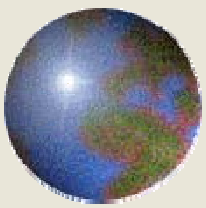
Position, Navigation and Timing: GPS Scientific Applications



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

Quick Overview

- Measuring space and time
- GPS a tool for science
  - Motivation - *disasters, climate change, sea level rise,…*
- Development of high precision JPL GPS receivers
  - GPS receivers on board Low Earth Orbiting satellites
- Technology & Application developments
  - NASA's GDGPS
  - International GNSS Service (IGS)
  - National Science Foundation's *Earthscope*

INTRODVCTIO GEOGRAPHICA PETRI APIANI IN DOCTISSIMAS VERneri Annotationes, cõtinens plenum intellectum & iudicium omnis operationis, quæ per sinus & chordas in Géographia confici potest, adiuncto Radio astronomico cum quadrante nouo Meteoroscopii loco longe vtilissimo.

HVIC ACCEDIT Translatio noua primi libri Géographiæ CL. Ptolemæi, Translationi adiuncta sunt argumenta & paraphrases singulorum capitum: libellus quoque de quatuor terrarum orbis in plano figurationib. Authore Vernero.

LOCVS etiam pulcherrimus desumptus ex fine septimi libri eiusdem Géographiæ Claudii Ptolemæi de plana terrarum orbis descriptione iam olim & à veterib. instituta Géographis, vnà cum opusculo Amirucii Constantinopolitani de iis, quæ Géographiæ debent adesse.

ADIVNCTA est & epistola IOANNIS de Regiomonte ad Reuerendissimum patrem & Dominum D. Bessarionem Cardinalem Nicenum, atque patriarcham Constantinopolitanum, de compositione & vsu cuiusdam Meteoroscopii armillaris, Cui recens iam opera PETRI APIANI accessit Torquetum instrumentum pulcherrimũ sane & vtilissimum.

INGOLSTADII. Cum Gratia & Priuilegio Imperiali. AN. M.D.XXXIII.

Figure 1
Geographia by Peter Apian, dated 1533.

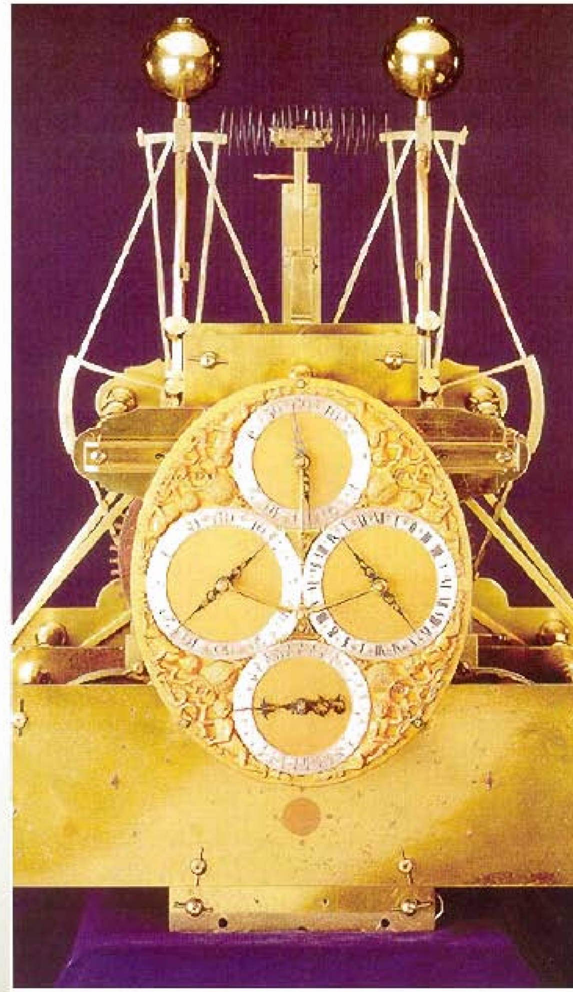


Figure 2
Harrison I, first marine Chronometer (credit: D. Sobel und W.J.H. Andrewes: Längengrad, Berlin Verlag 1999)

Global Positioning System

- Most significant recent advance in navigation and positioning technology. In the past, the ***stars*** were used for navigation. Today's world requires greater accuracy in real-time. The constellation of ***artificial stars*** provided by GPS do this.
- GPS uses satellites and ground equipment to determine position and time ***anywhere*** on Earth.

What a fantastic tool!

GPS Policy Affects Civil Use - 1980

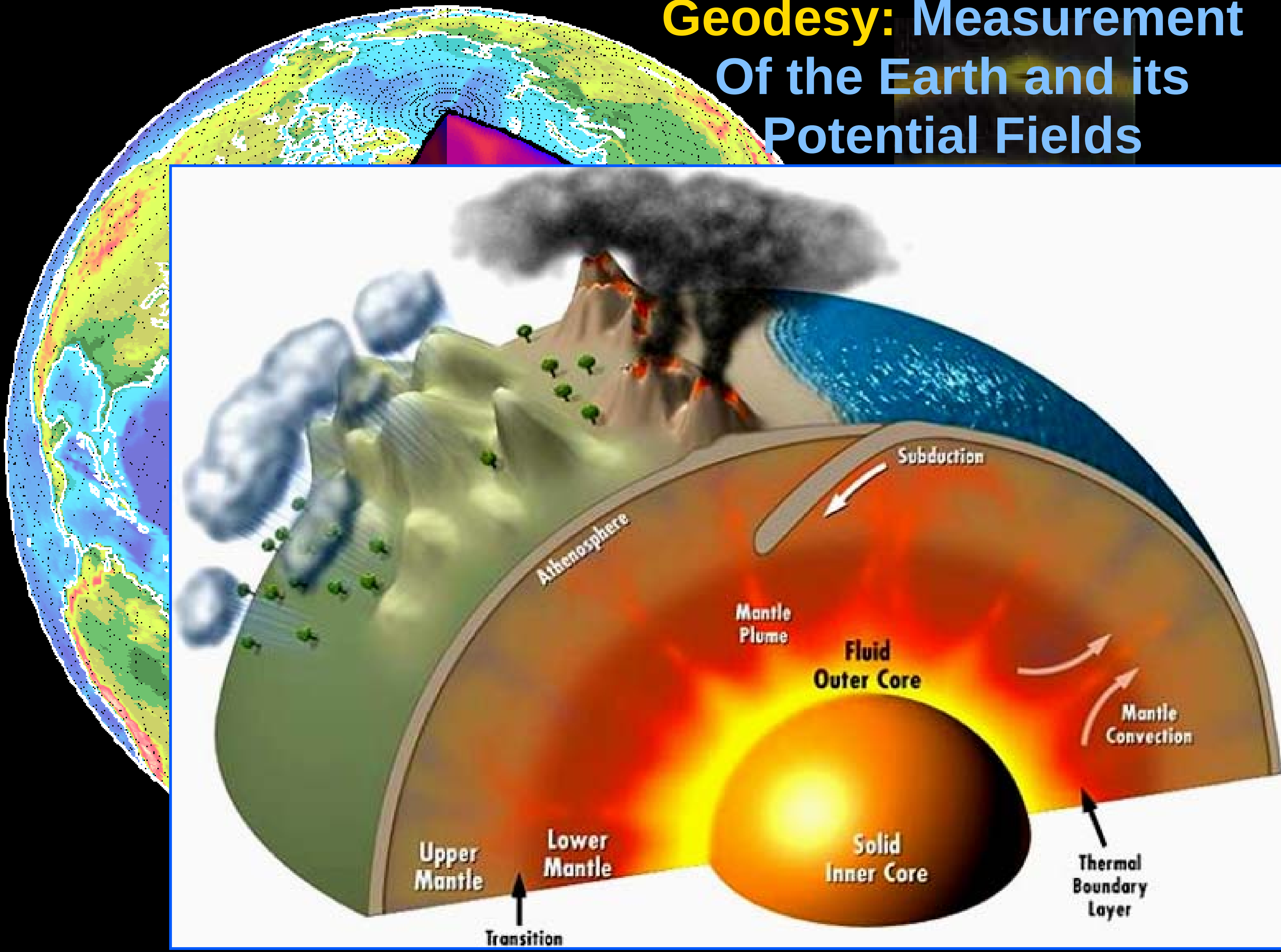
One of the notable Federal coordination efforts associated with GPS occurred in 1980 when NOAA, NASA, and USGS joined with the Department of Defense (DoD) to complete the "Interagency Coordination Plan for Development of the Application of the NAVSTAR Global Positioning System (GPS) for Geodetic Surveying" (NOAA et al. 1980). The 1980 coordination plan identified specific roles for each agency in the development of GPS applications, in the testing of GPS concepts, and in the eventual selection of the optimum method, based on costs and performance, for general use. This cooperative effort culminated in the first interagency tests of GPS receivers which was conducted in January and February 1984 in Southern California. The results were reported at the fall meeting of the American Geophysical Union in San Francisco (Goad et al. 1984).

