Space Geodesy and Measurements of Global Change

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Space Geodesy means

Metric Measurements

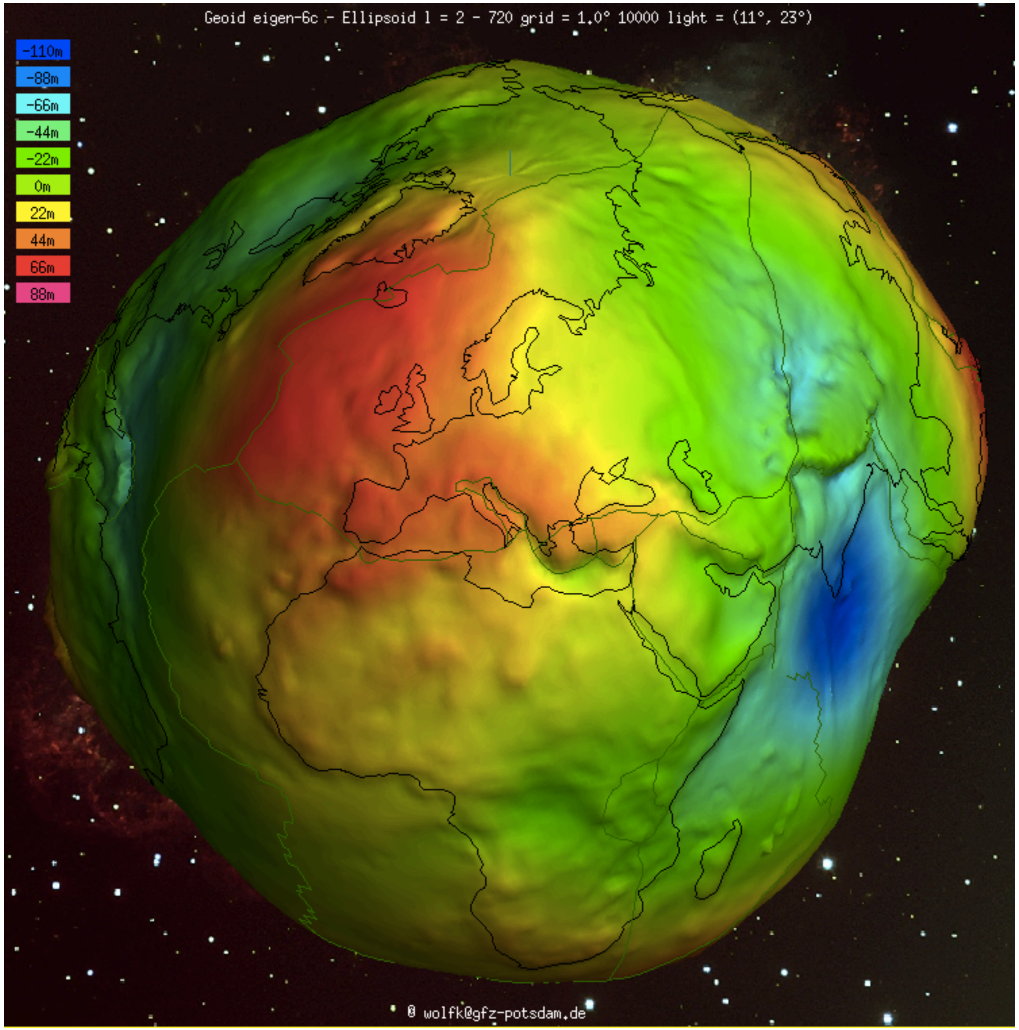
Examples:

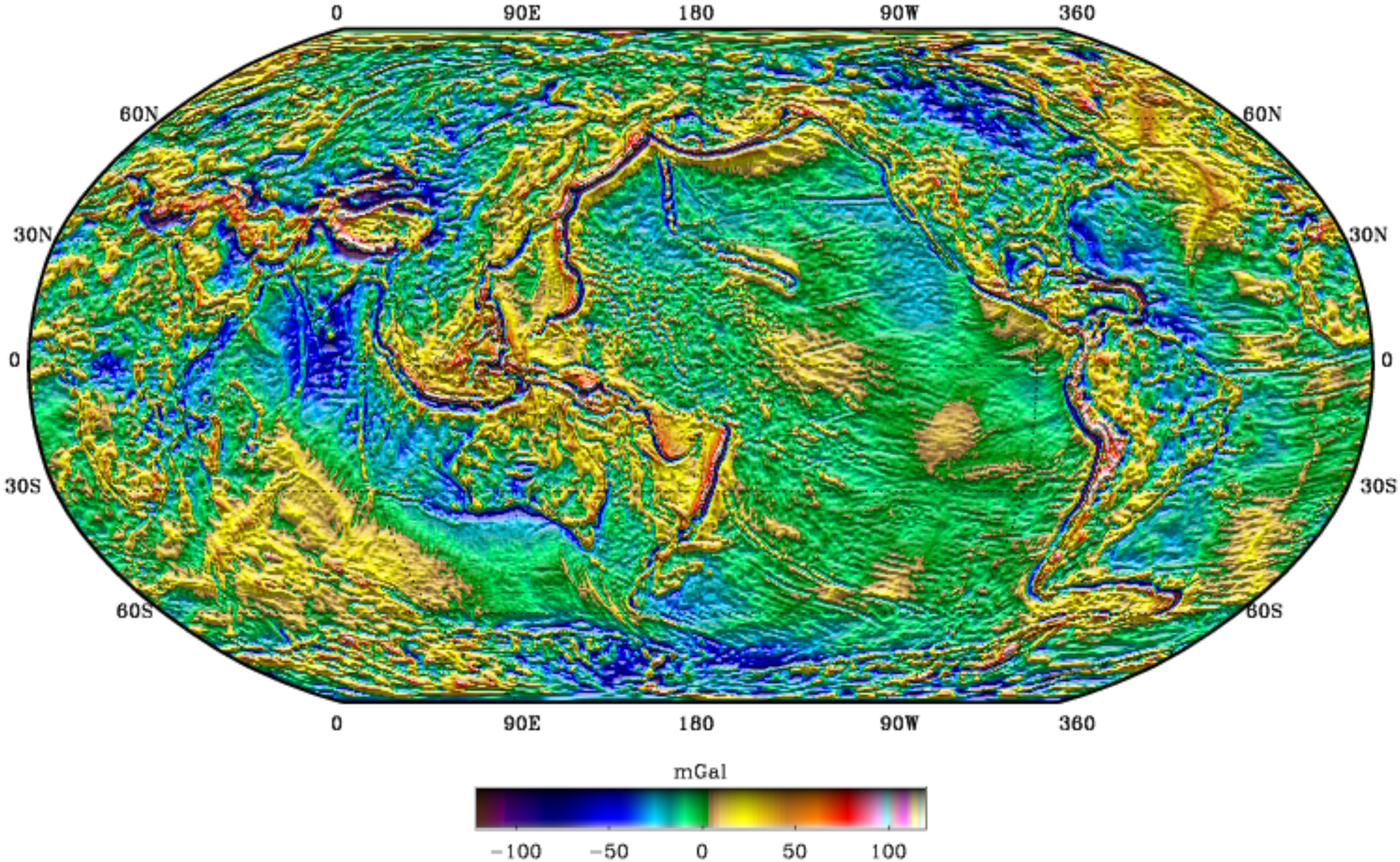
- Length, Velocity, Acceleration
- Weight, Volume
- Angles (arcseconds, radians, etc)
- Gals (gravity field ~ 980 gals)
- Orbital parameters (a, e, i, -----)

We can use other measurements

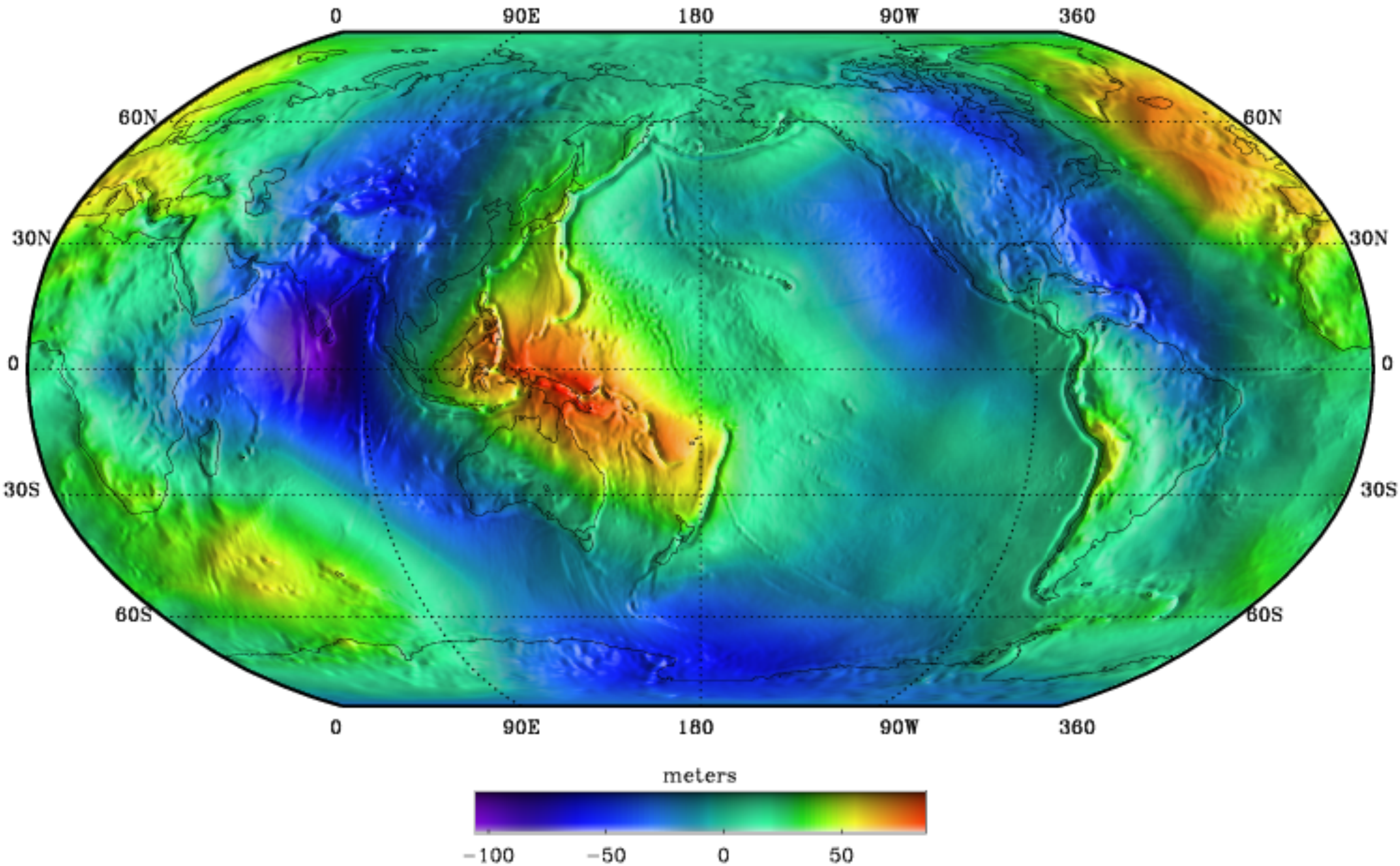
Some people think the Earth looks like this:

But really – it looks like this



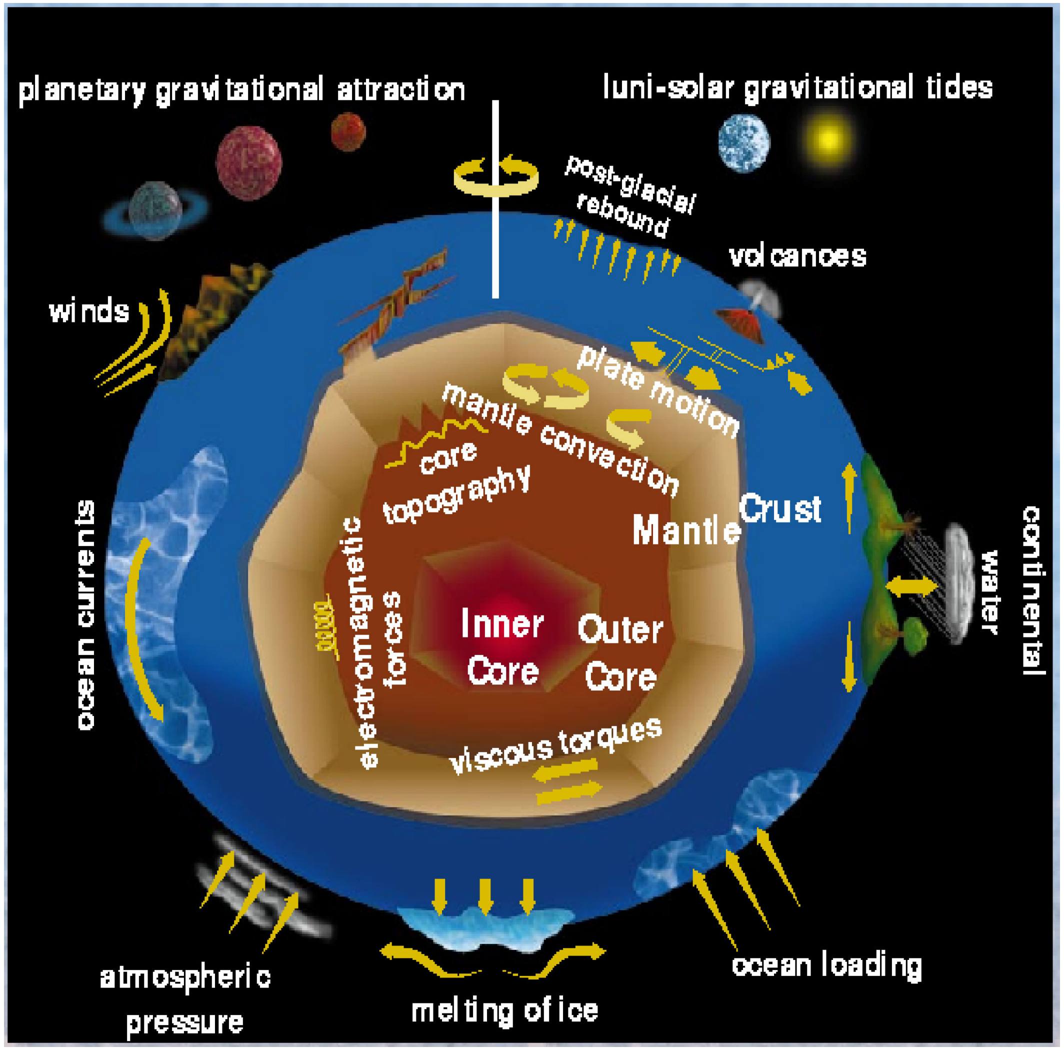


EGM96 Gravity Anomalies: Based on satellite tracking data (up to 30 satellites that used Doppler, Satellite laser ranging data, and GPS), altimeter-derived gravity anomalies (TOPEX and ERS and GEOSAT) and surface gravity data. Model to 360x360.



