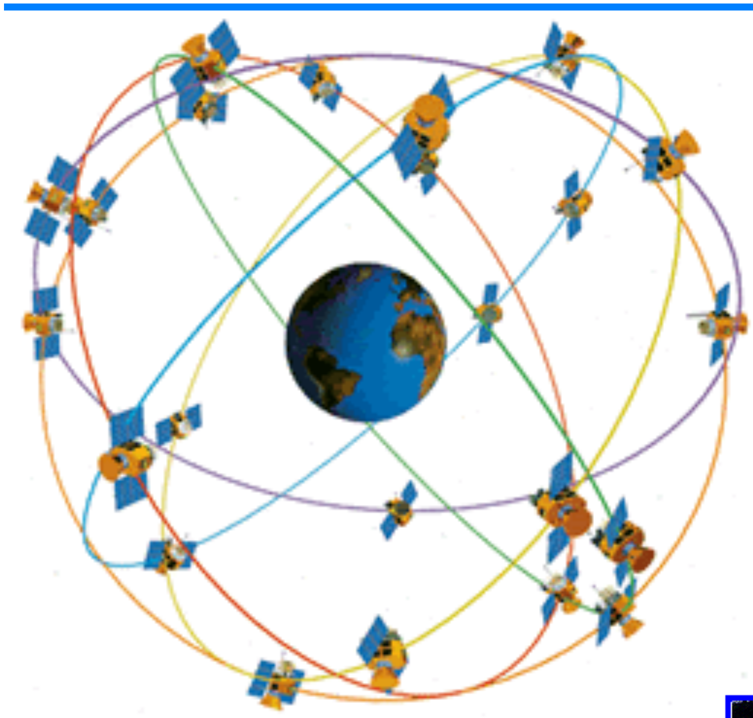
IDS

International DORIS Service

GPS Tracking System for OSTM

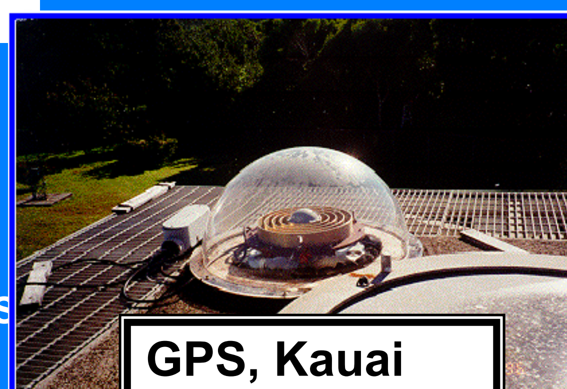
International GNSS Service
Formerly the International GPS Service

GPS Satellite Constellation

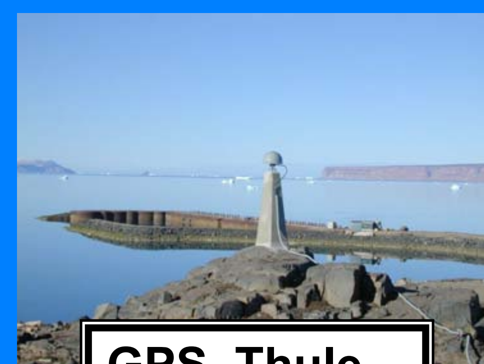


JASON GPS Receiver

Examples: Ground Receivers

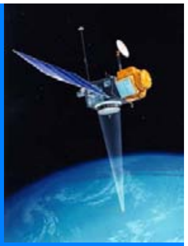


GPS, Kauai



GPS, Thule

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:

- Gravity: JGM-2 (Nerem et al. 1993) JGM-3 (Tapley et al. 1994)
- 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

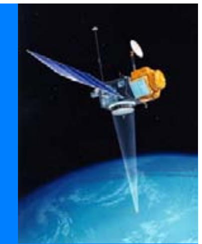
Diverse and cooperative POD Team: NASA GSFC, CNES, JPL, UT/CSR, CU,

… with contributions by many others e.g.. The Ohio State University.

Jason-1 (2001); Jason-2 (2008)

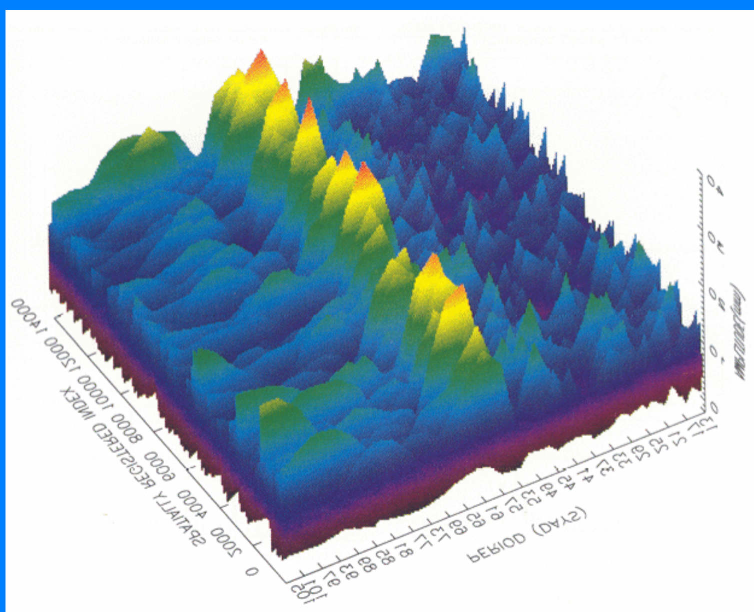
The 1-cm orbit …

- ***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).***
- ***<u>Applied Upgraded tracking technology</u>: GPS, SLR, DORIS (Especially JPL GPS BlackJack codeless receiver).***
- ***<u>Improved tracking network positions and measurement modelling</u> (e.g. GPS antenna phase center modeling)***
- ***<u>Improved application of the reduced dynamic solutions</u> 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***