Latest Policy: Space Based Position Navigation and Timing, December 2004

GPS - Vital for Science

- GPS enable amazing information technology
  - Navigation, Surveying, Geodesy,…
- Geodesy, the science of
  - measuring and monitoring the size and shape of the Earth
- Understanding changes and complex dynamic processes of our home planet - to better protect our world

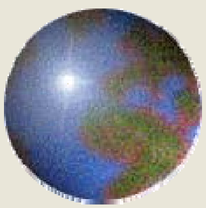
Geodesy: Measurement Of the Earth and its Potential Fields



Problem and fascination of measuring the Earth:

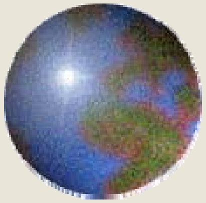
Everything is moving !

Monitoring today mainly by GPS permanent networks



Continuous observations are absolutely crucial!

Motivation



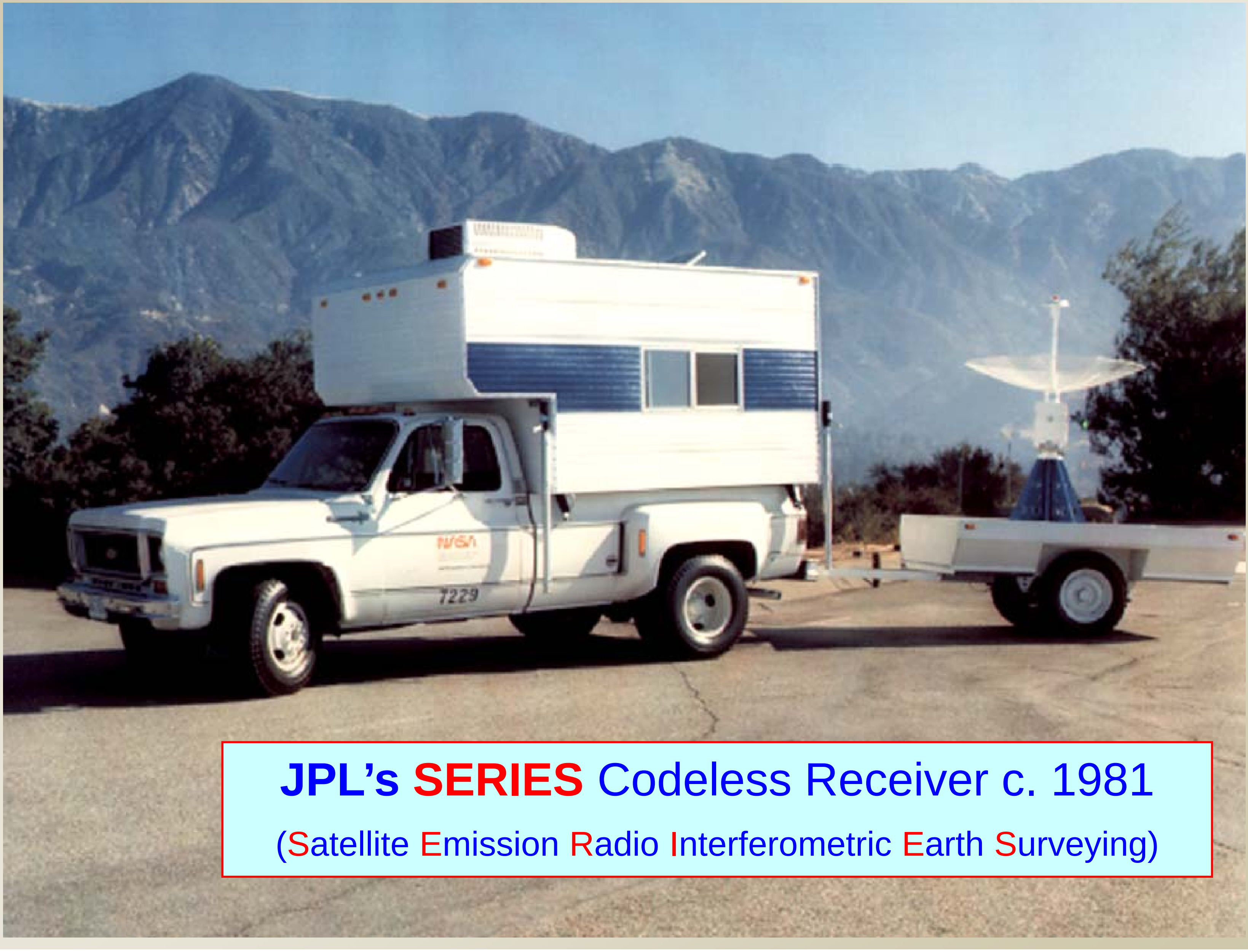
Helplessness *in the face of* ***natural disasters*** *demonstrates that our* ***knowledge*** *of the Earth's complex system is* ***rather limited.***

GPS Contributes to Monitoring the Earth

Global Geodetic Observing System - GGOS

GPS/GNSS combines with other space geodetic techniques, VLBI, SLR, DORIS, InSAR, UAVSAR

