Three Decades of Precision Orbit Determination and its Vital Role to Oceanography

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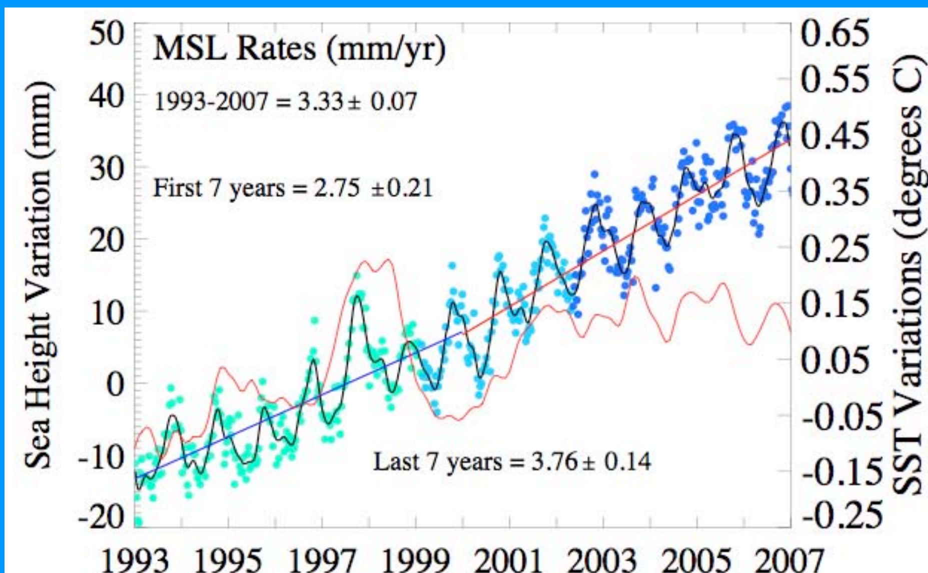
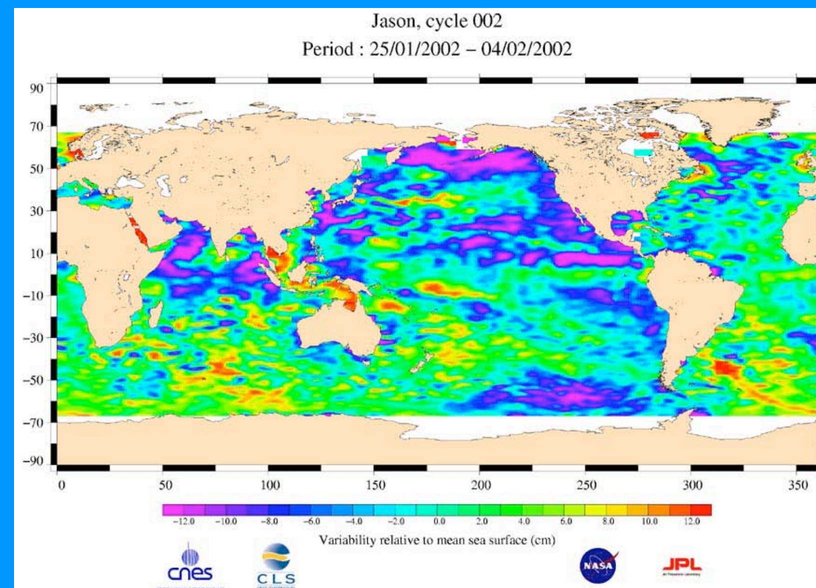
From the launch of the first spaceborne altimeters, Precision Orbit Determination (POD) has been driven by the science goals of the geodetic altimeter missions…





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…

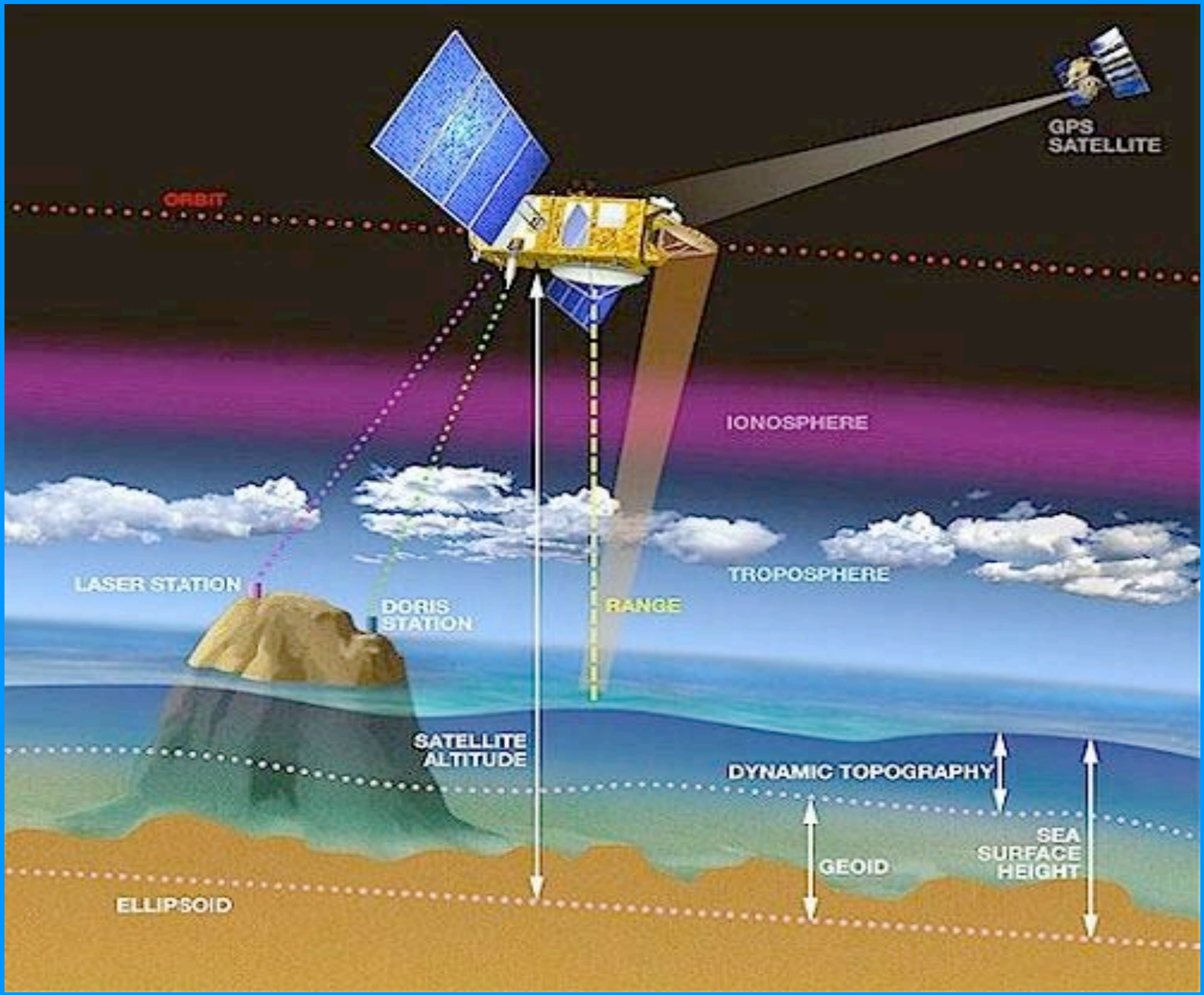
Meeting mission POD accuracy requirements has depended on advances in each of the following areas