EGM96 Geoid

The Earth is very dynamic:



Motivation: Monitoring the Earth System

Pillar 1: Geometry and Deformation of the Earth

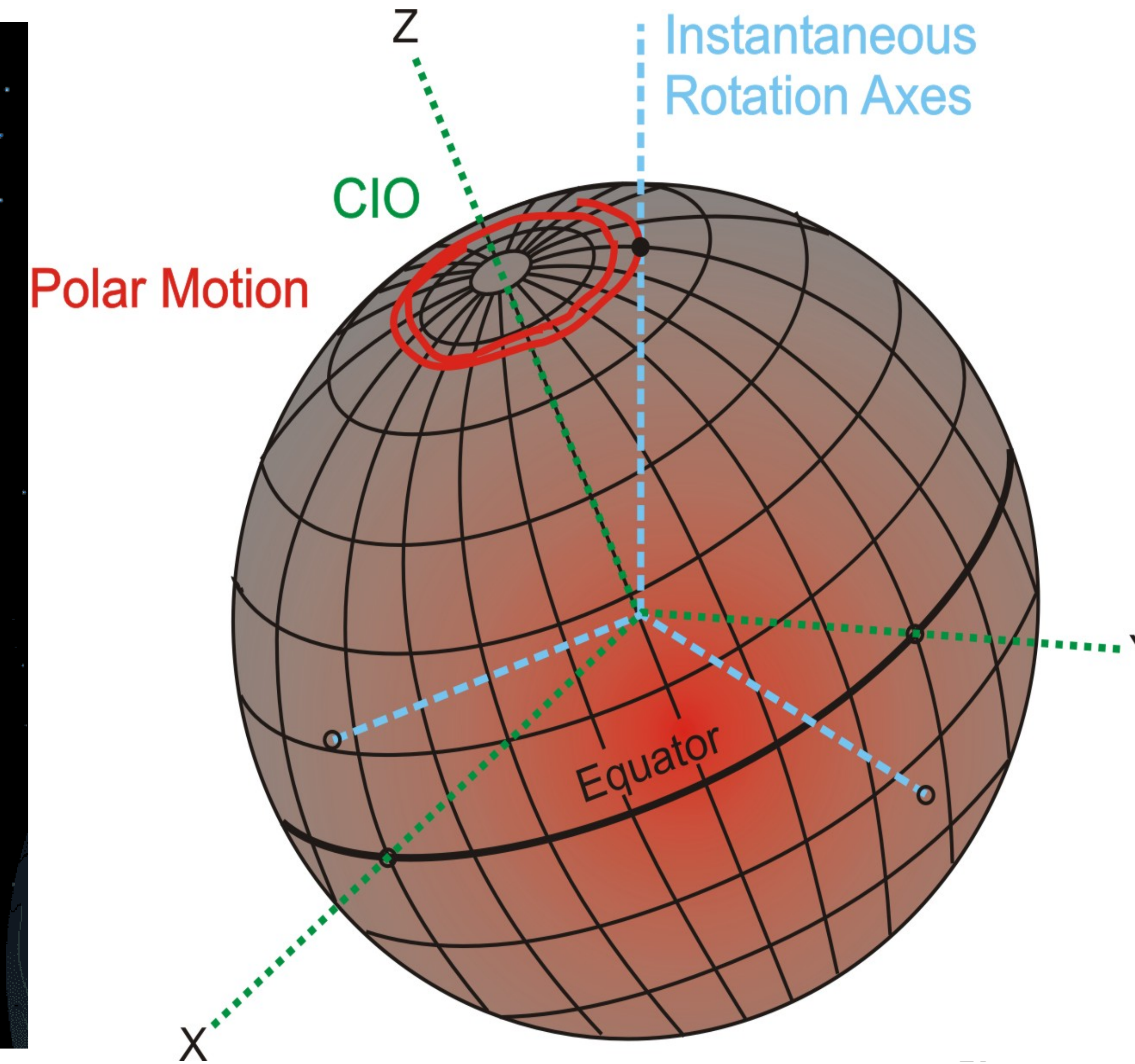
- Problem and fascination of measuring the Earth:

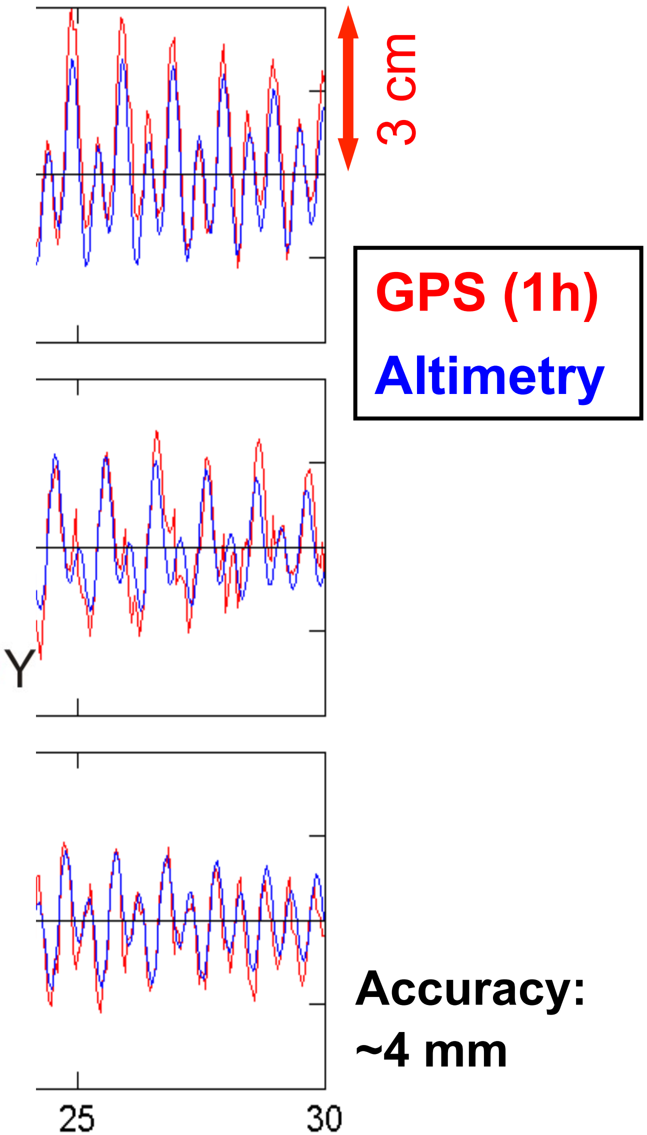
Everything is moving !

- 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**

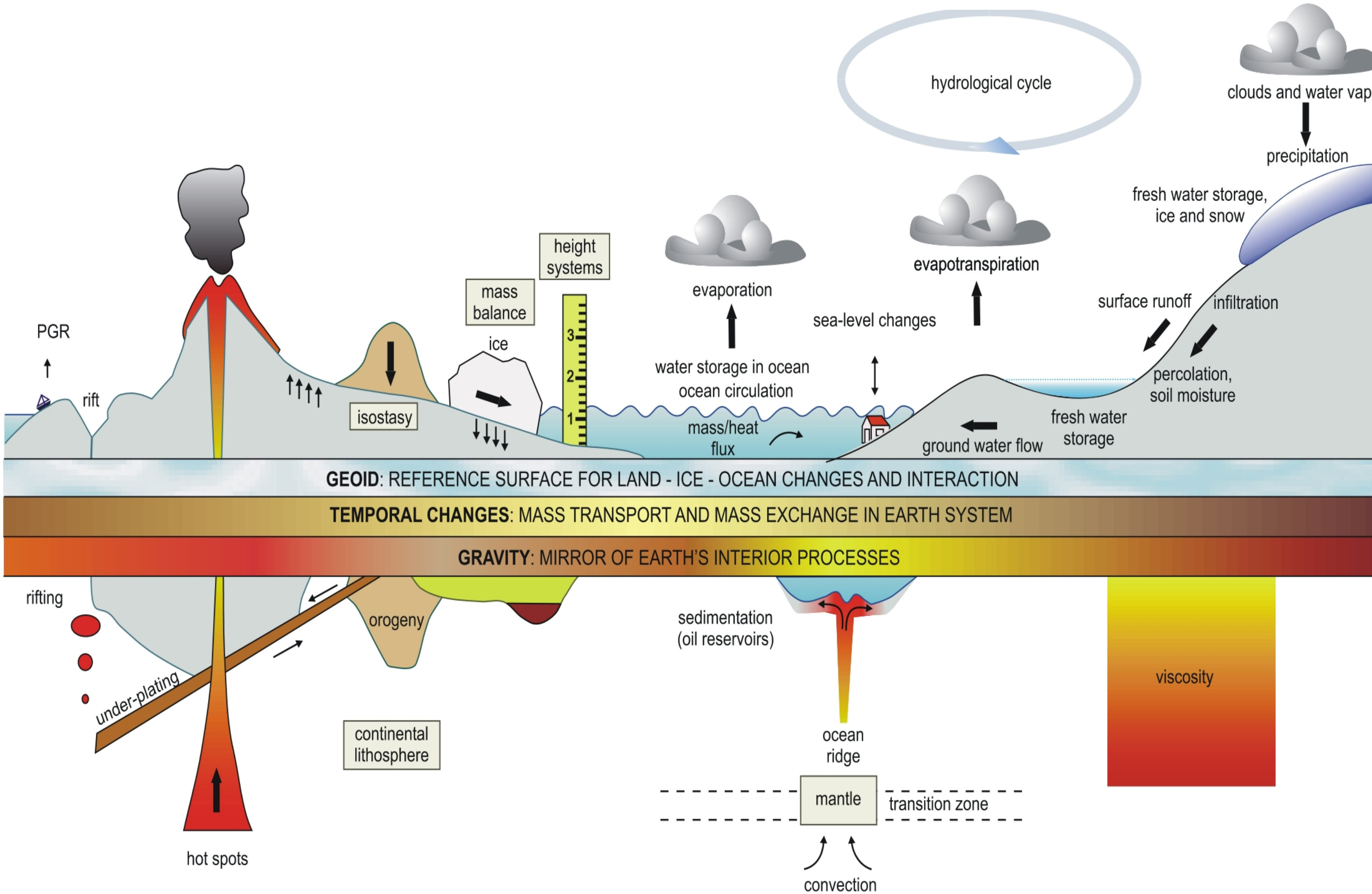
Pillar 2: Earth Rotation (Sub-Daily Variations)





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

Space Geodetic Ground-Based Instruments

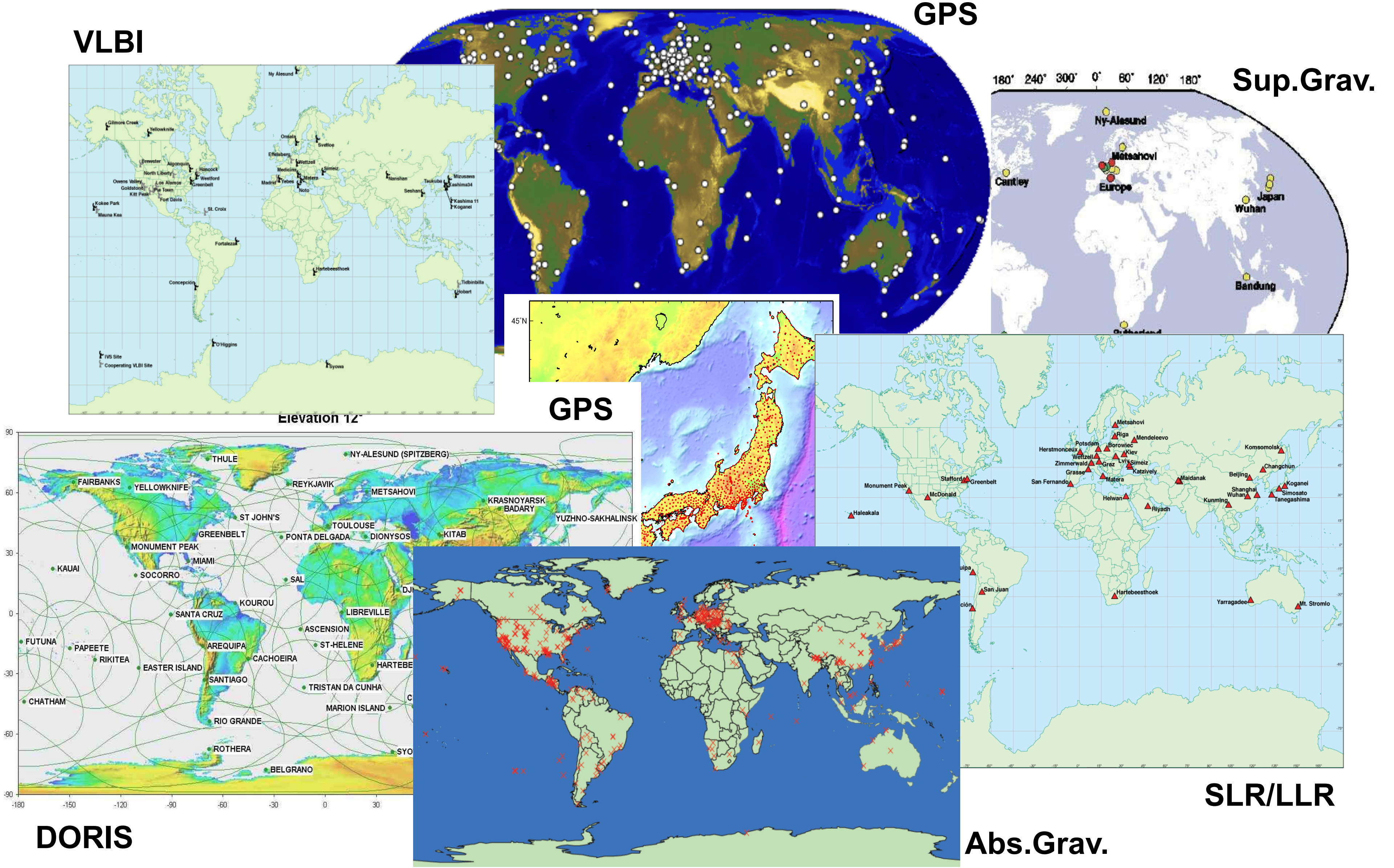
SLR/LLR

VLBI

GNSS

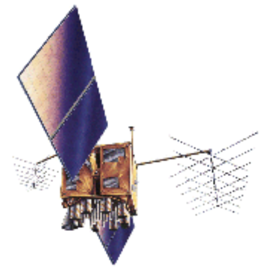
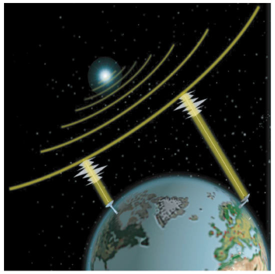
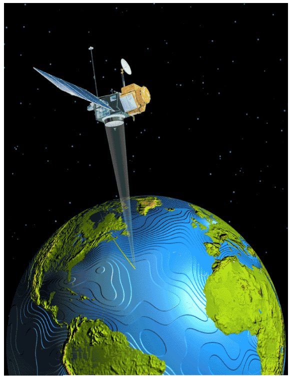
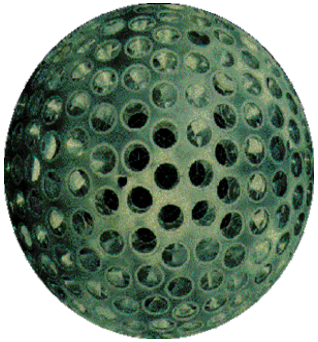
DORIS