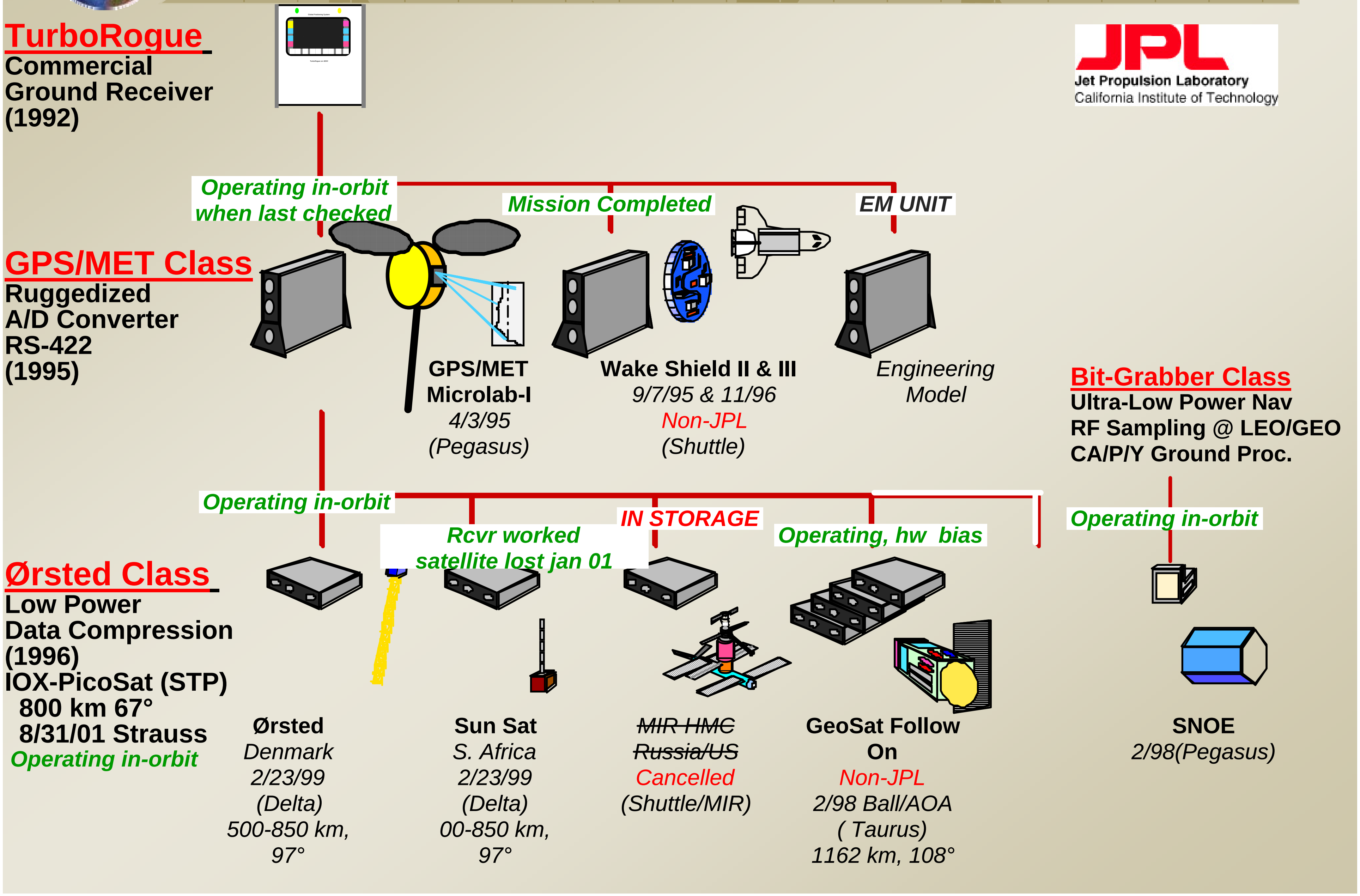
Early Mobile GPS Technology

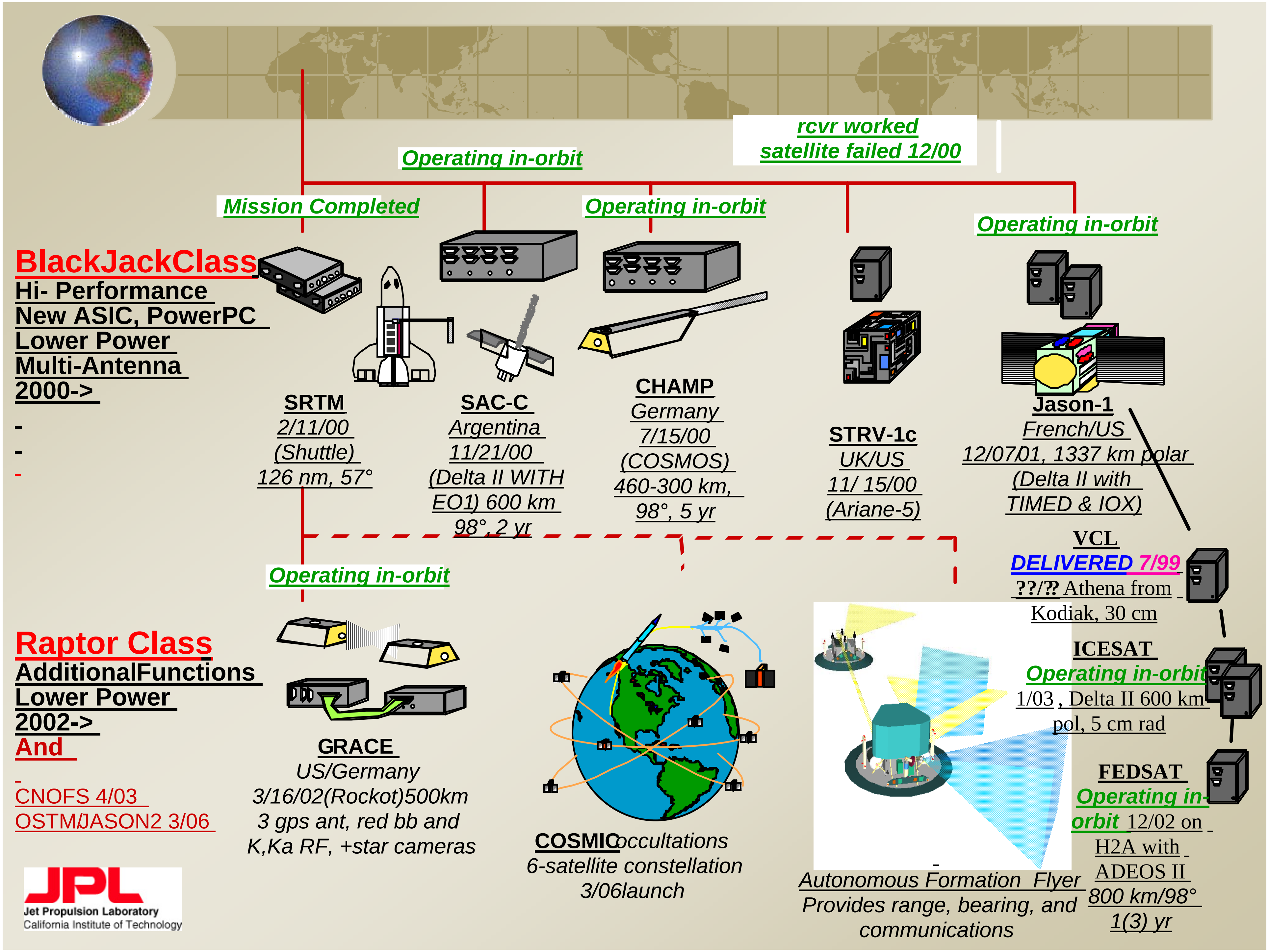


JPL's SERIES Codeless Receiver c. 1981

(Satellite Emission Radio Interferometric Earth Surveying)

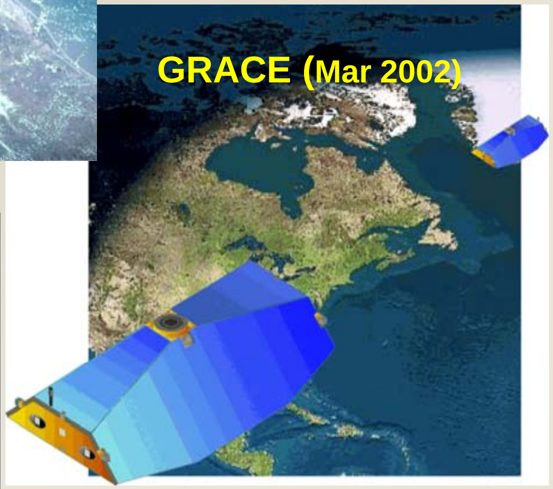
GPS Systems Group: TRSR Family Tree



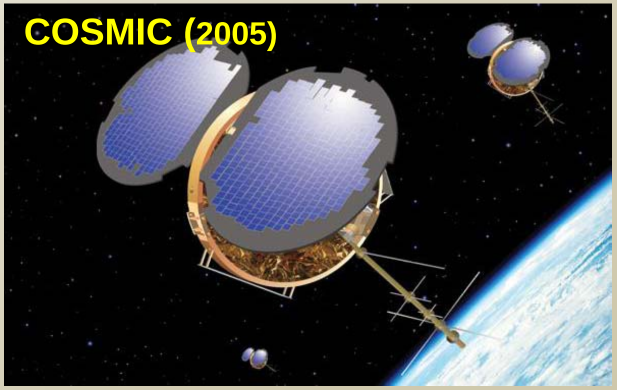


rcvr worked
satellite failed 12/00
Operating in-orbit
Mission Completed
Operating in-orbit
Operating in-orbit
BlackJackClass
Hi- Performance
New ASIC, PowerPC
Lower Power
Multi-Antenna
2000->
-
-
-
SRTM
2/11/00
(Shuttle)
126 nm, 57°
SAC-C
Argentina
11/21/00
(Delta II WITH
EO1) 600 km
98°, 2 yr
CHAMP
Germany
7/15/00
(COSMOS)
460-300 km,
98°, 5 yr
STRV-1c
UK/US
11/ 15/00
(Ariane-5)
Jason-1
French/US
12/07/01, 1337 km polar
(Delta II with
TIMED & IOX)
VCL
DELIVERED 7/99
??/?? Athena from
Kodiak, 30 cm
Operating in-orbit
Raptor Class
AdditionalFunctions
Lower Power
2002->
And
CNOFS 4/03
OSTM/JASON2 3/06
GRACE
US/Germany
3/16/02(Rockot)500km
3 gps ant, red bb and
K,Ka RF, +star cameras
COSMIC occultations
6-satellite constellation
3/06launch
ICESAT
Operating in-orbit
1/03 , Delta II 600 km
pol, 5 cm rad
FEDSAT
Operating in-orbit 12/02 on
H2A with
ADEOS II
800 km/98°
1(3) yr
Autonomous Formation Flyer
Provides range, bearing, and
communications
Jet Propulsion Laboratory
California Institute of Technology

GPS Precise Navigation - Low Earth Orbiters



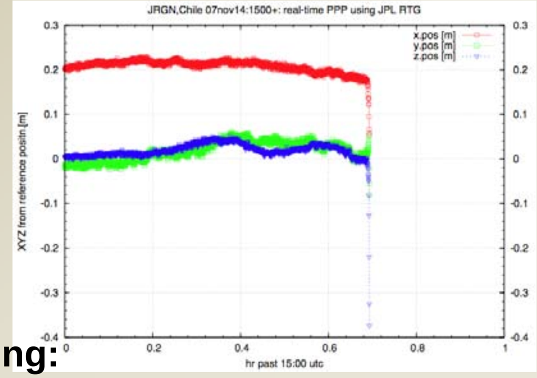
- *GPS Flight Receiver on board each*
- *LEO Missions Objectives/ Science Goals include:*
  - *Atmospheric remote sensing*
  - *Gravity, Magnetics*
  - *Ionospheric remote sensing*
  - *Ice and oceans*



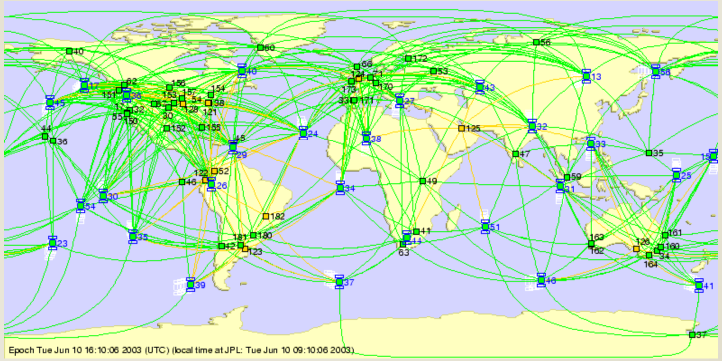
Broad Societal Benefits from NASA GDGPS

GDGPS: Global Differential GPS

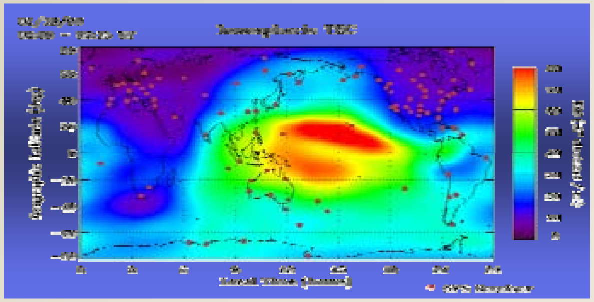
Natural hazard monitoring: real time earthquake damage assessment and Tsunami alerts



