National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Cutting Edge GPS Science Applications

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Stephen M. Lichten, Deputy Manager
Communications, Tracking and Radar Division (33)

Jet Propulsion Laboratory, California Institute of Technology

Outline of Presentation

- GPS Design Trade
- Ground GPS Networks for science
- High-precision space-based GPS positioning and remote sensing

The GPS Design Trade

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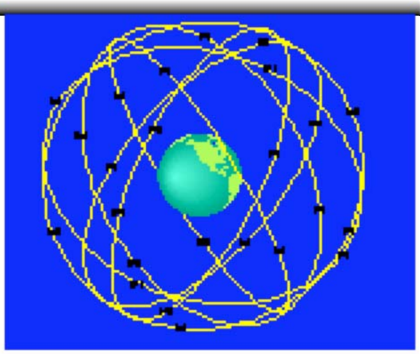
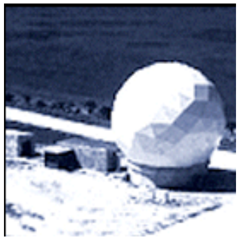
- **The Design Trade for GPS**
  - Accurate (atomic) clocks at ground sites and onboard GPS
  - Global tracking network accurately determines and updates GPS orbits and clocks at regular intervals
  - Relatively few USAF ground tracking sites means lower performance for GPS but higher security for the system
  - *Millions of GPS users can carry relatively simple equipment and do not require a good clock*
- Scientists typically favor better accuracy/performance versus getting real-time (but less accurate) information
- Natural hazard monitoring often requires real-time measurement and analysis





GPS MCS

GPS Performance Today

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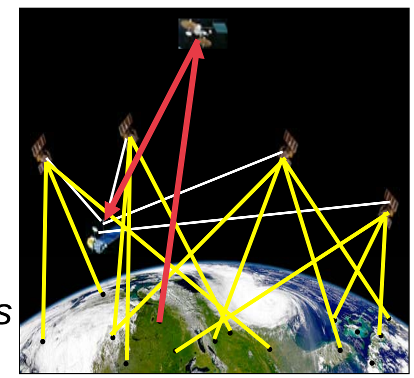
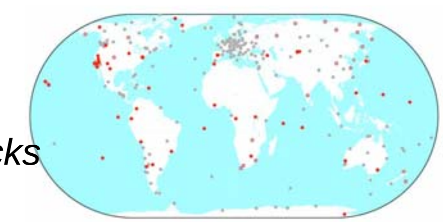
- Standalone low-cost commercial receiver
  - **5-15 meters** real-time positioning.
    - *Limited by broadcast GPS clocks/orbits, ionosphere and receiver simplicity*

- Military receiver, or commercial receiver + differential service
  - **1-5 meters** real-time positioning. Requires local/regional differential service subscription or WAAS.
    - *Limited by GPS clock & orbit modeling, ionosphere*



- NASA/JPL precise global differential GPS (GDGPS)
  - **10 cm** real-time positioning accuracy. Precise differential corrections (available via industry partner) and dual-band receiver
    - *Global network processing improves orbits, eliminates dependence on clocks*
    - *Terrestrial and space users*



- Non-real-time (minutes to days) geodetic positioning
  - **Millimeter to centimeter-level** non-real-time positioning accuracy. Requires global network, dual-band data + advanced software.
    - *Global network processing improves orbits, eliminates dependence on clocks*
    - *Terrestrial and space users*

JPL's Science Interests in GNSS

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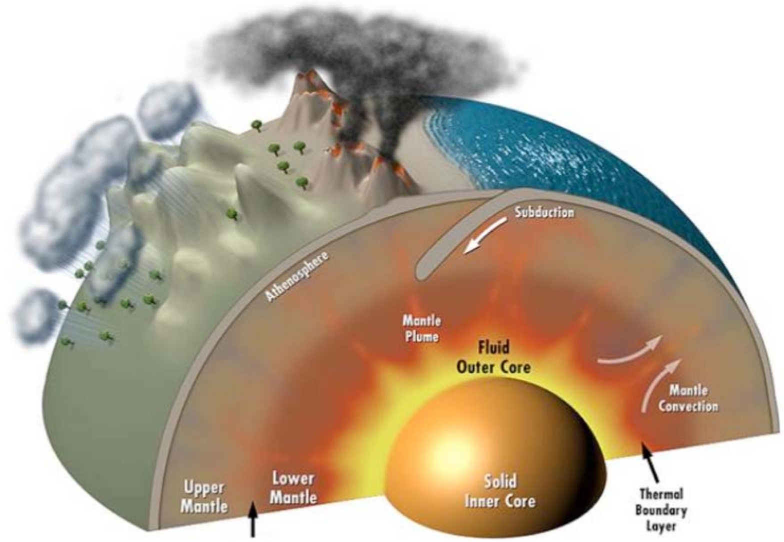
Jet Propulsion Laboratory
California Institute of Technology

- Global geodesy and geophysics; atmospheric and ionospheric remote sensing
- Earth platform critical calibrations in support of deep space missions
- Earth orbiter tracking, precise orbit determination, and remote sensing with flight GPS instruments
- Notable accomplishments
  - About a dozen patents (hardware and software)
  - Delivery of real-time GPS software to FAA for WAAS (late 1990s)
  - NASA Software of the Year (2000)
  - Space Technology Hall of Fame (2004)
  - Hundreds of scientific publications



Advanced GPS Applications

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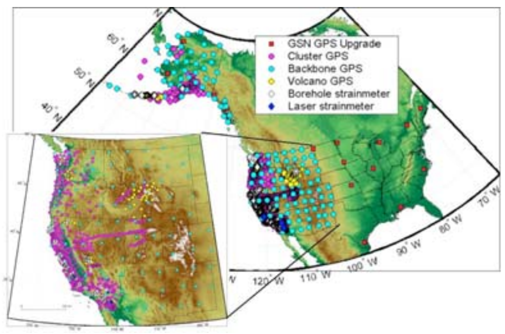
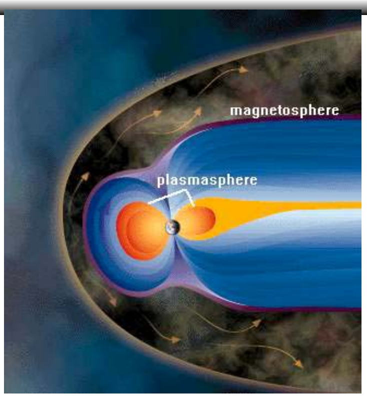
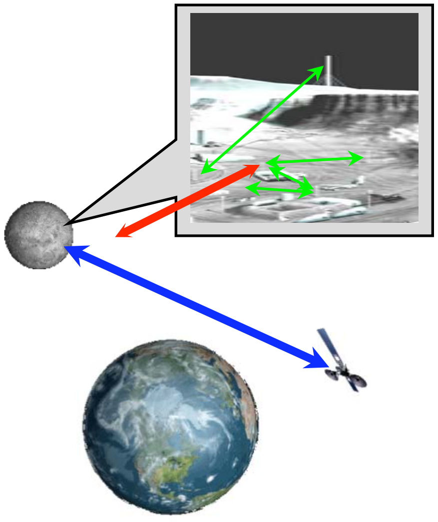
Mission critical support to DSN tracking



EarthScope

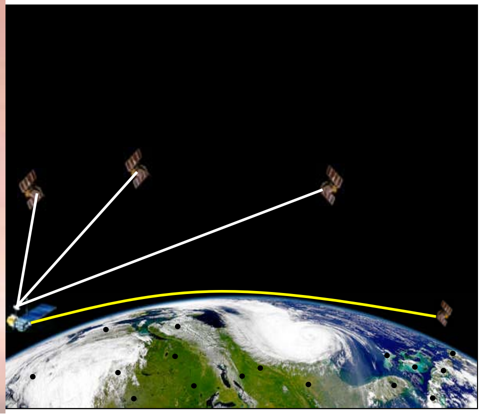


e^- density in space

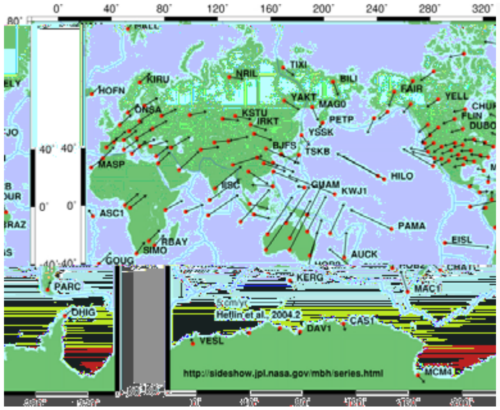


Lunar GPS & GNSS

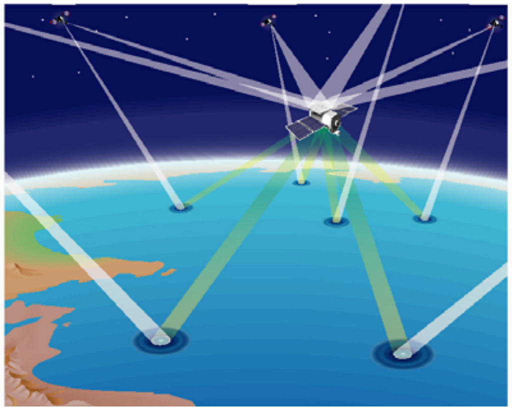
atmospheric occultations



terrestrial reference frame



ocean surface height



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Ground-Based Geodesy Using GPS: Plate Tectonics and Regional Deformations