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

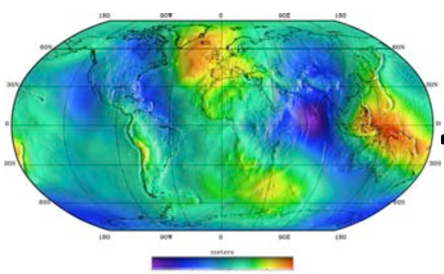


Orbit Determination

Onboard Tracking Systems
LRR
DORIS
GPS

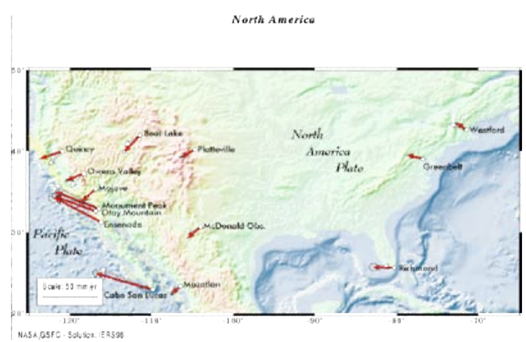
Atmospheric Modeling
Ionospheric Propagation Delay
Tropospheric Refraction
Atmospheric Density

Surface Forces
Modeling
S/C Attitude



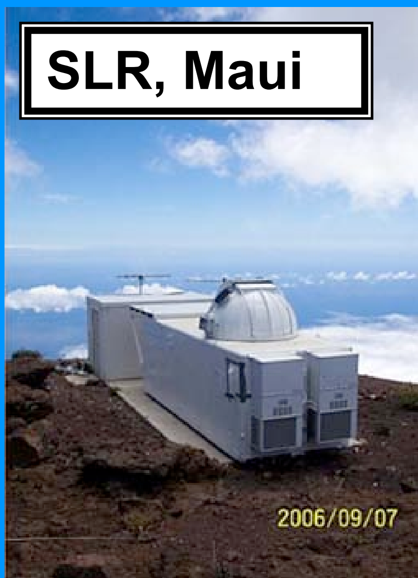
Orbit Determination
Force Modeling
Reference Frame
Tracking Technology

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

The Geodetic Networks are the Key to Altimeter Satellite Mission Success



SLR, Maui


SLR, Graz, Austria

Satellite Laser Ranging (SLR)

DORIS (Ground Network)

Rothera

Thule

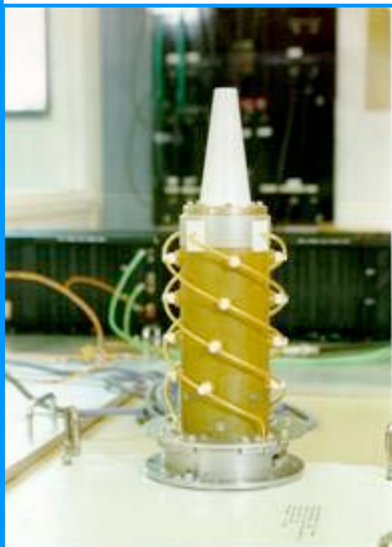
IDS

International DORIS Service

DORIS (Satellite Receivers)

(Table from Jayles et al. 2006)

DORIS antenna



2 kg
h 420 x ϕ160
(mm)

1st generation (WBUT = 18 kg)	**2nd generation (WBUT = 5.5 kg)**	**2nd generation miniaturised (WBUT = 3 kg)**
SPOT2, SPOT3, TOPEX-Poseidon (*), SPOT4	ENVISAT (*)	Jason-1 (*), SPOT5
1 channel	2 channels	2 channels

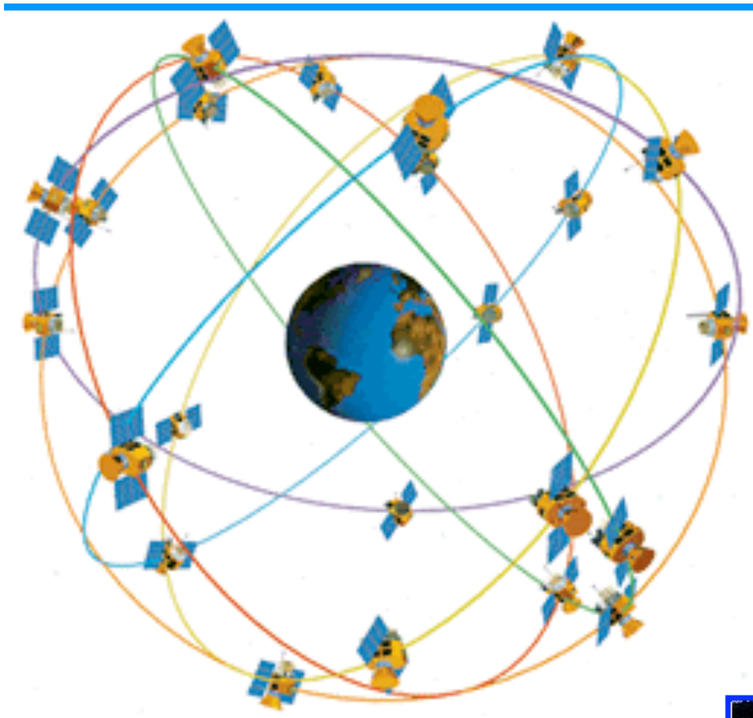
Intermediate DGXX (WBUT = 3 kg)	**Full DGXX generation (WBUT = 1.15 kg)**
CryoSat (*)	Jason-2, Pléiades, AltiKa
2 channels	2 x 7 channels
	twinned (redundant) in one box including USOs and automated antenna switching

1^{st}. Generation receivers can track one beacon at a time; 2^{nd} generation can track two beacons; Jason-2 & later can track up to seven beacons.
(*Therefore much more tracking data is available from ENVISAT & SPOT5 & Jason-1 than on SPOT2 & TOPEX/Poseidon*).

