Dr. Michael Pearlman (Mike)

Center for Astrophysics (CfA)
Cambridge MA USA
Harvard College Observatory (HCO)
Smithsonian Astrophysical Observatory (SAO)

The Center for Astrophysics

- HCO established in 1839
- SAO moved to Cambridge to be at Harvard University in 1955
- SAO Satellite Tracking Program established
- HCO and SAO formed a joint venture – CfA in 1973
- Research Areas
  - Atomic and Molecular Physics
  - High Energy Astrophysics
  - Optical and Infrared Astronomy
  - Radio and Geoastronomy
  - Solar, Stellar, and Planetary Sciences
  - Theoretical Astrophysics
- Ground-Based Telescopes
  - Fred Lawrence Whipple Observatory (Arizona)
  - Submillimeter Array (Mauna Kea, Hawaii)
  - Magellan Telescopes (Cerra Las Campanas, Chile)
  - South Pole Telescope
- Space-Based Telescopes
  - Chandra
  - Spitzer

Dr. Michael Pearlman (Mike)

Focus Area: Space Geodesy

1968	**Joined SAO as a Scientist, Satellite Tracking Program**
1971/2	**Visiting Scientist at NASA Headquarters (Office of Geodetic Satellites)**
1972	**Harvard-Smithsonian Center for Astrophysics (SAO and HCO) organized**
1972-83	**Chief, SAO Satellite Tracking Network**
1984 -	**Special Project Consultant, NASA Space Geodesy Program Crustal Dynamics Program**
	NASA Representative to WEGENER
1987-2005	**Program Manager, Infrared-Optical Telescope Array (IOTA)**
1998-01	**Secretary, Central Bureau, IAG International Laser Ranging Service**
2001-	**Director, Central Bureau, IAG International Laser Ranging Service**
2004-09	**Member Global Geodetic Observing System (GGOS) Executive Committee**
	Lead for GGOS Working Group for Ground Networks and Communications
2009 -	**Director, GGOS Bureau for Networks and Communication/Networks and Observations**

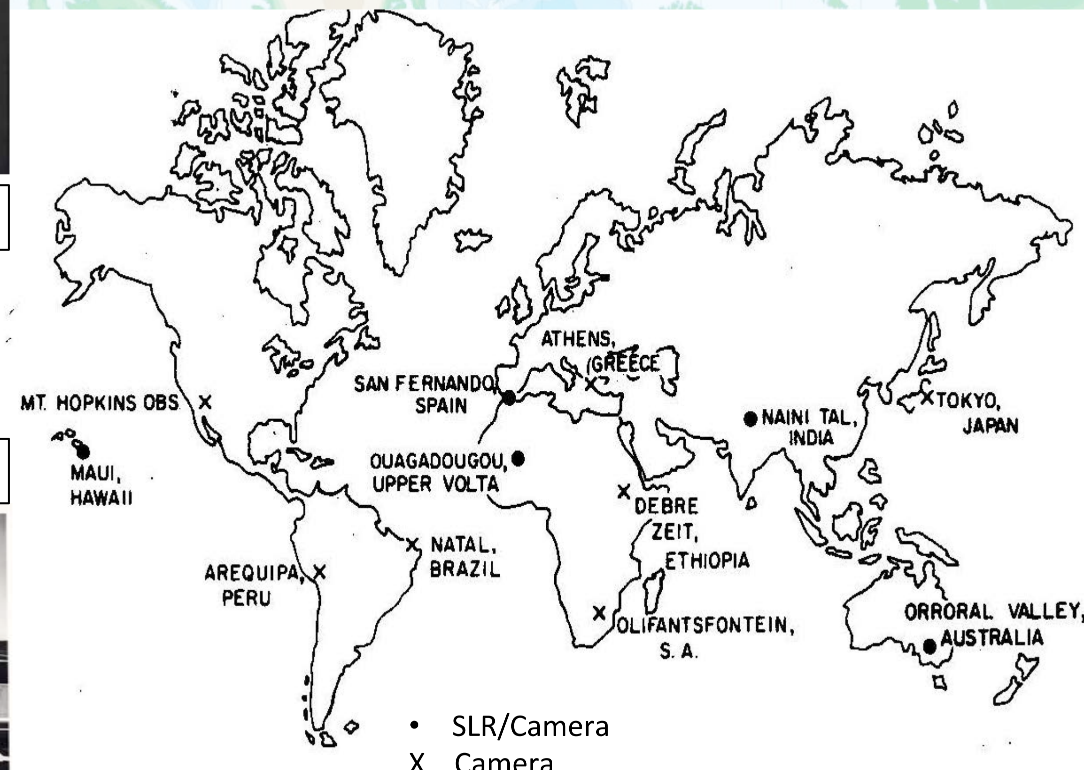
Satellite Tracking Program
SAO and Partner SLR and BN Camera Network

Moonwatch Network

Original SAO SLR

Baker –Nunn Camera

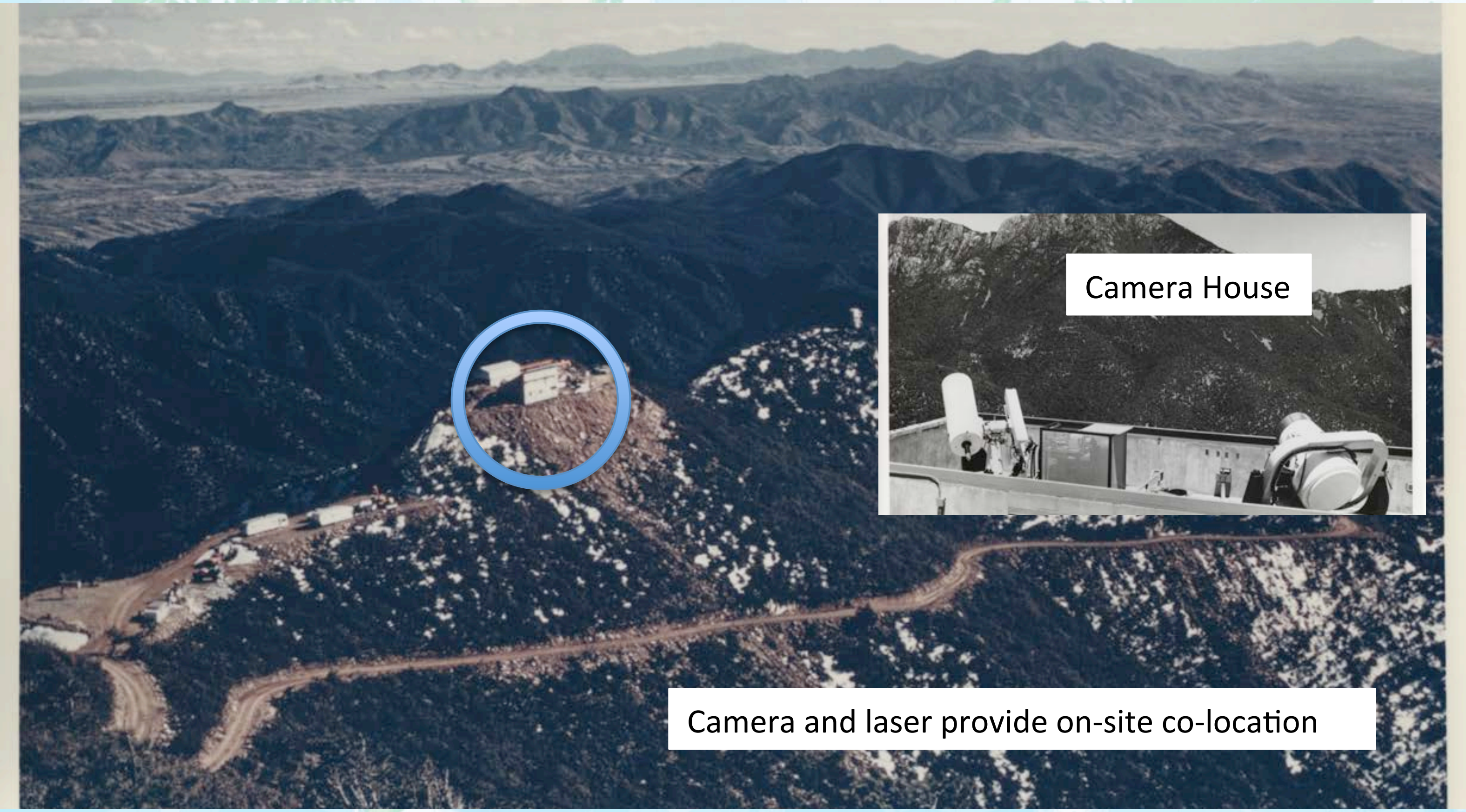
SAO Production SLR



1. Natal SLR moved to Matera in 1983
2. Olifantsfontein SLR moved to Orroral in 1975

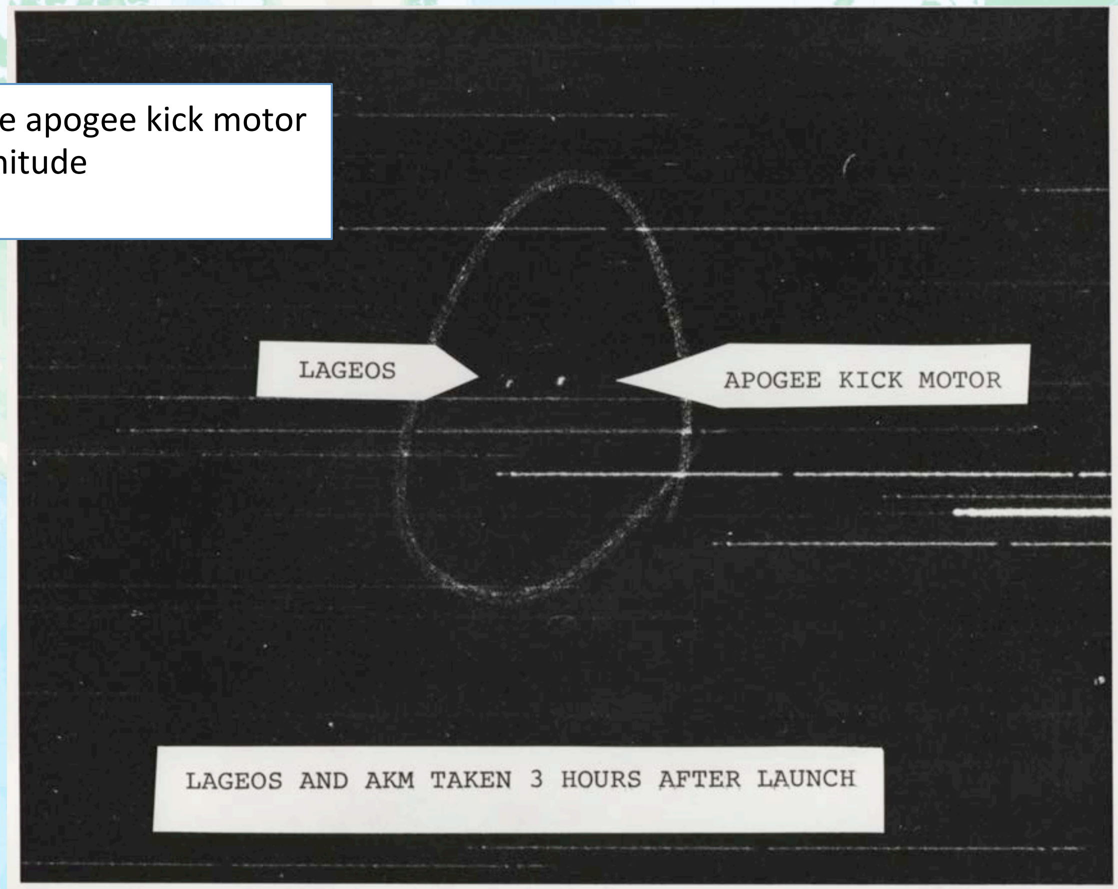
Mt. Hopkins (Arizona) Station

Primary Research and Development Site at 7600'



Lageos I BN Photo after Launch taken from Maui

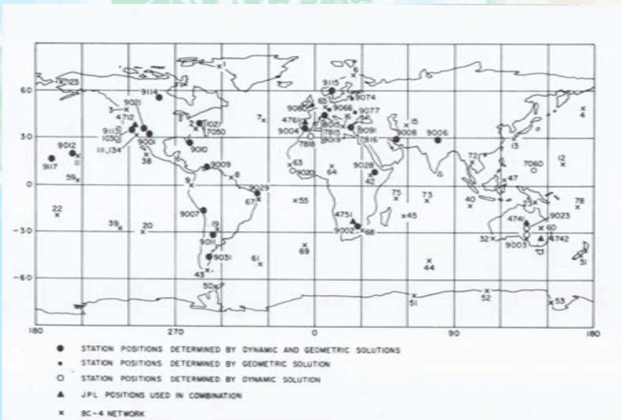
- With 4th stage apogee kick motor
- 12 – 13 magnitude
- May 4, 1976



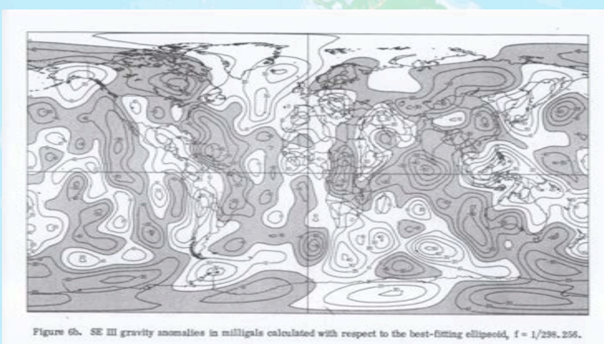
BN Photo of Comet Kohoutek 1973

Harvard-Smithsonian
Center for Astrophysics

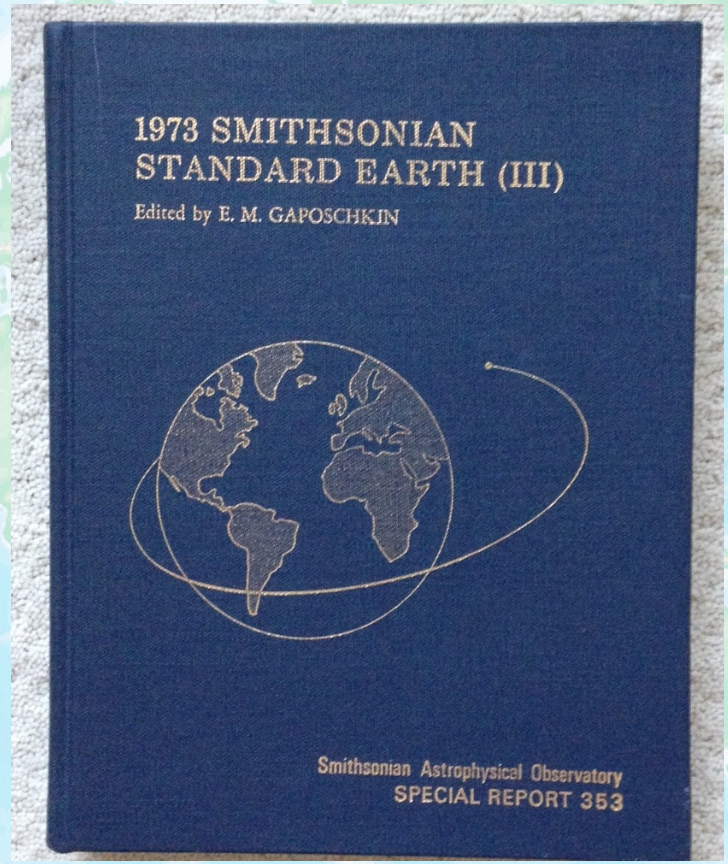
Smithsonian Standard Earth



Fiducial Networks

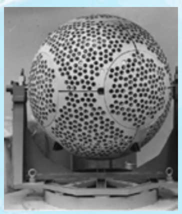


Gravity Field



Cooperation through the Years

- Meetings between Fred Whipple and Alla Messevich prior to launch of Sputnik
- Early tracking programs on Sputnik
- Early Campaigns on Beacon, GEOS, Diademe, etc.
- ISAGEX and EPSOC Campaign
- Helwan SLR Station
- VLBI/IVS Programs
- CSTG
- Etalon Satellites
- ILRS Network and Analysis (AWG)
- GGOS
  - IAA and ROSCOSMOS membership in the GGOS Network
  - IAA membership GGOS InterAgency Committee (Charter Member)
  - IAA and ROSCOSMOS participation in LARGE (GNSS) Project



