Space Geodesy Project

http://space-geodesy.nasa.gov/

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NASA/GSFC

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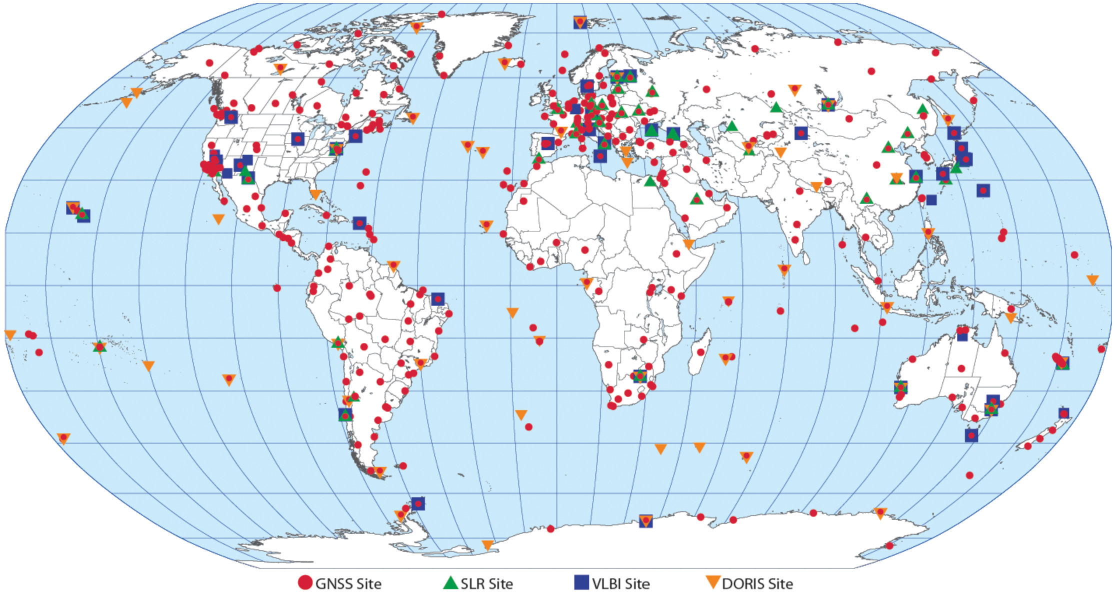
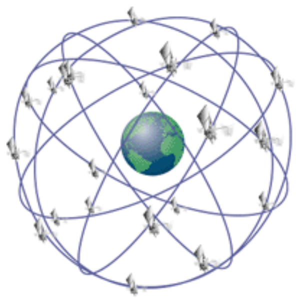


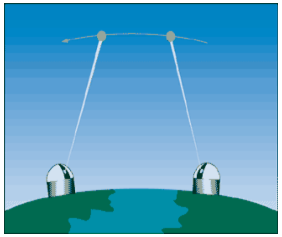
Space Geodesy Overview

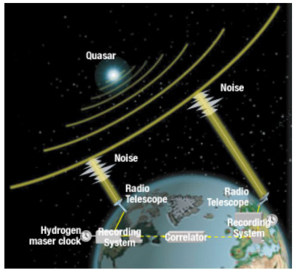
- Geodesy provides a foundation for all Earth observations
- Space geodesy is the use of precise measurements between space objects (e.g., orbiting satellites, quasars) to determine
  - Positions of points on the Earth
  - Position of the Earth's pole
  - Earth's gravity field and geoid



GNSS: Satellites (GPS-U.S., Russia-GLONASS, EU-Galileo) equipped with precise clocks transmitting messages such as ephemeris, clock offsets, etc. to ground (and spaced-based) receivers to measure station to satellite pseudo-range, phase delay

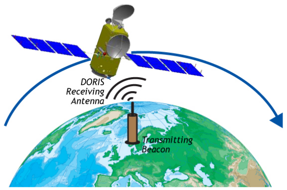
SLR/LLR: Ground-based short-pulse laser transmitting to satellites (or planetary targets) equipped with corner cubes to measure round-trip pulse time-of-flight to satellite





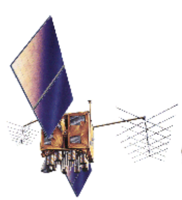
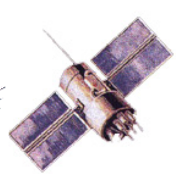
VLBI: Radio telescopes equipped with X/S wideband receivers record signals from quasars to measure difference in signal arrival times

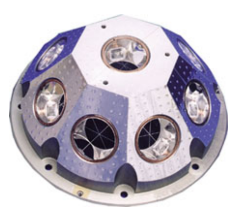
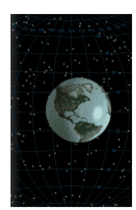
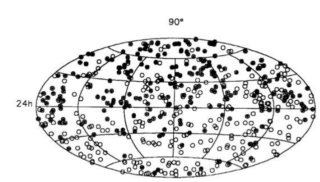
DORIS: Satellites equipped with DORIS receiver and uplink hardware transmit signals to ground beacons to measure Doppler shift on radiofrequency signals

