SPACE Geodesy and NASA data in Altimeter Satellite POD[1]

POD: Precise Orbit Determination

Altimeter satellites

Frank G. Lemoine
Planetary Geodynamics Laboratory, Code 698
NASA Goddard Space Flight Center
June 29, 2016

Precise Orbit Determination

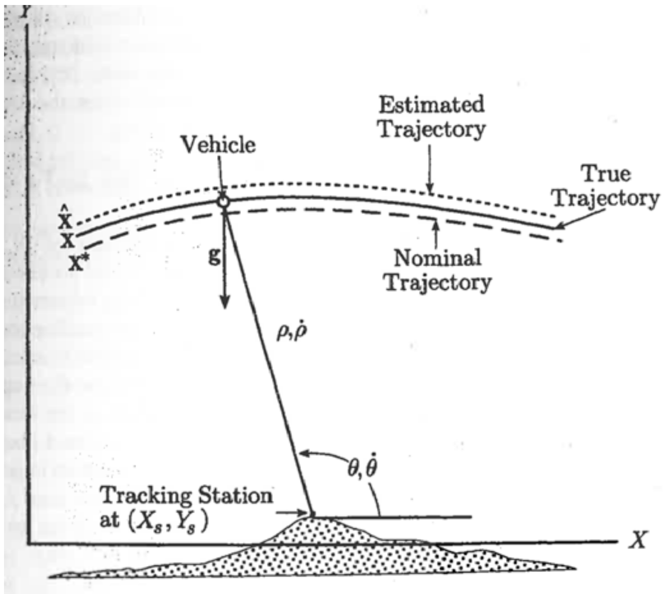


Figure 1.2.1: Uniform gravity field trajectory.

"Statistical Orbit Determination" BD Tapley, BE. Schutz, GH Born, Elsevier Academic Press, 2004.

<u>Orbit Determination</u>: The problem of determining the "best estimate of a satellite ephemeris (orbit) using observations that are influenced by random and systematic errors, using mathematical models of spacecraft motion that are not exact.

<u>What is meant by "precise"?</u>
In the past 25 years it has come to mean with a radial RMS accuracy of a few cm or less.

<u>Why?</u> Because the analysis of our science observations requires a "reference" that is accurate to this level; Sea level; Natural Hazards (Crustal Deformation); Glacier or Ice Sheet height changes.

Motivation for POD - I

GEOS-3

(Geodynamics and Earth Ocean Satellite)
<u>Launched</u>: Apr. 9, 1975
Operated through July 1979.

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

GEOS-3 COLLINEAR ALTIMETER DATA

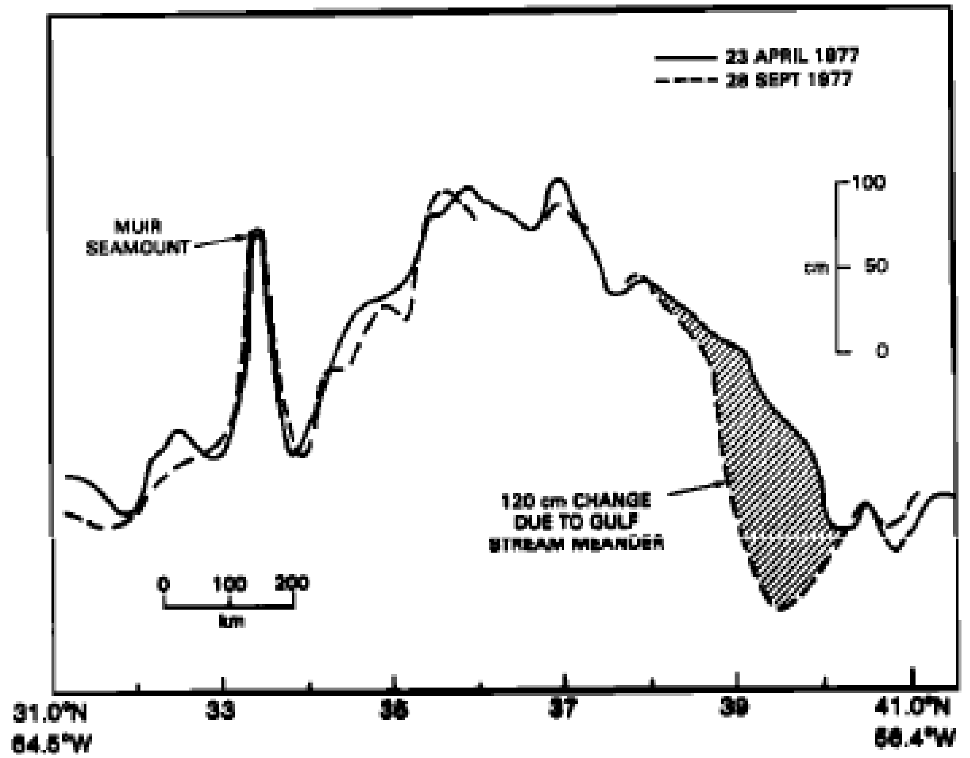
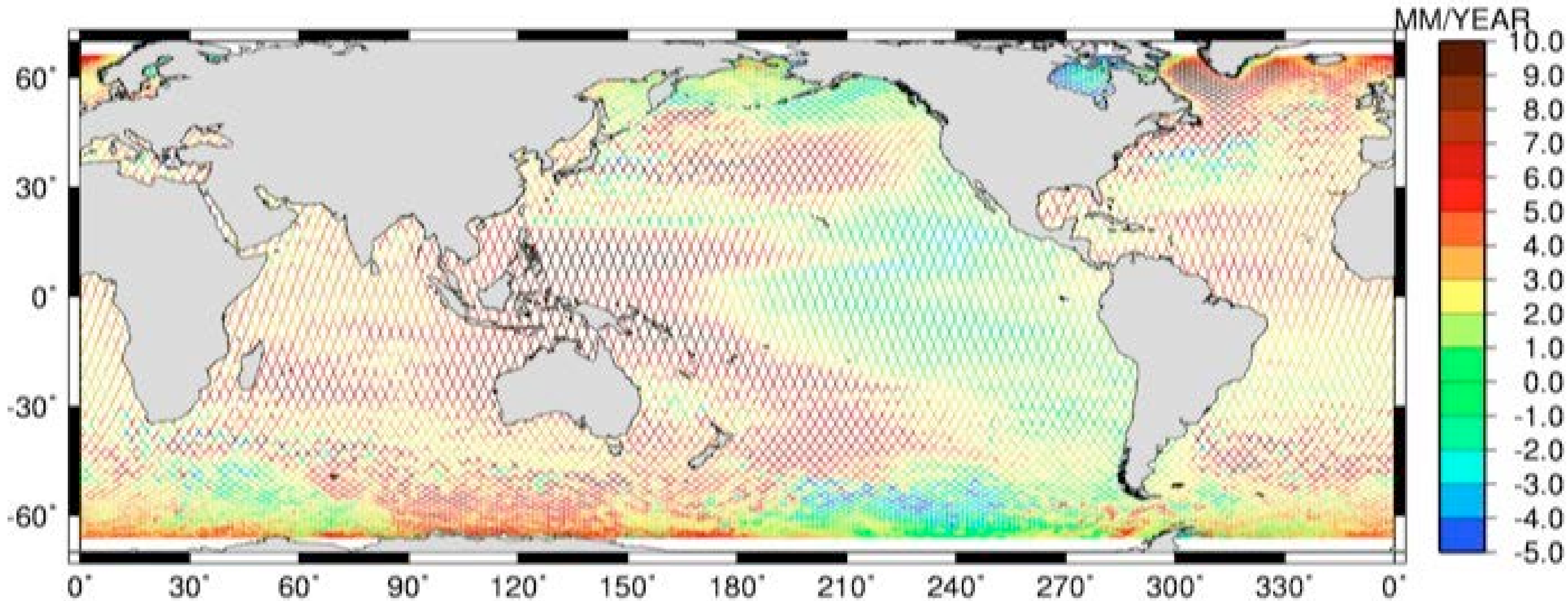


Fig. 3. A close collinear pair of altimeter profiles crossing the Muir seamount north of Bermuda. Note the identical geoid undulation in the profiles at the position of the seamount. The shaded area is due to a meander of the Gulf Stream.

An altimeter measures ocean height, which provides information on the geoid, and on the changes in the ocean circulation.

Motivation for POD - II

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)

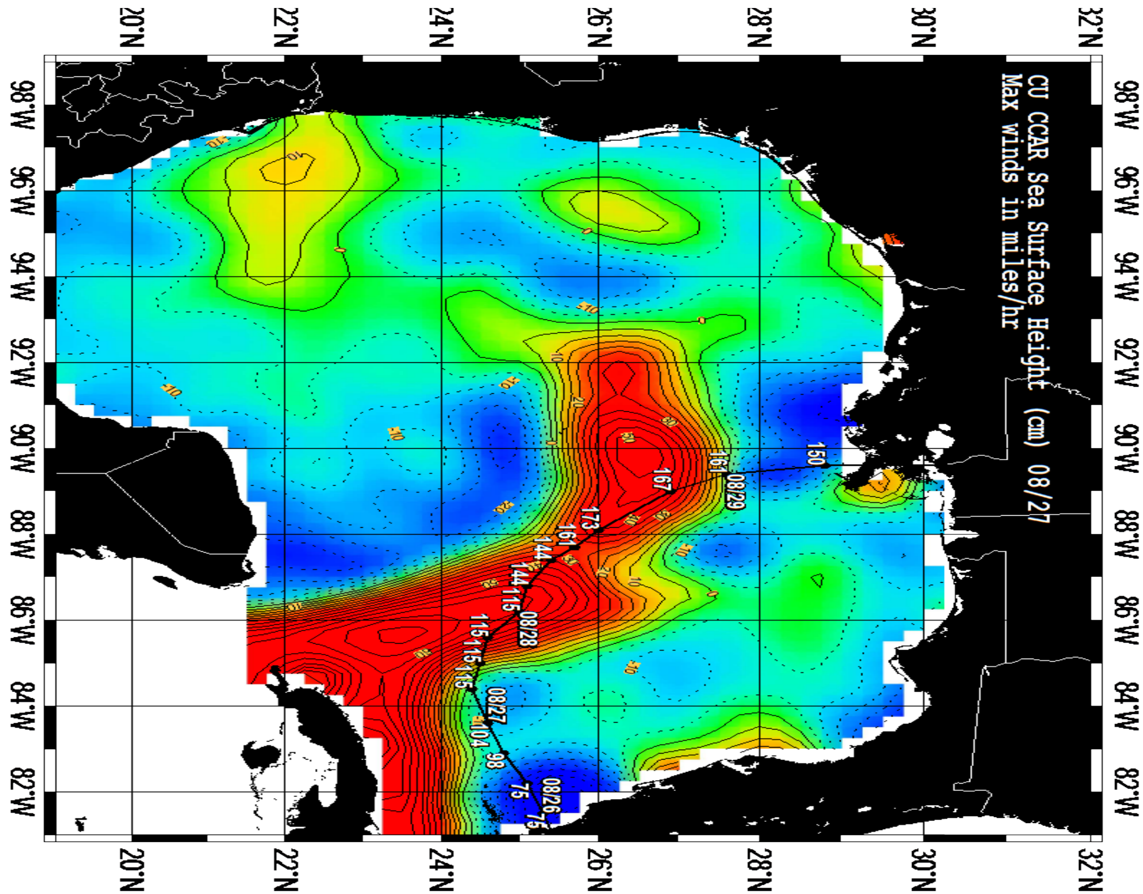
Jason-1, 2001-2009 (-2013)

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

Motivation for POD - III

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

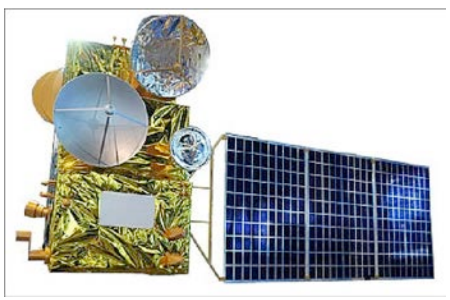
Current Ocean-radar mapping altimeter satellites (June 2016)

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

CRYOSAT-2, 2010-

ISRO (India)

SARAL, 2013-

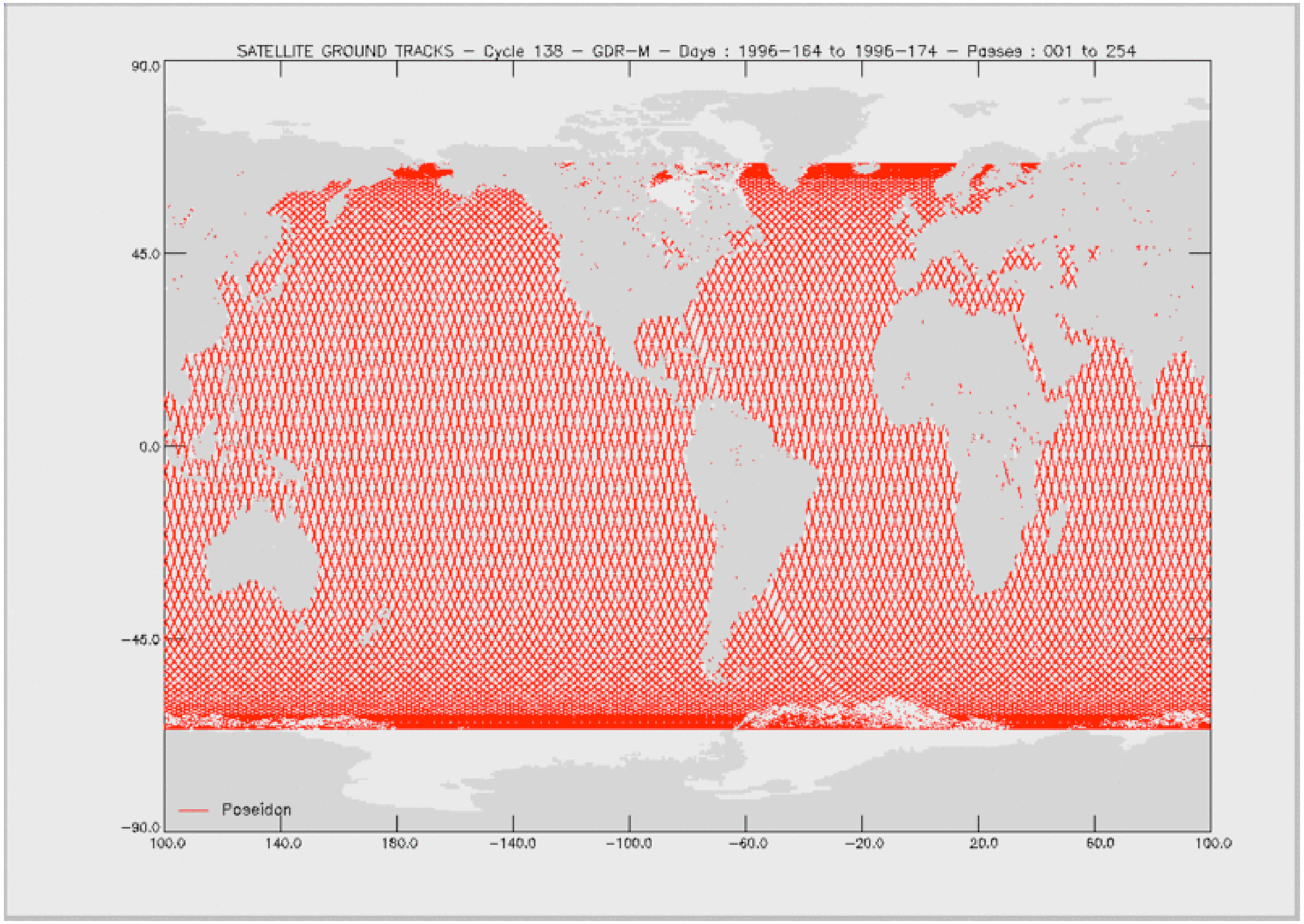


Haiyang (HY)-2A, 2011 (CNSA)