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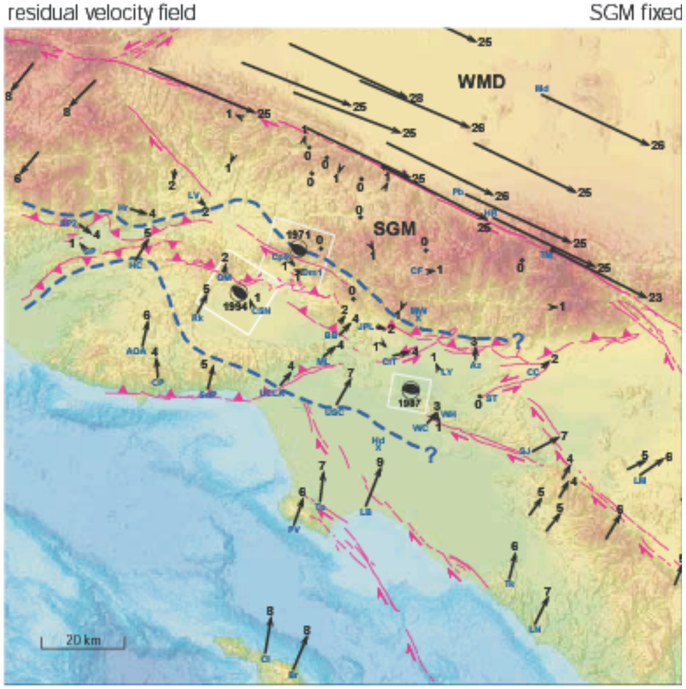
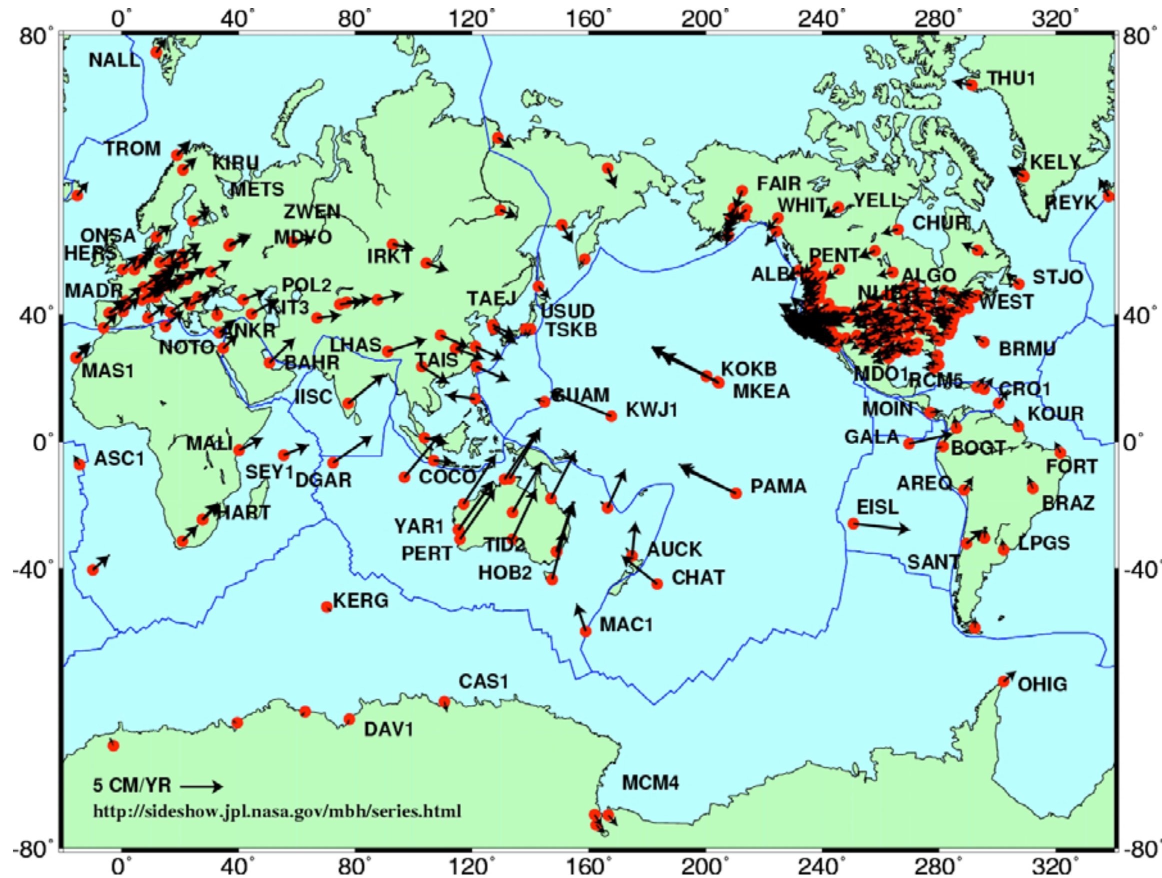
- **Global and regional networks (Global GPS Network, Southern California Integrated GPS Network). *Millimeter-level accuracy* of position estimates.**
- **Deriving GPS-based definition of the terrestrial reference frame**

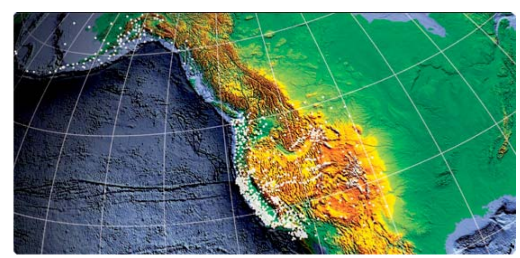
residual velocity field SGM fixed



Mojave segment, San Andreas F.
best 25 mm/yr 20 km



EarthScope/Plate Boundary Observatory



GPS Global Network

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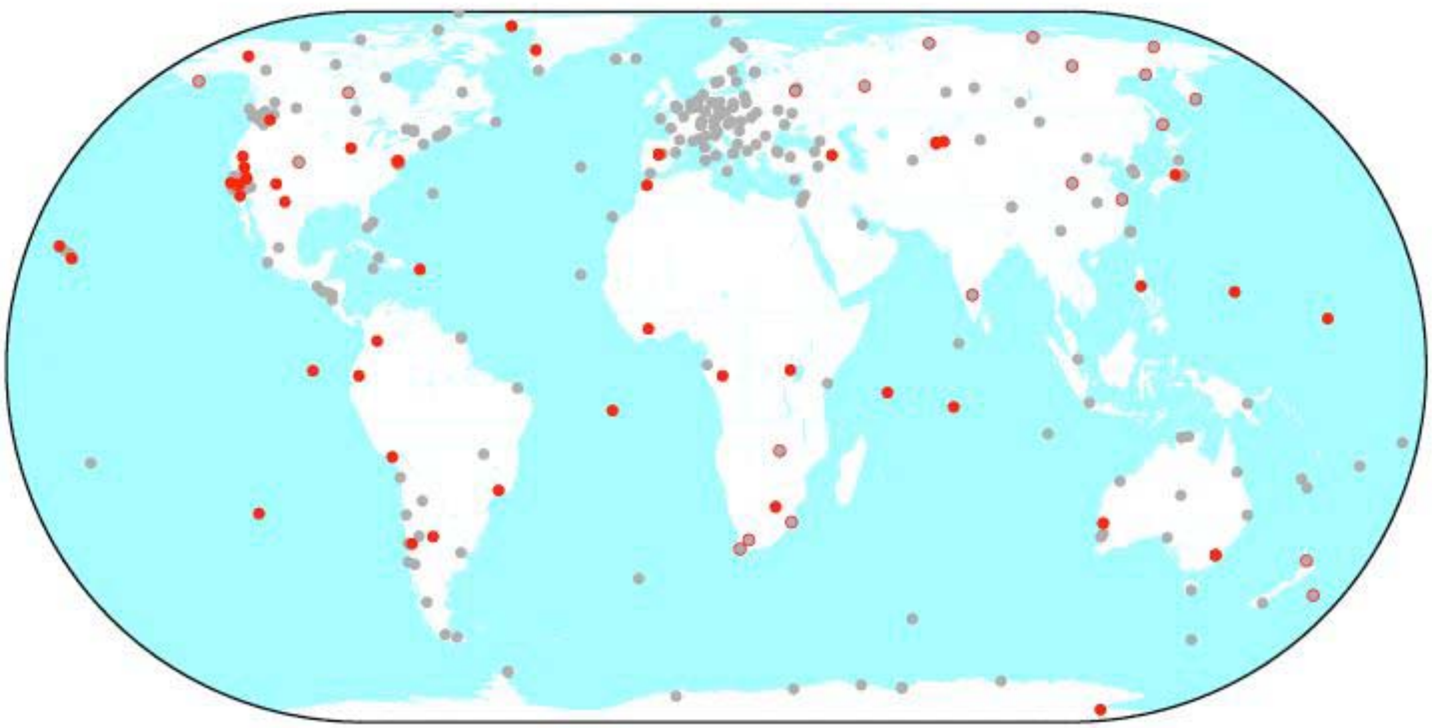
Tracking Network of the International GNSS Service (IGS) Highlighting NASA's Contributions