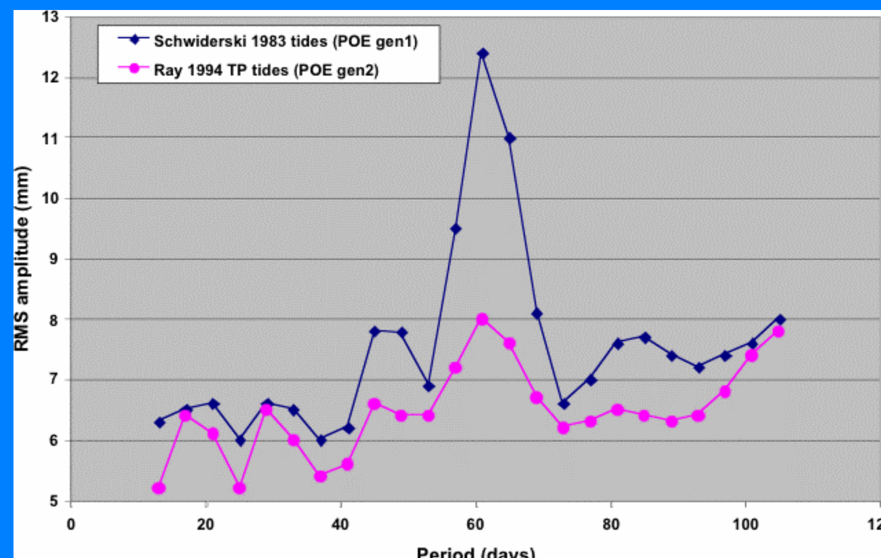


Intercomparison of Independent Orbits Produced by SLR/DORIS & GPS (Reduced Dynamic) allows insights into model and geodetic technique error ….. And helps to validate improvements ….

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



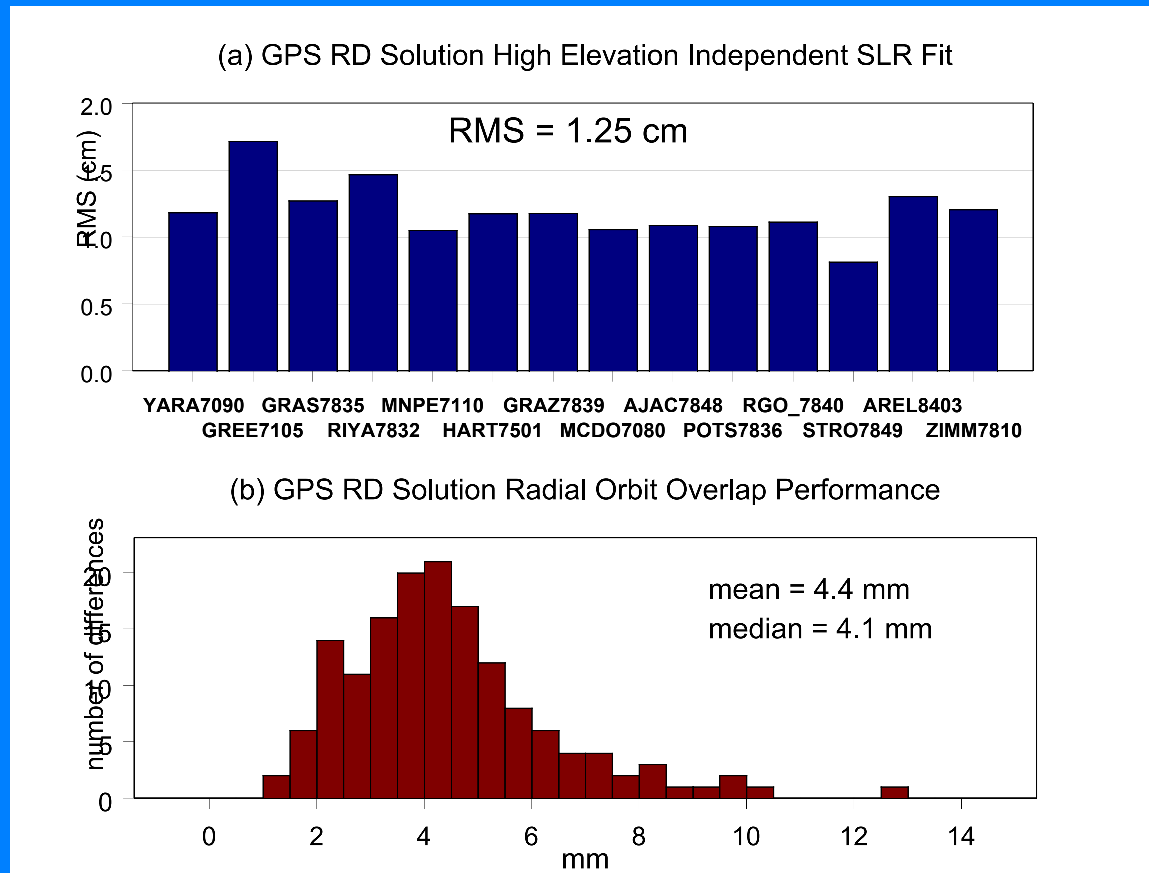
Tide model improvement using TOPEX altimeter data