National security (GPS integrity monitoring)



Natural hazard monitoring: space weather



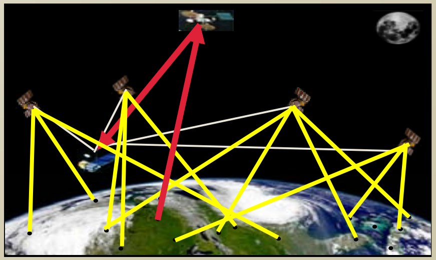
Deep space navigation

Precise real-time positioning anywhere

Civil Emergency systems (E911)

Location-based services

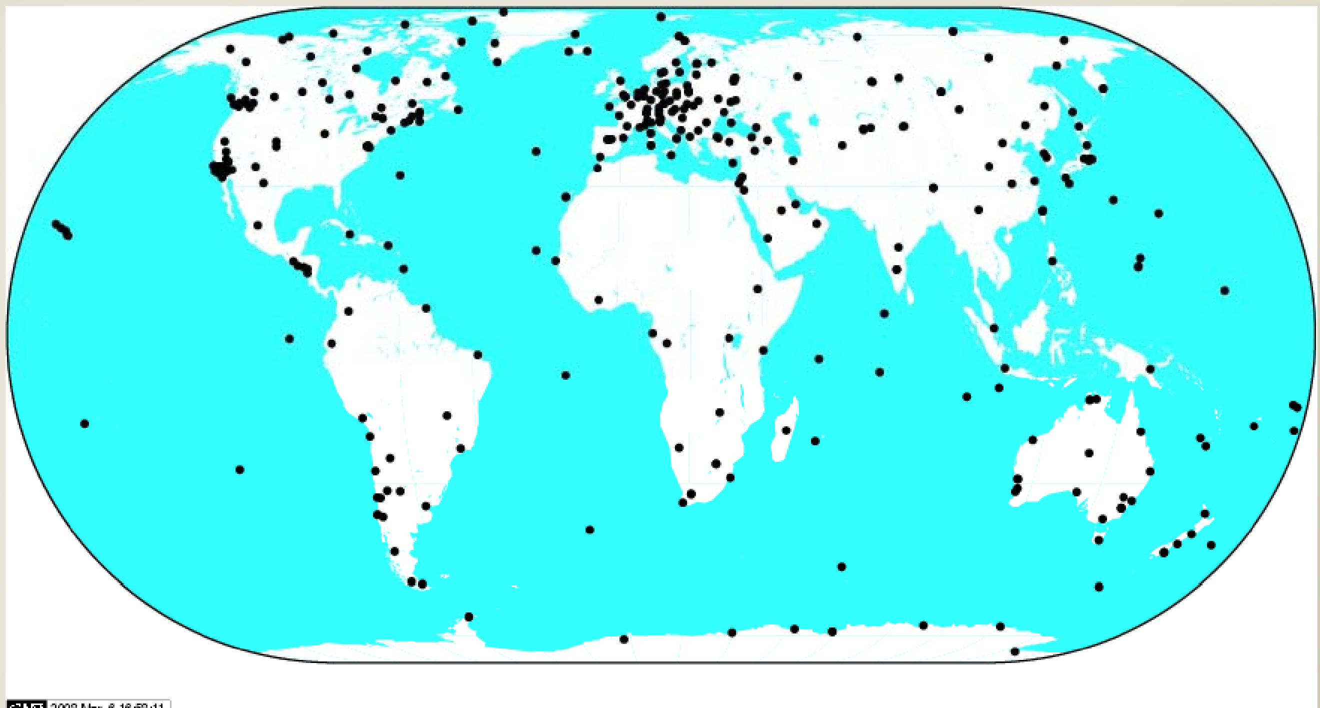
TASS: next generation navigation near Earth



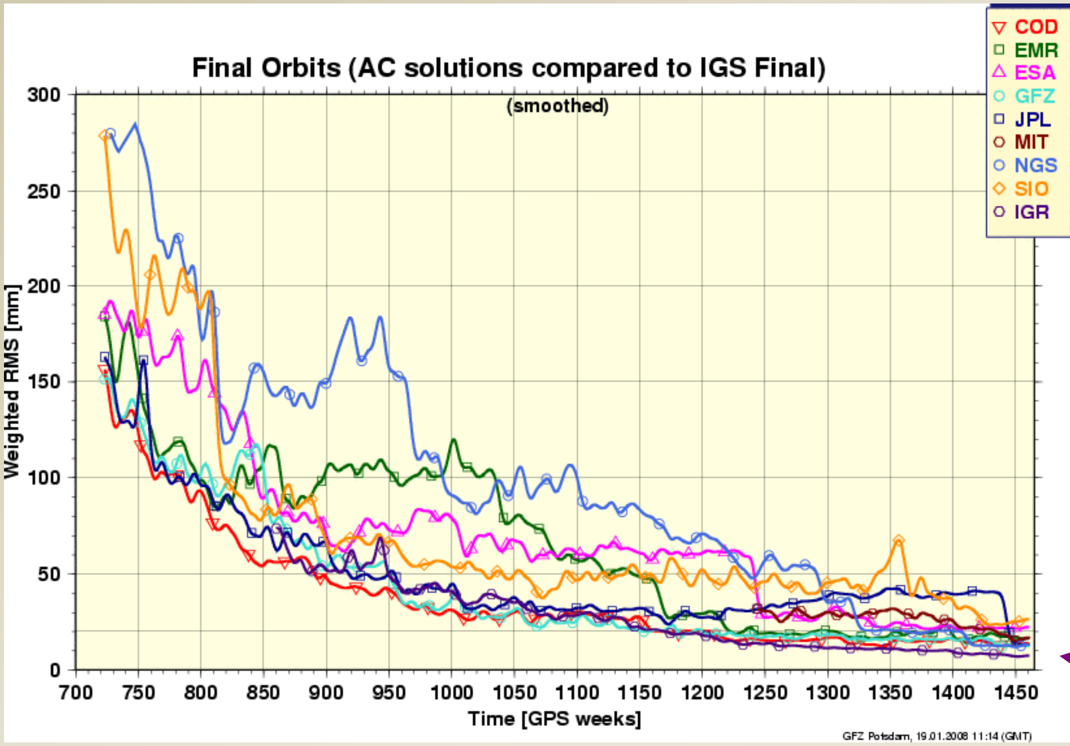
Quick answers: What is the IGS?

The International GNSS Service (IGS, formerly the International GPS Service) is a voluntary federation of more than ***200*** worldwide organizations in ***90+ countries*** that pool resources and permanent GNSS station data to generate precise GNSS products with ***'open data'*** policy. Currently the IGS supports two GNSS: GPS and the Russian GLONASS.

Over ***350*** permanent, geodetic GNSS stations operated by more than 100 worldwide agencies comprise the IGS network.



Quick answers: What is the IGS?



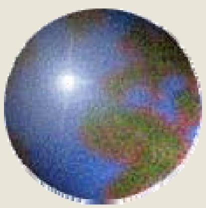
IGS products are formed by combining independent results from each of several Analysis Centers. Improvements in signals and computations have brought the centers' consistency in the Final GPS satellite orbit calculation to about **2cm**.

Many earth science missions and measurements, and multidisciplinary applications, rely upon the openly-available IGS products such as ephemerides and coordinate time series.

NGS is the IGS Analysis Center Coordinator for 2008-2011.The IGS Central Bureau at JPL handles overall coordination and day-to-day management of the IGS, view must be global.