- ● NASA GPS Stations
- o NASA Cooperative Stations
- ● Other Agency Stations

More than 400 GPS tracking stations in the IGS

IGS GPS Orbit Solution Quality

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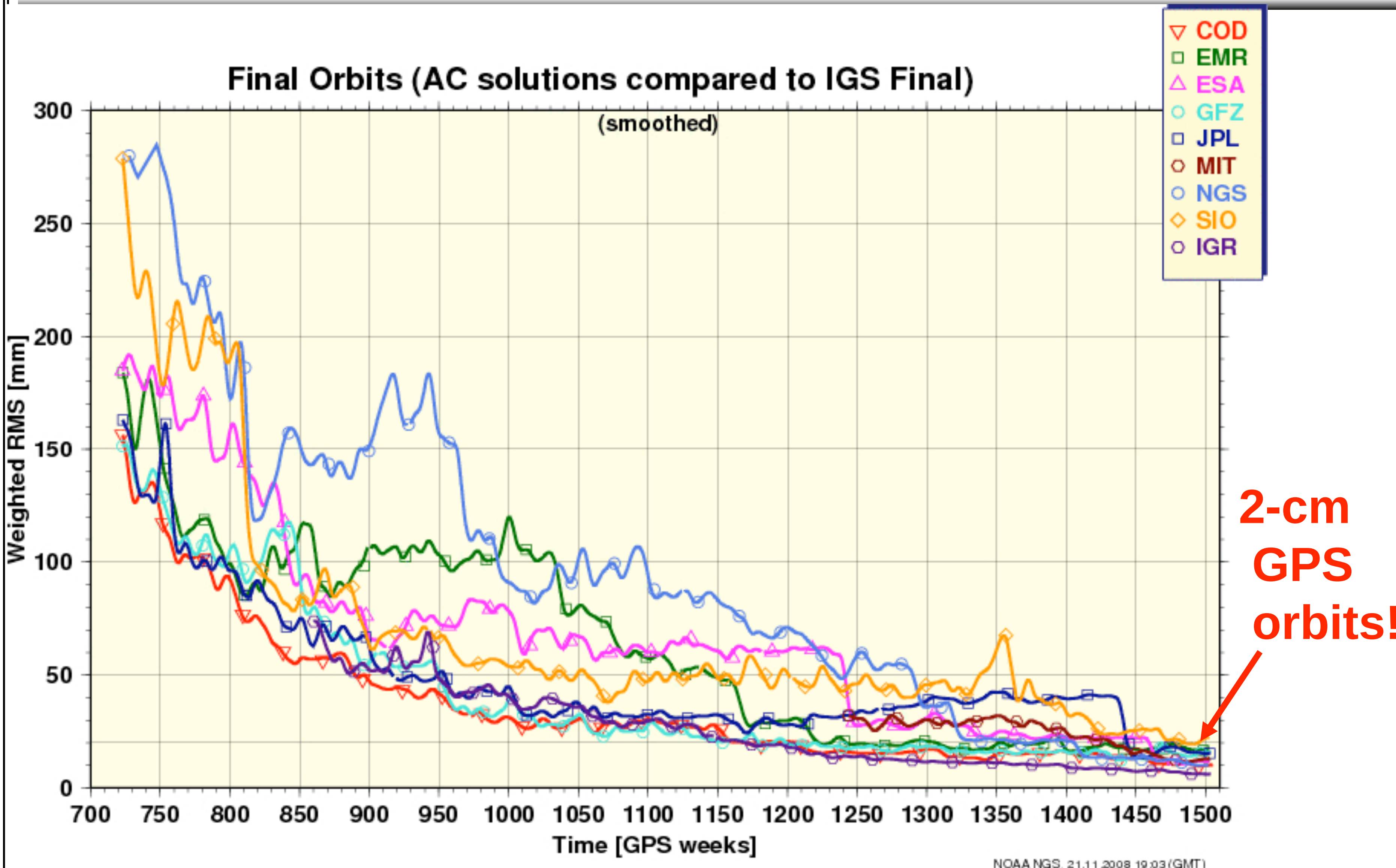
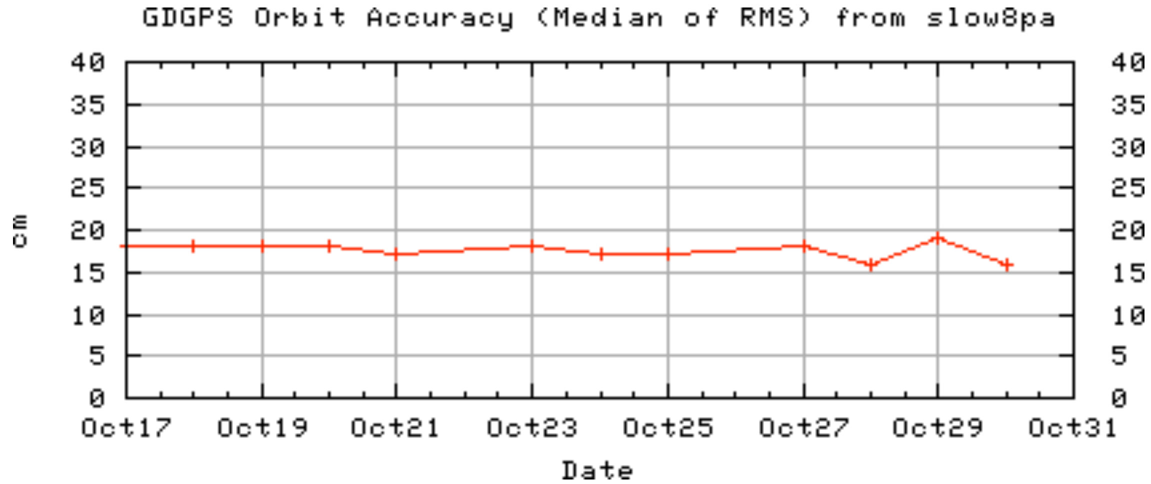


JPL Real-Time GPS Orbit Solution Accuracy: 15-20 cm

(available as real-time global differential corrections via industry partner)



NASA's Real-Time Global Differential GPS (GDGPS) System

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Terrestrial and airborne users

