NASA's Geodetic Networks: Incubators of Innovation

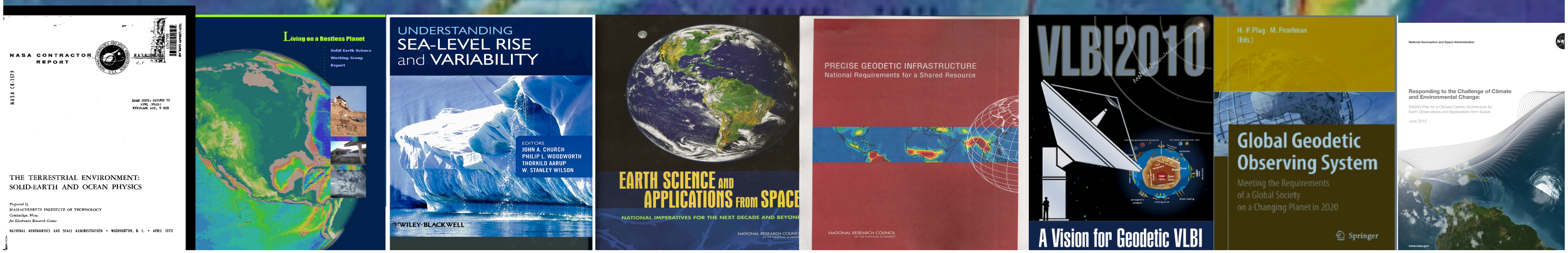
- Environmental Change: Reference
- Natural Hazards: Situational Awareness
- International Cooperation

John LaBrecque Craig Dobson Sanghamitra Dutta

Presentation to the

Earth Science Subcommittee of the NASA Advisory Council

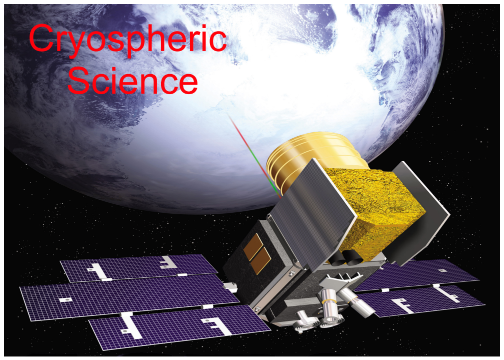
March 21, 2012

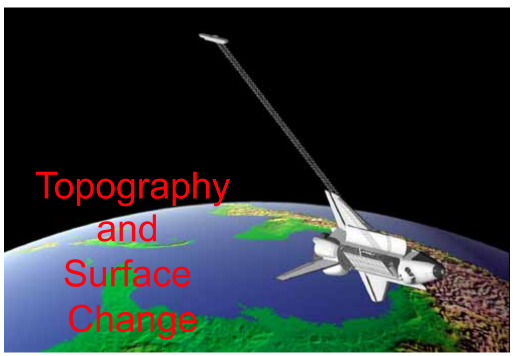


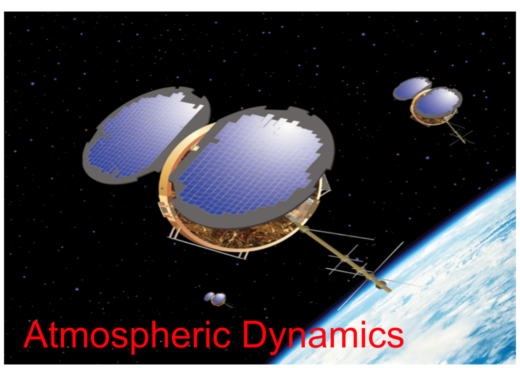
NASA Ground Geodetic Networks: Incubators of Innovation

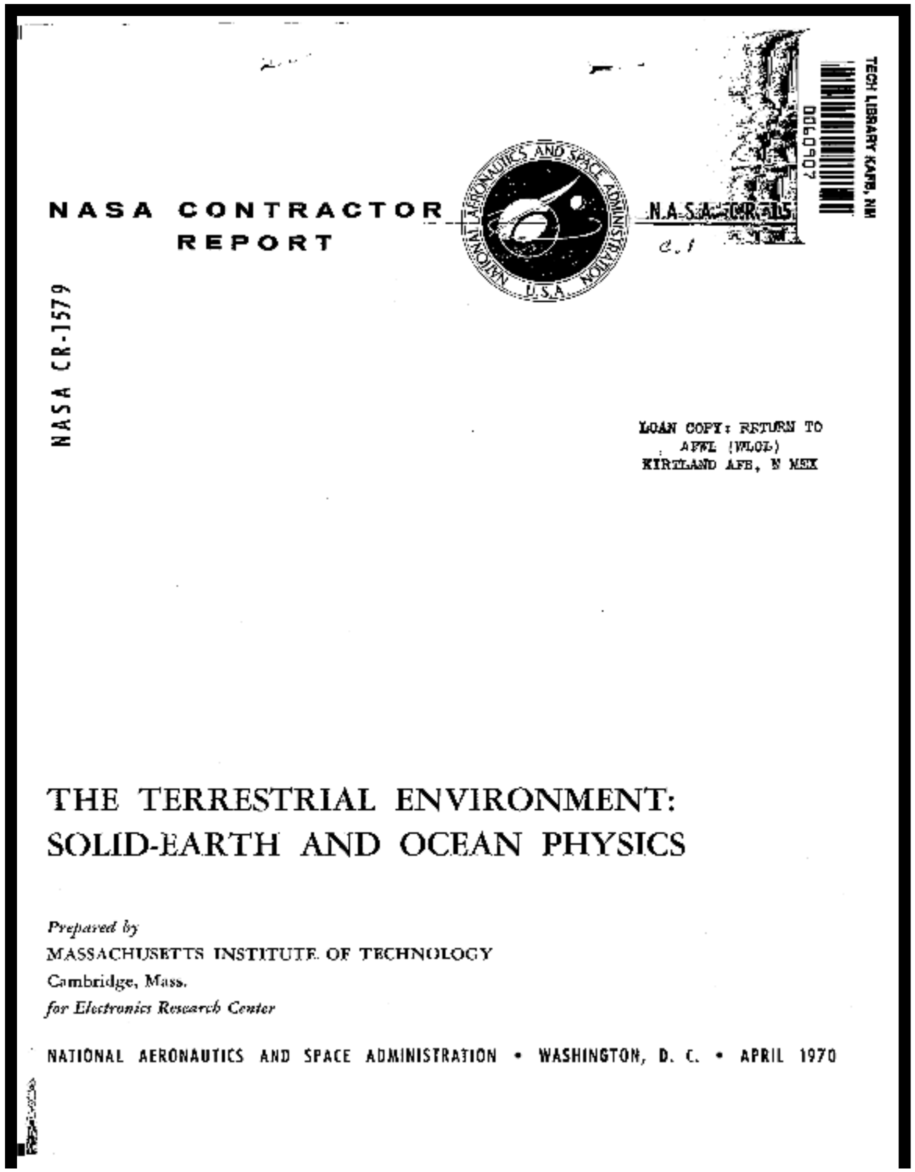
- **History and Foundation Documents**
- NASA's Interagency and International Collaboration
  - GGOS (IGS,IVS,ILRS, GIAC, Network and Communications Bureau)
  - NEOS National Earth Orientation Service (USNO,NOAA)
  - PNT Excom (NSPD 39)
  - International Committee on GNSS
  - EarthScope (PBO)
  - Disaster Early Warning Network
- System Status and Applications
  - Positioning, Navigation and Timing (PNT)
    - The Global Geodetic Observing System
    - The Global Differential GPS Network
    - Status and Development
    - SGP, GPS III
  - Environmental Measurement and Natural Hazards
    - Multipath for surface change
    - Real time Ionospheric Gravity Waves
    - Real time PNT- UAVSAR navigation

The Williamstown Report (1970) Recommended the Development of Space Geodesy for Solid Earth and Ocean Physics: Applications of Space Geodesy Have Blossomed









NASA CONTRACTOR REPORT

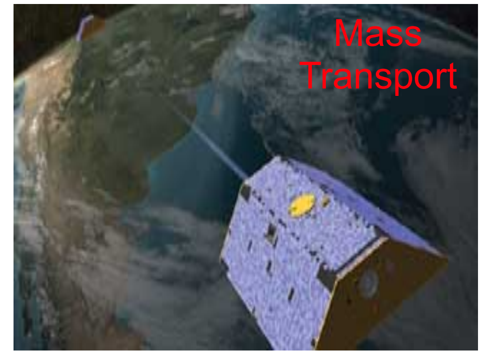
NASA CR-1579

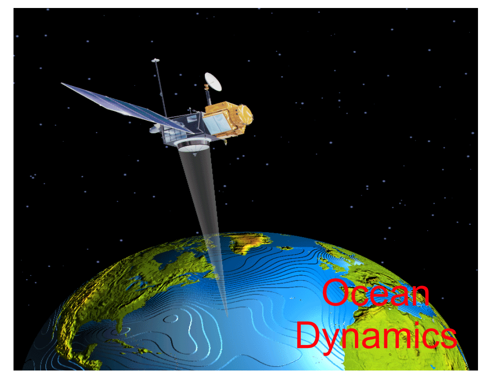
LOAN COPY: RETURN TO AFWL (WLOL) KIRTLAND AFB, N MEX

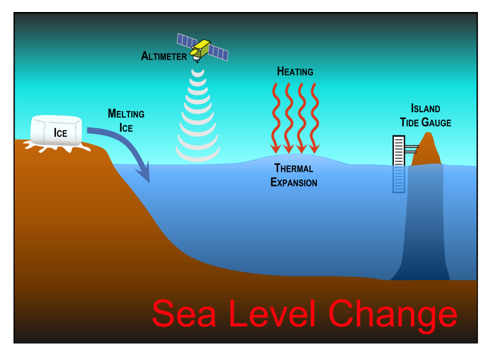
THE TERRESTRIAL ENVIRONMENT: SOLID-EARTH AND OCEAN PHYSICS

Prepared by
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge, Mass.
for Electronics Research Center

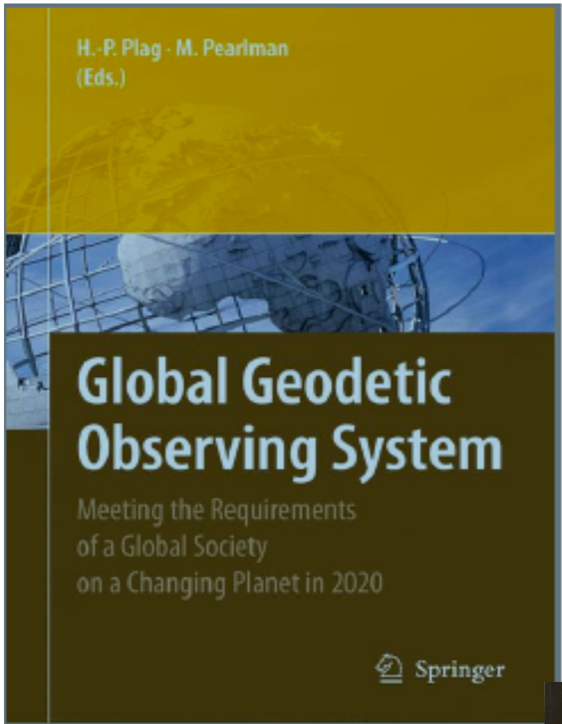
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1970