And many others

The Global Geodetic Observing System (GGOS) and the Important Role played by the Institute of Applied Astronomy, ROSCOSMOS, and other Russian Participants

6th All-Russian Meeting
“Fundamental and Applied Positioning, Navigation and Timing” (PNT-2015)
April 20-24, 2015

Space Geodesy Provides a Suite of Ground-based Metric Tools for Studying the Dynamics of the Earth System

VLBI

SLR

GNSS

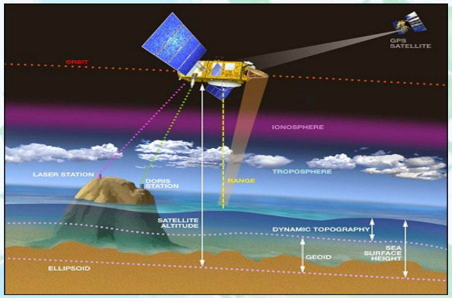
DORIS

Tide Gauge/GNSS

Gravimeters

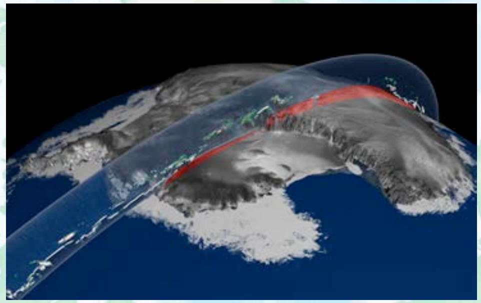
Space Geodesy Provides Space Base Metric Tools for Studying the Dynamics of the Earth System

TOPEX/Poseidon



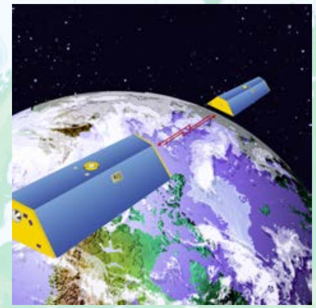
Satellite radar altimetry measures topography of ocean surfaces

IceSAT



Satellite Laser altimetry measures the topography of ice surfaces

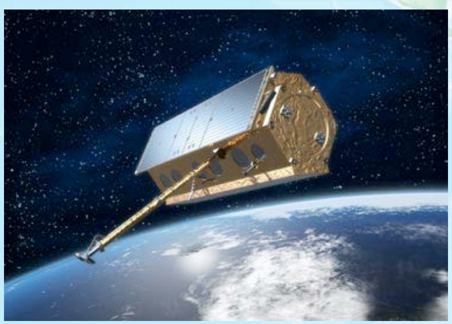
GRACE



GOCE

Gravity Field Missions map the gravity field structure that reflect the distribution or mass

TerraSAR-X



Synthetic aperture radar captures new high-quality radar images of the Earth

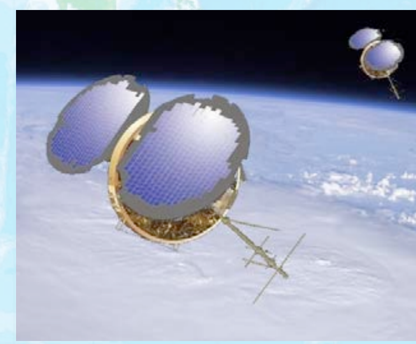
Tandem-X

Stereo viewing to provide a consistent global Digital Elevation Model

ERS ½ and Envisat

InSAR gives us maps of of change over time

COSMIC Constellation



Occultation measurements using GNSS reveal density of constituents in the atmosphere

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

GEOMETRY
GPS, Altimetry,
INSAR
Remote Sensing
Leveling
Sea Level

REFERENCE SYSTEMS
VLBI, SLR, LLR,
GPS, DORIS

EARTH ROTATION
VLBI, SLR, LLR,
GPS, DORIS
Classical: Astronomy
New: Ringlasers, Gyros

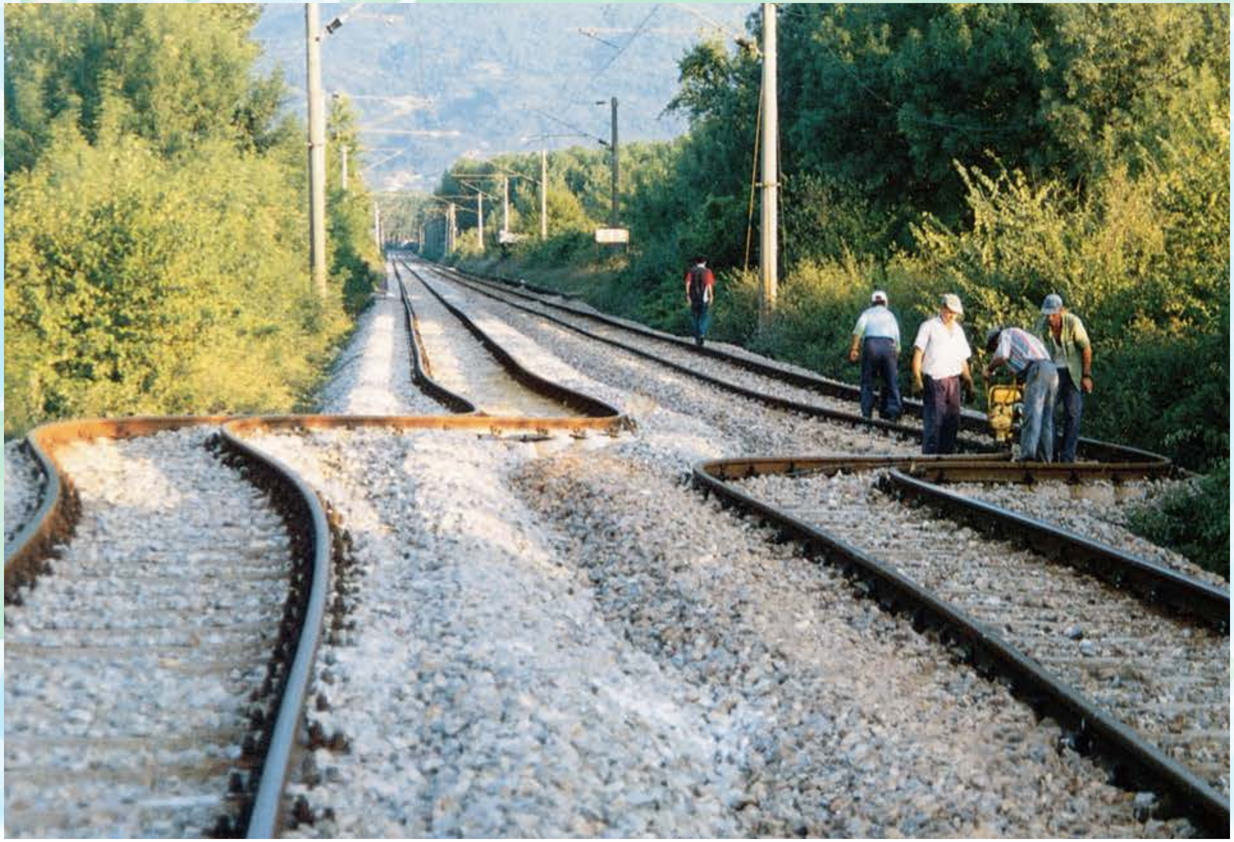
GRAVITY FIELD
Orbit Analysis
Satellite Gradiometry
Ship-& Airborne Gravimetry
Absolute Gravimetry
Gravity Field Determination

Geometry and Deformation of the Earth

- Problem and fascination of measuring the Earth:

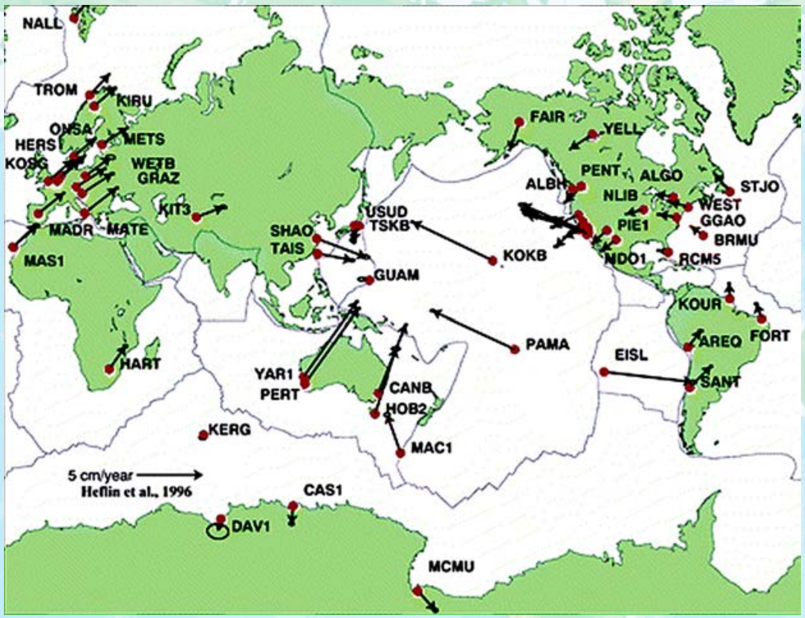
Everything is moving !

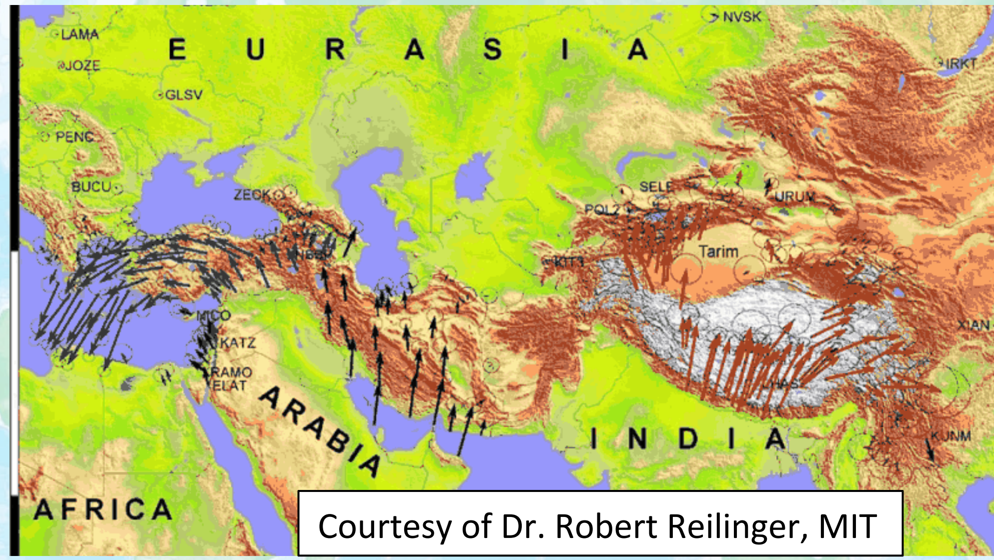
- Monitoring today mainly by GPS permanent networks



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

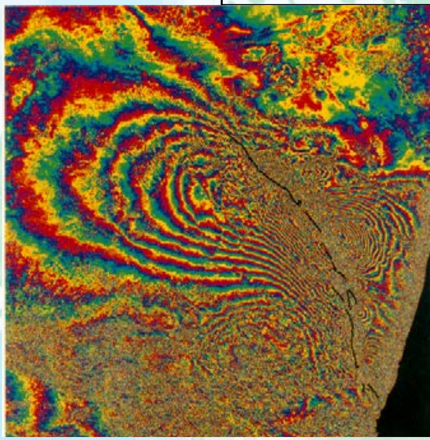
Ground based measurements with GNSS help us understand plate and regional crustal motions and their role in Earthquakes



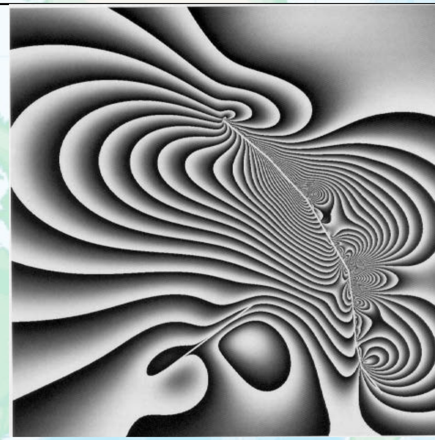


Courtesy of Dr. Robert Reilinger, MIT

Interferometer Measurements with Satellite Radar allows us to understand Localized Motions (Earthquake and Ice Stream Motion)



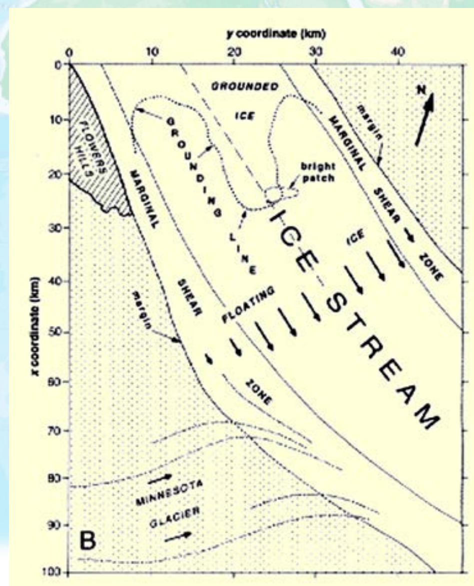
wrapped interferometric phase
April 24 – Aug 7, 1992
~100 x 100 km image



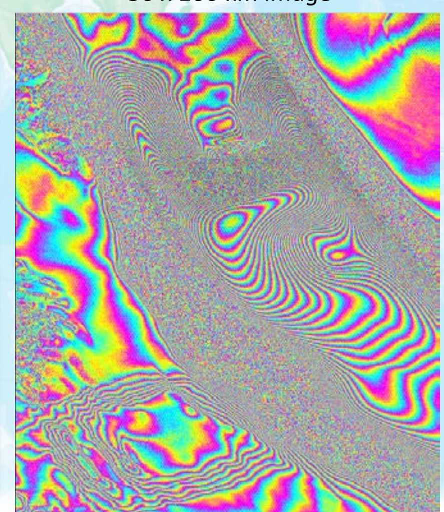
synthetic interferogram derived from elastic half-space dislocation model

1992 Landers, CA coseismic deformation
[Massonnet et al., Nature, 1993]

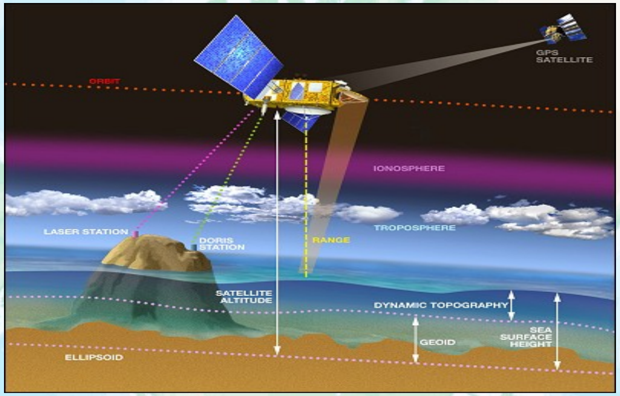
Rutford (Antarctic) ice stream motion
[Goldstein et al., Science, 1993]