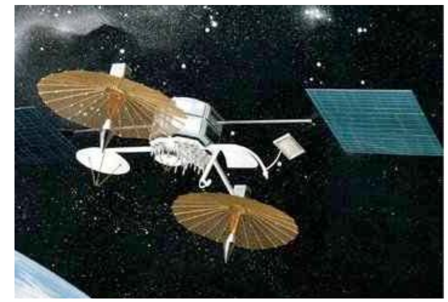
Land lines

Iridium
Inmarsat

GDGPS Operations Center

Uplink

TDRS

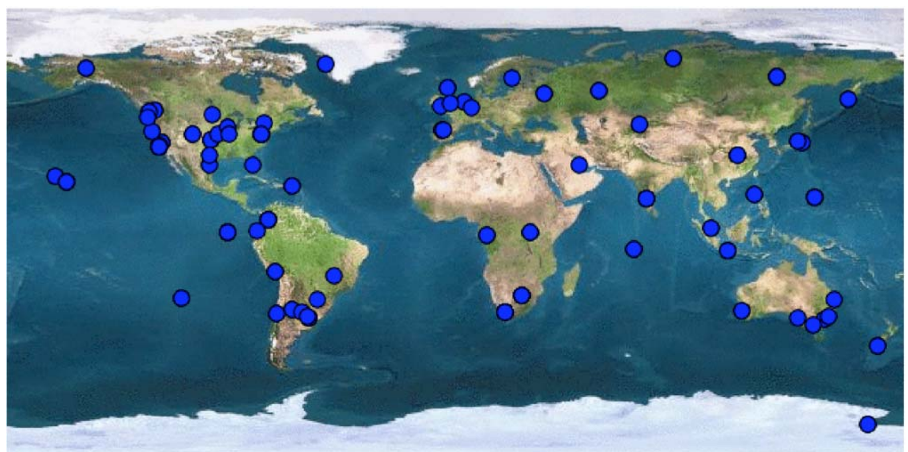


Broadcast

Frame

Internet

GDGPS real time network



Space users

Redundant architecture: no single point of failure

99.999% reliability since inception in early 2000

Commercialized with industry partner

For more info see:

www.gdgps.net

Real-Time GDGPS Support for Missions and Projects

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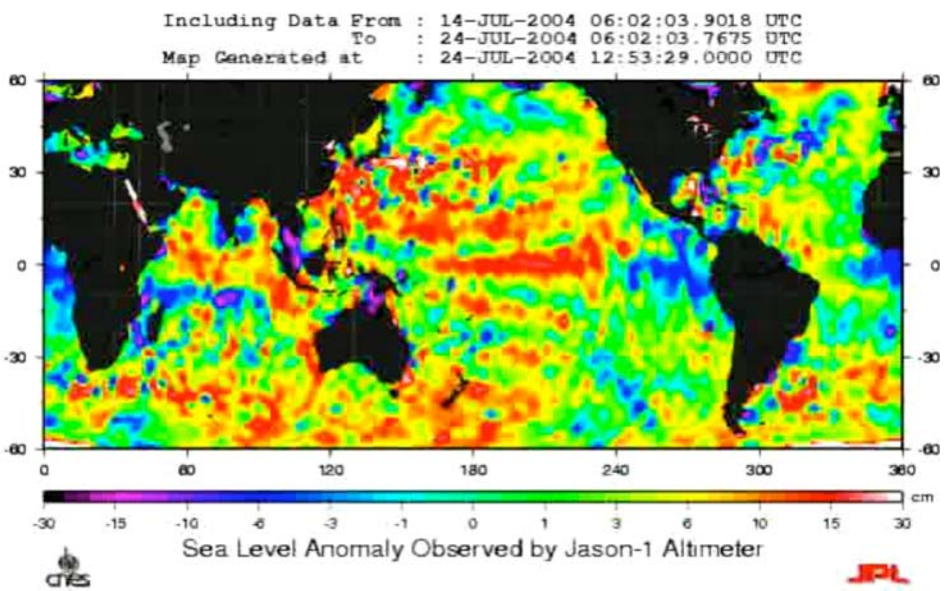
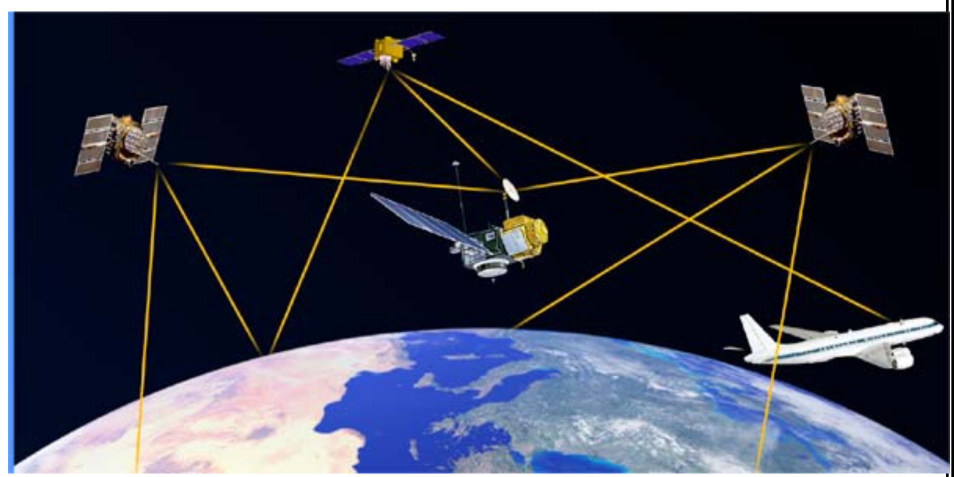
- **Natural hazard monitoring (earthquakes, volcanoes …)**
- **Atmosphere and Earth orientation measurements in support of deep space operations**
  - Mars Exploration Rover, Phoenix entry/descent/landing, Cassini orbit injection
- **Real time on-board positioning for AirSAR radar system calibration**
- **UAVSAR on-board, real-time positioning for flight control of repeat pass interferometry**
- **Near-real time low-Earth orbit determination and sea surface height**
- **JPL's real-time GPS software was licensed and delivered to the FAA for use by the prime WAAS contractor. It has been commercialized by an industry partner.**





JPL Performs GPS Integrity Monitoring

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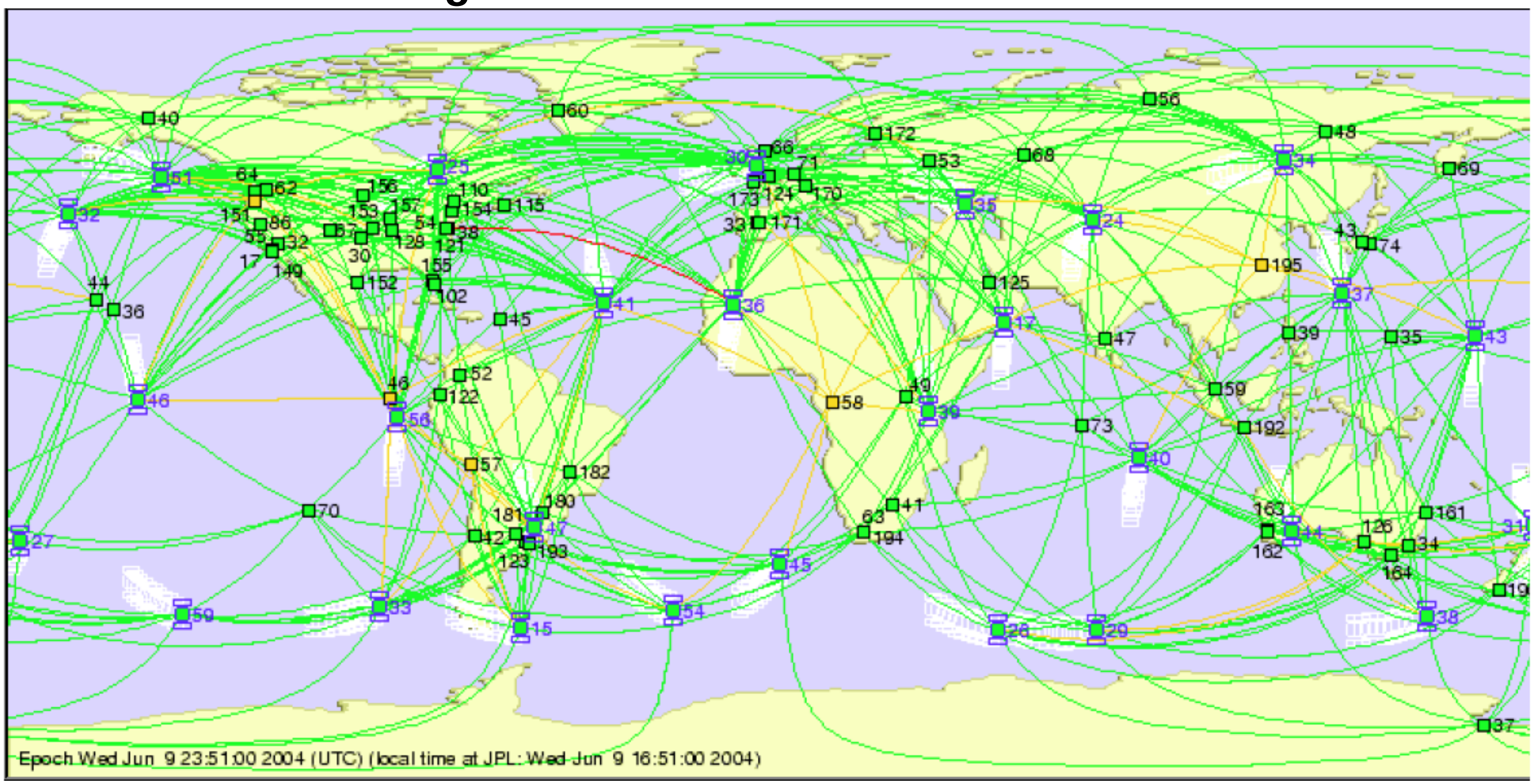
As a strategic national security asset and a critical global infrastructure undetected GPS failures can have enormous consequences, however, operational GPS lacks integrity monitoring due to sparse tracking network

