Global Geodetic Observing System and Core Sites

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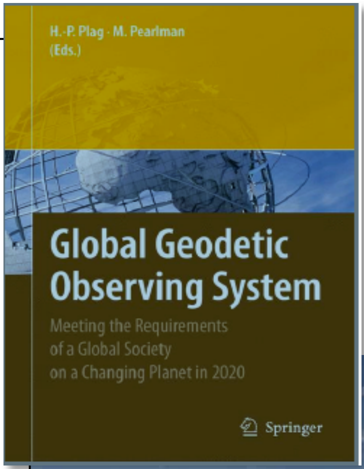
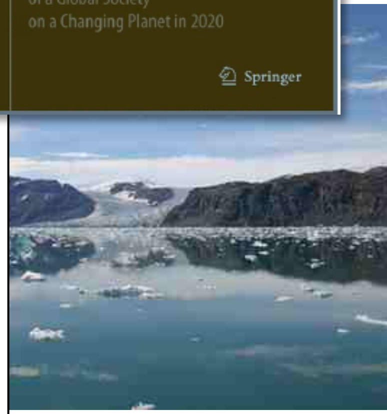
[6]Jet Propulsion Laboratory and California Institute of Technology, Pasadena, USA

Meeting with Delegation from Nigeria
NASA Goddard Space Flight Center
Greenbelt MD

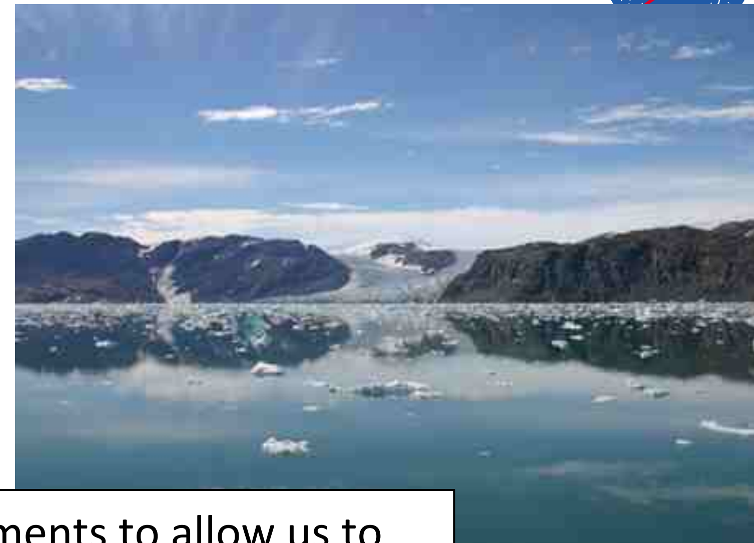
Global Geodetic Observing System (GGOS)

- Established by the IAG to integrate the three fundamental areas of geodesy (Earth's shape, gravity field, and rotation), to monitor geodetic parameters and their temporal variations in a global reference frame with a target relative accuracy of 10E-9 or better (See GGOS 2020)
- Provide products & services with the geodetic accuracy necessary to address important geophysical questions and societal needs, and to provide the robustness and continuity of service which will be required of this system in order to meet future needs and make intelligent decisions
- Constituted mainly from the Services (ILRS, IVS, IGS, IDS, and IERS)
- Main focus at the moment is the International Terrestrial Reference Frame





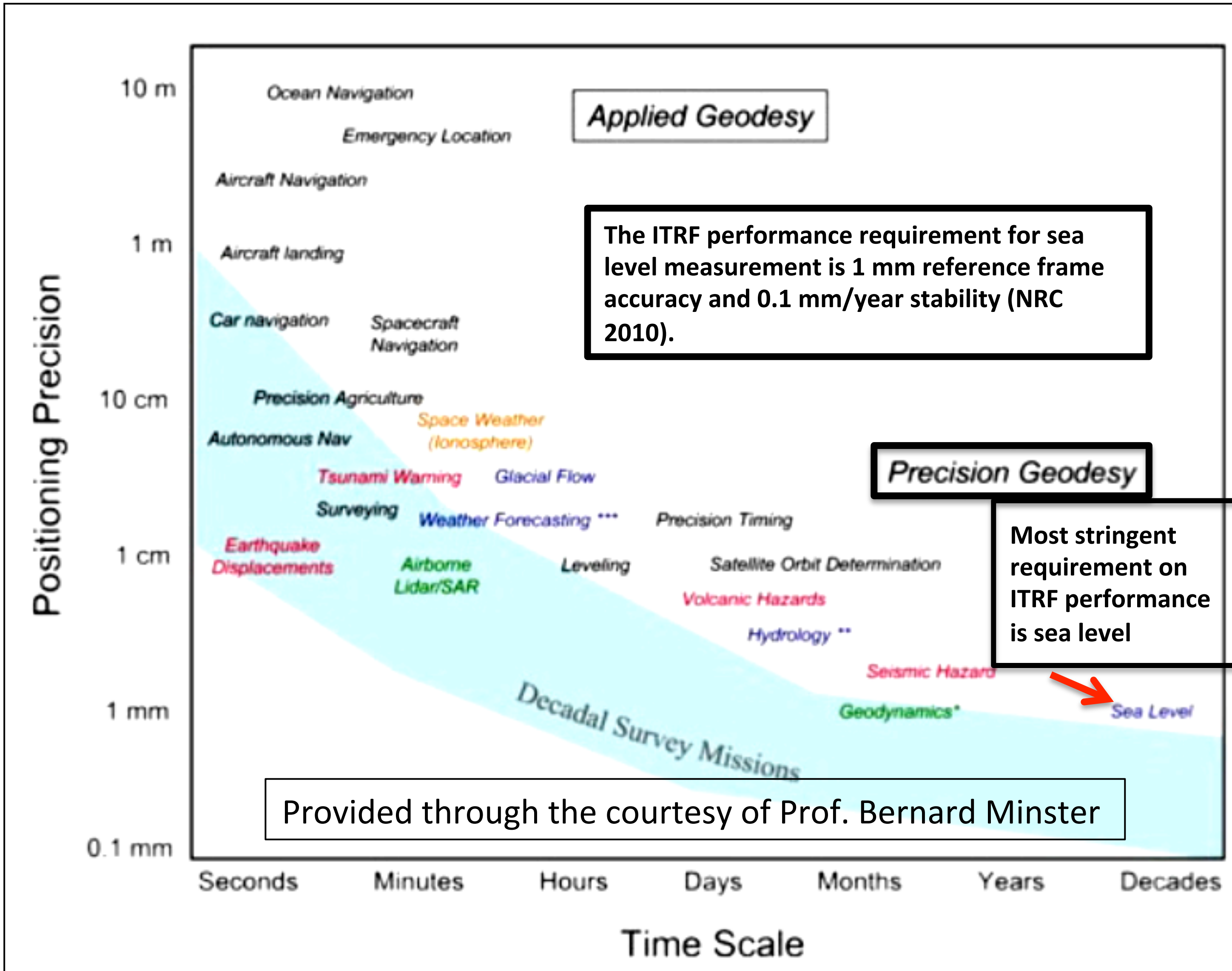
Motivation: Monitoring the Earth System



Perform proper measurements to allow us to make intelligent societal decisions?

Practical applications of Space Geodesy
US National Research Council Study

- **Geodesy** is the science of the Earth's shape, gravity and rotation, including their evolution in time.
- **Techniques** used to observe the geodetic properties of the Earth **provide the basis for the International Terrestrial Reference Frame (ITRF)**
- The **ITRF** is the foundation for virtually all **airborne, space-based, and ground-based Earth observations**, and is fundamentally important for **interplanetary spacecraft tracking and navigation**.

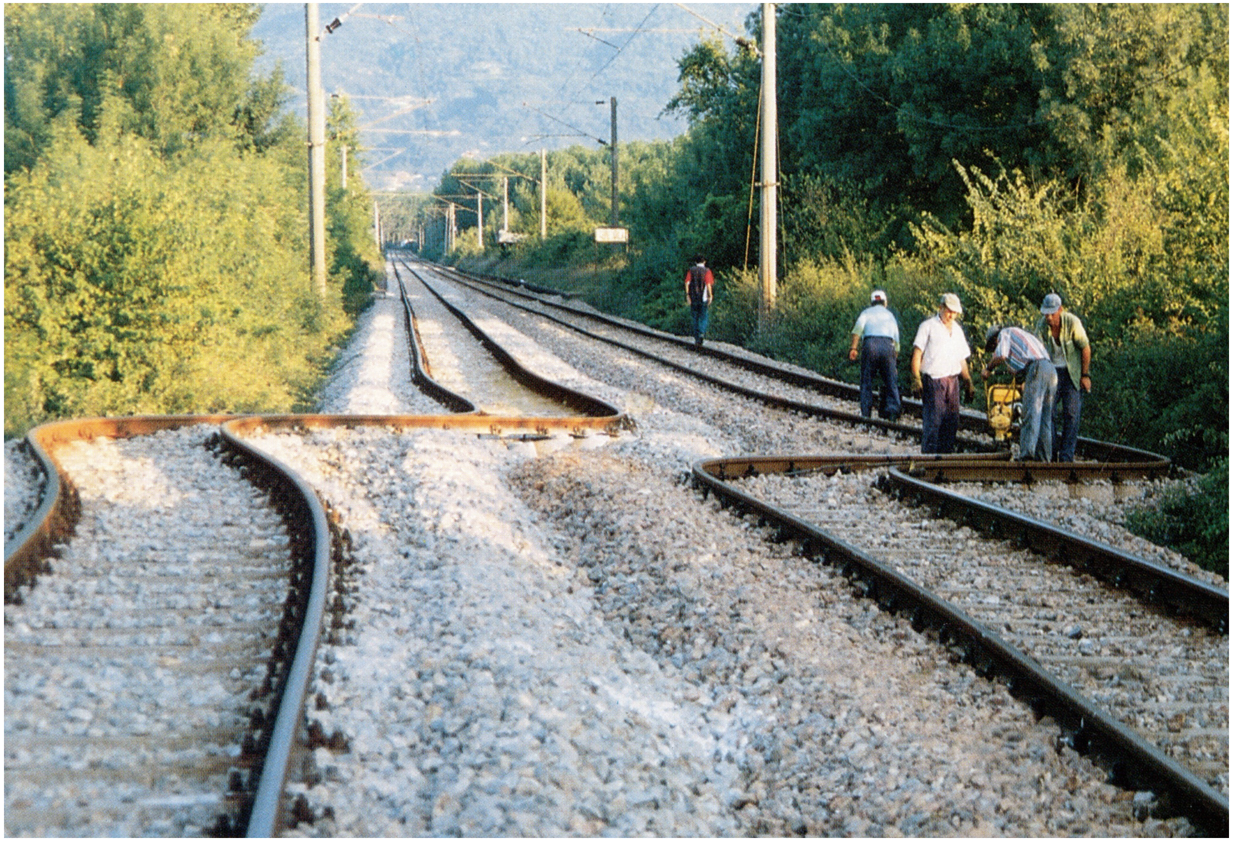


Pillar 1: Geometry and Deformation of the Earth

- Problem and fascination of measuring the Earth:

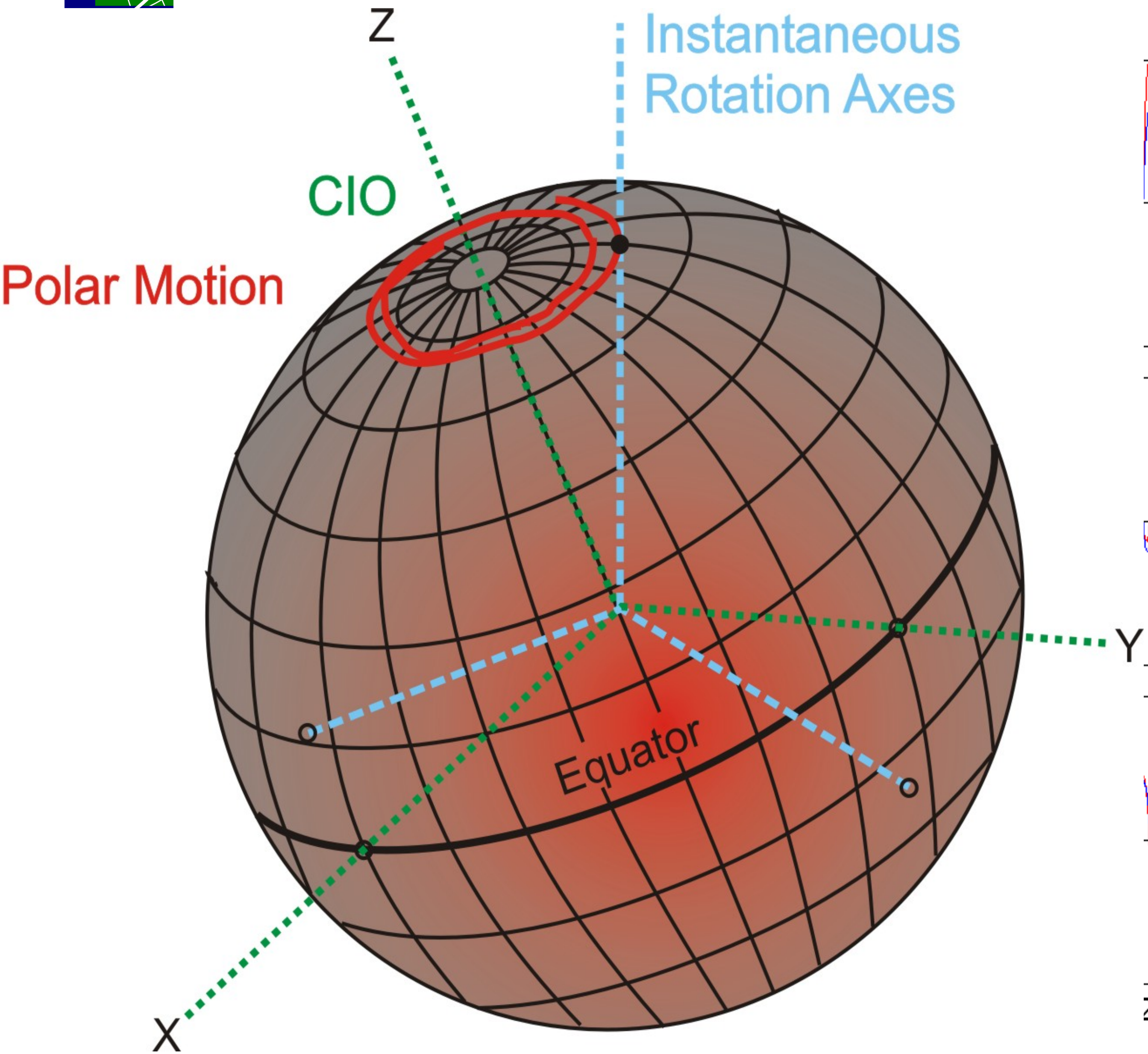
Everything is moving !