Sentinel-3A 2016

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

Example Ground Track Coverage for TOPEX (& Jason-1, Jason-2, Jason-3)



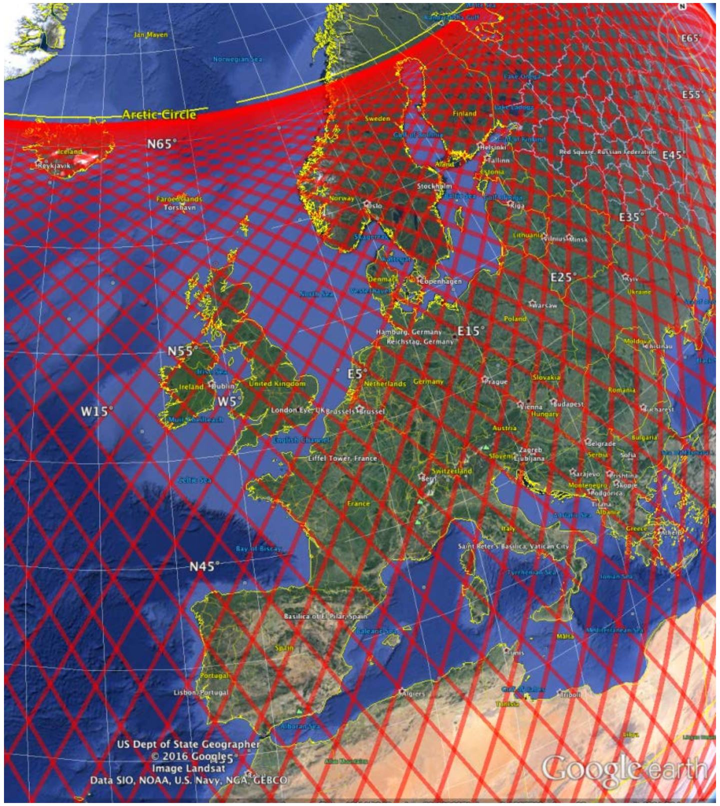
TOPEX/Poseidon
1992-2006

Jason-3
2016 –

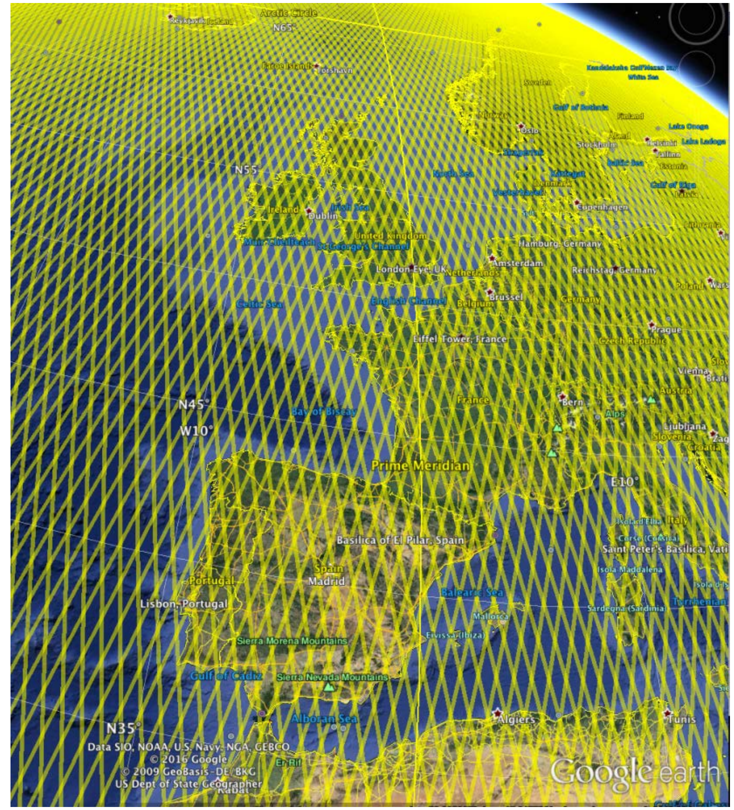
Image from AVISO (Toulouse, France)

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



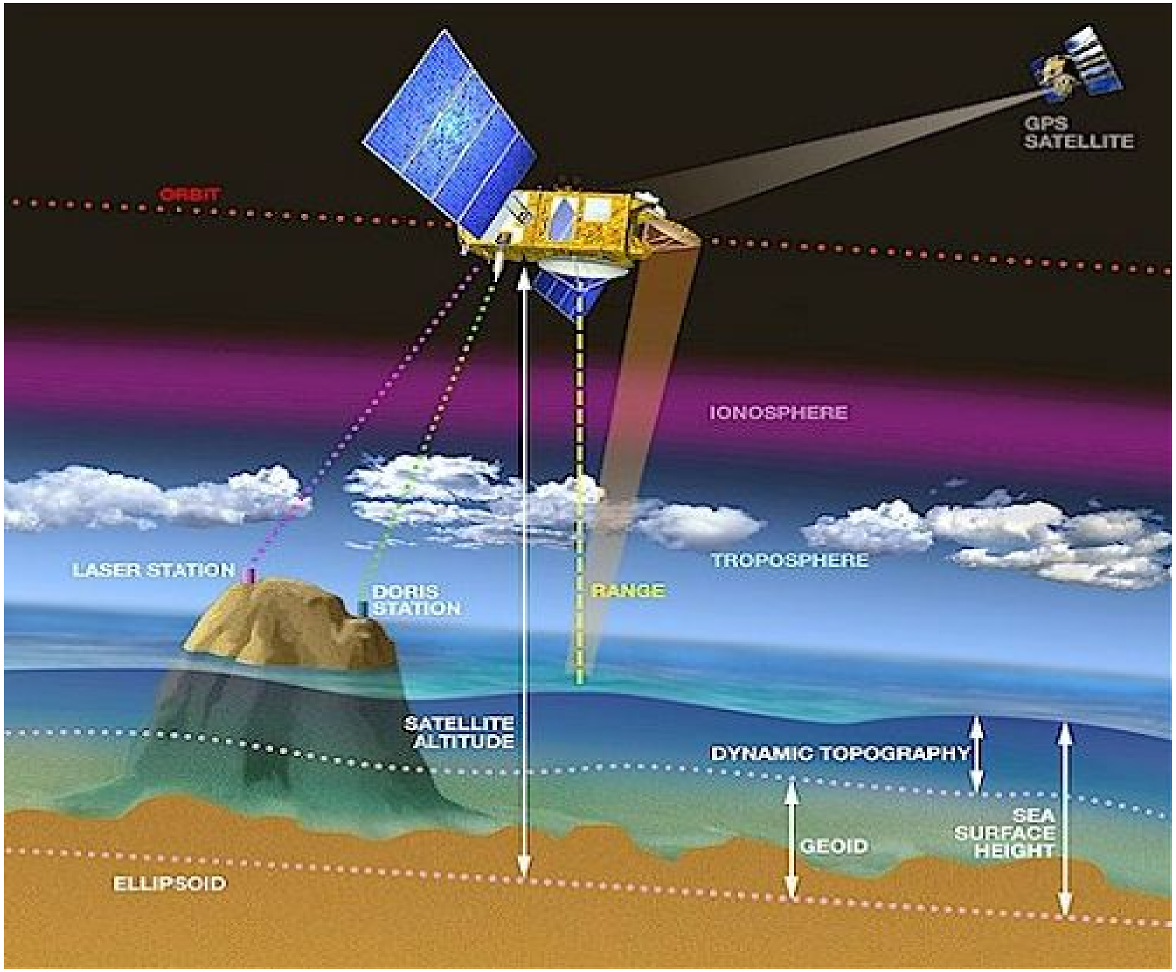
TOPEX/Jason-1,2,3



ERS & Envisat & SARAL

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

POD - Schematic

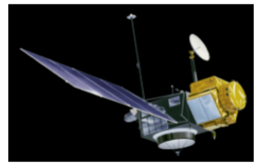


This example is for TOPEX, but the same principle applies for all altimeter satellites.

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

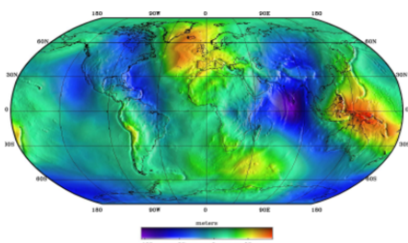
Orbit Determination Schematic

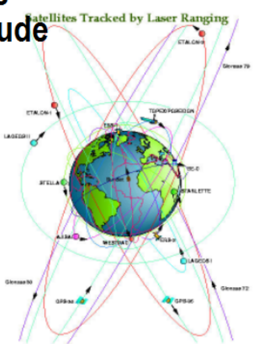
Onboard Tracking Systems
SLR
DORIS
GPS (GNSS)



Atmospheric Modeling
Ionospheric Propagation Delay
Tropospheric Refraction
Atmospheric Density

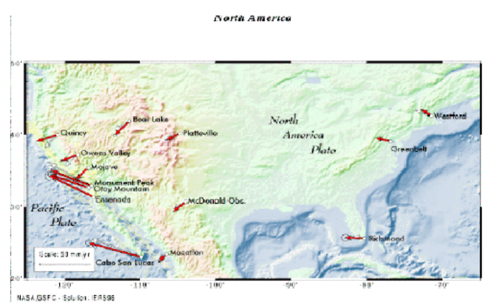
Surface Forces
Modeling
S/C Attitude





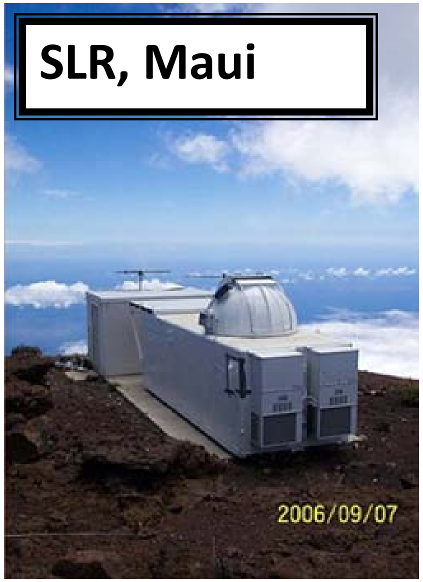
Orbit Determination
Force Modeling
Reference Frame
Tracking Technology

Geophysical Models
Gravity Models
Tide Models
Time Variable Gravity



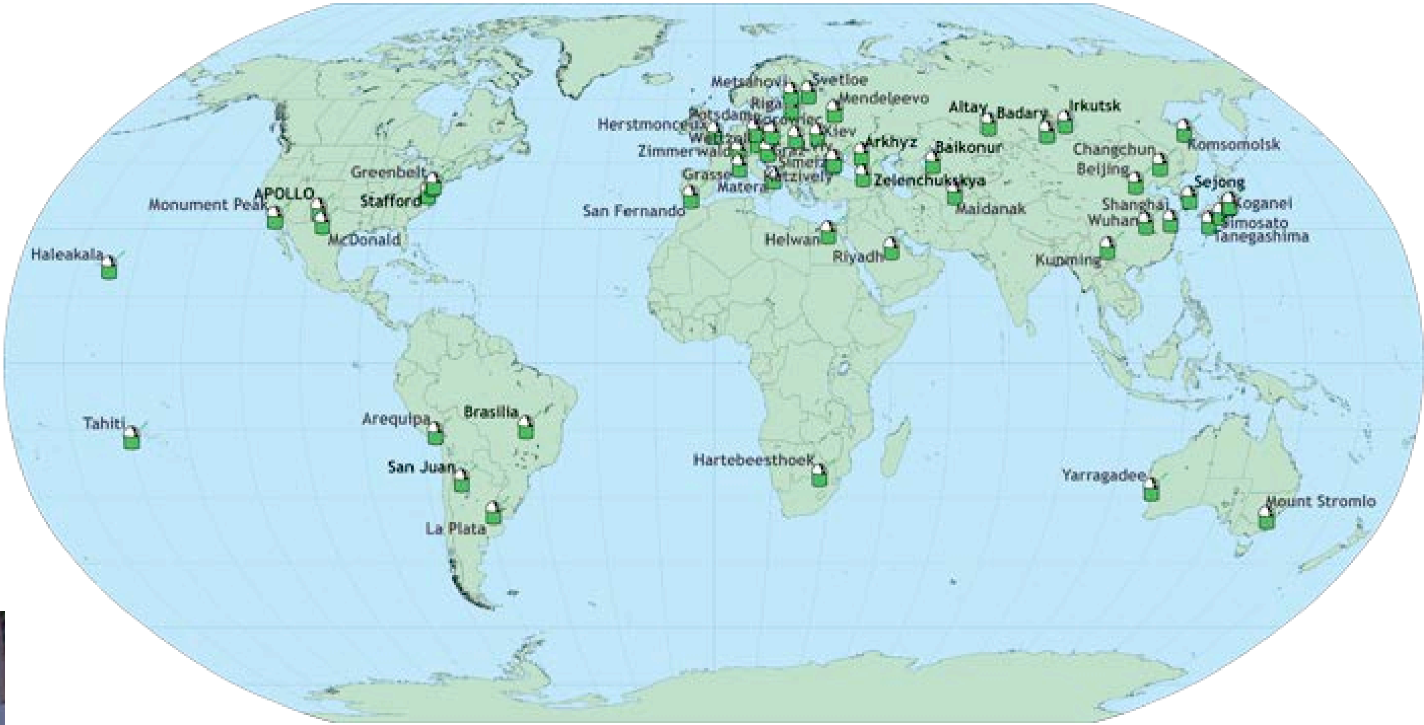
Reference Frame
International Terrestrial Reference Frame
Horizontal plate and vertical site motion
Geocenter motion
Polar Motion and Earth Orientation