Jason GPS Reduced Dynamic POD Achieved the 1-cm radial orbit accuracy goal…

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

Other error sources are included beyond radial orbit error.

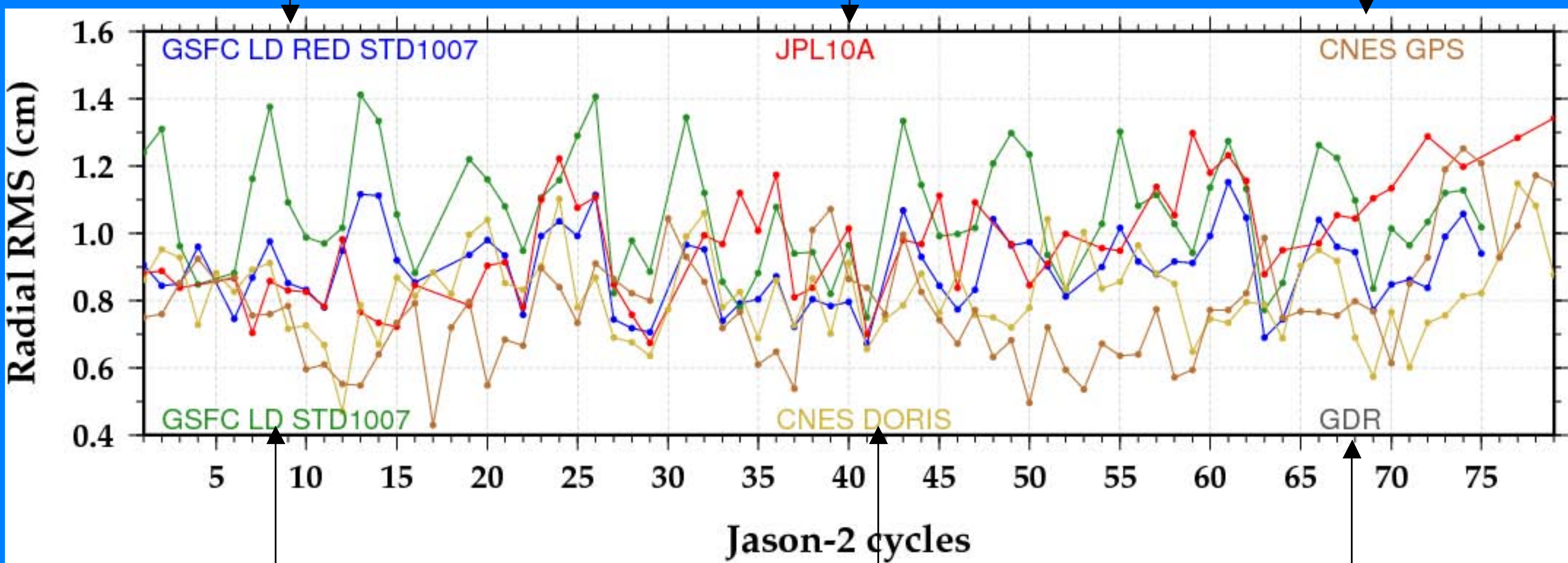


Jason-2 Orbit Intercomparisons Allow Validation of Radial Orbit Accuracy

SLR DORIS red-dyn (GSFC)

GPS-only red-dyn (JPL)

GPS-only (CNES)



SLR DORIS dyn. (GSFC)