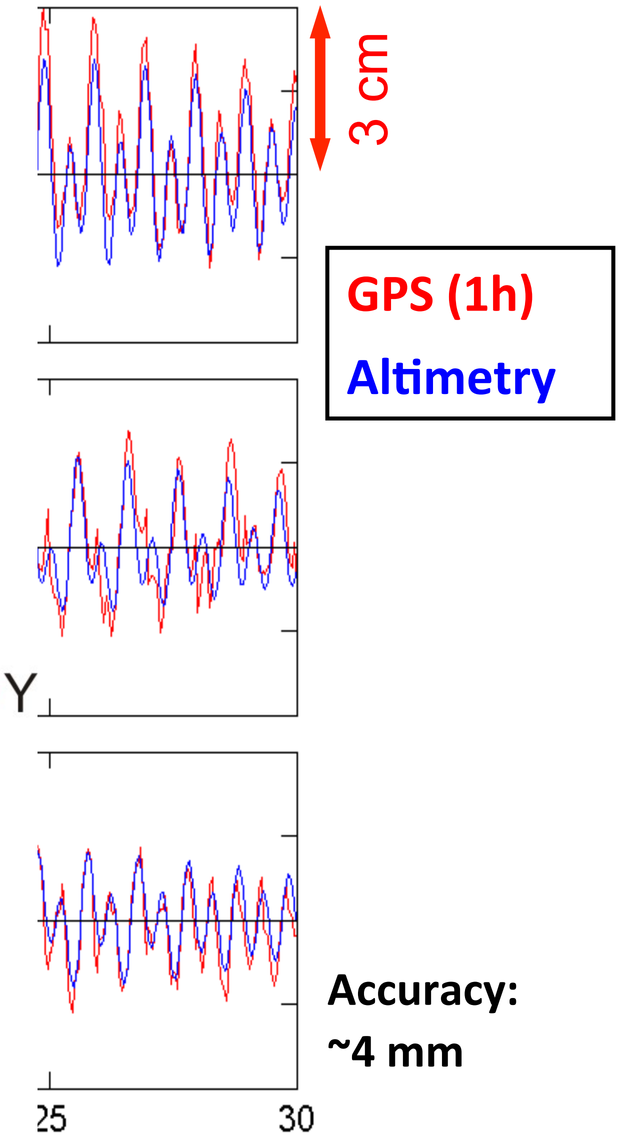
- Monitoring today mainly by GPS permanent networks



- Examples:
  - Plate motions
  - Solid Earth tides (caused by Sun and Moon)
  - Loading phenomena (ice, ocean, atmosph.)
  - Earthquakes …
- **Continuous monitoring is absolutely crucial**

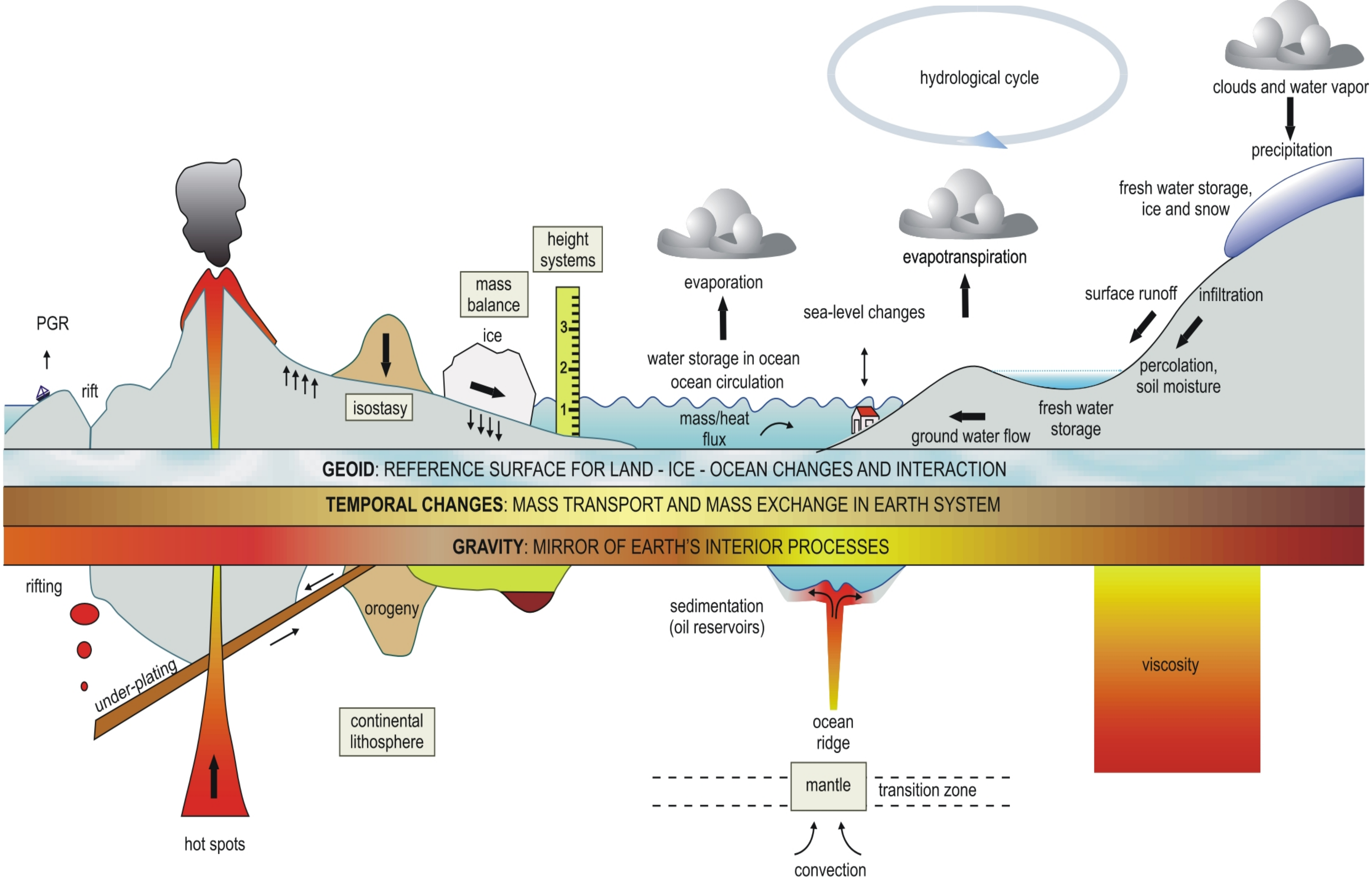
Pillar 2: Earth Rotation (Sub-Daily Variations)





Accuracy: ~4 mm

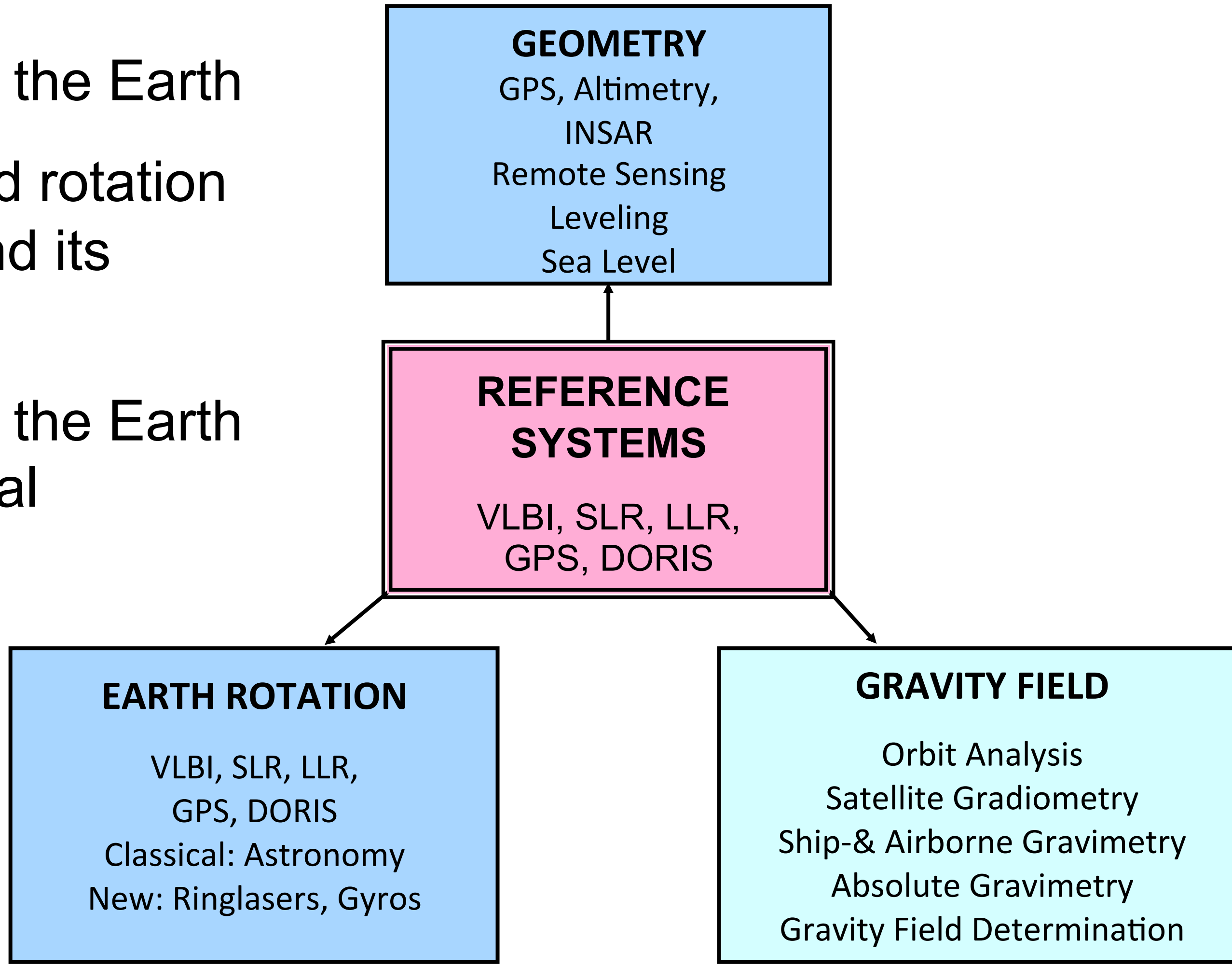
Pillar 3: Gravity Field, Mass Transport



Ilk et al. (2005) Mass Transport and Mass Distribution in the Earth System, 2nd Edition, SPP1257 DFG

The Reference Frame and Precision Orbit Determination impact all Three Pillars of Geodesy

1. Geometry and deformation of the Earth
2. Orientation and rotation of the Earth and its variation
3. Gravity field of the Earth and its temporal changes