GPS Tracking System for OSTM

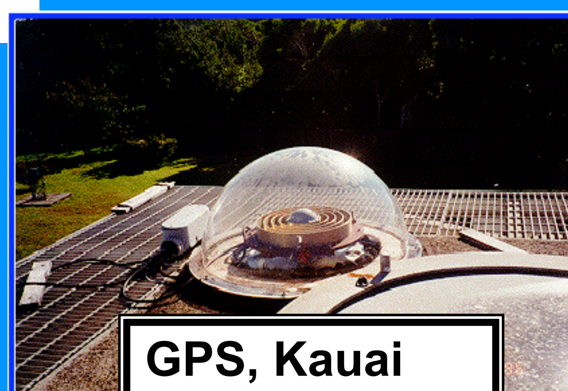
International GNSS Service
Formerly the International GPS Service

GPS Satellite Constellation

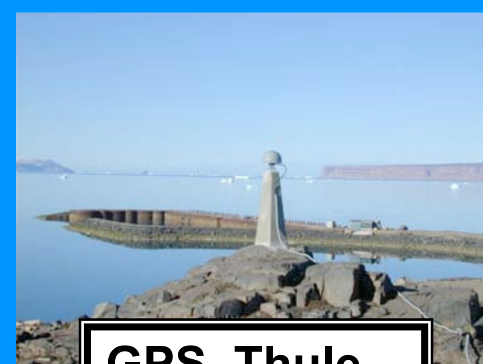


JASON GPS Receiver

Examples: Ground Receivers



GPS, Kauai

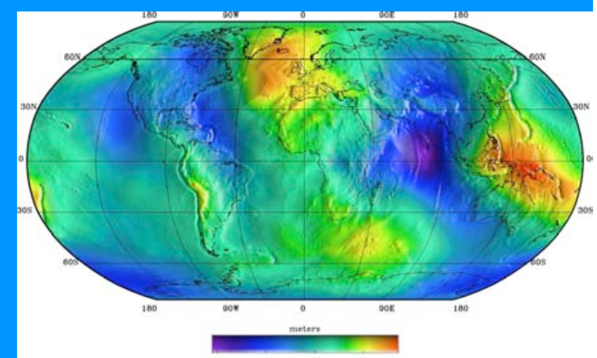


GPS, Thule

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



Significant advancement in POD accuracy achieved for GEOS-3 (1979) due to gravity field modeling improvement…

Armed with a suite of tracking technologies, including Satellite Laser Ranging (SLR), GEOS-3 tracking data significantly advanced the gravity field model and orbit accuracy (Lerch et al. 1979):

- **_GEM-9 and 10 complete to degree and order 20_**
- **_GEOS-3 radial orbit accuracy improvement from ~500 cm to ~130 cm_**

LERCH ET AL.: SC

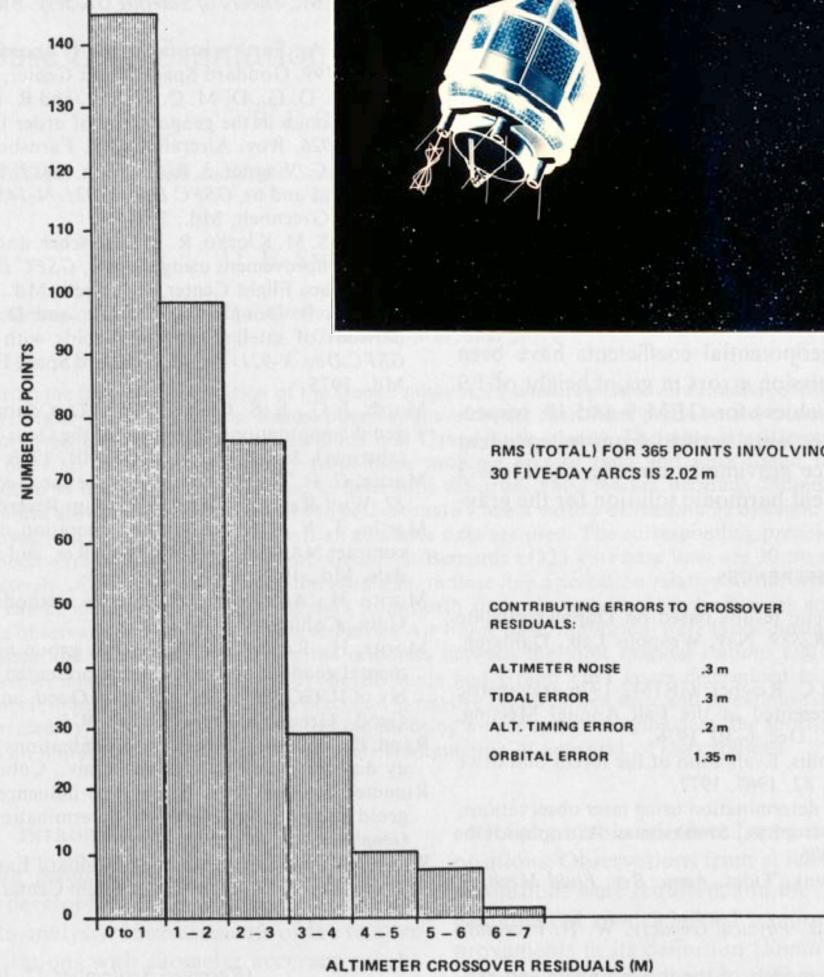
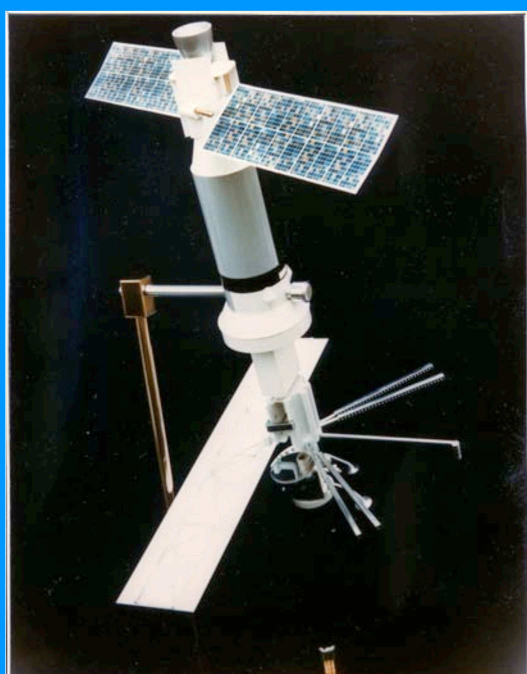