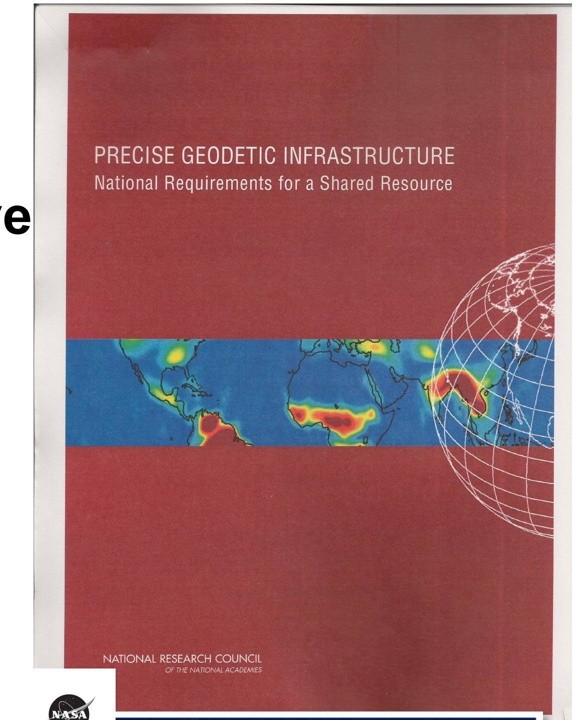




Foundation Documents Guiding Development of Space Geodesy

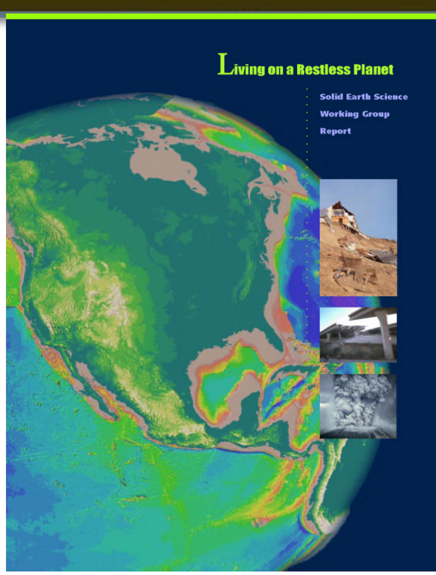


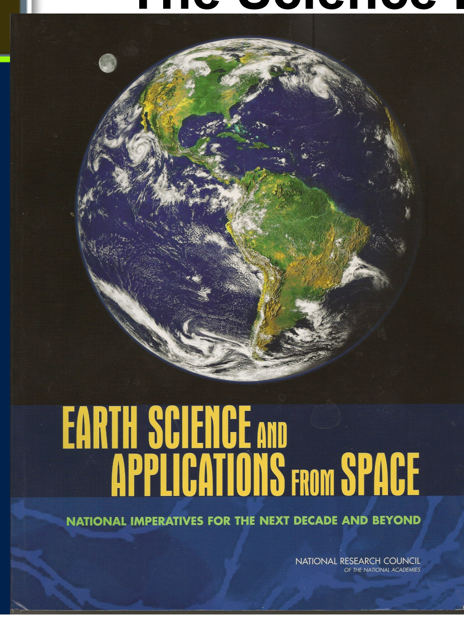
The National Imperative

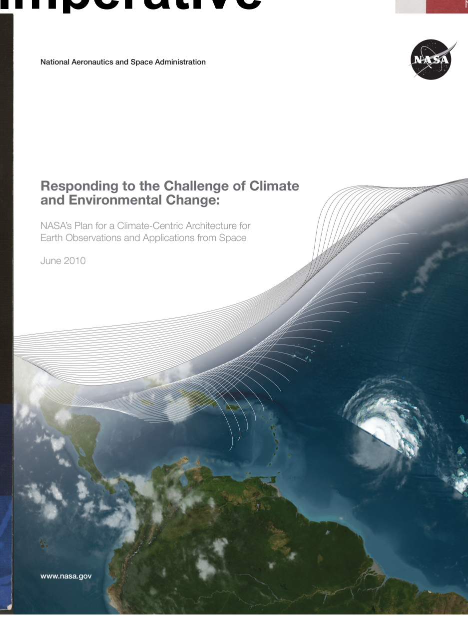


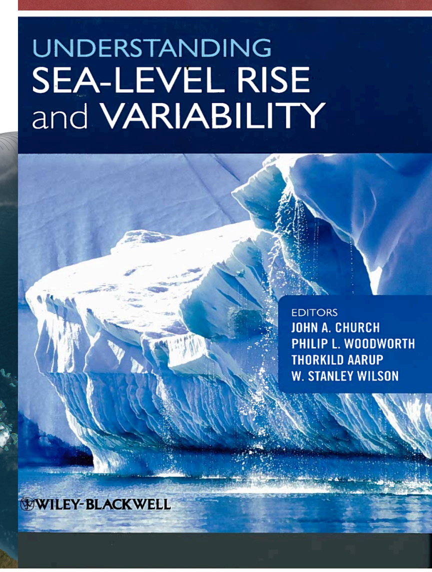
The Global Organization

The Science Imperative

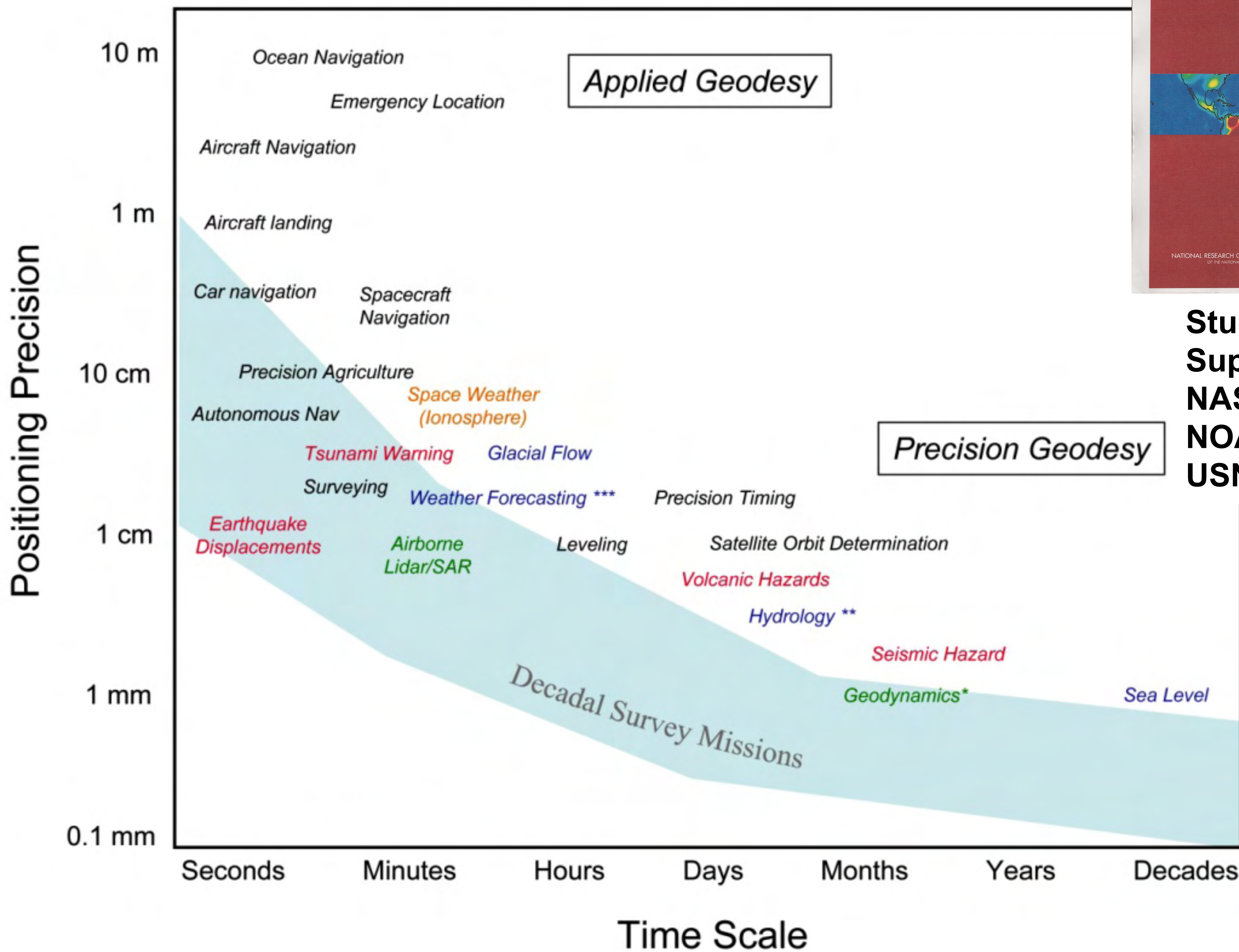


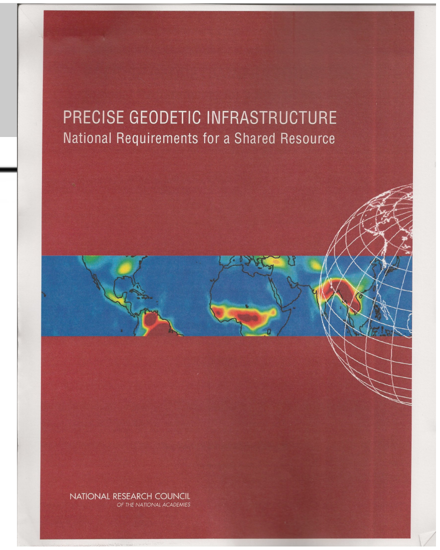






Space Geodesy Provides Positioning, Navigation, and Timing Reference Systems and Earth System Observations

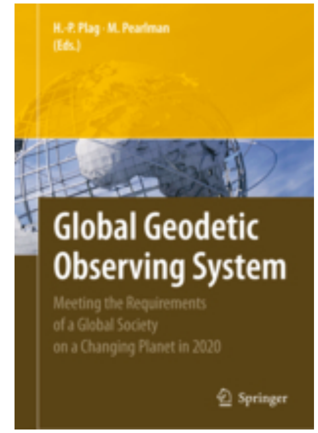




Study Supported by: NASA, NGA, NOAA, NSF, USNO, USGS

Global Geodetic Observing System (GGOS)

Official Component (Observing System) of the International Association of Geodesy (IAG) with the objective of:



Ensuring the availability of geodetic science, infrastructure, and products to support global change research in Earth sciences to:

- *extend our knowledge and understanding of system processes;*
- *monitor ongoing changes;*
- *increase our capability to predict the future behaviour; and*
- *improve the accessibility of geodetic observations and products for a wide range of users.*

Accepted as a Sub-Task under the Group on Earth Observations (GEO)

<u>International Cooperation and Support</u>

- The GGOS data products are from the IAG Services (IGS, IVS, ILRS, and IDS) and dependent upon strong international cooperation and broad international investment.
- Internationally, many organizations support ground stations, product development, and analysis:

Each does a part; each benefits from the whole

- Currently, over 250 institutions in over 90 countries contribute to these IAG services

Global Geodetic Observing System (GGOS) Services & Products

International Terrestrial Reference Frame (ITRF)
(Accurately positioned points wrt to the Earth's Center of Mass and the Curtain of Quasars)

International Earth Rotation Service (IERS)

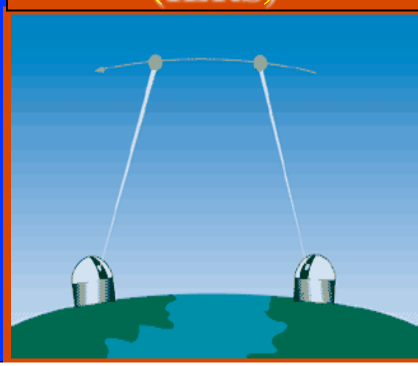
Precision GPS Orbits and Clocks, Earth Rotation Parameters, Station Positions

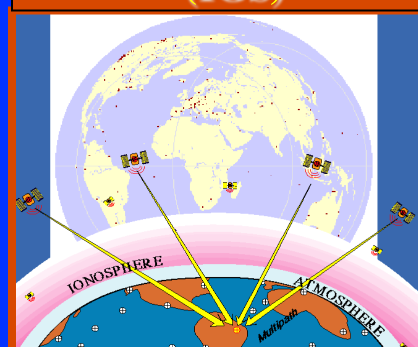
Very Long Baseline Interferometry (IVS)

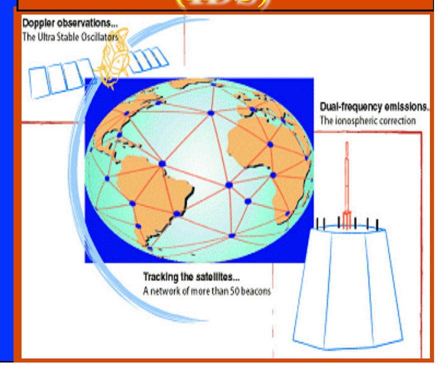
Satellite Laser Ranging (ILRS)

Global Navigation Satellite Systems (IGS)

Doppler Orbit Determination and Radiopositioning Integrated on Satellite (IDS)



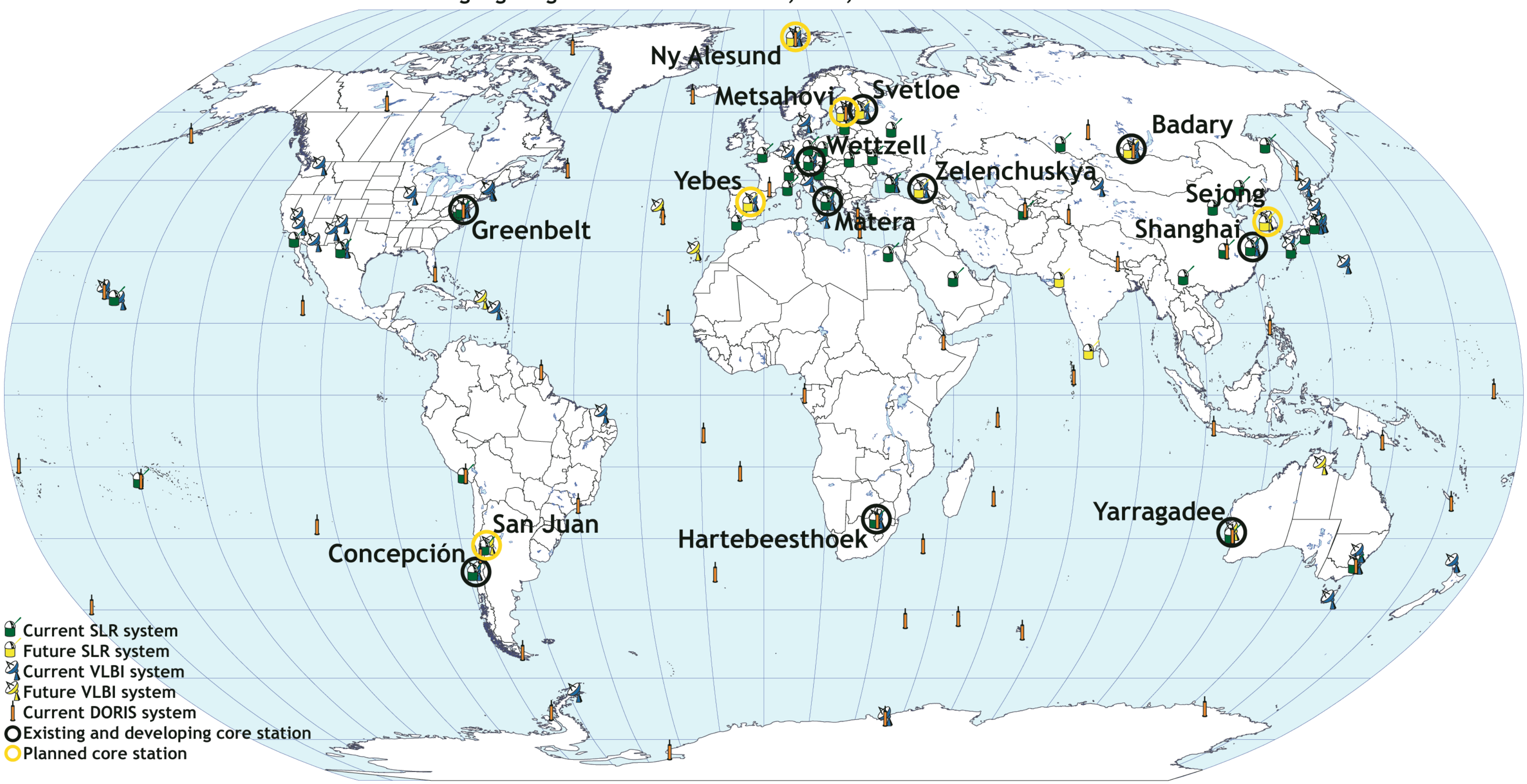




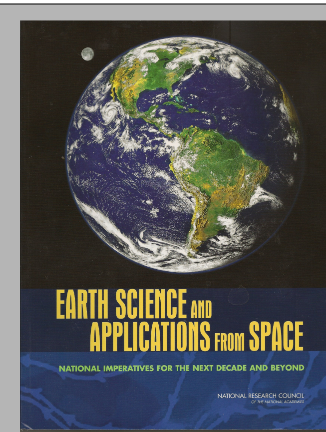
The Global Geodetic Observing System
Global Geodetic Network

SLR, VLBI, and DORIS Networks

Highlighting Core Stations with SLR, VLBI, and GNSS Co-Locations



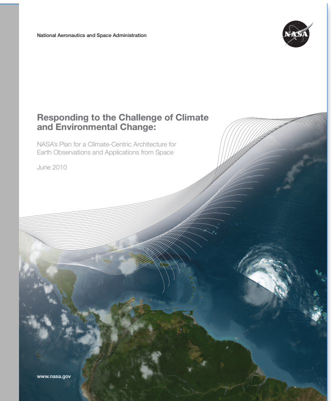
The Requirement for Precise Measurement and Maintenance of the Terrestrial Reference Frame: (*Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, NRC,2007)*



"The geodetic infrastructure needed to enhance, or even to maintain the terrestrial reference frame is in danger of collapse (cf. Chapter 1). Improvements in both accuracy and economic efficiency are needed. Investing resources to assure the improvement and the continued operation of this geodetic infrastructure is a requirement of virtually all the missions for every Panel in this study.

The terrestrial reference frame is realized through integration of the high precision networks of the Global Positioning System (GPS), Very Long Baseline Interferometry (VLBI), and Satellite Laser Ranging (SLR). It provides the foundation for virtually all space-based and ground-based observations in Earth science and global change, including remote monitoring of sea level, sea surface topography, plate motions, crustal deformation, the geoid, and time-varying gravity from space. It is through this reference frame that all measurements can be inter-related for robust, long-term monitoring of global change. A precise reference frame is also essential to interplanetary navigation and diverse national strategic needs."

Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space , June, 2010



2.2.4 Calibration of Multi-satellite Global Data Sets

The FY2011 budget request will provide improved capability for the production of consistent multi-instrument/multi-platform data sets for space-based observations through increases in support for calibration laboratories, facility instruments, ground networks, and airborne calibration, as well as for competed tasks contributing to an interagency national calibration capability. A near-doubling of the annual investment in the space geodesy activity will allow for deployment of next-generation geodetic ground stations to assure accuracy of future altimetric and gravimetric satellite missions. ……

The budget request will enable improvements to our national calibration and inter-calibration capability that will allow NASA to work more closely with its international and domestic partners to assure the consistency of data across platforms and the traceability of data to recognized standards. Specific tasks to be enhanced as part of this activity are:

a. **Building a prototype and then multiple copies of the next generation geodetic ground network that includes a new generation of Satellite Laser Ranging, Very Long Baseline Interferometry, and Global Navigation Satellite Systems (GPS, Galileo, GLONASS, Compass).** This network of next generation instruments will replace the present aging and deteriorating network that cannot fully support the many geodetic and gravimetric missions that NASA will be implementing (ICESat-2, DESDynI, SWOT, LIST, GRACE FO, GRACE II) as well as its current set of operating missions (especially GRACE, Jason, and OSTM). These missions are particularly important because they provide the observations essential to the measurement and understanding of sea level change due to the transport of water between ice sheets and glaciers, the oceans, and the continental aquifers. The World Climate Research Program publication on sea level change (in press) identifies the need for an improved Terrestrial Reference Frame to be provided by this next generation network as essential for the measurement and understanding of sea level change over multi-decadal time scales. **The NASA contribution to the next generation network will be strongly augmented with the significant contributions from other nations (e.g. Australia, Germany, Norway, South Korea, France, and Germany) that participate within the Global Geodetic Observing System (GGOS2020).**

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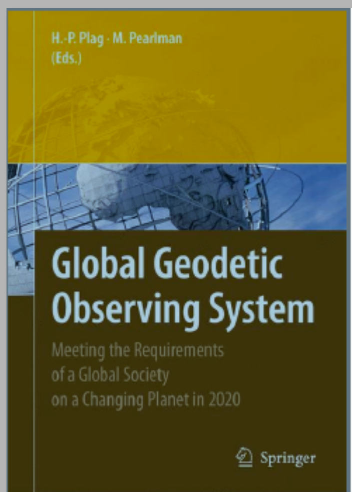
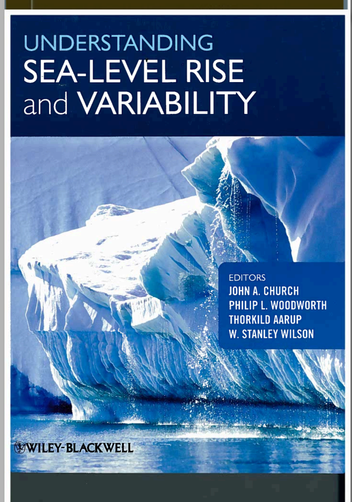
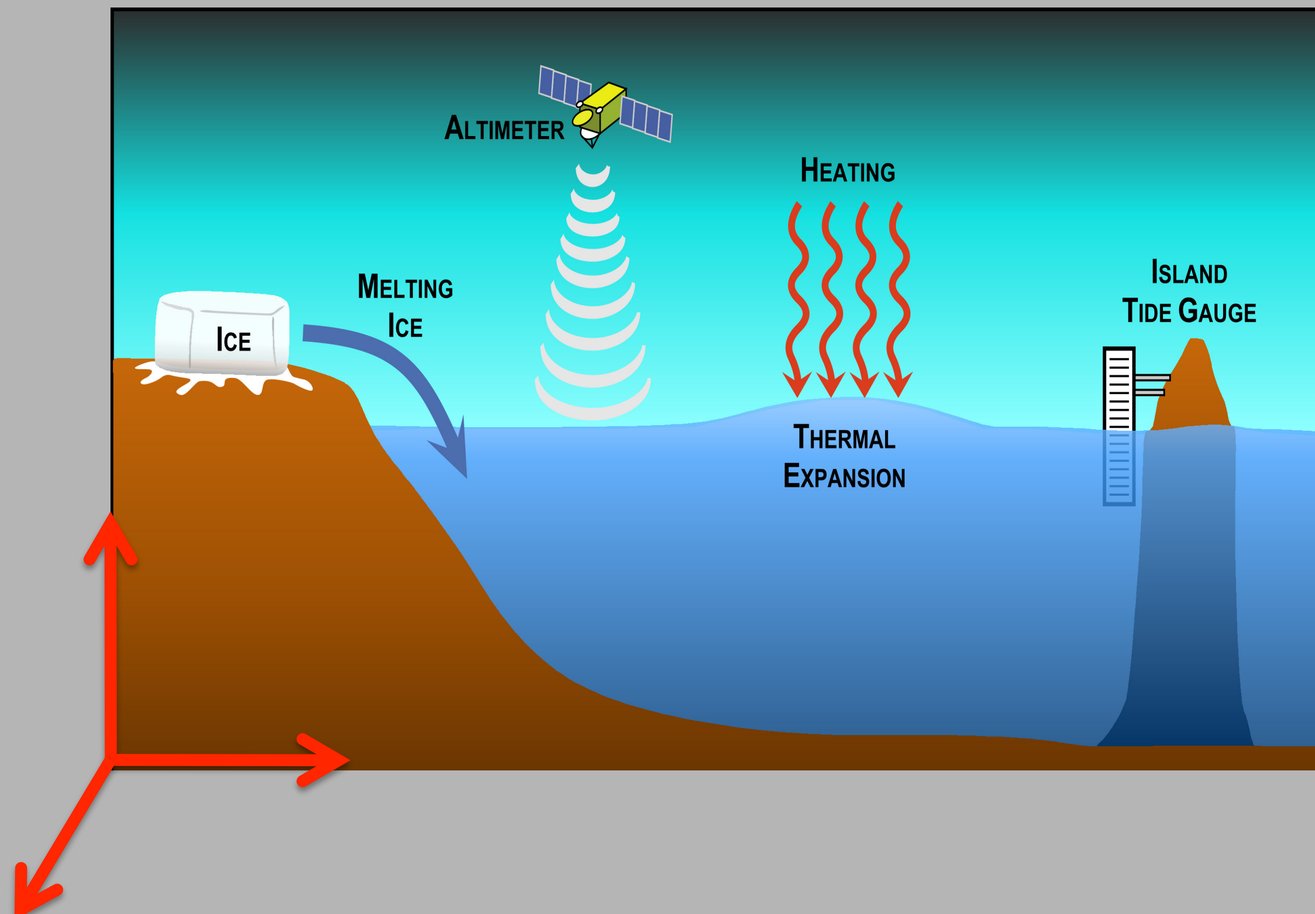
NASA's Program to Advance Space Geodetic Science and the GGOS

- **Development Studies**
  - NASA supports a Geodetic Study Group to develop the requirements for the next Generation Geodetic Network
    - Encouraged development of GGOS Standard based upon Sea level Change requirements. (1.0 mm accuracy, 0.1 mm/yr stability)
    - Supporting Development Network Performance Simulations to inform Network Design
    - SLR Retro-reflector Standard
    - Supporting Network and Communications Bureau of the GGOS
    - Supporting Central Bureaus of the IGS, IVS, ILRS
  - Six US Agencies (NASA, NGA, NOAA, NSF, USNO, and USGS) supported NRC's National Requirements for Precision Geodetic Infrastructure report.
    - Supports Placement of Satellite Laser Reflectors on GPS III Satellites
    - Final Discussions underway with the Air Force Space Command
- **Instrument and Technique Development**
  - Prototype development of Next Gen Geodetic Observatory
  - TRIG Spaceborne GNSS Science Receiver Development
  - *Insitu* and Space-based Continuous Co-location and Bias monitoring
- **Encourage International Investments through Multilateral & Bilateral Discussions**

Improving the performance of the Global Geodetic Observing System and the International Terrestrial Reference Frame is critical to understanding the future impact of Sea level Change



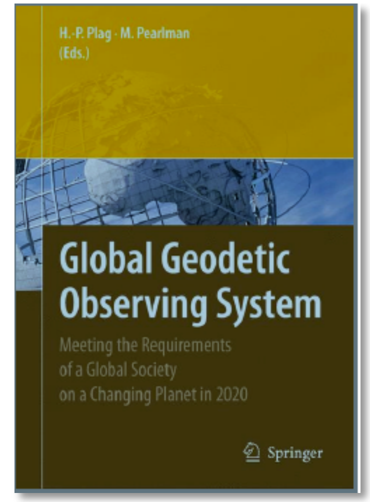




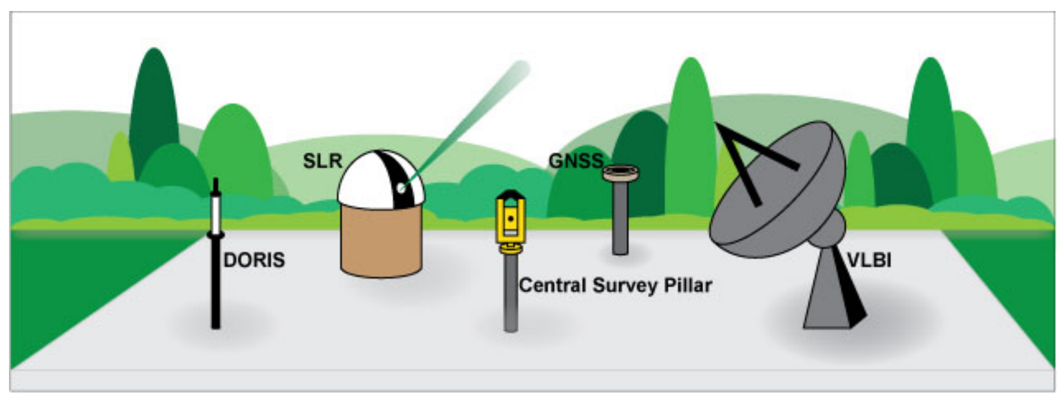
The GGOS Geodetic Reference Frame Requirement for Sea Level Measurement

1 mm reference frame accuracy and 0.1 mm/yr stability

GGOS2020 Recommends the Development of a NextGen Network of Co-located Core Ground Network Stations



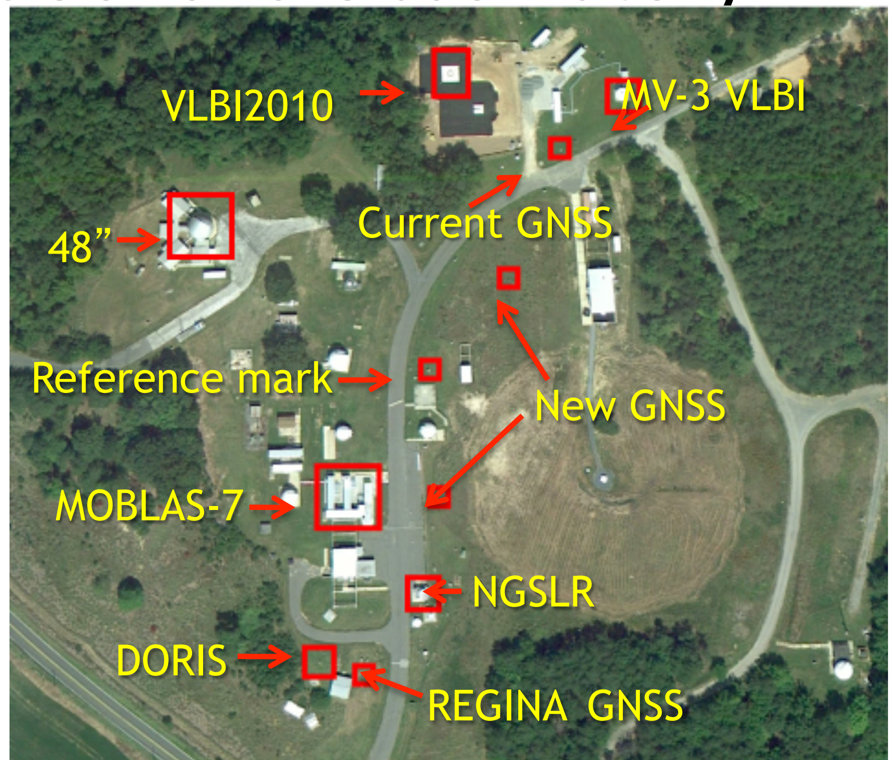
- A fundamental station includes four space geodesy techniques co-located so that the measurements among them can be related to sub-mm accuracy
- The four techniques are:
  - Global Navigation Satellite System (GNSS, e.g., GPS, GLONASS, Galileo)
  - Satellite Laser Ranging (SLR)
  - Very Long Baseline Interferometry (VLBI)
  - Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)
- Why do we need four techniques?
  - 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

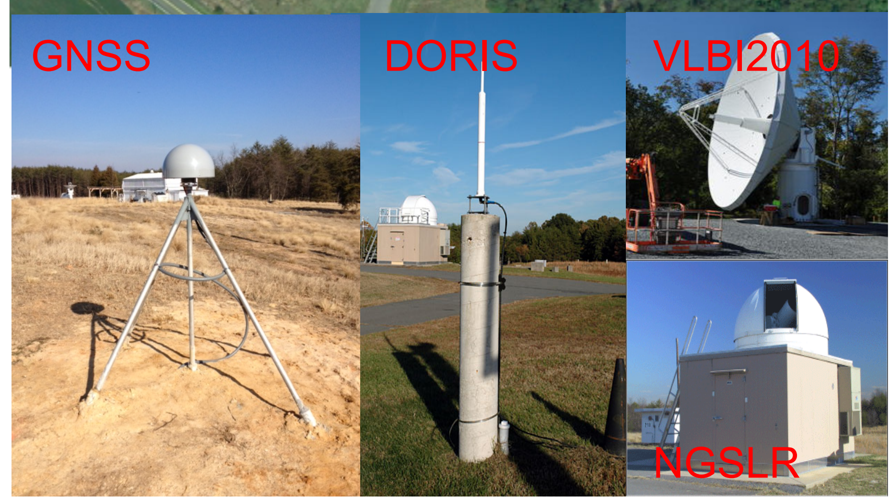


Space Geodesy Project (SGP)

Develop the Prototype GGOS2020 Observatory

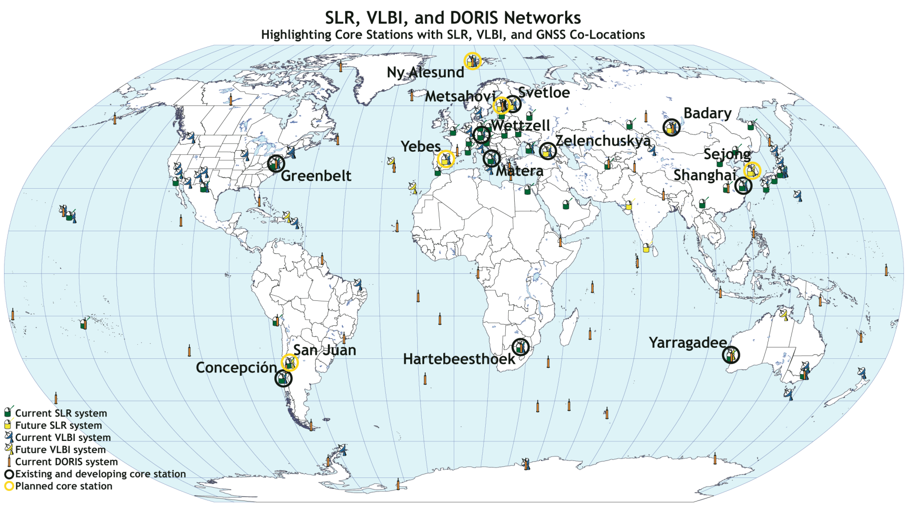
- **Two year delivery schedule.**
  - **Task 1: Network Design Studies**
  - **Task 2: Prototype Station Development**
  - **Task 3: Implementation Plan**
- **Major Milestones:**
  - **Prototype Station Integrated: February 2013**
  - **Station Performance Verification: July 2013**
  - **Implementation Plan: July 2013**