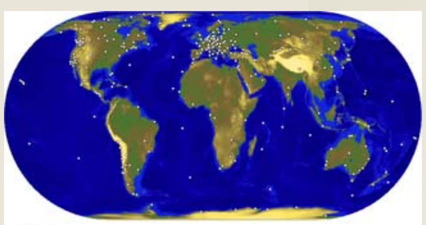
International GNSS Service

Formerly the International GPS Service



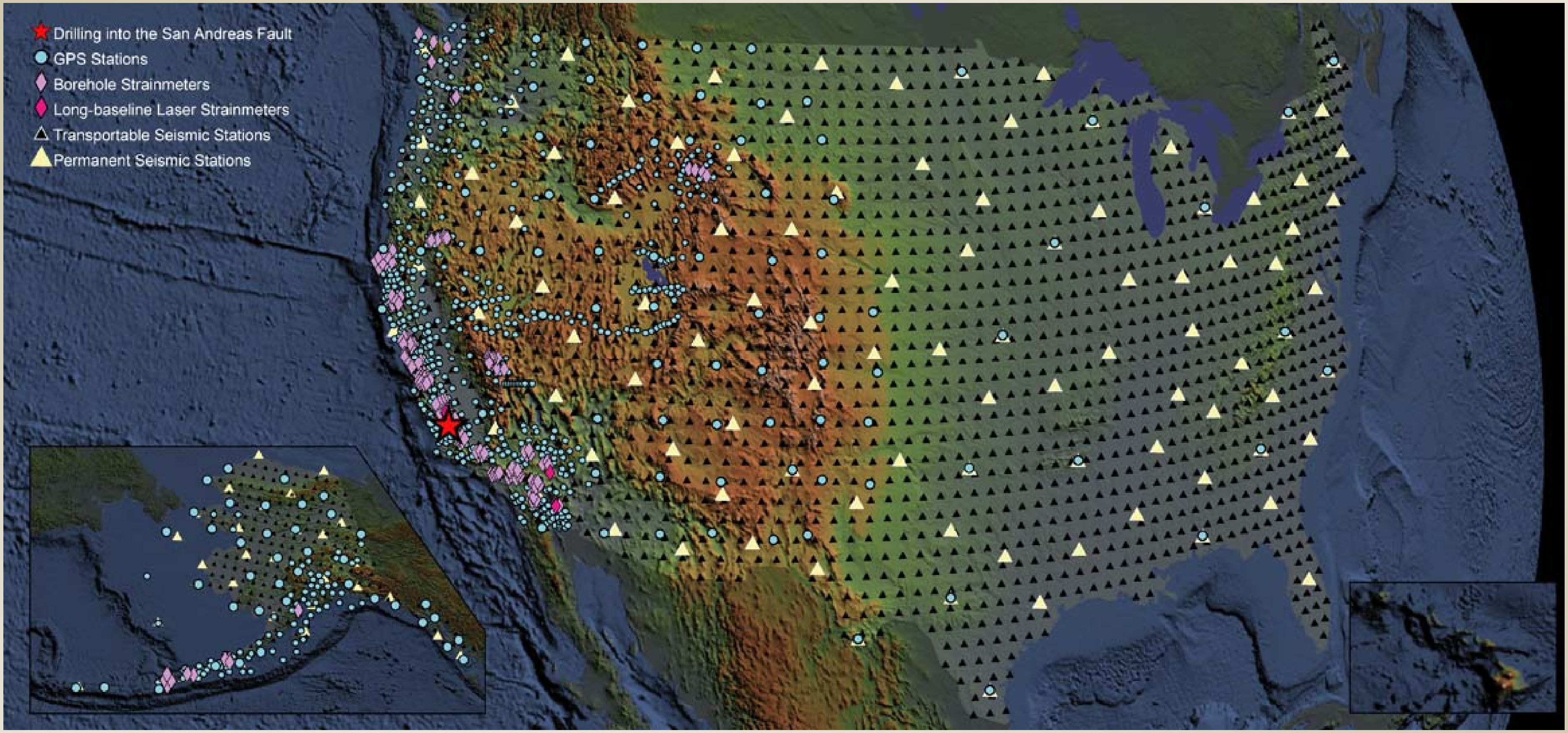
US agencies and organizations that contribute to the IGS:

- ***National Aeronautics and Space Administration (NASA)***
- ***National Geospatial-Intelligence Agency (NGA)***
- ***National Oceanic and Atmospheric Administration (NOAA)***
  - ***National Geodetic Survey (NGS), IGS Analysis Center Coordinator***
- ***Naval Research Laboratory (NRL)***
- ***National Science Foundation (NSF)***
- ***National Institute of Standards and Technology (NIST)***
- ***US Naval Observatory (USNO)***
- ***US Geological Survey(USGS)***
- ***Numerous universities & research organizations.***



GNSS: Global Navigation Satellite System

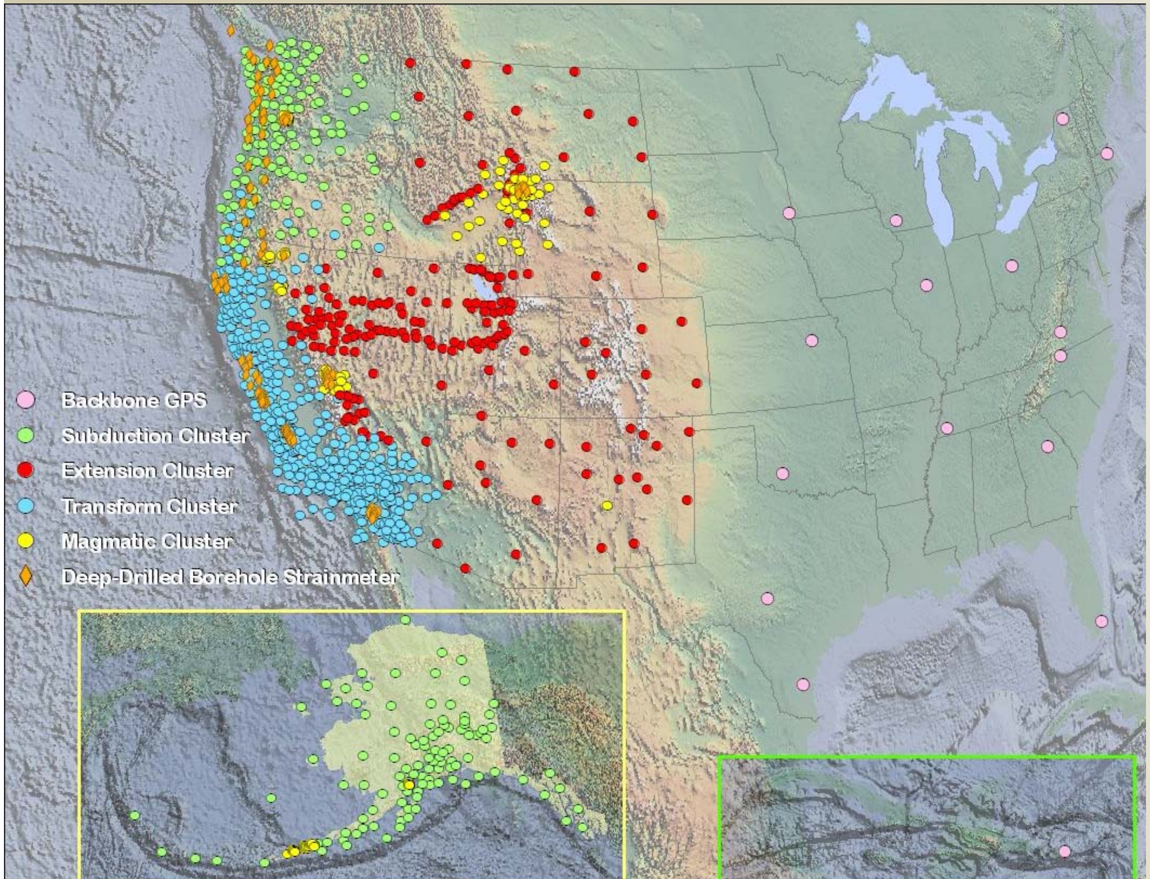
EarthScope



- EarthScope is an NSF funded Major Research and Facilities Construction (MREFC) Observatory
- Construction complete September 2008 at a cost of $200 million dollars

- EarthScope is a broad-based earth science program that is taking a multidisciplinary approach to studying the structure and evolution of the North American continent and the physical processes controlling earthquakes and volcanoes

EarthScope Plate Boundary Observatory



- The Plate Boundary Observatory (PBO) is a geodetic observatory designed to study plate & tectonic deformation of the United States.
- The observatory is being constructed by UNAVCO and consists of arrays of Global Positioning System (GPS) receivers (1000) and strainmeters combined with air/satellite imagery.
- Requires the global IGS infrastructure to meet US science requirements.

University NAVSTAR Consortium is a joint NSF/NASA facility

Closing Remarks

- GPS provides a unique and valuable tool for observing and understanding our planet
  - Climate change, sea-level change, ice and glacier melting, earthquakes, tsunamis, volcanoes, subsidence, severe weather, severe space weather,…
- ***Scientific observations and understanding can lead to actions in order to better protect our world today and for future generations***

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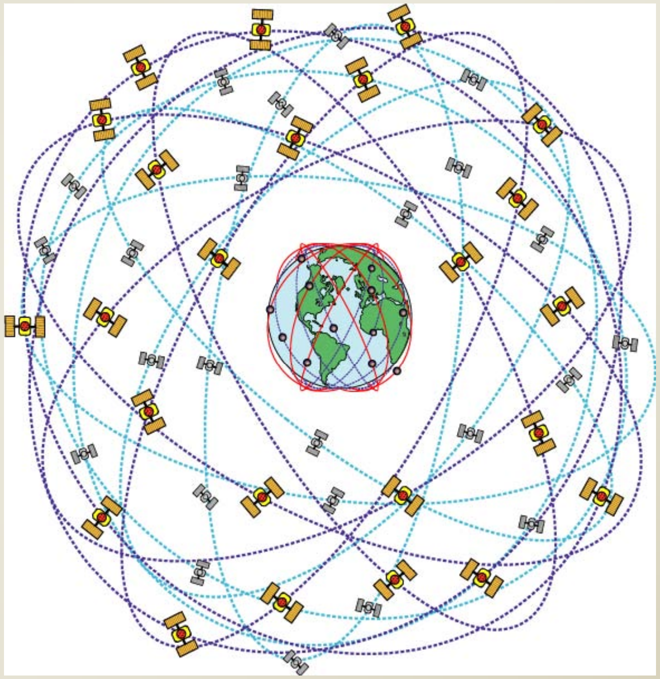


Part of the work for this presentation was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Some Back-ups

Bossler's Paper

BACKGROUND OF FEDERAL GPS ACTIVITIES

The NAVSTAR GPS program is a joint service program managed by the U. S. Air Force with representation from the Army, Navy, Marine Corps, Defense Mapping Agency (DMA), Department of Transportation, NATO, and Australia. The National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and the U. S. Geological Survey (USGS) also recognized early on that they each had an interest in either the development or in the application of GPS for geophysical and geodetic purposes.