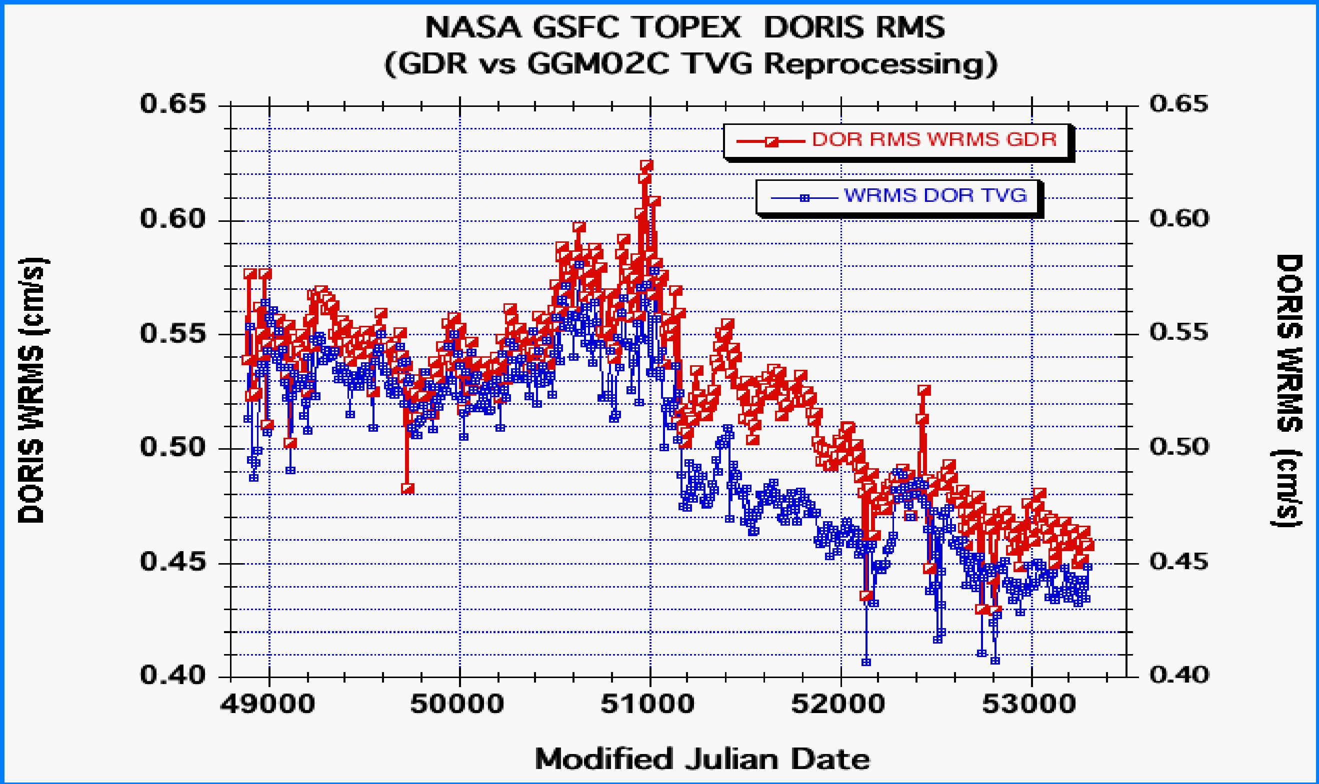
DORIS-only (CNES)

SLR+DORIS+GPS (CNES)

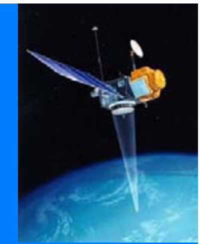
Cerri et al. (2010)

Synopsis of Some Recent Improvements (1) …
Tracking System & Model Improvements (e.g.)

DORIS Evolution from TOPEX re-analysis

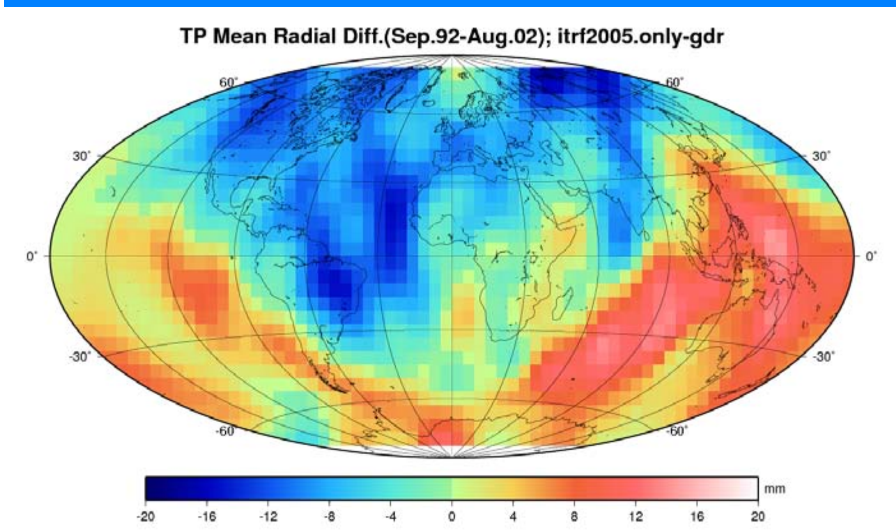


DORIS monument improvement and systematic application of site quality criteria significantly improved system performance *(cf. Fagard, 2006)*