The NASA Global Differential GPS system is providing real-time global GPS performance monitoring services to the U.S. Air Force



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JPL/NASA BlackJack GPS Receivers: >50 Flight Years of Successful Space Operations

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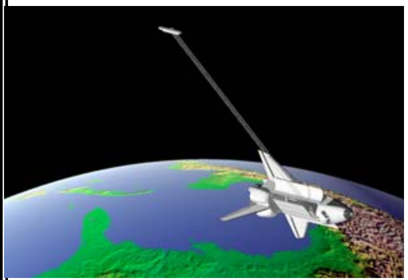
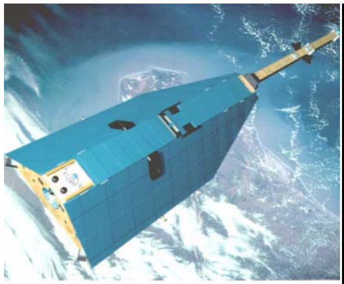
The most precise GPS receivers flown in space -- enabling new science and navigation capabilities



45-cm accuracy

SRTM

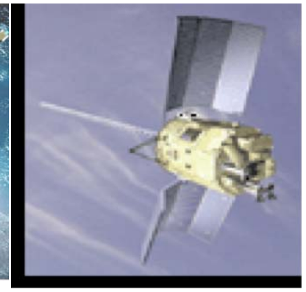
Feb 2000



4-cm accuracy

CHAMP

Jul 2000



4-cm accuracy
Sub-meter real-time demo

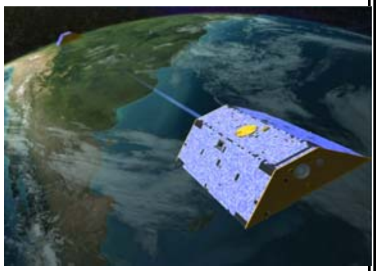
SAC-C

Nov 2000

1-cm accuracy

JASON-1

Dec 2001



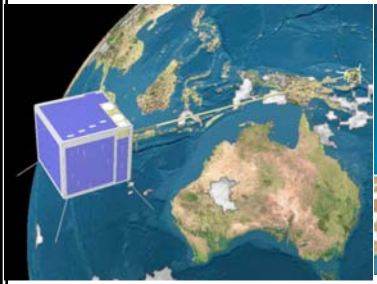
1-cm accuracy

GRACE

Mar 2002

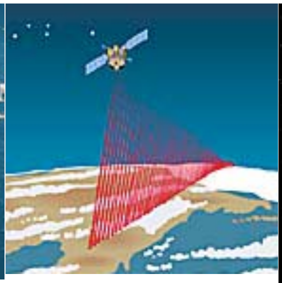
Dec 2002

FedSat



Dec 2002

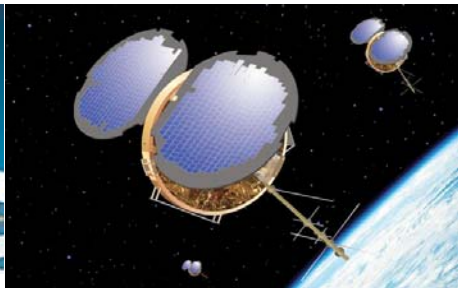
ICEsat



5-cm accuracy

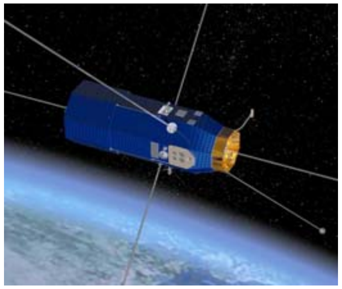
Apr 2006

COSMIC



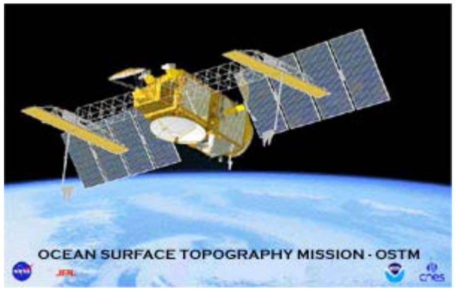
Apr 2008

C/NOFS



Jun 2008

OSTM



GPS Flight Receiver Science Remote Sensing

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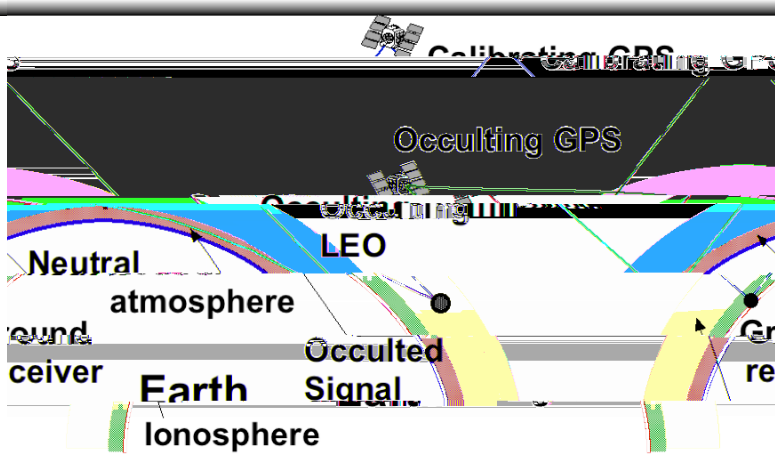
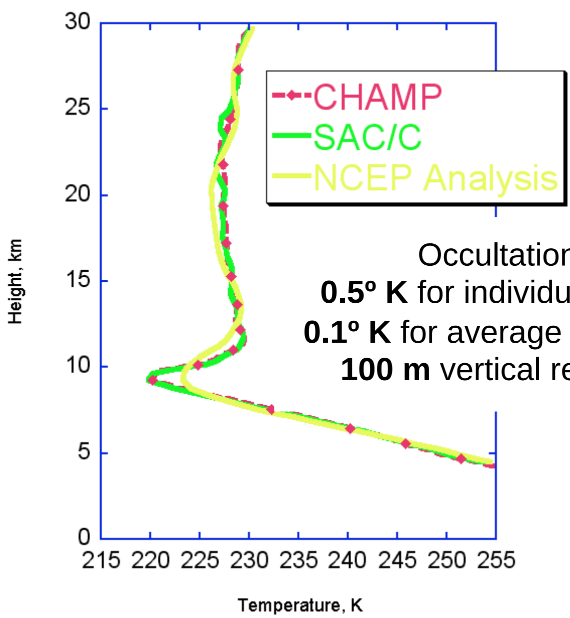
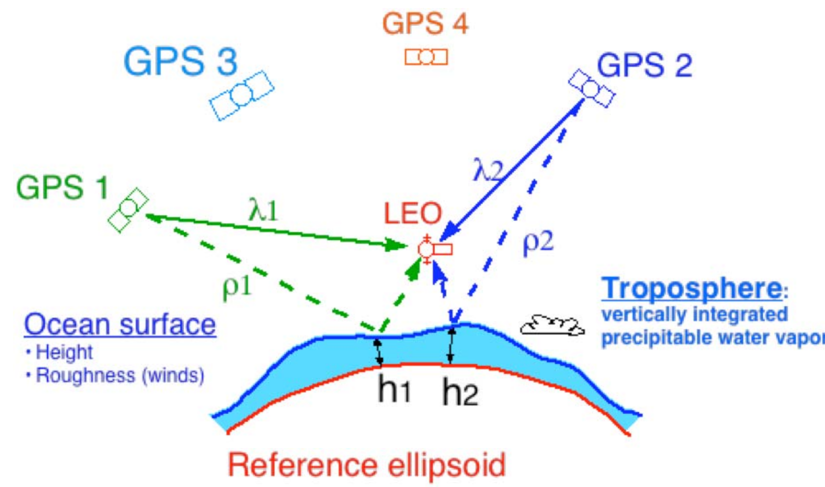