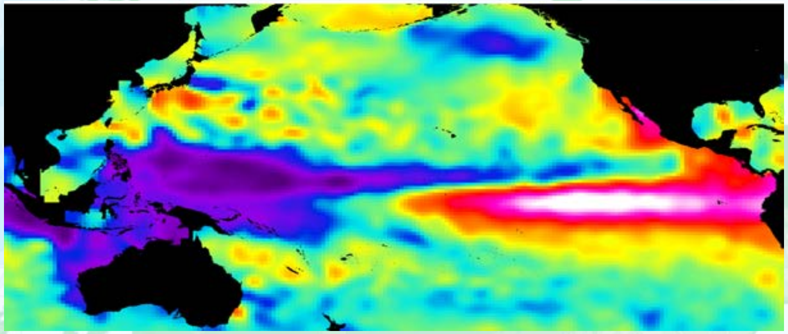
6-day interferogram
~50 x 100 km image



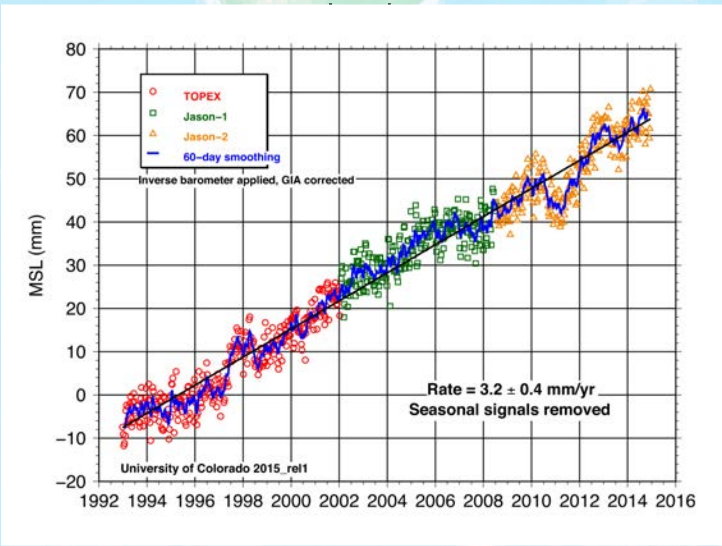
Satellite Altimeters allow us to map the ocean surface and monitor sea level changes



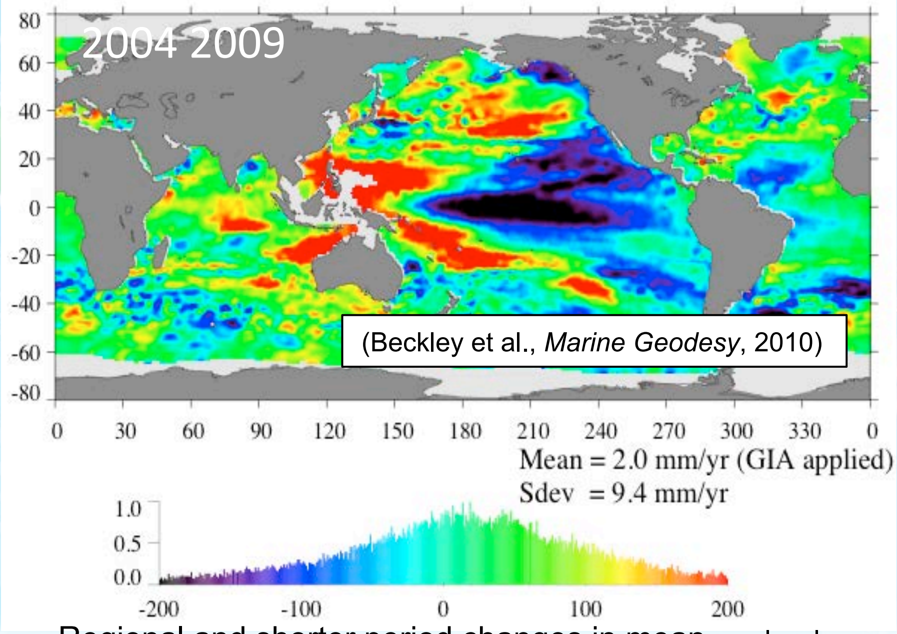
Altimeter satellite orbit determination based on SLR, DORIS and GPS has improved to the 1-3



Sea level variation due to the 1997/98 El Nino observed by TOPEX/Poseidon.

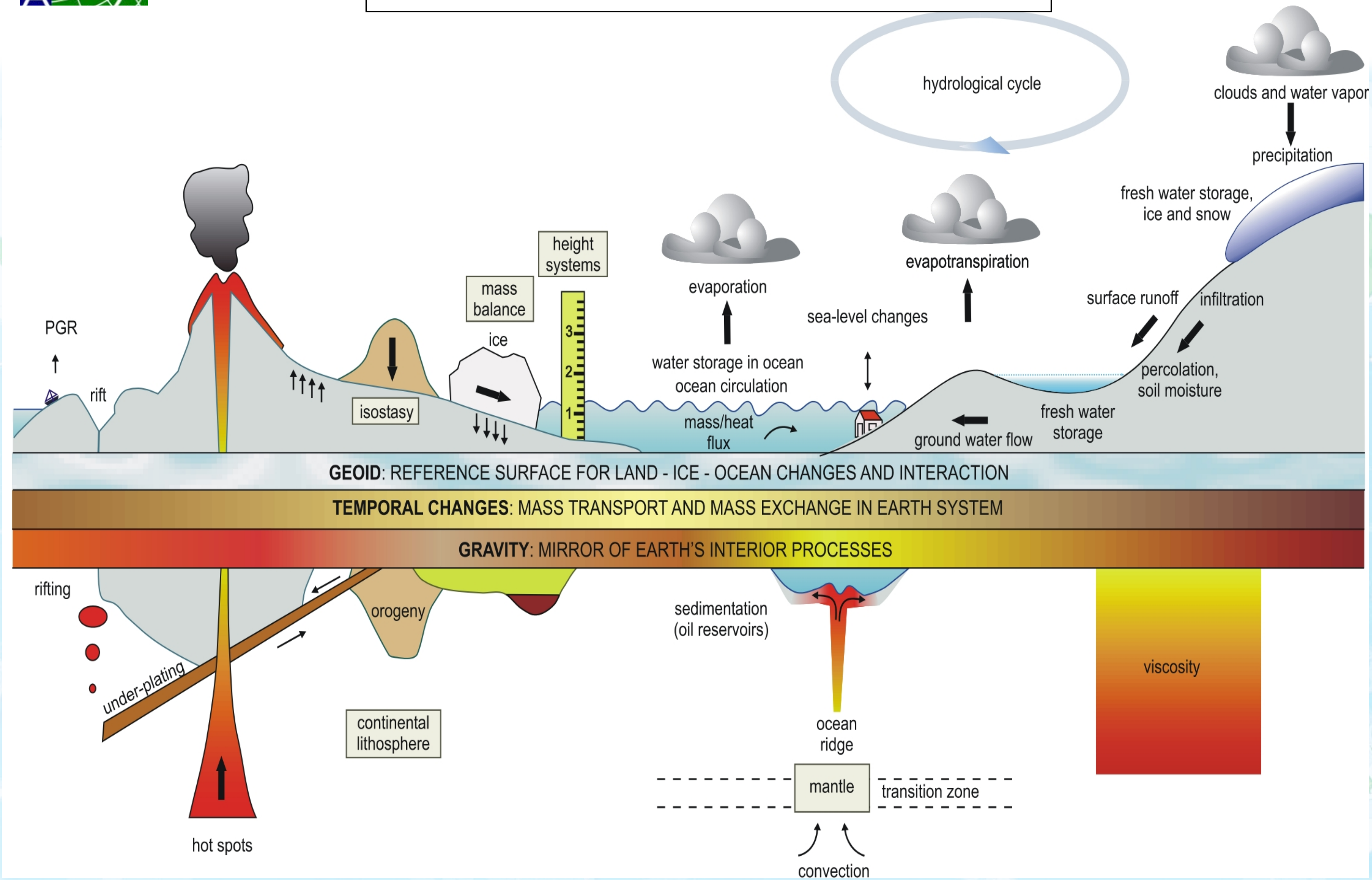


Global mean sea level change observed from TOPEX/ Poseidon, Jason-1 and Jason-2 (http:// sealevel.colorado.edu/)



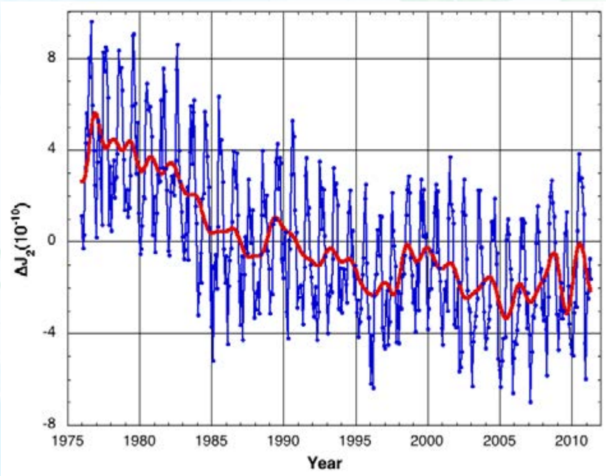
Regional and shorter period changes in mean sea level.

Gravity Field and Mass Transport

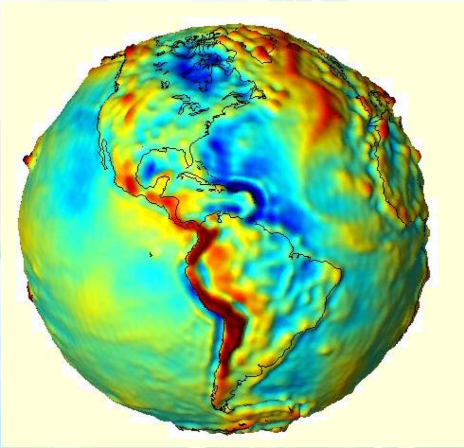


Ilk et al. (2005) Mass Transport and Mass Distribution in the Earth System, 2nd Edition, SPP1257 DFG

Global Gravity Structure and Changes in that structure tell us about mass distribution and how that distribution changes with time



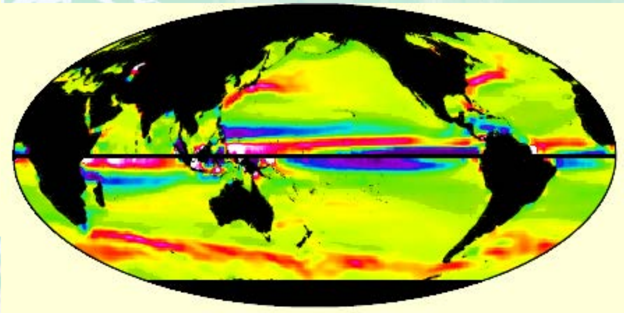
Long-term trends in J2 due to PGR as well as mass redistribution due to water exchange between and within the cryosphere and hydrosphere



Global gravity anomalies from GRACE

Global mean gravity field model improved by orders of magnitude

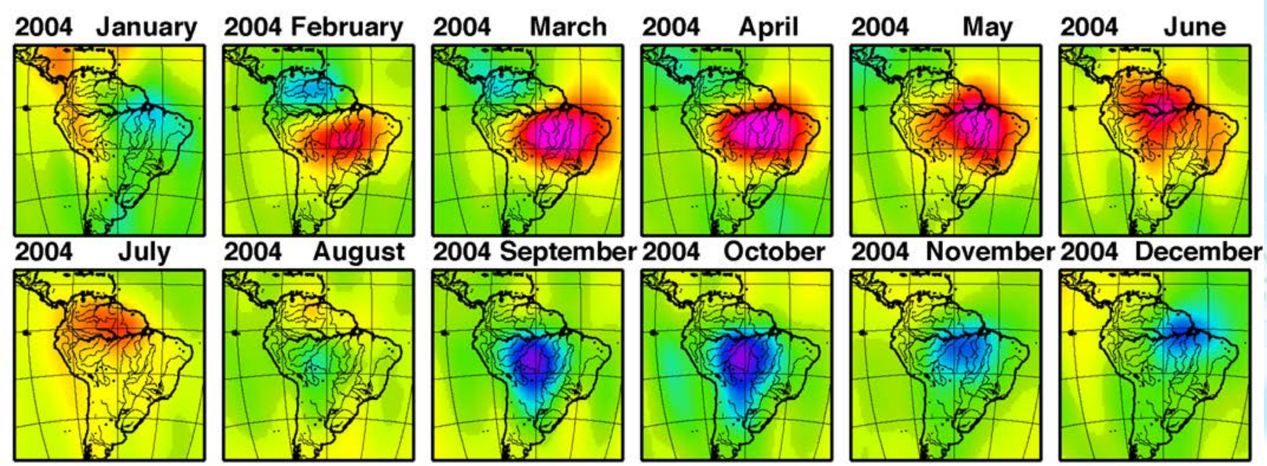
Absolute ocean surface currents can be clearly resolved with unprecedented accuracy



Zonal ocean circulation inferred from GRACE geoid and altimetry-based mean sea surface

Temporal gravity changes observed by GRACE

A clear separation can be observed between the large Amazon watershed and the smaller watersheds to the north, indicating that basin-scale variability is being resolved

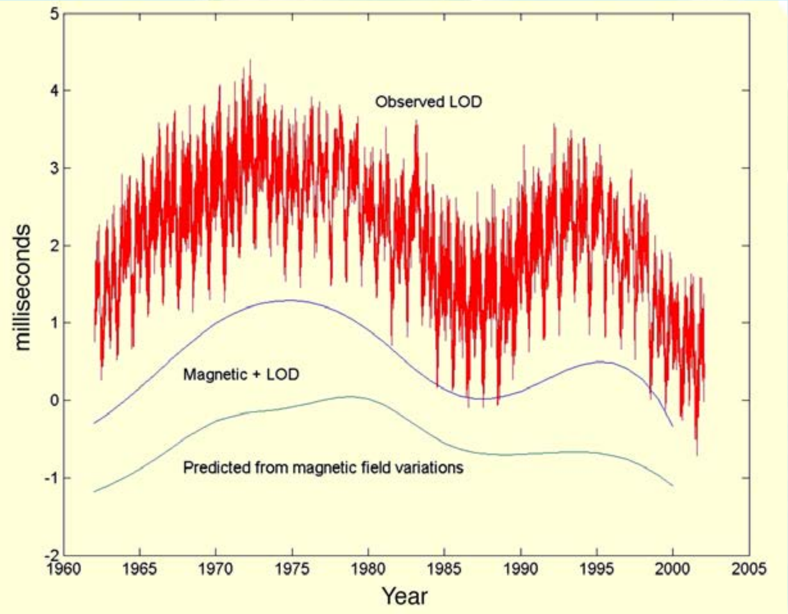


Mass variations are observed in Amazon basin with ~400 km resolution (range is from -12 to +12 cm of water)

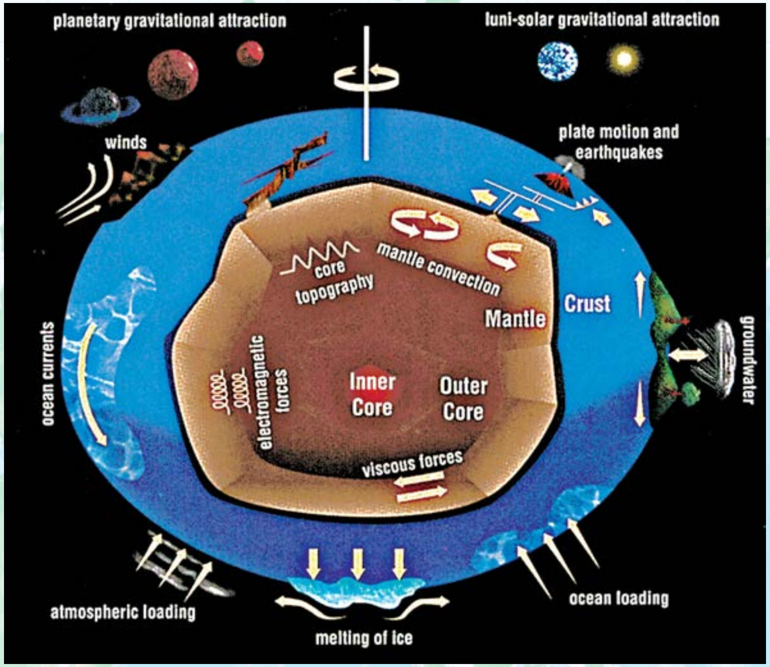
Measuring Earth Rotation tells about the Earth's Angular Momentum and how it changes- Core Effects, Atmospheric effects, Ocean Circulation, Shifting of Mass, etc

Space geodetic observations, starting in the 1970's, brought orders of magnitude improvement in Earth rotation (and polar motion) determination

- *High frequency changes forced by the ocean and atmosphere revealed*
- *Earth rotation (and polar motion) variations provide an integrated measure of mass and momentum exchange with the atmosphere and oceans, allowing us to use the angular momentum budget to test the truth of ocean, atmosphere, and hydrologic global climate models.*