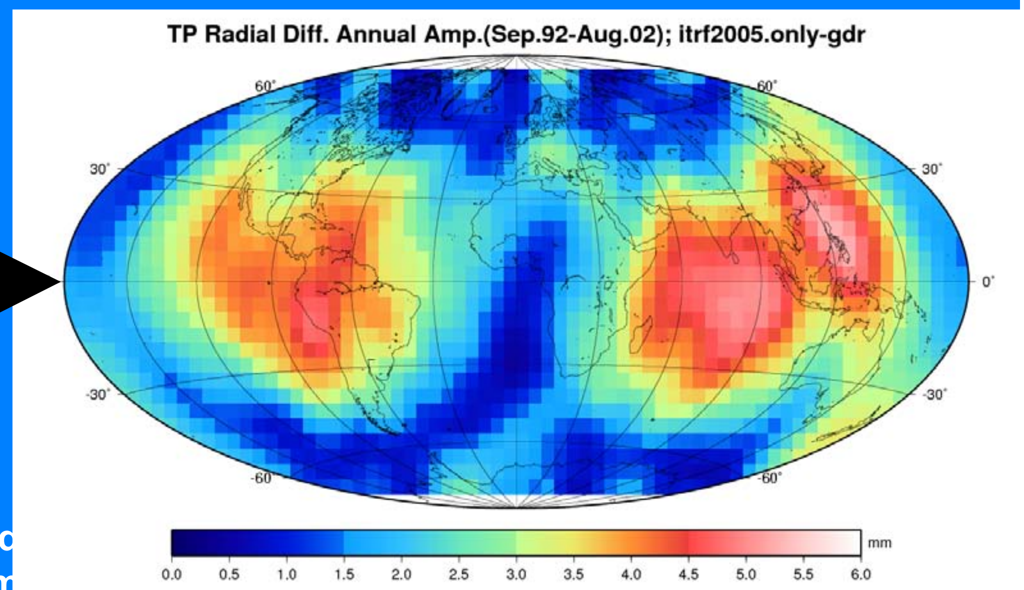
Synopsis of Recent Improvements … (2)

Improved gravity modelling using products from the GRACE mission

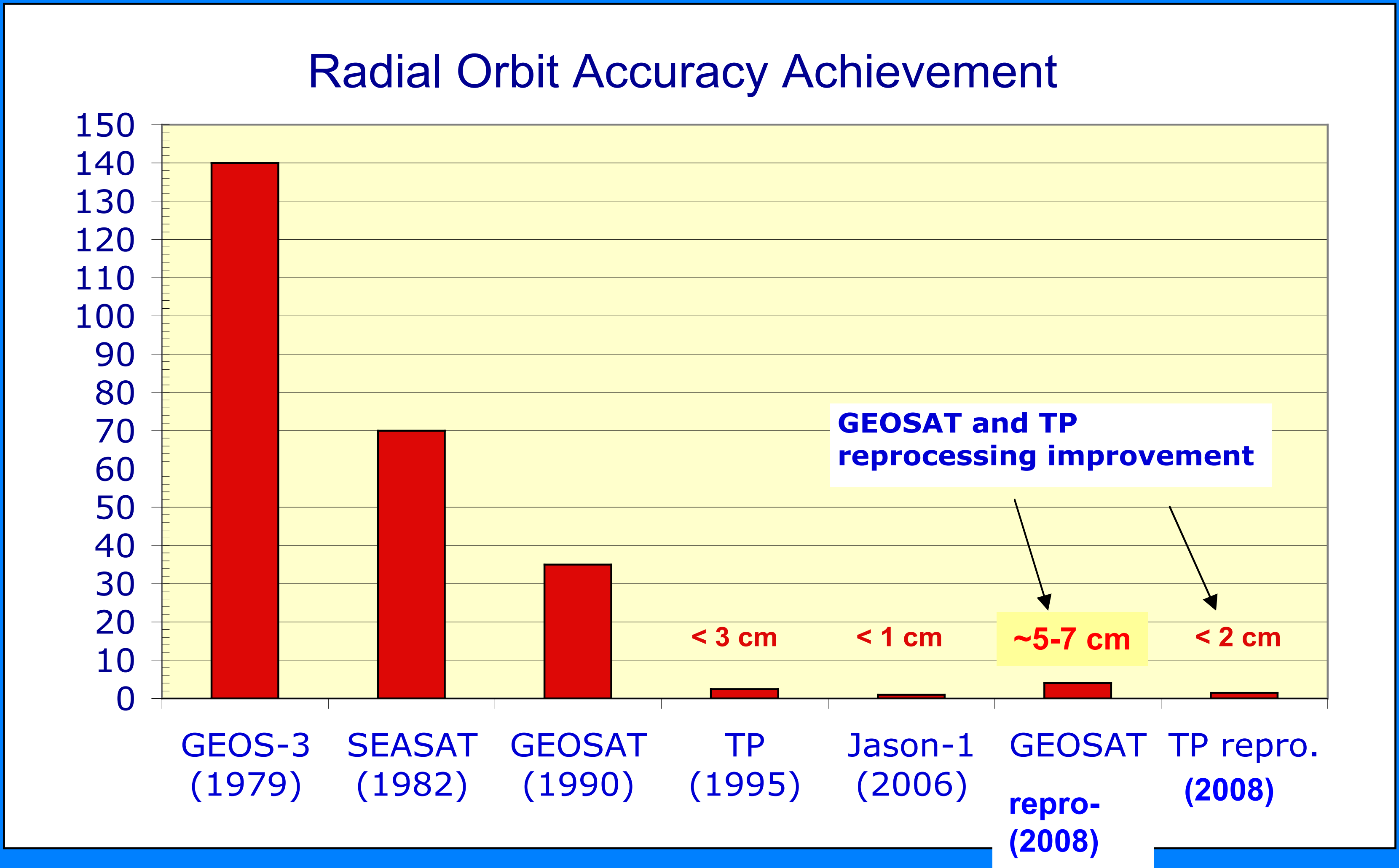


Geographically correlated error removed (GGM02C vs. JGM3)