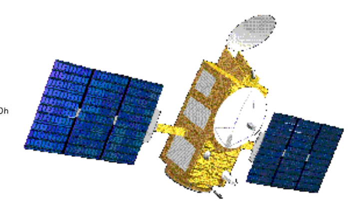


Space Geodesy Data

- Data from space geodesy measurements archive are utilized for direct science observations and geodetic studies, e.g., plate motion, gravity field, earthquake displacements, Earth orientation, atmospheric angular momentum, etc.
- Data also contribute to the determination of the Terrestrial Reference Frame, an accurate set of positions and velocities
  - TRF provides the essential stable coordinate system that allows measurements to be linked over space and time; independent of the technology used to define it
  - Space geodetic networks (GNSS, SLR, VLBI, DORIS) provide the critical infrastructure necessary to develop and maintain the TRF
- Data used for Precise Orbit Determination (POD)
  - SLR and DORIS data used to calculate and verify precise orbits for Earth observation missions (e.g., ERS-1/2, ALOS, Jason-1/2, Envisat, TOPEX, etc.)
  - SLR data and GPS flight receiver data also utilized for POD efforts for other geophysical missions (e.g., GFO-1, CHAMP, GRACE, ICESat, GOCE, etc.)
- Additional products include atmosphere measurements to aid in weather forecasting, etc.
- Measurements provide critical information for accurate deep space navigation

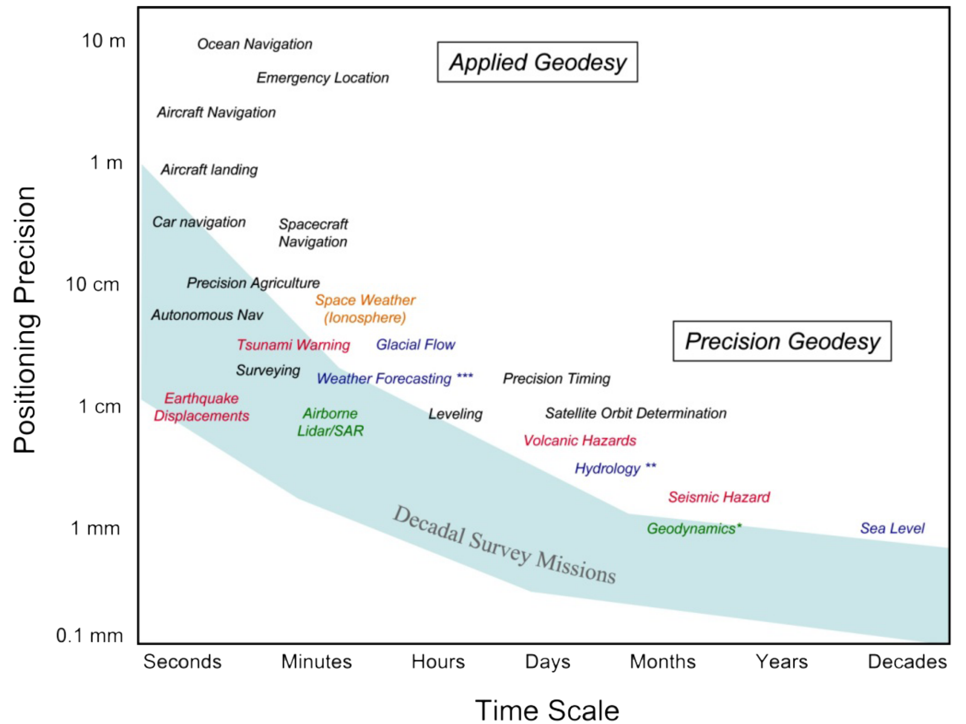



Who are the Users of the Data?

- International Association of Geodesy (IAG) Services
- NASA and non-NASA Flight Missions
- NSF Polar Programs
- USGS National Earthquake Hazards Reduction Program
- DoD
- Land Surveyors
- NOAA/NGS
- …

Scientific Contributions of Space Geodesy

- Terrestrial Reference Frame (TRF):
  - Station positions and velocities: GNSS, SLR, VLBI, DORIS
  - TRF scale and temporal variations: VLBI, SLR
  - Network densification: GNSS
  - Homogenous network distribution: DORIS
- Celestial Reference Frame: VLBI
- Precise Orbit Determination (POD):
  - Accurate satellite ephemerides: GNSS, SLR, DORIS
  - Calibration/validation for remote sensing missions, instruments: SLR, GNSS
  - Sea level monitoring: GNSS, SLR, DORIS
- Earth Orientation Parameters (EOP):
  - Polar motion and rates: VLBI, SLR, GNSS, DORIS
  - Length-of-day: GNSS, SLR, DORIS
  - UT1-UTC and long-term stability of nutation: VLBI
- Atmosphere:
  - Tropospheric zenith delays: GNSS, VLBI
  - Global maps of ionosphere mean electron content: GNSS, DORIS
  - Limb sounding for global profiles of water vapor: GNSS
- Gravity:
  - Static and time-varying coefficients of the Earth's gravity field: DORIS, SLR
  - Total Earth mass: SLR
  - Temporal variations of network origin with respect to Earth center of mass: SLR
- Timing:
  - Station and satellite clock solutions: GNSS
  - Time and frequency transfer between time laboratories: GNSS
- Fundamental Physics:
  - General relativity and alternative theories: SLR/LLR
  - Light bending, time dilation: VLBI