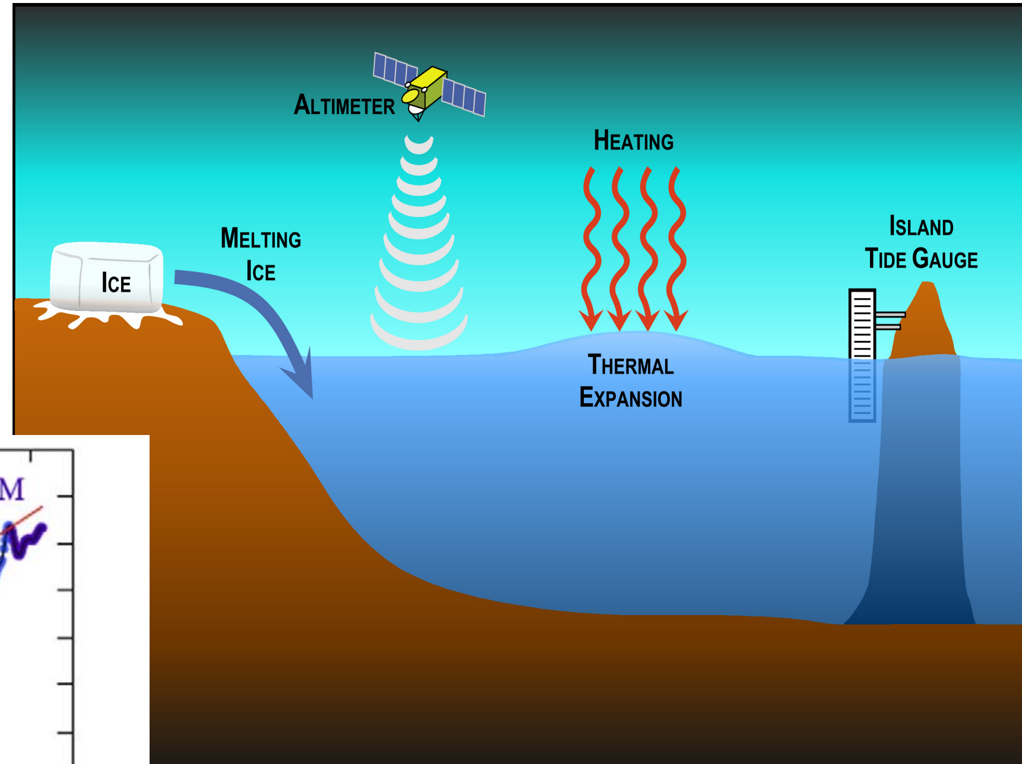


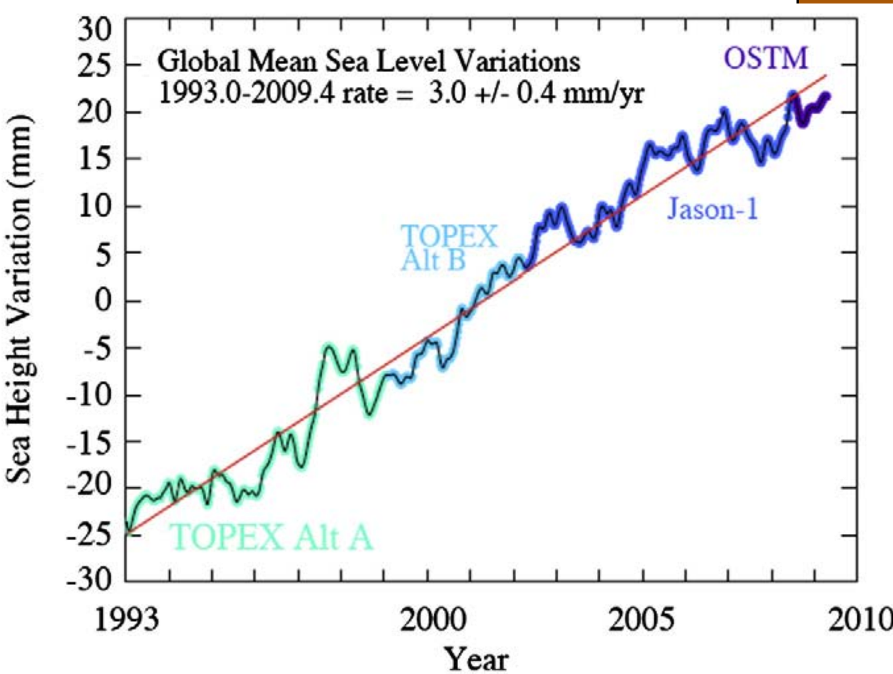
GPS Mapping of Velocity Fields

Courtesy of Dr. Robert Reilinger, MIT

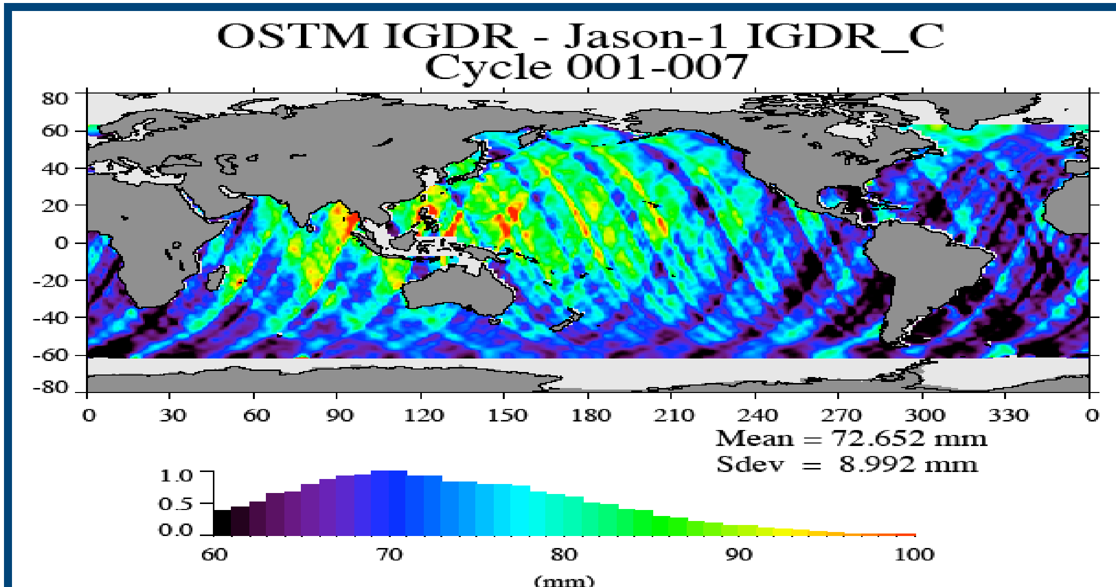
Measure Sea Surface Height with Altimetry

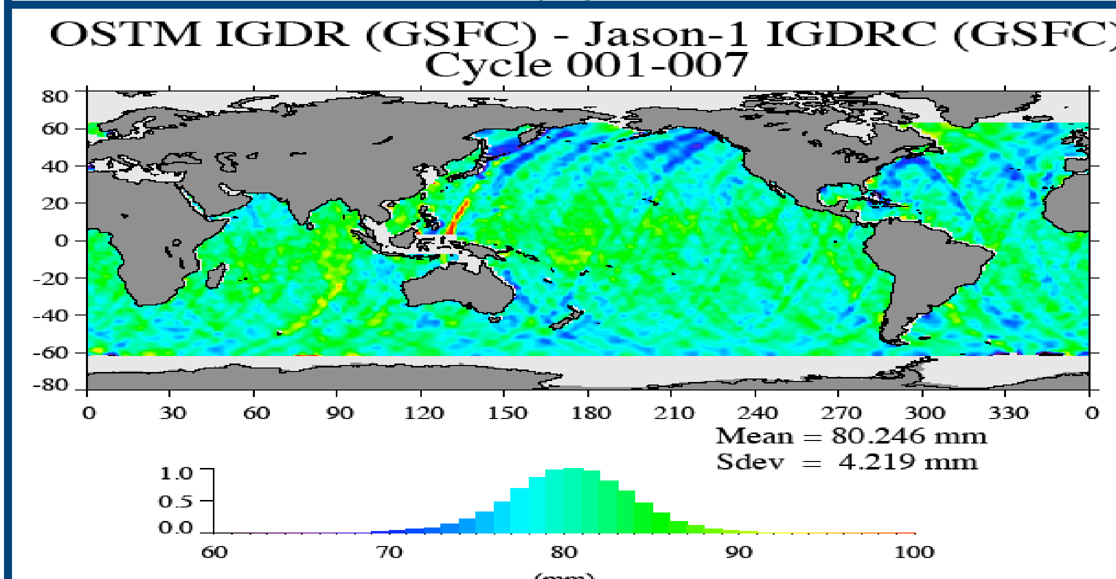
Global mean SSH variations from TOPEX, Jason-1, Jason-2 with respect to 1993–2002 mean, plotted every 10 days using the NASA GSFC orbits from Lemoine et al. (2010), and the latest GDR releases and corrections for the altimetry.



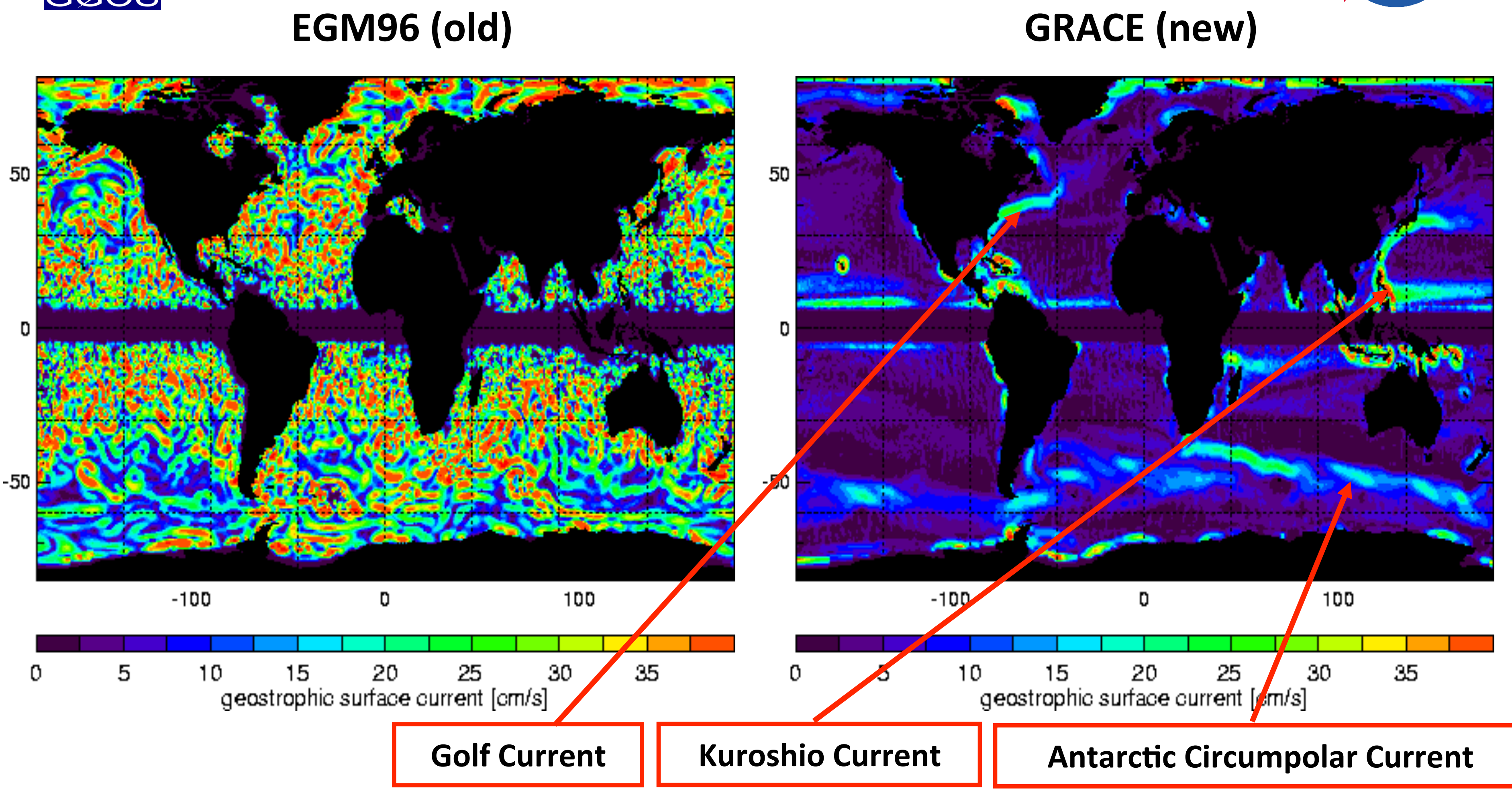


Source: Lemoine, F.G., et al. Towards development of a consistent orbit series for TOPEX, Jason-1, and Jason-2. J. Adv. Space Res. (2010), doi:10.1016/j.asr.2010.05.007


OSTM IGDR - Jason-1 IGDR_C
Cycle 001-007
80
60
40
20
0
-20
-40
-60
-80
0
30
60
90
120
150
180
210
240
270
300
330
0
Mean = 72.652 mm
Sdev = 8.992 mm
1.0
0.5
0.0
60
70
80
90
100
(mm)


OSTM IGDR (GSFC) - Jason-1 IGDRC (GSFC)
Cycle 001-007
80
60
40
20
0
-20
-40
-60
-80
0
30
60
90
120
150
180
210
240
270
300
330
0
Mean = 80.246 mm
Sdev = 4.219 mm
1.0
0.5
0.0
60
70
80
90
100
(mm)

Ocean Currents from GRACE and Altimetry

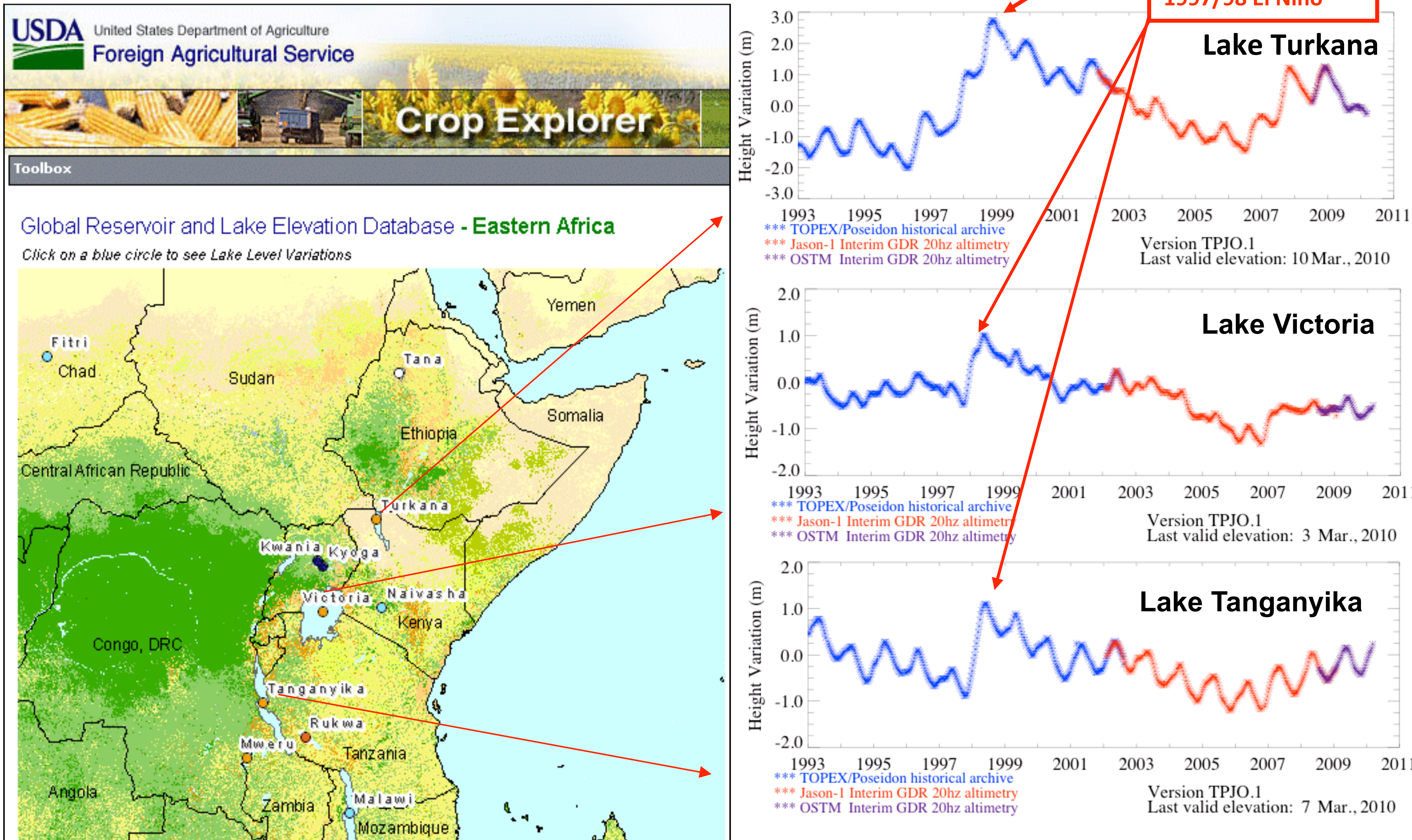


Geostrophic surface currents (altimetry Mean Sea Surface Height – Geoid)

- EGM96: noise and systematic errors dominate the picture
- GRACE: all the major ocean currents visible

Near Real Time Lake Level Monitoring

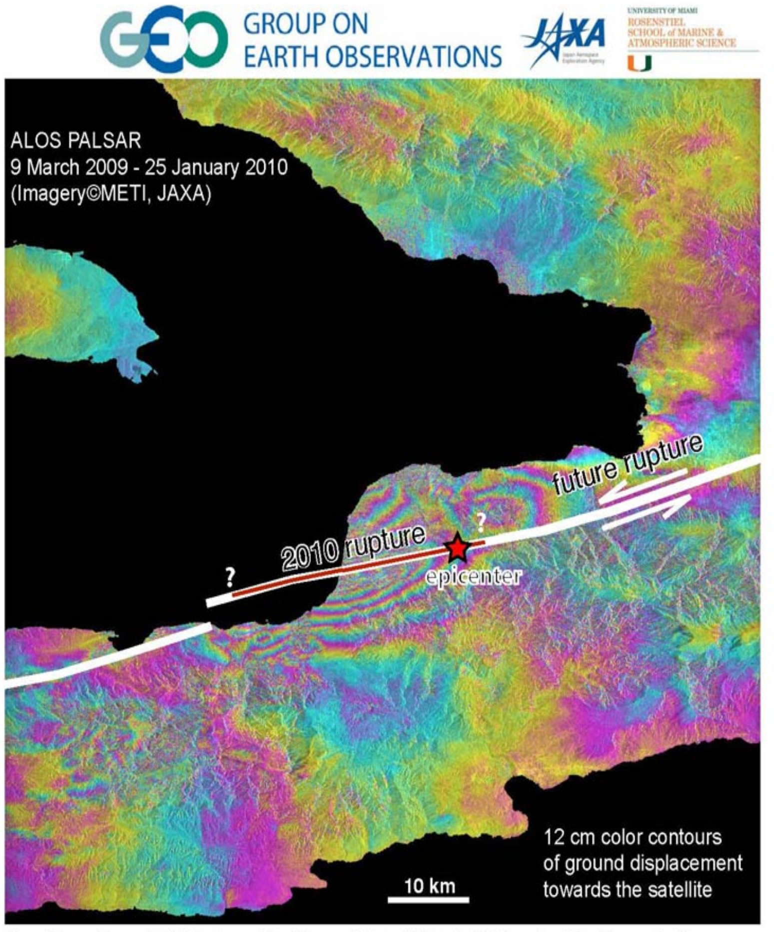
Decrease in lake water levels since 1997/98 El Nino



Reprocessed altimeter data better enables the monitoring of lake levels for the Foreign Agriculture Service under the U.S. Department of Agriculture for crop predictions and irrigation management.