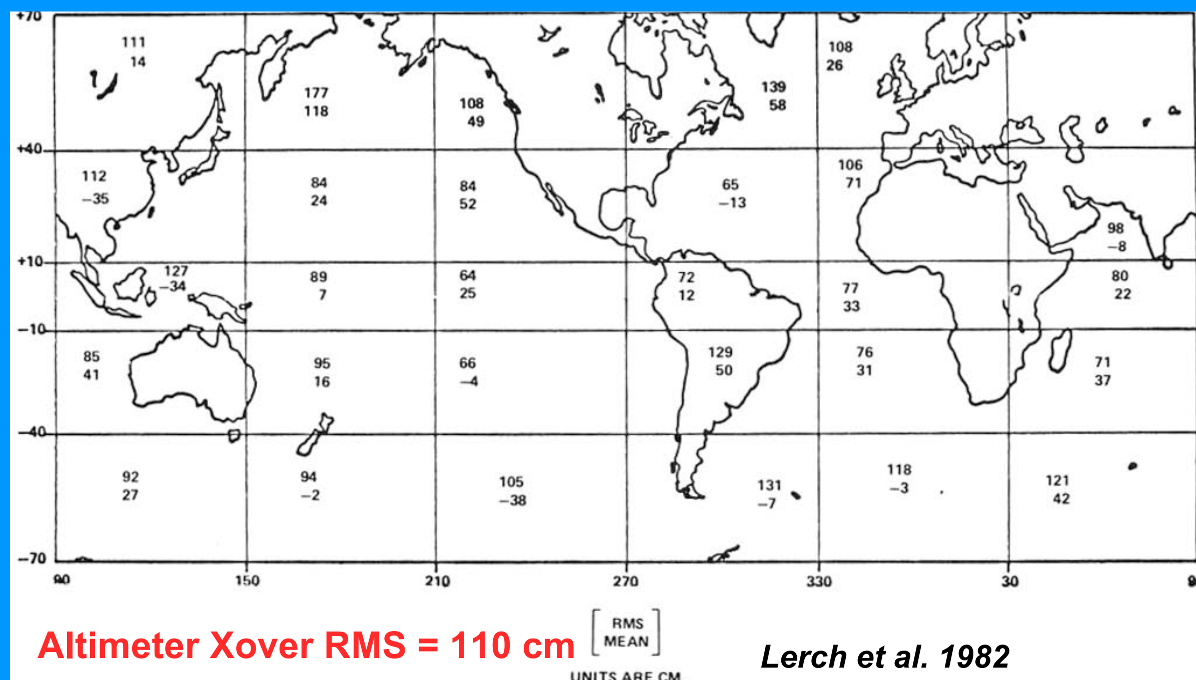
Fig. 11. Histogram of GEM 10 altimeter crossover residual differences.

SEASAT (1982) orbit accuracy improvement gained through tailored geopotential model…

Combining SEASAT SLR and USB tracking data along with SEASAT altimeter data with the GEOS-3 based GEM-10 normals produced a SEASAT tailored gravity field, PGS-S4 (Lerch et al. 1982) …

- ***PGS-S4 complete to degree and order 36.***
- ***SEASAT radial orbit accuracy improvement from ~400 cm to 70 cm.***





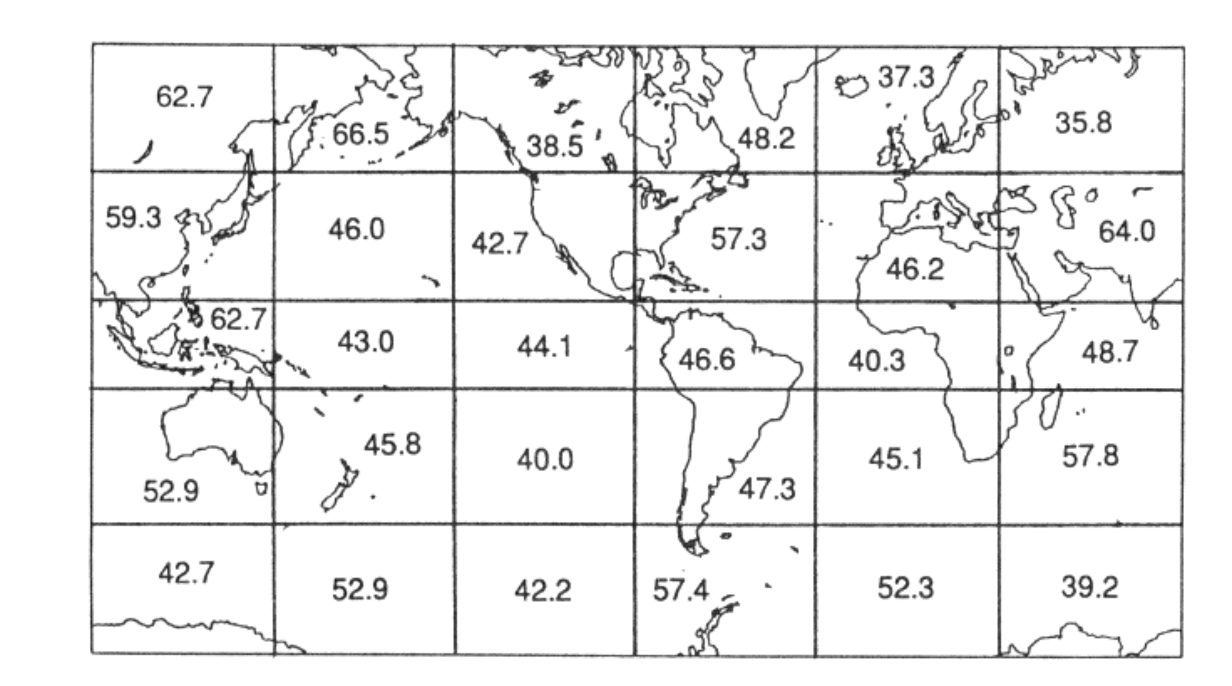
Altimeter Xover RMS = 110 cm

Lerch et al. 1982

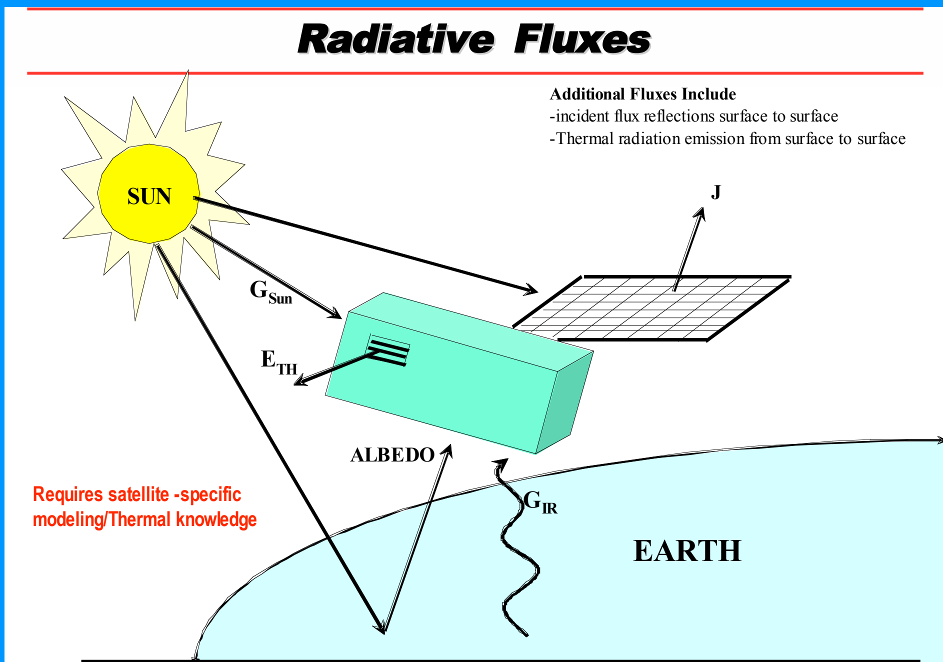
GEOSAT, another leap forward in gravity field modeling and orbit accuracy…

GEM-T2 gravity model advancement including 80-days of GEOSAT ERM TRANET doppler tracking data (Marsh et al. 1989)

- *GEM-T2 complete to degree and order 36 with selected terms to 50x50*
- *Radial orbit accuracy ~35 cm (Haines et al. 1990)*



Radiation Pressure Modelling is the largest source of orbit error after gravity model error ….