The GGOS is Rebuilding the Global Network to Meet Its Accuracy and Stability Requirements

The Present Day Global Geodetic Observing Network

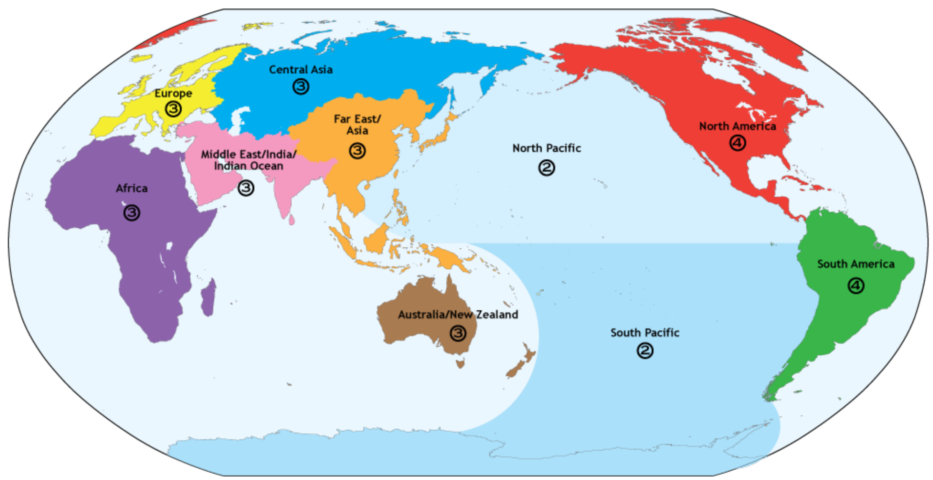


The Global Geodetic Network does not meet current GGOS requirements.

- •Old equipment
- •Poor network Distribution
- •Poor co-location of techniques
- •Large systematic observational errors
- •Need ~20 times improvement in measurement accuracy

GGOS Next Generation Network of Core Observatories

- 30 globally distributed, multi-technique co-located ground stations
- 4 techniques/site



Countries with core site activities:

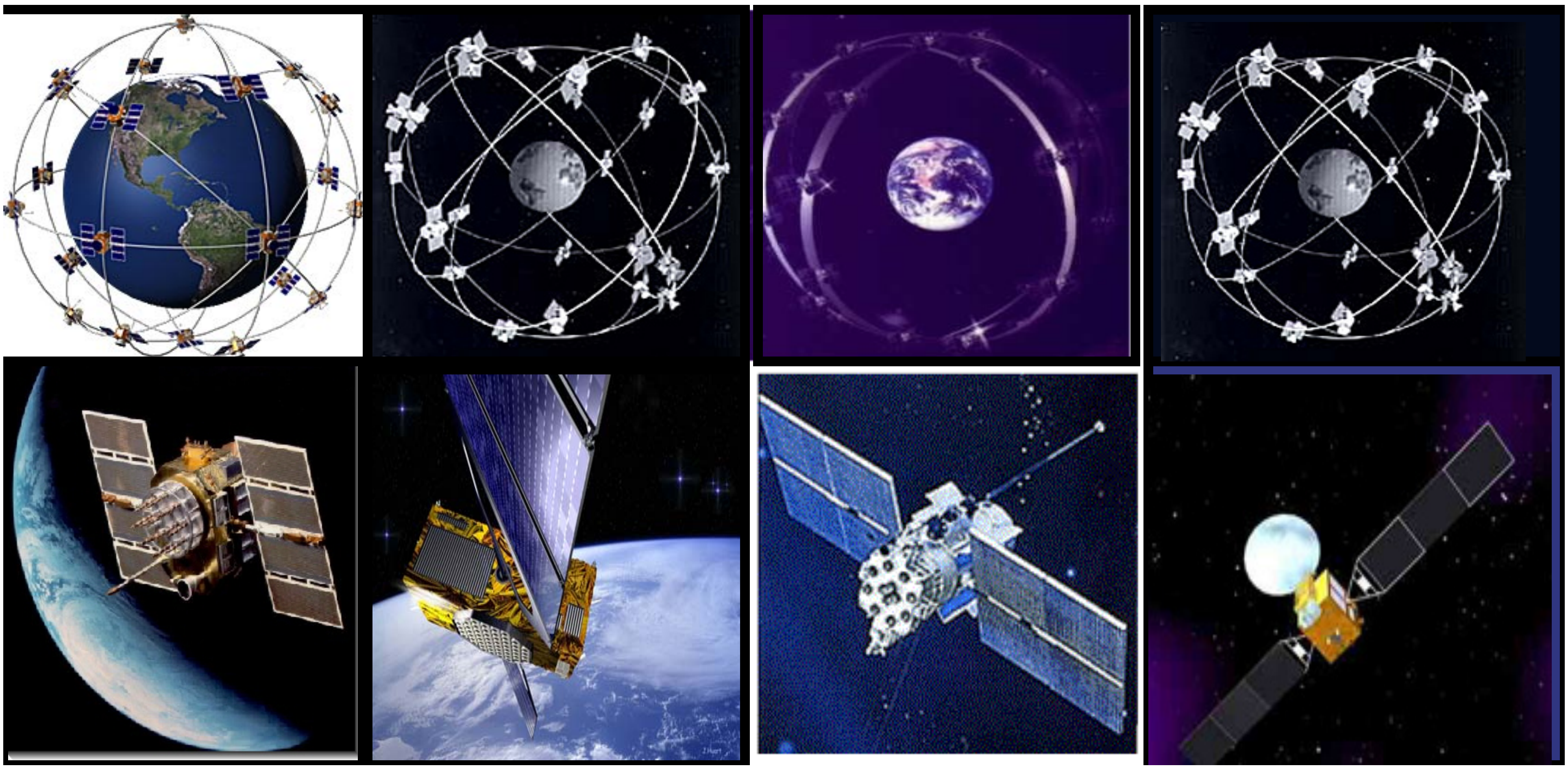
United States	Norway
Germany	Japan
China	Korea
Australia	Russia
New Zealand	Saudi Arabia \
South Africa	Spain

GPS has proven to be the most effective means of relative positioning within the ITRF

This Decade will see an explosion of new Global Navigation Satellite Systems (GNSS)- All but GPS will be tracked by Satellite Laser Ranging

NASA and the GGOS are moving to insure that these systems contribute to Earth System Science by working to improve their accuracy to meet the GGOS 2020 requirements.

GPS | Galileo | GLONASS | Beidou



Co-Location in Space: Laser Tracking of the Global Navigation Satellites to Reduce Orbit and Clock Errors

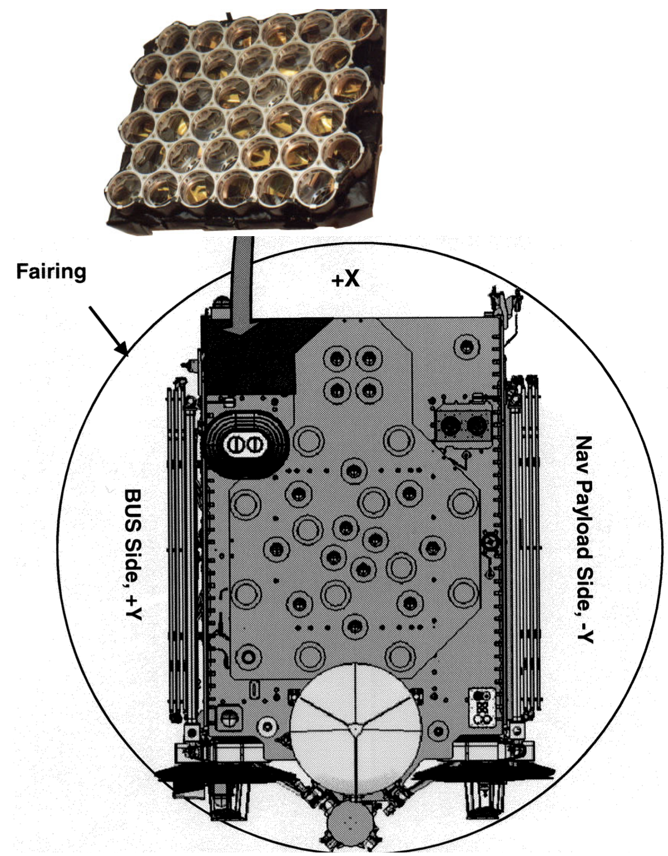
The International Laser Ranging Service Standard (GGOS) adopted by GLONASS, Galileo, COMPASS

Retro-reflector payloads for the GNSS satellites GPS, GLONASS, and COMPASS should have an "effective cross-section" of 100 million sq. meters (5 times that of GPS-35 and -36) for GNSS satellite;

The parameters necessary for the precise definition of the vectors between the effective reflection plane, the radiometric antenna phase center and the center of mass of the spacecraft be specified and maintained with an accuracy of a mm;

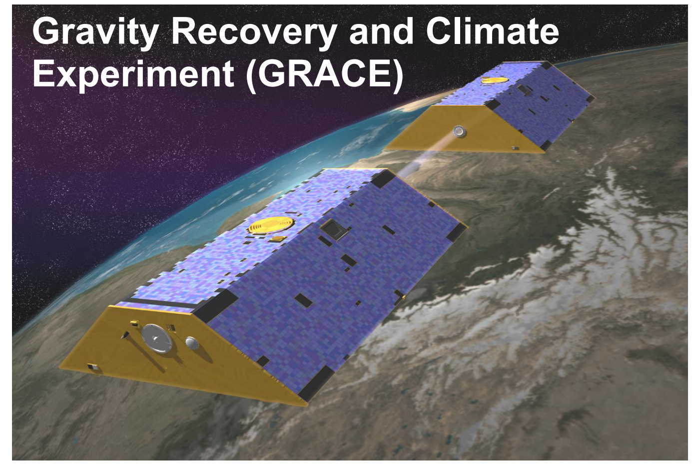
Further Recommendation: Retro-reflector payloads for satellites such as Galileo in higher orbits should scale the "effective cross-section" to compensate for the R**4 reduction in signal strength;

SLR Tracking for GPS III- NASA (SMD, HEOMD,GSFC,JPL), NGA, USGS, NRL, Air Force Space Command

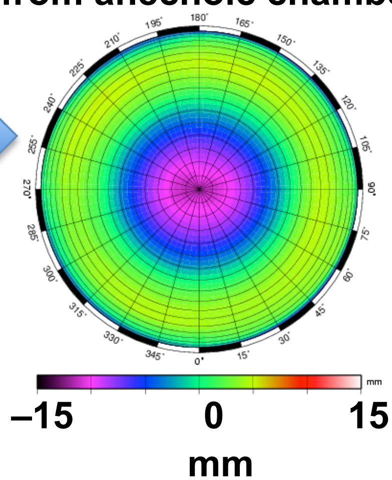


Co-location in Space:
Reference Antennae in Space to Resolve GPS Satellite Errors

- **GRACE mission (2002–) is used as orbiting geodetic lab for characterizing the GPS satelliite Antenna Phase Variation (APV). APV can be a significant source of positioning error for satellites and ground stations.**
- **GRACE advantages:**
  - **Scale (mean height) can be determined at cm level from dynamical POD constraint (depends only on GM, and independent of the TRF).**
  - **GRACE is precision tracked by the GGOS Laser Ranging Network**
  - **Clean spacecraft and simple attitude laws facilitate modeling of surface forces.**
  - **Ground calibration of the GRACE GPS antenna is high fidelity due to low multipath environment of the spacecraft**
  - **Simple and fixed geometry enables modeling of residual multipath**
  - **Long-duration measurements (2002–) with dense global coverage (89.5° inclination).**
  - **500 km altitude implies no troposphere to confound APV interpretation.**



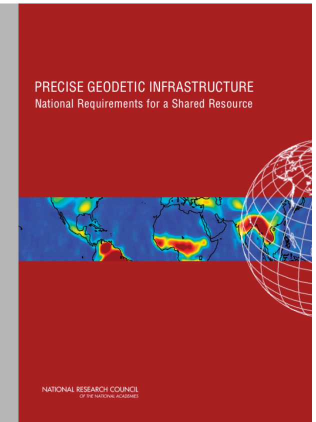
GRACE *a priori* antenna phase variation model from anechoic chamber



U.S. National Research Council Report, 2010

"Precise Geodetic Infrastructure: National Requirements for a Shared Resource"

(http://dels.nas.edu/Report/Precise-Geodetic-Infrastructure-National-Requirements/12954)



Recognizing the growing reliance of a wide range of scientific and societal endeavors on infrastructure for precise geodesy, and recognizing geodetic infrastructure as a shared national resource, the NRC Study Committee strongly recommends that the U.S. (NASA, NSF, NOAA, USGS, NGA-sponsoring agencies) should:

- **Deploy the next generation of automated high-repetition rate SLR tracking systems at the four current U.S. tracking sites in Hawaii, California, Texas, and Maryland;**
- **Install the next-generation VLBI systems at the four U.S. VLBI sites in Maryland, Alaska, Hawaii and Texas;**
- **Deploy additional stations to complement and increase the density of the international geodetic network, in a cooperative effort with its international partners, with a goal of reaching a global geodetic network of fundamental stations;**
- **Establish and maintain a high precision GNSS/GPS national network constructed to scientific specifications, capable of streaming high rate data in real time;**
- **Make a long-term commitment to maintain the International Terrestrial Reference Frame (ITRF) to ensure its continuity and stability;**
- **Continue to support the activities of the GGOS;**
- **Make a long term commitment to the maintenance of ITRF;**
- **Develop a "National Geodesy Service" to coordinate and facilitate the modernization and long term operation of the national and global infrastructure;**
- **assess the workforce required to support precise geodesy in the United States and the research and education programs in place at U.S. universities as part of a follow-up study focused on the long-term prospects of geodesy and its applications.**