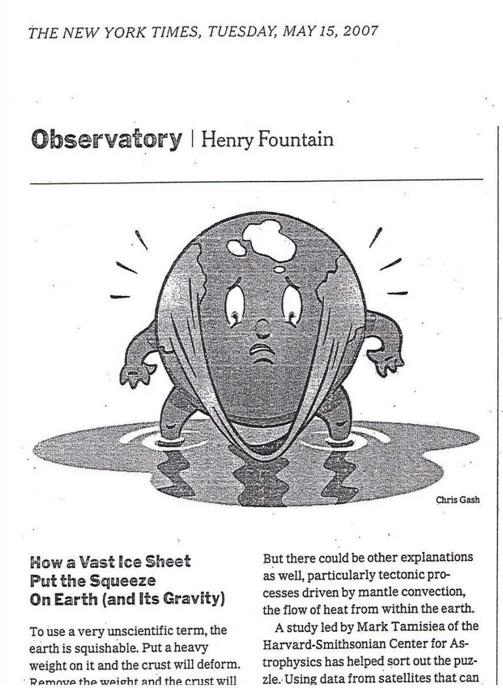
Geodesy and Natural Hazards

- Measure the deformation of the ground for a number of applications
- Provides unique information on the deformation due to natural hazards (volcanoes, landslides, earthquakes, etc.)
- At right is an InSAR map of the ground displacement from the January 2010 M7 Haiti earthquake
- Each band of color contours is 12 cm of, so the total displacement was ~1 m over a large area
- Measurements help us predict areas of future risk



Sang-Hoon Hong, Falk Amelung, Tim Dixon, Shimon Wdowinski, Guoqing Lin, Fernando Greene
Rosenstiel School of Marine & Atmospheric Science, University of Miami

The Impact of Ancient Ice Sheets


THE NEW YORK TIMES, TUESDAY, MAY 15, 2007

Observatory | Henry Fountain

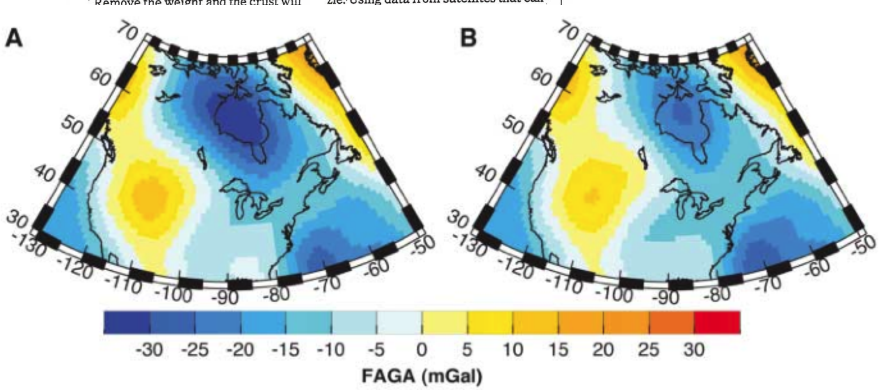
Chris Gash

How a Vast Ice Sheet Put the Squeeze On Earth (and Its Gravity)

To use a very unscientific term, the earth is squishable. Put a heavy weight on it and the crust will deform. Remove the weight and the crust will

But there could be other explanations as well, particularly tectonic processes driven by mantle convection, the flow of heat from within the earth.

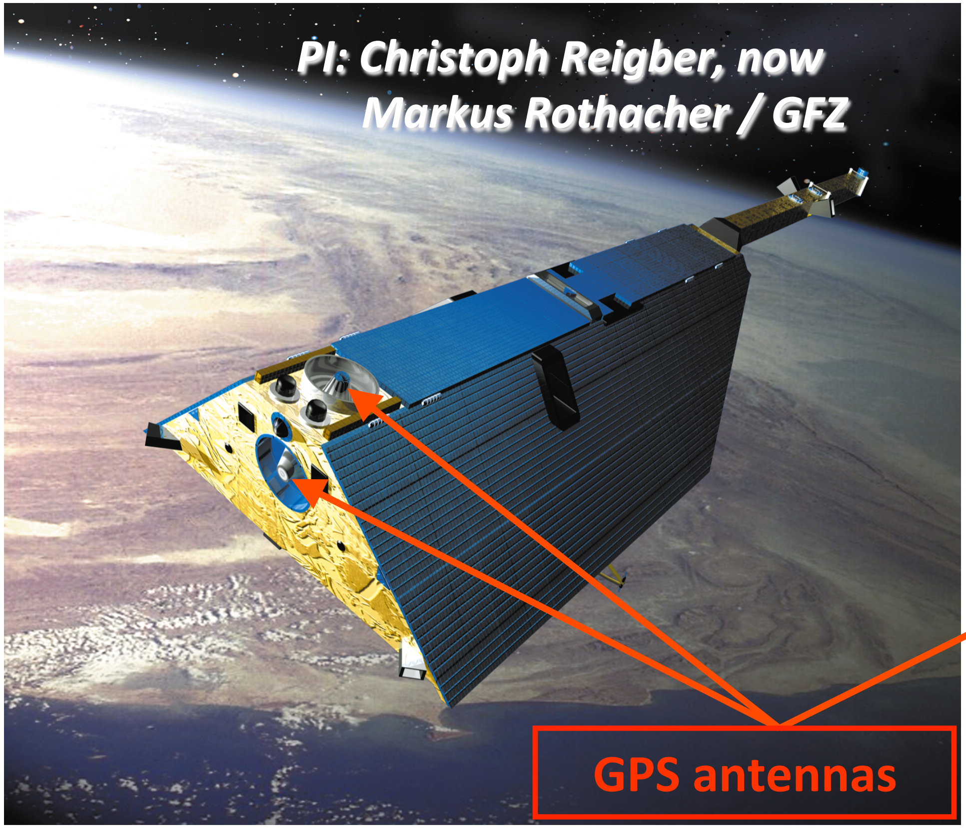
A study led by Mark Tamisiea of the Harvard-Smithsonian Center for Astrophysics has helped sort out the puzzle. Using data from satellites that can



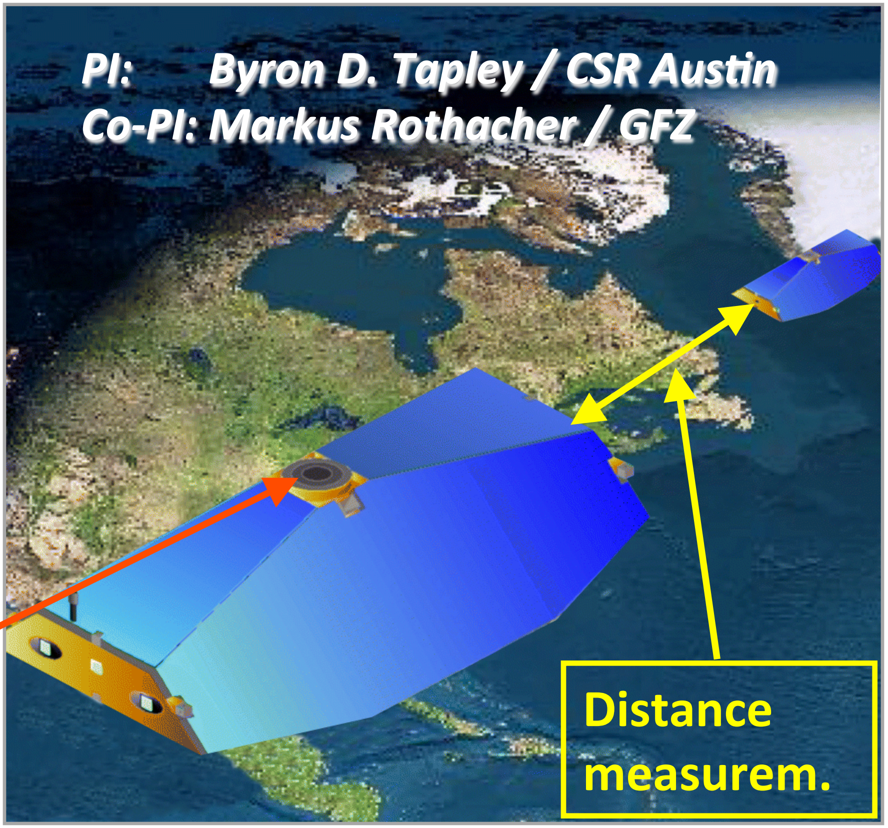
- The thick (~3 km) ice sheets that began melting ~20,000 years ago have left the Earth deformed
  - Is this the cause of the "low" in the free air gravity anomaly (FAGA) of northern Canada? (left, A, as measured by GRACE)
  - The best predictions of the viscoelastic deformation using GRACE rates (left, B) only explain about 50% of the signal
  - The conclusion of *Tamisea et al.* [2007] is that the remaining 50% is caused by convection in the Earth's mantle

Gravity Field Missions: CHAMP and GRACE

CHAMP (2000): GFZ, DLR



GRACE (2002): USA, GFZ, DLR

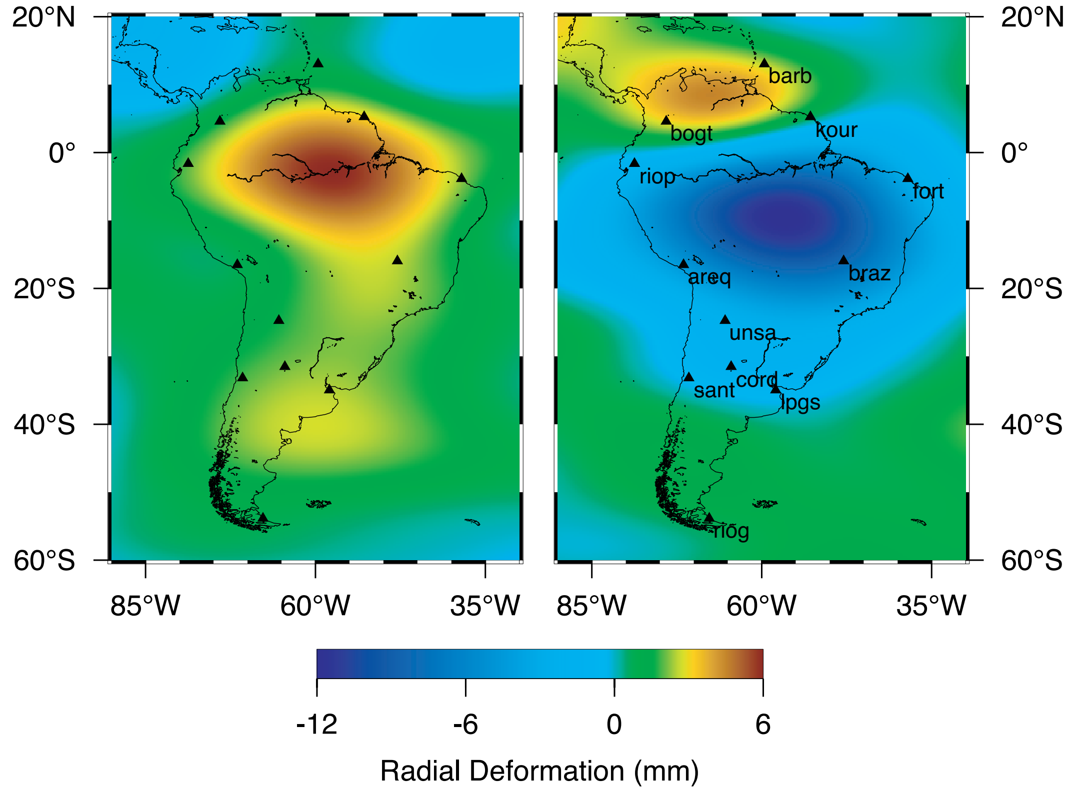


- Gravity field and magnetic field
- Atmosphere & ionosphere sounding
- GPS, accelerometer, magnetometers

- Gravity field
- Atmosphere & ionosphere sounding
- K-band (5 µm), GPS, accelerometer