Micromodel

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

Box-Wing model

- *(Marshall & Luthcke. 1994)*

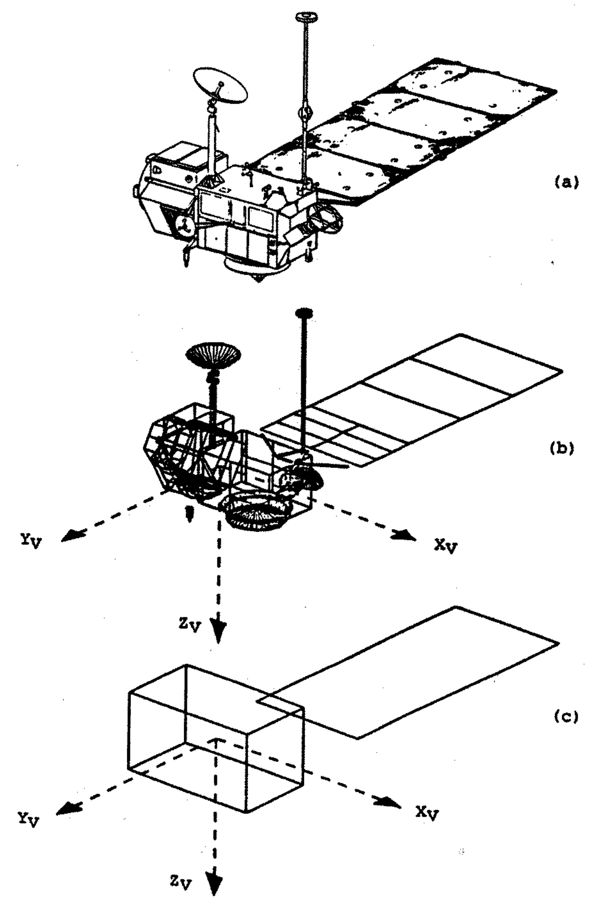


Figure 1. (a) The TOPEX/Poseidon Spacecraft, (b) Micro-Model Approximation, (c) Macro-Model Approximation

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)

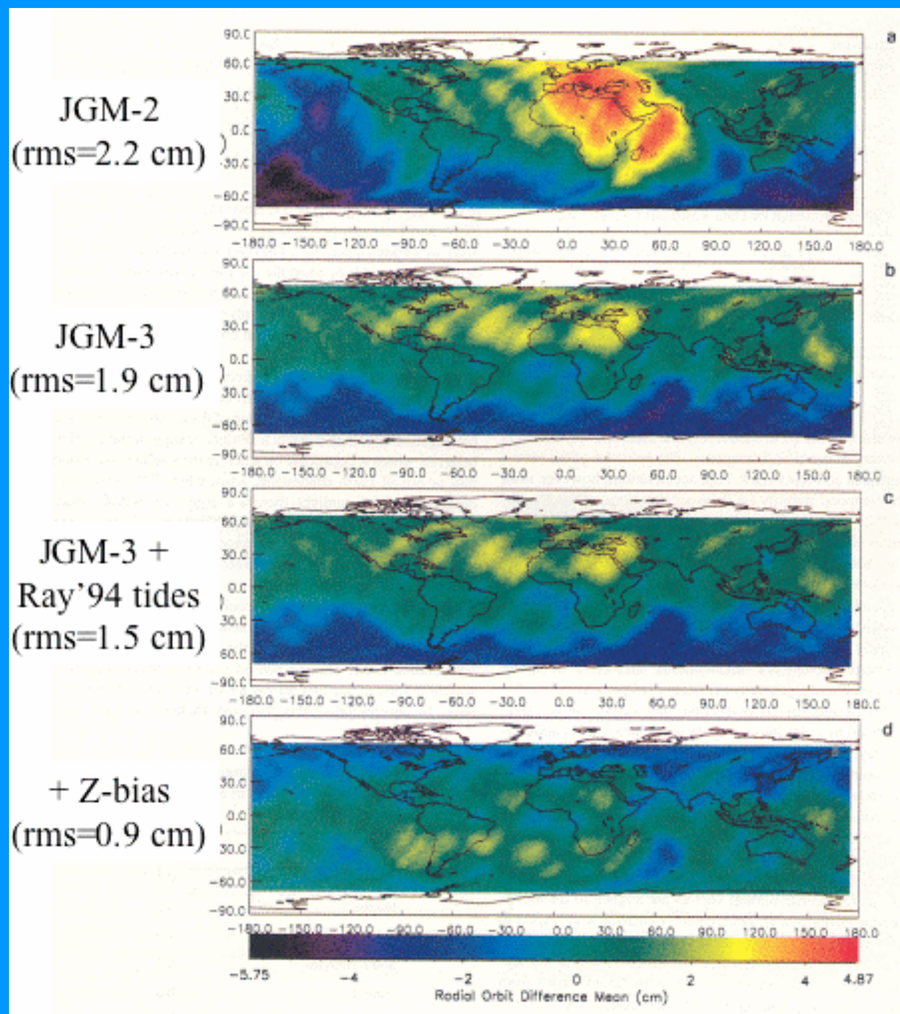
- ***GPS and DORIS near-continuous orbit observability is a significant advancement***
- ***Ability to characterize orbit error through the comparison of high accuracy orbits determined from independent data (SLR/DORIS vs. GPS)***

Tracking network, reference frame and measurement modeling improvements

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

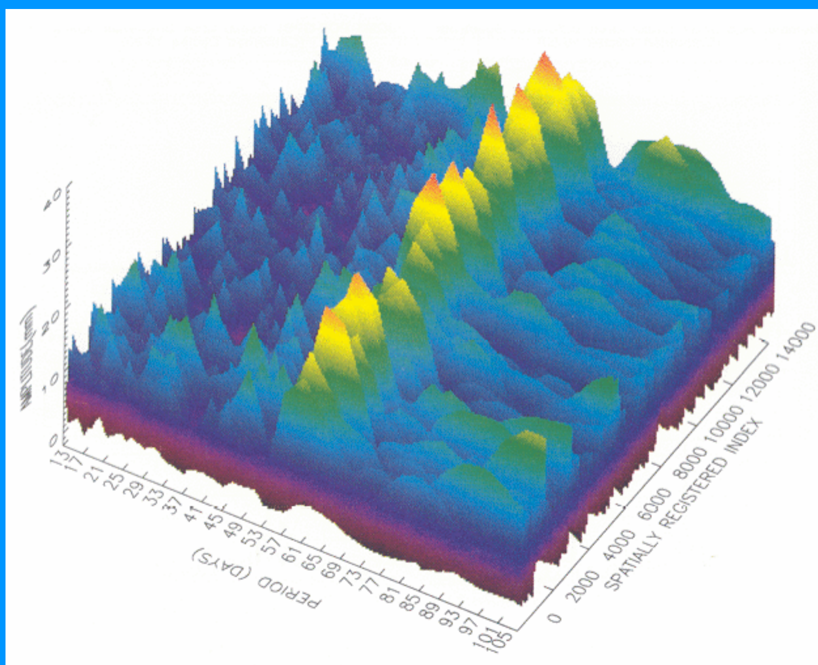
… with contributions by many others e.g.. The Ohio State University.