Observed Length of Day (LOD) and estimates of core effects

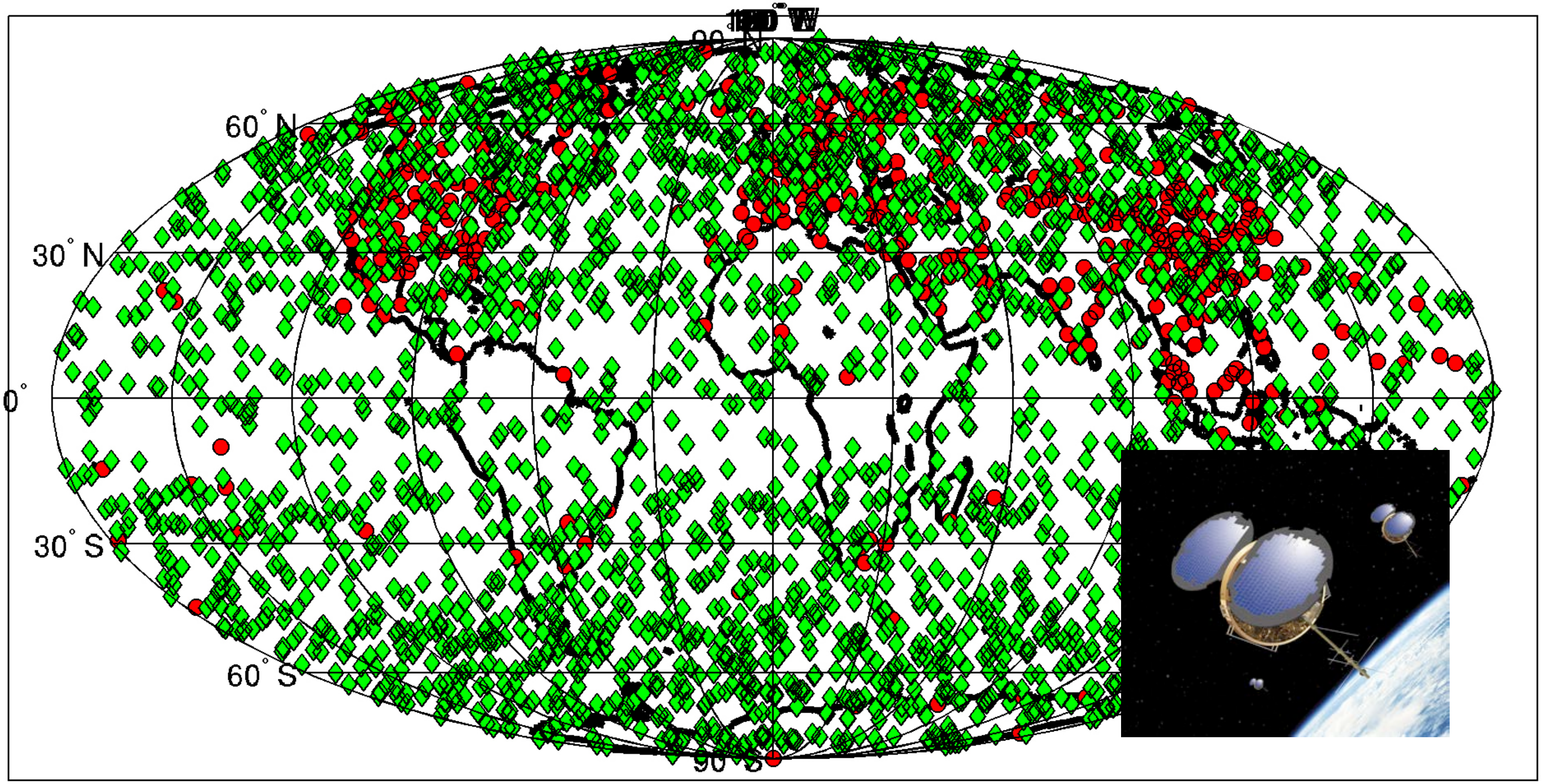


On decadal time scales, the variations in the LOD have been shown to be correlated with magnetic field variations

- *These LOD variations are thus believed to be associated with the changes in the core angular momentum (CAM)*
- *Core-mantle coupling is an important modulation for crustal deformations, and decade-scale correlations can be used to improve the reliability of earthquake precursor identification*

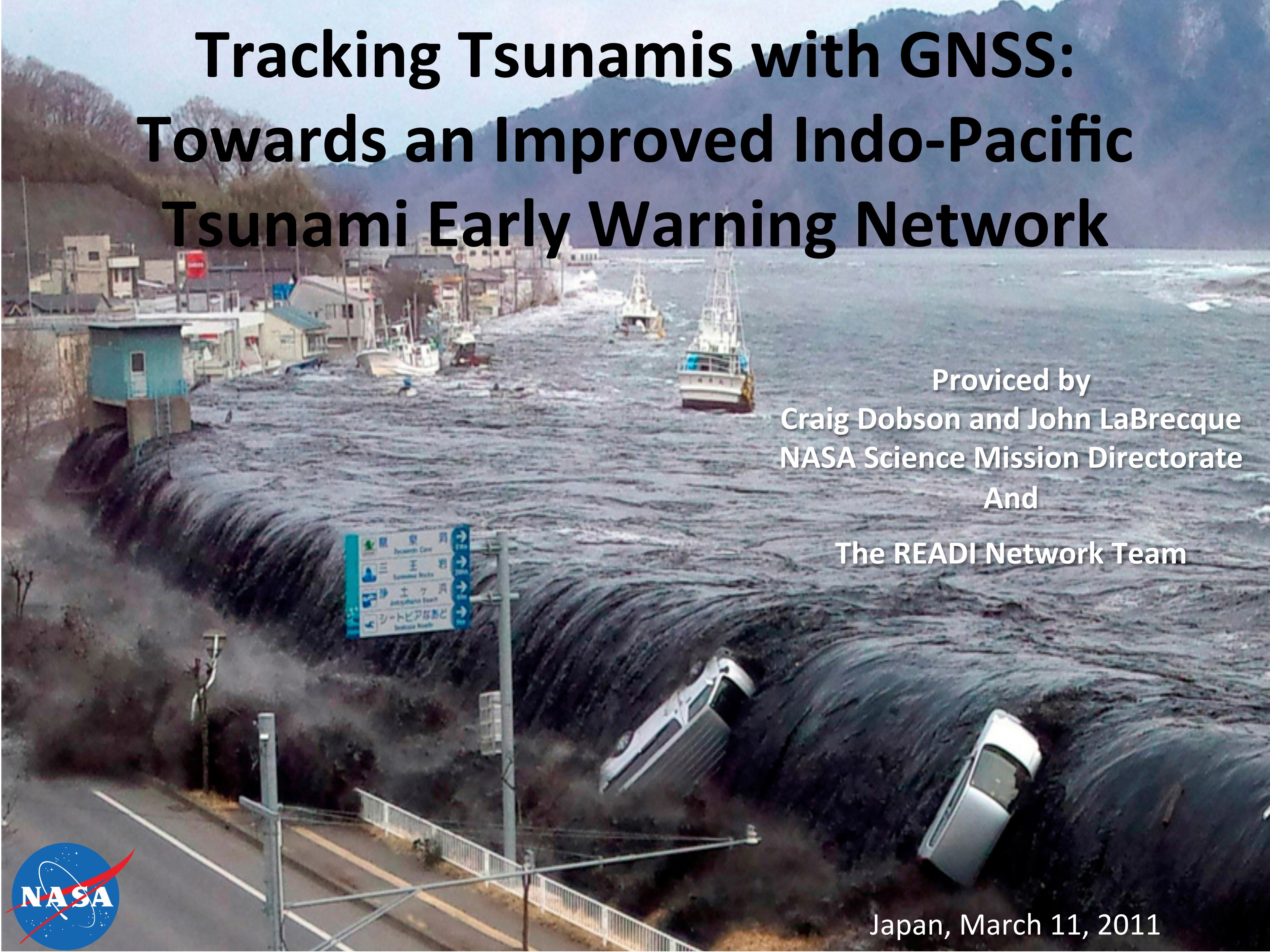
Occultations between the COSMIC Constellation and the GNSS Satellites will give us Synoptic Measurements of Atmospheric Constituents

Occultation Locations for COSMIC, 6 S/C, 6 Planes, 24 Hrs



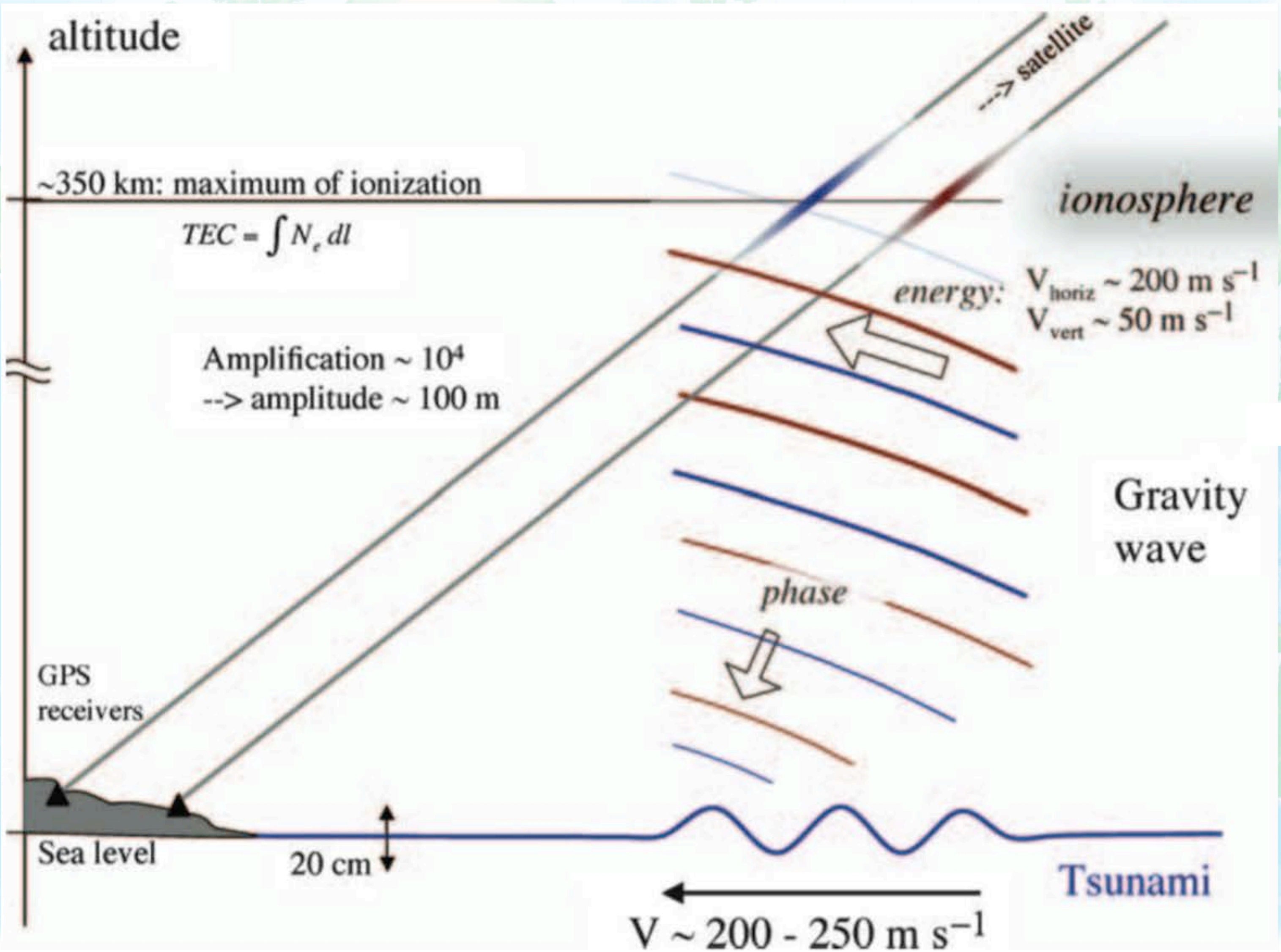
Tracking Tsunamis with GNSS: Towards an Improved Indo-Pacific Tsunami Early Warning Network

Proviced by
Craig Dobson and John LaBrecque
NASA Science Mission Directorate
And
The READI Network Team



Japan, March 11, 2011

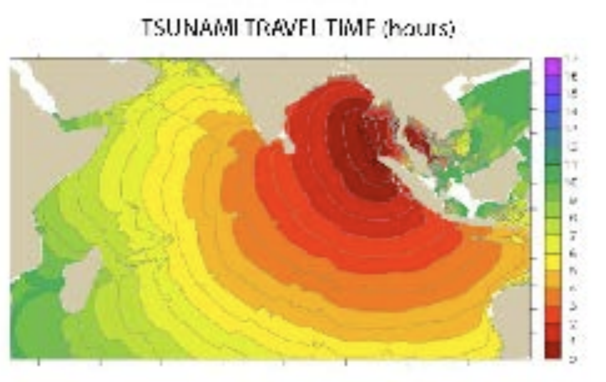
The Tsunami Generated Displacement of the Ocean Surface Couples to the Ionosphere

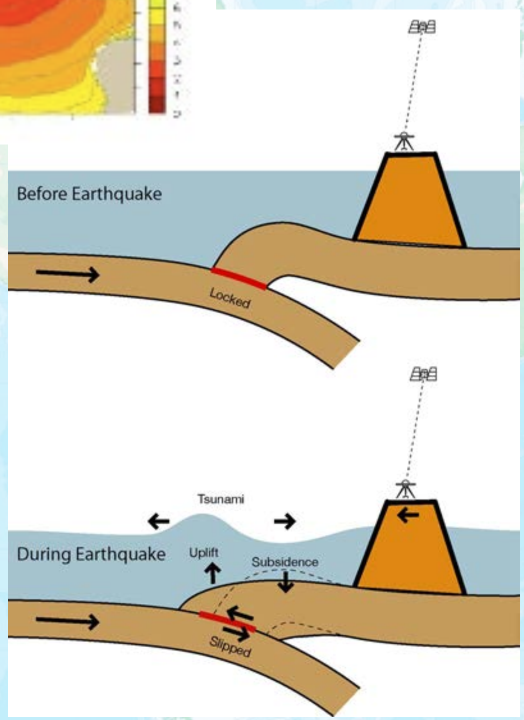


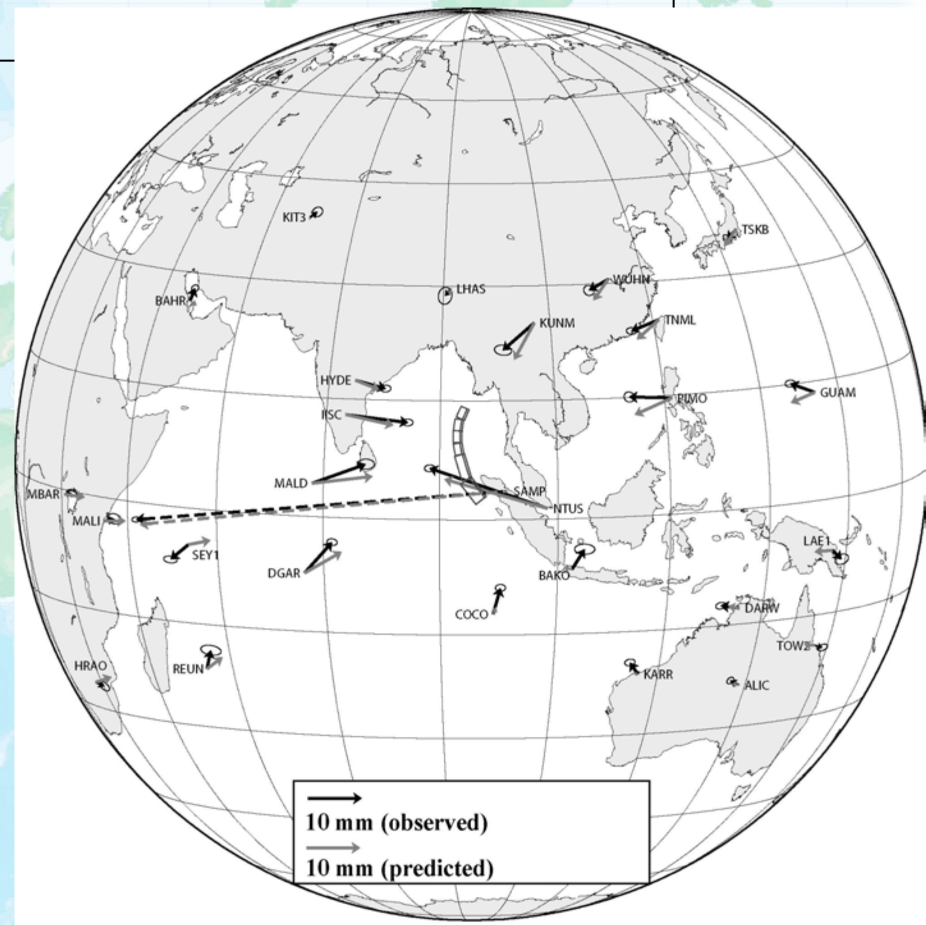
From *Artru et al.,* 2005

Post Processing of regional geodetic data taken on December 26 2004 Demonstrated the Value of a Global Regional GNSS Real Time Network