Satellite Laser Ranging (SLR)



SLR, Maui

SLR, Yarragadee, Australia



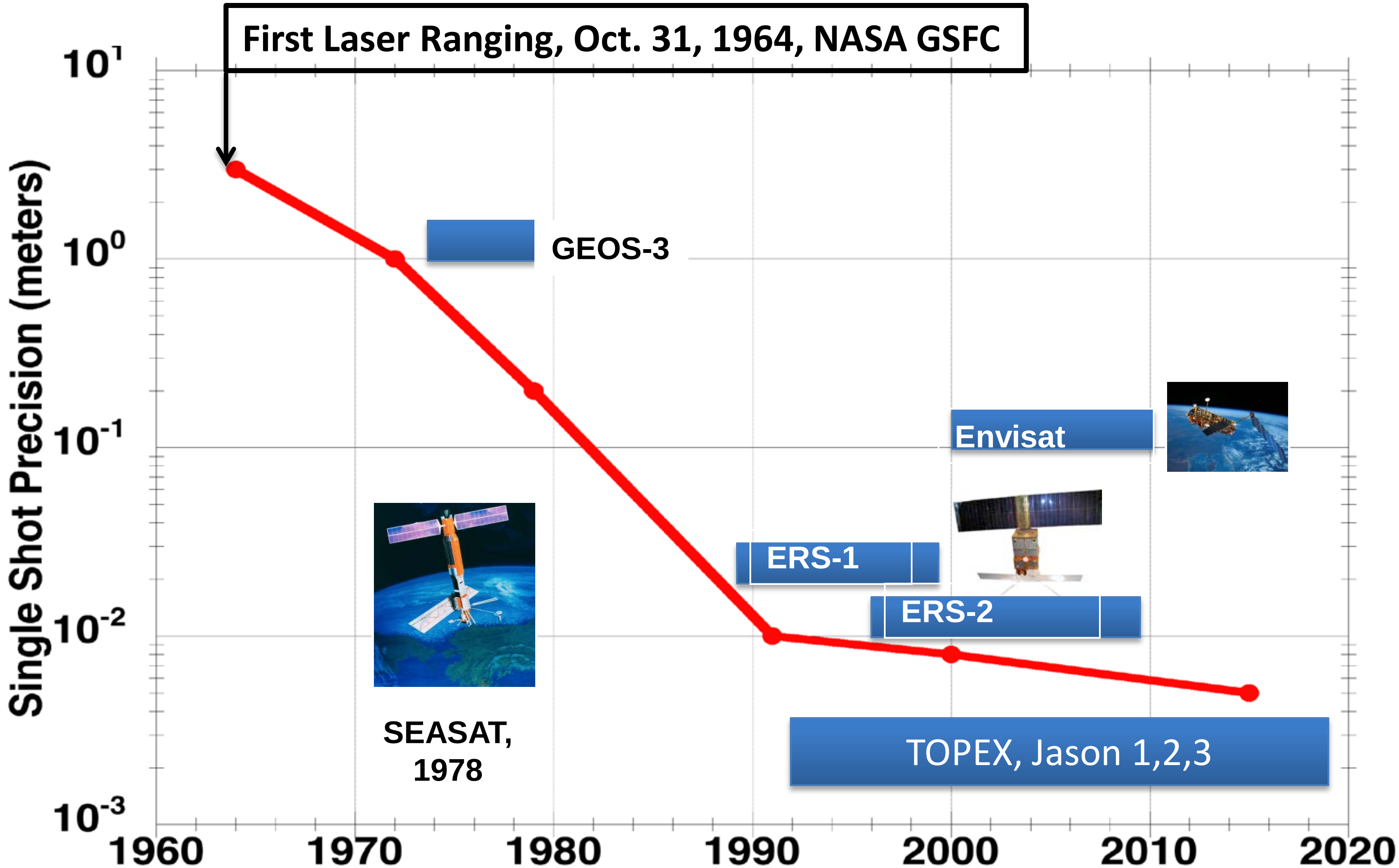
- Wavelength: 532 nm.
- Best stations have mm precision.
- Preponderance of stations in N. Hemisphere.
- First satellite ranging 1964, NASA GSFC.

http://ilrs.gsfc.nasa.gov

International Laser Ranging Service

11

Representative SLR precision vs. time

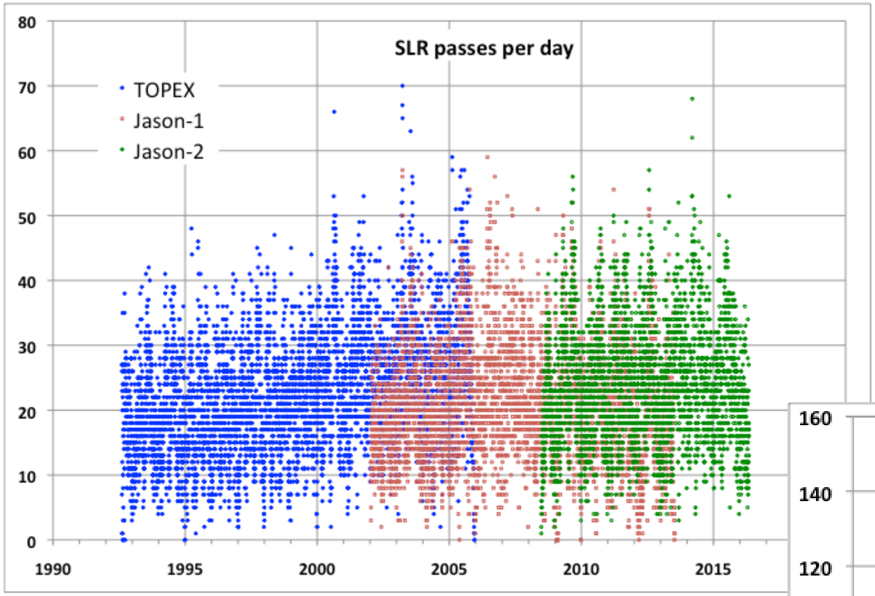


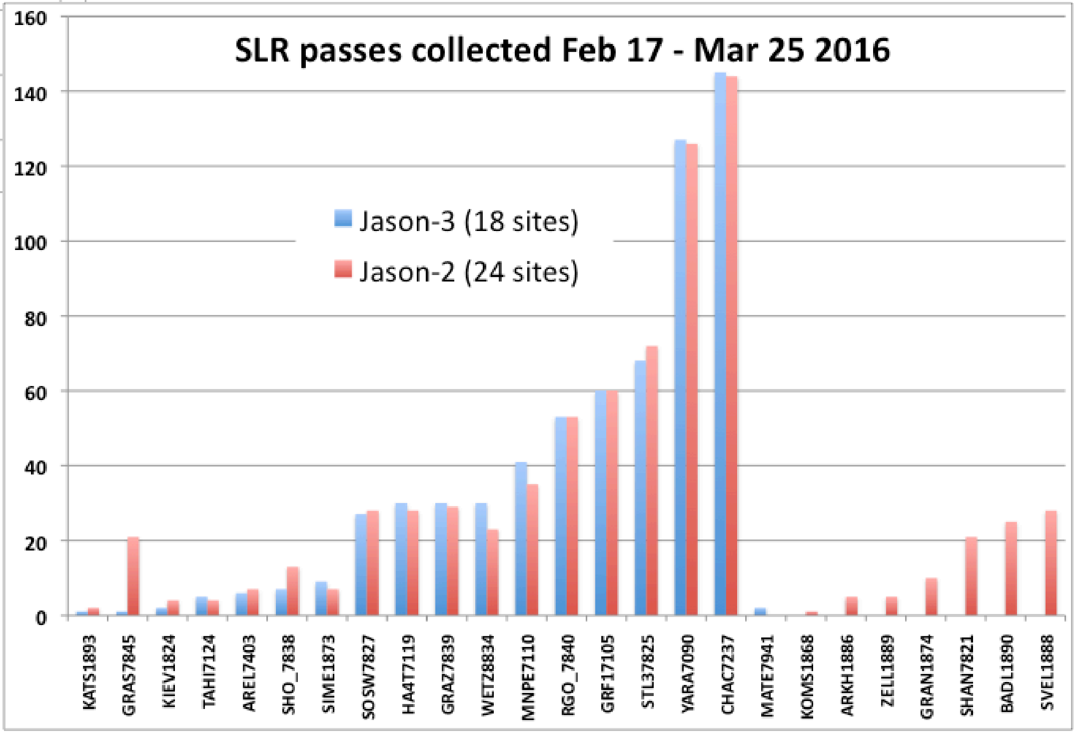
Adapted from J. Degnan. "Impact of SLR Technology Innovations on Modern Science", 18th ILRS Workshop, Fujiyoshida, Japan, Nov. 11, 2013.
http://cddis.gsfc.nasa.gov/lw18/docs/presentations/Session0/13-0001-Degnan_2.pdf

SLR Tracking of TOPEX, Jason-1 & Jason-2

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

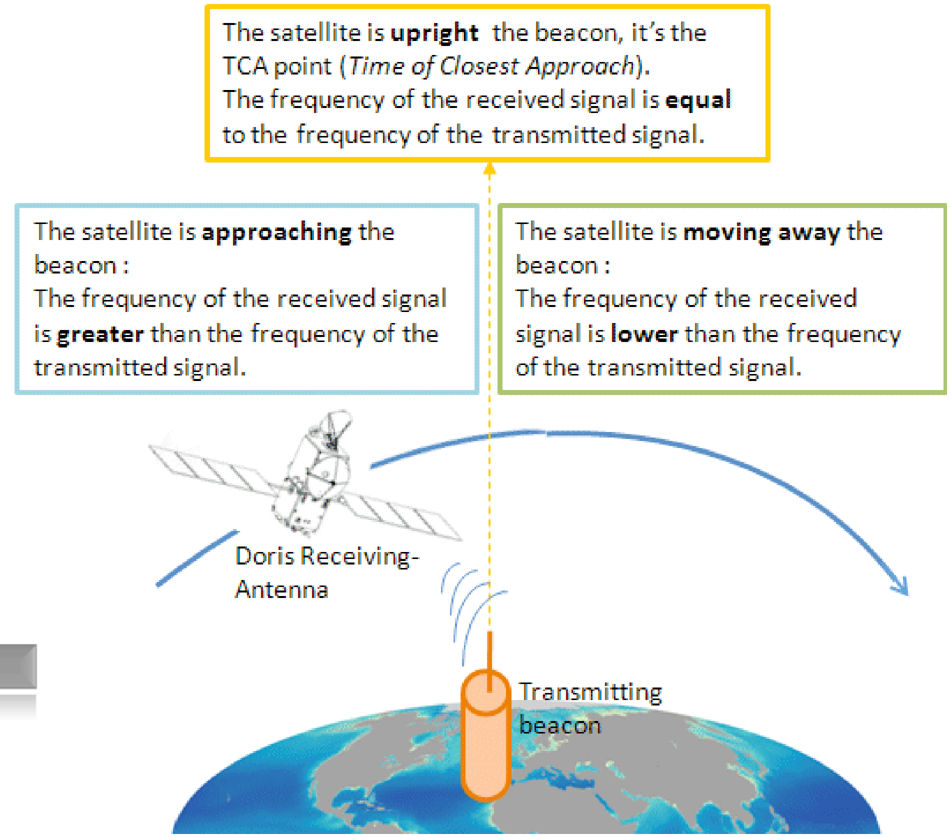
On average 20-30 stations have tracked TP, J1, J2/day; There is a "week-end" and a "Christmas" effect.

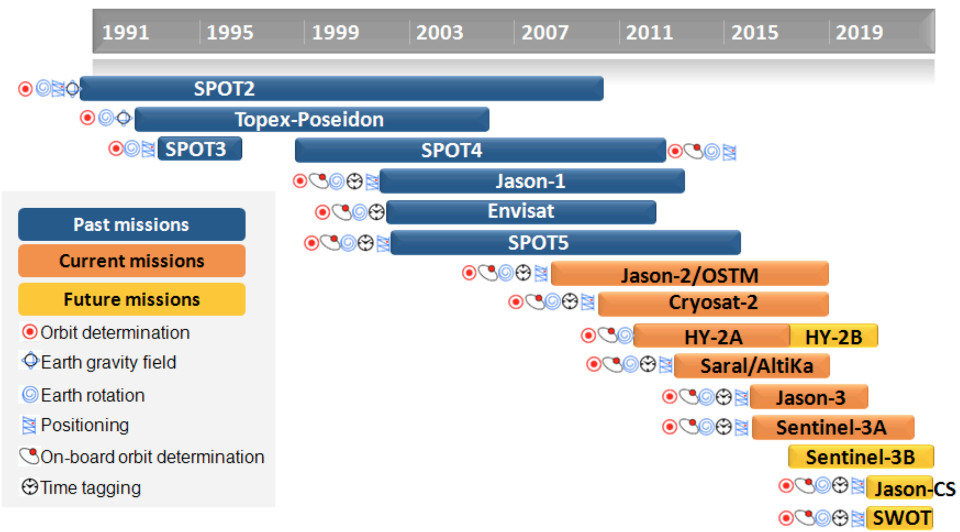




DORIS (Doppler)

- DORIS: Doppler Orbitography and Radiopositioning Integrated by Ranging.
- CNES (*French Space Agency*) & IGN (*Institut Géographique National*)
- 55-60 stations, around the world.
- Dual-frequency beacons, ~401.25 MHz + 2.036 GHz.
- **DORIS receiver: 1 channel (1990's); 2 channels (Envisat & Jason-1, SPOT-5); 7 channels (Jason-2 and all later satellites)**





Images Credit:.