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

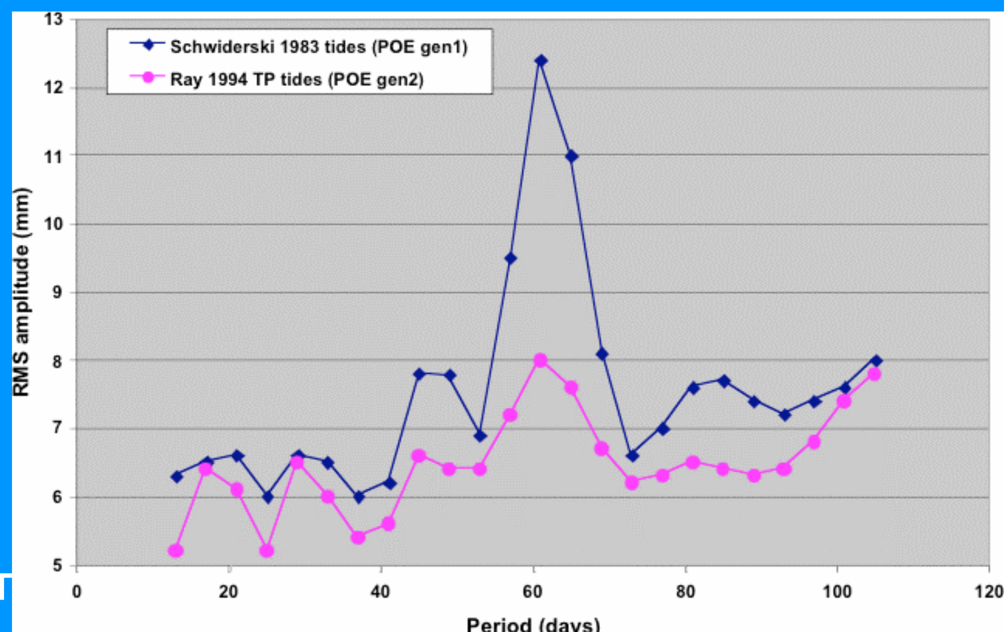


Intercomparison of SLR/DORIS (dynamic) & GPS (reduced-dynamic) orbits revealed Tide model induced orbit error

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



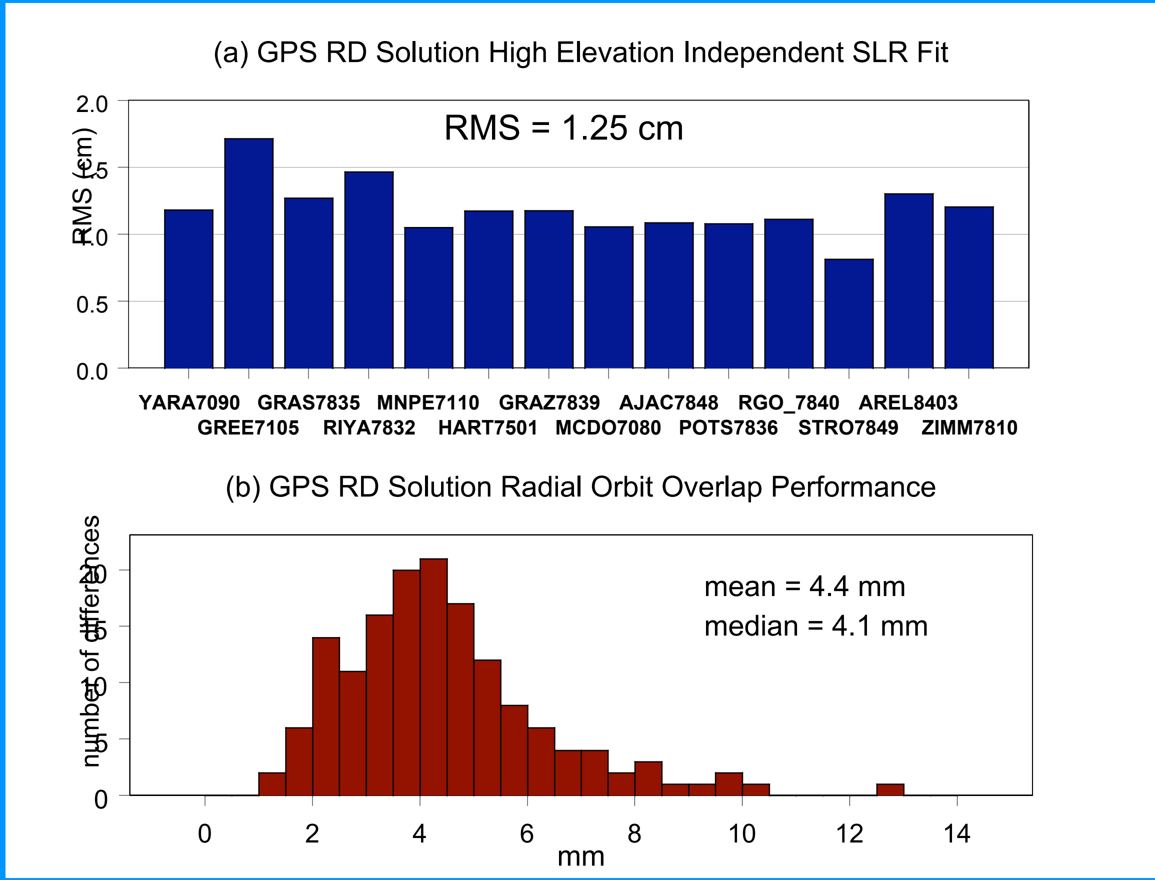
Jason-1 (2001): The 1-cm orbit …

- *1 cm radial orbit accuracy demonstrated (Luthcke et al. 2003, Haines et al. 2004, Choi et al., 2004).*
- *Retained T/P's diverse and cooperative POD Team: CNES, JPL, NASA GSFC, UT/CSR.*
- *Applied Upgraded tracking technology: GPS, SLR, DORIS (Especially JPL GPS BlackJack codeless receiver).*
- *Improved tracking network positions and measurement modelling (e.g. GPS antenna phase center modeling)*
- *Improved application of the reduced dynamic solutions 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*