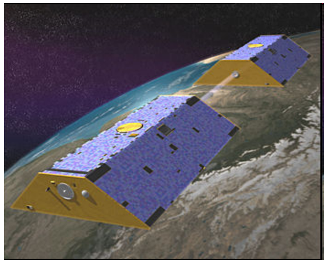
GGOS: the Ground-Based Component



Space Components

- Quasars (VLBI)
  - Positions and velocity
  - EOP
  - Reference Frame
- Navigation Satellites
  - Position and velocity
  - Reference Frame (GNSS)
  - Space weather (occultation)
- Geodynamics Satellites
  - Positions and velocity
  - Reference Frame (Lageos)
  - Gravity Field (Starlette, Stella)
- Remote Sensing LEO Satellites
  - Altimetry (Jason, Envisat)
  - Gravity Field (Champ, Grace)
  - SAR, InSAR (TerraSAR-X, TanDEM-X)

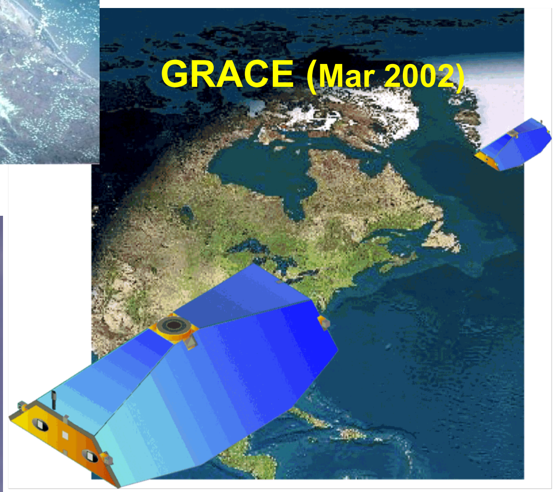



Global Positioning System
(Really GNSS: includes Galileo, Glonass, and COMPASS)

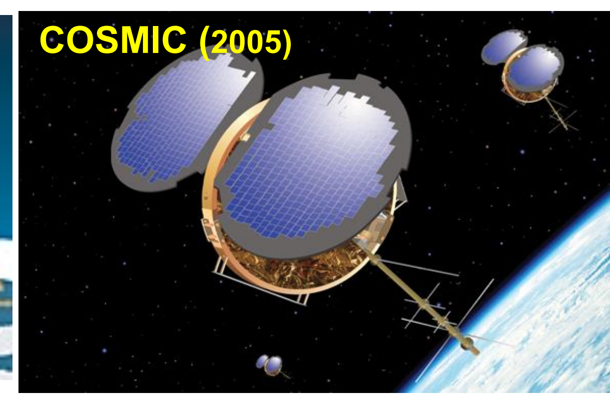
- The modern navigation tool
- The satellites broadcast and the ground stations receive to determine position and time ***anywhere*** on Earth
- Real-time position monitoring on the ground
- Receiver equipped satellites receive for precision orbit determination
- Navigation, Surveying, Geodesy
- Understanding complex dynamic processes of the Earth
- Atmospheric and Space weather

Community is organized under the International Global Navigation Satellite System Service (IGS)

GPS Precise Navigation - Low Earth Orbiters

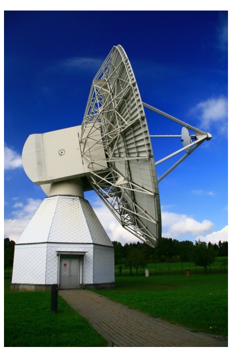


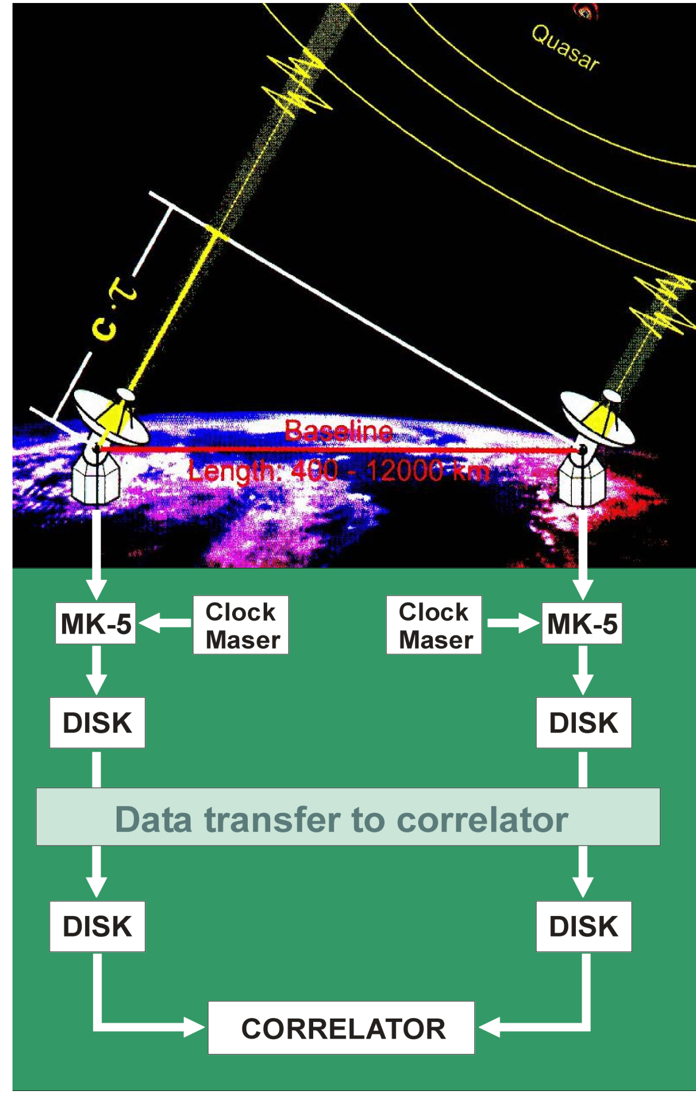
- *GPS Flight Receiver on board each*
- *LEO Missions Objectives/ Science Goals include:*
  - *Atmospheric remote sensing*
  - *Gravity, Magnetics*
  - *Ionospheric remote sensing*
  - *Ice and oceans*



VLBI Observing System

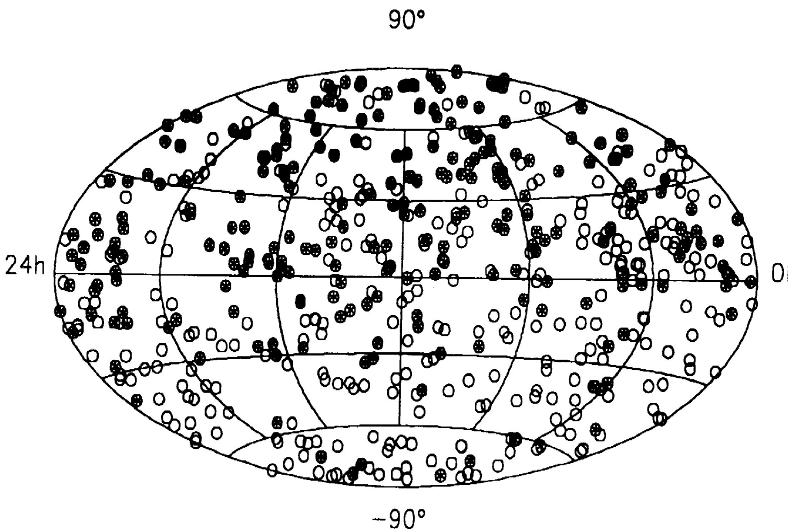
- Radio signals from quasars or radio galaxies
  - 8 channels X-Band
  - 6 channels S-Band
  - Data stream 512 Mbit/s
  - Time & Frequency
    - ($DF/F \sim 10^{-14}$)
  - Data recording
    - Harddisk (MK-5)
    - e-transfer
- Correlation
  - $\sigma_t \sim$ 10 to 30 ps





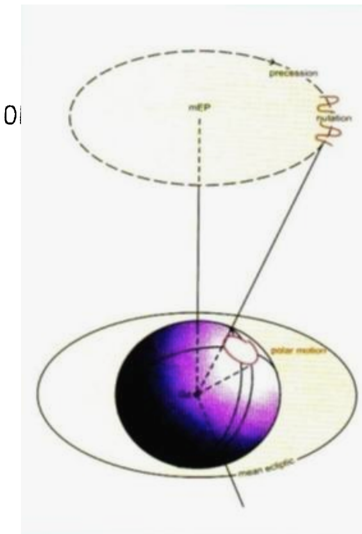
Community is organized under the International VLBI Service for Geodesy and Astrometry (IVS)

Role of VLBI



ICRF: International Celestial Reference Frame

- Quasar positions

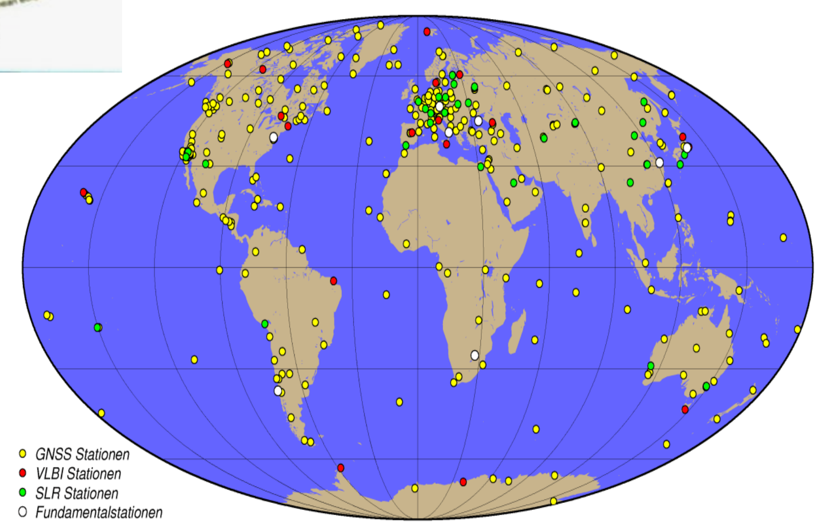


EOP: Earth Orientation Parameters

- Precession/Nutation
- Polar motion
- UT1 - UTC

ITRF: International Terrestrial Reference Frame

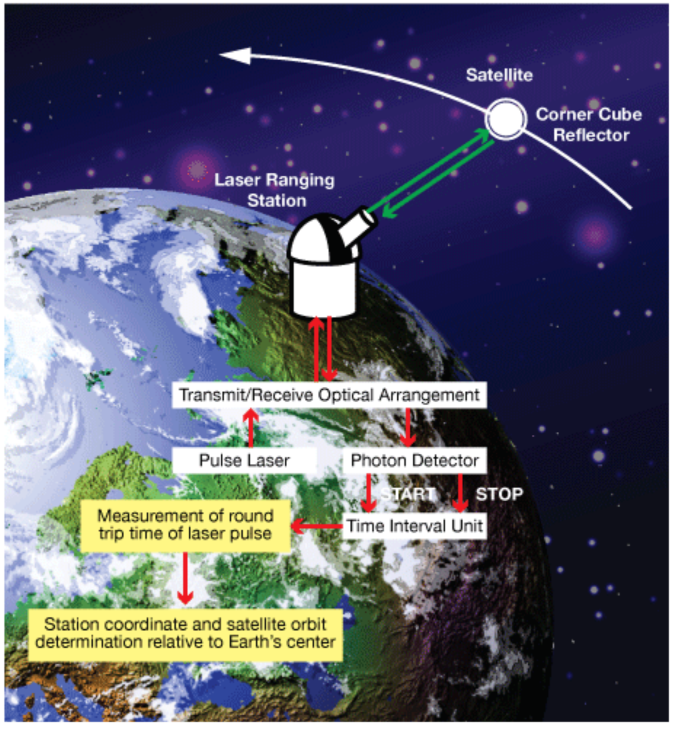
- Positions
- Velocities
- Time series
- EOP and Scale



Satellite Laser Ranging Technique

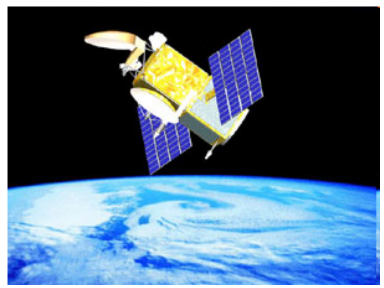
Precise range measurement between an SLR ground station and a retroreflector-equipped satellite using ultrashort laser pulses corrected for refraction, satellite center of mass, and the internal delay of the ranging machine.