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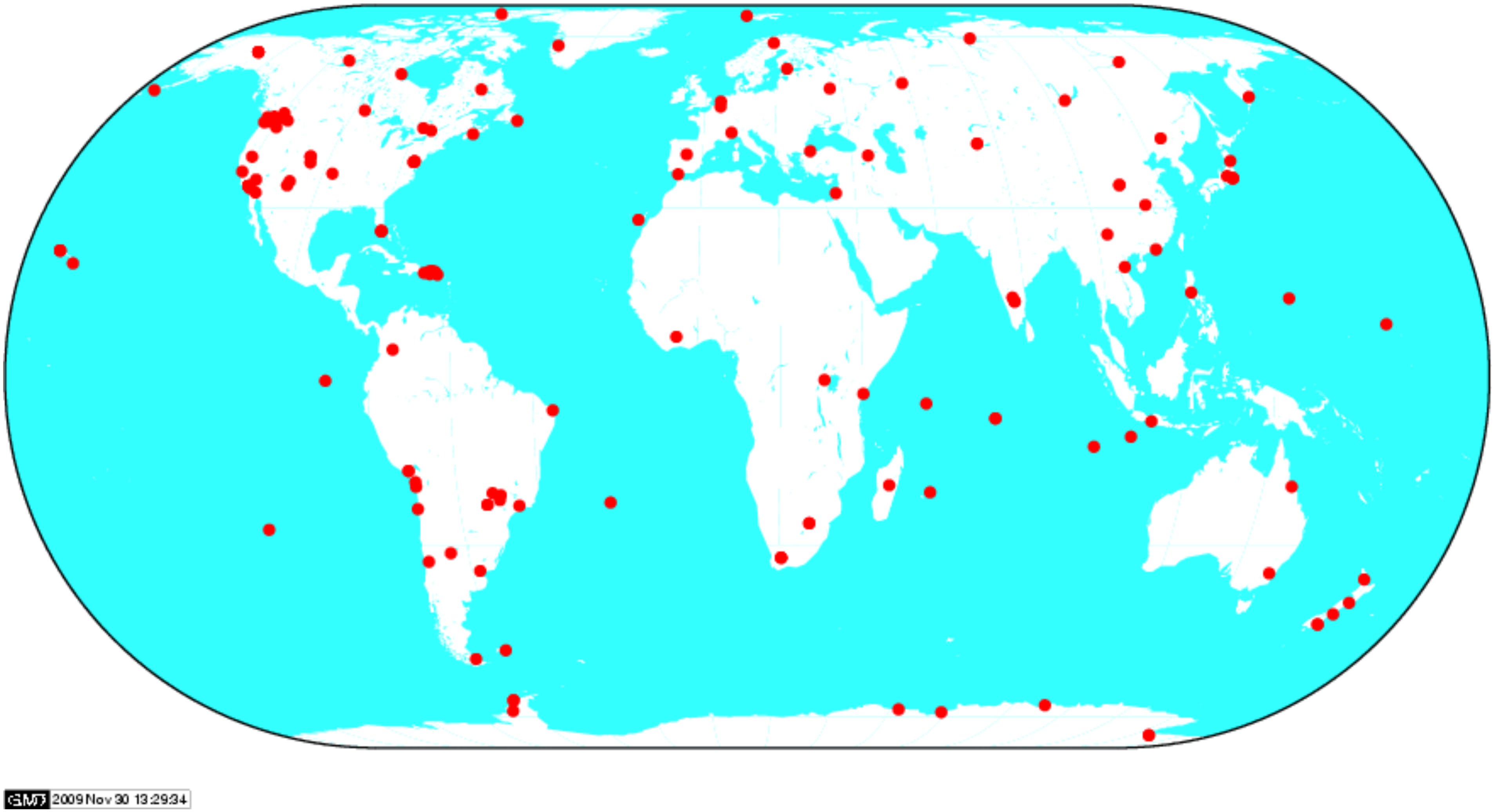
    - SGP, GPS III
  - Environmental Measurement and Natural Hazards
    - Multipath for surface change
    - Real time Ionospheric Gravity Waves
    - Real time PNT- UAVSAR navigation, Disaster Early Warning

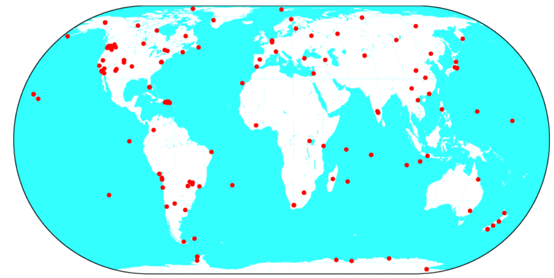
Global Differential GPS Network (GDGPS) Real Time PNT for GPS and GLONASS (http://www.gdgps.net/)



UAVSAR http://uavsar.jpl.nasa.gov

High temporal and spatial resolution surface deformation

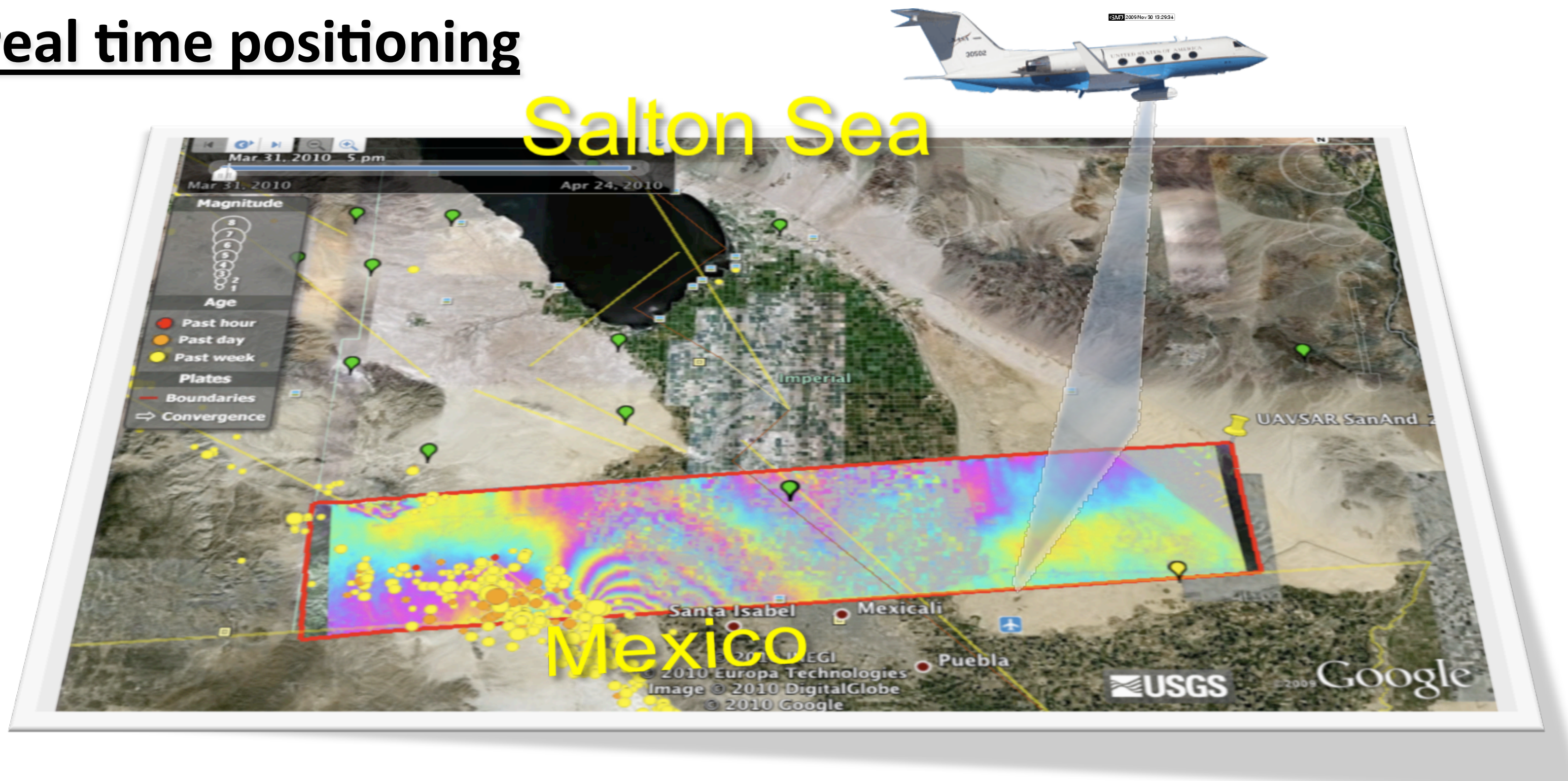
- **Response:** Displacement and disturbance maps
- **Forecasting:** Strain migration



<u>GDGPS PNT Enables UAVSAR Global Operations</u>

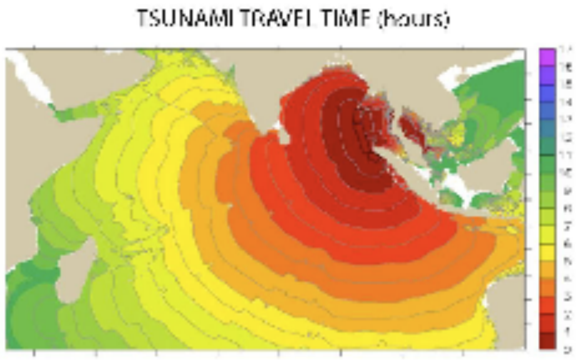
<u>Repeat flight within 5 meter tube with</u>

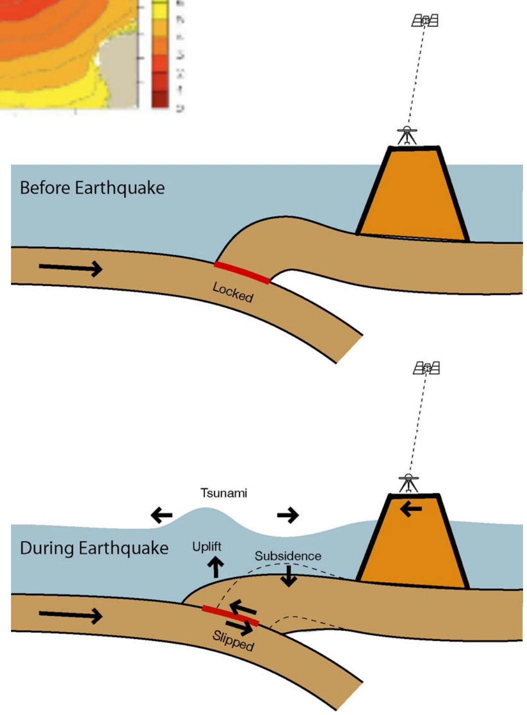
<u><10 cm real time positioning</u>



Post Processing of regional geodetic data taken on December 26,2004 Demonstrated the Advantages and Utility of a Dense Global Regional GNSS Real Time Network

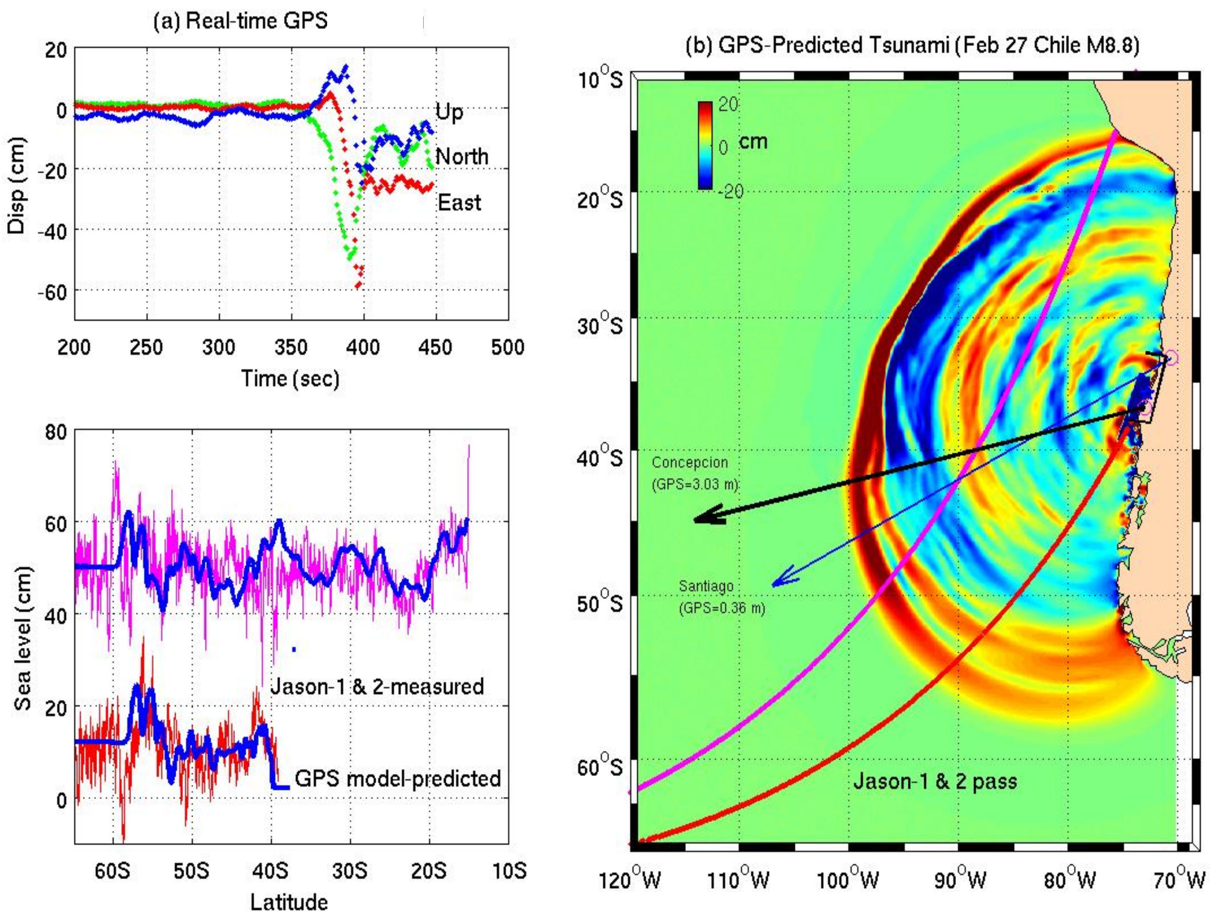
A Dense Global Real Time GPS Network would have warned of the Indian Ocean Tsunami within minutes- hours before the seismic analysis-





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.

February 27, 2010: Chile M8.8 Earthquake Demonstrated First Real Time GPS based Tsunami Prediction using GDGPS with NASA Applied Sciences funding to The GREAT Alert Project



(a): NASA's Global Differential GPS (GDGPS) measures the Chile M8.8 earthquake displacement in real time at Santiago.

(b): JPL GREAT alert team predicts a moderate sized tsunami using the real-time GPS and the Song tsunami generation model.

(c): NASA/CNES satellites Jason-1 and Jason-2 confirm the tsunami amplitude prediction of the GPS-based model prediction.

(d): Next steps: Strengthen real time GDPS network, automate models.