A Dense Global Real Time GPS Network would have warned of the Indian Ocean Tsunami within minutes- hours to days before the seismic analysis-





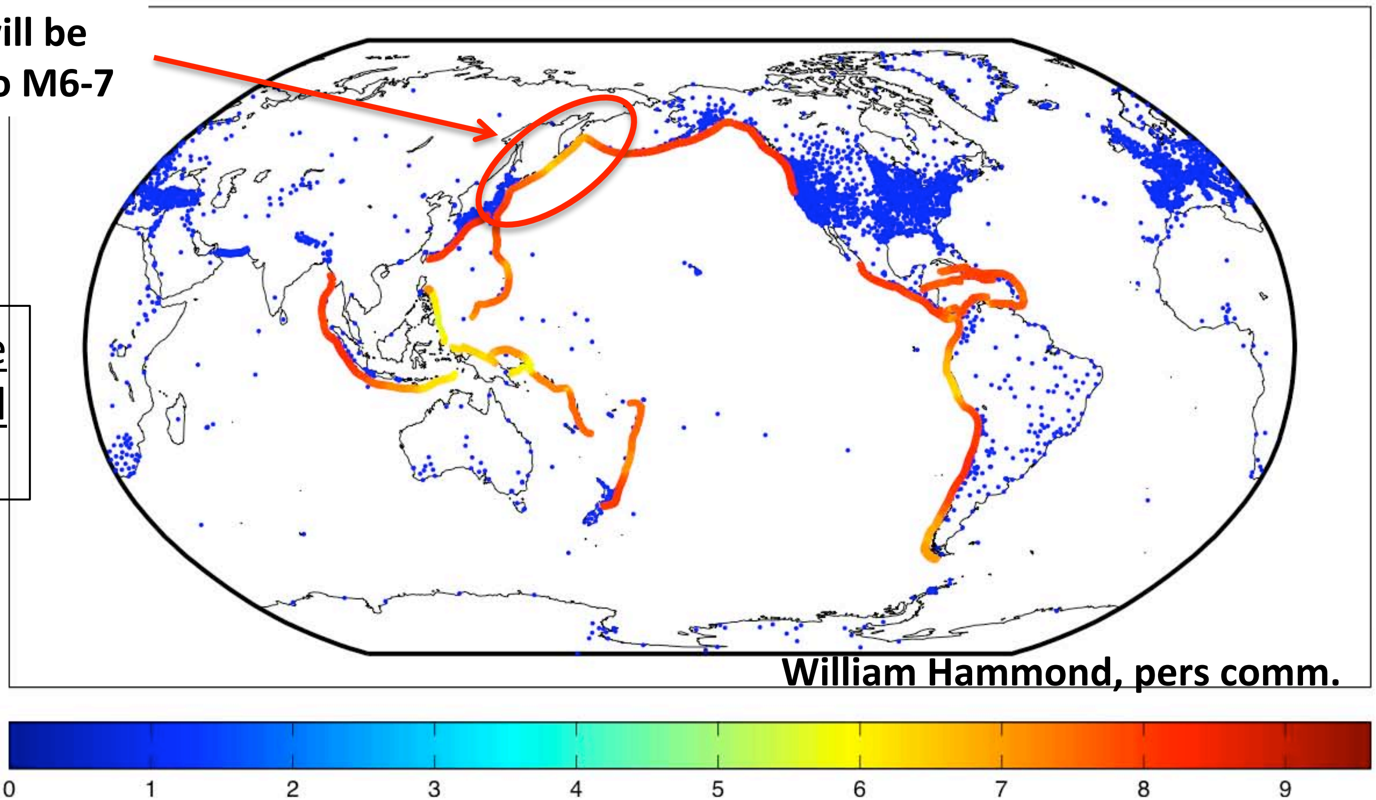


GPS station displacements on 26 December, 2004 observed by the International GNSS Service Network (IGS/GGOS). The largest arrow (SAMP) has been scaled down by a factor of two for clarity. Ref: Blewitt, Hammond, Kreemer, Plag, Stein, Okal, 2009,J. Geodesy.

Tsunami Prediction Capability of the Current Network

Simulating the ability to resolve a M9 Earthquake along the "Ring of Fire" using available GPS networks

M9 earthquake will be under-resolved into M6-7



Requires real-time GNSS from the full GNSS netwrok

Simulations indicate that the Kamchatka-Kuril region (as well as many other regions along the "ring of fire") is not equipped with sufficient density of GNSS receivers to enable GNSS-based resolution of large earthquakes

Common Thread: Reference Frame

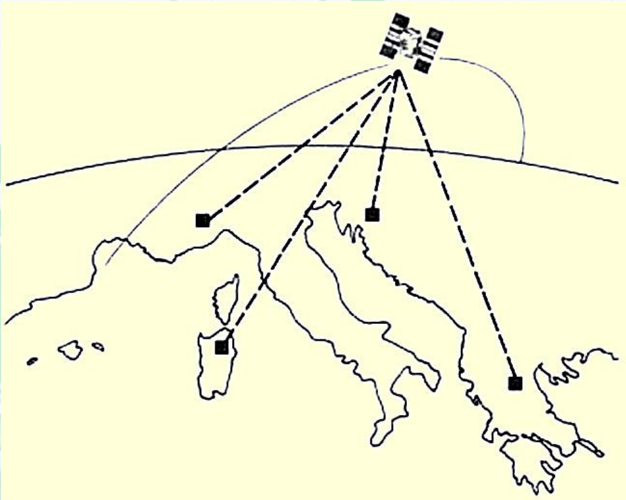
The TRF and the associated Earth Orientation Parameters provide the stable coordinate system that allows us to link measurements over space, time, and evolving technology

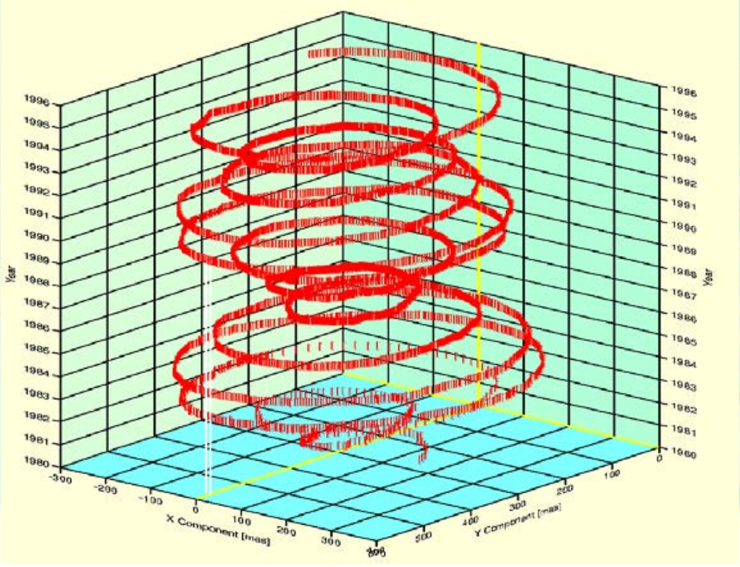
They provide the background against which absolute position/velocity have meaning

While VLBI uniquely provides the absolute orientation wrt the stars, only satellite-based techniques can tie the TRF to the Earth's mass center or monitor the Earth's surface motion at hundreds or thousands of locations

Satellite orbits can only be described in terms of a well-defined terrestrial reference frame

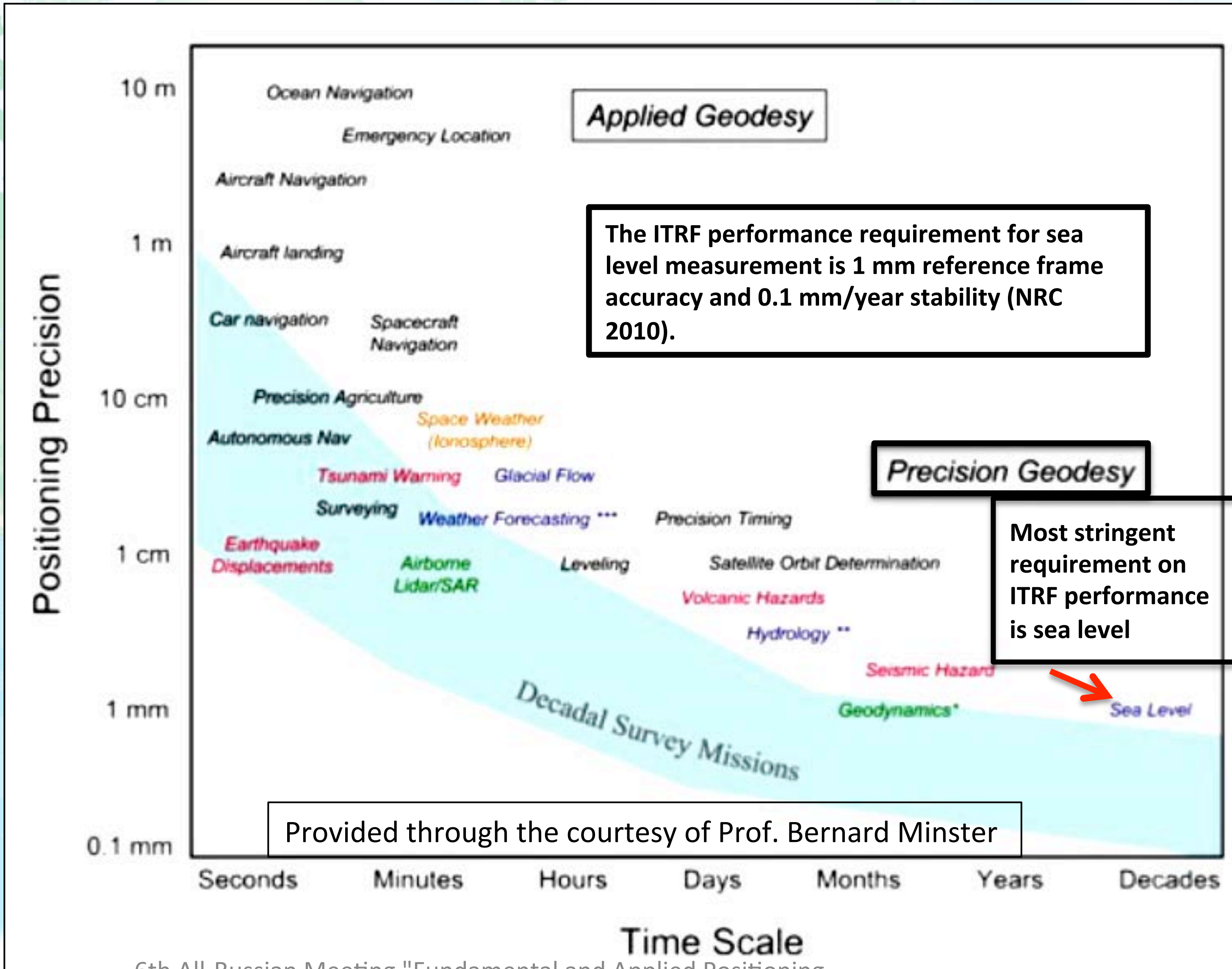
Tide gauge vertical rates can be accurately defined only in the context of a terrestrial reference frame





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.**



GLOBAL Reference Frame
(Terrestrial and Celestial)

- Most stringent requirement from sea level rise, but other applications are close behind
  - "accuracy of 1 mm, and stability at 0.1 mm/yr" (a factor of 10-20 improvement)
- Accessibility: 24 hours/day; worldwide
  - Users anywhere on Earth can position their measurements in the reference frame
- Space Segment:
  - LAGEOS, LARES, Etalon, 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 GNSS ground station network to distribute the frame globally to the users
- Reference Frame Formulation provided by the IERS from data provided by the IAG Services: IGS, IVS, ILRS, and IDS

VLBI	SLR	GNSS	DORIS	Vector Tie
				

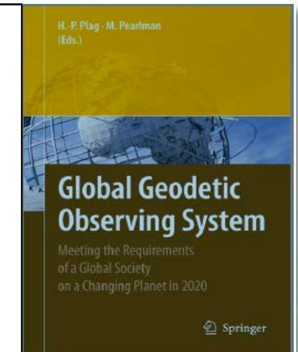
Global Geodetic Reference Frame (ITRF and ICRF combination) for Sustainable Development (GGRF) resolution

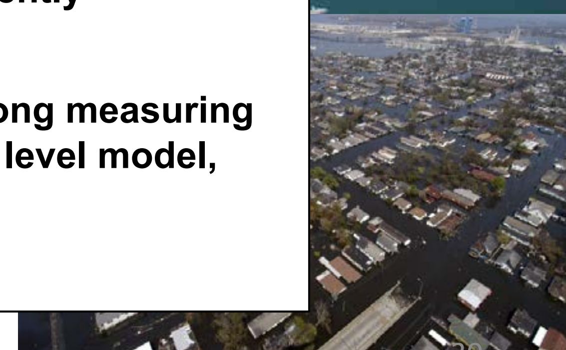
- No. A/69/L.53 -

- adopted by the United Nations General Assembly on 26 Feb 2015
- co-sponsored by 52 Member States

Global Geodetic Observing System (GGOS)

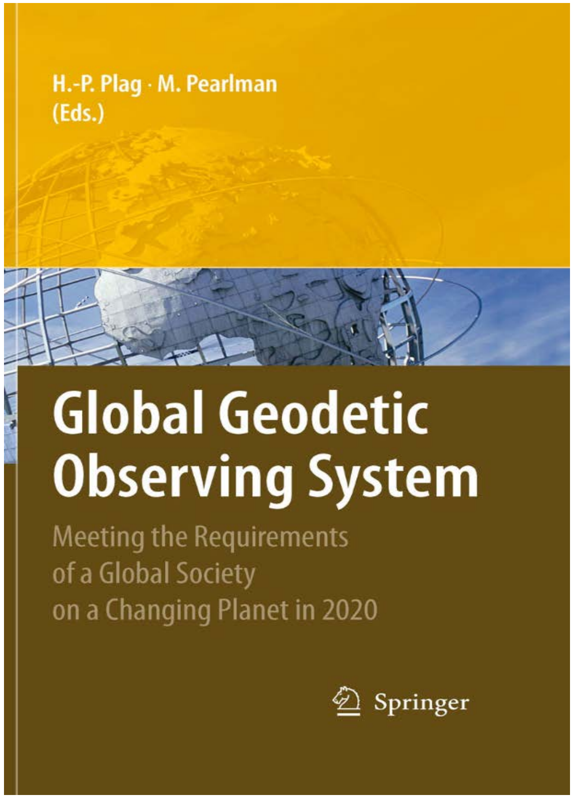
- **Established by the International Association of Geodesy (IAG) be its Observing System**
- **Vision: Advancing our understanding of the dynamic Earth system by quantifying our planet's changes in space and time to:**
  - **Advance Earth Science (Earth, oceans, ice, atmosphere, etc)**
  - **Help us make intelligent societal decisions**
- **Mode of Operation: Works with the IAG components (IGS, ILRS, IVS, IDS, IGFS, IERS, IAG commissions, etc.) to provide the geodetic infrastructure necessary for monitoring the Earth System and Global Change:**
  - **observations needed to monitor, map, and understand changes in the Earth's shape, rotation, and mass distribution;**
  - **the TERRESTRIAL REFERENCE FRAME and CELESTIAL REFERENCE FRAME for measuring and consistently interpreting key global change processes;**
  - **Other data products that require integration among measuring techniques: Unified height systems, Unified sea level model, Natrual hazard warning tools, etc**