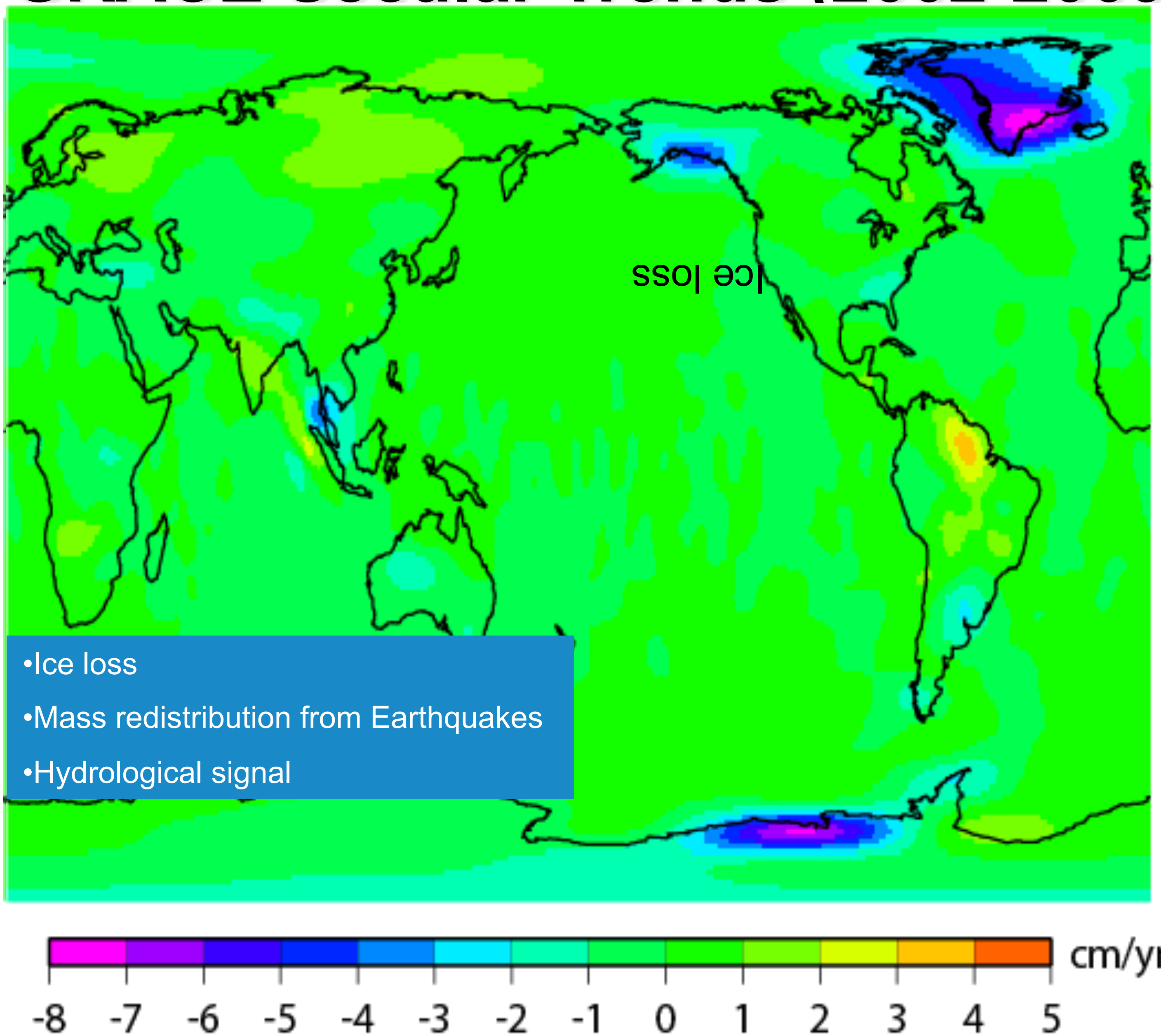
Deformational Impact of the Hydrological Cycle

- Annual hydrological cycle will act as a gravitational load, deforming the Earth
- The GRACE mission can measure the presence of water on the surface
- At the right is a map of the annual amplitude of surface deformation in South America estimated from GRACE data [*Davis et al.*, 2004]
- Also shown in map: some continuous GPS sites



GRACE Secular Trends (2002-2009)

PGR model removed

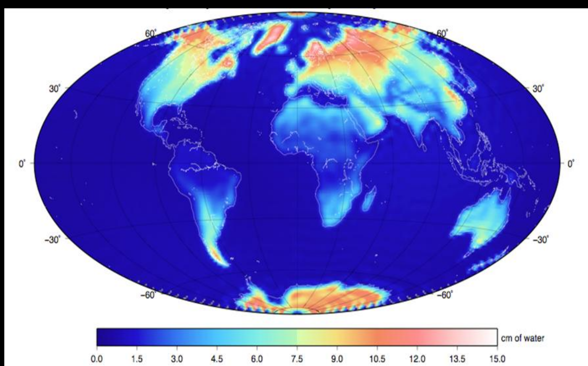


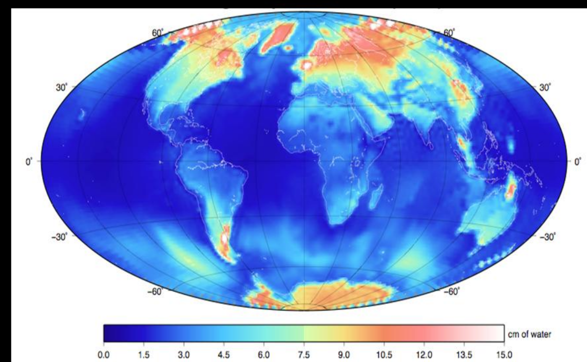
[Wahr, 2009]

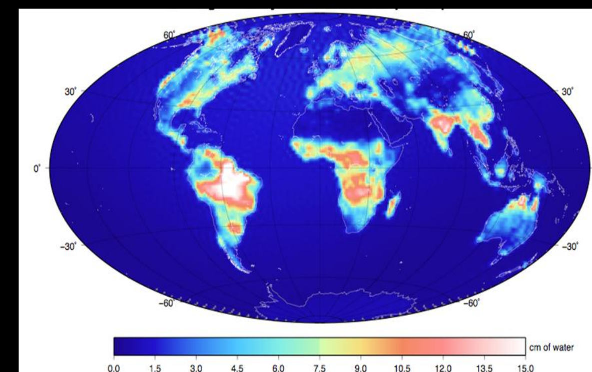
POD: Time Varying Gravity Components

Atmospheric gravity (NCEP-6hr)	Atgrav(ECMWF-3hr)+Ocean(MOG2D)	Hydrology (GLDAS)

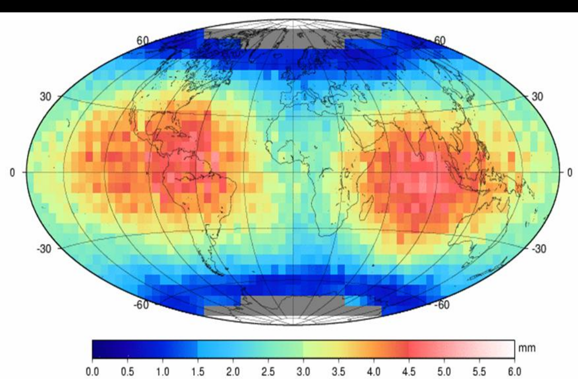
Signal (RMS cm of water)

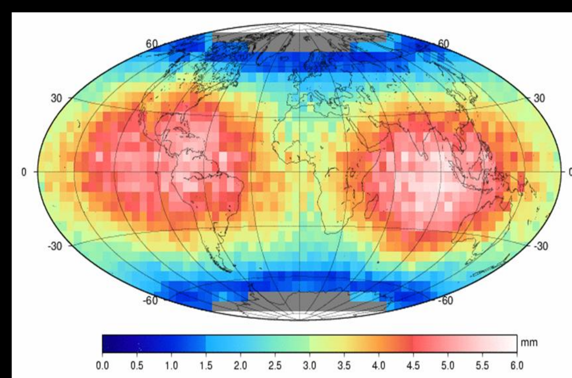


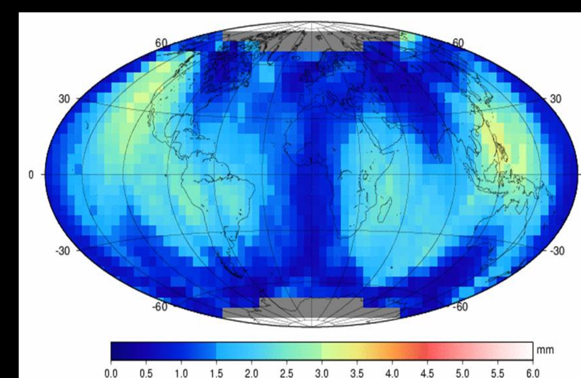




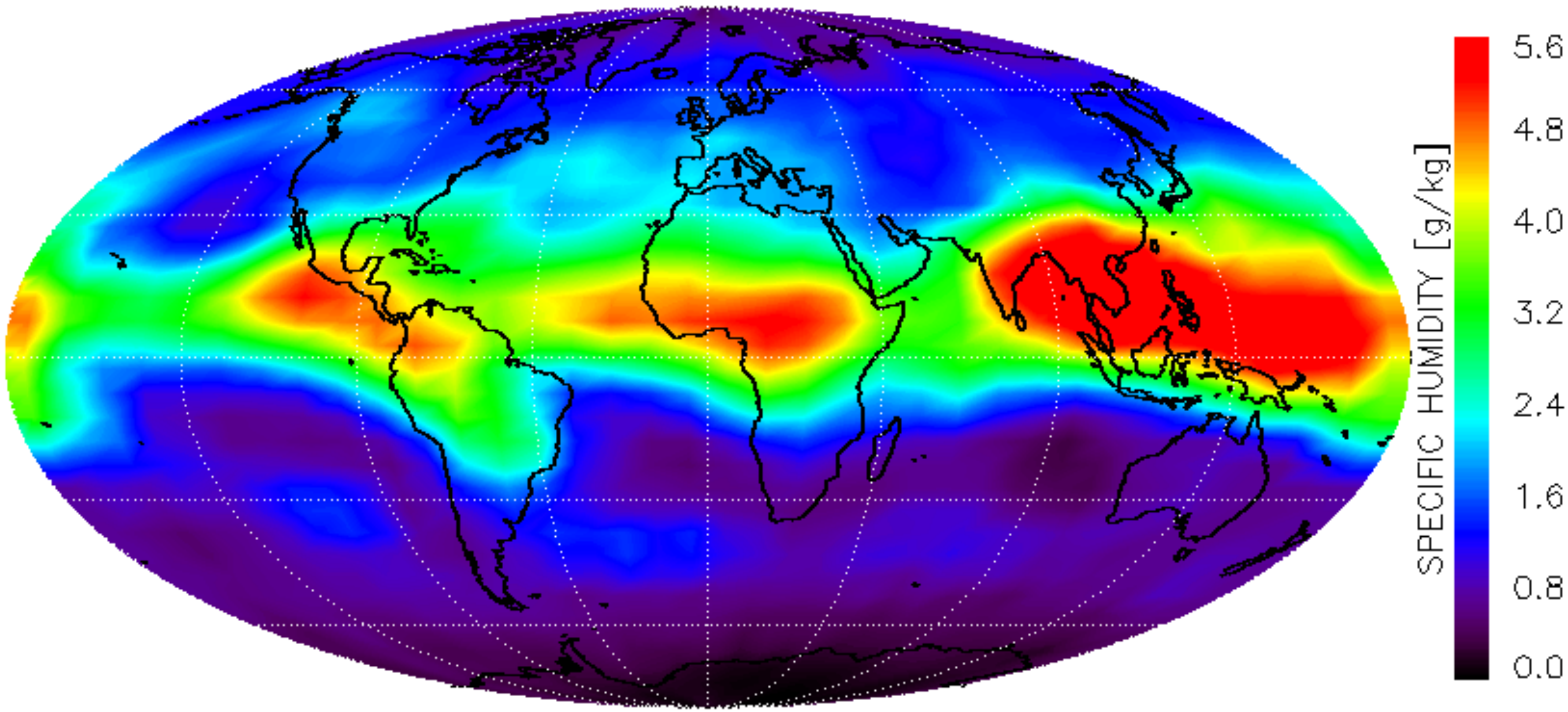
Jason radial orbit RMS (mm)