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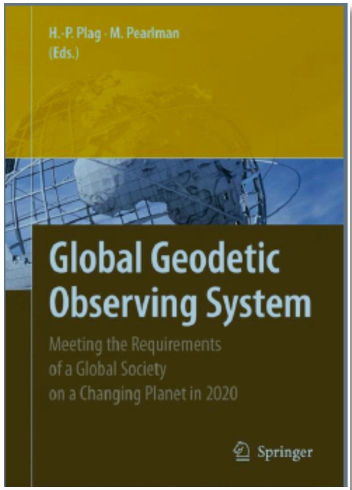
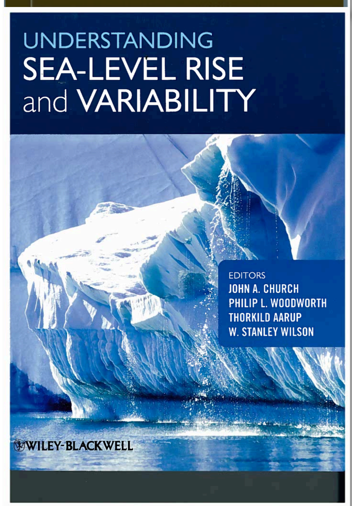
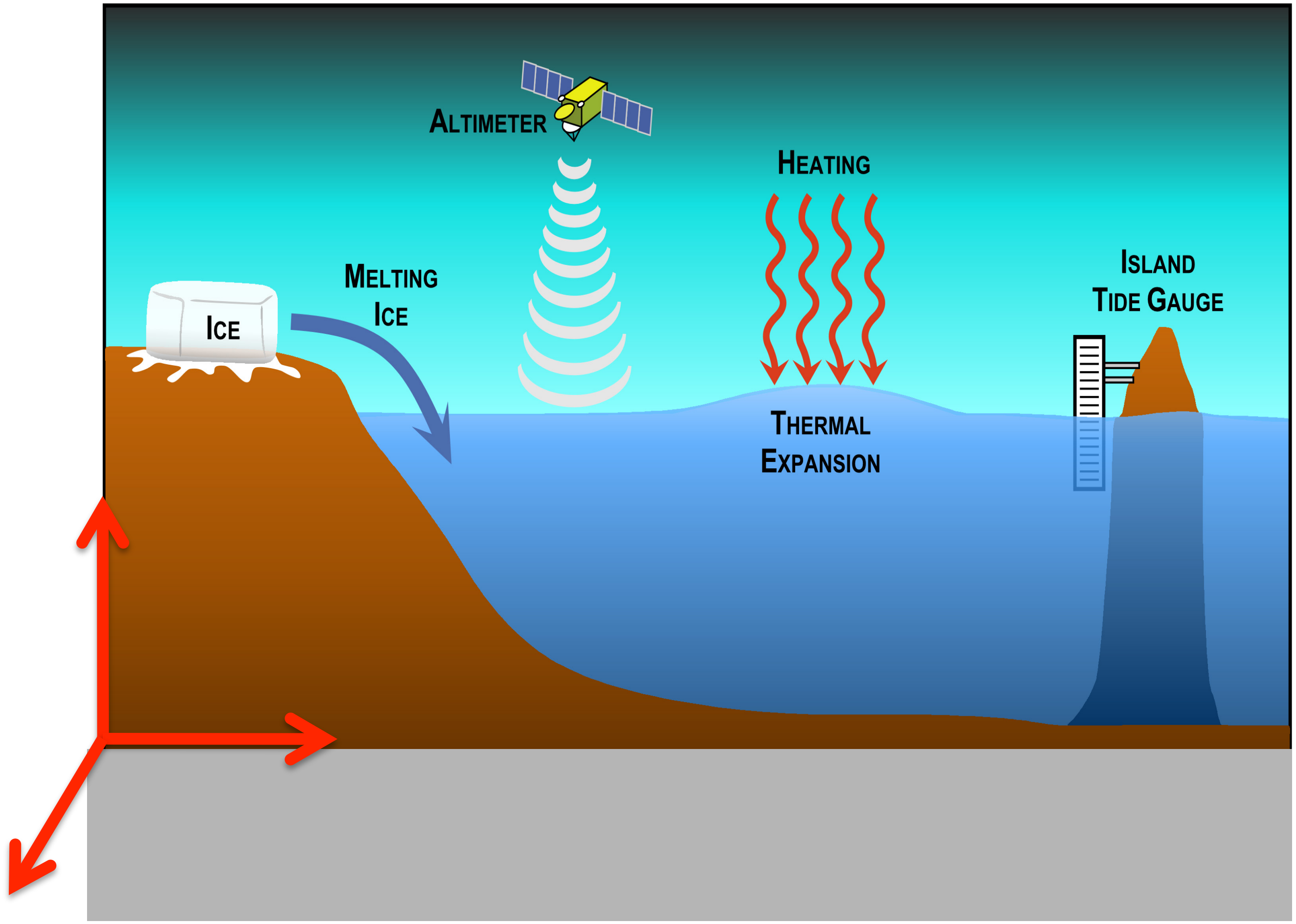
Improving the performance of the Global Geodetic Observing System and the ITRF is critical to understanding the future impact of sea level change







The GGOS geodetic reference frame requirement for sea level measurement:
1 mm reference frame accuracy and 0.1 mm/year stability.