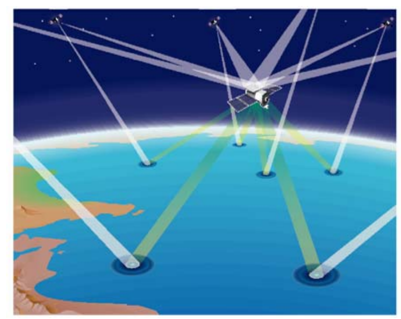
Atmospheric and Ionospheric Remote Sensing and Science



Occultations:
0.5º K for individual profiles
0.1º K for average ensembles
100 m vertical resolution



Bi-Static Ocean Reflectometry



2 cm precision altimetry in 1-sec using phase from fixed receiver (Crater Lake, OR)

GPS Ionosphere Remote Sensing

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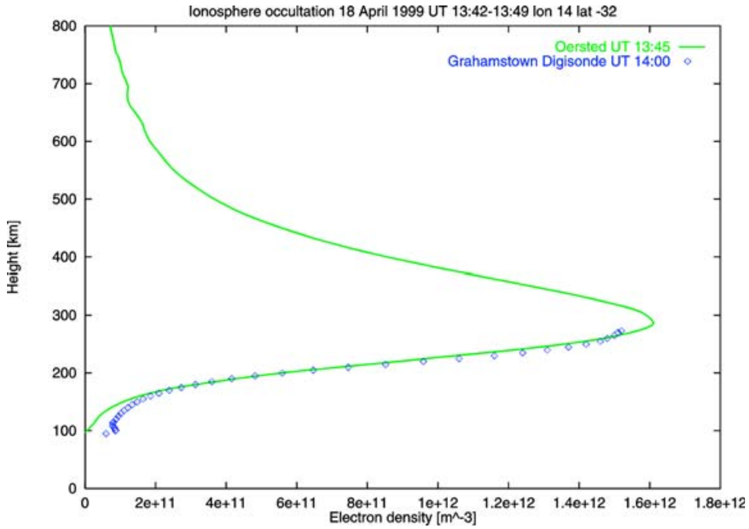
Capabilities:

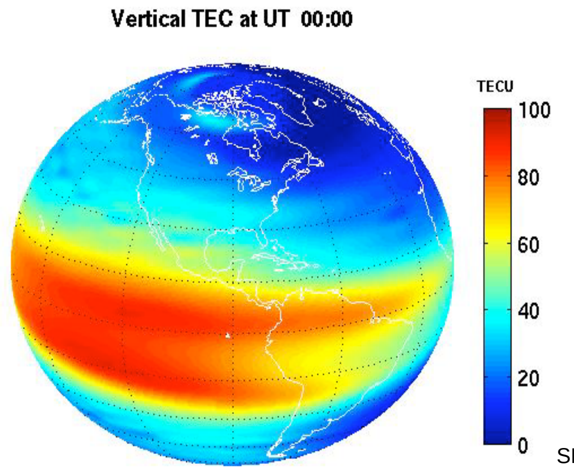
- **Electron density profiles at <1km vertical resolution**
- **2D global maps of vertical TEC and ionospheric response to magnetic storms**
- **3D images of electron density as a function of time**
- **Maps of ionospheric scintillations**

Applications:

- **Sun-Earth Connection science**
- **Key input to Navy/AF advanced space weather models**
- **FAA's Wide Area Augmentation System**
- **Mitigate effects on communications**
- **Improved understanding of ionospheric dynamics**



Above: Example of electron density profile obtained with GPS occultations on Oersted. Below: Example of global vertical TEC maps obtained by the Global Assimilative Ionospheric Model (GAIM)



GPS Operations and Science Support for Ocean Altimetric Missions

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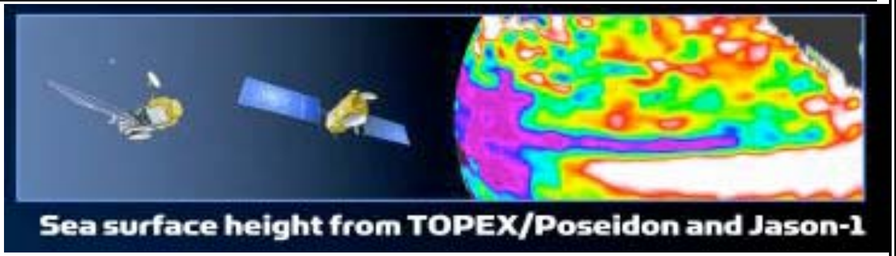
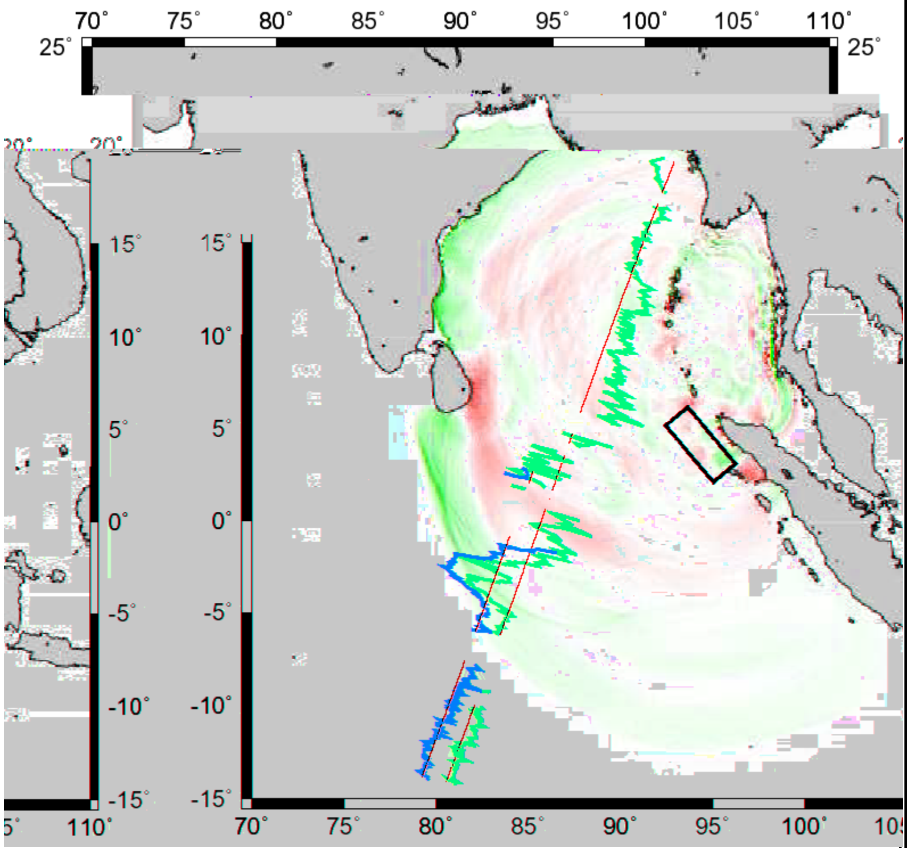


- **JPL GPS flight receiver**
- **Orbit determination for Jason and Topex**
  - Near-real-time, daily, final
  - Sub-cm RMS radial accuracy for Jason
- **Tsunami** Jason (orange) and Topex (green) ocean height measurements 15 minutes after the 2004 Sumatra earthquake superimposed on a model of the tsunami (shades of red and blue)