One of the notable Federal coordination efforts associated with GPS occurred in 1980 when NOAA, NASA, and USGS joined with the Department of Defense (DoD) to complete the "Interagency Coordination Plan for Development of the Application of the NAVSTAR Global Positioning System (GPS) for Geodetic Surveying" (NOAA et al. 1980). The 1980 coordination plan identified specific roles for each agency in the development of GPS applications, in the testing of GPS concepts, and in the eventual selection of the optimum method, based on costs and performance, for general use. This cooperative effort culminated in the first interagency tests of GPS receivers which was conducted in January and February 1984 in Southern California. The results were reported at the fall meeting of the American Geophysical Union in San Francisco (Goad et al. 1984).

NASA Activities

Under the GPS coordination plan, the NASA role and mission were to:

1. Develop and demonstrate interferometric GPS positioning.
2. Participate in the development of advanced GPS receivers.
3. Use GPS for accurate positioning of satellites.

A major aspect of NASA's involvement has been the development of the Satellite Emission Radio Interferometric Earth Surveying (SERIES) concept (MacDoran et al. 1982). More recently, NASA has been actively involved with applications of GPS for crustal motion monitoring and with the development of GPS orbit prediction and tracking systems. NASA/Jet Propulsion Laboratory is conducting another interagency test this spring. That activity is the subject of one of the presentations at this conference. NASA is also investigating the use of GPS receivers on board geodetic satellites for precise ephemeris determination throughout scientific missions.

NOAA Activities

The NOAA activities related to GPS fall under the basic National Geodetic Survey authorization and include:

1. Using GPS for operational geodetic control surveys.
2. Development of specifications for GPS operations.
3. Investigations and research in GPS-related technology.
4. Using GPS results for monitoring and modeling crustal motion.

In addition to the active participation of National Geodetic Survey, NOAA contributed to a tri-agency receiver development project through a contract with the Applied Research Laboratories, The University of Texas at Austin. DoD and USGS also participated in this contract which lead to the current hardware

available from Texas Instruments. NOAA is currently using the Texas Instruments TI 4100 as well as the MACROMETER[tm] V-1000 for operational GPS surveys. Several of NOAA's ideas and programs will be presented at this meeting. Preliminary results from simultaneous mobile very long baseline interferometry (VLBI) and GPS surveys in Alaska will also be presented.

DoD Activities

Within DoD, DMA serves as Deputy Program Manag
Additionally, DMA provides:

1. Static positioning tests for the GPS/Joint
2. Development of GPS satellite for LANDSAT i
3. Point of contact for the geodesy interest
4. Lead in tri-agency development of GPS rece

Under a separate agreement, the DoD GPS role als
Geophysical Laboratory (AFGL) research and devel
in response to DMA requirements in mapping, char
activities have included extensive GPS research
receivers for precise relative geodesy and orbit
Draper Laboratory (CSDL) and at the Massachusett

USGS Activities

The USGS is primarily concerned with its geoph
GPS from the perspective of a user. USGS GPS act

1. Identify applications of GPS to USGS progr
2. Provide support for GPS research at CSDL a
3. Contribute towards the tri-agency prototyp

Currently, the USGS is purchasing five GPS recei
networks now being measured by other techniques,
regions of California (Kerr 1985).

FGCC Activities

The Federal Geodetic Control Committee (FGCC) h
Federal agencies involved with geodetic surveying
include the testing and evaluation of new surveyi
establishment of standards and specifications for

In January 1983, the FGCC Instrument Subcommitt
demonstration of the MACROMETER[tm] interferometric
Fronczek 1983). The tests compared MACROMETER[tm]
azimuths, and ellipsoidal height differences with
The test showed that the MACROMETER[tm] V-1000 is a
be used successfully to establish geodetic contro
National Geodetic Reference System.

ICCG GPS Panel

Under the auspices of the Interagency Coordinat
(ICCG), Federal agencies involved with GPS will c

purpose of the recently reconstituted ICCG GPS Panel for Operational Coordination and Long Range Planning will be to:

1. Compile agency needs and plans for use of GPS receivers.
2. Formulate procedures for interagency sharing of receivers.
3. Facilitate cooperative data acq
4. Develop standardized data forma
5. Recommend procedures and locati

This panel has just been formed and i
meeting tentatively scheduled for Oct

GPS SATELLI

The recent launch of the tenth GPS
the testing and development phase. T
operational GPS satellites has planne
continuing on until December 1988. T
satellites are available and continuo
expected to begin in late 1987. The
available by the end of 1988.

FEDERAL

As referred to earlier in the Instr
dependent on access to the C/A (coars
code for field operations. These cod
transmissions and provide timing, sat
position information. Other systems
"codeless" mode, treating the GPS sat
interferometric measurement technique

Separate from the field use code re
processing of GPS data with precisely
the highest quality geodetic results.
post orbit ephemerides must now be ex

Co

The C/A code, under the DoD label c
will be made available to a wide vari
broadest possible commercial, civil,
world. However, the GPS system will
SPS accuracy during times of national

Access to the P code, under the DoD
is another matter. Originally the Do
applications of high national securi
to the U. S. and Allied military use
policy on PPS use in the civil commu

Under the proposed policy framewor
could apply for access to the PPS.

application to ensure consideration of national security needs. Once an application has been approved, a certification would be issued specifying the geographic area and time frame. The approved applicant would then contract with the U. S. Government, or perhaps a third party agent, for delivery of the equipment, the cryptography, and the supporting services. Additional details on this access policy will be covered later in this session.

Precise Ephemerides

Under a proposed agreement, NOAA, NASA, and DMA will participate in the tracking of the 18 GPS satellites, computing the precise ephemerides for the satellites, and then distributing the ephemerides to military and civilian users for post processing of their GPS observations (NOAA et al. 1984). The computations and distribution activities will be for the purpose of producing geodetic quality data, and will not occur in real time.

In addition to each agency providing technical expertise to support the development of orbit determination procedures, the specific NOAA responsibilities will include:

1. Operating satellite tracking stations at VLBI sites in Massachusetts, Texas and Florida.
2. Distributing the tracking data and geodetic quality ephemerides generated at DMA to domestic requestors.

The specific NASA responsibilities will include:

1. Operating tracking stations in Spain, California, and Australia.
2. Providing tracking data and geodetic quality ephemerides to those with whom NASA has cooperative research programs.

The specific DMA responsibilities will include:

1. Establishing agreements for the operation of some tracking stations.
2. Operating the Satellite Tracking Network Control Center.
3. Maintaining the Satellite Tracking Data Base.
4. Generating the geodetic quality ephemerides.
5. Providing the precise ephemerides to foreign requestors.

The proposed agreement has been accepted by both NOAA and NASA. We are now awaiting final approval from DMA where the memorandum of understanding is being circulated for comments.

SUMMARY

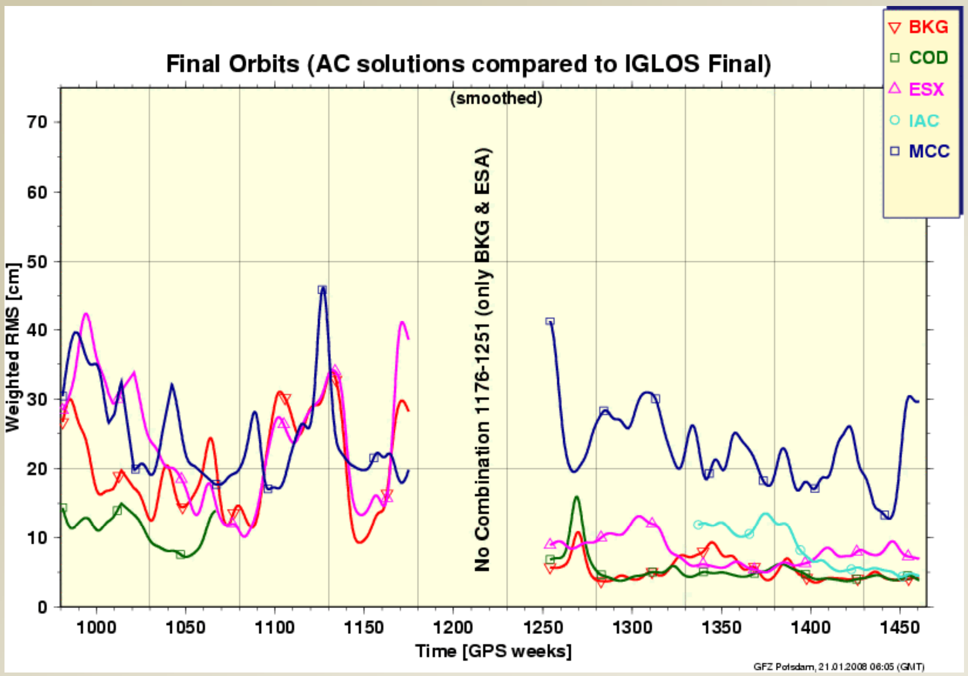
The GPS will permit rapid, economic point positioning with accuracies of a few centimeters over distances of 100 km or more. The development of GPS geodetic surveying instruments has come about because of the significant cooperation within the Federal sector. This cooperation, together with the recognition of GPS potential by the private sector, brings us to this symposium today. Those of us in the Federal environment recognize our roles and our responsibilities to provide orbits, standards and specifications, SPS access, limited PPS access, continued research and development, and to continue and expand our cooperative relationship with the civil sector.