Satellite Laser Ranging (SLR)

- Currently 23 operational stations worldwide acquiring data daily.
- GSFC operates five SLR stations:
  - GGAO, Greenbelt, Maryland,
  - McDonald Observatory, Fort Davis, Texas (Univ. of Texas at Austin),
  - Monument Peak, Mount Laguna, California,
  - Haleakala, Maui, Hawaii (Univ. of Hawaii, Institute for Astronomy),
  - Arequipa, Peru (Universidad Nacional de San Agustin (UNSA)).
- GSFC supports three partner stations:
  - Tahiti, French Polynesia (CNES, Univ. of French Polynesia),
  - Hartebeesthoek, South Africa (NRF, Hartebeesthoek Radio Observatory),
  - Yarragadee, Australia (Geoscience Australia).
- GSFC provides the Central Bureau of the International Laser Ranging Service (ILRS) that coordinates the worldwide SLR network, observing, data processing and analysis.
- GSFC maintains the archival and distribution of the worldwide SLR data using the Crustal Dynamics Data Information System (CDDIS).

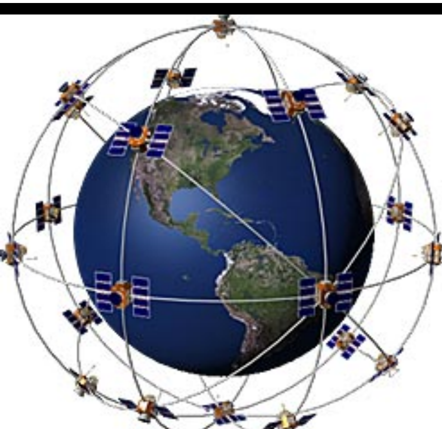
Very Long Baseline Interferometry (VLBI)

- 40 stations worldwide acquiring data, some daily.
- GSFC operates 3 VLBI stations:
  - GGAO, Greenbelt, Maryland,
  - Westford, Massachusetts (MIT, Haystack Observatory),
  - Kokee Park, Hawaii.
- GSFC provides support for 3 partner stations:
  - Svalbard, Norway (Norwegian Mapping Authority),
  - Fortaleza, Brazil (Mackenzie University),
  - Hobart, Australia (University of Tasmania).
- GSFC provides oversight and training to VLBI partners.
- GSFC provides the Coordinating Center and an Analysis Center of the International VLBI Service for Geodesy and Astrometry (IVS) that schedule all international geodetic VLBI networks and observing, oversee data correlation and distribution to the global archive, and perform VLBI data processing and analysis.
- GSFC maintains the archival and distribution of the worldwide VLBI geodetic data using the Crustal Dynamics Data Information System (CDDIS).

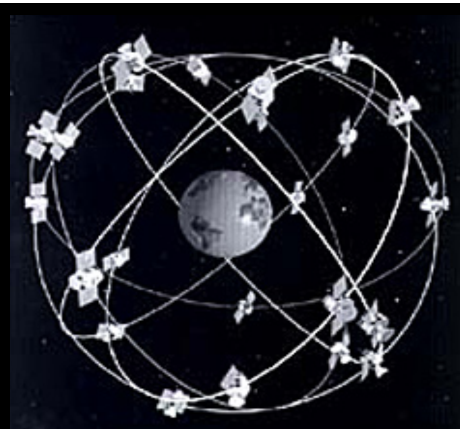
Global Navigation Satellite Systems (GNSS)

- This Decade will see an explosion of new Global Navigation Satellite Systems (GNSS).
- 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.
- NASA is partnering with the Department of Defense to provide SLR tracking of the next generation GPS satellites.