Tsunami Detected in Raw Jason-1 Altimetry Data

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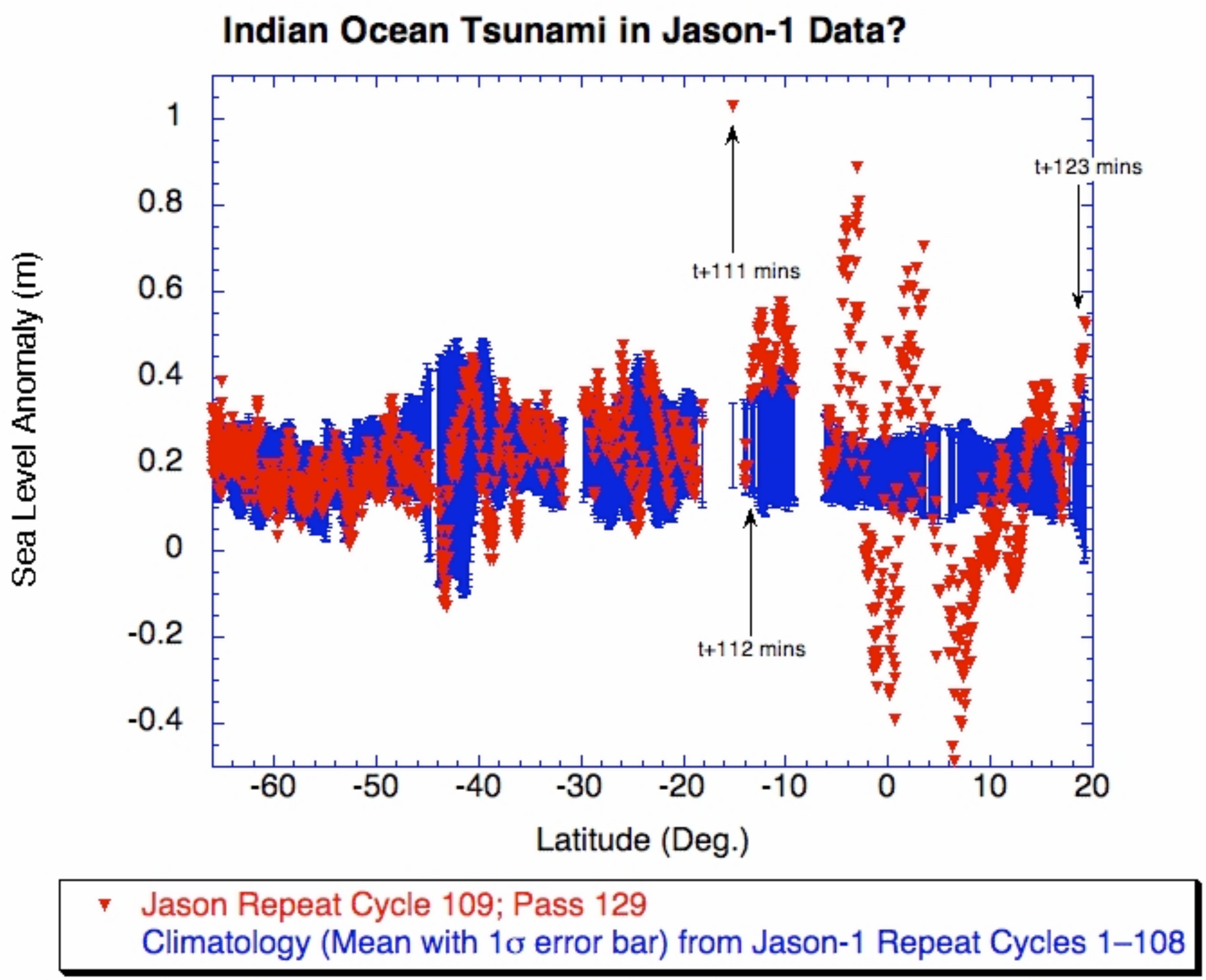
- December 26, 2004 tsunami from Sumatra earthquake was seen in "raw" altimetry data from Jason satellite passing overhead
- Unfortunately, these data were not available in real-time

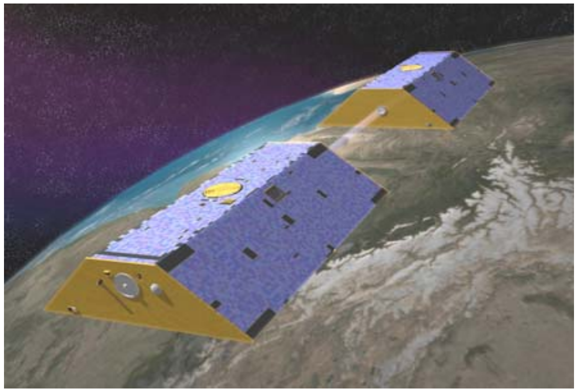


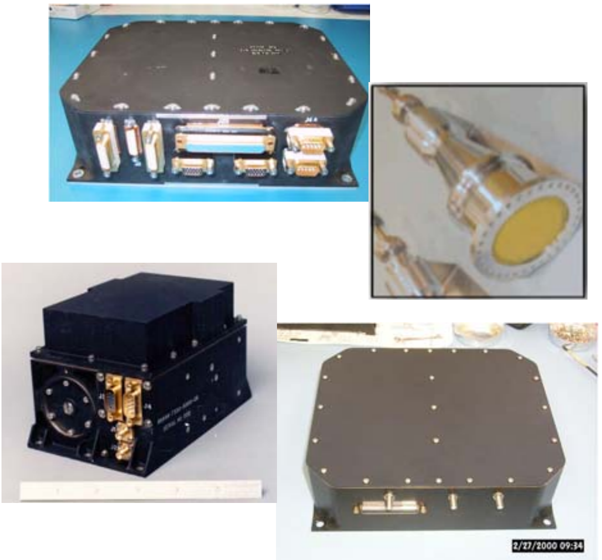
Spotlight on GRACE

Gravity Recovery And Climate Experiment

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

- Twin satellites launched March 2002
  - 500 km near-polar orbit; 200 km nominal baseline
- Mission goal:
  - High-resolution mean and time-variable gravity field mapping
- Science Instrument System (JPL):
  - K-band ranging (KBR) sensor supports micron-level ranging between satellites
  - Advanced “BlackJack” GPS for precise orbit determination
- Unprecedented science results
  - First direct measurement of seasonal exchanges of water between land and oceans
  - Tracked the changing water content of Amazon basin
  - Demonstrated impact of the Dec 2004 Great Sumatra Earthquake on Earth's gravity field
  - Detected a significant loss of ice from the Antarctic ice sheet between 2002 and 2005
- In addition to revolutionizing gravity-field measurements, GRACE has been an ideal testbed for:
  - Formation-flying concepts
  - Ultra precise orbit determination experiments
  - Precise baseline determination





GPS, Signal and Instrument Processing Units, K/Ka-band horn, ultra-stable oscillator -- GRACE flight hardware provided by JPL

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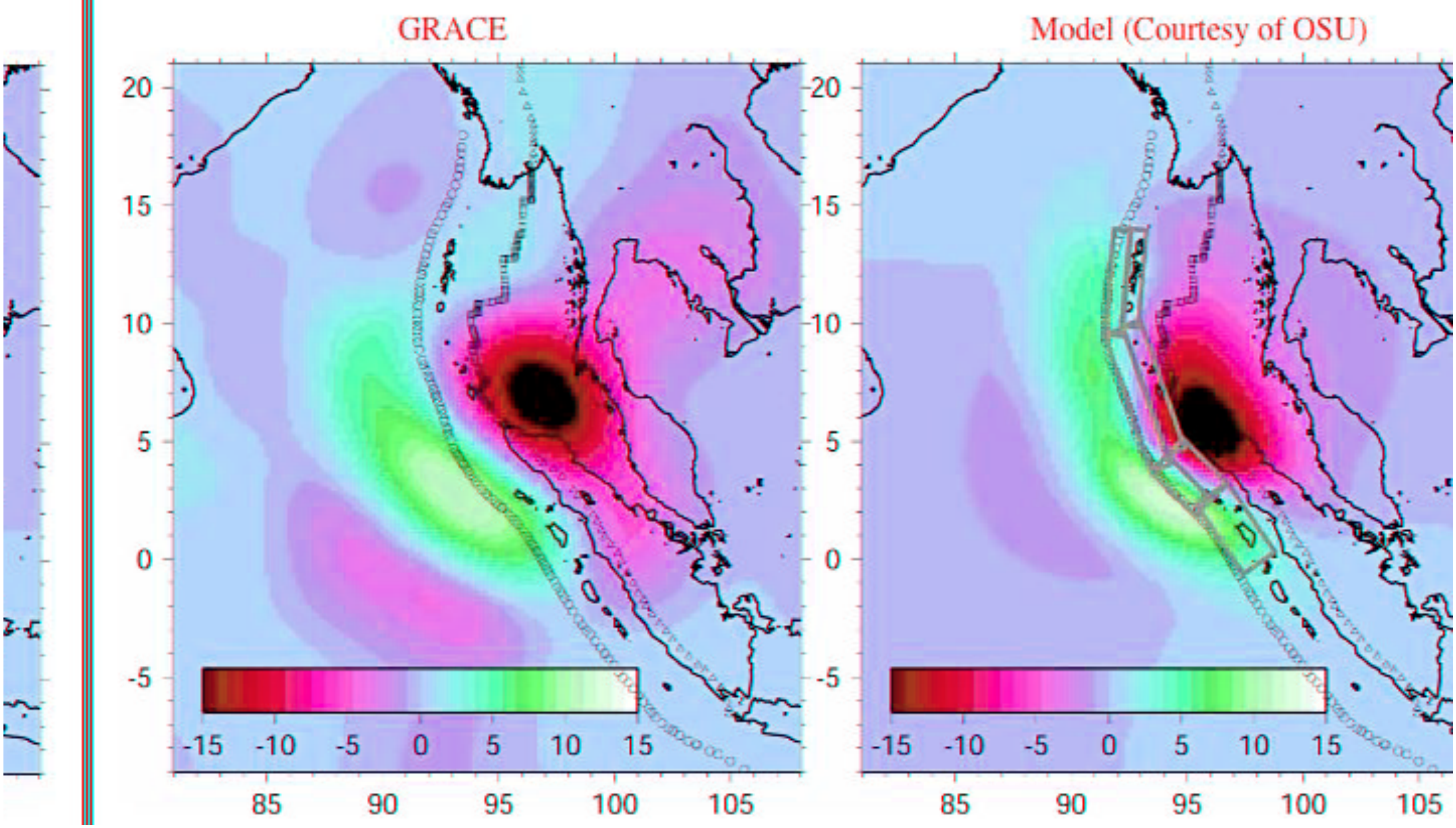
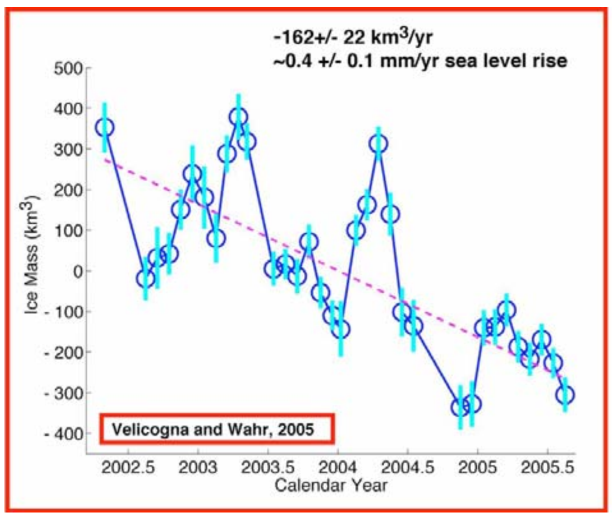
GRACE Mission