Centre National d'Etudes Spatiales (CNES)

Collecte Localisation Satellites (CLS)

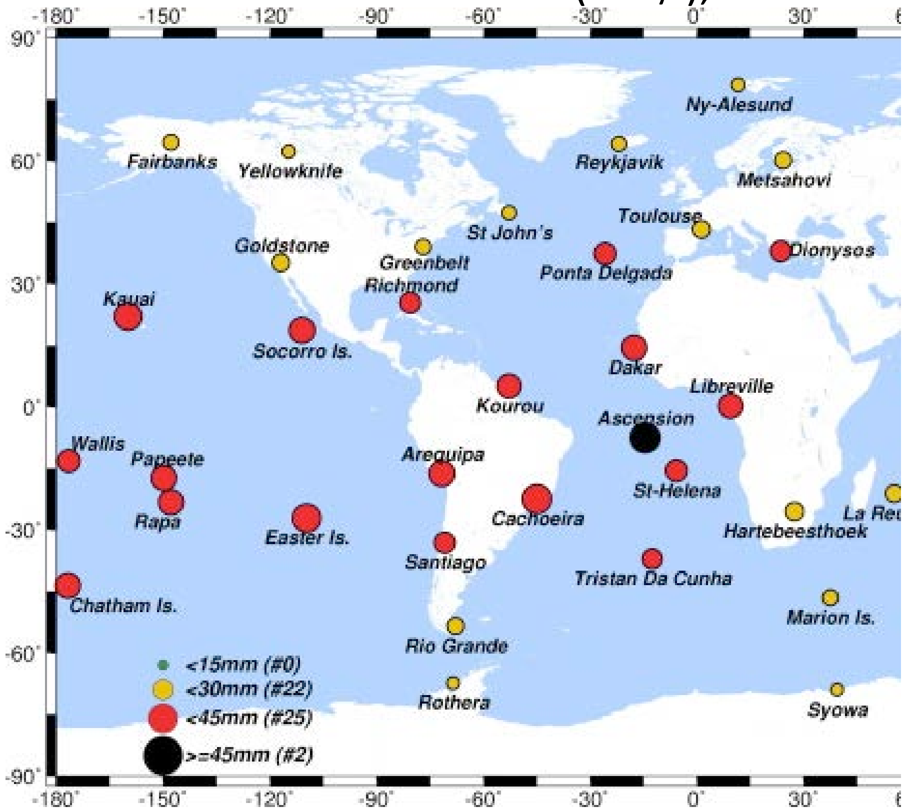
DORIS Network (as of June 2016)

http://ids-doris.org/

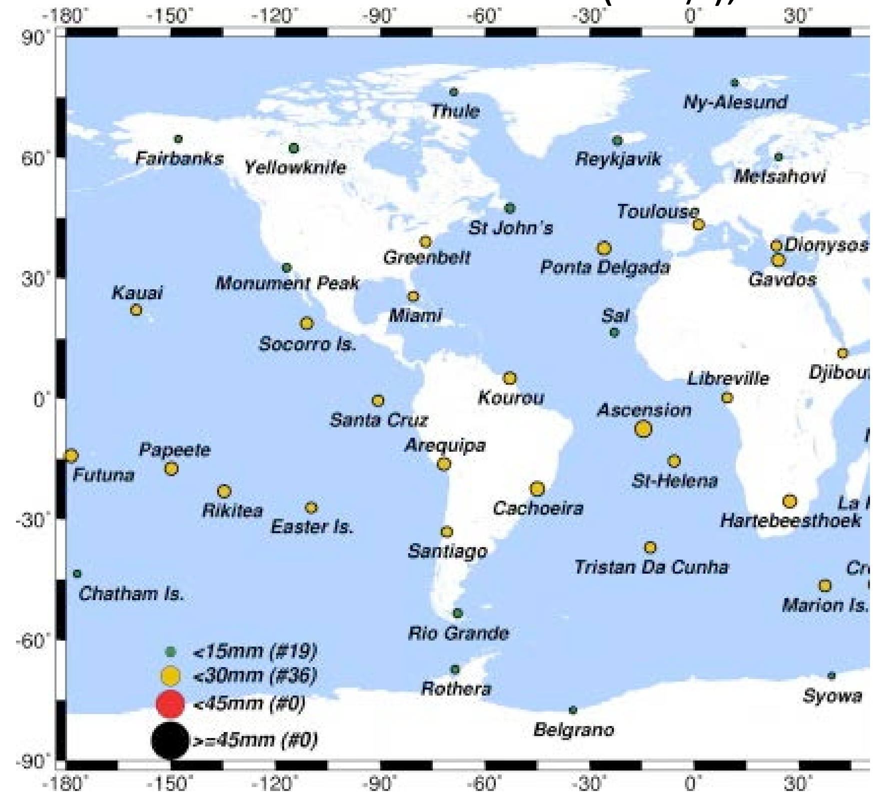
International DORIS Service

DORIS Network Evolution

DORIS Station Precision (7-days), 2000



DORIS Station Precision (7-days), 2014



DORIS Network station positioning precision has improved in time, due to (1) improvements monumentation stability, (2) increasing number of satellites, (3) DORIS receiver improvements (more channels).

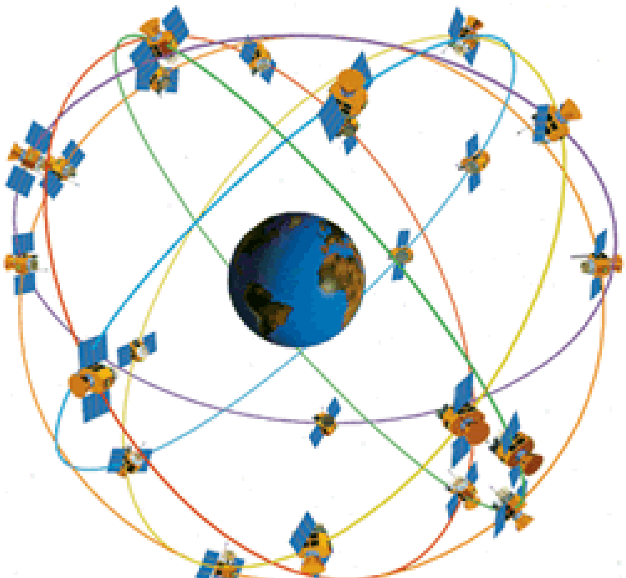
Reference: Guilhem Moreaux et al., Adv. Space Res., In press, 2016, doi: 10.1016/j.asr.2015.12.021

See also. Fagard, H., "Twenty years of evolution for the DORIS permanent network ....", J. Geodesy, 80 (8–11), (2006), pp. 429–456, doi: 10.1007/s00190-006-0084-2.

GPS Tracking System for TOPEX, Jason-1, Jason-2, Jason-3 – I

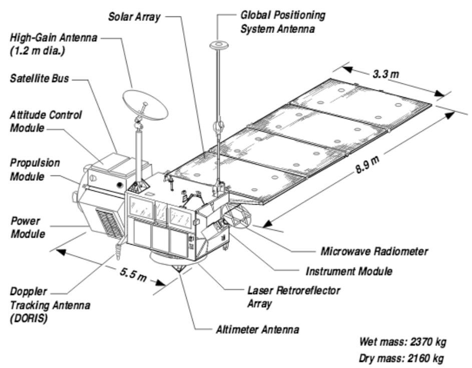
IGS INTERNATIONAL GNSS SERVICE

GPS Satellite Constellation



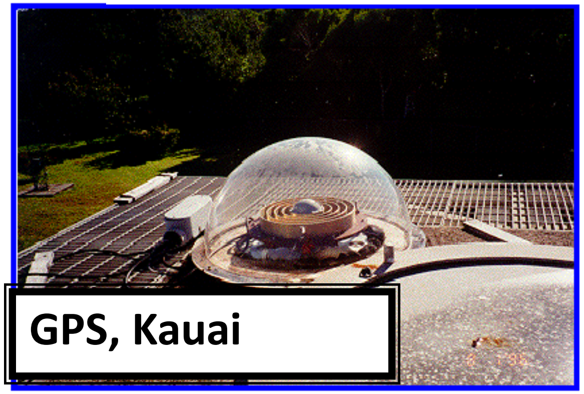
http://www.igs.org
For latest information on IGS, see website and proceedings of IGS workshop, Sydney Australia, February 2016

TOPEX GPS: Demonstration Receiver



JASON 1-2-3: GPS Receiver

Examples: Ground Receivers



GPS, Kauai

GPS, Thule

GPS Tracking System for TOPEX, Jason-1, Jason-2, Jason-3 - II

screenshot from www.igs.org

- The IGS includes hundreds of stations that stream data to the IGS data centers, including the NASA Crustal Dynamics Data Information System (CDDIS).
- Analysis centers around the world analyze the data over different latencies and deliver products (e.g. precise orbits) to users – the NASA CDDIS is one of the archives for these data products.

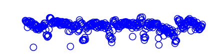
GPS Tracking System for TOPEX, Jason-1, Jason-2, Jason-3 - III

GPS Data Quality Over Time (J1 & J2)

From W. Bertiger et al., "Stability of Stability of GPS Bias-Resolved JASON and JASON2/OSTM Orbits, 2002-2011 in ITRF2008", Presentation to San Diego, CA OSTST Meeting, October 2011

JASON-2

JASON-1



The primary advantages of GPS as a (spaceborne) tracking system are the data density (# of observations per epoch) and geometrical strength of the observations.

Types of orbit determination - IV

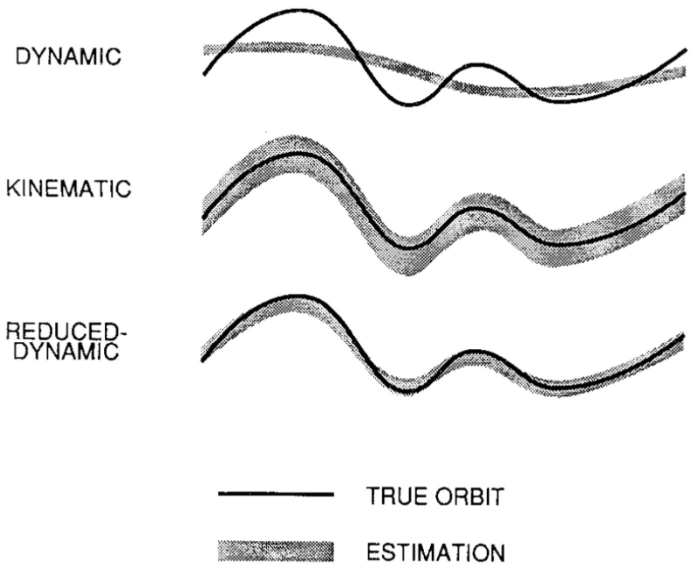


Fig. 1 Qualitative comparison of dynamic, kinematic, and reduced-dynamic tracking performances.

Reduced-Dynamic Technique for Precise Orbit Determination of Low Earth Satellites

S. C. Wu,* T. P. Yunck,† and C. L. Thornton‡
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109

J. Guidance & Control., 1991

Data density from GNSS, lately also from DORIS allows a reduced-dynamic orbit determination – which means empirical parameters can be adjusted frequently to reach the “true” orbit – and compensate for errors in force or measurement models.

Comparison of red.-dynamic & dynamic orbits allows insight into model errors – leads to improvement into dynamic models.

Why do we need multiple tracking systems?

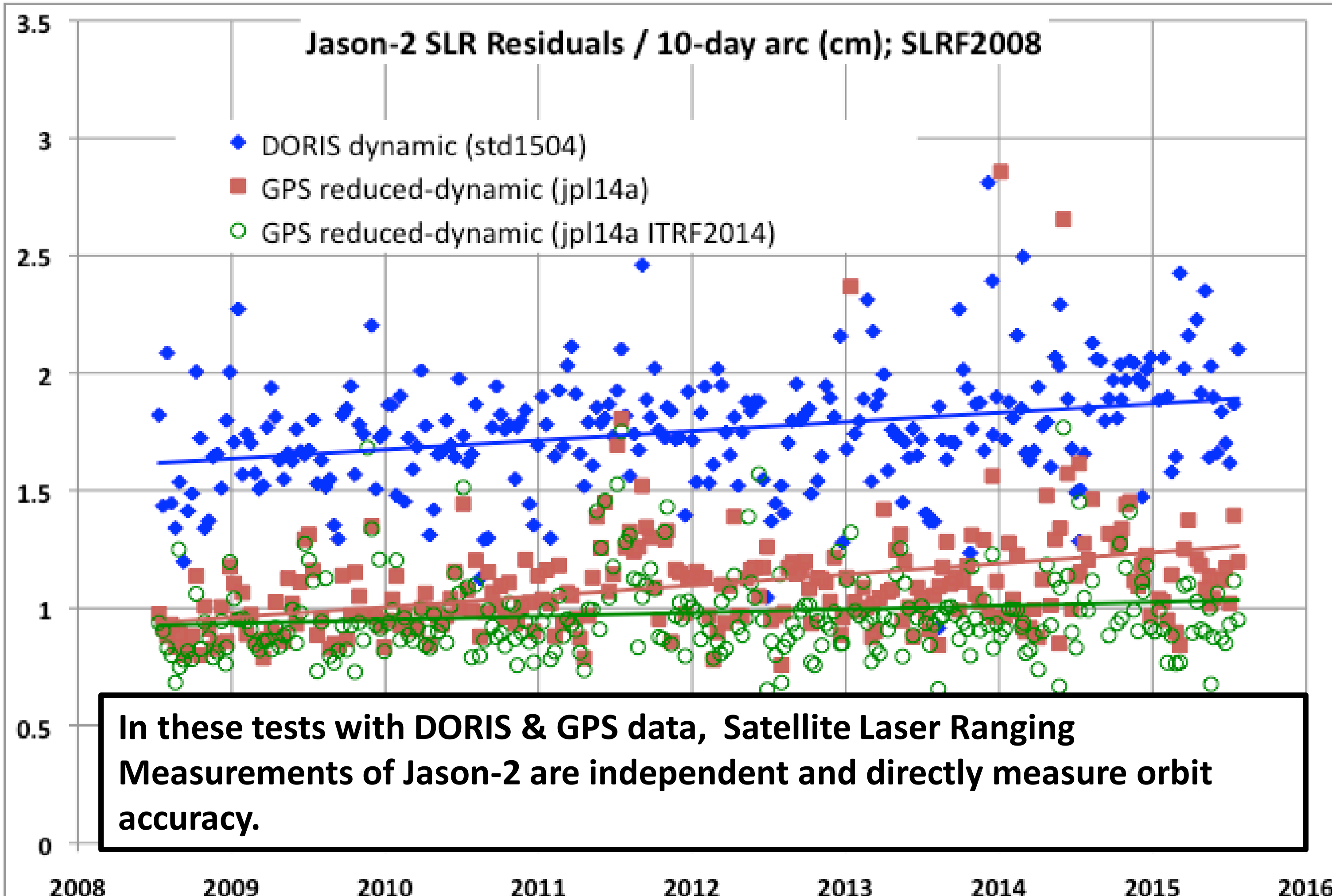
We need multiple tracking systems
(a) to ensure and establish orbit accuracy;

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.

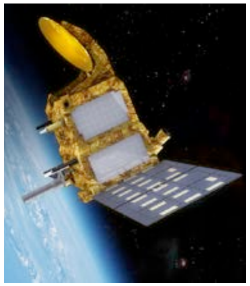
(I) GFO. Failure of GPS. SLR + altimeter crossovers only reliable tracking system.
(II) Jason-1. DORIS Oscillator not hardened before launch – perturbed by passage through S. Atlantic anomaly, Apply a "correction" model.