HOW BIG IS AFRICA?
Approximate Area in Square Miles
Africa 11,668,545 (30,221,532 sq. km.)
China 3,681,089
Europe 3,979,405
USA 3,678,235
Total 11,338,729 (29,367,308 sq. km.)
EUROPE
3,979,405 sq. mi.
(10,306,659 sq. km.)
(Alaska)
UNITED STATES
3,678,235 sq. mi.
(9,526,629 sq. km.)
CHINA
3,681,089 sq. mi.
(9,534,021 sq. km.)
Outreach Program
African Studies Center
Boston University
270 Bay State Road
Boston, MA 02215
Mollweide Equal Area Projection

Observation Changes

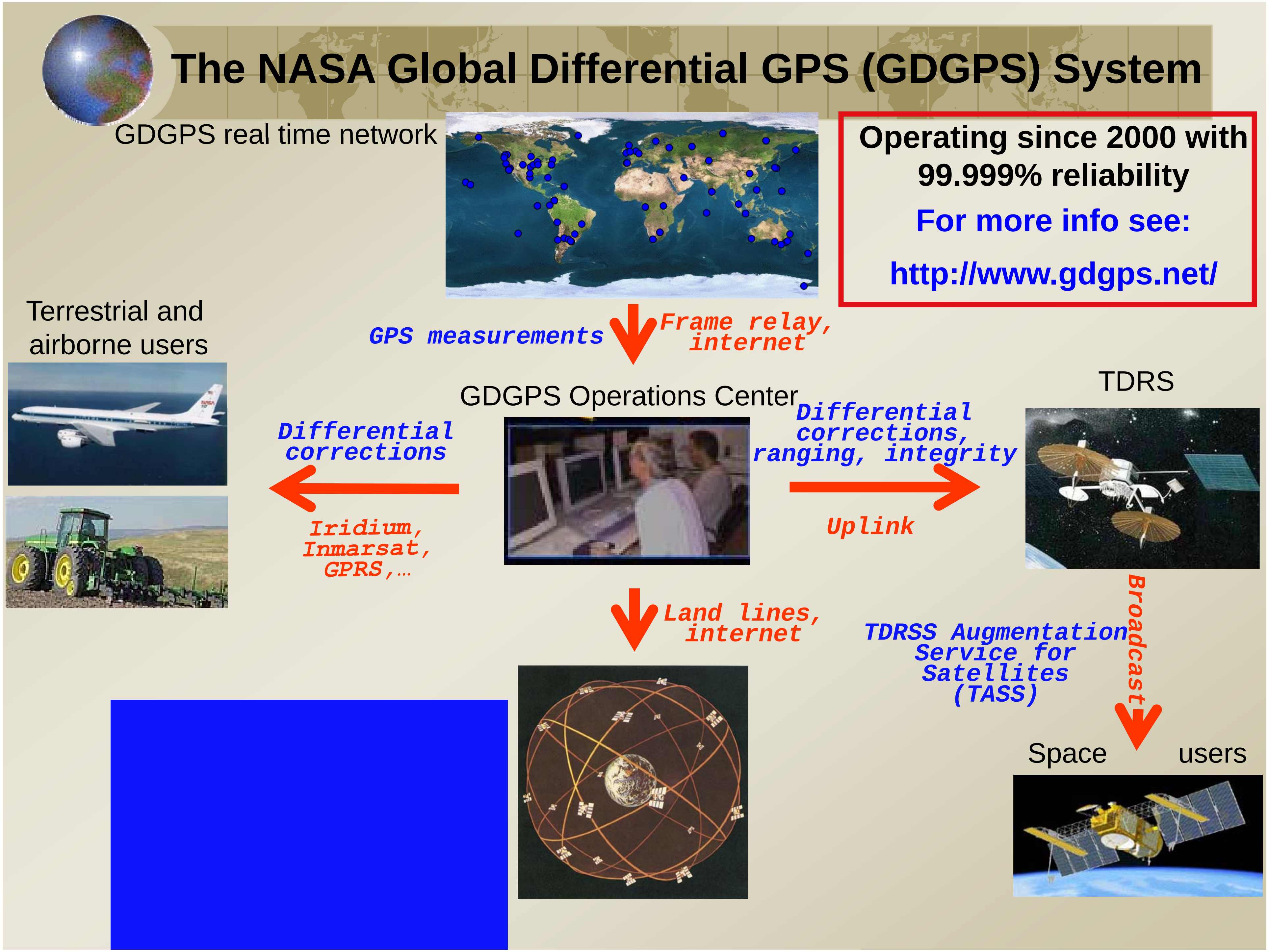
Inside the SERIES Truck

Macrometer & TI-4100



GLONASS Network and Final Orbit Comparison

1.21.08


The NASA Global Differential GPS (GDGPS) System
GDGPS real time network
Operating since 2000 with 99.999% reliability
For more info see:
http://www.gdgps.net/
Terrestrial and airborne users
GPS measurements
Frame relay, internet
GDGPS Operations Center
TDRS
Differential corrections
Iridium, Inmarsat, GPRS,…
Differential corrections, ranging, integrity
Uplink
Land lines, internet
TDRSS Augmentation Service for Satellites (TASS)
Broadcast
Space users

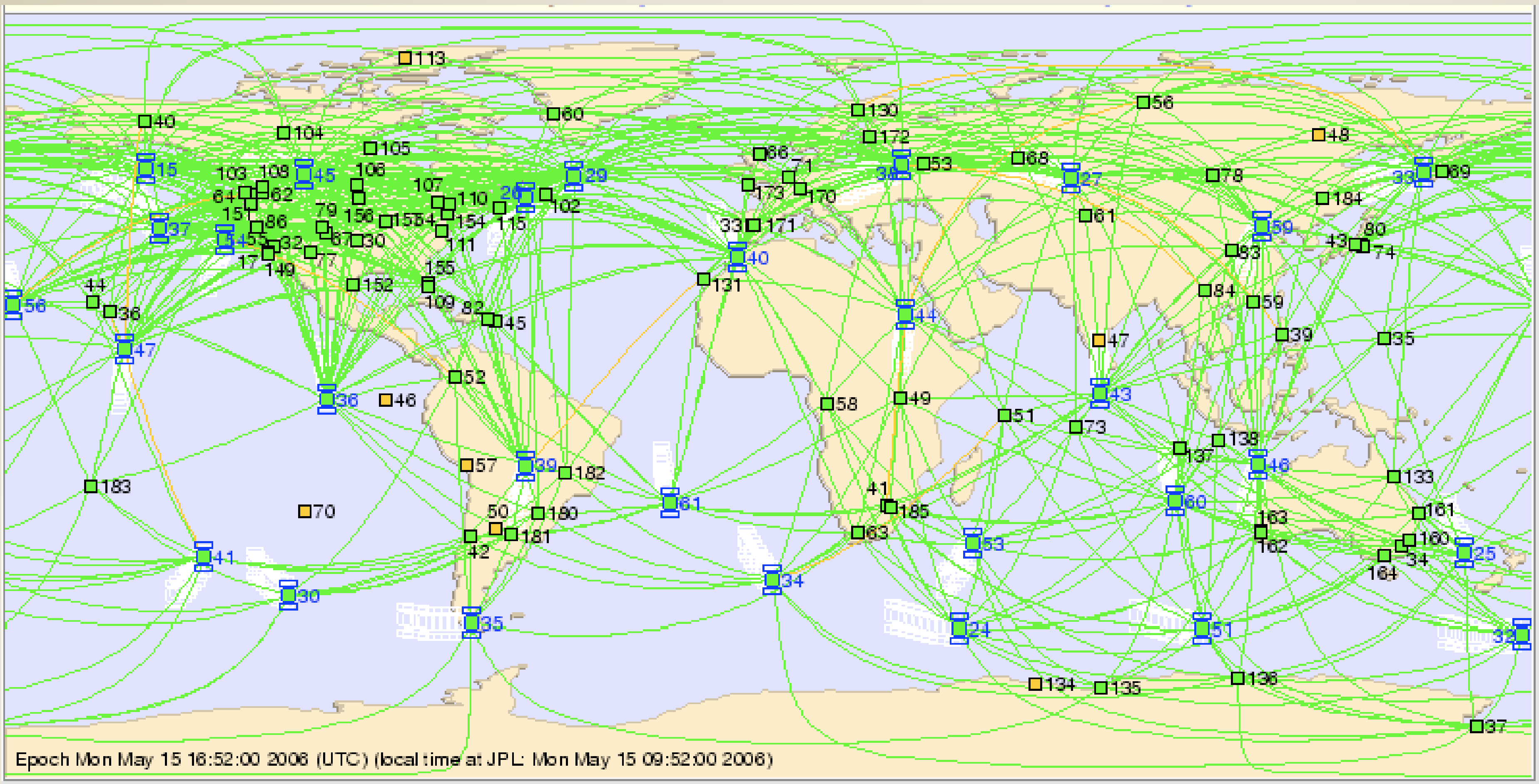
Gold Standard for Accuracy and Reliability