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



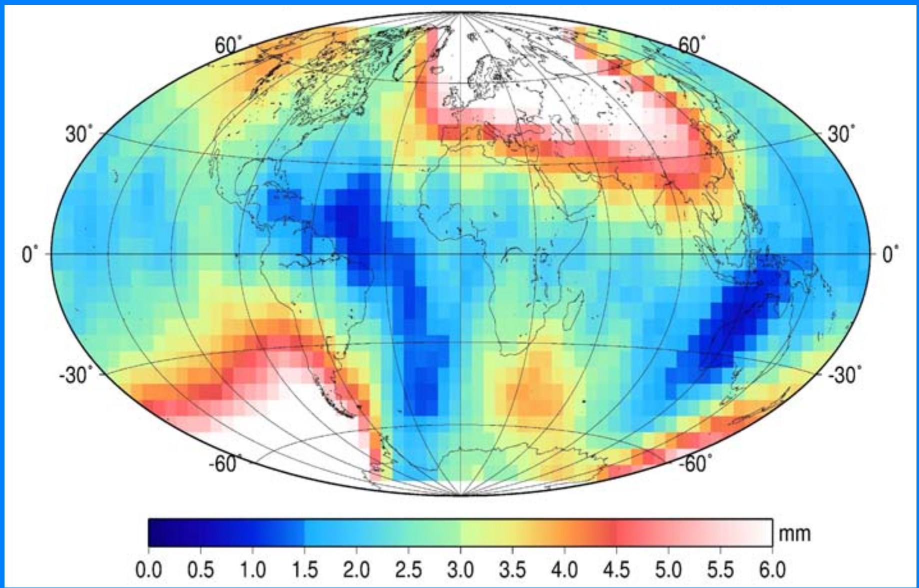
Altimeter Satellite POD Summary



Continued Challenges

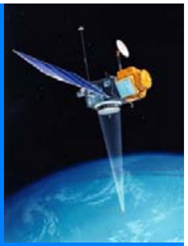
Radiation Pressure Modelling:

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

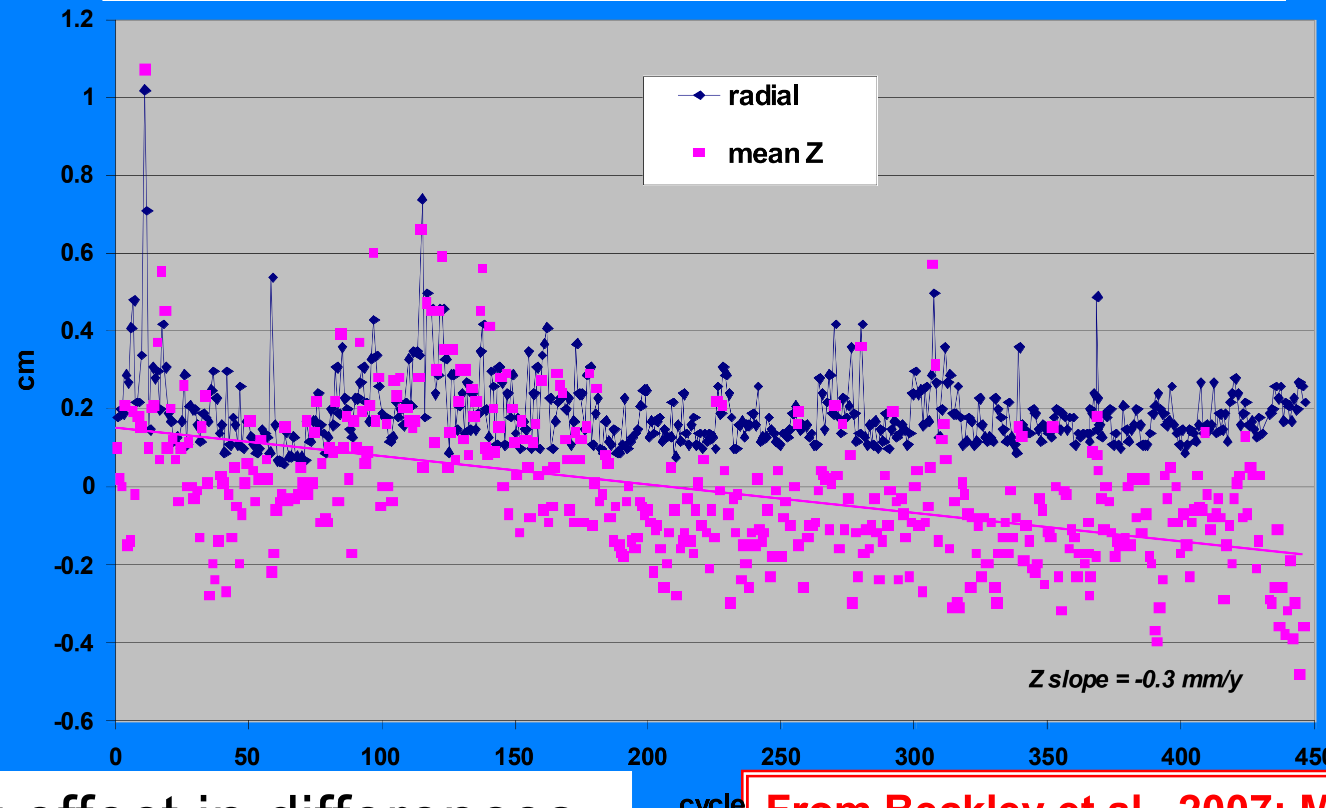


1. **Providing a consistent orbit time series for altimeter data over 16+ years, spanning three missions, and four altimeters - to better resolve interdecadal signals & MSL change.**
2. **Radiation Modelling Improvements.**
3. **Reference Frame Stability.**
4. **Measurement model improvements for SLR, GPS & DORIS.**
5. **Geocenter.**
6. **Deployment of Next Generation Geodetic Stations (SLR, GPS).**