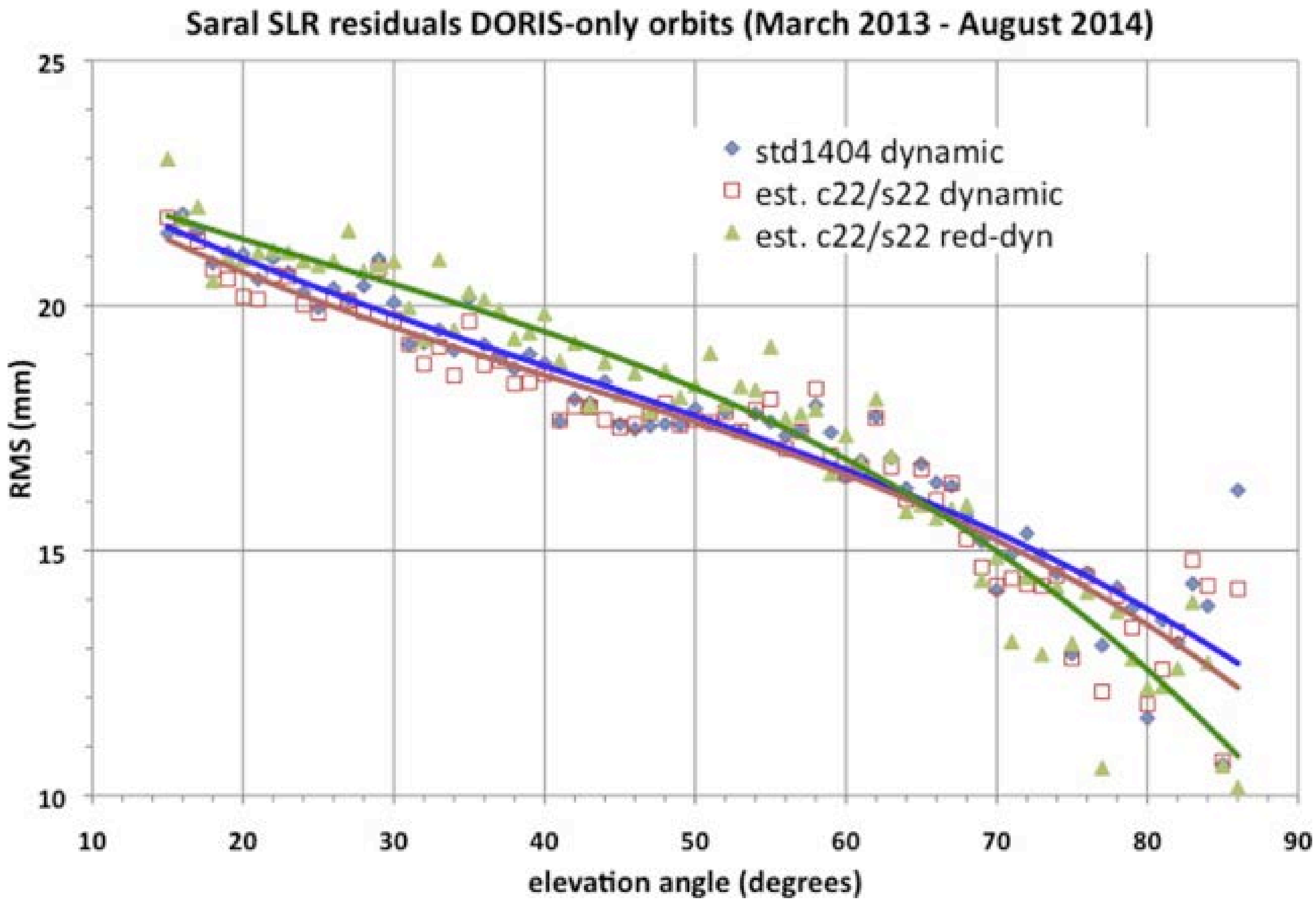
SLR – Validation of Jason-2 GPS & DORIS orbits



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)



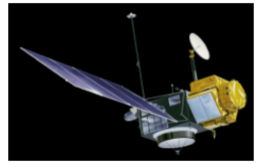


At high elevations SLR measures directly the radial orbit error; So in this example, we can say the DORIS-only orbits on SARAL have an orbital accuracy of 10-15 mm.

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

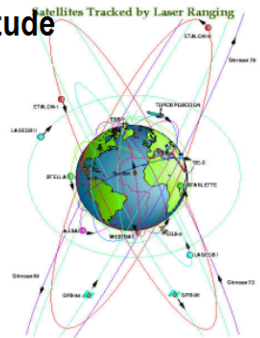
Orbit Determination Schematic

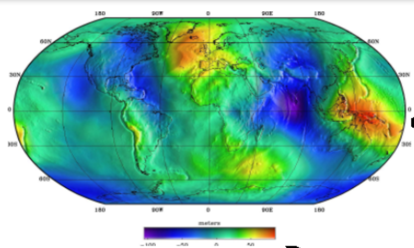
Onboard Tracking Systems
SLR
DORIS
GPS (GNSS)



Atmospheric Modeling
Ionospheric Propagation Delay
Tropospheric Refraction
Atmospheric Density

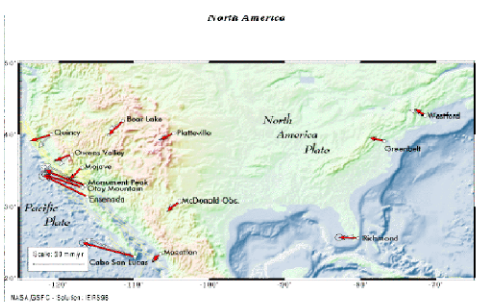
Surface Forces
Modeling
S/C Attitude





Orbit Determination
Force Modeling
Reference Frame
Tracking Technology

Geophysical Models
Gravity Models
Tide Models
Time Variable Gravity



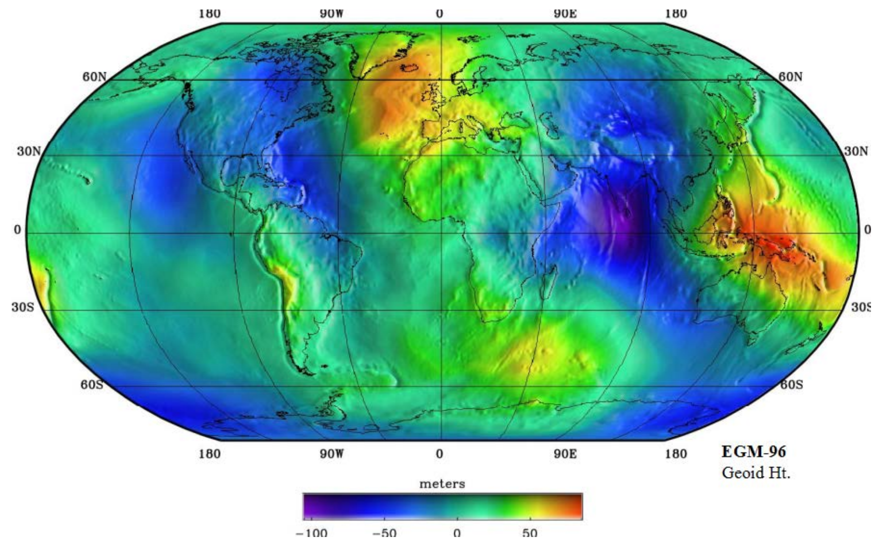
Reference Frame
International Terrestrial Reference Frame
Horizontal plate and vertical site motion
Geocenter motion
Polar Motion and Earth Orientation

Gravity Model Impact on Orbit Determination-I

Representation of Gravity Field of the Earth
(Spherical Harmonic Expansion)
(Heiskanen & Moritz, 1967; Kaula, 1966)

$$U = \frac{GM}{r} + \frac{GM}{r} \sum_{\ell=2}^{\infty} \sum_{m=0}^{\ell} \left(\frac{R_e}{r}\right)^{\ell} \overline{P}_{\ell m}(\sin\theta)$$
$$\left(\overline{C}_{\ell m}\cos(m\varphi) + \overline{S}_{\ell m}\sin(m\varphi)\right), \qquad (1)$$

where G is the gravitational constant, M is the mass of the Moon, $\overline{P}_{\ell m}$ are the normalized associated Legendre polynomials of degree ℓ and order m, R_e is the reference radius (6378 km), and φ, θ, and r are the longitude, latitude, and radius at the evaluation point. $\overline{C}_{\ell m}$ and $\overline{S}_{\ell m}$ are the normalized Stokes coefficients, the main parameters of interest of our work.



EGM96 Geoid
(Surface of constant equipotential)

Gravity Model Impact on Orbit Determination-II

Radial Orbit Perturbations Due to the Earth's Gravity Field on TP Orbit

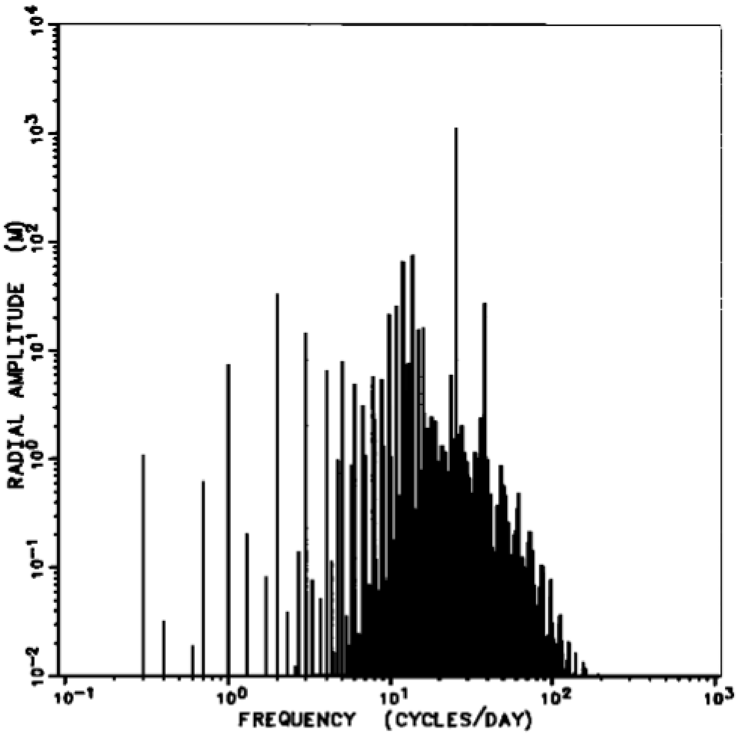


Fig. 1. TOPEX radial perturbation spectrum using the GEM-10B geopotential model.

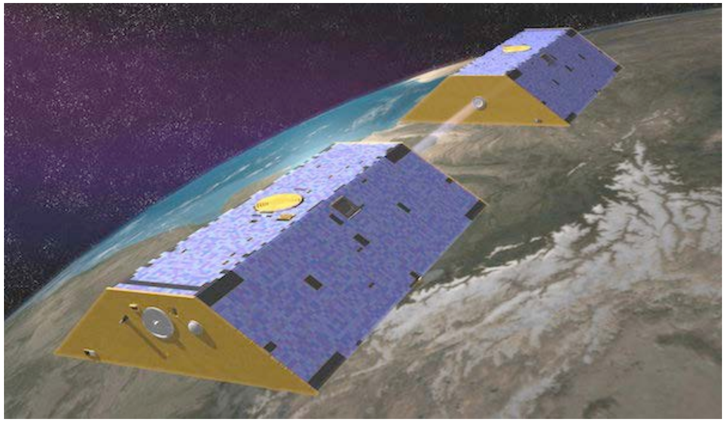
(BD Tapley & GW Rosborough, "Geographically Correlated. Orbit Error and Its Effect on Satellite Altimetry Missions" J. Geophys. Res., 1985, doi:10.1029/JC090iC06p11817)

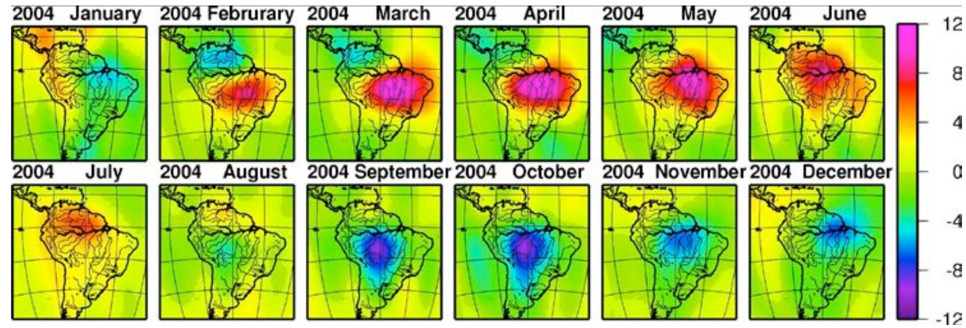
Errors in Models of the Earth's Gravity Field were the largest source of orbit error for altimeter missions … Until the launch of TOPEX/Poseidon ….

Model	L max x Mmax	SLR RMS of fit (cm)
GEML2, 1982	20x20	105.9
GEMT1, 1988	36x36	31.4
JGM-1S, 1991	70x70	7.7
JGM-2S, 1992	70x70	4.0
JGM-3, 1995	70x70	3.2
EGM96, 1996	70x70	2.8

The latest gravity models derived from GRACE & GOCE data eliminate static gravity error on the TP (J1, J2, J3) orbit and allow us to model in detail the temporal gravity variations ….

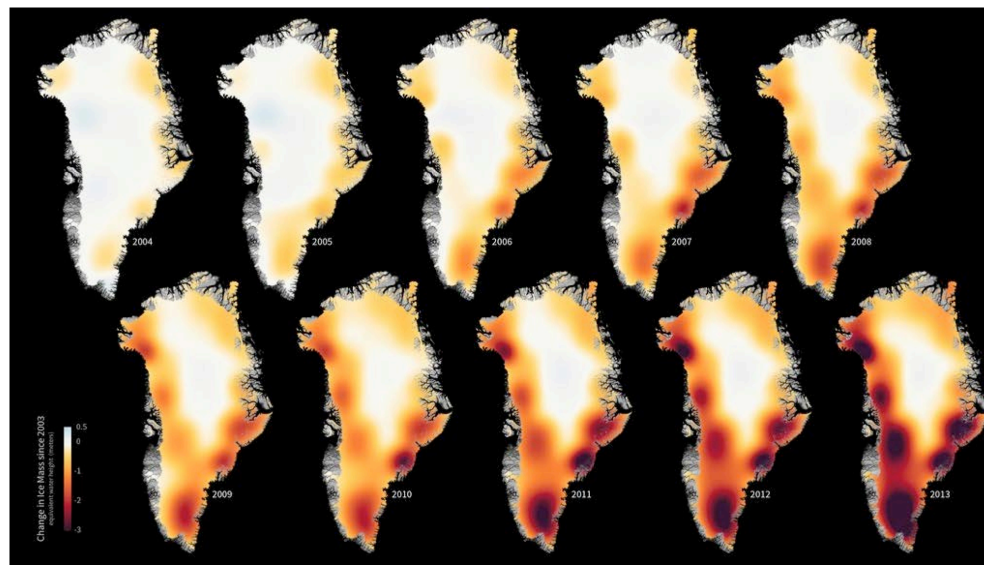
Gravity Model Impact on Orbit Determination-IV





Amazon mass change seen by GRACE
http://grace.jpl.nasa.gov

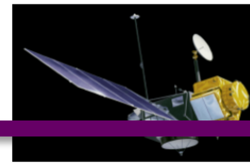
- US (NASA/JPL/UT CSR) + Germany (DLR),
- Launched 2002.
- Reliable 10-day to monthly solutions since January 2003 to present; Three official analysis centers (Univ. Texas, JPL, GFZ (Germany)); Also GRGS/CNES, NASA GSFC ...
- Most recent data has periodic gaps due to aging of s/c.