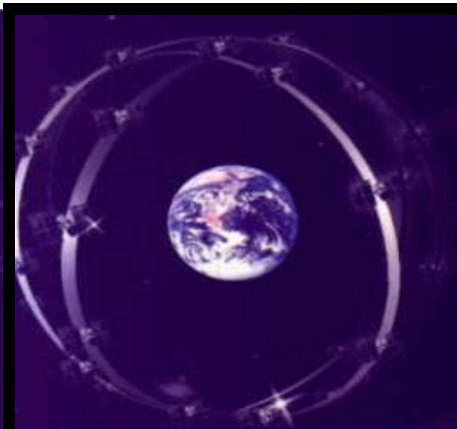
GPS

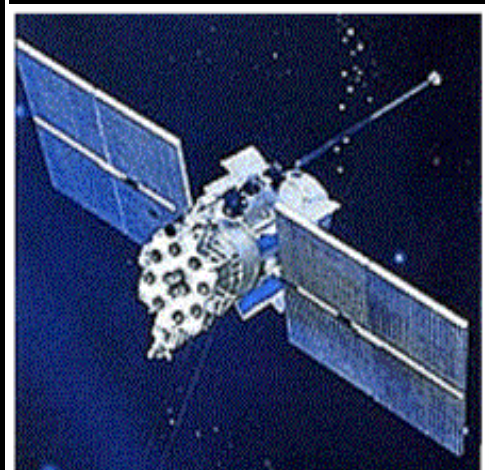


Galileo

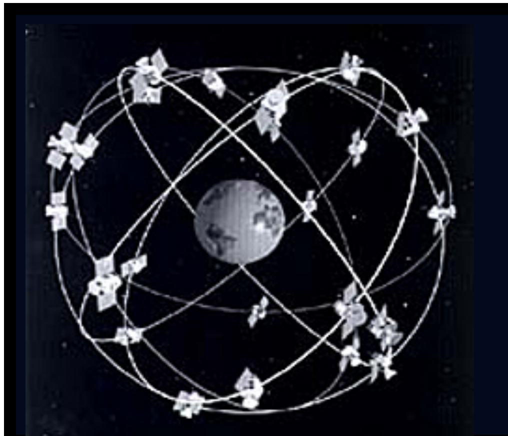


GLONASS



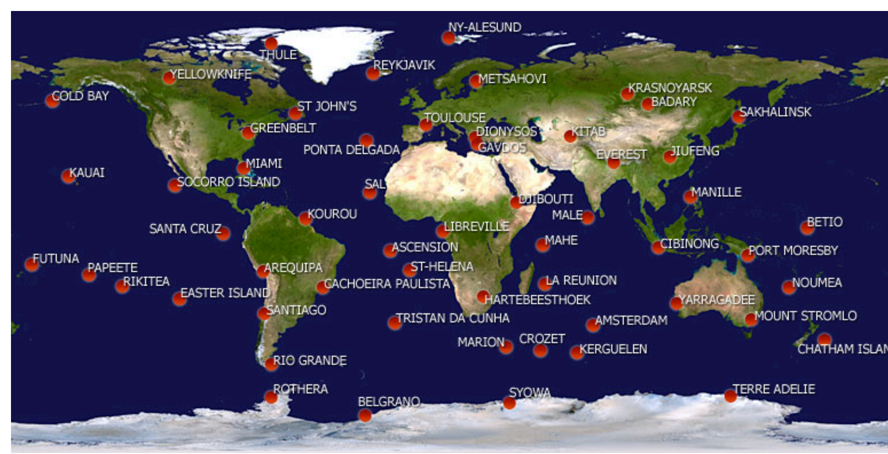


Beidou

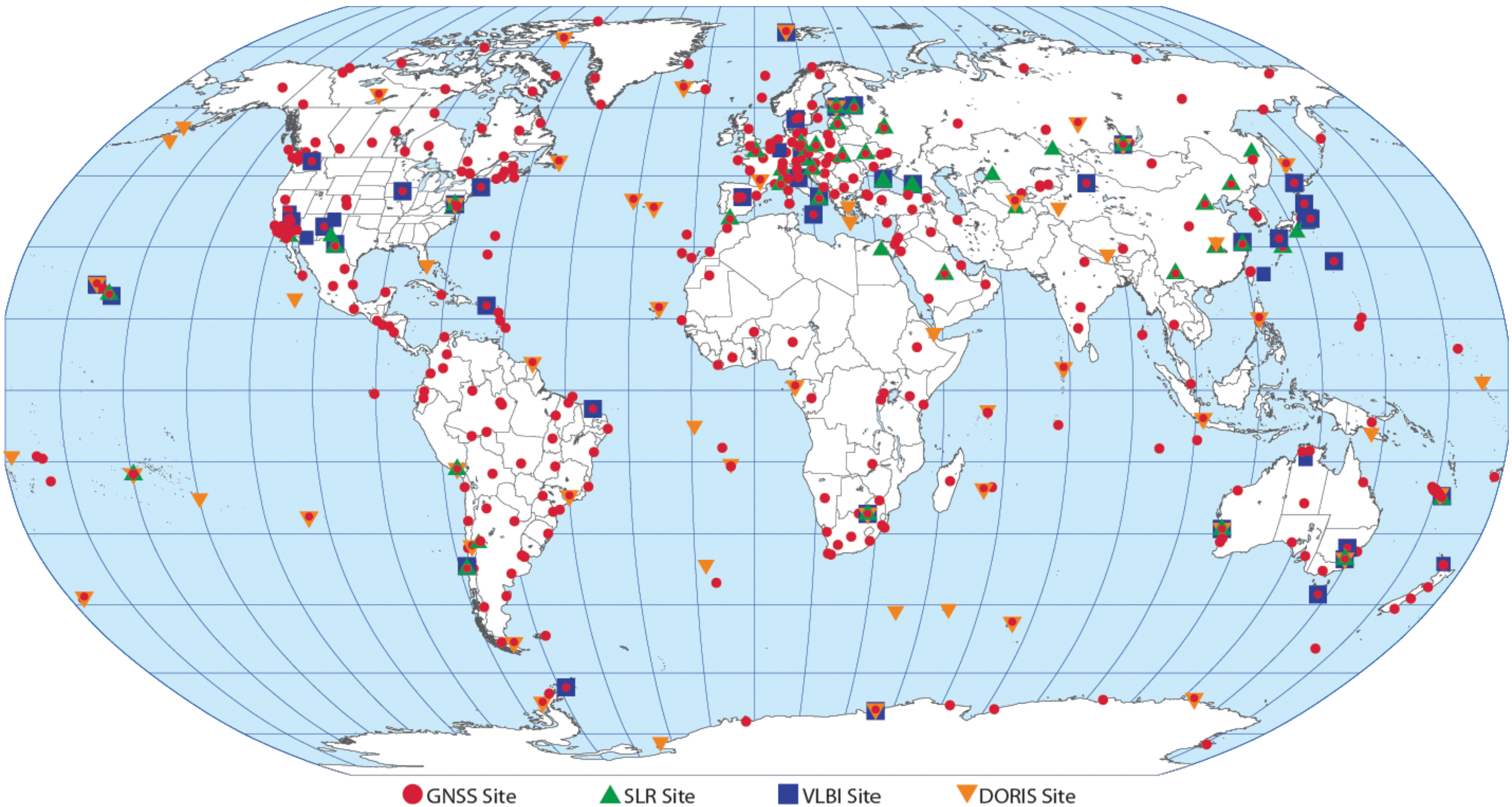


Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)

- GGAO DORIS beacon is part of a global network of ~57 stations since June 2000.
- DORIS receivers are used on altimeter (TOPEX, Jason1, Jason2, ENVISAT, Cryosat-2) and remote sensing (SPOT) satellites; Future Missions: Jason-3, SWOT & SENTINEL-3, GRASP.
- GSFC maintains the archival and distribution of the worldwide DORIS geodetic data using the Crustal Dynamics Data Information System (CDDIS).



Global Geodetic Network



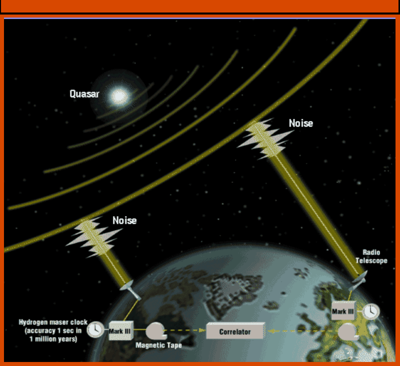
Global Geodetic Observing System (GGOS) Services & Products

International Terrestrial Reference Frame (ITRF)
(Accurately positioned points with respect to the Earth's Center of Mass and the fixed background of Quasars)

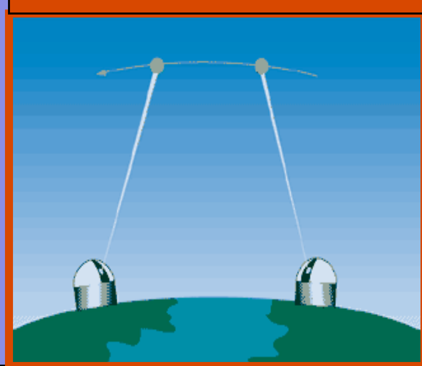
International Earth Rotation and Reference Systems Service (IERS)

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

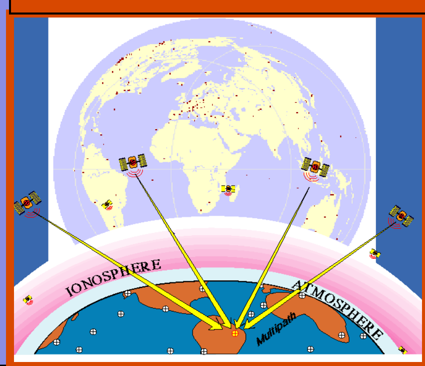