GGOS 2020 Book (2009)

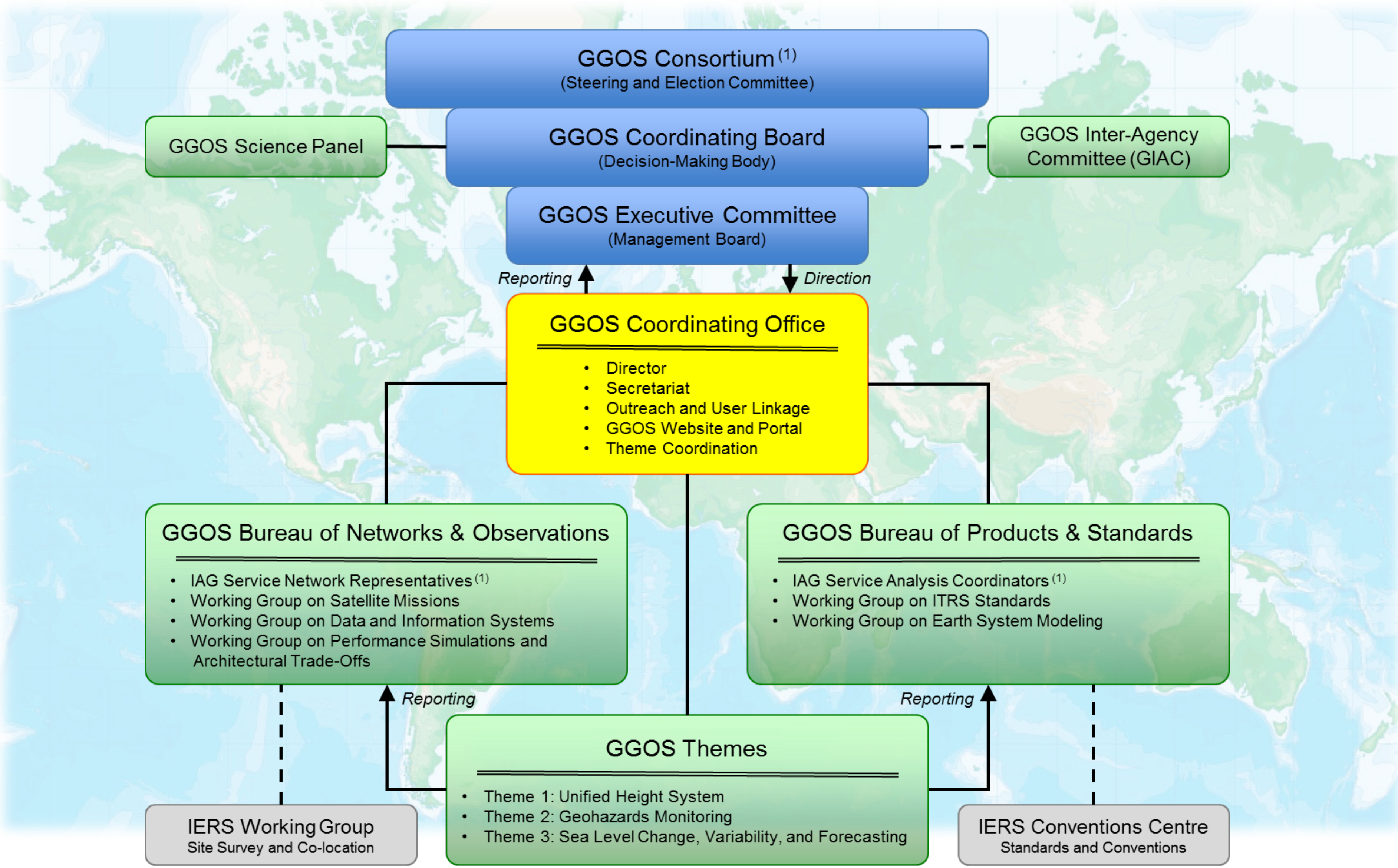
GGOS: Meeting the Requirements of a Global Society on a Changing Planet in 2020. Eds. H.-P. Plag and M. Pearlman. Springer 2009. p. 332



Content: main arguments for GGOS

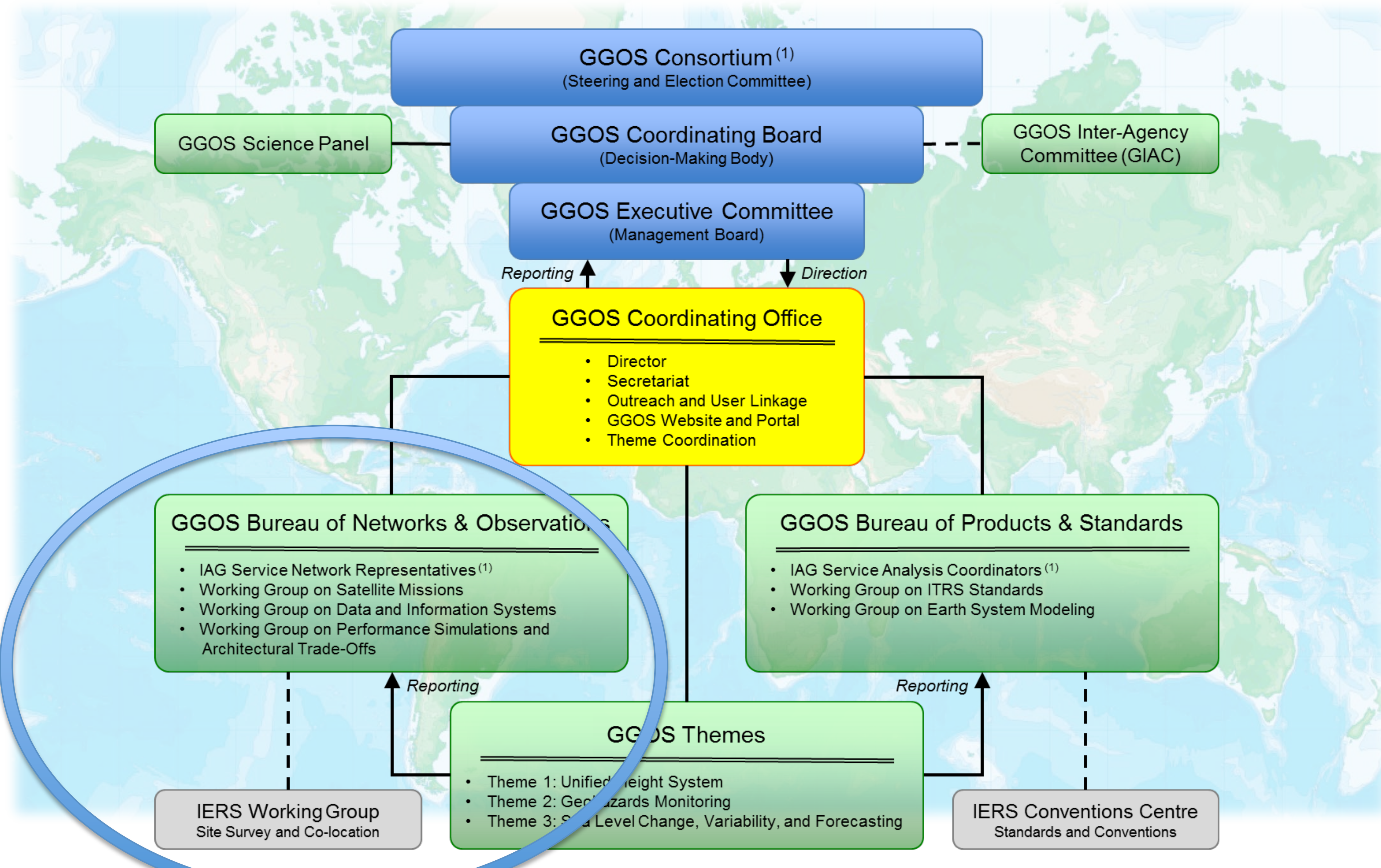
- Goals, achievements and tools of modern geodesy
- Earth science requirements for geodesy
- Maintaining a modern society (9 societal benefit areas)
- Future geodetic reference frames
- Future Global Geodetic Observing System (GGOS)
- GGOS 2020

GGOS Organizational structure



(1) GGOS is built upon the foundation provided by the IAG Services, Commissions, and Inter-Commission Committees

GGOS Organizational structure



[1] GGOS is built upon the foundation provided by the IAG Services, Commissions, and Inter-Commission Committees

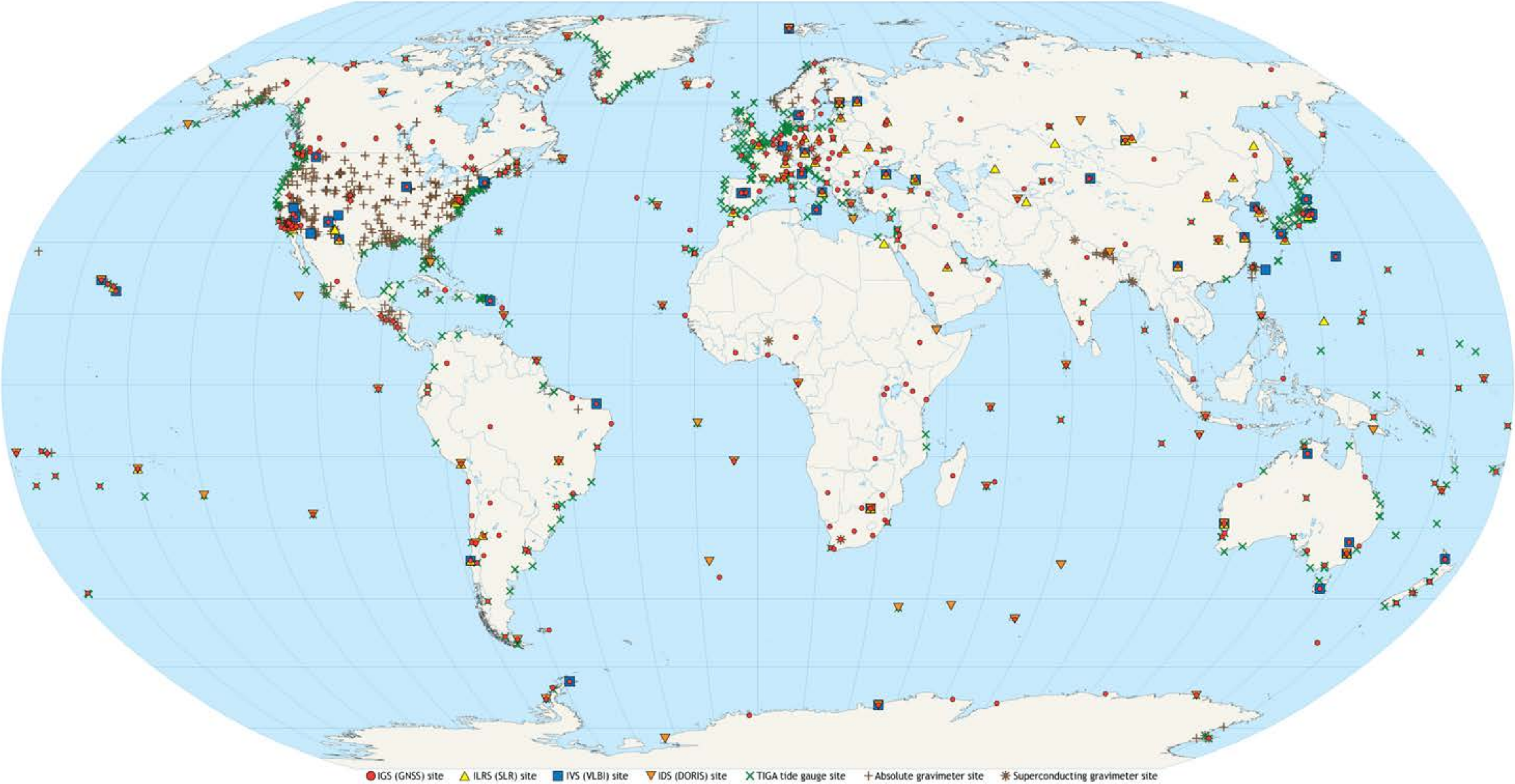
Bureau of Networks and Observations

- Focus on the measurement (network) infrastructure;
  - How do we use the current infrastructure to provide the most benefit;
  - How do we advocate for expansion
- Data from multiple techniques are required to support new integrated data products;
- Currently working on the Reference Frame (ITRF and ICRF) and the networks necessary to support them;
- Currently working to provide improved global tracking coverage including GNSS;
- Working to include gravity field and tide gauges
- Working with new missions to be in a position to help support them after launch

Data Products

- Synergy of the Techniques in building more powerful data products
  - Reference Frame
  - Precision Orbit Determination
  - Unified Height System
  - Ocean Surface Monitoring
  - Monitoring for Other Natural Hazards
    - Tsunami Warning System

Stations Participating in the GGOS Affiliated Network

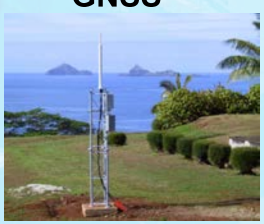


Why a Core Site?


SLR

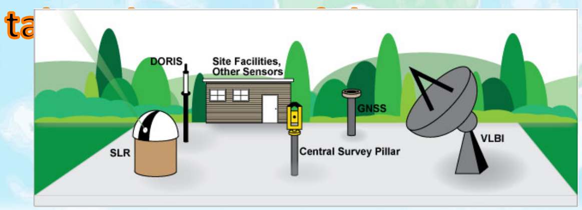

VLBI


GNSS


DORIS

- Co-located SLR, VLBI, GNSS and DORIS (where available) so that their measurements can be related to sub-mm accuracy

- Why do we need multiple techniques?
  - 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 (Co-location) allows us to ta strengths and mitigate the weaknesses



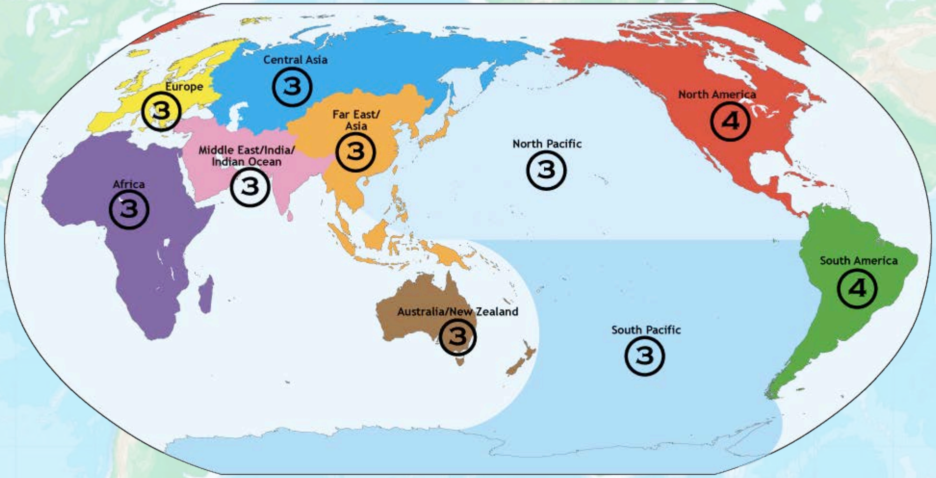
What does each technique provide to the Reference Frame

- SLR: Uniquely provides Earth Center of Mass;
- VLBI: Provides EOP parameters and the connection with the Celestial Reference Frame;
- SLR and VLBI independently provide Scale
- GPS: Global coverage and density
- DORIS: Global coverage
- Gravimetry: Help interpret station dynamics

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.