Mass loss in Greenland (2003-2013)
https://svs.gsfc.nasa.gov/30478

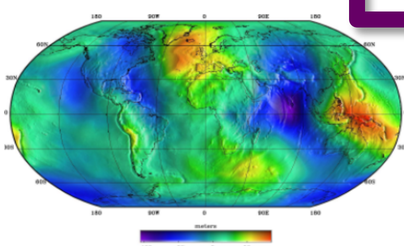
Orbit Determination Schematic

Onboard Tracking System
- SLR
- DORIS
- GPS (GNSS)



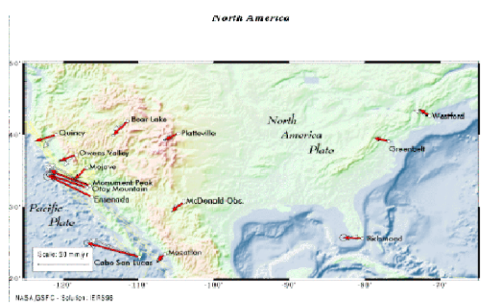
Surface Forces
- Modeling
- S/C Attitude

Atmospheric Modeling
- Ionospheric Propagation Delay
- Tropospheric Refraction
- Atmospheric Density



Orbit Determination
- Force Modeling
- Reference Frame
- Tracking Technology

Geophysical Models
- Gravity Models
- Tide Models
- Time Variable Gravity

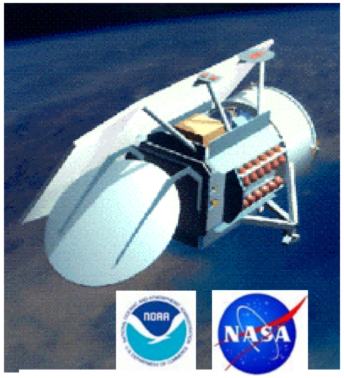


Reference Frame
- International Terrestrial Reference Frame
- Horizontal plate and vertical site motion
- Geocenter motion
- Polar Motion and Earth Orientation

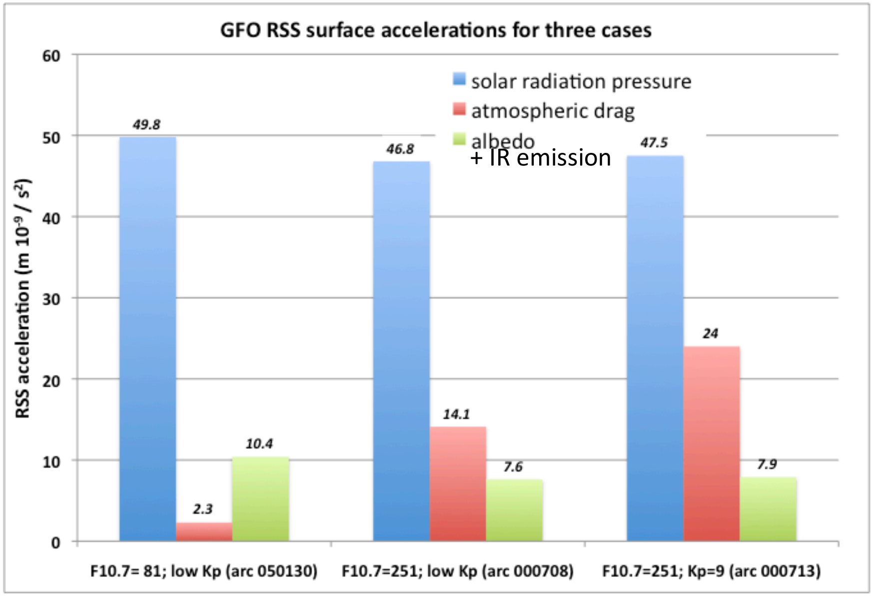
Magnitude of Perturbing Forces on GEOSAT Follow On

Perturbing Acceleration	m/s^2
GM	~7.7
$C_{2,0}$	$\sim 9 \times 10^{-3}$
$C_{20,20}$	$\sim 1 \times 10^{-7}$
Ocean tides	$\sim 3 \times 10^{-6}$
Moon (third body)	$\sim 1 \times 10^{-6}$
Sun (third body)	$\sim 6 \times 10^{-7}$
Relativity – Schwarzschild	$\sim 1.4 \times 10^{-8}$
Solar Radiation Pr.**	$\sim 10^{-8}$
Atmospheric Drag **	$\sim 10^{-7}$ to 10^{-10}
** Depends on Area/Mass ratio & Position in solar cycle	

Impact of Surface Forces depend on spacecraft shape & orientation, and for drag, on timing w.r.t solar cycle

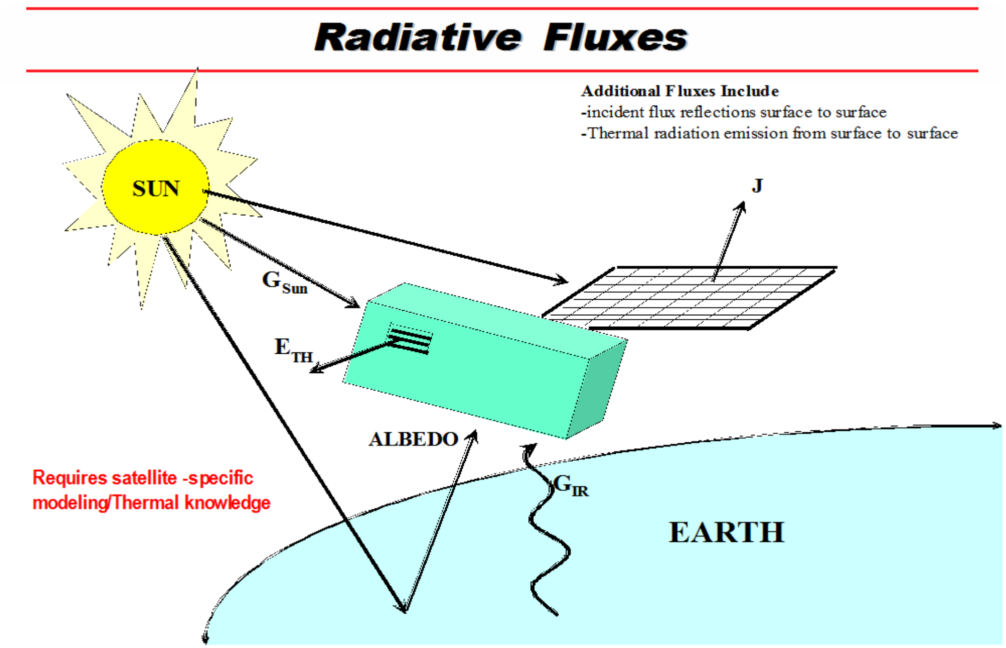


GFO-1, 1998-2008



GFO Surface Force Accelerations calculated by N. Zelensky (SGT @ NASA GSFC)

Radiation Pressure Modelling is the largest source of orbit error after gravity model error …. And remains a challenge



Most simplistic representation of s/c for surface force modeling is as a cannonball. It was realized before T/P launch that this was not good enough. This led to the "macromodel" approach.

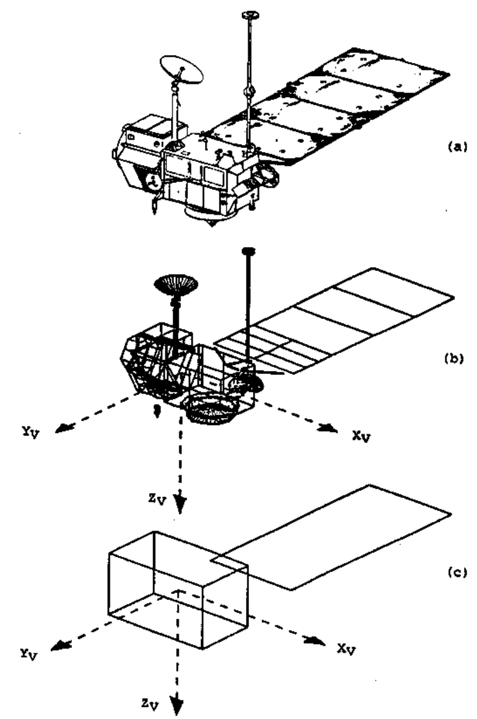


Figure 1. (a) The TOPEX/Poseidon Spacecraft, (b) Micro-Model Approximation, (c) Macro-Model Approximation

Micromodel:

(Antreasian, 1992; Antreasian & Rosborough, 1992)

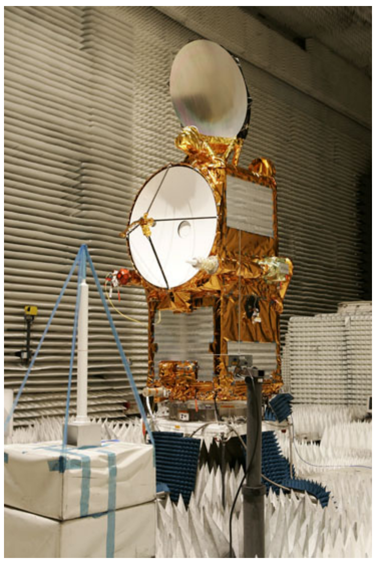
Box-Wing model

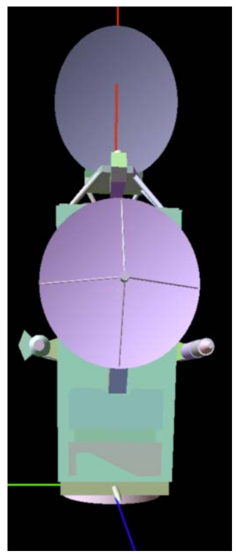
(Marshall & Luthcke. 1994)

30

Radiation Pressure Modelling Improvement

<u>One example:</u>
University College London models for LEO spacecraft.
(*Ziebart, 2004; Ziebart et al., 2005*)





Clean room photo (left)
Mathematical model (right)

A detailed s/c model with a thermal properties at ever node is illuminated from a simulated solar source over many orientations. Ray-tracing is used to “pre-calculate” the radiation-pressure accelerations as a function of spacecraft orientation.

These calculations are computationally intensive. We only initiate them if the mission requirements demand the highest orbit accuracy.

The extra effort can remove systematic signals in orbits & altimeter data.

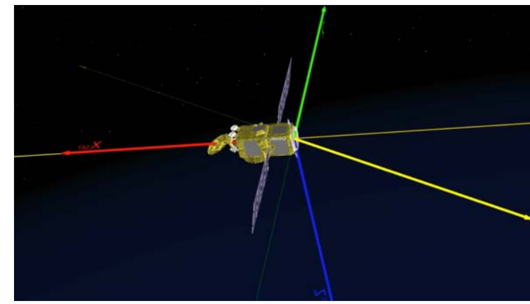
Animation – Orbital Motion of Jason-2 Spacecraft

3D Animation of Jason-2 spacecraft in orbit provided by the International DORIS Service (IDS)

http://ids-doris.org/satellites.html

HY-2A, Cryosat-2, SPOT-5, Envisat also available.

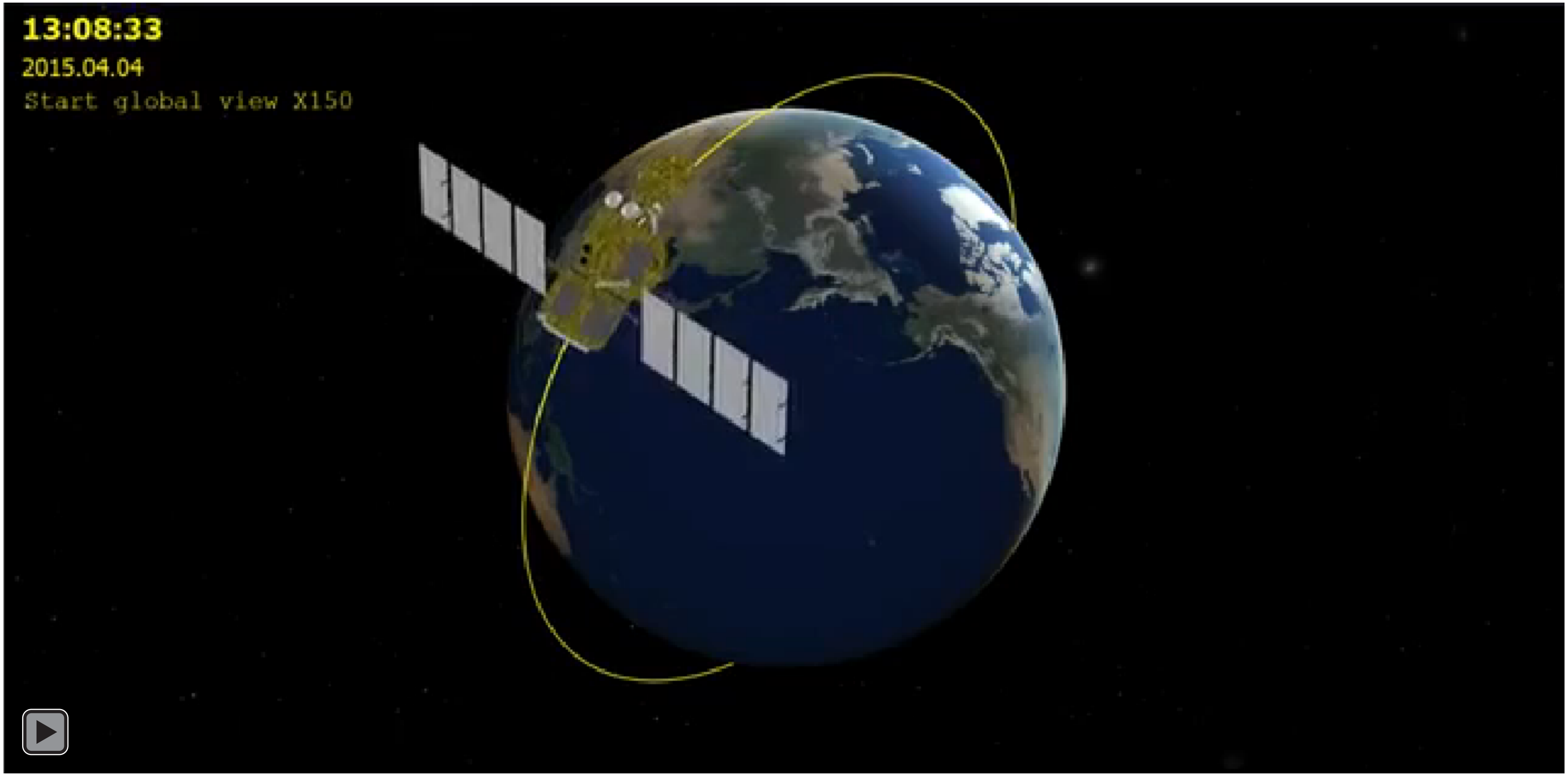
International DORIS Service



Conclusion: We need detailed attitude information about orientation of spacecraft and solar arrays as a function of time in order to properly model the surface forces.