(Some) Reference Frame Issues (1)



TOPEX SLR+DORIS Orbit Differences (ITRF2005 - ITRF2008)

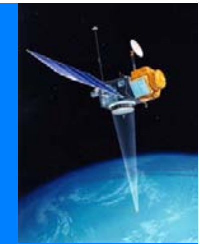


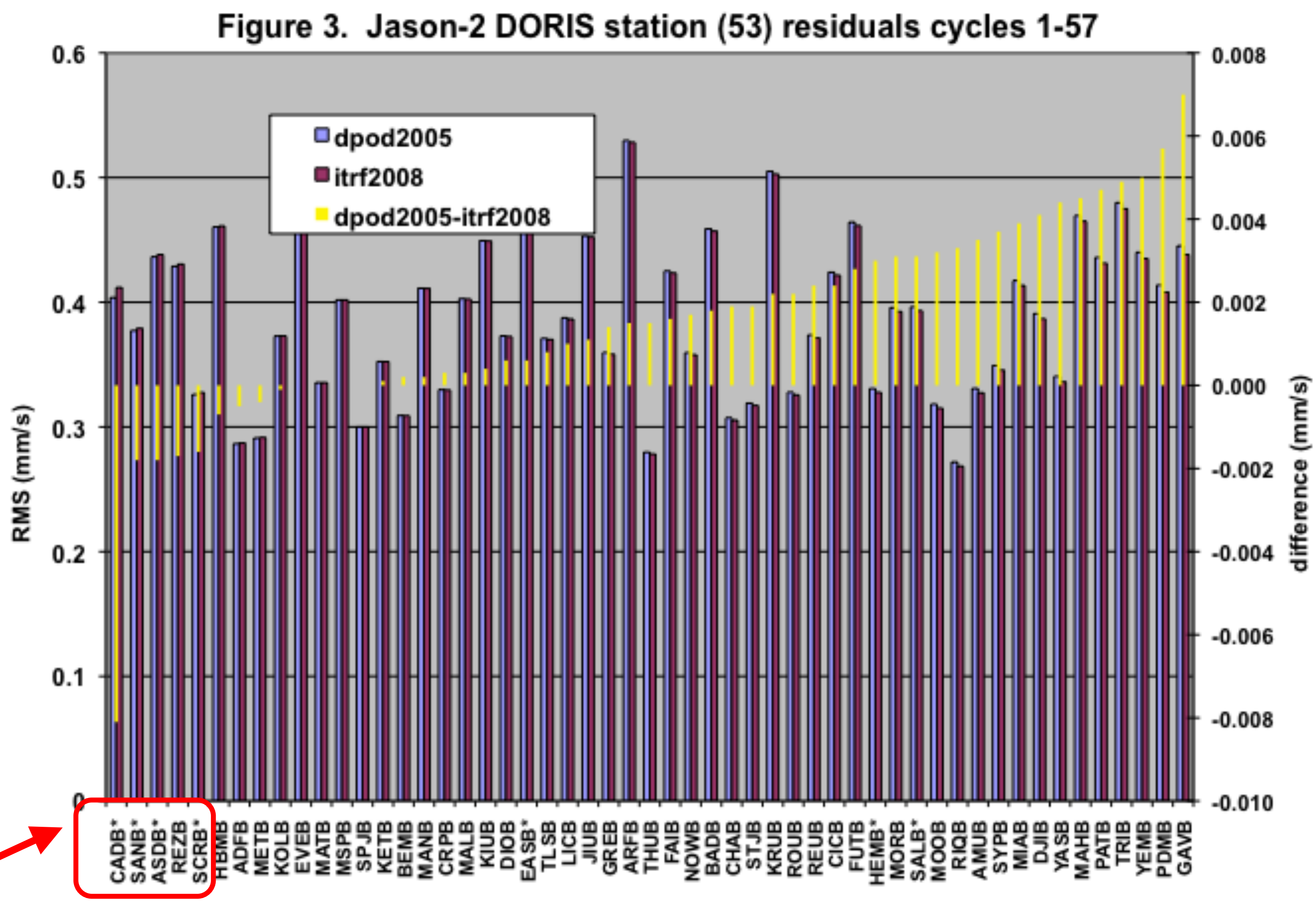
Network effect in differences, centered ~1996?

From Beckley et al., 2007; Morel & Willis, 2005, change in sea level rate will be ~0.06 mm/yr.