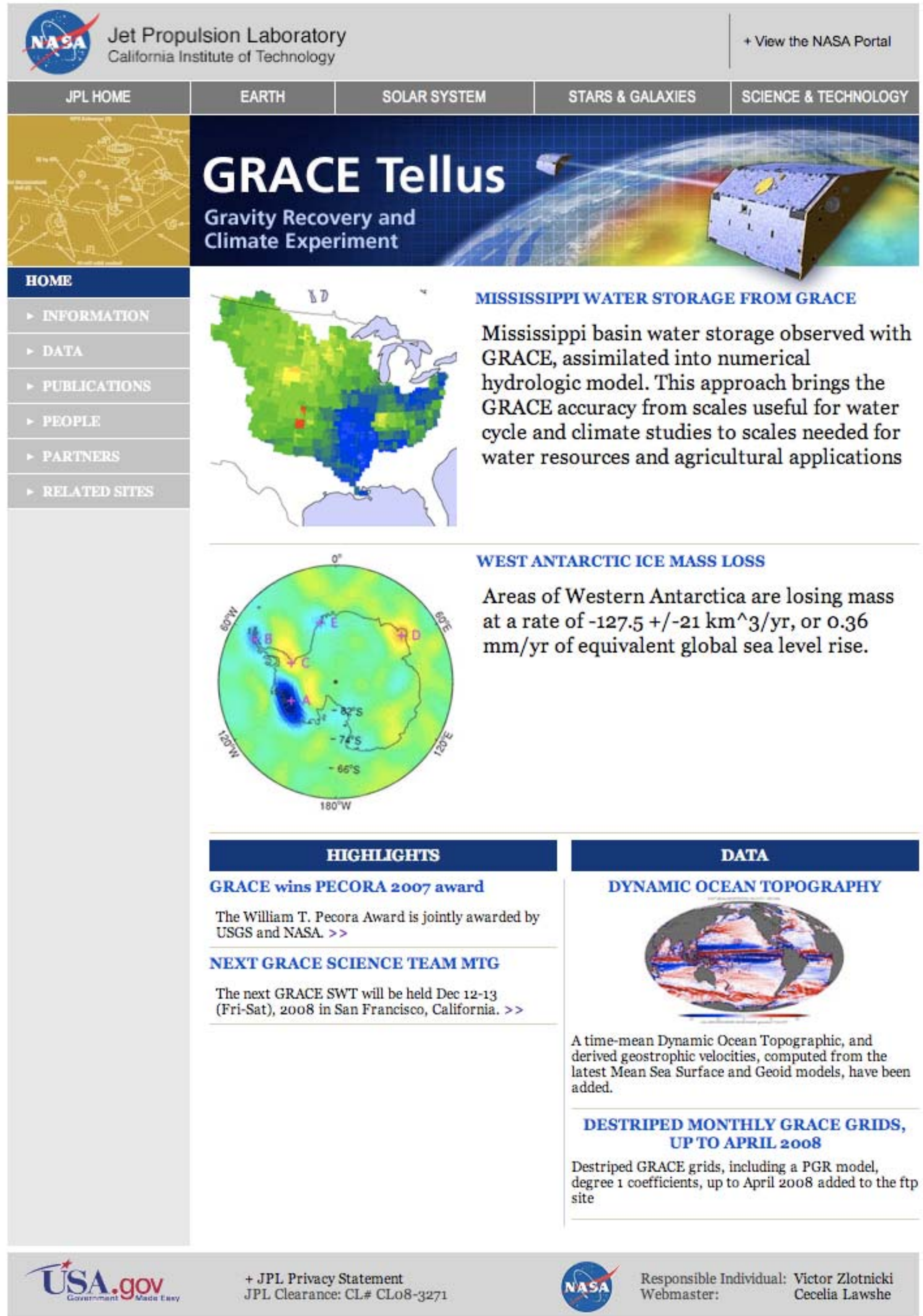


GRACE satellites detected Earth gravity field changes (nanometers/sec2) from mass shifts during the Sumatra Earthquake in Dec 2004**

GRACE Science Results

- GRACE has measured changes in the gravity field that indicate loss of Western Antarctica ice of 127 cubic kilometers per year, contributing about 0.36 mm/yr to global sea level rise, and loss rate for Greenland ice of 162 cubic kilometers per year, contributing about 0.4 mm/yr to global sea rise





Global Navigation Satellite System Science Instruments

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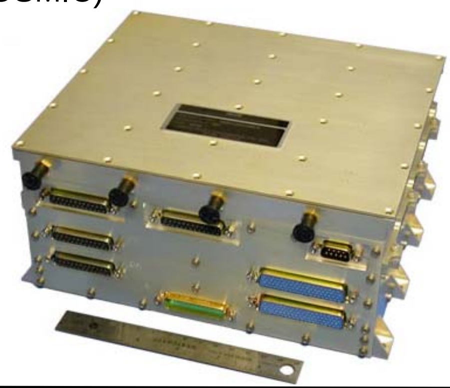
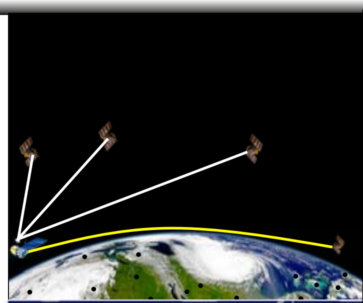
Representative Instrument

Constellation Observing System for Meteorology, Ionosphere & Climate (COSMIC)





- **GPS has proven to be an unprecedented "tool" for science using precise receivers deployed in ground networks and onboard Earth orbiters**
- ***We expect to be able to do all these things with GNSS, only better!***

Science Applications

GPSRO 2011

- GNSS (Global Navigation Satellite System
  - GPS, GLONASS, Galileo) occultations: high accuracy, all -weather temperature, water vapor, and electron density profiles for weather, climate, and space weather
- GNSS reflections (technology in development)
  - ocean altimetry
  - ocean surface winds
  - ice elevation maps
  - ice type and land moisture indicators
  - monitor mesoscale ocean processes
  - timely sensing of tsunamis

Contacts

Dr. Stephen M. Lichten
Deputy Manager: JPL Communications, Tracking & Radar Division
818-354-1614
Stephen.M.Lichten@jpl.nasa.gov

Dr. James Zumberge
Manager: JPL Tracking Systems and Applications Section
818-354-6734
James.F.Zumberge@jpl.nasa.gov

Dr. Frank Webb
Deputy Manager: JPL Tracking Systems and Applications Section
818-354-4670
Frank.W.Webb@jpl.nasa.gov