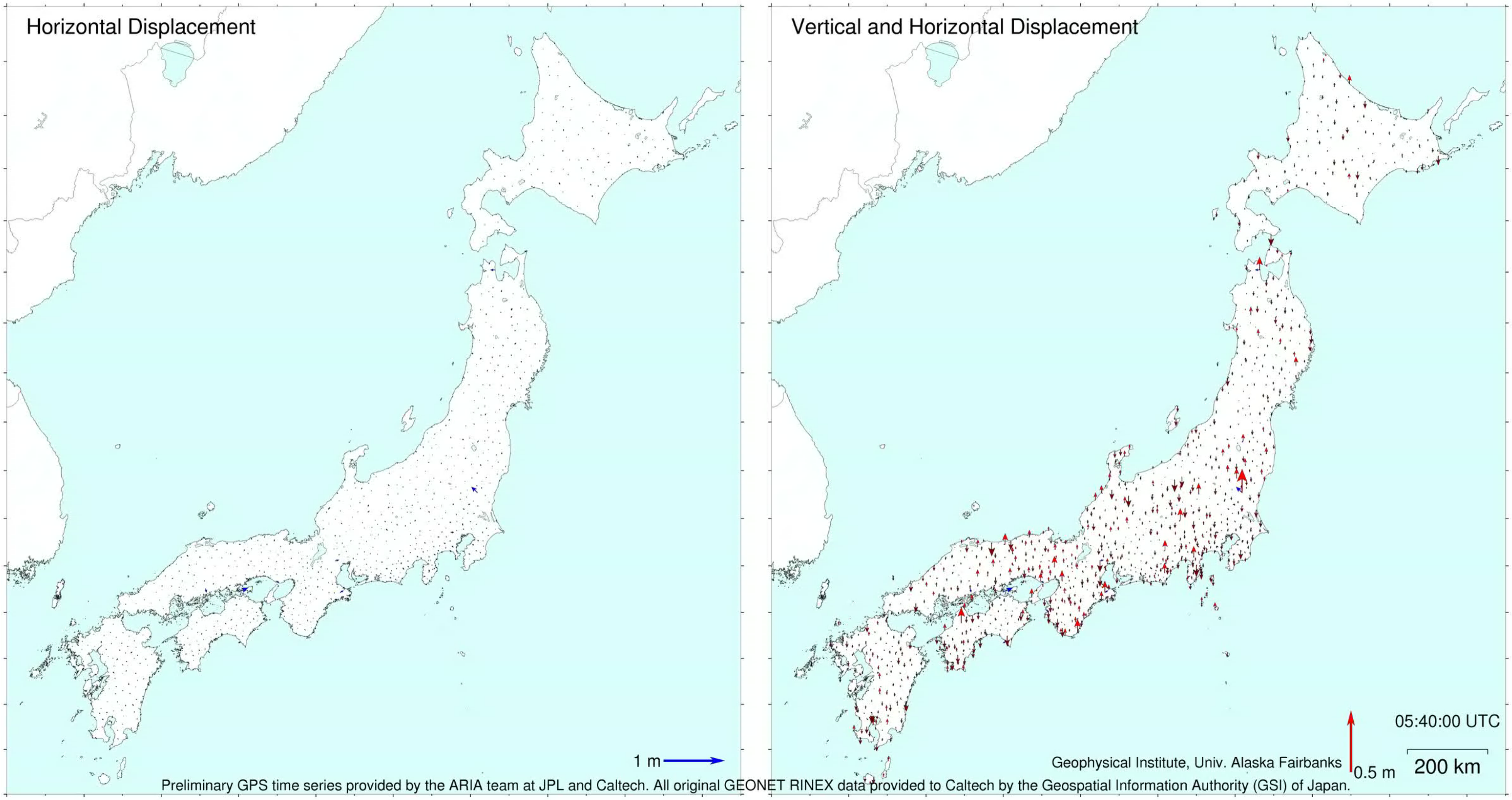
Tony Song , Yoaz Bar-Sever, et al. /JPL

Song Y.T., 2007, Detecting tsunami genesis and scales directly from coastal GPS Stations, Geophys Res. Ltts.

March 11, 2011:The GSI GEONET GPS Array

Demonstrated Capability to Predict a Tsunami and the First use of GPS to Predict AND Observe the Resulting Tsunami

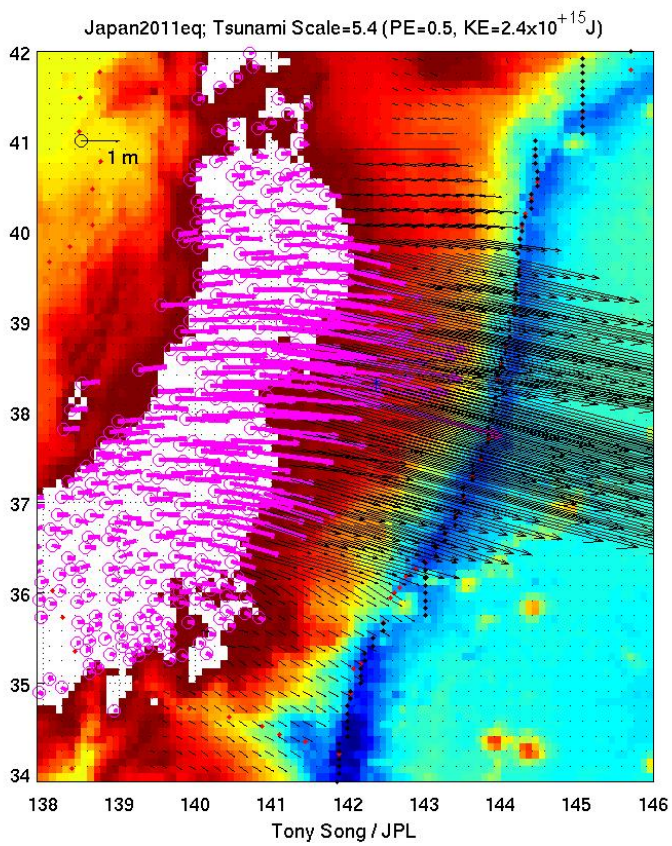
http://gps.alaska.edu/ronni/sendai2011.html: Ronni Grapenthin

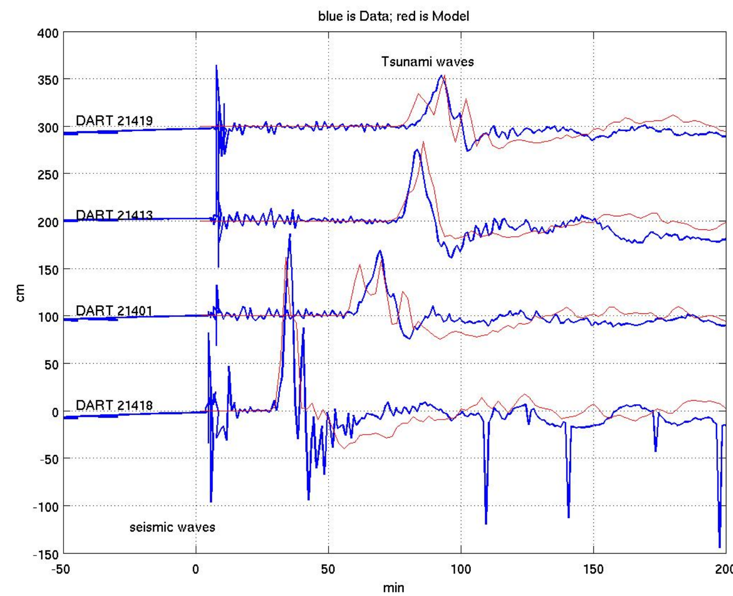


March 11,2011: Tohoku Oki Tsunami Energy & Scale Predicted and Confirmed

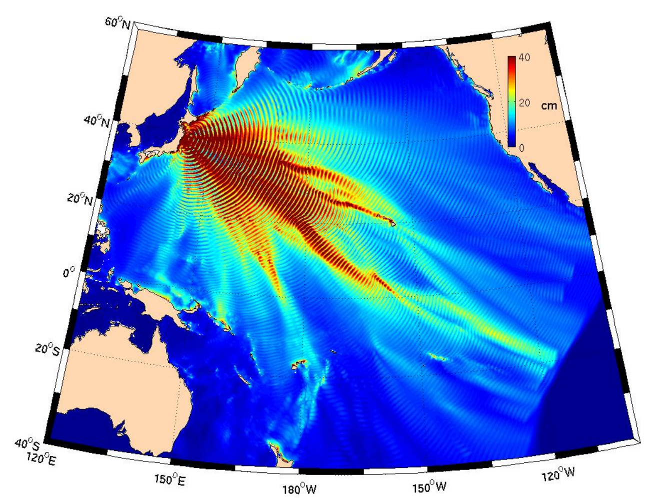
GPS data + model predictions match tsunami height data (tsunami station data in blue; model+GPS in red)

GPS-measured horizontal displacements (pink arrows) over Japan





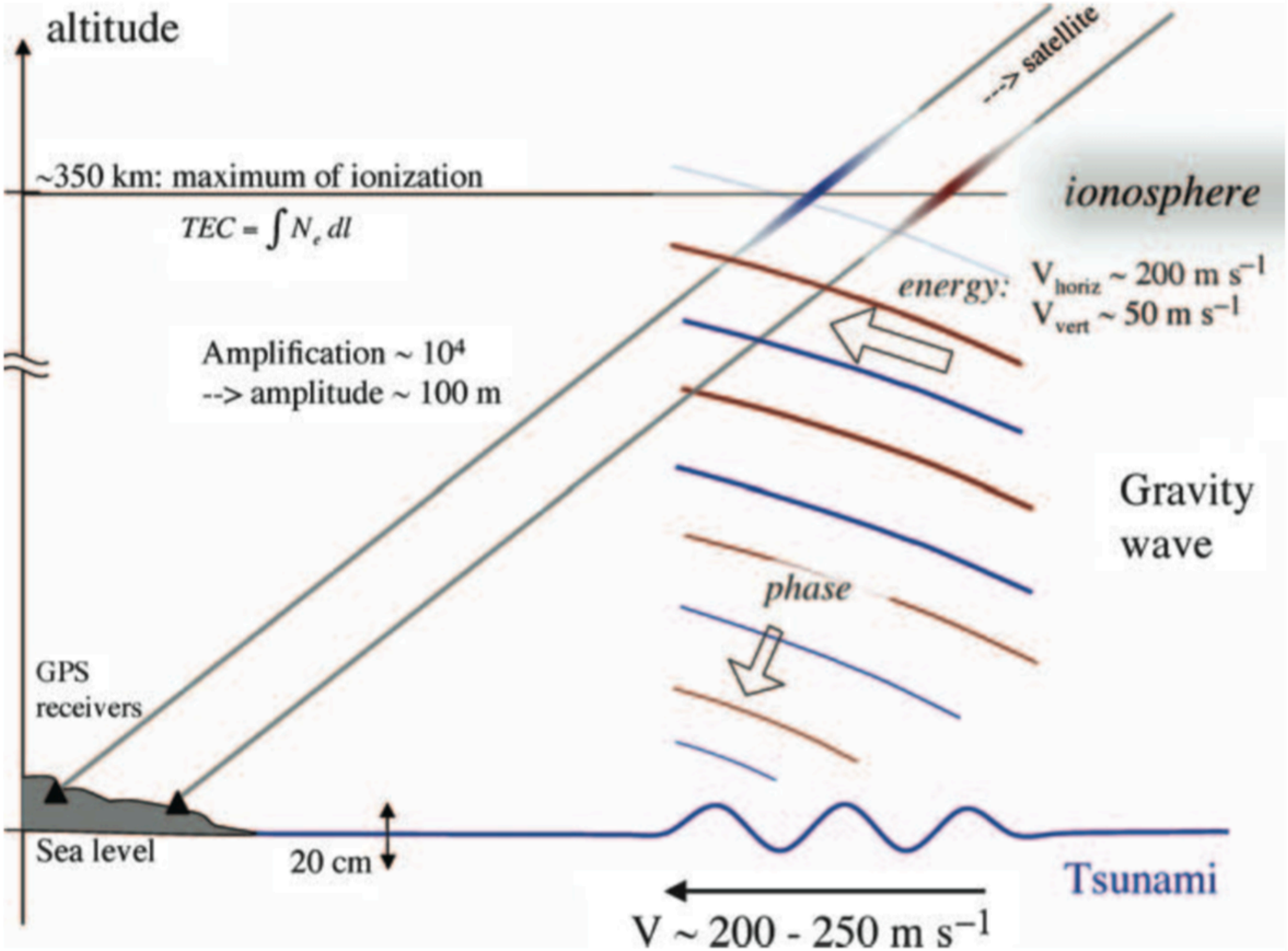
Sea level predicted from the ocean model using the GPS