- Design Initiative, but it a major Challenge
- Will require time, significant resources, and strong international participation

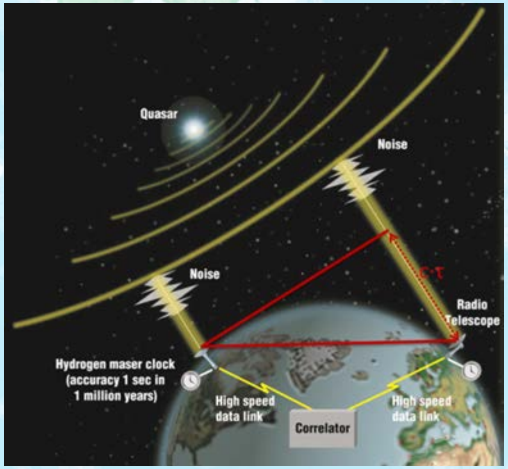
Next Generation VLBI: VGOS
VLBI Global Observing System

Features:

- small and agile telescopes
  - small: 12–13 m dish diameter
  - fast: 12º/s and 6º/s slew speeds
- large bandwidth: 2–14 GHz
- flexible frequency allocation
- dual linear polarization

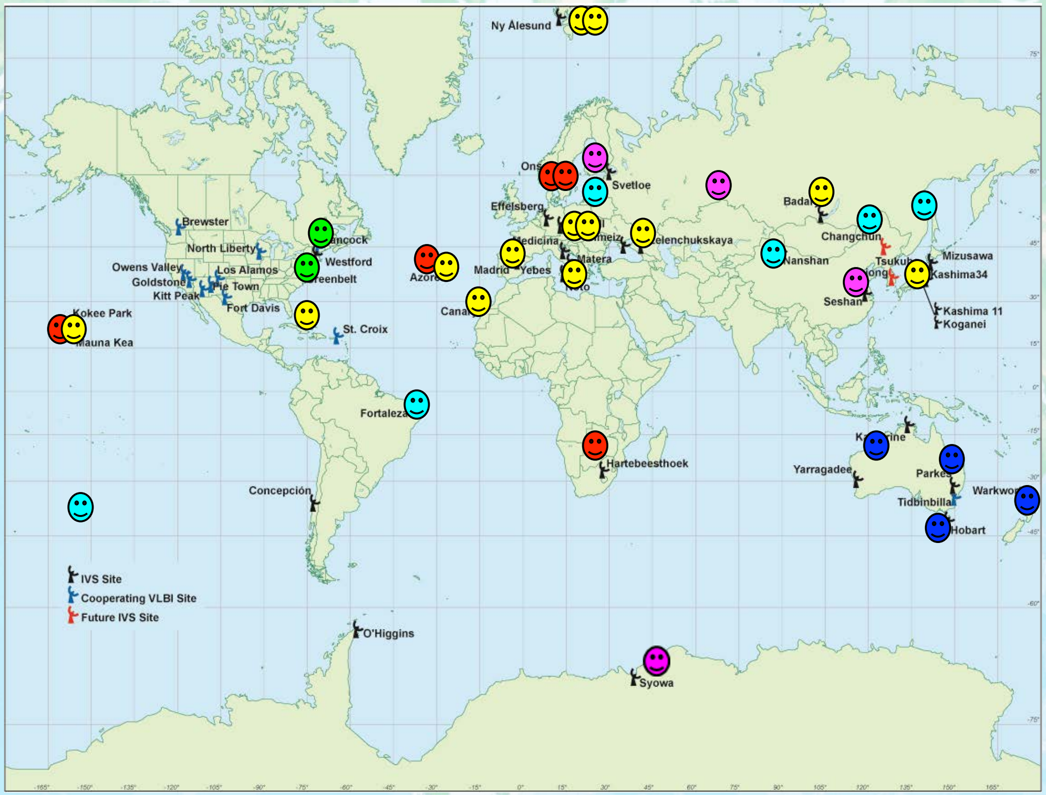
Implies:

- dense sampling of atmosphere
- up to 2 observations per minute (2880/day)



VGOS World

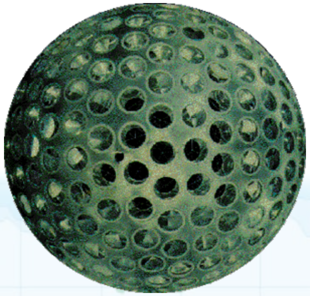
New VGOS radio telescopes for the IVS



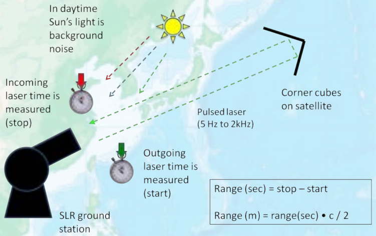
- operational
- under construction
- funded
- proposal submitted
- planning phase
- planning phase upgrade

Courtesy H.Hase/VPEG, based on available information February 2014

Next Generation
Satellite Laser Ranging System
Basis for the Next Generation System

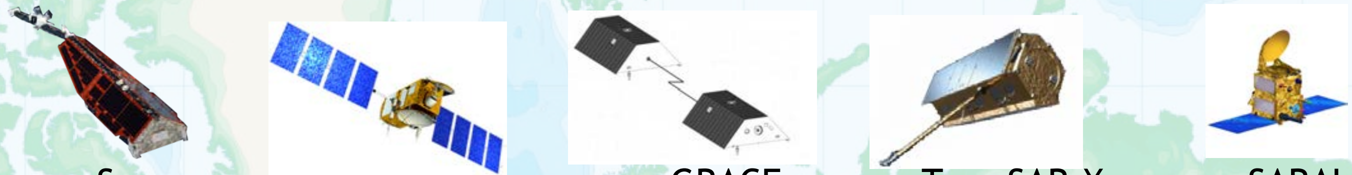


- Higher pulse repetition rate (KHz) for faster data acquisition;
- Smaller, faster slewing telescope for more rapid target acquisition and pass interleaving;
- Range from LEO to GNSS;
- More accurate pointing for link efficiency;
- Narrower laser pulse width (10 – 30 ps) for greater precision;
- Single photon detection for greater accuracy;
- More automation for economy (24/7);
- Greater temporal and spatial filtering for improved S/N
- Modular construction and more off the shelf components for lower fabrication/operations/maintenance cost;



Sample of SLR Satellite Constellation

LEO Satellites



Satellite	Swarm	Jason-2	GRACE	TerraSAR-X	SARAL
Inclination	92°	66°	89°	66°	98.55°
Perigee ht. (km)	720	1,336	450	1,350	814

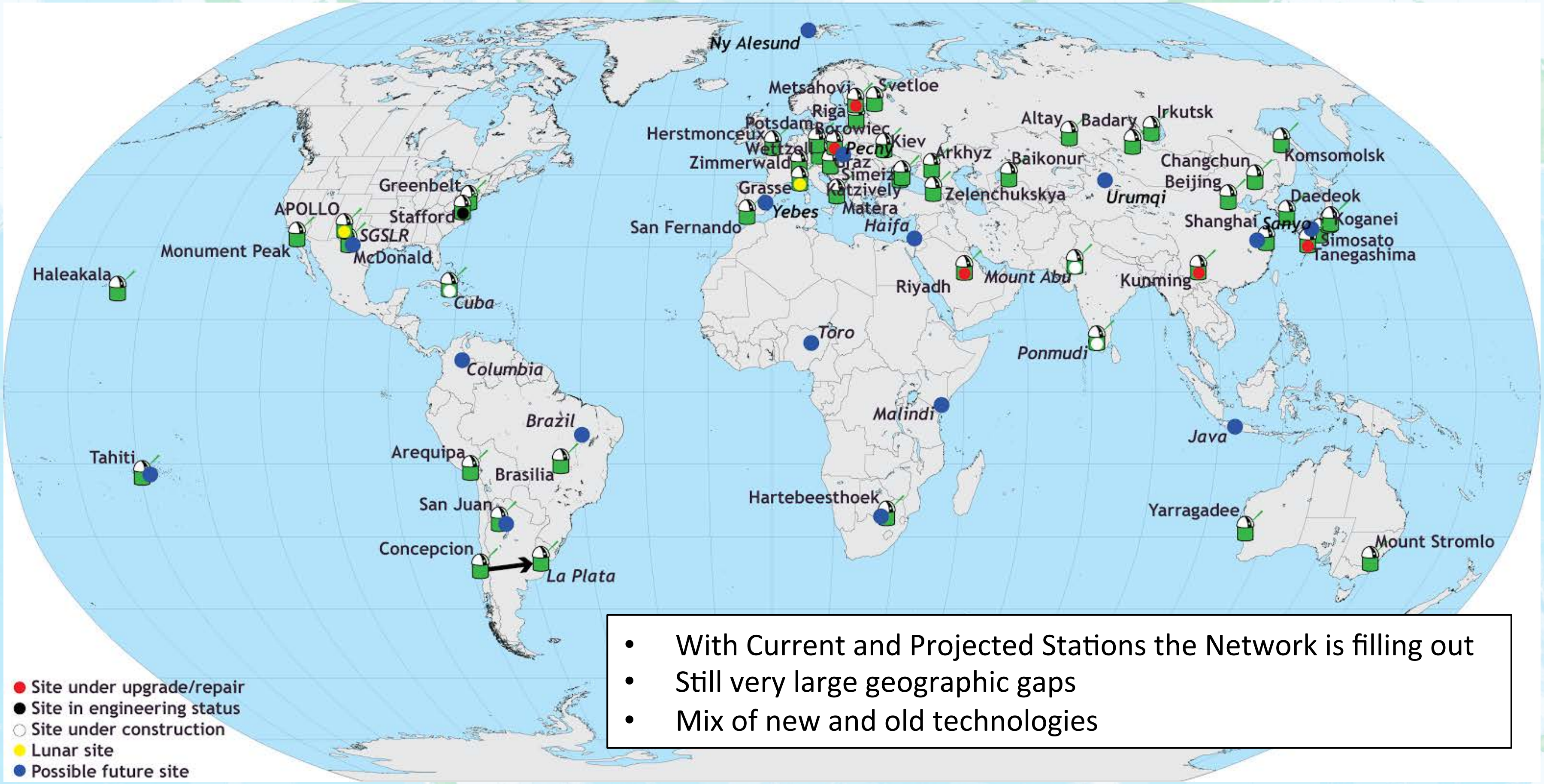
Geodetic Satellites

Satellite	Ajisai	LAGEOS-1	LAGEOS-2	Etalon-1/-2	Starlette	Stella	LARES
Inclination	64.8°	109.8°	52.6°	50°	50°	98.6°	69.5°
Perigee ht. (km)	19,120	5,860	5,620	1,490	810	800	1460
Diameter (cm)	129.4	60	60	215	24	24	36.4

GNSS/GEO Satellites

Satellite	GLONASS	Galileo	Beidou	IRNSS	QZS
Inclination	65°	56°	55.5°	29°	45°
Perigee ht. (km)	19,140	23,220	42,161	42,164	32,000

Projected SLR Network



- With Current and Projected Stations the Network is filling out
- Still very large geographic gaps
- Mix of new and old technologies

New Generation GNSS Receiver

- Multi-constellation receiver (GPS, Galileo, GLONAS, COMPASS, etc)
- Installed with stable monumentation (deep-drilled brace monuments);
- Real-time data transmission
- Registered for the IGS

Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)

- Global network of ~57 stations;
- New, higher performance ground stations and satellite payloads can track more satellites simultaneously;
- DORIS receivers are used on altimeter (TOPEX, Jason1, Jason2, ENVISAT, Cryosat-2) and remote sensing (SPOT) satellites; Future Missions: Jason-3, SWOT & SENTINEL-3;

Two Recent Initiatives

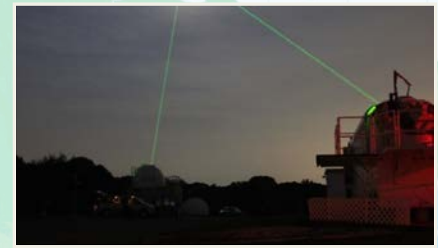
- Expansion of the Russian Network to Support:
  - GLONASS accuracy and time transfer
  - GGOS
- NASA Space Geodesy Project to support the NASA role in International Space Geodesy and GGOS

The development of the foreign segment of the Russian SLR network

In addition to existing stations Baikonur (Kazakhstan) and Brasilia (Brazil) the same SLR station will be installed in 2015 near Havana, Cuba (the station is ready). Four new-generation stations of submillimeter accuracy will be installed in future in 4 from 6 possible sites: San Juan (Argentina), HartRAO (South Africa), Haifa (Israel), the branch of the Shanghai Observatory (China), Java (Indonesia), Tahiti (French Polynesia). - staions is ready - next generation stations

NASA's Space Geodesy Project

- Demonstration of prototype next-generation core site:
  - NGSLR demonstrated required performance and is tracking current ILRS satellites including daylight ranging to GNSS.
  - Prototype VLBI2010 system demonstrated required performance and successfully performed several end-to-end geodetic sessions.
- Implementation (with USNO) of new VGOS station in Hawaii underway; Upgraded SLR site planed for Mt Haleakala;
- McDonald selected for Western US site for VLBI and SLR .
- Upgrade underway to the NASA GNSS network to support new constellations (Galileo, GLONASS, Beidou) in addition to GPS.
- Ongoing discussions and planning with international partners for the deployment of the new NASA network overseas.



NGSLR & MOBLAS-7 simultaneously ranging at the Goddard Geophysical and Astronomical Observatory (GGAO)

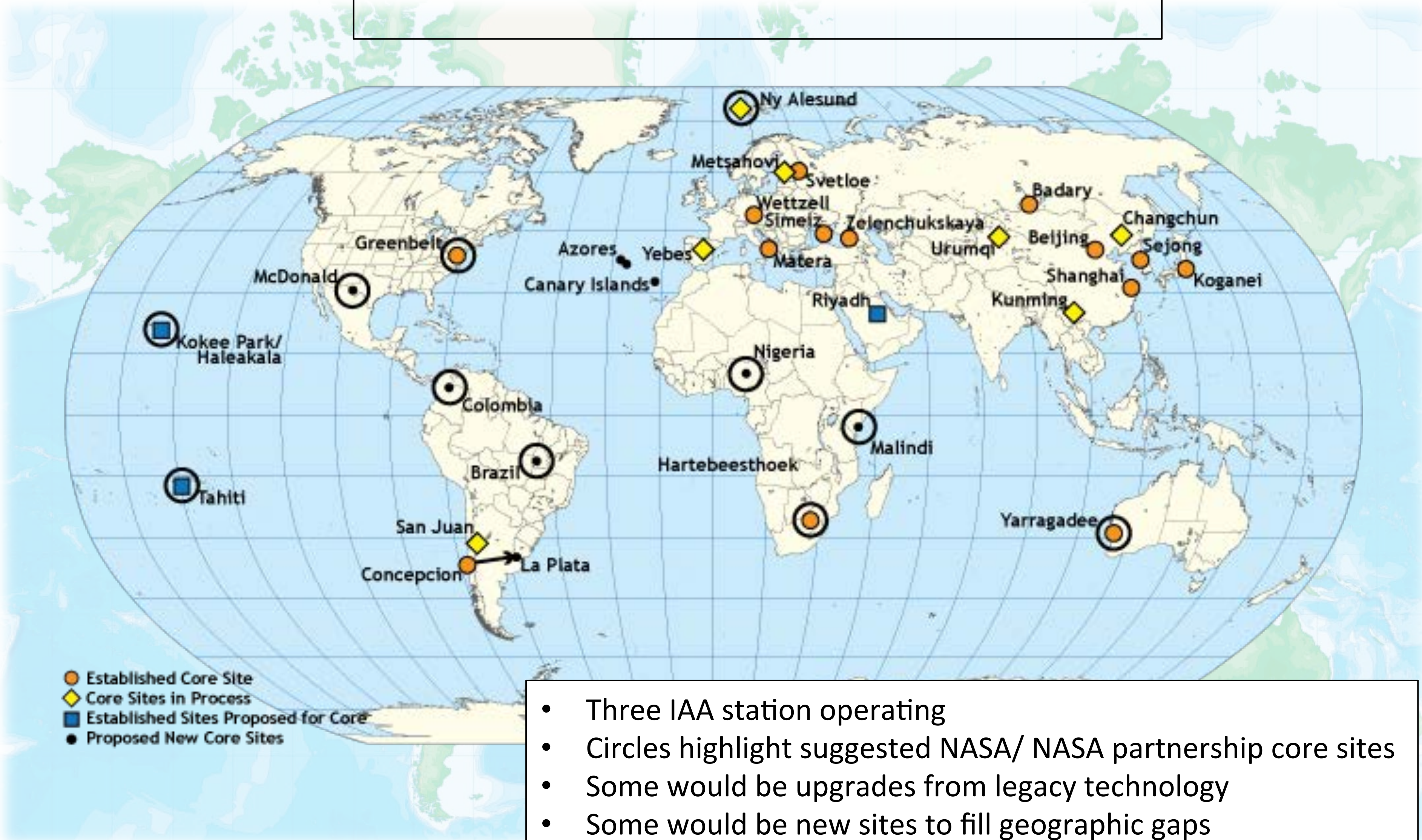
Next Generation Satellite Laser Ranging (NGSLR)