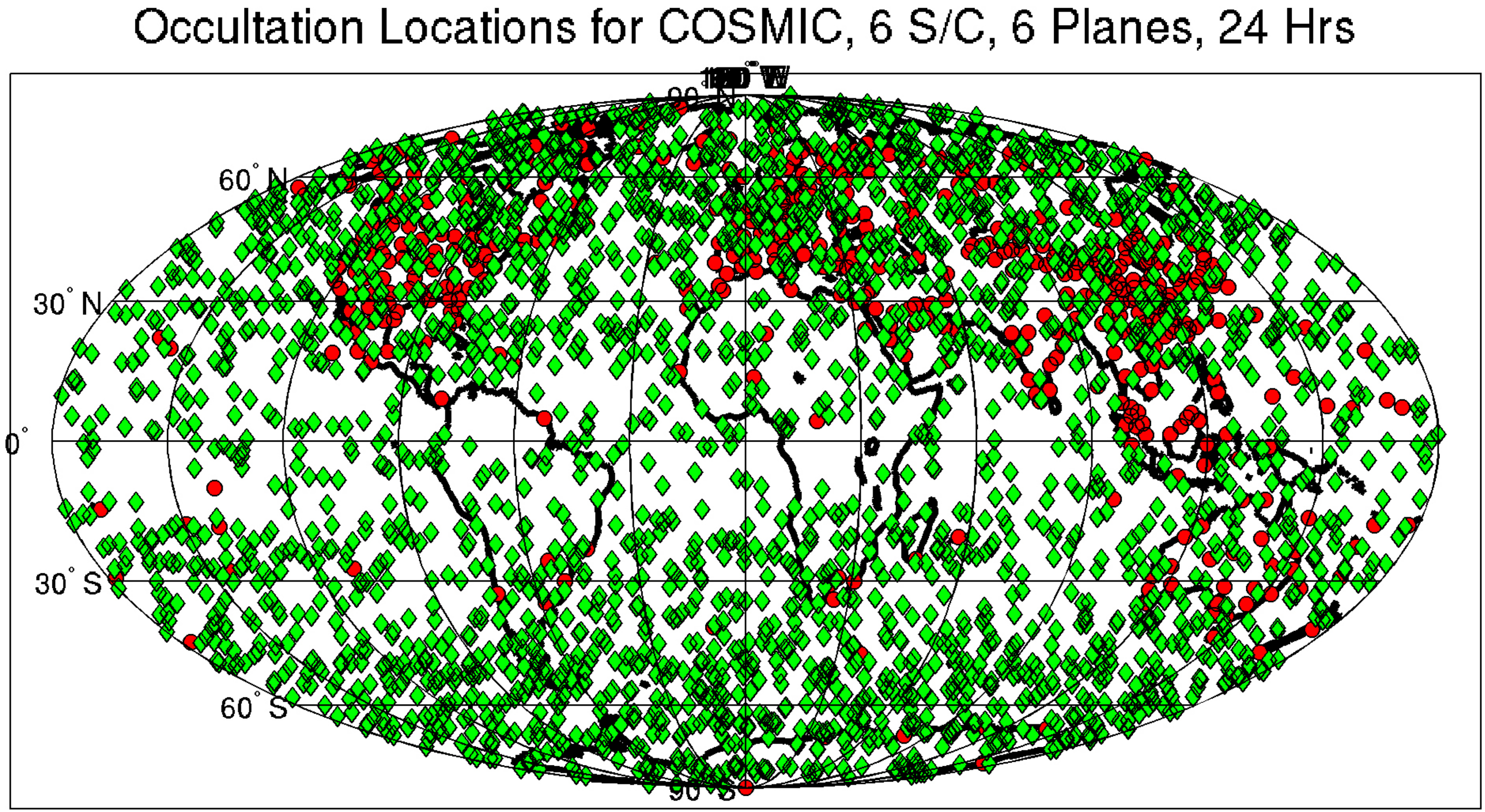


Global Water Vapor Distributions

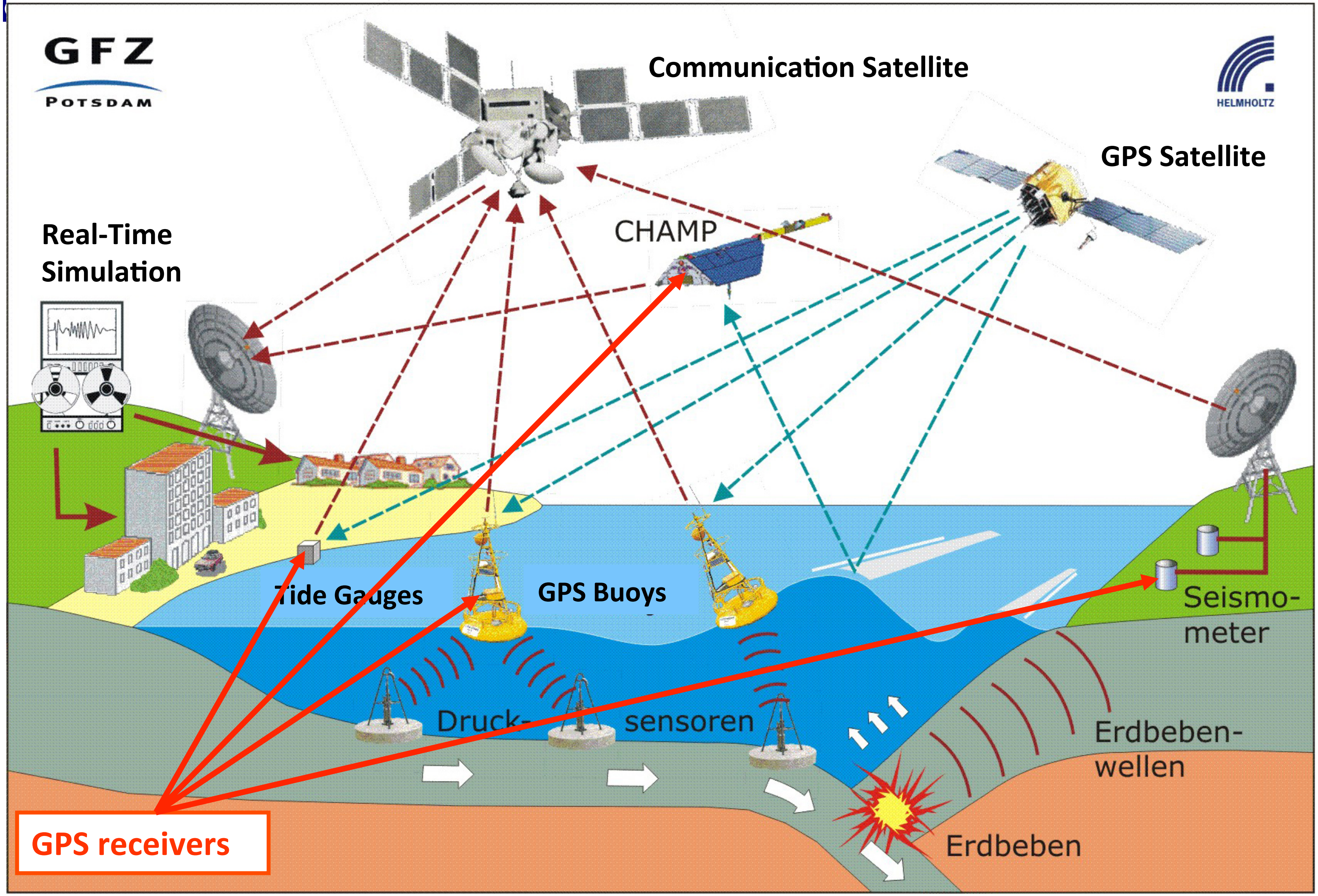


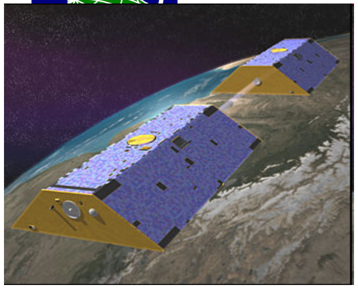
Mean global water vapor distribution at 4 km height from CHAMP and GRACE (September 2006)

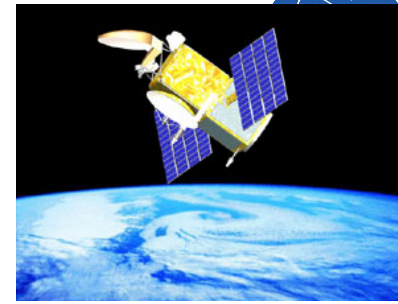
COSMIC: 2500 Occultations per Day



Example: GPS and a Tsunami Early Warning System

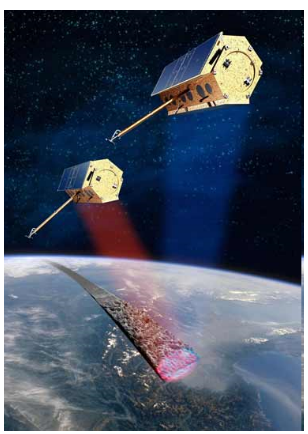


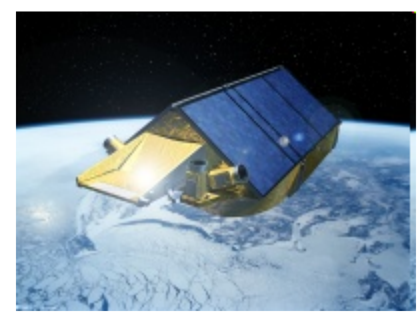




Common Thread:

- Reference Frame
- Precision Orbit Determination

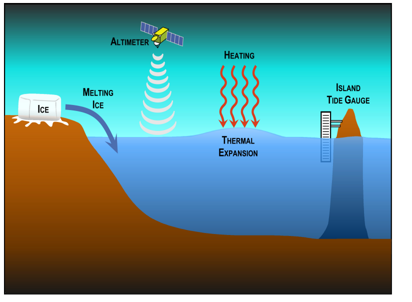




GGOS Reference Frame Requirement

- Basis upon which we measure change over space, time, and evolving technology
- Most stringent requirement from sea level rise:
  - "accuracy of 1 mm, and stability at 0.1 mm/yr"
  - This is a factor 10-20 beyond current capability
- Accessibility: 24 hours/day; worldwide

  Users anywhere on the Earth can position their measurements in the reference frame



- Space Segment:
  - LAGEOS, LARES, GNSS, DORIS to define the reference frame
- Ground Segment (Core Sites):
  - Global distributed network of "modern technology", co-located SLR, VLBI, GNSS, DORIS stations locally tied together with accurate site ties
  - Dense network of GNSS ground stations distributes the reference frame globally to the users
  - Co-locate with other measurement techniques including gravity field, tide gauges, leveling, etc.

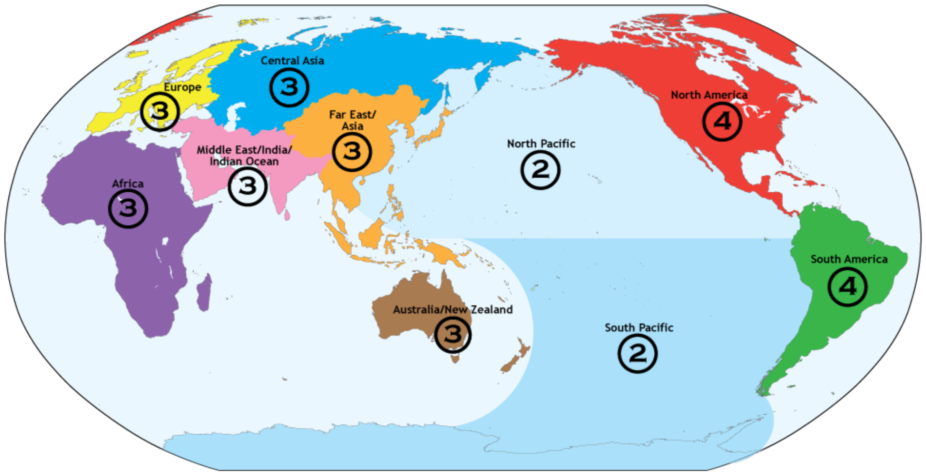
Simulation Studies to Scope the Network

(impact on the Reference Frame)

(Erricos Pavlis)

Simulation studies show:

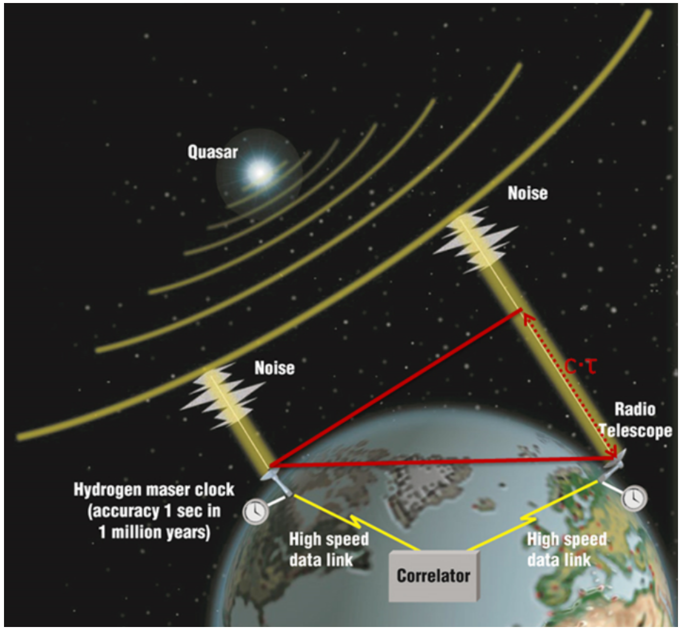
- ~32 globally distributed, well positioned, new technology, co-location sites will be required to define and maintain the reference frame;
- ~16 of these co-location stations must track GNSS satellites with SLR to calibrate the GNSS orbits which are used to distribute the reference frame.



- Major challenge, requiring time, significant resources, and strong international participation

Very Long Baseline Interferometry (VLBI)

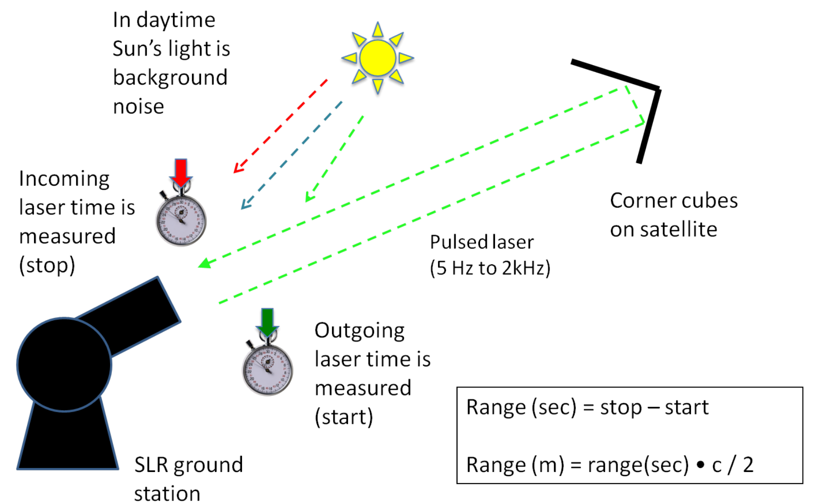
- Geometric technique measures the difference in arrival time between two Earth-based antennas of a radio wavefront emitted by a distant quasar.
- From a many of these time difference measurements from a global network of antennas, VLBI determines the inertial (celestial) reference frame defined by the quasars and simultaneously, the precise positions and velocities of the antennas.



- Since the antennas are fixed to the Earth, their locations track the instantaneous orientation of the Earth in the inertial reference frame and relative changes in position (tectonic plate motion, regional deformation, and local uplift or subsidence)
- The current uncertainty of the delay observable is ~10-15 ps with precision at 4 ps.
- New systems are implementing much broader bandwidth detection and recording, and real-time data transmission

Satellite Laser Ranging (SLR)

- Direct optical measurement of range to satellites
- KHz ranging for faster satellite acquisition and pass interleaving.
- The state of the art is sub-millimeter precision average measurements (called normal points) with centimeter level accuracies.
- Tracks satellites from 300 km to 22,000+ km in day & night.
- Each station tracks independently but a network of station can be scheduled together to optimize the tracking.
- Requires only a passive retro-reflector array on the satellite.



Global Navigation Satellite System

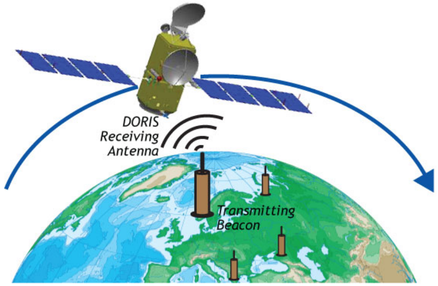
- Operates with GPS, Glonass, Compass, Galileo, etc
- GNSS receivers are used as a local survey tool for epoch measurements of 3 dimensional vectors between two control points. The GNSS local survey tool data is used to transform the local reference frame to the ITRF.
- There are several different types of antennas available. Due to their ability to mitigate multipath of satellite signals, choke ring antennas are the most widely used in geodetic surveys.

Trimble TRM 29659.00 GPS Choke Ring Antenna

TOPCON CR-G5 Full Wave Geodetic Choke Ring with Radome (GNSS Receiver)

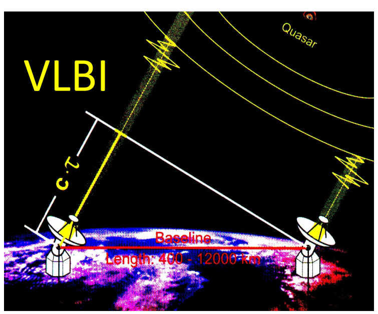
Doppler & Radiopositioning Integrated by Satellite (DORIS).