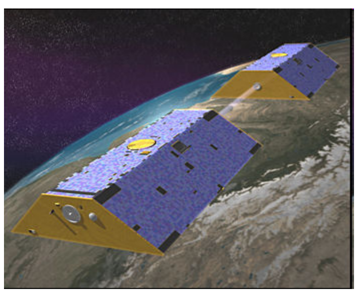
- Simple range measurement
- Space segment is passive
- Simple refraction model
- Night / Day Operation
- Near real-time global data availability
- Satellite altitudes from 400 km to synchronous satellites, and the Moon
- Centimeter satellite Orbit Accuracy
- Able to see small changes by looking at long time series

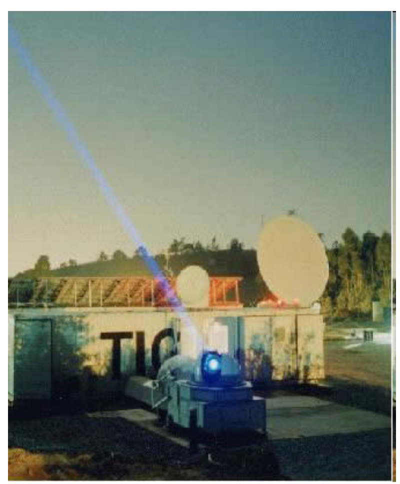


- Unambiguous centimeter accuracy orbits
- Long-term stable time series

Role of Satellite Laser Ranging





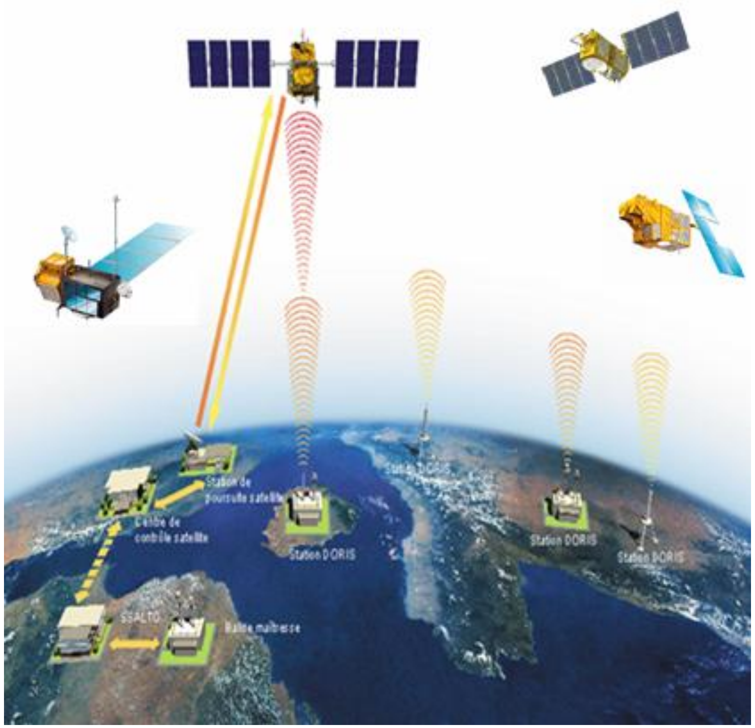


SLR/LLR products support:

- Terrestrial reference frame (Center of mass and scale)
- Position and velocity
- Static and time-varying gravity field
- Earth orientation and rotation (polar motion, length of day)
- Orbits, calibration, and validation of altimetry missions (oceans, ice)
- Total Earth mass distribution
- Space science (tether dynamics, etc.)
- Relativity measurements and lunar science

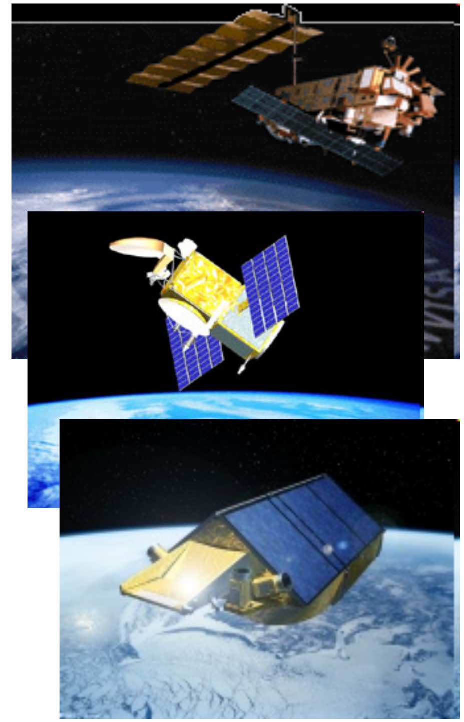
Doppler & Radiopositioning Integrated by Satellite (DORIS).

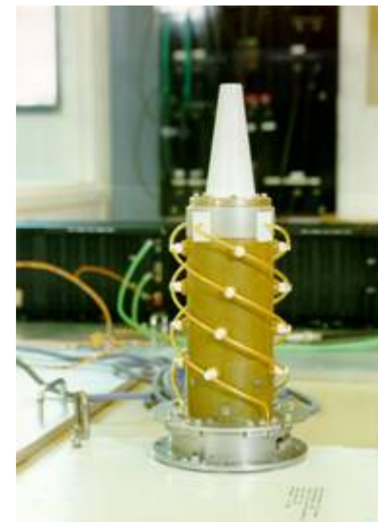
- Dual-Frequency Doppler Beacons (2.036 Ghz & 401.25 Mhz), Distributed at Ground Stations Around the World.
- Signals received and recorded on DORIS equipped satellites
- Developed by the CNES (Centre National d’Etudes Spatiales) & IGN (Institut Géographique National).
- The network was developed to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



Role of DORIS

- Precise Orbit Determination for Earth Sensing Missions
- Station Position and Velocity
- Polar Motion
- ITRF
- Comprehensive Global Coverage
- Gravity field, geoid
- On board real time orbit determination for payload products location or platform navigation

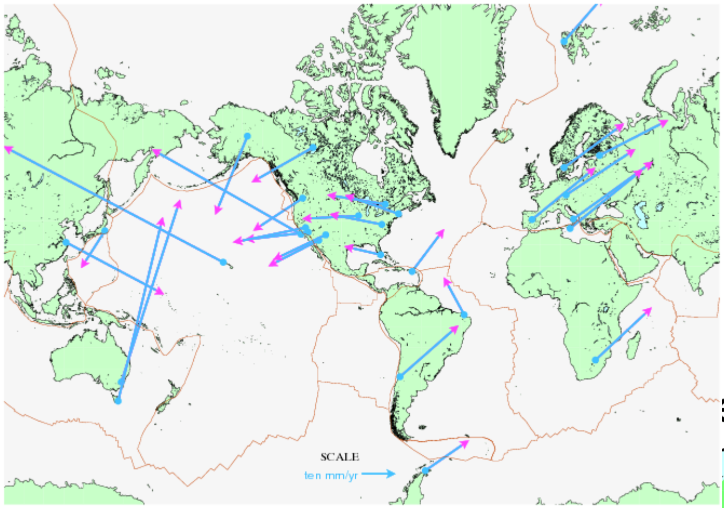




Earth Science Products

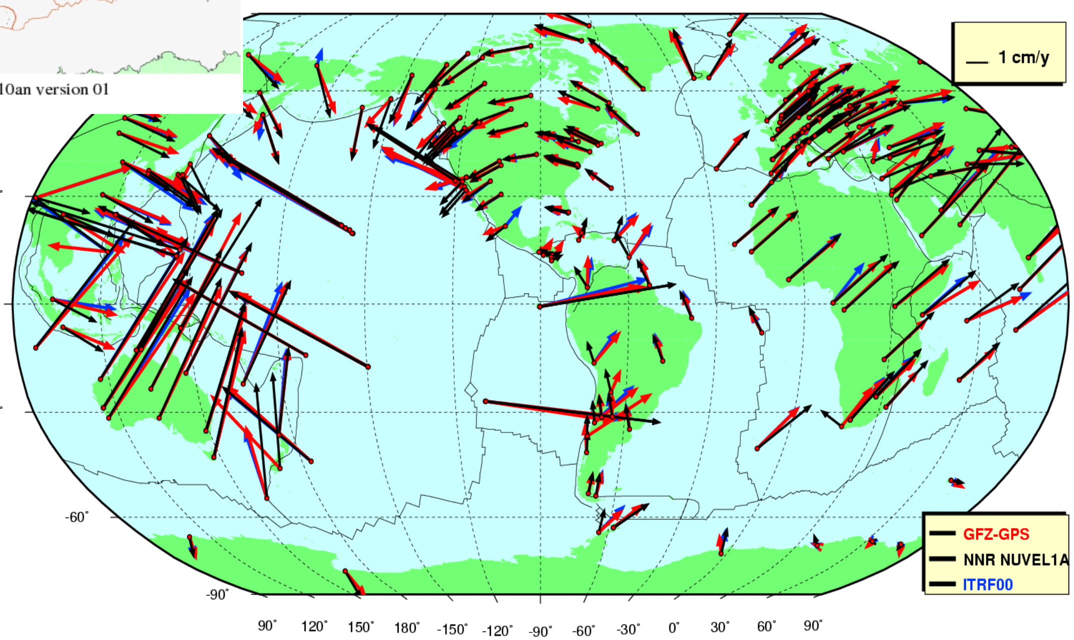
Global Plate Motion

Selected VLBI Velocities



Goddard Space Flight Center VLBI solution KB 2010an version 01
NUVEL1A-NNR reference frame.

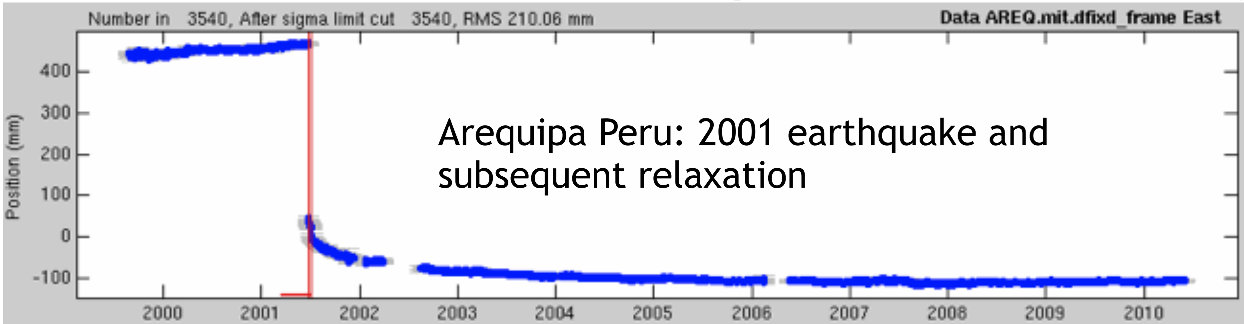
e velocities from 12 years of GPS data

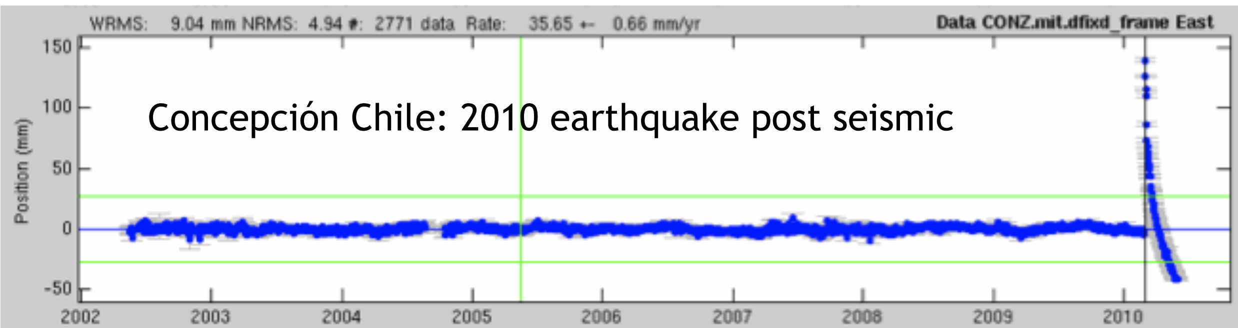


GPS data from 1993.0 to 2005.1

Time History of Station Positions

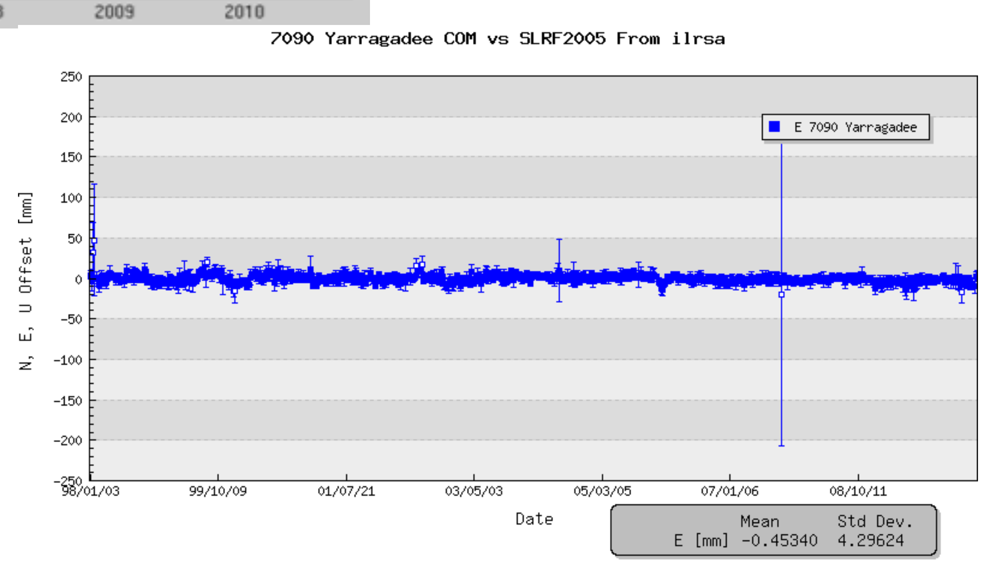
Examples of Local Stability





Arequipa and Concepción plots courtesy Tom Herring/MIT

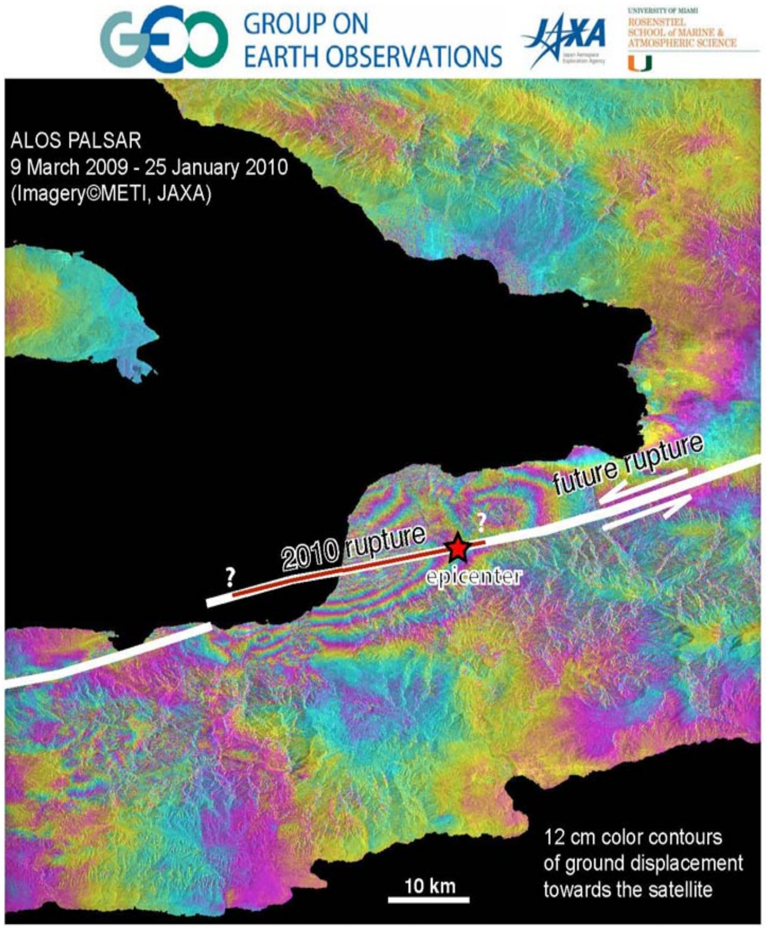
Yarragadee Australia: stable site



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.)