- Seamless global coverage
- Unparalleled accuracy on the ground, in the air, and in space
- Redundant and secure operations; no single points of failure
- Services for critical operations world-wide, including GPS performance monitoring

Powerful GPS Monitoring with GDGPS

With more than 90 real-time tracking sites, the GDGPS System tracks each GPS satellite by at least **10 sites**, and by **25 sites** on average, enabling robust, real-time GPS performance monitoring with **4 sec** to alarm

Optimal integrity is ensured by complete independence from the OCS tracking network



Classic IGS station: short pillar monument, choke ring antenna, desirable VLBI co-location

(Pie Town, NM)

Photo courtesy of D. Stowers, JPL

Photo courtesy NGS/NOAA

Tall pillar, newer antenna, radome, new paint job

(American Samoa)

Photo courtesy ESA/ESOC

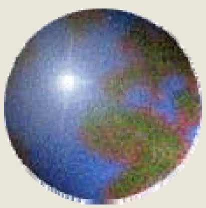
Think you can solve for the snow depth from this station's data? (Kiruna, Sweden)

Relocating a station to a better-monumented spot (Thule, Greenland)

Photos courtesy F.B. Madsen, DNSC

IGS Mission

Science in service to society



"The International GNSS Service provides the highest-quality GNSS data, products, and services in support of the Earth observations and research, positioning, navigation and timing, the terrestrial reference frame, Earth rotation, and other applications that benefit society."

The Basics

International GNSS Service

- Recognized as an *international scientific service*
  - Advocates an ***open data*** policy, equal access
- Name change from GPS to GNSS in 2005 reflects including:
  - **GLONASS** and future planning for **Galileo, QZSS, Compass, …**
- Highest accuracy GPS & GLONASS satellite orbits available ***anywhere***
  - -3-5 cm 3-d wrms GPS solutions
  - ~10-20 cm GLONASS solutions
  - mm-level station positions and velocities, since 1992 (map)
- Network of over 350+ stations precision geodetic receivers produce GPS data on a continuous basis
  - ~ 35 also track GLONASS
  - ~100 report hourly
  - Real-time IGS network initiated,
    - prospects of integrity monitoring, other products
  - ***Still major gaps, esp. in developing countries - AFREF***

WHY IGS? Historical notes

- Geodynamics, geodetic, and space agency organizations realized the potential of GPS by late 1980's
- Motivating goal: *millimeter* positioning in support of science & engineering anywhere in the world
- No single agency can or should assume the capital investment & recurring operations costs for the entire infrastructure
- Join with key international partners to form federation, define cooperation, set standards, driven by science quality
- Global framework for virtually all regional & national networks
- Implement a global *civilian* GPS tracking system for science and research
- Participants are enthusiastic!
- Later, more products (tropospheric, ionospheric…) from the same rich data set

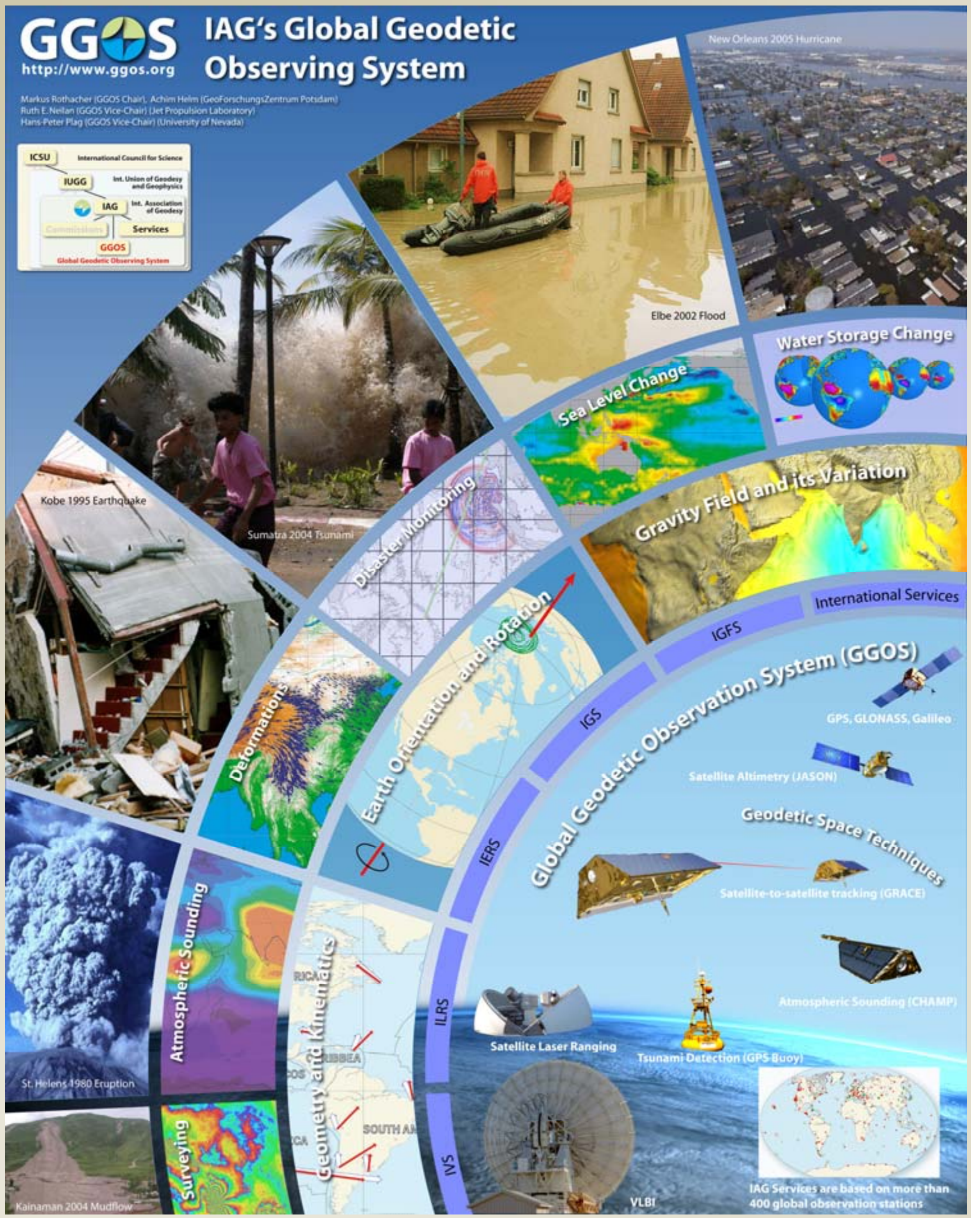
Unique Applications

GNSS/GPS Applications in IGS Projects & Working Groups

- IGS Reference Frame - GNSS contribution and densification
  - Supporting AREF - African Reference Frame
- Precise Time & Frequency Transfer - Clock Products - NRL & BIPM
- GLONASS Pilot Service Project, now routine within IGS processes
  - Leadership by NGA
- Low Earth Orbiters Project
- Ionosphere WG
- Atmosphere WG - JPL lead
- Sea Level - TIGA Project - sea level change & variability
- Real-Time Project - new
- Data Center WG - GSFC
- GNSS WG - IGS colleagues lead GGRF (Galileo Geodetic Reference Frame) in Europe, ensuring interoperability; focus on GPS modernization and other developments

What IGS Offers

- Partnerships - Bi-lateral and Multi-lateral
  - True sense of community
- Robust, highly leveraged and redundant network
  - Improvements needed in developing countries and Africa - AFREF
- Data from global and dense regional networks that aspire to IGS standards matches global standards
- Combined precise & accurate analyses products are *'world class'*
- Calibration, validation, verification - the 'go to' for
  - Ephemerides, clocks, predicts
  - Tracking station coordinates and velocities -> Reference Frame
  - Earth rotation: polar motion, rate, length of day
  - Tropospheric delays: weather and severe storm warning
  - Ionospheric TEC: space weather
  - Time scale
- Signal monitoring: GPS, GLONASS, L2C, GIOVE (*Galileo*), interference, integrity - more potential here, QZSS, COMPASS,…



Catch the Earth!

GGOS is a program of the International Association of Geodesy (IAG):

- Ensures observations of the three fundamental geodetic observables and their variations: Earth's shape, gravity field and rotational motion
- Integrates different geodetic techniques, models, and approaches to ensure long-term, precise monitoring of observables in agreement with the Integrated Global Observing Strategy (IGOS)
- Is a recognized member of the Global Earth Observing System of Systems (GEOSS)
- Is a powerful tool consisting mainly of high quality services (e.g., IGS), standards and references, and of theoretical and observational innovations