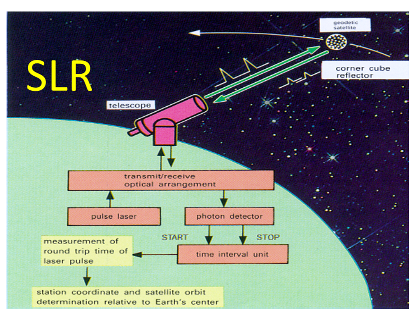
- Dual-Frequency Doppler Beacons (2.036 Ghz & 401.25 Mhz), Distributed Around the World.
- Developed by the CNES (Centre National d' Etudes Spatiales) & IGN (Institut Géographique National).
- The network was developed to support Precision Orbit Determination (POD) for LEO satellites, such as the SPOT Remote Sensing Satellites & Altimeter Satellites such as TOPEX/Poseidon.
- The oldest sites in the network have been occupied since the late 1980' s (DORIS data are routinely available since 1992, or the launch of TOPEX/Poseidon).

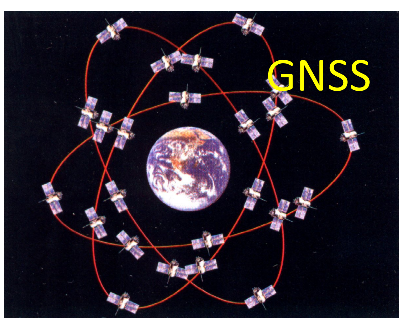


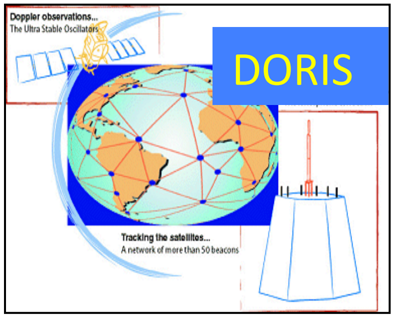
Why do we need co-location of techniques? (Core Sites)

- Measurement requirements are very stringent
- Each technique makes its measurements in a different way and therefore each measures something a little different:
  - Terrestrial (satellite) verses celestial (quasar) reference
  - Range verses range difference measurements
  - Broadcast up verses broadcast down
  - Radio verses optical
  - Active verses passive
  - Geographic coverage
- Each technique has different strengths and weaknesses
- The combination allows us to take advantage of the strengths and mitigate the weaknesses

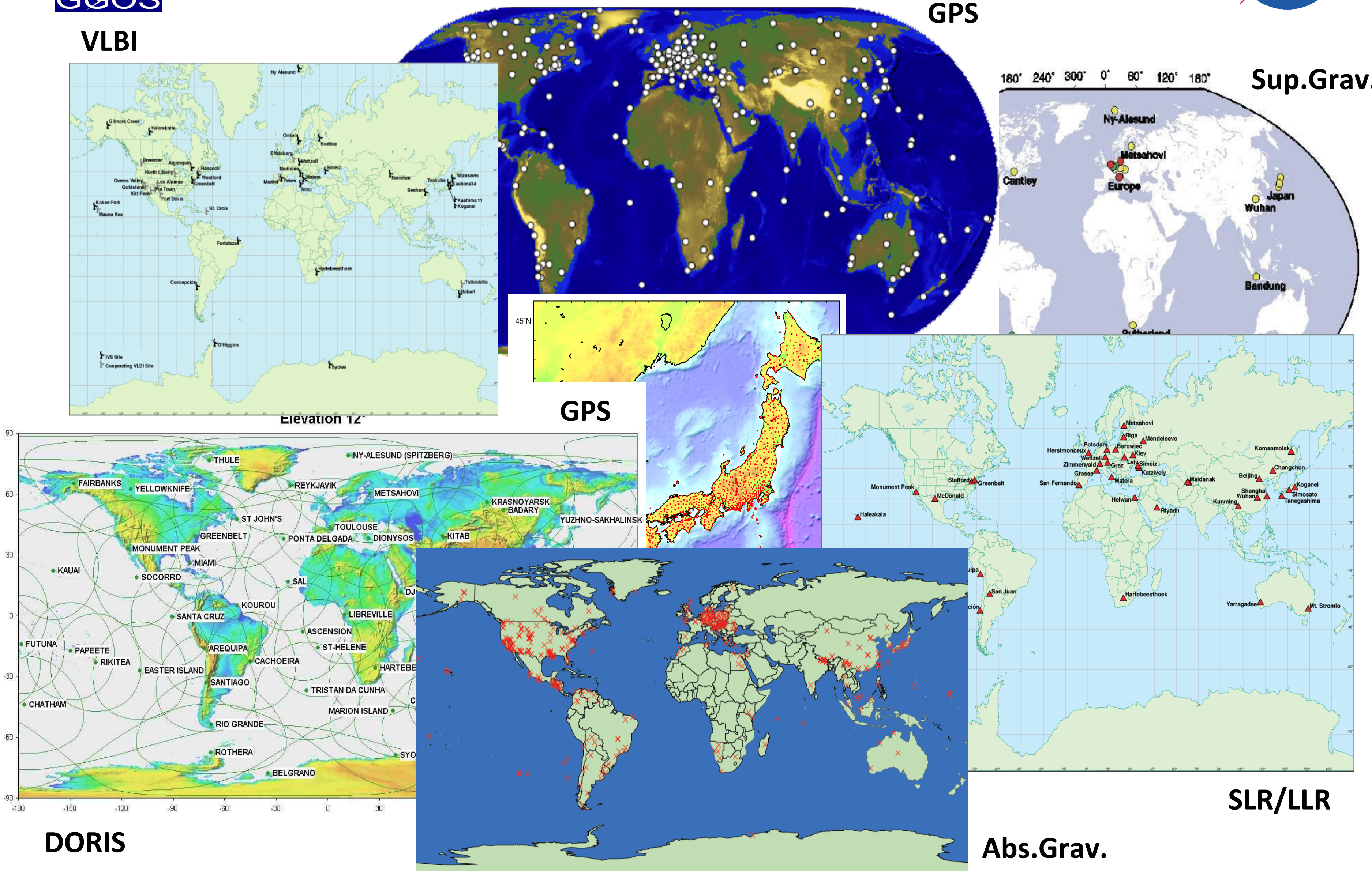






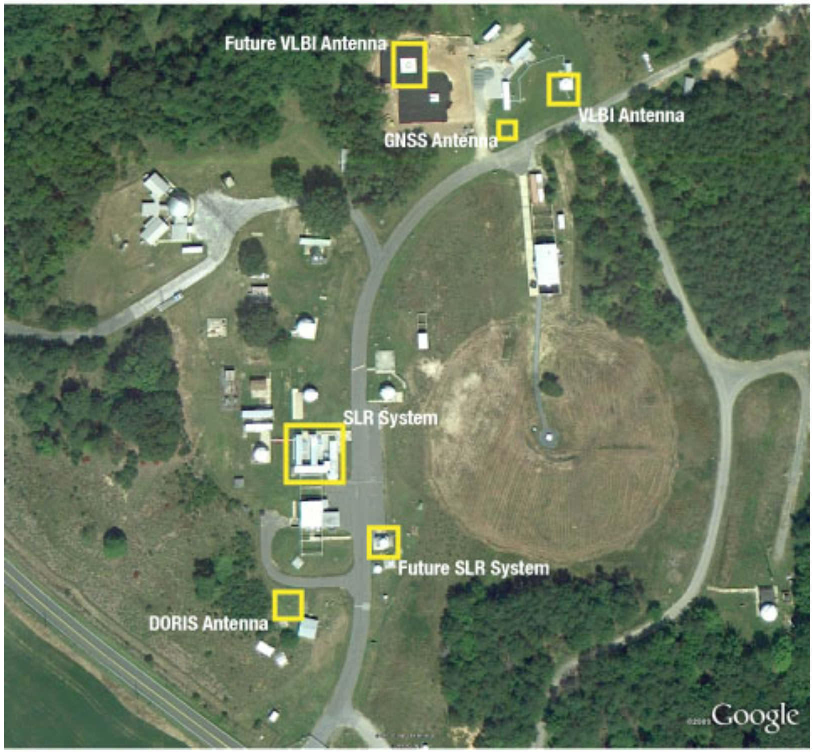


GGOS: the Ground-Based Component



Example Fundamental Station

NASA Goddard Space Flight Center, Greenbelt MD, USA

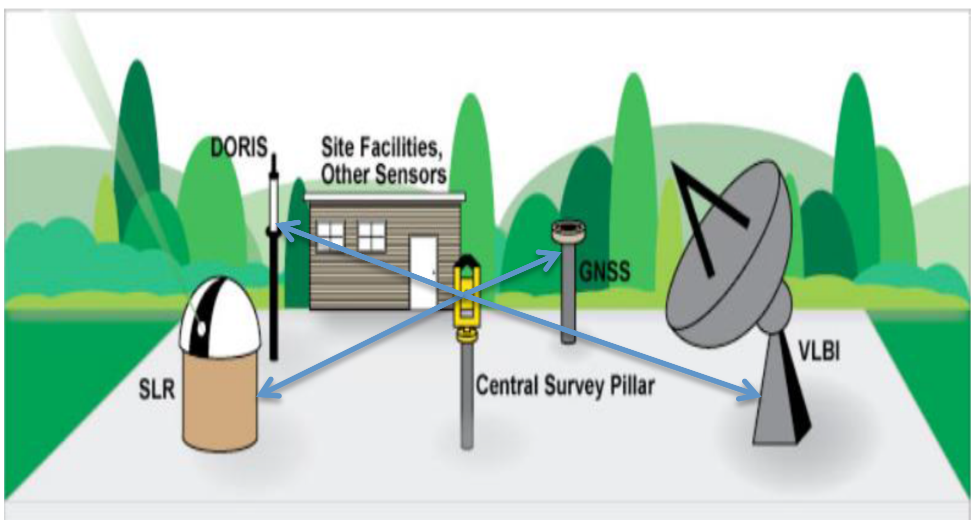


Goddard Geophysical and Astronomical Observatory (GGAO) has four techniques on site:

- Legacy SLR, VLBI, GPS, DORIS
- NGSLR
- VLBI2010
- New generation GNSS

Local Ties Between Geodetic Stations

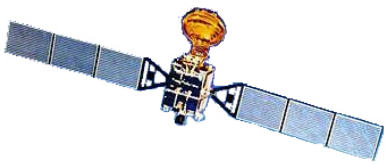
- "...no technique currently contributing to the ITRF has a direct connection to any other technique. Each realizes its own internally consistent set of coordinates, but it is only through local ties at co-located sites that a completely resolved reference frame is realized." (NRC 2010 pg. 93).
- "In terms of accuracy, the typical uncertainty of the local ties used for the current ITRF is 2-5 mm... With the increased precision available from geodetic techniques, a precision of 1 mm or better should be the goal of all new local tie surveys." (NRC 2010 pg. 93).
- These "tie vectors" enter the combination of space geodetic solutions **effectively as a fifth technique** and are not only necessary for rigorous ITRF realization but also serve to highlight the presence of site-specific biases.



Local Reference Frame tie to all geodetic Stations

GGAO Robotic Total (Range) Station

Co-location in Space

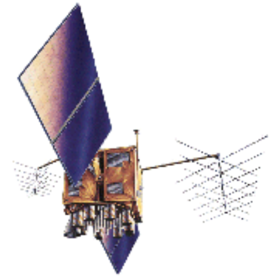


Compass

GNSS/SLR

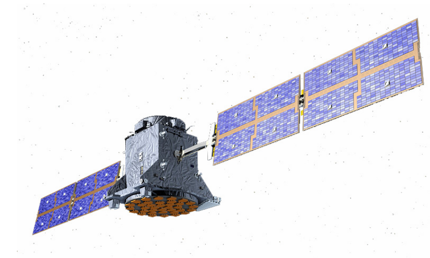
GLONASS

GNSS/SLR



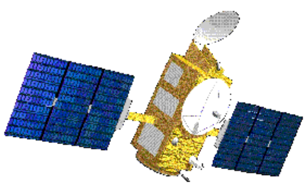
GPS

GNSS/SLR



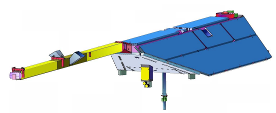
GIOVE/Galileo

GNSS/SLR



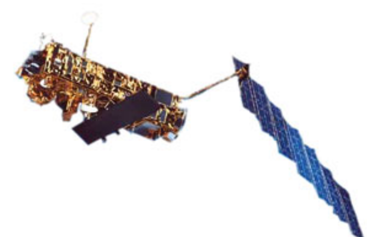
Jason

DORIS/GNSS/SLR



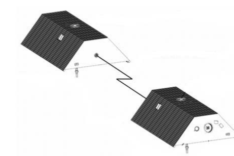
CHAMP

GNSS/SLR



Envisat

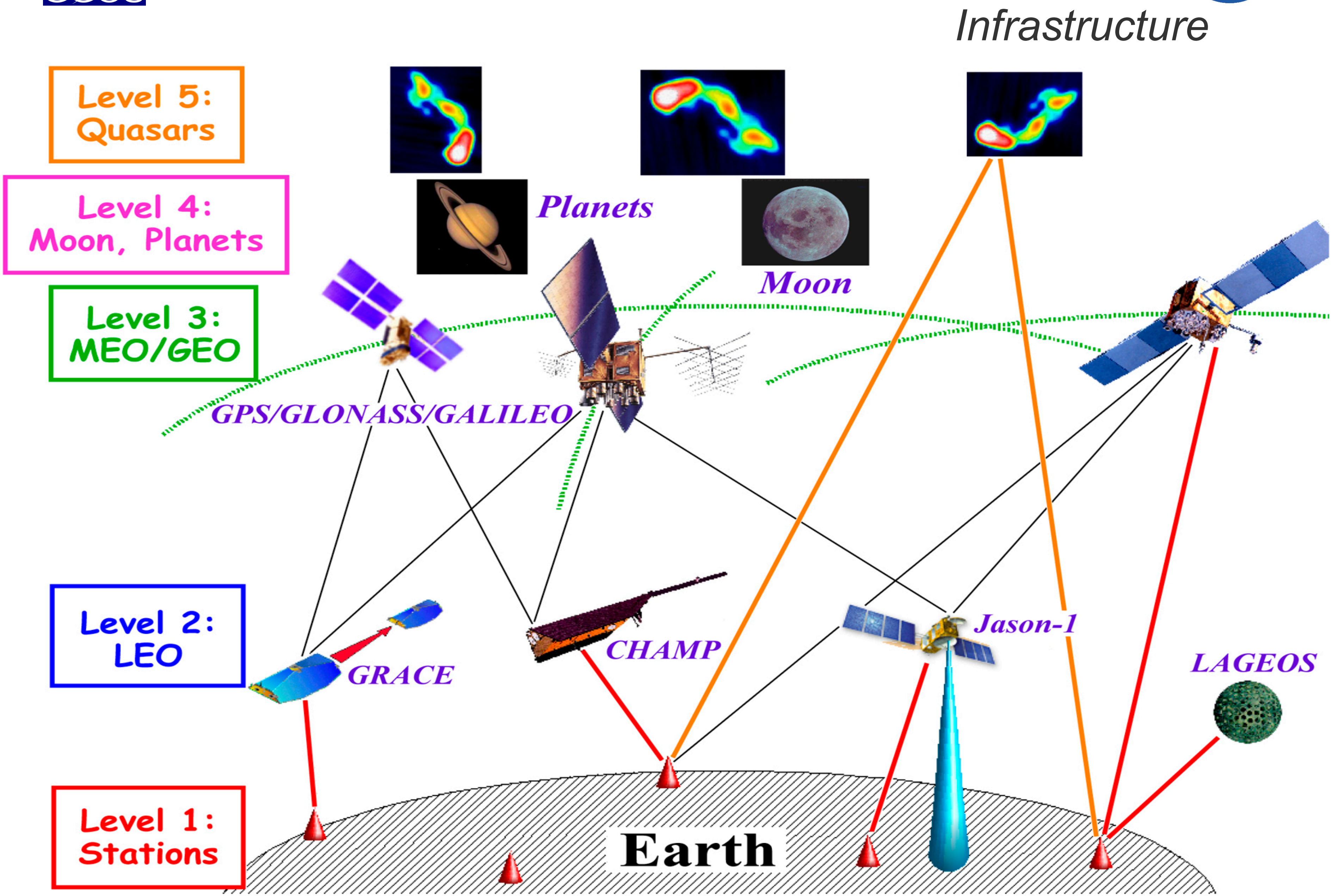
DORIS/SLR



GRACE

GNSS/SLR

Levels of Activity



GGOS Site Requirements Document

(http://cddis.gsfc.nasa.gov/docs/GGOS_SiteReqDoc.pdf)