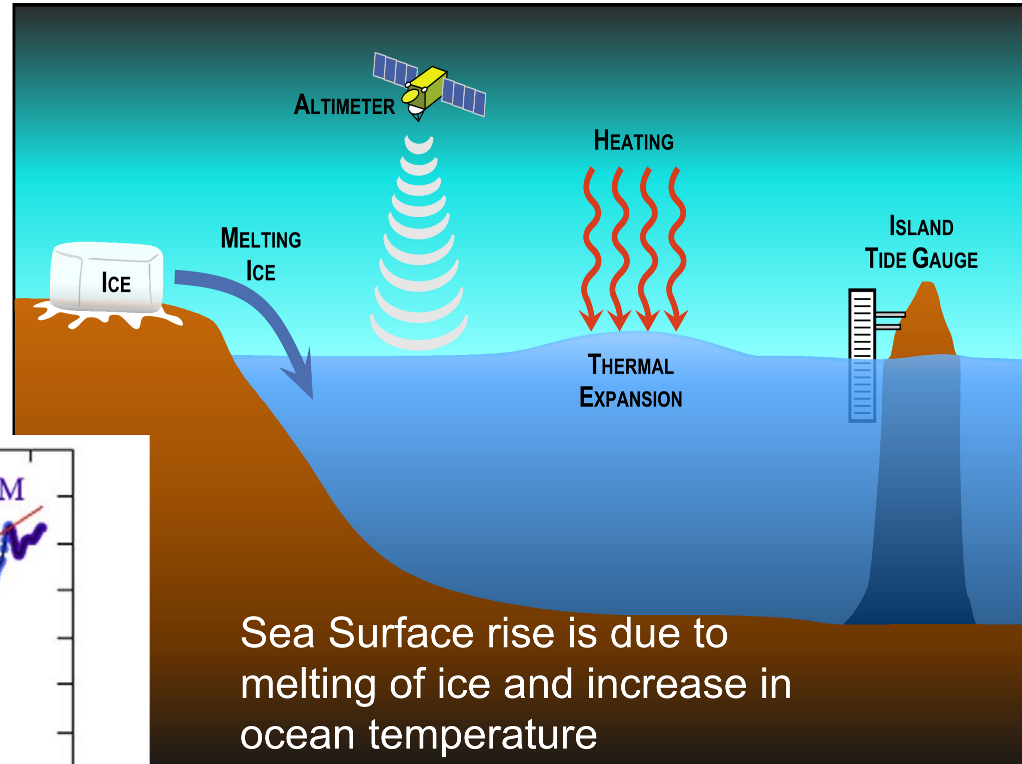
- At right is an InSAR map of the ground displacement from the January 2010 M7 Haiti earthquake
- Each band of color contours is 12 cm of, so the total displacement was ~1 m over a large area
- Measurements help us predict areas of future risk

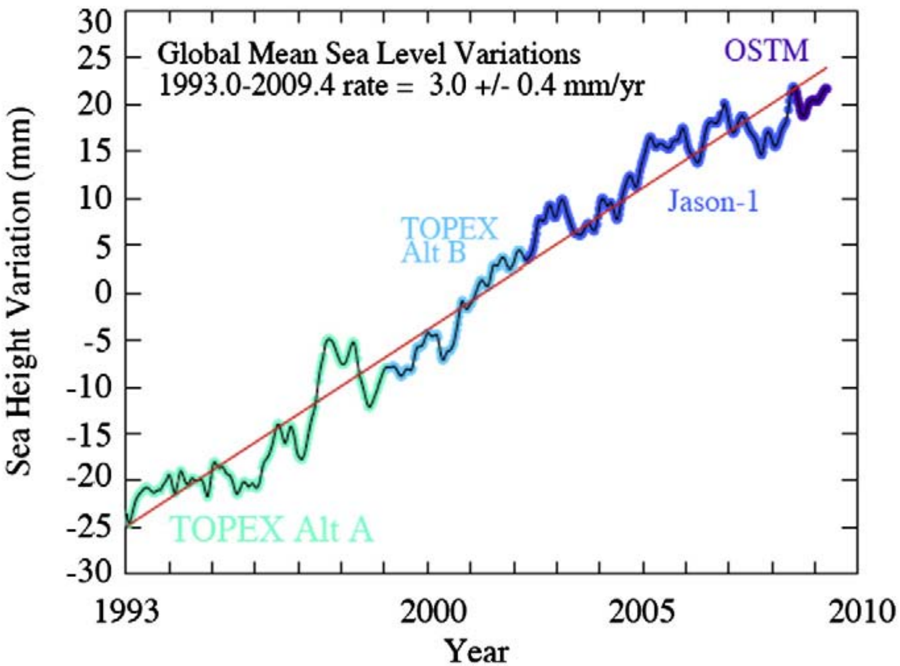


Sang-Hoon Hong, Falk Amelung, Tim Dixon, Shimon Wdowinski, Guoqing Lin, Fernando Greene
Rosenstiel School of Marine & Atmospheric Science, University of Miami

Measure Sea Surface Height with Altimetry

- What kinds of things effect Sea Level?
  - –Water Volume
  - –Water temperature
  - –Tides
  - –Currents
  - –Tsunamis
  - –Weather
  - –Coast Line. etc

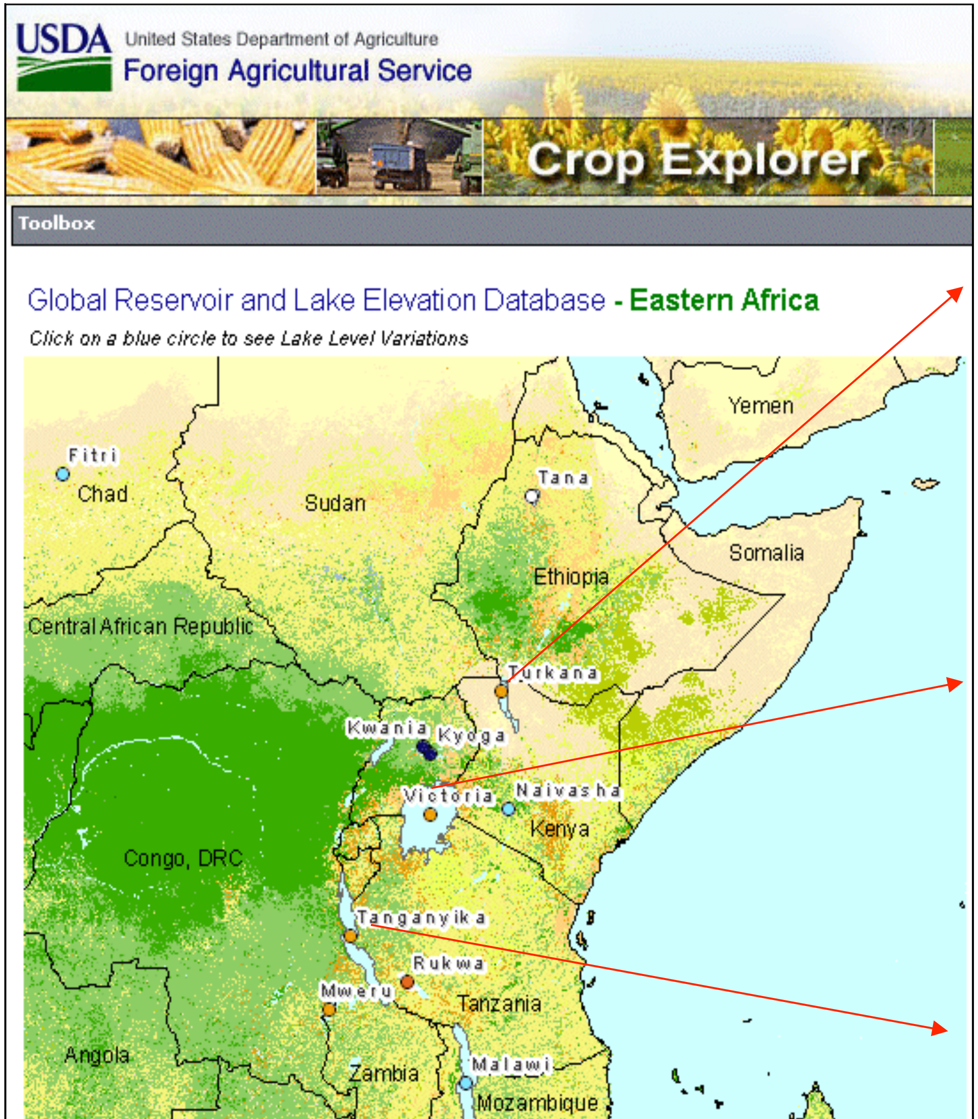


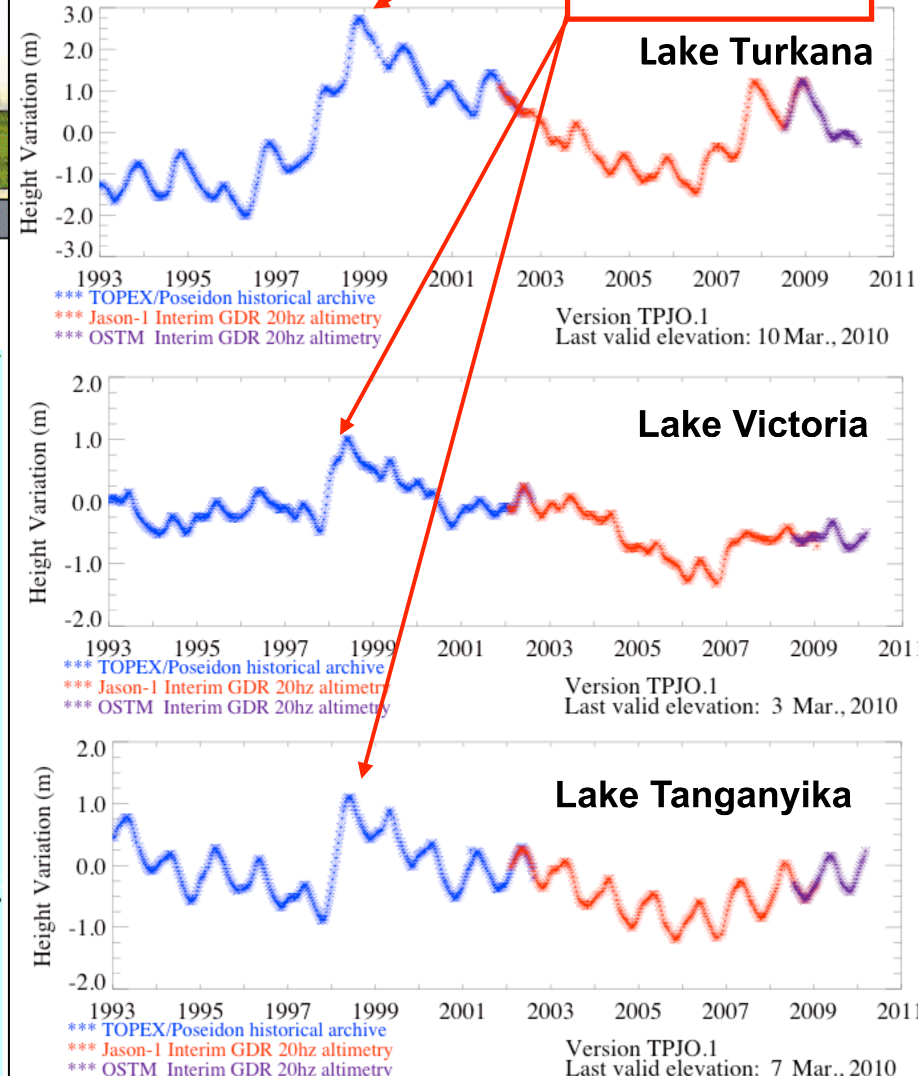


Source: Lemoine, F.G., et al. Towards development of a consistent orbit series for TOPEX, Jason-1, and Jason-2. J. Adv. Space Res. (2010), doi:10.1016/j.asr.2010.05.007