(Some) Reference Frame Issues (2)

DORIS Station Performance: ITRF2005 vs. ITRF2008



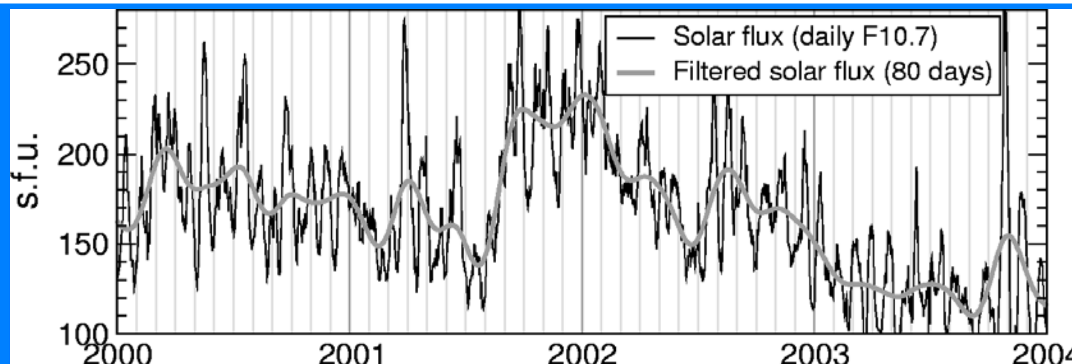


Predominantly SAA stations show degradation for Jason-2

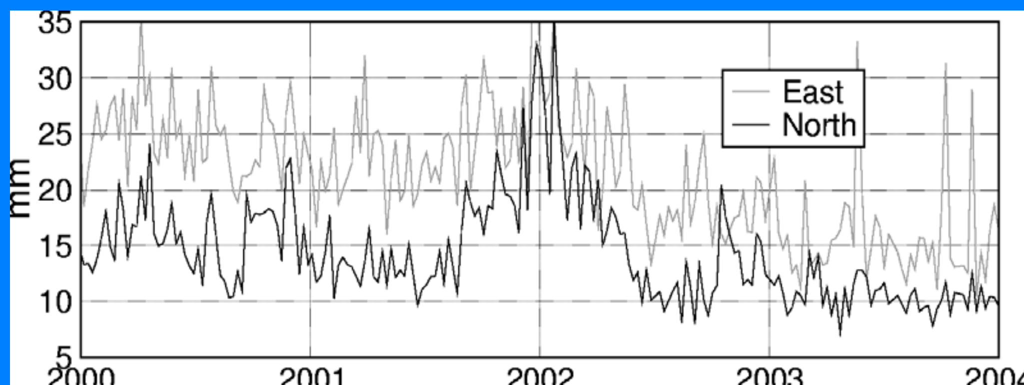
(Some) Reference Frame Issues (3)

DORIS Station Determination affected by Atmospheric Drag Increase near Solar maximum

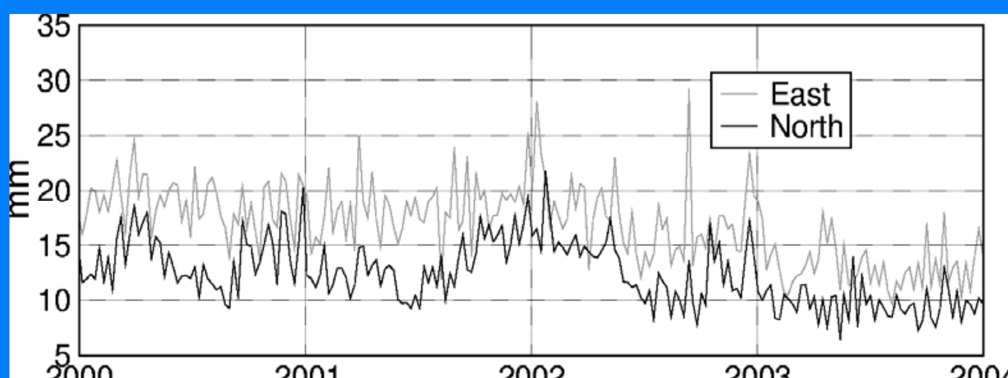
Solar Flux



IDS-1
Horizontal Residuals

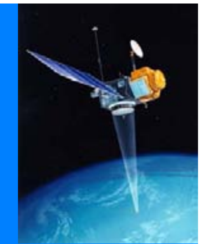


IDS-3
Horizontal Residuals



Valette et al., 2010.

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*), *(Launched August 2011; Then HY2B, HY2C ….)*	**963 km, 99.3°**	**DGXX+SLR+GPS**
SARAL/ALTIKA (*ISRO/CNES*) *(Launch: 2012)*	**880 km, 98.5°**	**DGXX+SLR**
SENTINAL 3A (*GMES*) *(Launch: April 2013)*	**814 km, 98.6°**	**DGXX+SLR+GPS**
JASON-3 (*NOAA/EUMETSAT/CNES/NASA*)*(2013; Follow-on to TOPEX, Jason-1, Jason-2)*	**1336 km, 66°**	**DGXX+SLR+ GPS**
ICESAT-2 (*NASA, Laser altimeter*) *(Launch ~2015)*	**~600 km, 94°**	**GPS+(SLR)**
SWOT (*CNES, NASA*) *(Surface Water Ocean Topography; Launch 2018-2020)*	**970 km, 78°**	**DGXX+SLR+GPS**