Significance:
Tsunami early warnings directly from GPS

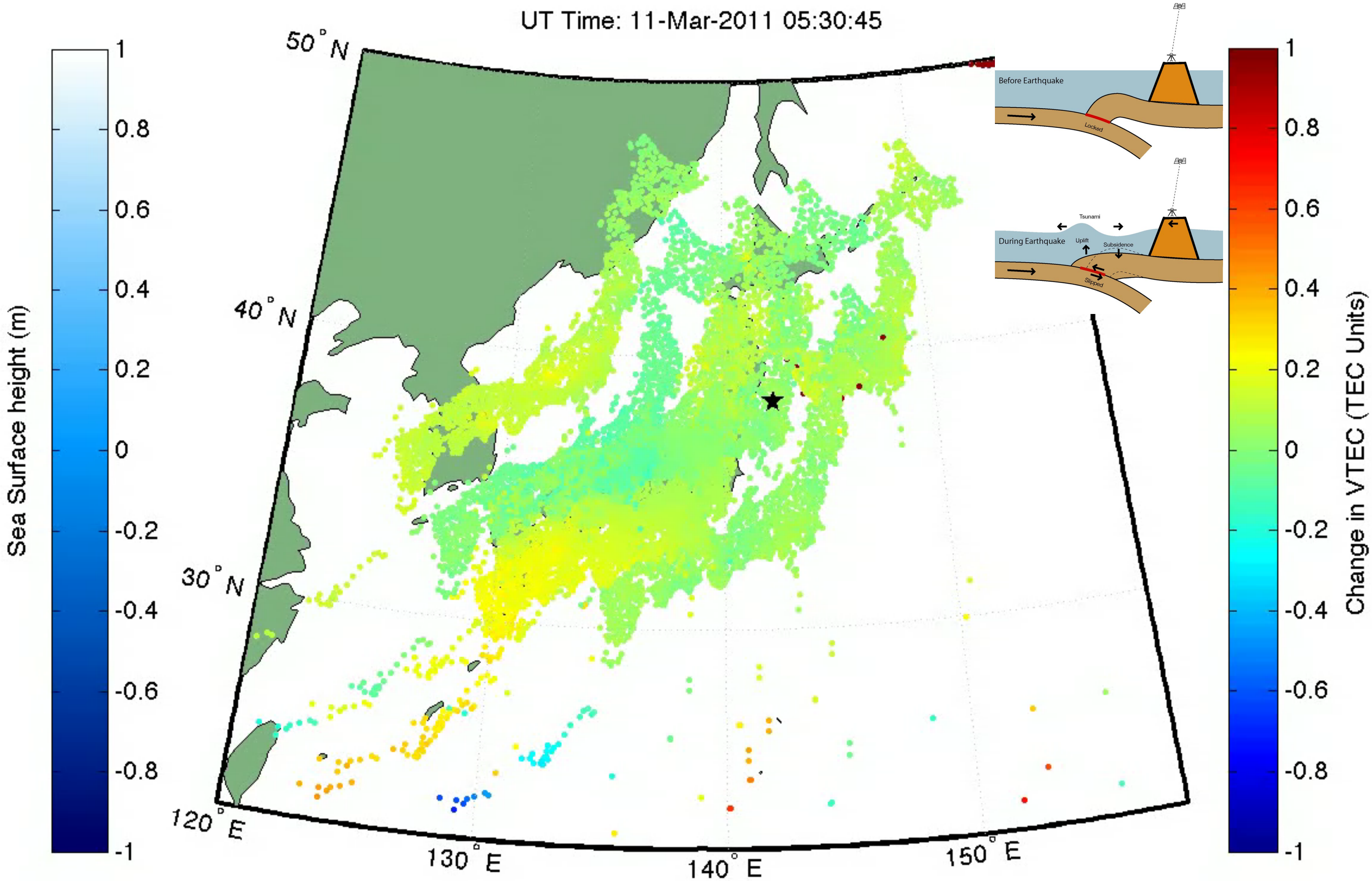
Tony Song, Mar 2011

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

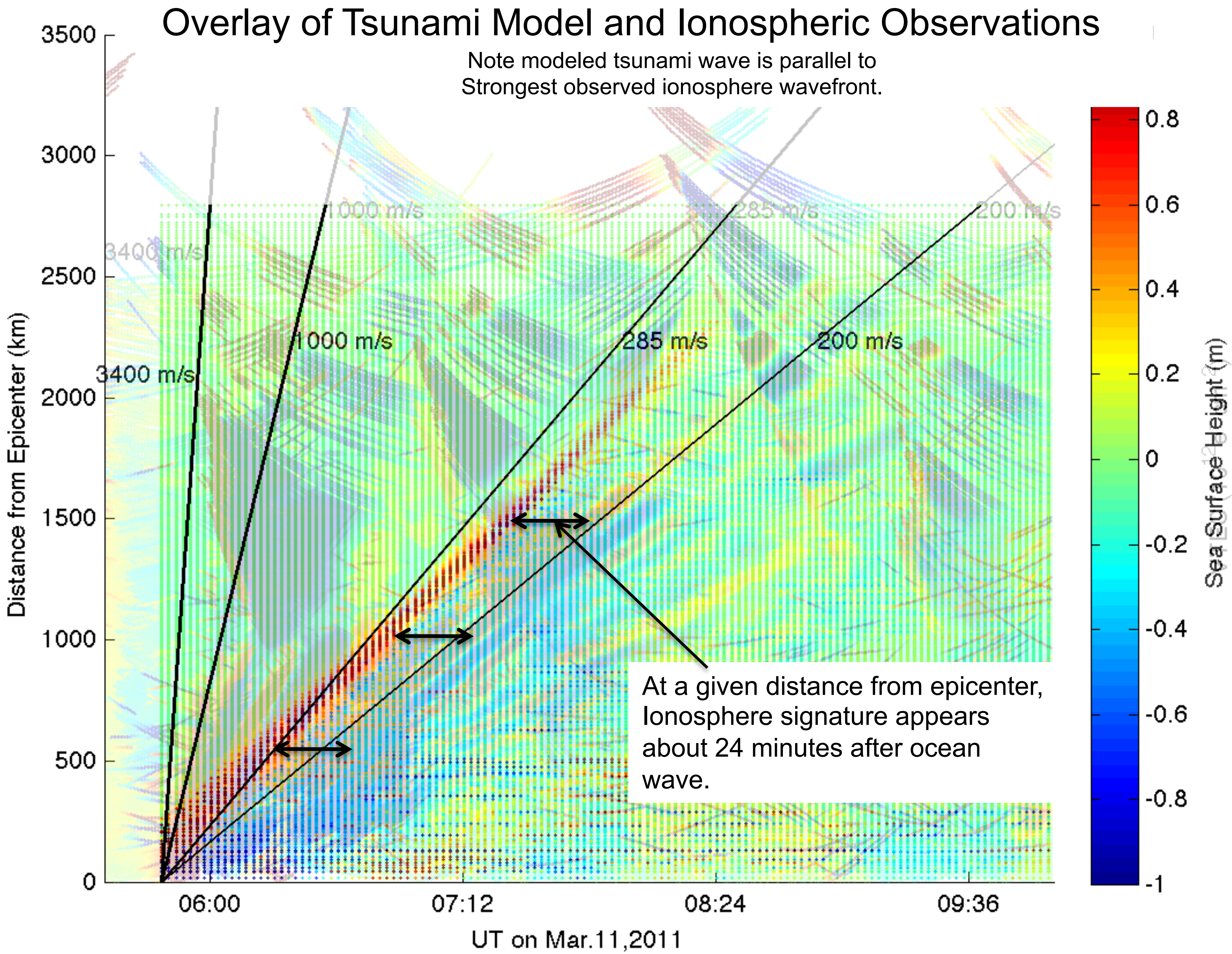


From *Artru et al.,* 2005

GSI's GEONET Also Captured the Ionospheric Coupled Waves and Imaged the Tsunami Generation and Propagation-For the First Time



Ionospheric Response to Mw9.0 Tohoku Earthquake and Tsunami in Japan on March 11, 2011, A.Komjathy, D.A.Galvan, M.P Hickey, P.Stephens, Mark Butala, and A.Mannucci, submitted GRL

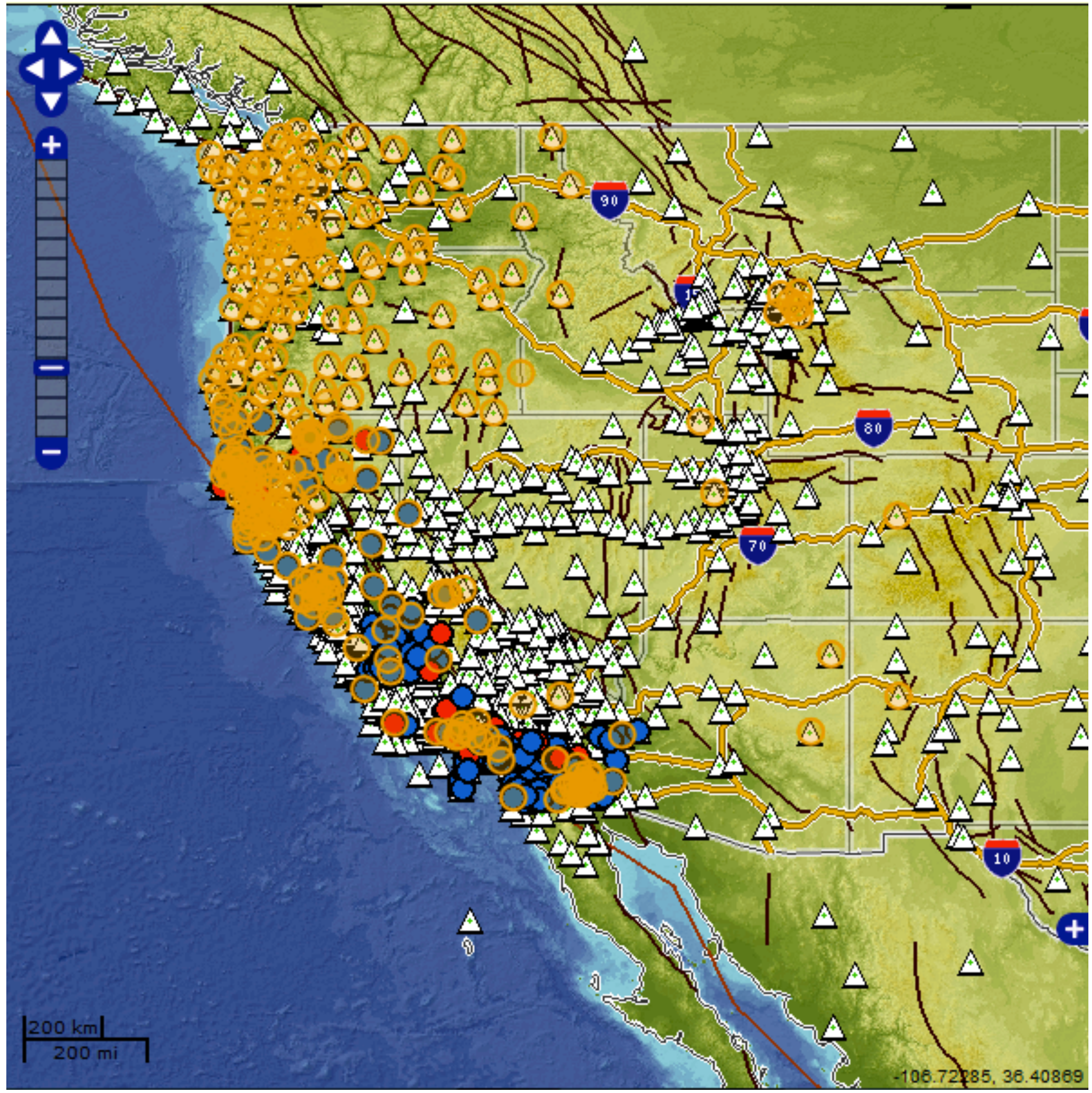


From the work of Song, Galvan, Komjathy, JPL

Proposed: A GNSS Based Disaster Early Warning Network (DEWN)

DEWN is NASA's effort to build upon the lessons learned from the disasters of this decade.

In Orange are the currently available 473 GPS receivers broadcasting real time data streams supported by federal and state agencies and private enterprise. The DEWN system is an experimental prototype network to develop communications protocols, data formats, algorithms, etc to explore the utility of real time Geodetic networks. Integration of real time seismic data will likely improve the accuracy of the early warning system.



Proposed: Pacific Basin
Low Latency Shared Access GNSS Network

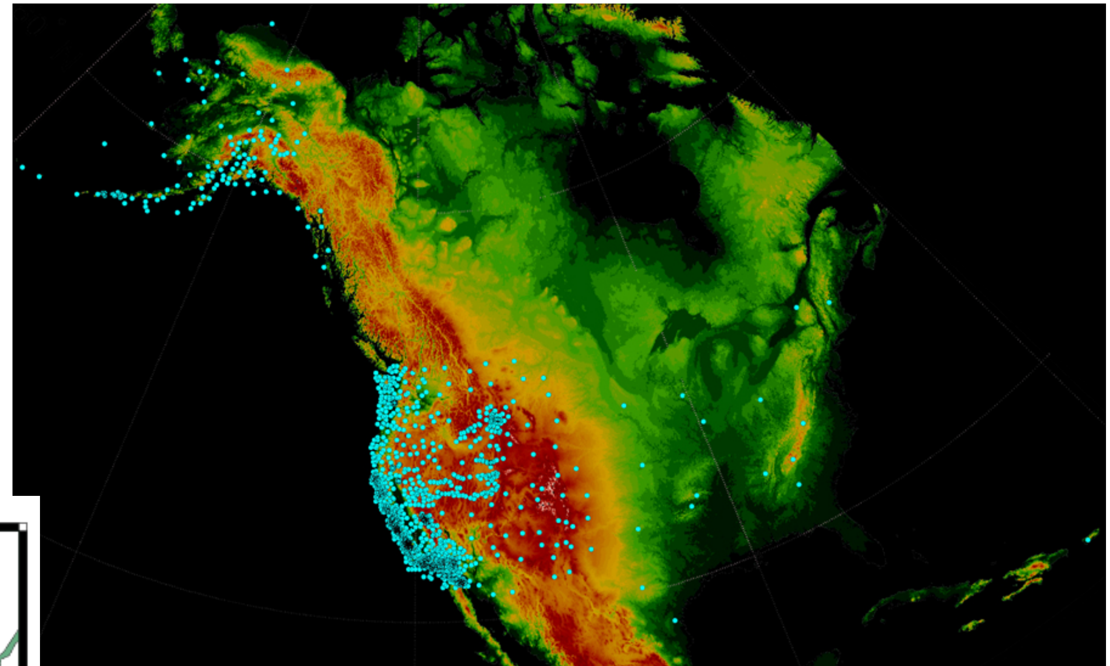
Pacific Basin Earthquakes and Volcanic Eruptions pose regional hazards that do not obey national boundaries.

The Pacific Basin is ringed by subduction zones and violent volcanoes with demonstrated ability to generate large earthquakes, devastating tsunamis, and volcanic ash plumes that propagate basin wide.

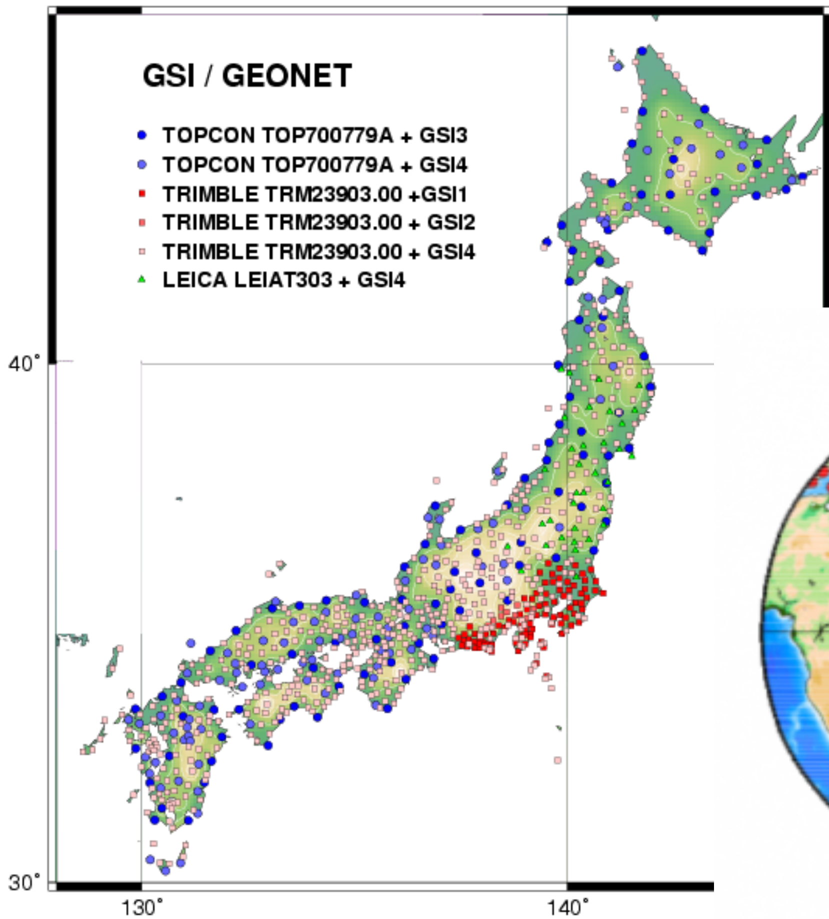
Dense GNSS regional networks are being deployed within the circum-Pacific and on Pacific Islands.

Communication infrastructure is available for near real time GNSS data distribution either continuous or event responsive.