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).*

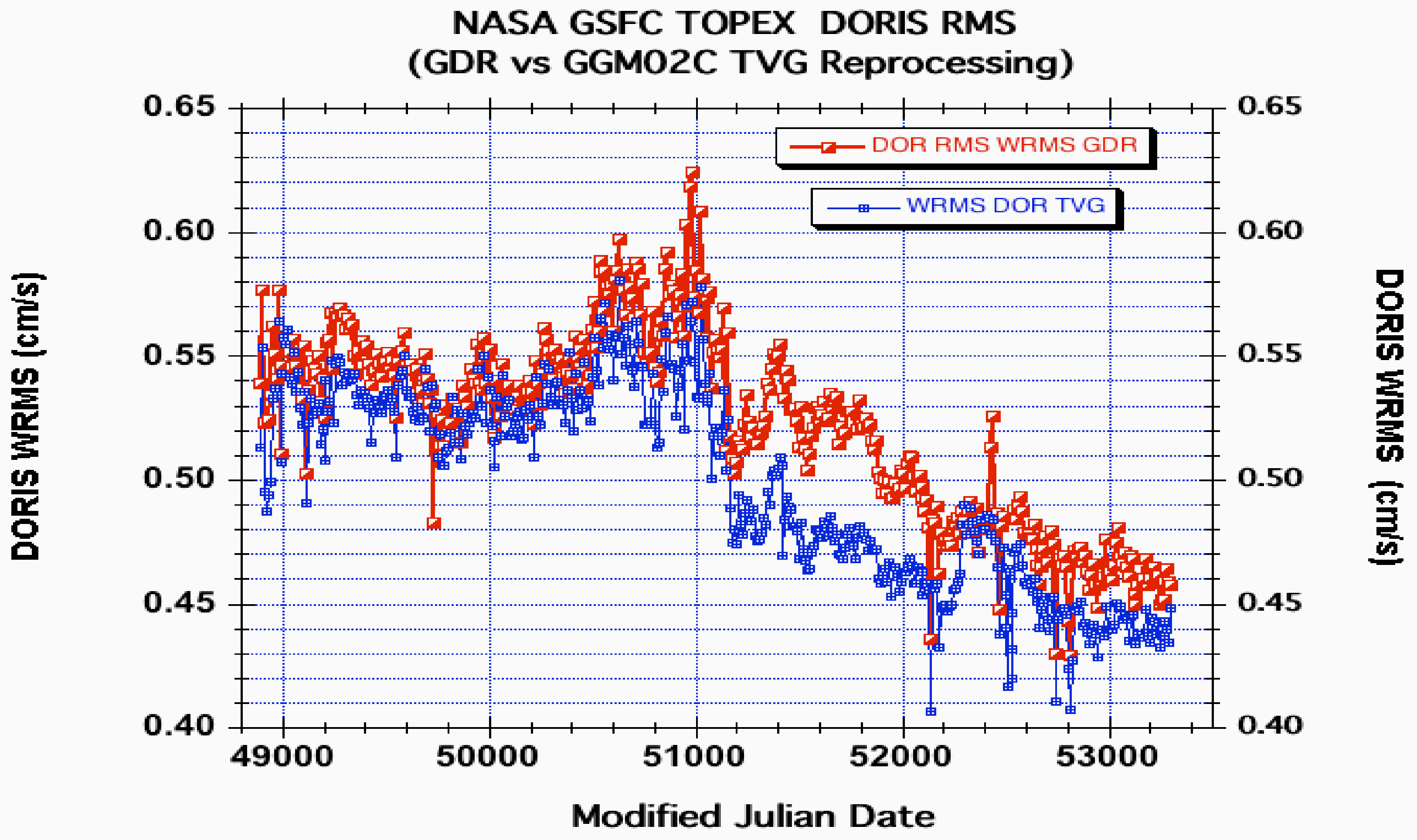
Other error sources are included beyond radial orbit error.



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

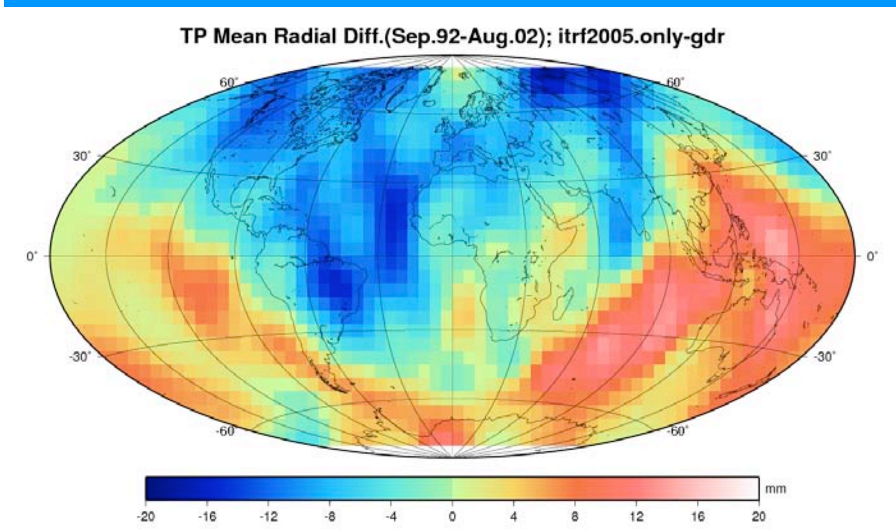
DORIS Evolution from TOPEX re-analysis

(Fagard, H., *J. Geodesy, 2006*, Description of system improvements)



Synopsis of Recent Improvements … (2)

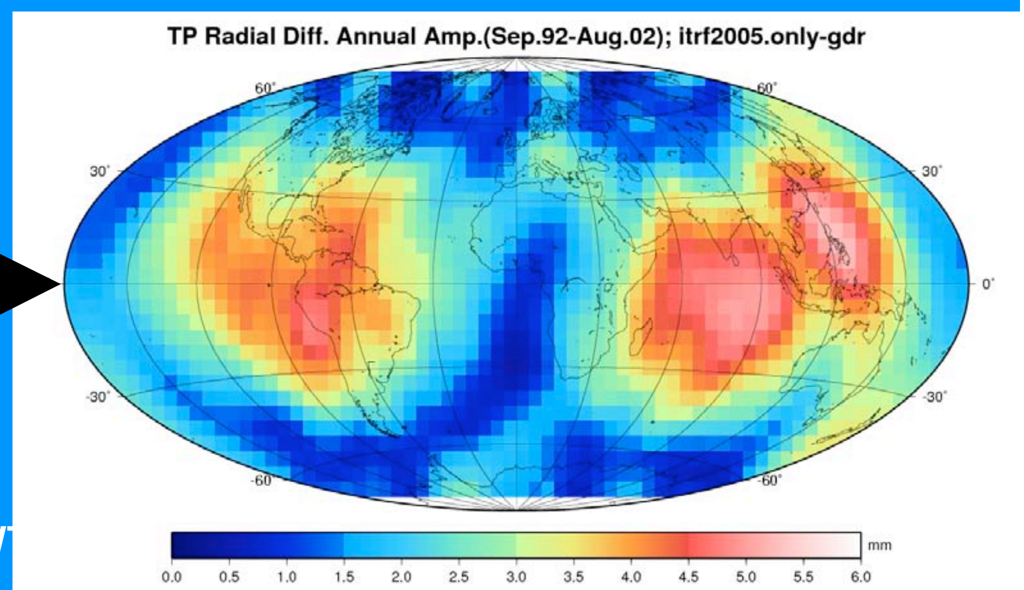
Improved gravity modelling using products from the GRACE mission