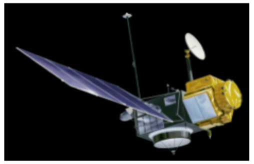
For the Jason s/c these are supplied as quaternions which the project archives on the NASA CDDIS;

For TOPEX, we have this attitude information for 5-10% of the 10-day cycles over the entire mission – so we use an analytical model.


13:08:33
2015.04.04
Start global view X150

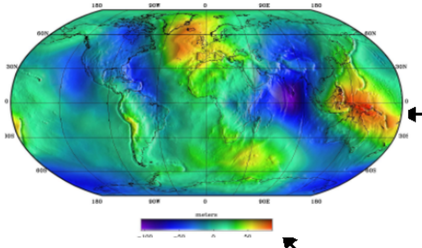
Orbit Determination Schematic

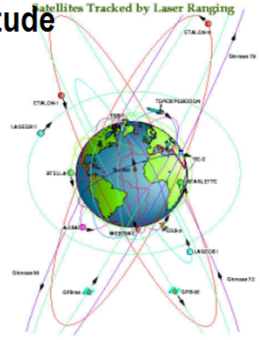
Onboard Tracking Systems
SLR
DORIS
GPS (GNSS)



Atmospheric Modeling
Ionospheric Propagation Delay
Tropospheric Refraction
Atmospheric Density

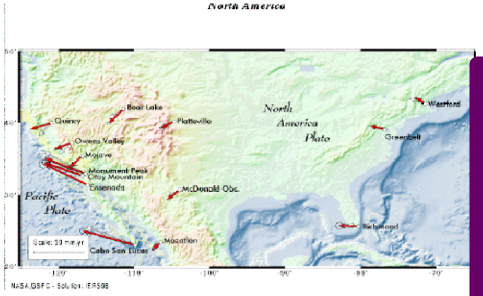
Surface Forces
Modeling
S/C Attitude





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

Reference Frame: What is it?

SLR

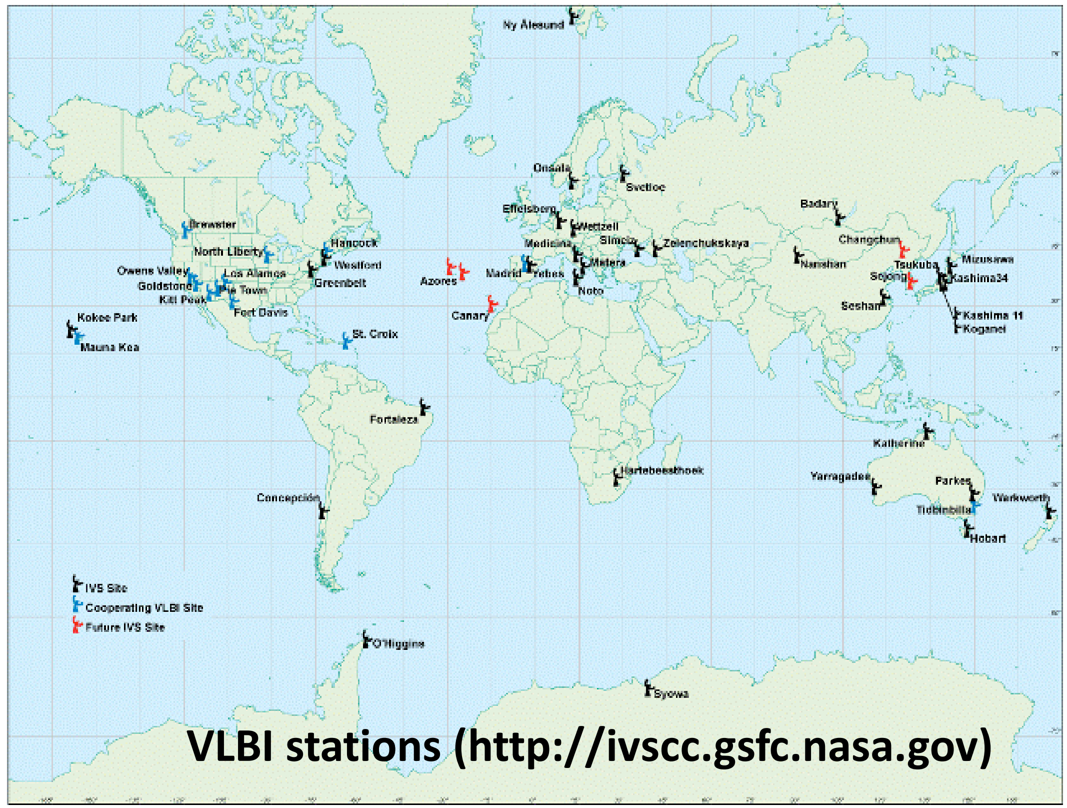
e.g. Hartebeesthoek (South Africa)

+ GPS

e.g. Greenbelt, Maryland

+ VLBI

e.g. Greenbelt; Wettzell (Germany)



VLBI stations (http://ivscc.gsfc.nasa.gov)

+ DORIS

e.g. Yarragadee (Australia)

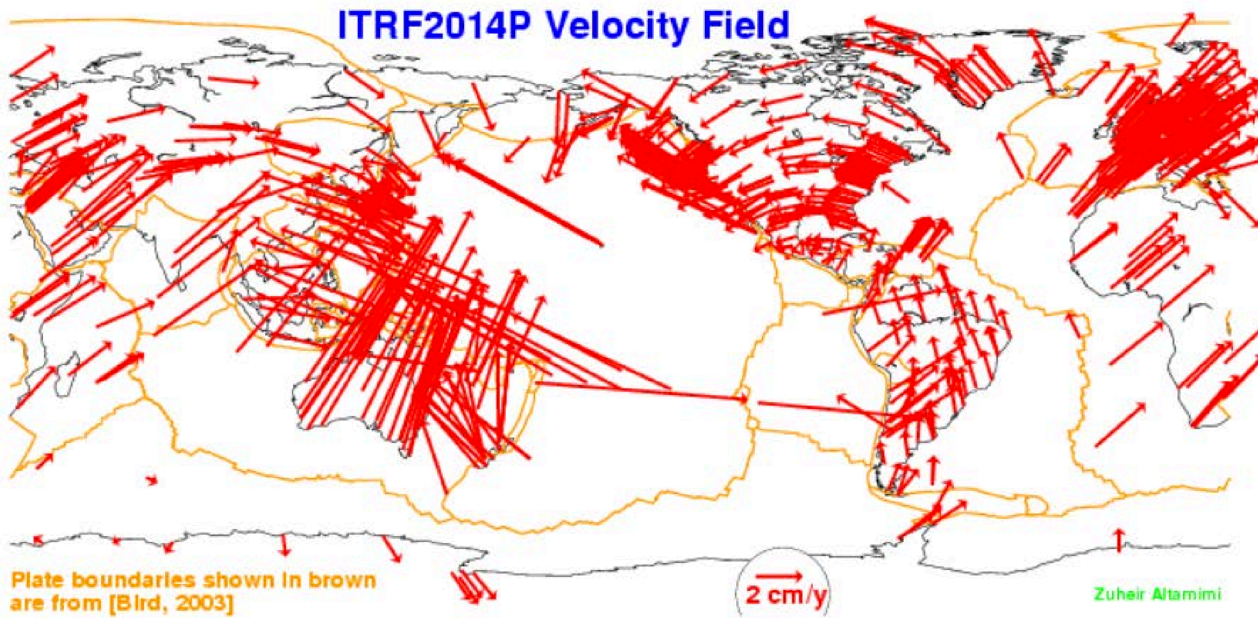
+ site ties

= an ITRF Realization, e.g. ITRF2014

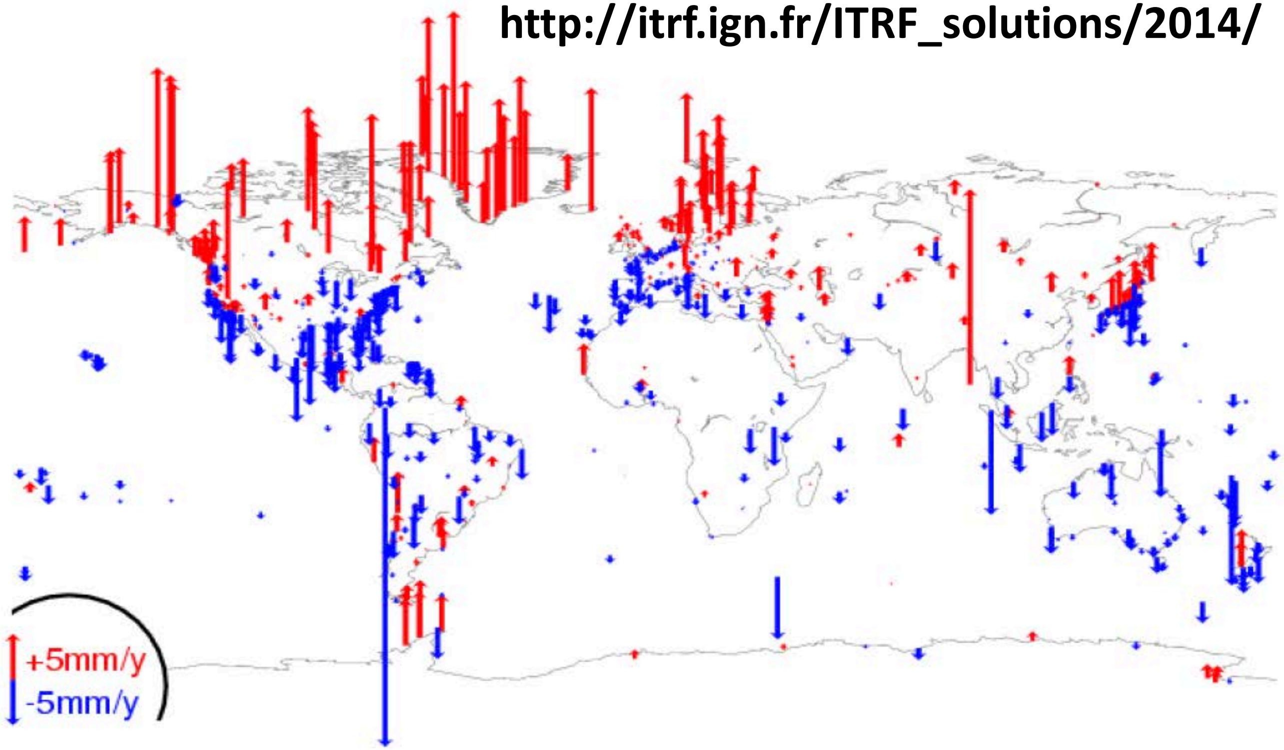
A reference frame realization consists of **positions and velocities of the reference points**.

For ITRF2014, post-seismic relaxation is also modeled for the first time.

Figures from Zuheir Altamimi, IGN/France



http://itrf.ign.fr/ITRF_solutions/2014/

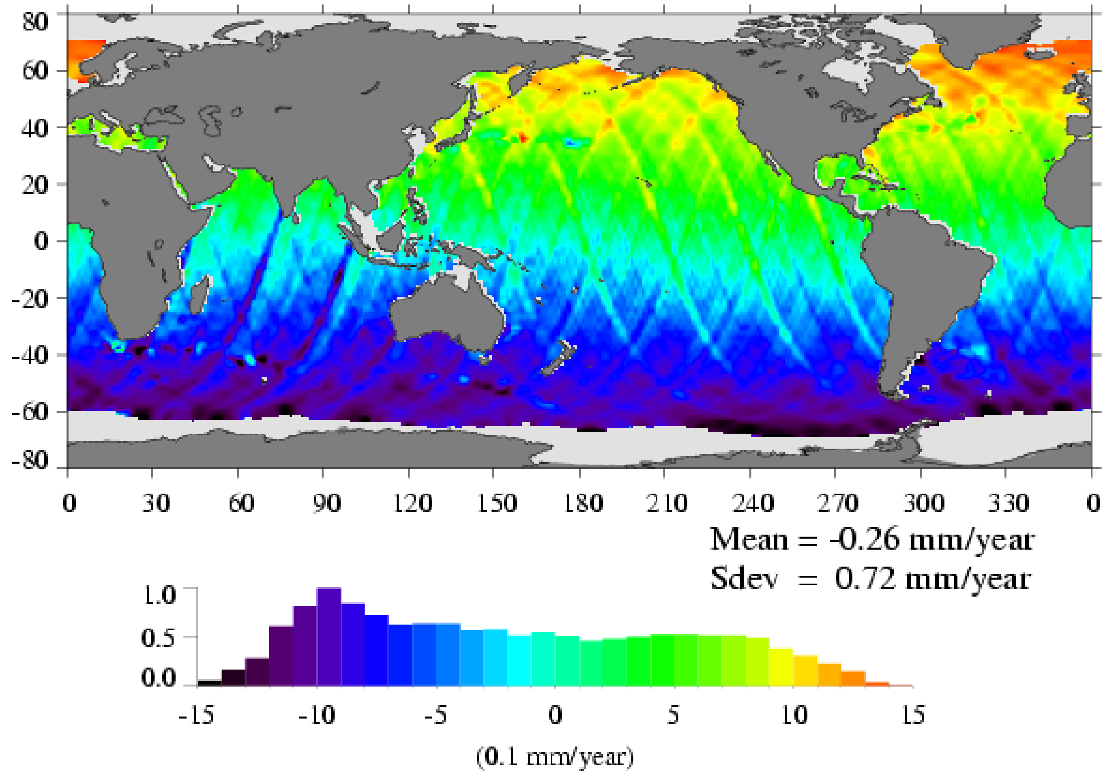


Altimeter satellites & TRF error

Reference Frame Realizations used in Altimeter Satellite POD.