Near Real Time Lake Level Monitoring

Decrease in lake water levels since 1997/98 El Nino





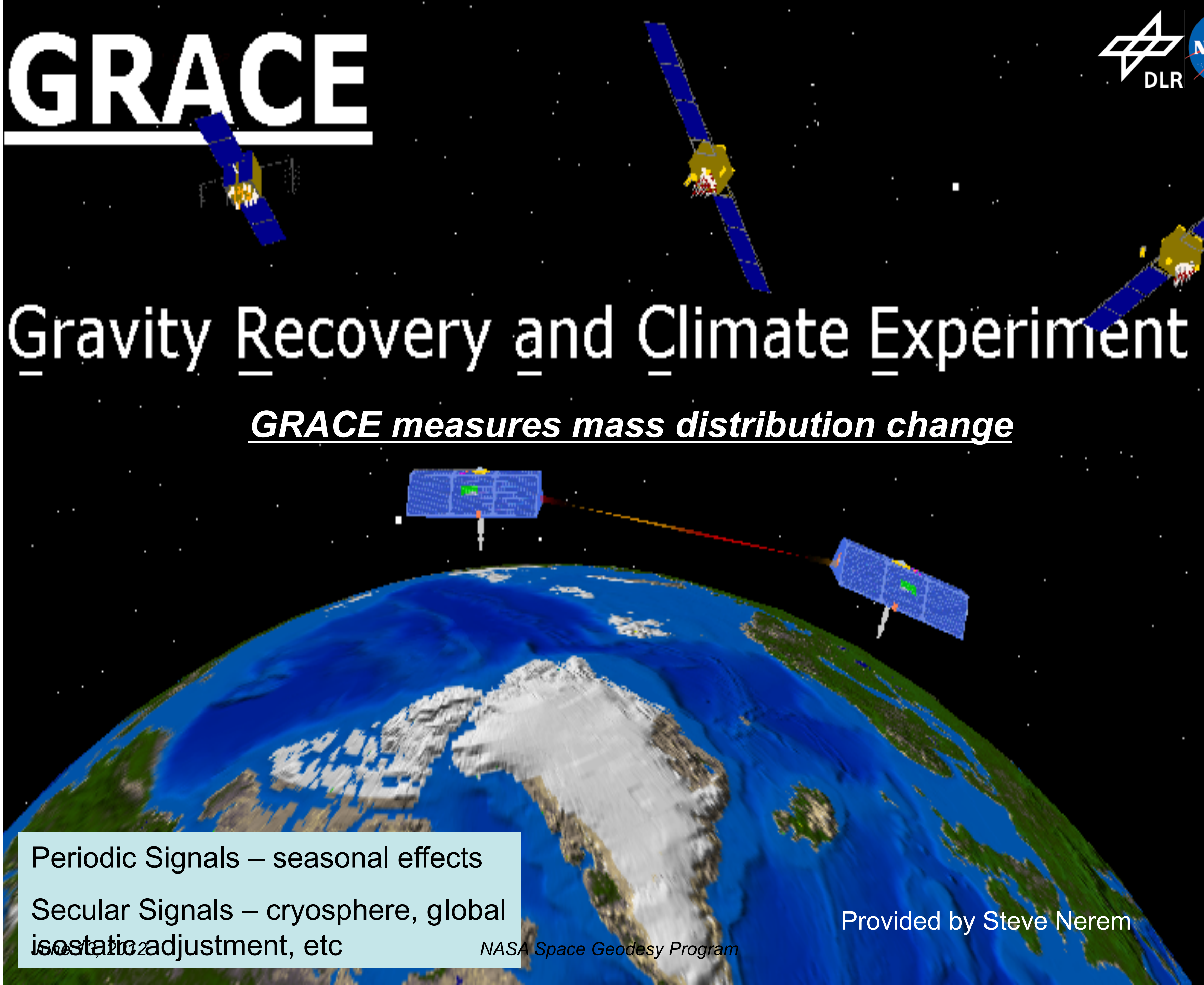
Reprocessed altimeter data better enables the monitoring of lake levels for the Foreign Agriculture Service under the U.S. Department of Agriculture for crop predictions and irrigation management.

Provided by Steve Klosko

GRACE

Gravity Recovery and Climate Experiment

GRACE measures mass distribution change



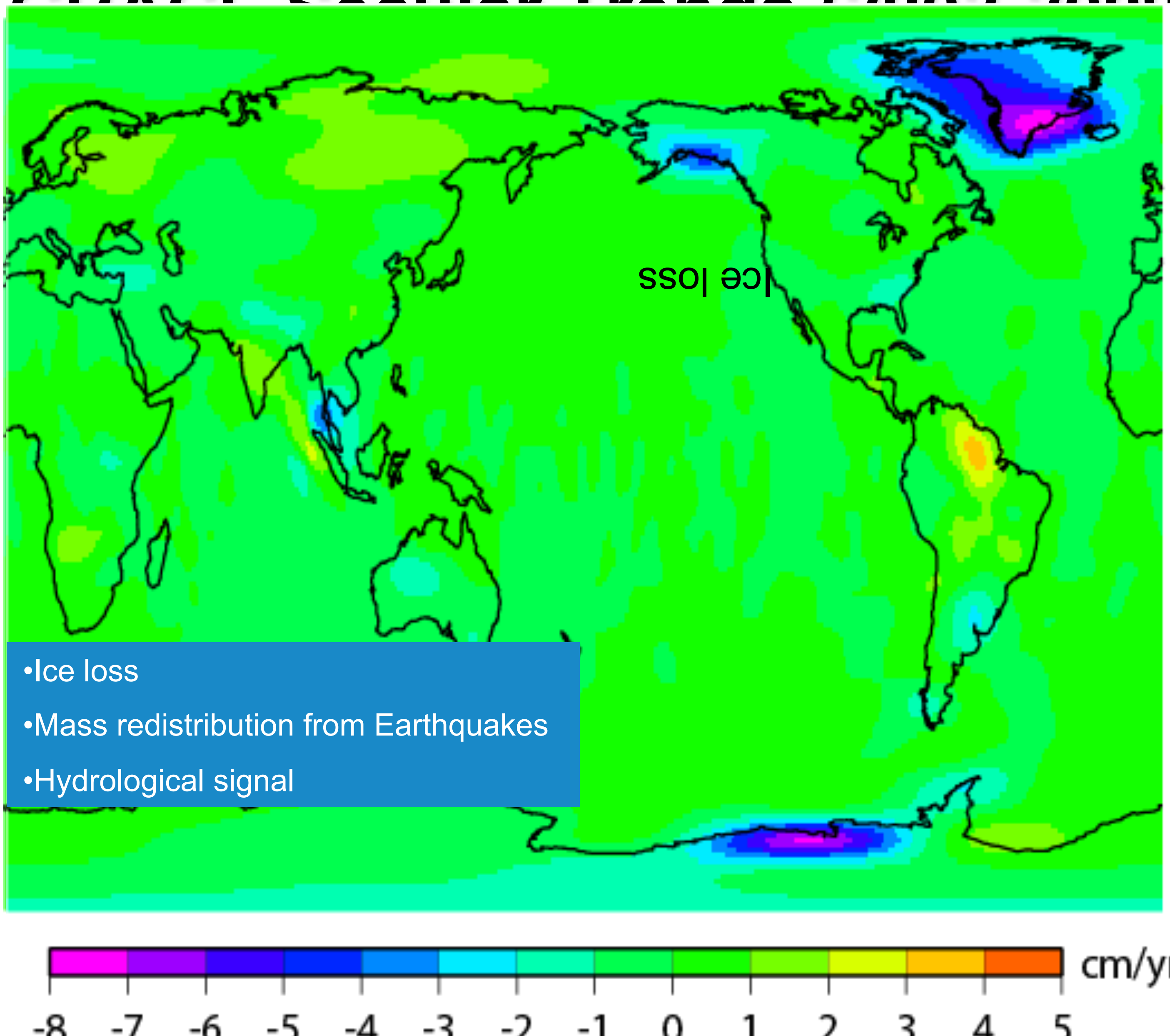
Periodic Signals – seasonal effects

Secular Signals – cryosphere, global isostatic adjustment, etc

Provided by Steve Nerem

GRACE Secular Trends (2002-2009)

PGR model removed

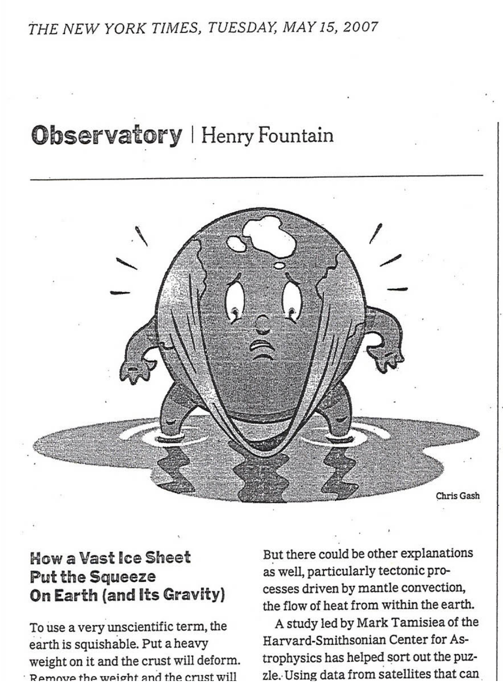


- Ice loss
- Mass redistribution from Earthquakes
- Hydrological signal

[Wahr, 2009]

The Impact of Ancient Ice Sheets

GRACE measures mass redistribution from post glacial uplift



THE NEW YORK TIMES, TUESDAY, MAY 15, 2007

Observatory | Henry Fountain

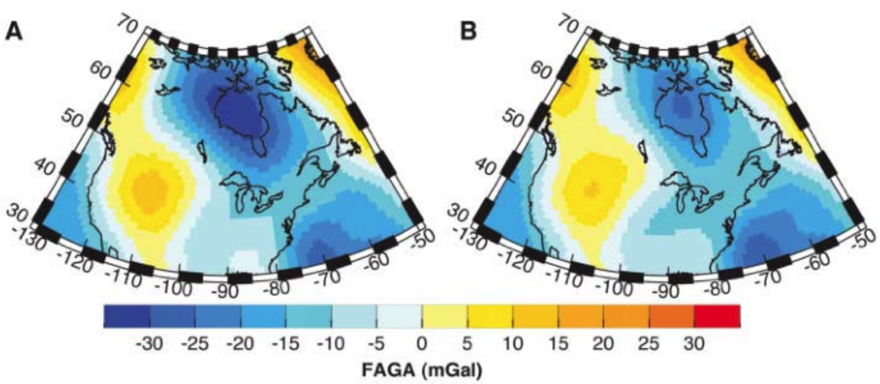
Chris Gash

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



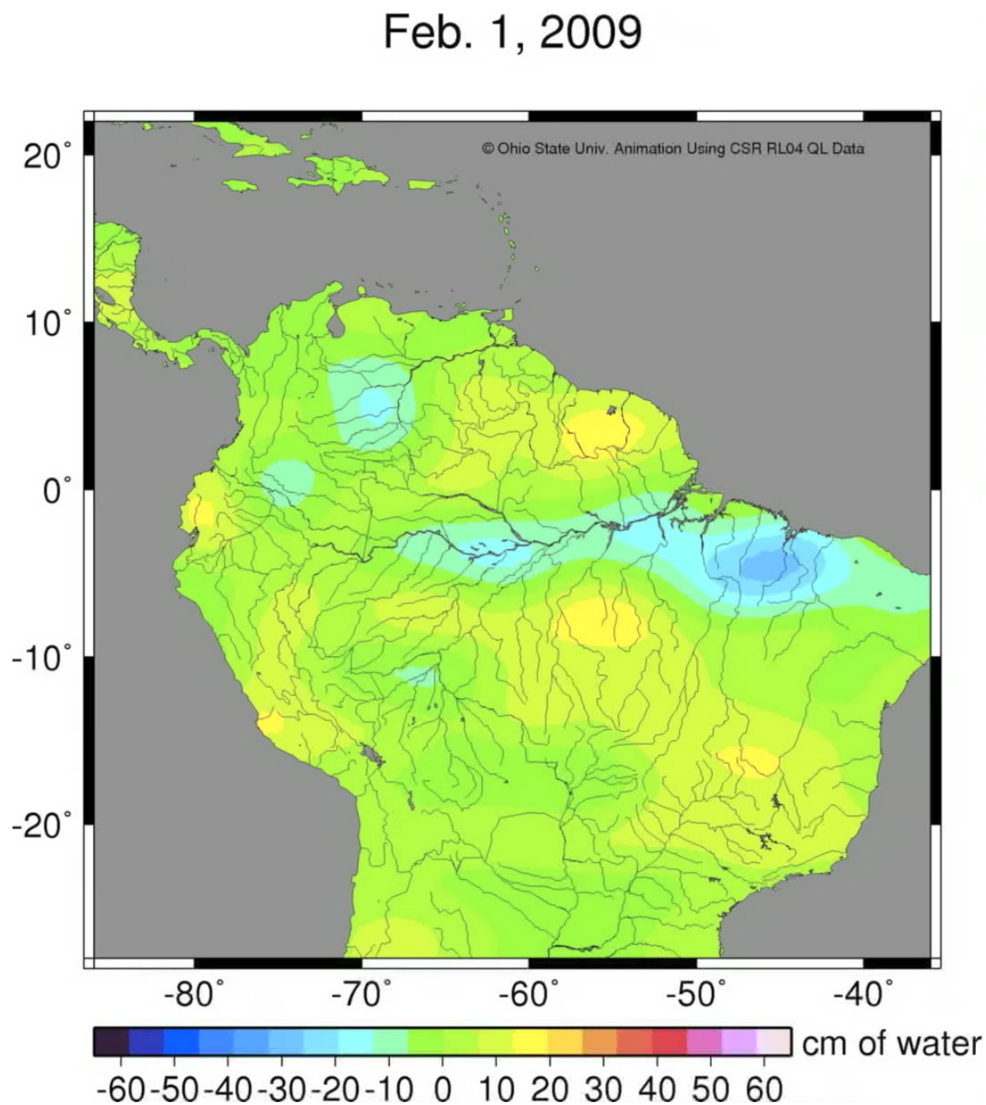
- The thick (~3 km) ice sheets that began melting ~20,000 years ago have left the Earth deformed