Very Long Baseline Interferometry (VLBI)

Global Navigation Satellite System (GNSS)

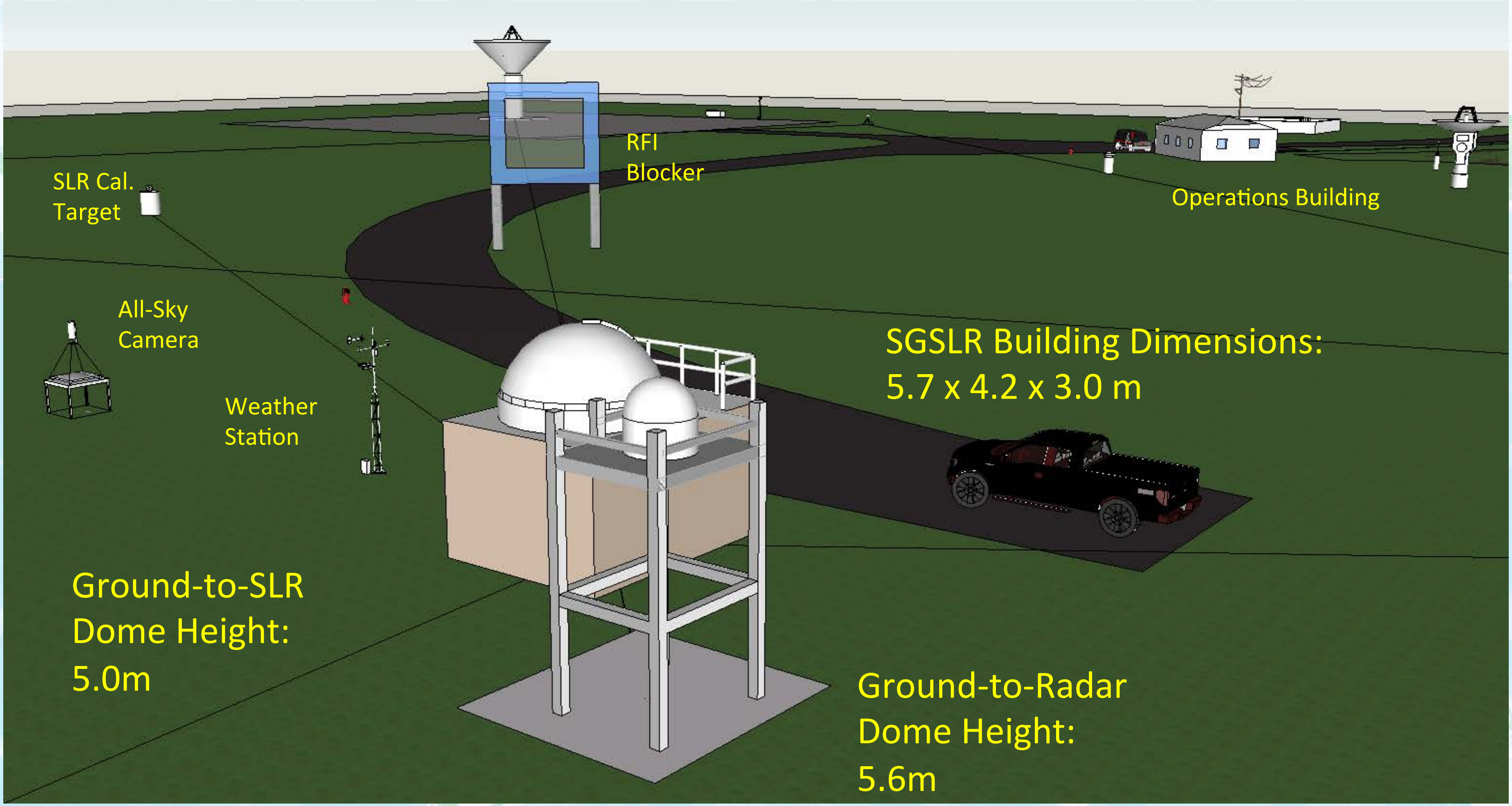
Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)

Current and Projected Core Sites



- Three IAA station operating
- Circles highlight suggested NASA/ NASA partnership core sites
- Some would be upgrades from legacy technology
- Some would be new sites to fill geographic gaps

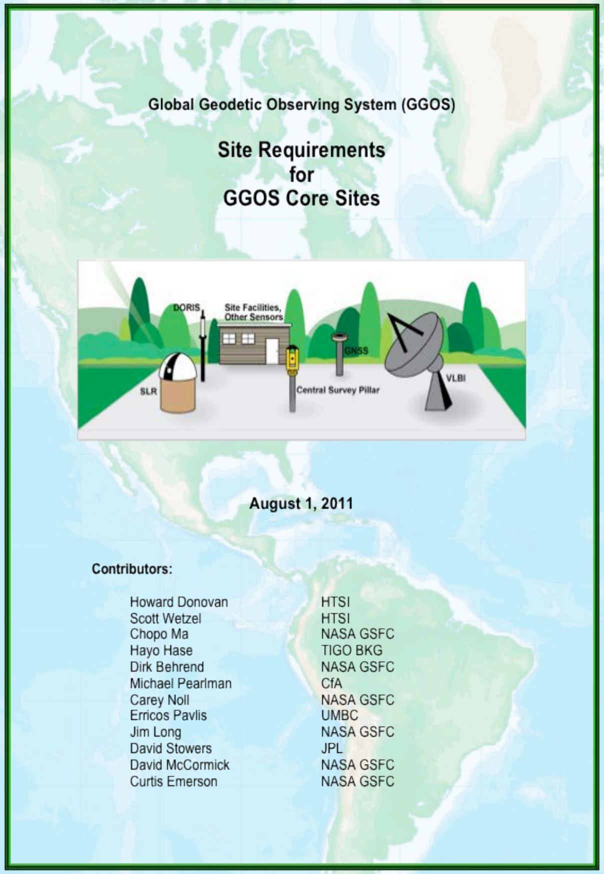
Site layout needs to recognize the issue of RF interference among the new technology systems



Approximate building dimensions shown

GGOS Site Requirements Document

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



Global Geodetic Observing System (GGOS)

Site Requirements
for
GGOS Core Sites

August 1, 2011

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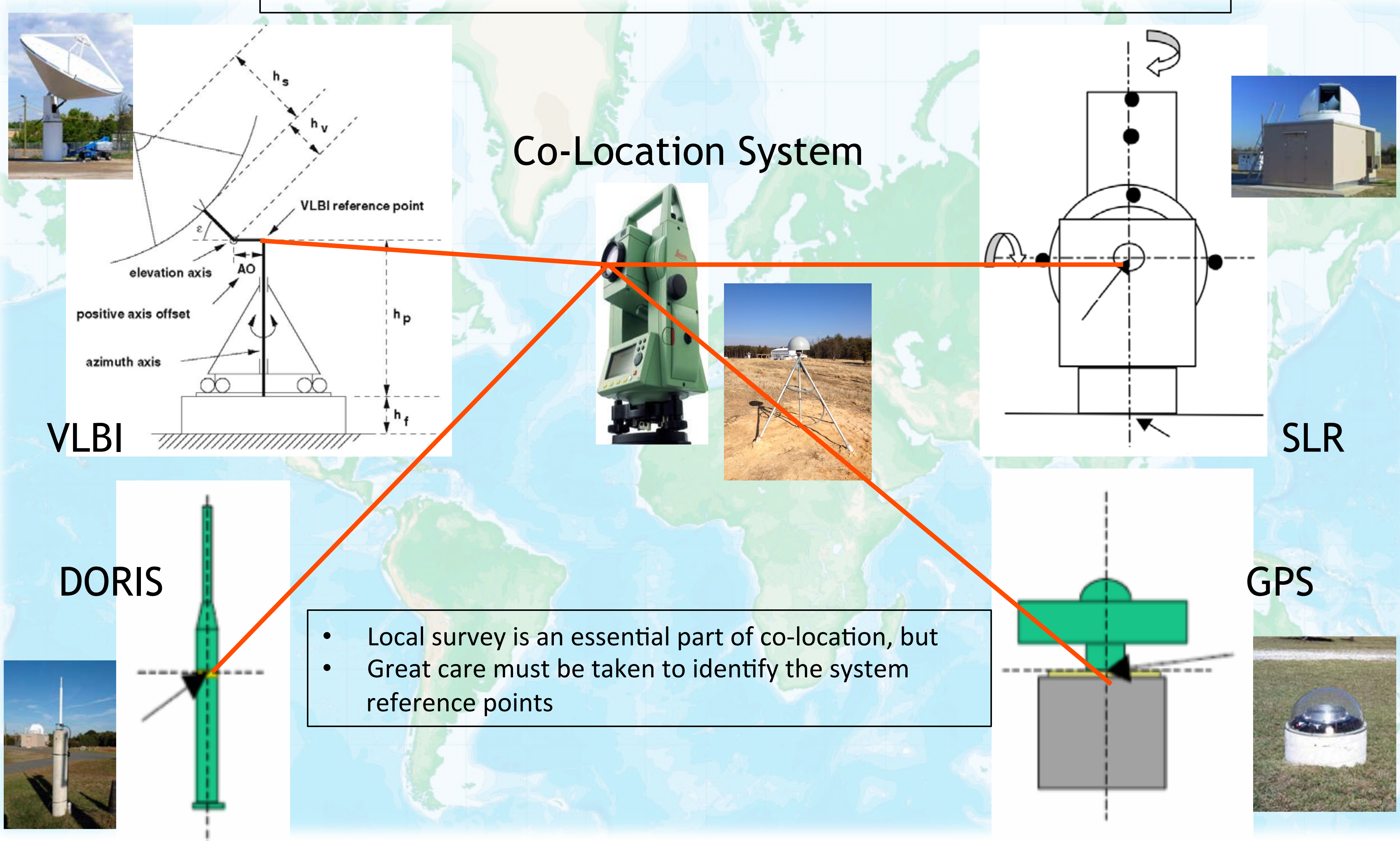
- Introduction and Justification
  - What is a Fundamental Station?
  - Why do we need the Reference Frame?
  - Why do we need a global network?
  - What is the current situation?
  - What do we need?
- Site Conditions
  - Global consideration for the location
  - Geology
  - Site area
  - Weather and sky conditions
  - Radio frequency and optical Interference
  - Horizon conditions
  - Air traffic and aircraft Protection
  - Communications
  - Land ownership
  - Local ground geodetic networks
  - Site Accessibility
  - Local infrastructure and accmmodations
  - Electric power
  - Site security and safety
  - Local commitment

Local Ground Survey is an Essential Part of Co-location



- Local survey is an essential part of co-location, but
- Great care must be taken to identify the system reference points

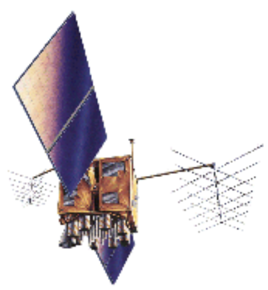
Co-location in Space

Compass

GNSS/SLR

GLONASS

GNSS/SLR

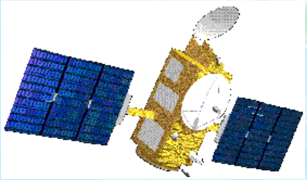


GPS

GNSS/SLR

GIOVE/Galileo

GNSS/SLR

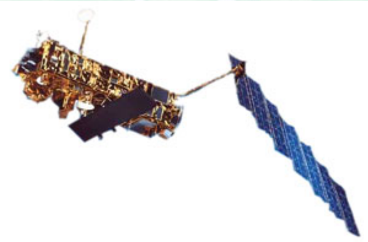


Jason

DORIS/GNSS/SLR

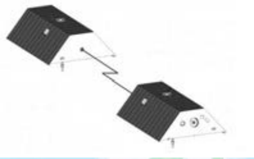
CHAMP

GNSS/SLR



Envisat

DORIS/SLR



GRACE

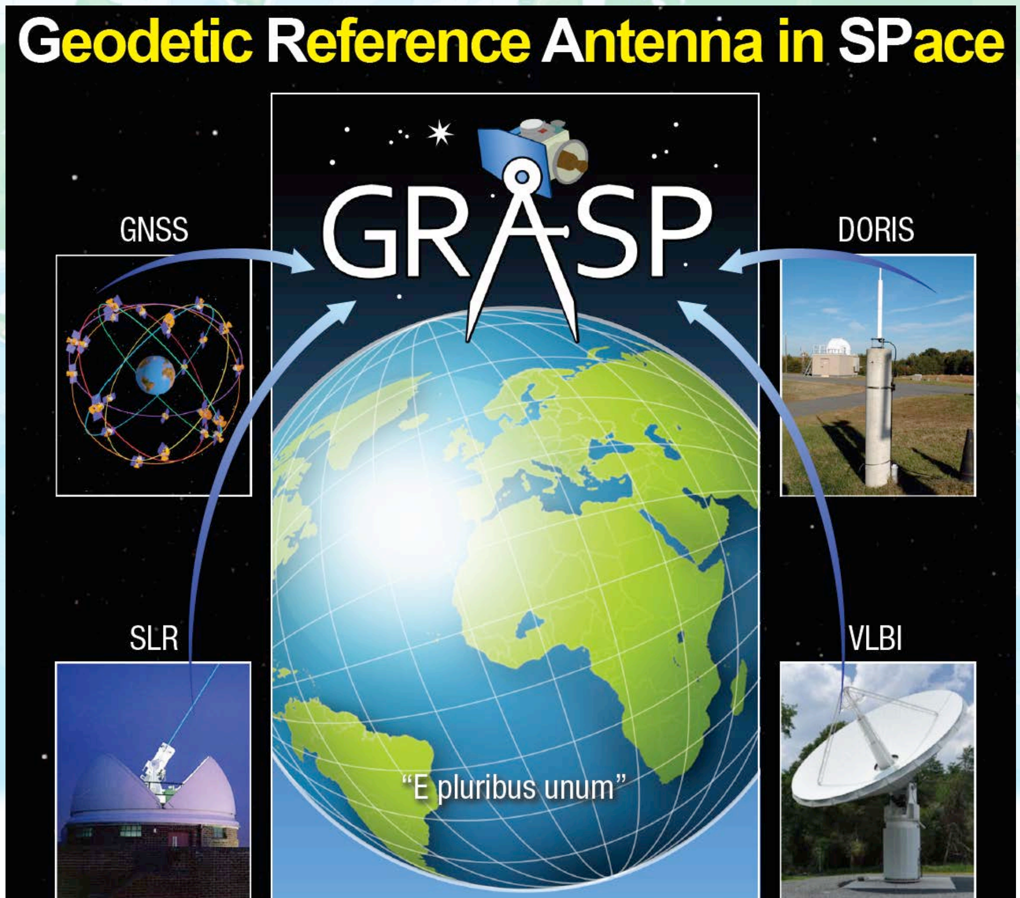
GNSS/SLR

The Geodetic Reference Antenna in Space (GRASP): A Mission to Enhance the Terrestrial Reference Frame

Yoaz Bar-Sever[1], R. Steven Nerem[2], and the GRASP Team

[1] Jet Propulsion Laboratory

[2] University of Colorado, Boulder



Reality

Recognizing that:

- Many sites will not be at ideal locations nor have ideal conditions;
- Some new technology stations are being deployed, but not co-located;
- Core site deployment will occur over many years;
- We will have a mix of new and legacy technologies for many years;

As a result:

- Co-location sites (non-core sites) will continue to play a vital role in our data products;
- Quality of our output will be the product of network Core Sites, Co-location sites, mix of technologies, adherence to proper operational and engineering procedures, and making best use of the data once it leaves the field;

But – many groups are taking the initiative to join, build and upgrade

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
- Need to engage young scientists and students
- Success will depend on partnerships

- Thank you for your attention
- I am very honored with the award. It means a great deal me.