Very Long Baseline Interferometry (IVS)



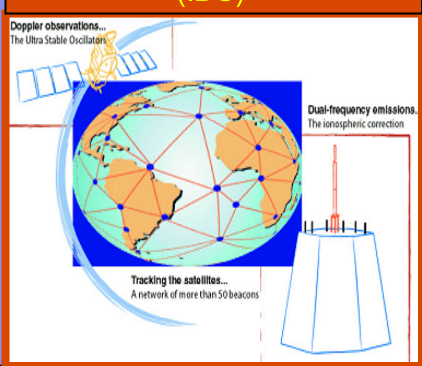
Satellite Laser Ranging (ILRS)



Global Navigation Satellite Systems (IGS)



Doppler Orbit Determination and Radiopositioning Integrated on Satellite (IDS)



IAG Services

- Services function as cooperating federations dedicated to a particular space geodesy technique
- Provide data and products on an operational basis to geodesy analysts as well as a broader scientific community
- Examples of a successful model of community management:
  - develop standards
  - self-regulating
  - monitor performance
  - define and deliver products using pre-determined schedules
- 200+ organizations in 80+ countries
- Successful operation through cooperation of many international organizations who leverage their respective limited resources to all levels of service functionality
- NASA actively participates in the services
  - International GNSS Service (IGS)
  - International Laser Ranging Service (ILRS)
  - International VLBI Service for Geodesy and Astrometry (IVS)
  - International DORIS Service (IDS)
  - International Earth Rotation and Reference Frame Service (IERS)
- Services respond to NASA's program needs