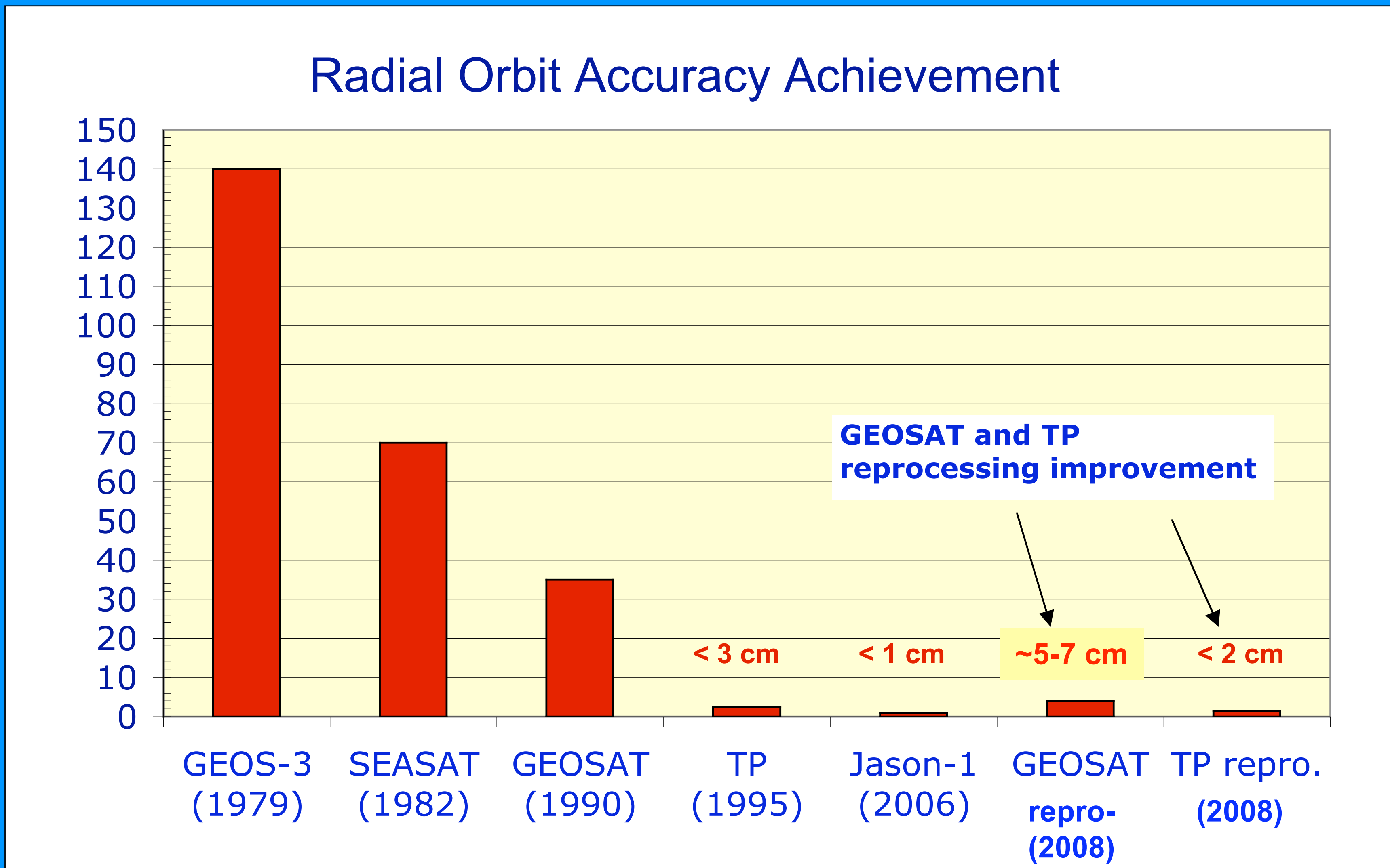


Geographically correlated error removed

(GGM02C vs. JGM3)

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



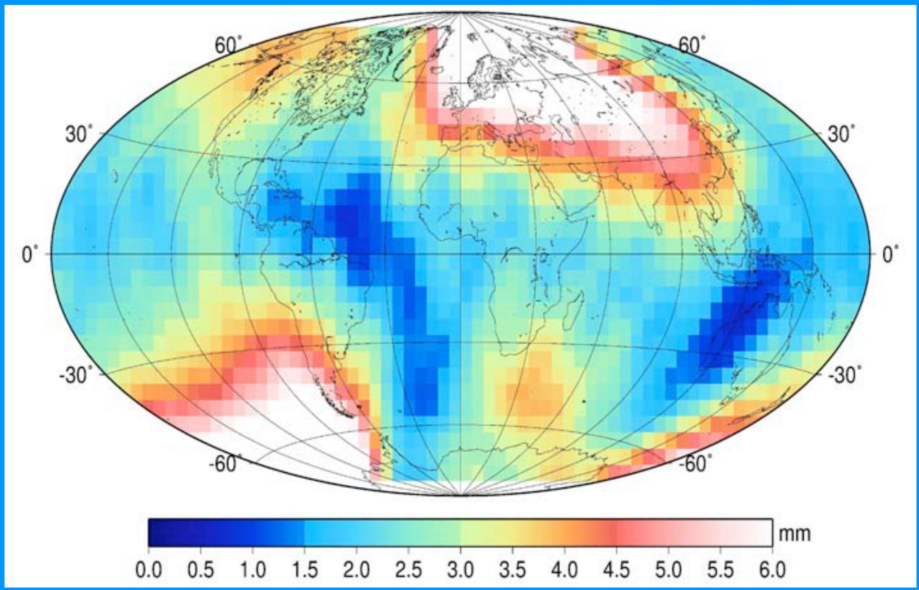


Radial Orbit Accuracy Achievement
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
GEOSAT and TP reprocessing improvement
< 3 cm
< 1 cm
~5-7 cm
< 2 cm
GEOS-3 (1979)
SEASAT (1982)
GEOSAT (1990)
TP (1995)
Jason-1 (2006)
GEOSAT repro- (2008)
TP repro. (2008)

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).**