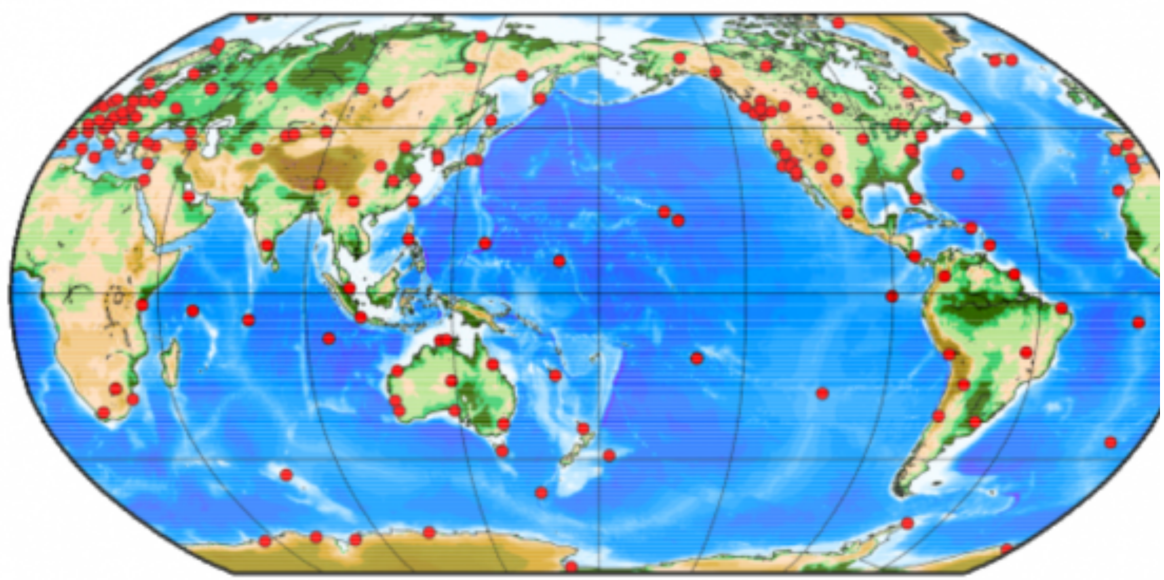
Over 3,000 Pacific Basin GNSS Stations

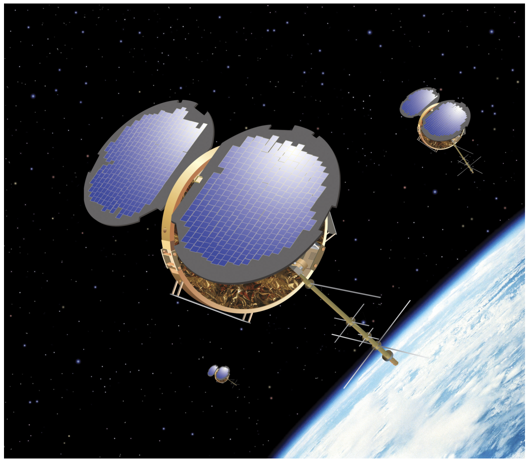


Earthscope Plate Boundary Observatory



GGOS/IGS Network





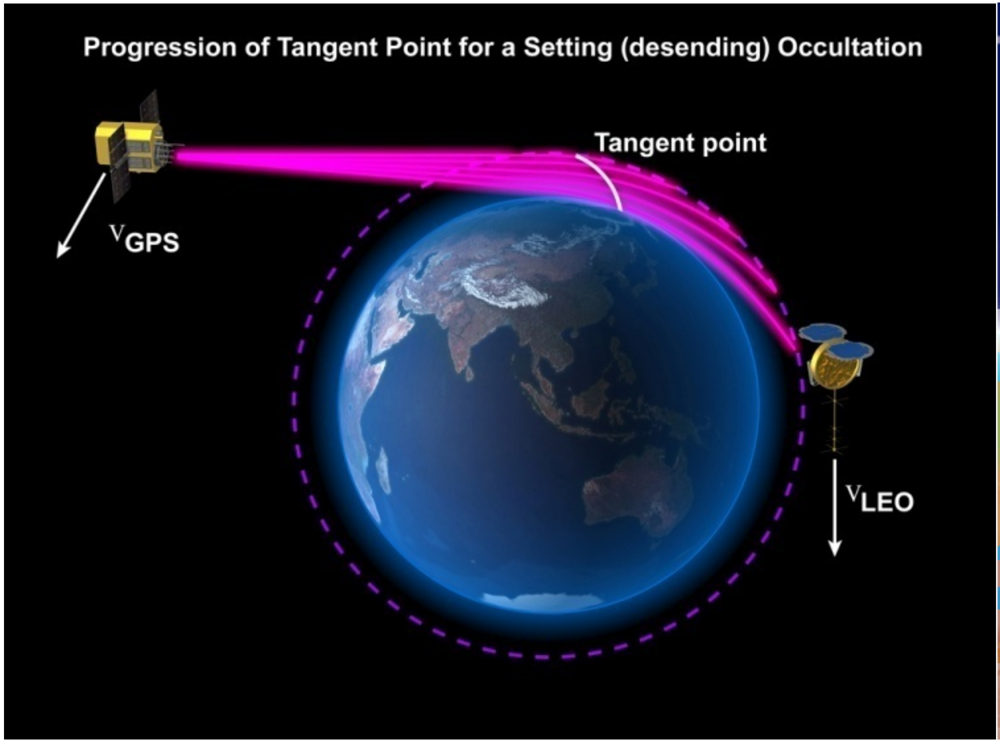
GNSS Remote Sensing

The TriG space-borne receiver will advance the space-borne science demonstrated by NASA's BlackJack receivers but within the expanded GNSS constellations of 2015 and beyond.

The TriG will bring GNSS Remote Sensing to Provide Tomographic Measurements of the Ionosphere, Atmosphere and to Characterize the Earth's Surface

TriG performance in GNSS remote sensing is dependent upon an equally capable ground geodetic reference network.

REFRACTION



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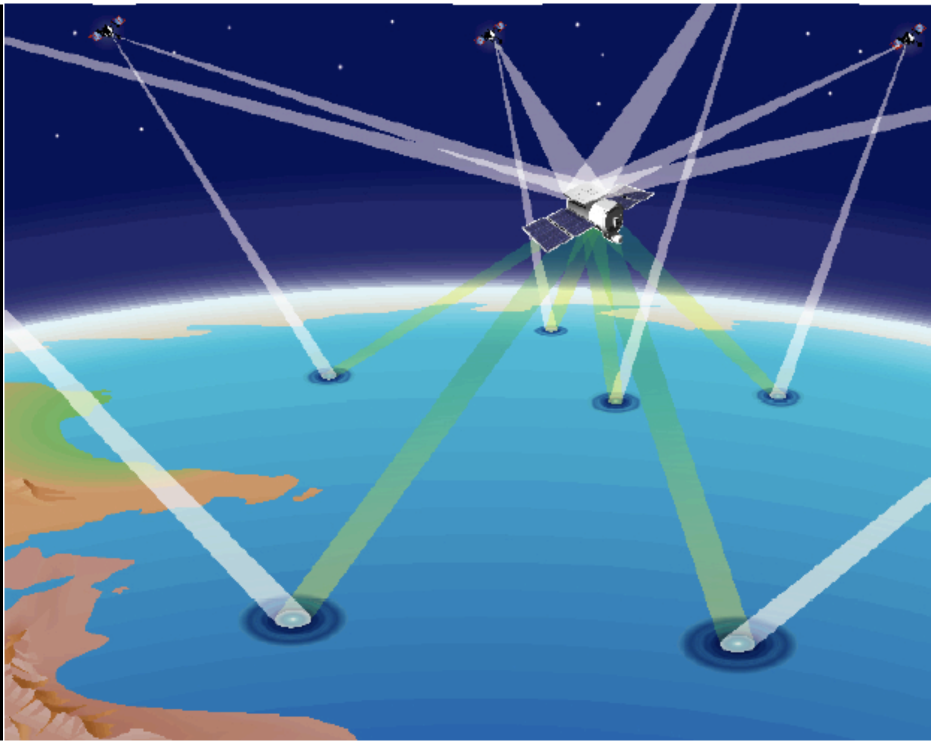
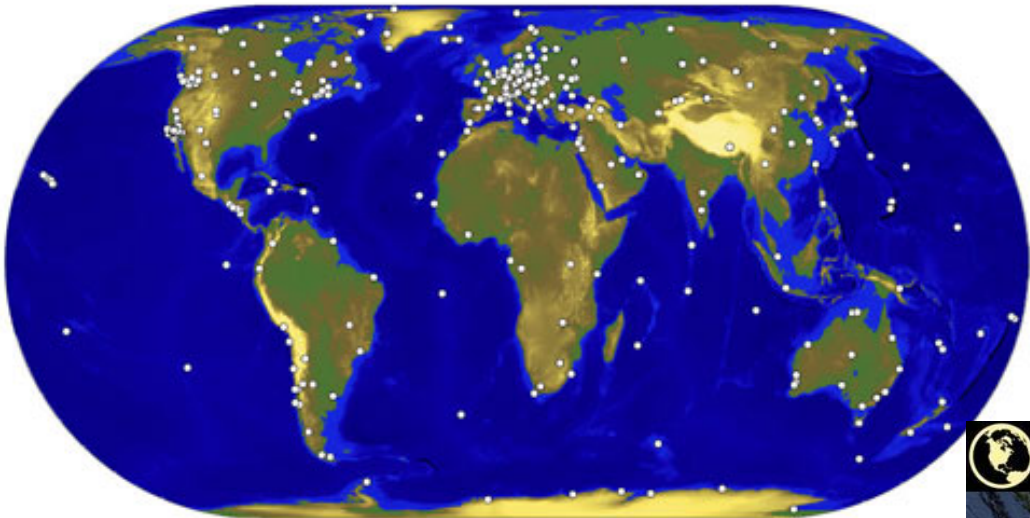
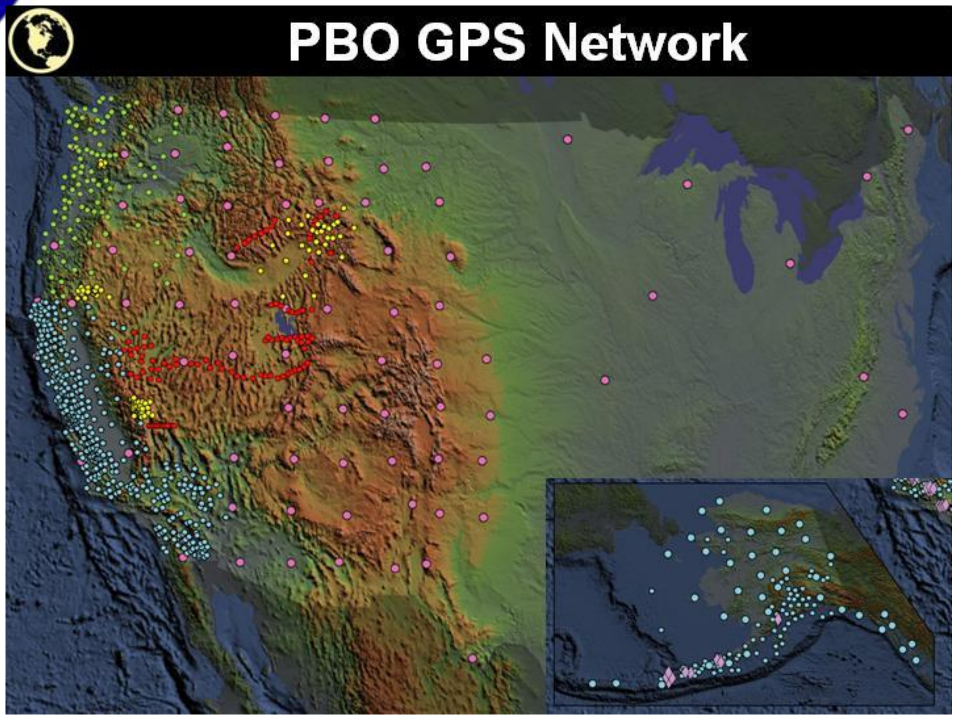


Can the large GNSS Ground Networks Provide New Environmental Data Products?



The GGOS International GNSS Service (IGS) GNSS network > 800 receivers

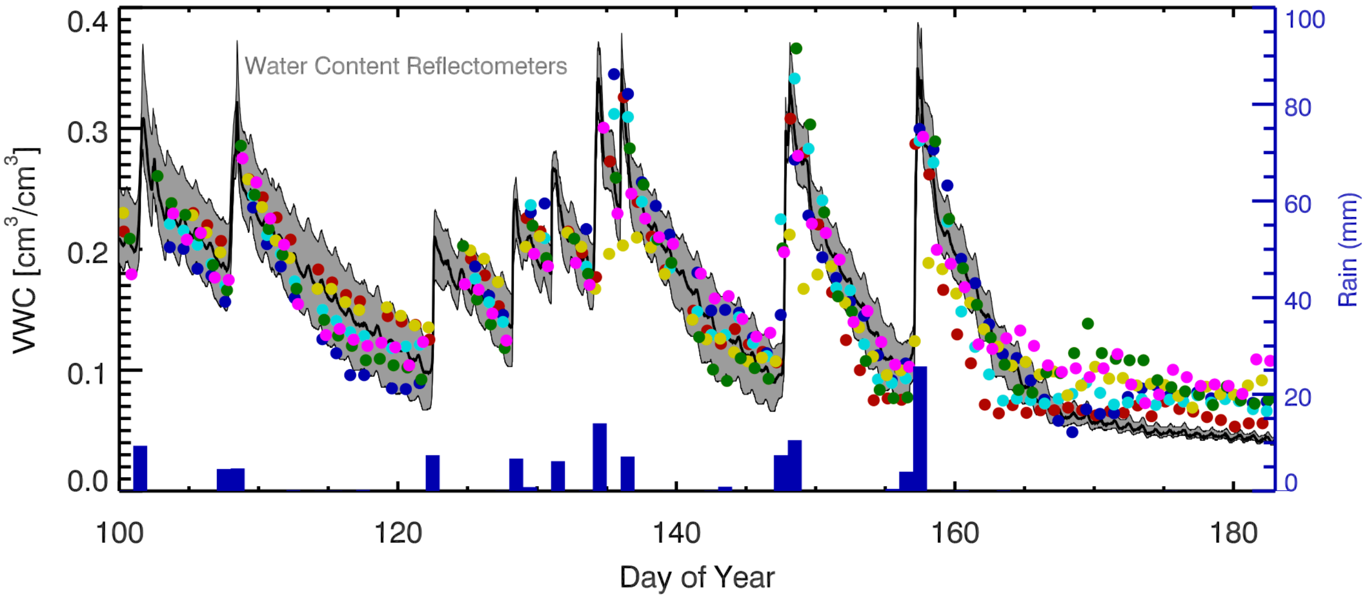


The Earthscope Plate Boundary Observatory (PBO) > 1100 GPS Stations

Water Cycle Studies Using GPS Ground Networks

GPS reflections is a new technique that uses data from existing GPS sites to monitor water stored on land in soil, plants, and snow. Water cycle products are derived from the interference between the direct and reflected GPS signals; they represent a region ~25m in radius around the antenna.

GPS site in West Yellowstone, Montana



Soil Moisture

Reflected GPS signals (colors represent different GPS satellites) correlate well with *in-situ* sensors (gray region) and rain (blue bars).

Kristine M. Larson (Univ. Colorado, Aero), Eric Small (Univ. Colorado, Geol. Sci.), John Braun (UCAR)

Now for a little entertainment…..