NASA's Role Among Global Collaborators

- Operational Networks, through the TRF, provide critical infrastructure to support flight projects

- NASA leverages its resources by cooperating with international partners
  - NASA supports and coordinates the geodetic services through central offices GSFC (ILRS and IVS) and at JPL (IGS)
  - This NASA coordination is a highly successful international activity endorsed by international organizations such as the IAG
  - NASA's space geodetic data sets are augmented by data contributed by other agencies to the international pool
  - These activities are supported by the Crustal Dynamics Data Information System (CDDIS), a key data center supporting the IGS, ILRS, IVS, IDS, and IERS
  - This results in access to greater and enhanced data sets and products

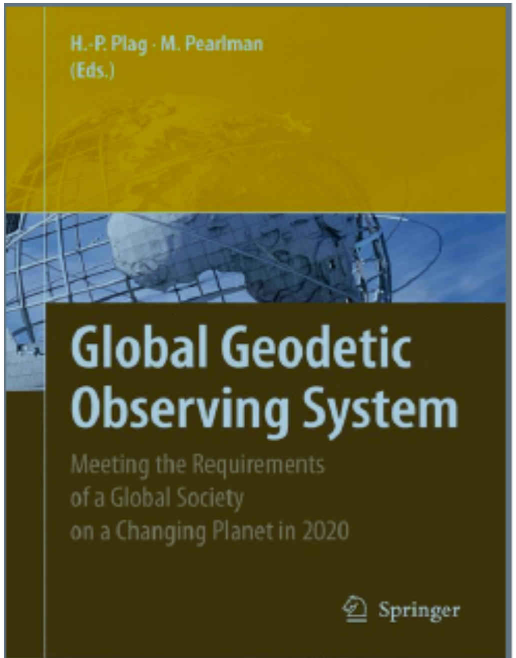
NASA Needs for Geodetic Networks

- Long term, systematic measurements of the Earth system require the availability of a terrestrial reference frame (TRF) that is stable over decades and independent of the technology used to define it.
- The space geodetic networks provide the *critical infrastructure* necessary to develop and maintain the TRF and the needed terrestrial and space borne technology to support the Earth science goals and missions.
- This infrastructure is composed of the:
  - Physical networks,
  - Technologies that compose them, and
  - Scientific models and model development that define a TRF

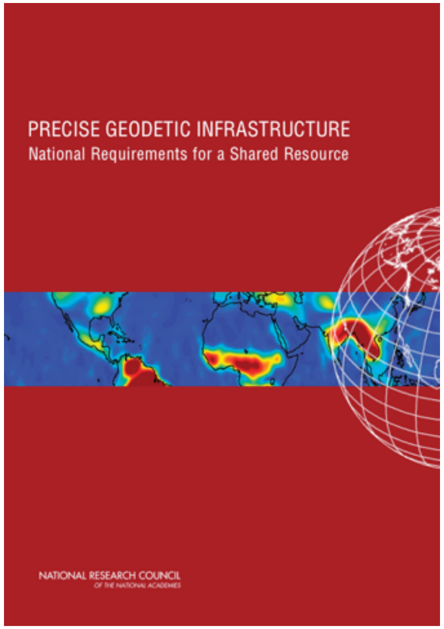
Supporting Future Requirements

- Requirements for the ITRF have increased dramatically since the 1980's
  - Most stringent requirement comes from sea level studies:
    - "accuracy of 1 mm, and stability at 0.1 mm/year"
  - This is a factor 10-20 beyond current capability.
- Simulations show the required ITRF is best realized from a combination solution using data from a global network of ~30 integrated stations having all available techniques with next generation measurement capabilities.
  - The current network cannot meet this requirement, even if it could be maintained over time (which it cannot).
- The current core NASA network is deteriorating and inadequate. NASA's Space Geodesy Project is addressing this need.