- Introduction and Justification
  - What is a Fundamental Station?
  - Why do we need the Reference Frame?
  - Why do we need a global network?
  - What is the current situation?
  - What do we need?
- Site Conditions
  - Global consideration for the location
  - Stable Geology (free from dislocations and long relaxation times)
  - Sufficient Site area (7- 8 hectares)
  - Good Weather and sky conditions
  - Low Radio frequency and optical Interference (terrain shielding)
  - Clear horizon conditions (10 – 15 degrees)
  - Manageable air traffic conditions and aircraft protection
  - Wide band communications
  - Land ownership/control
  - Local ground geodetic networks
  - Site Accessibility
  - Local infrastructure and accommodations
  - Sufficient electric power
  - Site security and safety
  - Local commitment


Global Geodetic Observing System (GGOS)

Site Requirements
for
GGOS Core Sites
(Revision 1a)

July 18, 2012

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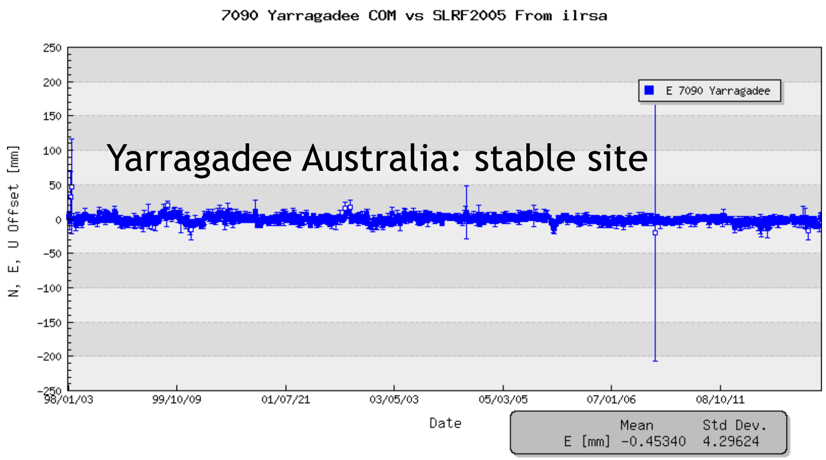
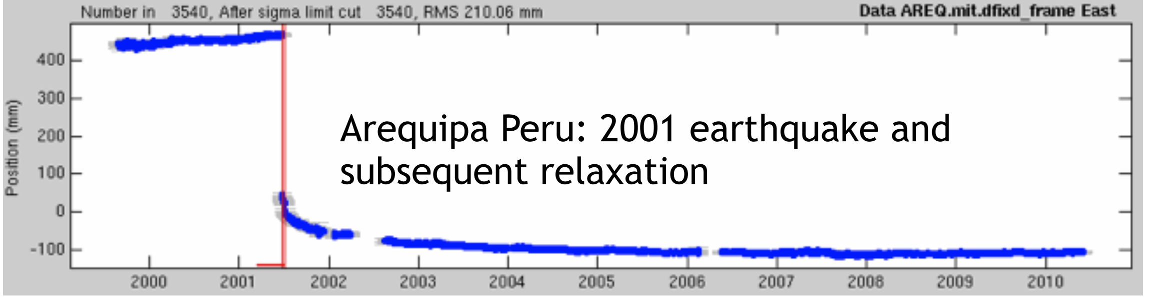
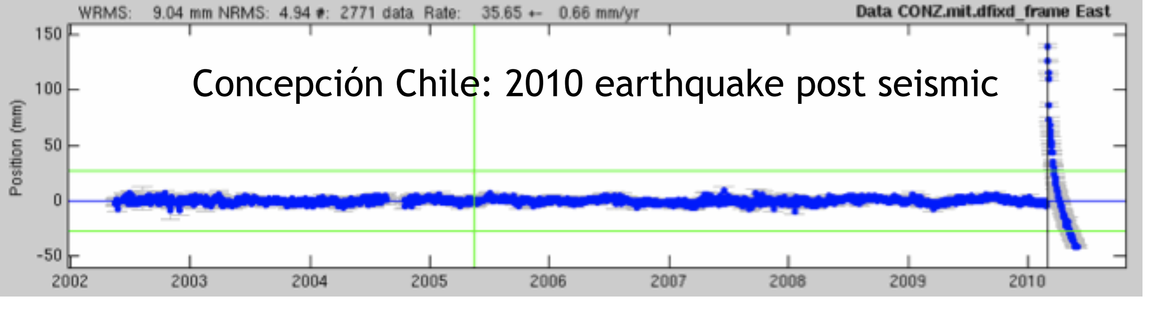
Examples of Local Site Stability
(time history of GPS)



A stable time history is essential for the development of the Reference Frame

Arequipa and Concepción plots courtesy Tom Herring/MIT

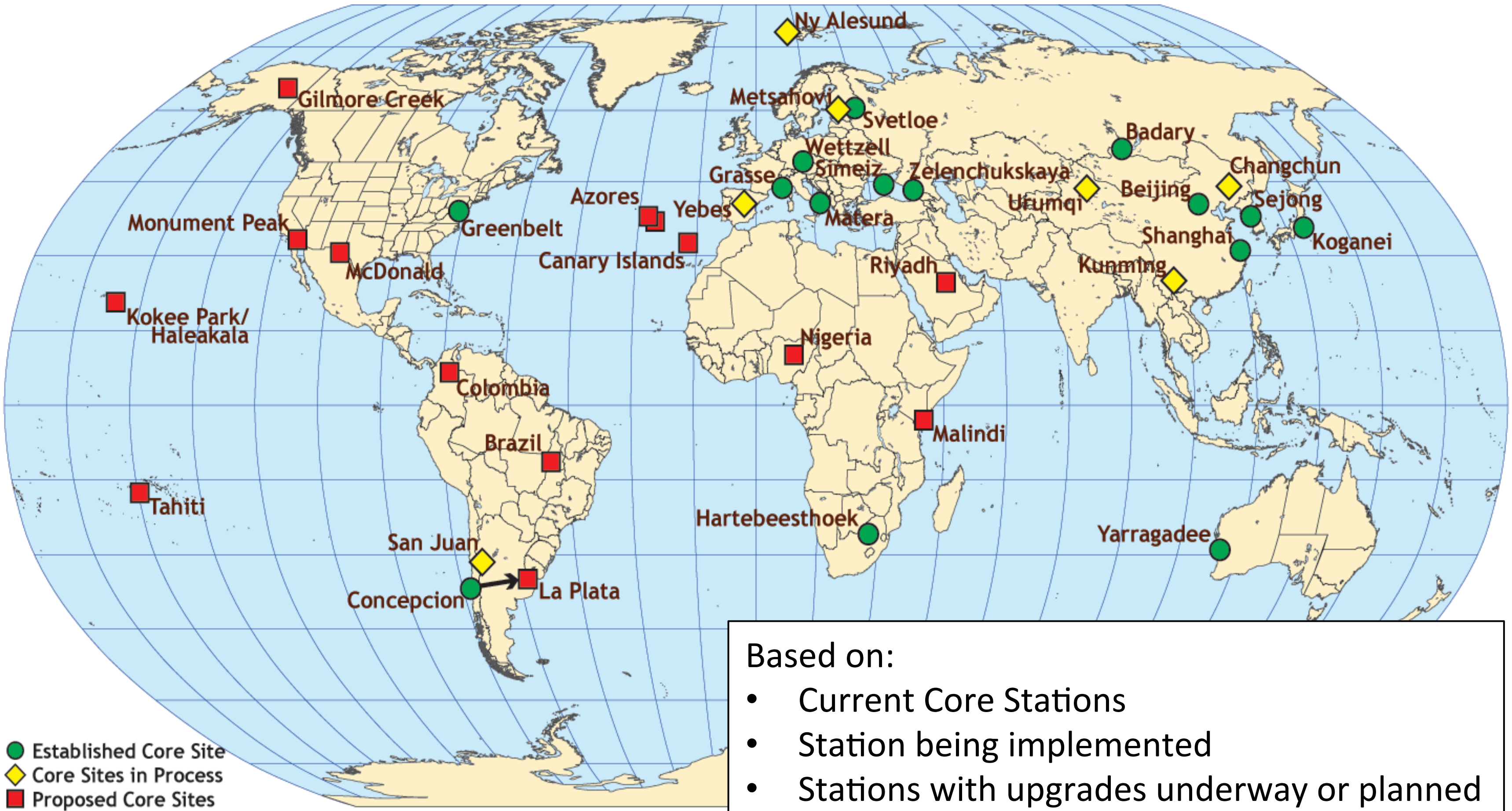




Eighteen Responses covering 38 Sites have been submitted to the GGOS Call for Participation

Agency (Country)	Sites
BKG/FESG (Germany)	Wettzell
NERC (UK)	Herstmonceux
IRA (Italy)	Medicina, Noto, Sardinia
OSO (Sweden)	Onsala
FGI (Finland)	Metsahovi
IGN Spain)	Yebes
SPC (Poland)	Borowiec
SHAO (China)	Shanghai, Beijing, Changchun, Wuhan, Kunming, Urumuqi, Sanyo, (San Juan)
GA (Australia)	Yarragadee, Mt. Stromlo, Katherine, Hobart
NASRDA (Nigeria)	Toto
NASA (US)	GSFC, Westford, Kokee Park, Monument Peak,Fortaleza, McDonald, Mt. Haleakala, Hartebeesthoek, Papeete, Arequipa
RIG (Czech Republic)	Pecny
NRF (South Africa)	Hartebeesthoek,
ASI (Italy)	Matera
KACST (Saudi Arabia)	Riyadh (SALRO)
NMA (Norway)	Ny Alesund
RAS (Russian Federation)	Svetloe, Zelenchukskaya, Badari
CNES	DORIS Network
Yellow denotes additions during the last year	

Network of Current, Planned and Potential Core Sites

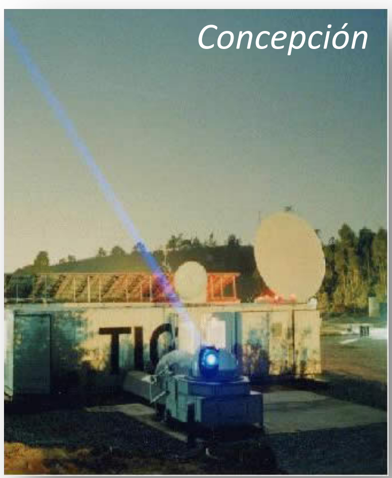


Based on:

- Current Core Stations
- Station being implemented
- Stations with upgrades underway or planned
- Sites being offered for Partnerships

Activities Underway in South America

- Discussions underway with:
  - Colombia: Instituto Geográfico Agustín Codazzi (IGAC)
  - Brazil: National Institute For Space Research (INPE)
- TIGO to move from Concepción to La Plata
- San Juan (NAOC):
  - Planning 40m VLBI2010 compatible system in 2015



Core Site Location Under Consideration French Polynesia

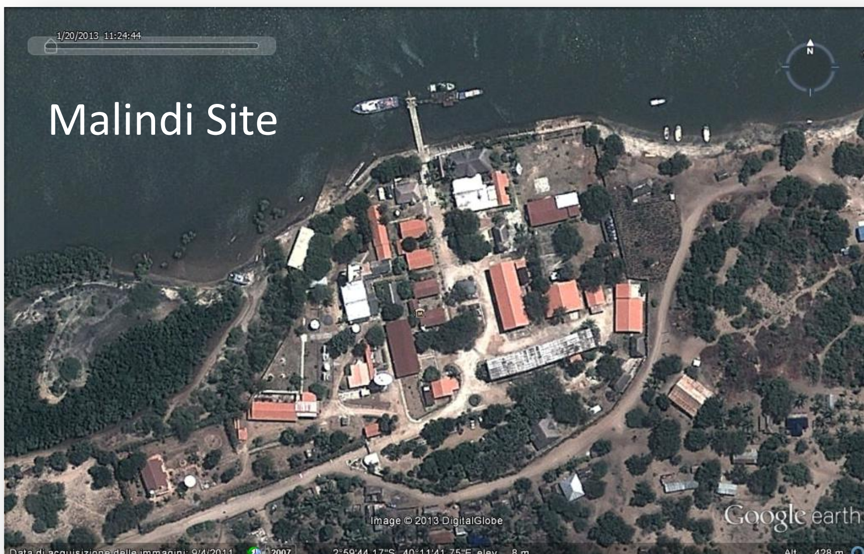
- Cooperation between NASA, CNES, and UFP
- SLR:
  - MOBLAS-8 operational since 1997
  - Co-located GNSS and DORIS
- VLBI:
  - Discussions underway

Current SLR site (MOBLAS-8) in Punaauia

Proposed future VLBI site in Vairao

Core Site Locations Under Consideration
Malindi, Kenya and Toto, Nigeria
(speculative)

- Discussions initiated with the Italian Space Agency (ASI) for a partnership site
- GGOS CfP site offered in Toro, Nigeria



Summary

- Challenging program with very important science and societal benefits
- Technologies are maturing
- Global distribution is essential
- Very large opportunity for participation in analysis and scientific research
- Should engage young scientists and students
- Success will depend on partnerships
- Partners will have to make a strong commitment