- 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

Provided by Jim Davis

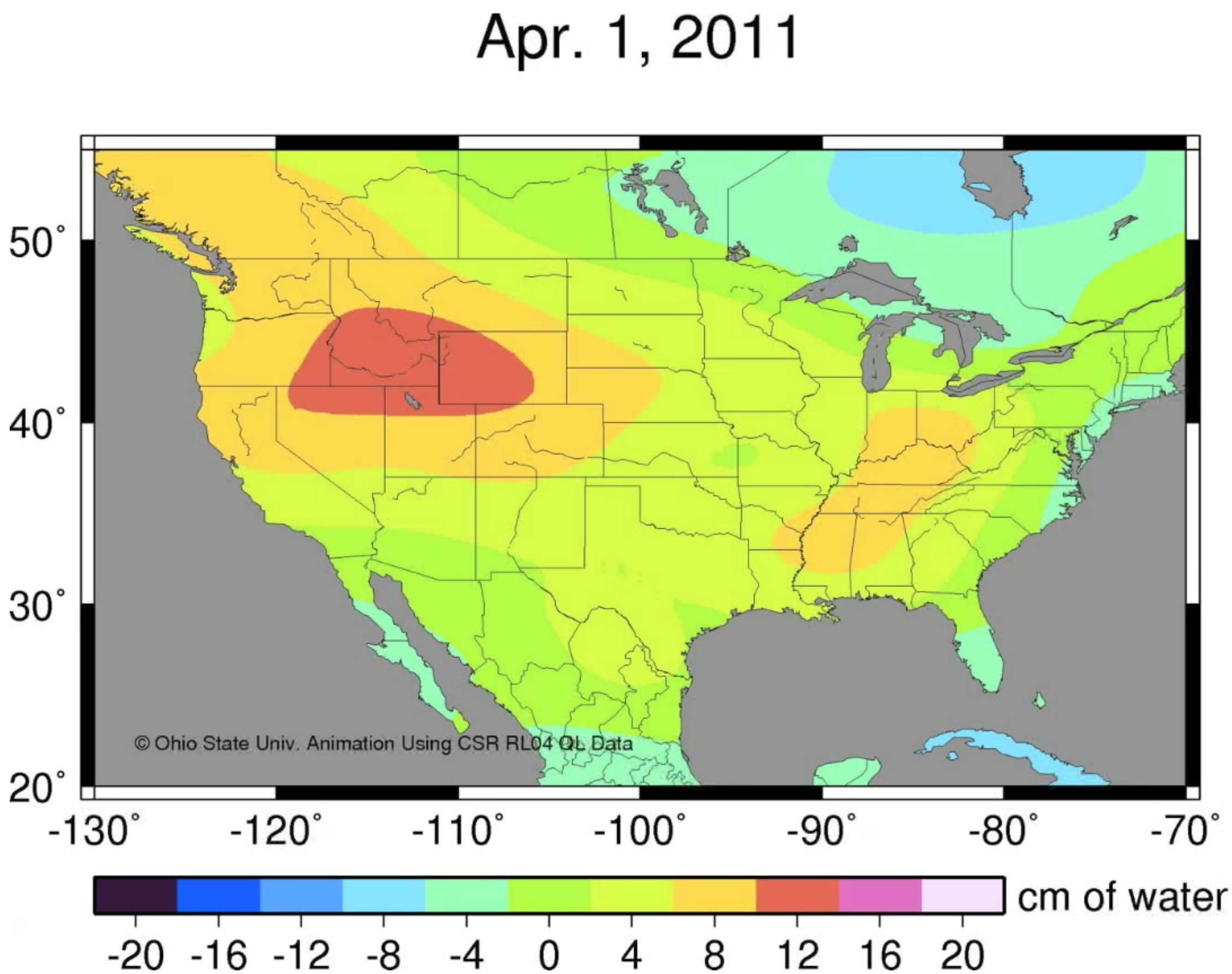
2009 Amazon Flooding

From Prof. C. K. Shum, OSU



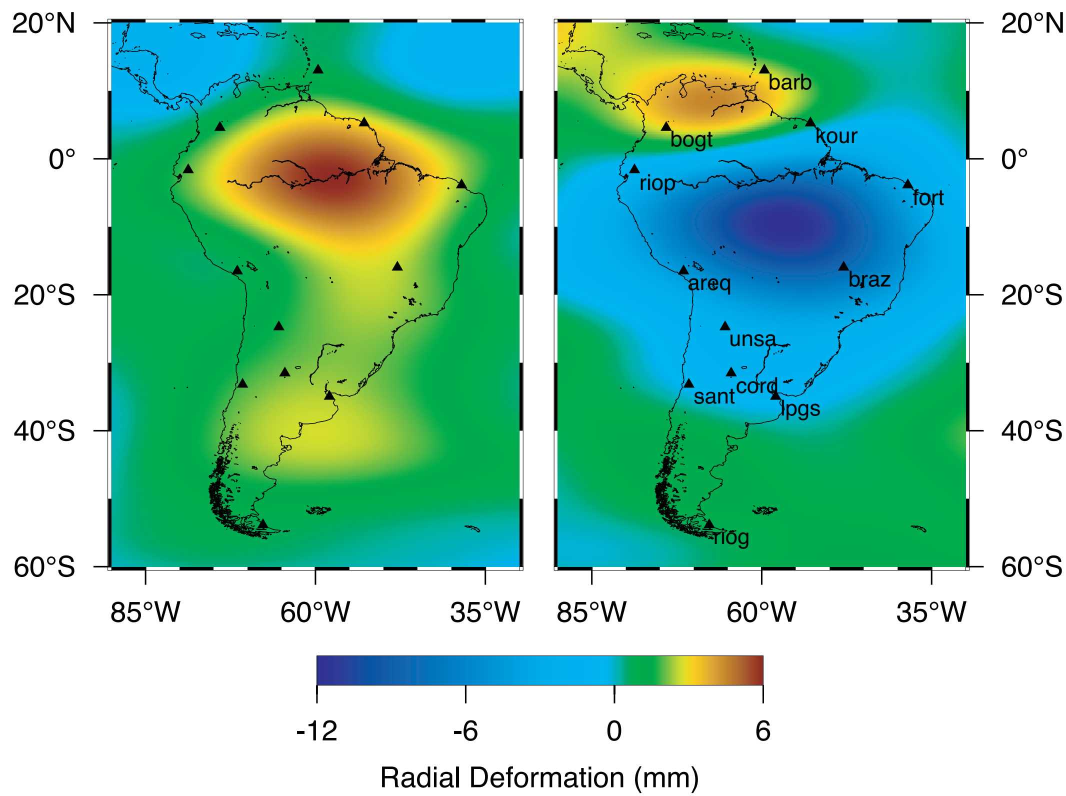
Mississippi Flooding 2009

From Prof. C.K. Shum, OSU



Deformational Impact of the Hydrological Cycle

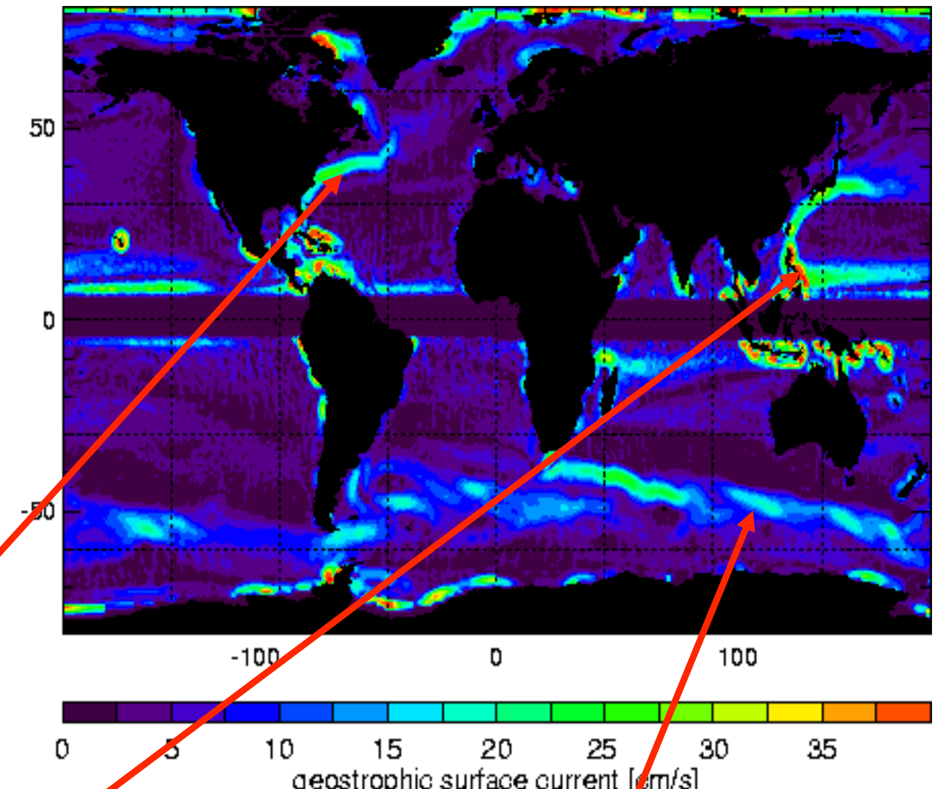
- Annual hydrological cycle will act as a periodic change in gravitational load, deforming the Earth
- The GRACE mission measures the presence of water on the surface
- At the right is a map of the annual amplitude of surface deformation in South America estimated from GRACE data [*Davis et al.*, 2004]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



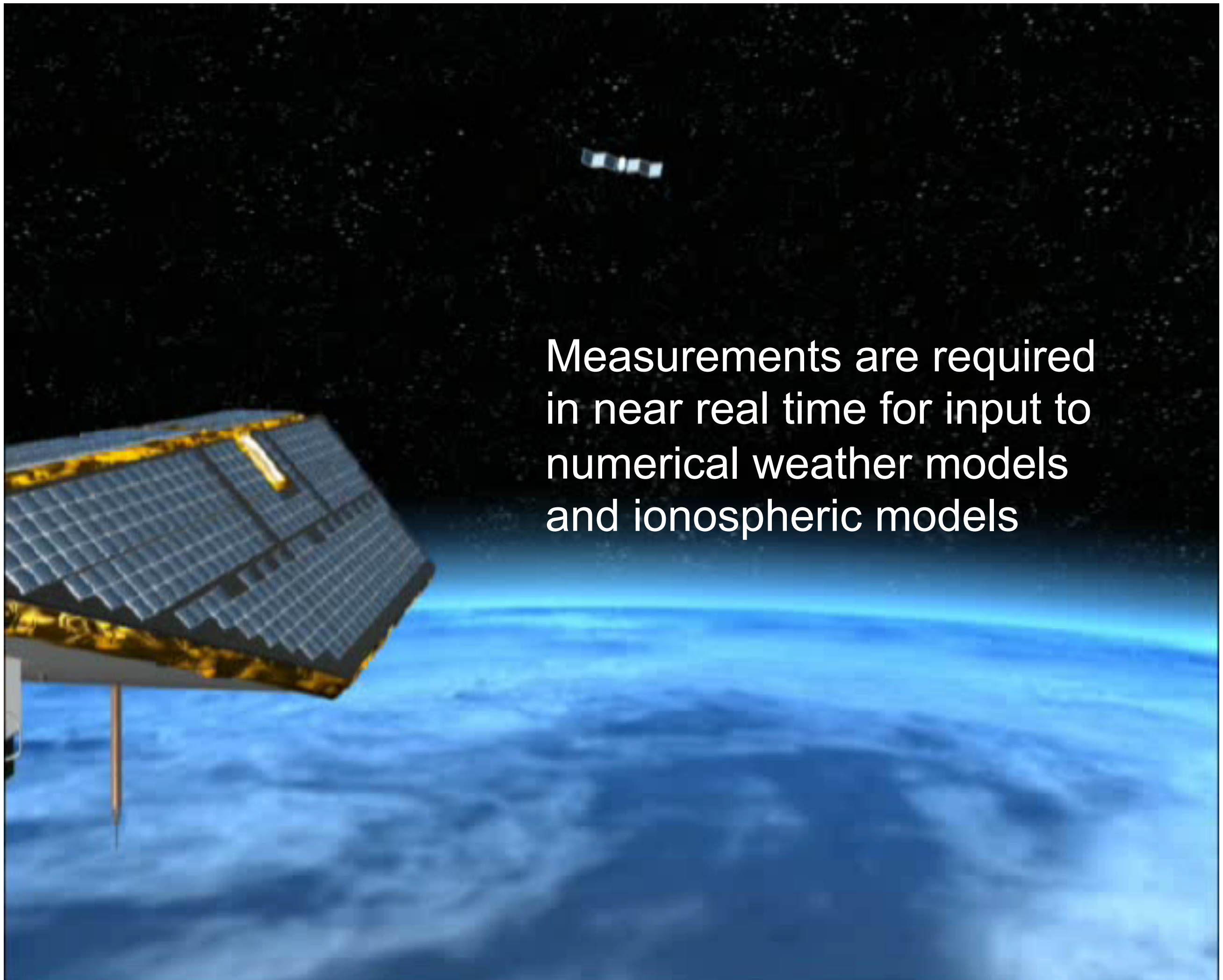
Provided by Jim Davis

Ocean Currents from GRACE and Altimetry

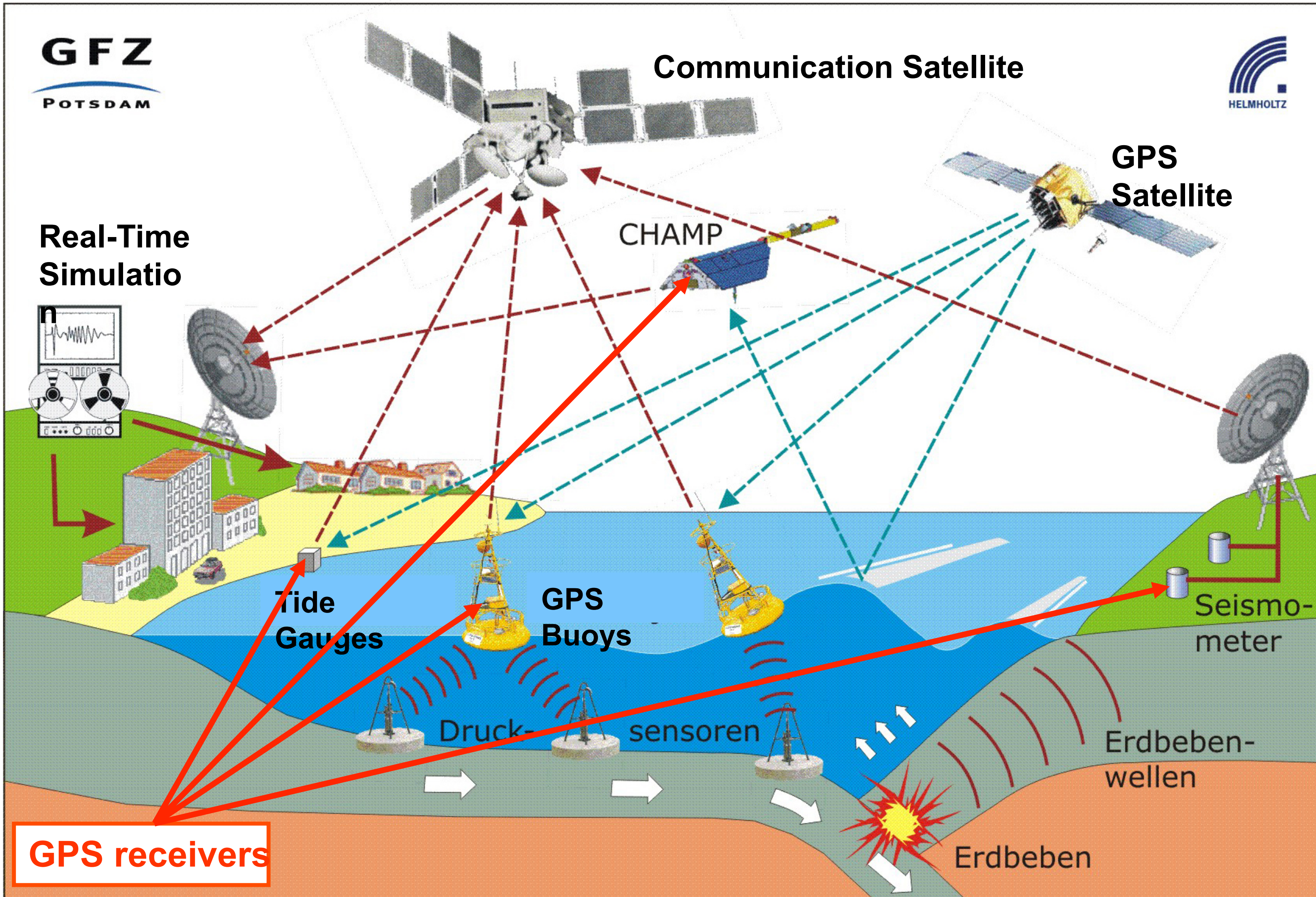
- Altimetry (Topex, Jason, etc) provides the mean sea surface topography
- GRACE provides the Geoid
- Altimetry – Geoid = Sea Surface Topography
- Sea Surface Topography reflects the global mean ocean currents