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

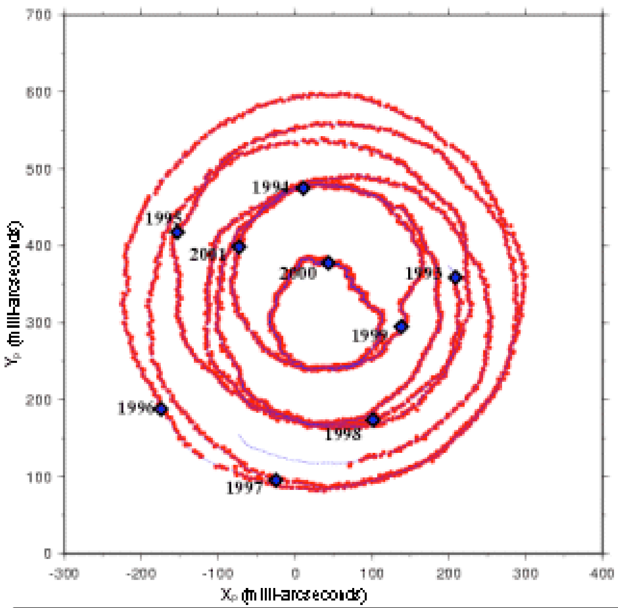
Next. **ITRF2014.**

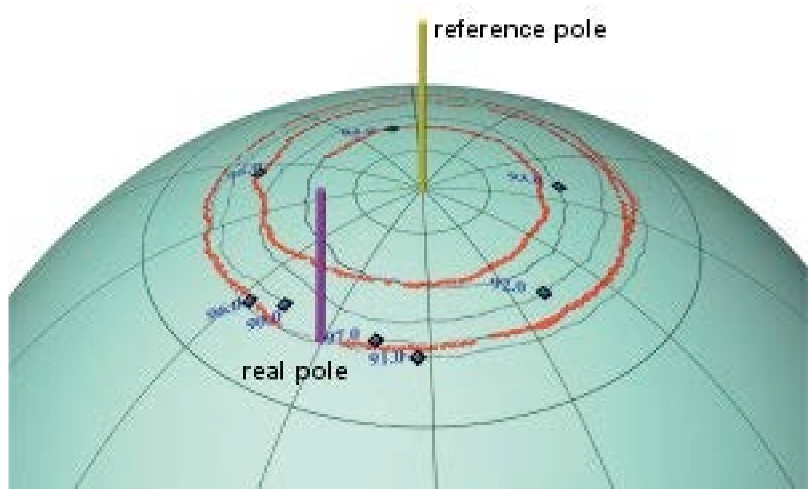


Regional **TOPEX** (**1993-2002**) Sea Surface Height Trend differences from direct impact of the **ITRF2005** (GGM02C) minus **CSR95** (JGM3) orbit differences. **(from Beckley et al.,** *Geophys. Res. Lett*., **2007).**

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

Polar Motion



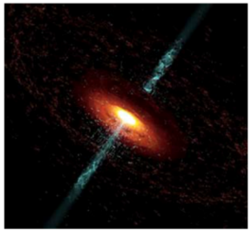


1 arcsec = 1/3600th of a degree; 0.1 arcsec = ~ 3 meters

The Earth rotates in an irregular fashion due to mass shifts and changes in its rotational velocity; The "true pole" can deviate by up to ten meters from the "reference pole". So on a regular basis, we must be supplied with updates which are provided by the IERS (International Earth Rotation and Reference Systems Service) – based on analysis of the space geodetic data (GPS, SLR, VLBI) that has been described.

Images Credit:.
Group de Recherche de Géodésie Spatiale (GRGS/CNES), Toulouse, France.

Altimetry Satellites, Earth Rotation, Quasars & VLBI



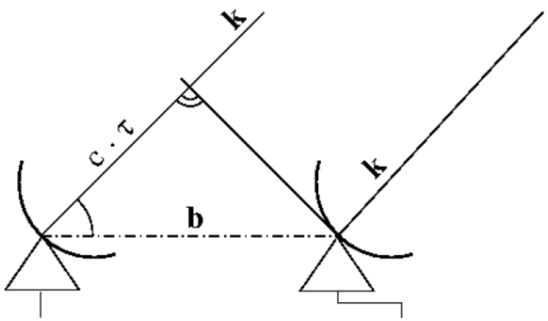
Active galactic nuclei, galaxies, quasars

Distance 2 – 8 billion light years

Point sources

No proper motions

→quasi-inertial reference system



1 ms -> 7.4 cm on the Earth's equator

UT1 Determination Accuracy:
1972-1979: ~1 ms (Lunar Laser Ranging)
1979-1983: 0.4 ms (early VLBI)
1983-1991: 0.05 ms (campaign VLBI)
(*Feissel & Gambis, Adv. Space Res, 1993*)

VLBI is the only technique to measure the rotation "phase" of the Earth – how it changes with time.

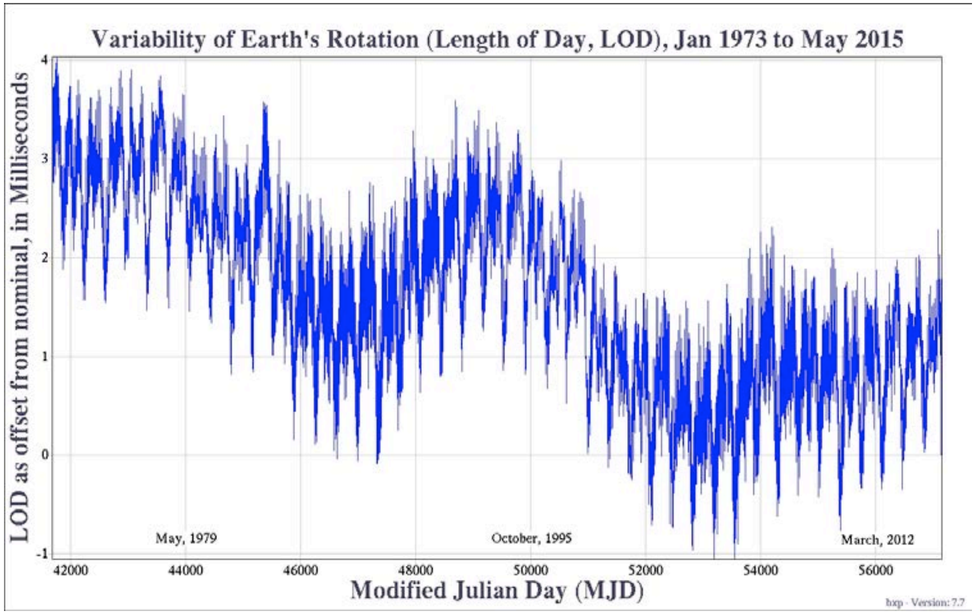
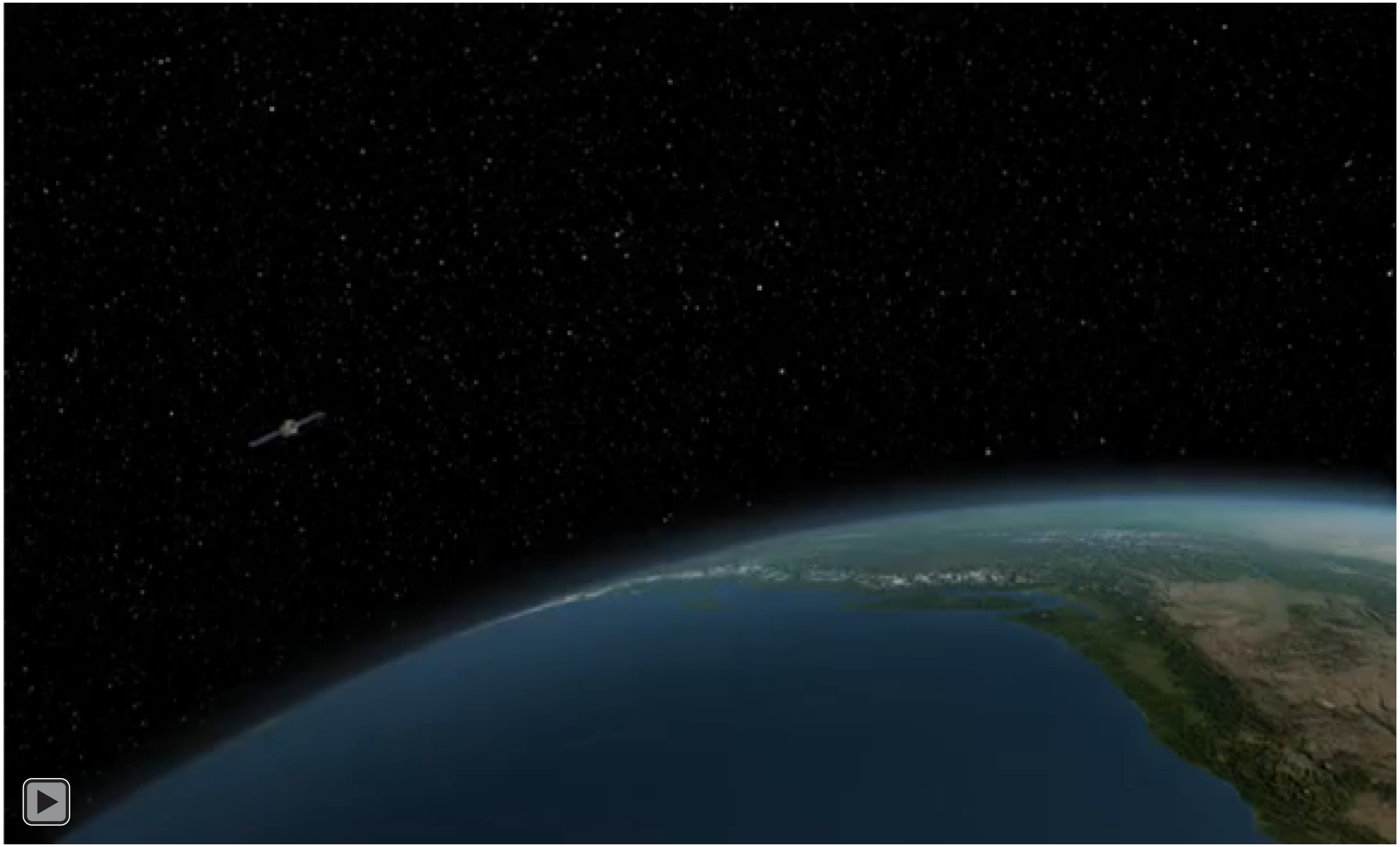


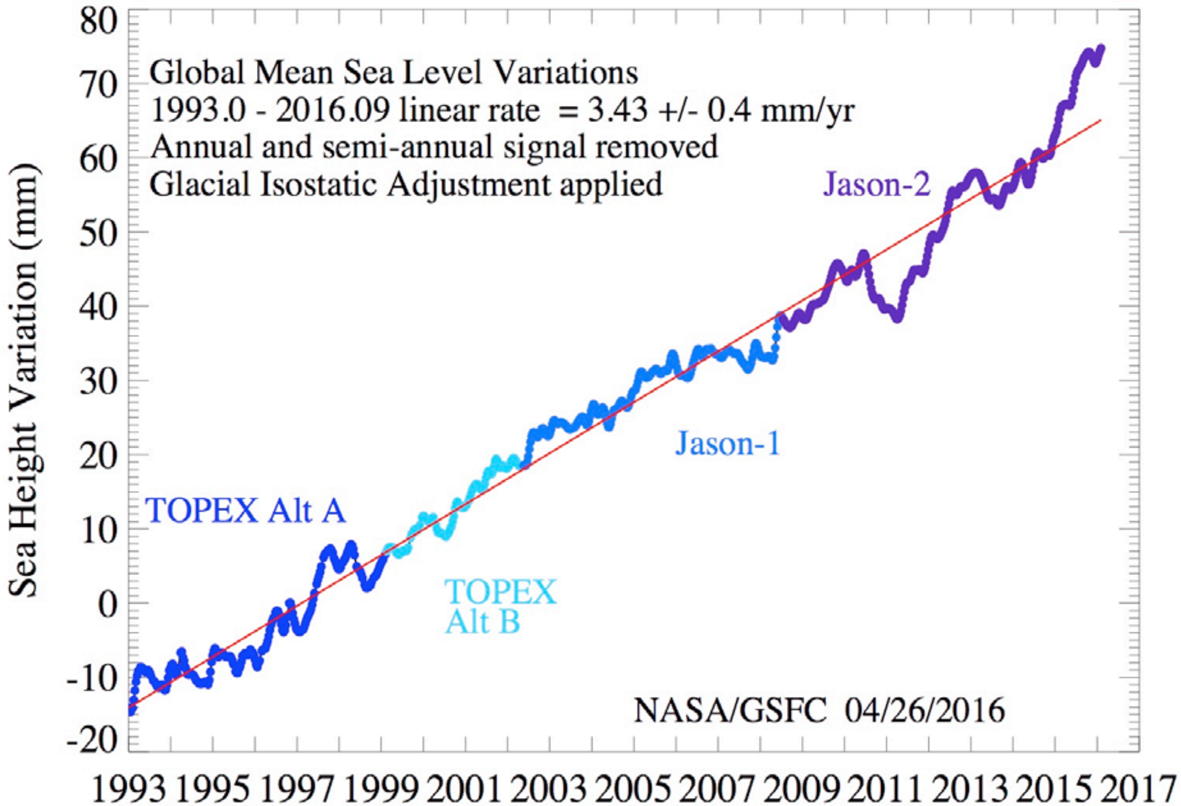
Image from US Naval Observatory, Earth Orientation Department

Application - Synoptic mapping of ocean height variations



Application – 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

Summary

• The Earth is a dynamic planet. In order to operate an observing system of altimeter satellites to monitor the global variations in ocean topography – we need to rely on precision tracking systems, detailed models of the forces that perturb the spacecraft orbit, and we must model in detail the observations, including target and propagation (media) effects.

• Inputs for Precise Orbit Determination Include

(1) Terrestrial reference frame (updated every five years). ---

(2) Precise model of Earth's gravity field – including time variations – determined from GRACE+GOCE data + supplemented by analysis of other satellite data.

(3) Model the mass motions of the atmosphere → So we rely on atmosphere models (ECMWF, NCEP) to account for these motions.

(4) Polar motion and Earth rotation information (updated delay for near-real time products; every few weeks for higher precision products)