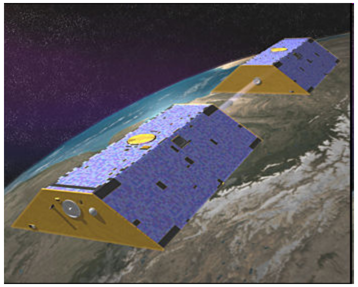


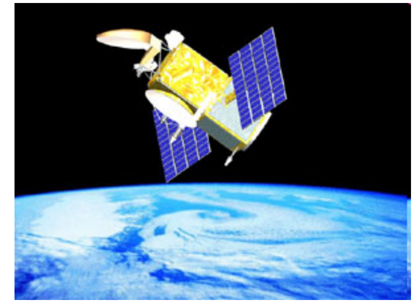
Occultation measurements between GPS and LEO satellites provide height profiles of water vapor, pressure, and temperature and ionospheric profiles



Example: GPS and a Tsunami Early Warning System

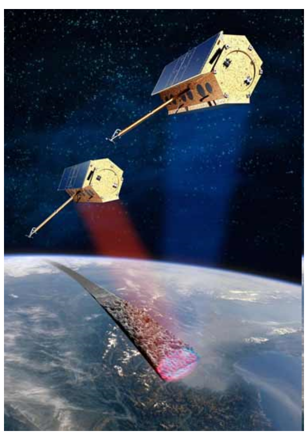


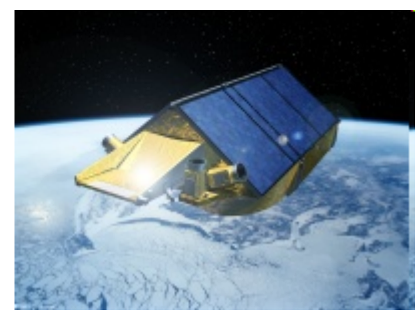




Common Thread:

- Reference Frame
- Precision Orbit Determination

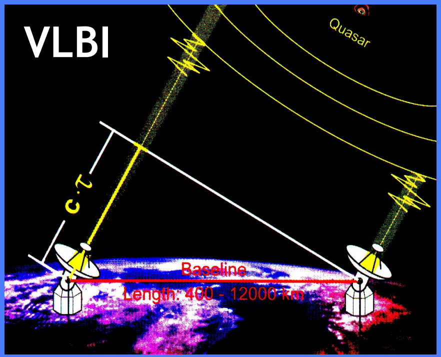




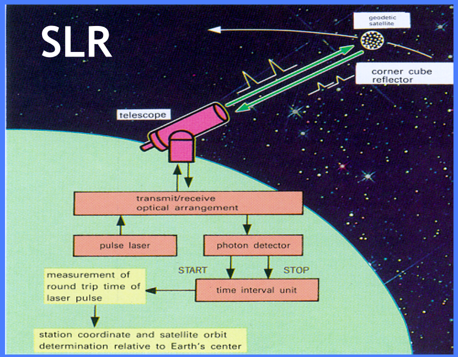
International Terrestrial Reference Frame (ITRF)

- Provides the stable coordinate system that allows us to measure change (link measurements) over space, time and evolving technologies.
- An accurate, stable set of station positions and velocities.
- Foundation for virtually all space-based and ground-based metric observations of the Earth.
- Established and maintained by the global space geodetic networks.
- Network measurements must be precise, continuous, robust, reliable, and geographically distributed (worldwide).
- Network measurements interconnected by co-location of the different observing techniques

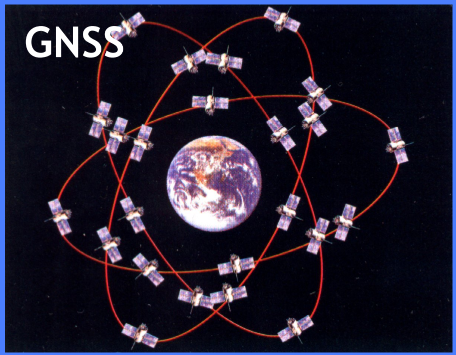
Space Geodetic Techniques



Very Long Baseline Interferometry

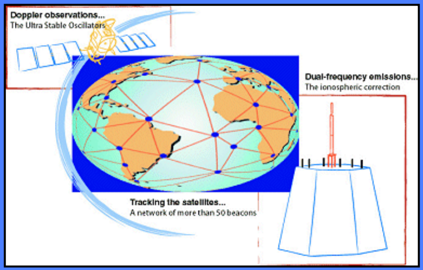


Satellite Laser Ranging



Global Navigation Satellite System

DORIS



Doppler Orbitography and Radio Positioning Integrated by Satellite

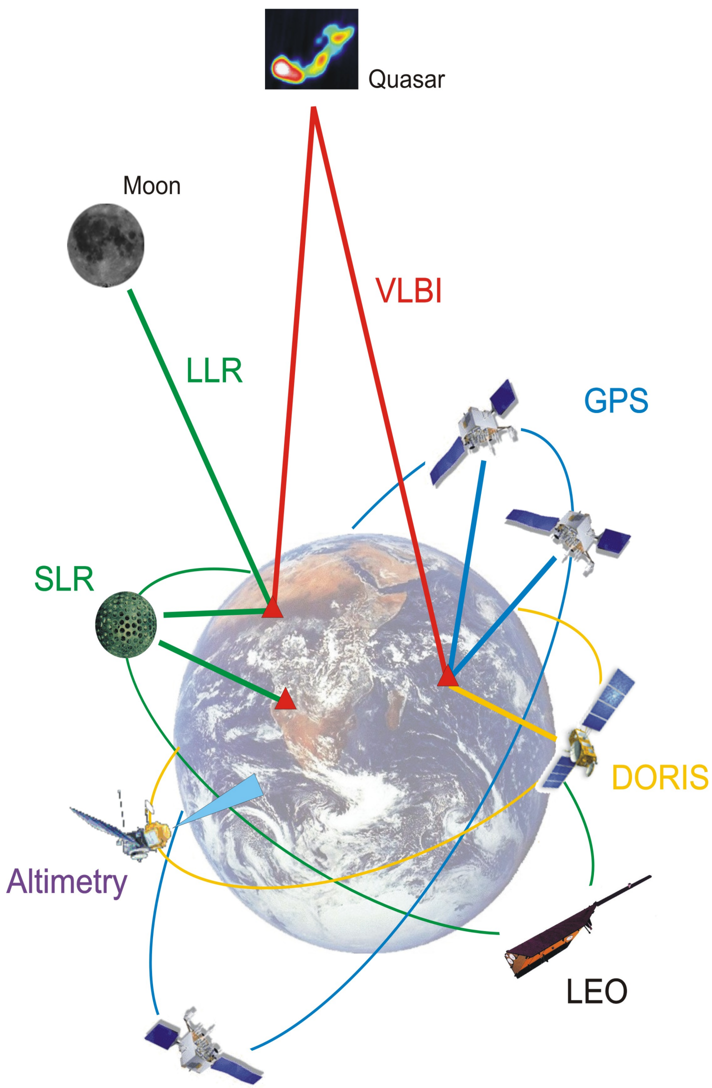
- **Space geodetic systems provide the measurements that are needed to define and maintain the International Terrestrial Reference Frame (ITRF)**
- **Each of the space geodetic techniques has special properties that bring unique strengths to the reference frame;**
  - Radio verses optical
  - Active verses passive
  - Terrestrial (satellite) verses celestial (quasar) reference
  - Broadcast up verses broadcast down
  - Range verses range difference measurements
  - Geographic coverage

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 semi - “operational”
  - VLBI2010 systems in testing
- GGAO will be the location for the prototype next generation multi-technique station

Combination / Integration



- Ensure the **consistency** and can improve the **accuracy** of the resulting geodetic products
- **Complementary use** of the individual techniques to strengthen the solutions
- Benefits from observing instruments **co-located at the same site/satellite**
- Distinguish **genuine geodetic/geo-physical signals** from **technique-specific systematic biases**
- Crucial to **separate different components and processes** in the Earth System (e.g. mass transport)

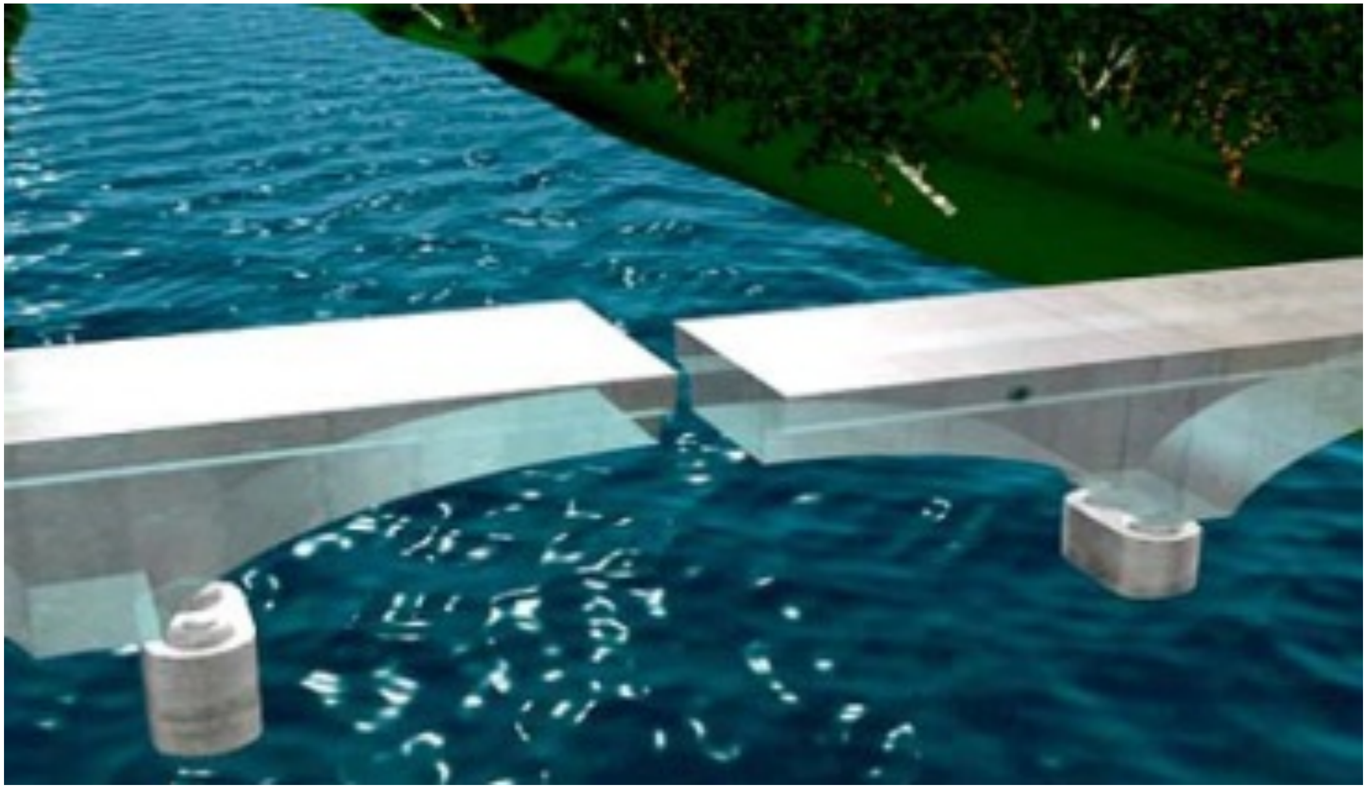
International Terrestrial Reference Frame

- VLBI provides EOP
- SLR provides Earth Center of Mass
- VLBI and SLR together provide Scale
- GNSS and DORIS strengthen the RF and provide global coverage and distribution

Global Geodetic Observing System Reference Frame Requirement

- Most stringent requirement comes from sea level studies:
  - "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
- Space Segment: LAGEOS, GNSS, DORIS Satellites
- Ground Segment: Global distributed network of "modern", co-located SLR, VLBI, GNSS, DORIS stations
- Co-locate with and support other measurement techniques including gravity, tide gauges, etc.
- Simulation studies to date indicate:
  - ~30 globally distributed, well positioned, co-location stations 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.

When National Reference Frames are not integrated!



Design error at bridge construction in Laufenburg (2003): During the construction of the bridge across the Rhine river in Laufenburg, a control showed that a height difference of 54 centimeters exists between the bridge built from the Swiss side and the roadway of the German side. Reason of the error is the fact that the horizons of the German and Swiss side are based on different reference frames. Germany refers to the sea level of the North Sea, Switzerland to the Mediterranean.

Courtesy of Hermann Drewes/DGFI

Final Message

- We want you to have an Exciting Summer with an opportunity to Explore Space Science
- We are very pleased that you are with us.