Foundation Documents

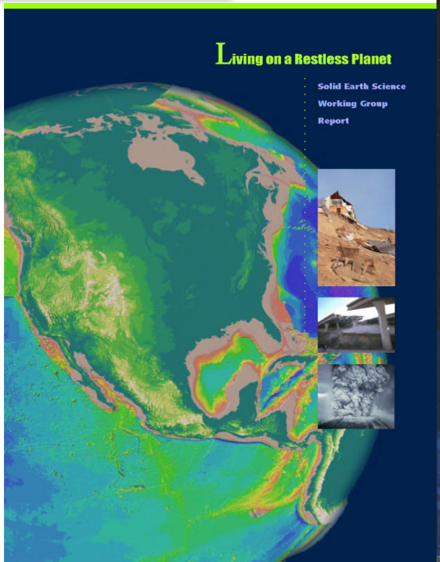


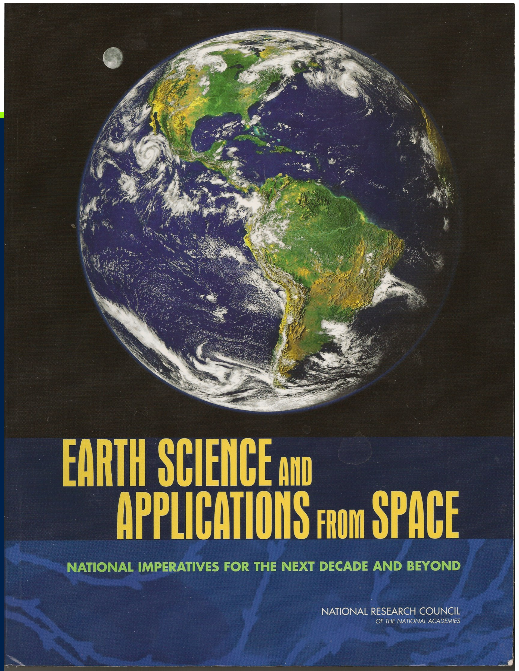
The National Imperative

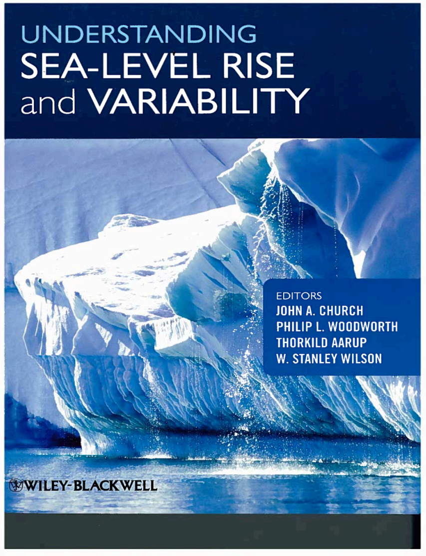


The Global Organization

The Science Imperative





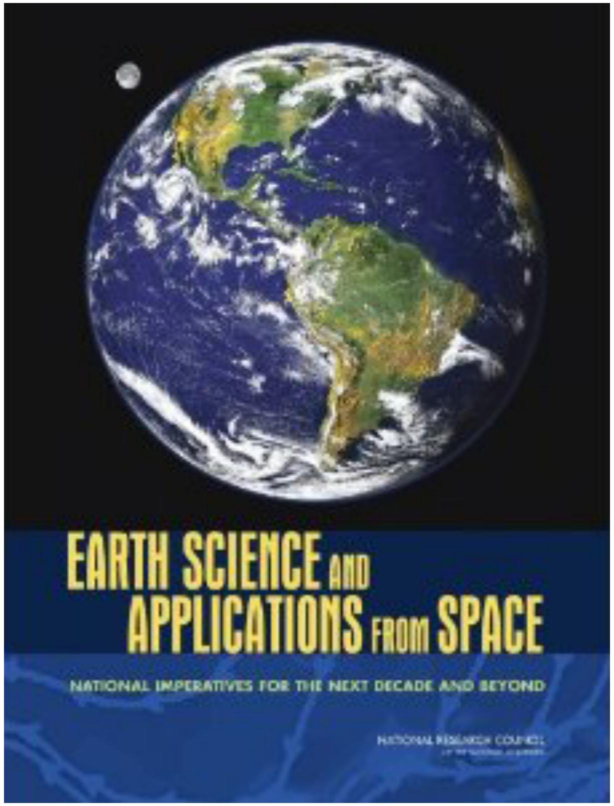


"Collapsing" Infrastructure

"Requirement for precise measurement and maintenance of the terrestrial reference frame.

The geodetic infrastructure needed to enhance or even to maintain the terrestrial reference frame is in danger of collapse (see Chapter 1). Improvements in accuracy and economic efficiency are needed. Investing resources to ensure the improvement and continued operation of the geodetic infrastructure is a requirement of virtually all the missions proposed by 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 studies of 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 interrelated for robust, long-term monitoring of global change. A precise reference frame is also essential for interplanetary navigation and diverse national strategic needs."



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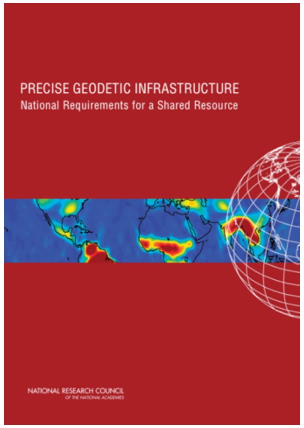
NRC Recommendations



- 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.

http://www.nap.edu/catalog/12954.html

NASA Response

- Contribute to building a new global network of integrated next generation SLR, VLBI, and GNSS stations.
- Network should be there for the coming Decadal Survey missions.
- NASA proposes to provide 6-10 of these stations if the next generation technology can be demonstrated to function as required.
- Next Generation SLR and VLBI technology pathways known and under development.

The Space Geodesy Project

- New initiative started at the end of FY11 in response to the Earth Science Decadal and the National Research Council study “Precise Geodetic Infrastructure.” Part of the President’s Climate Initiative.

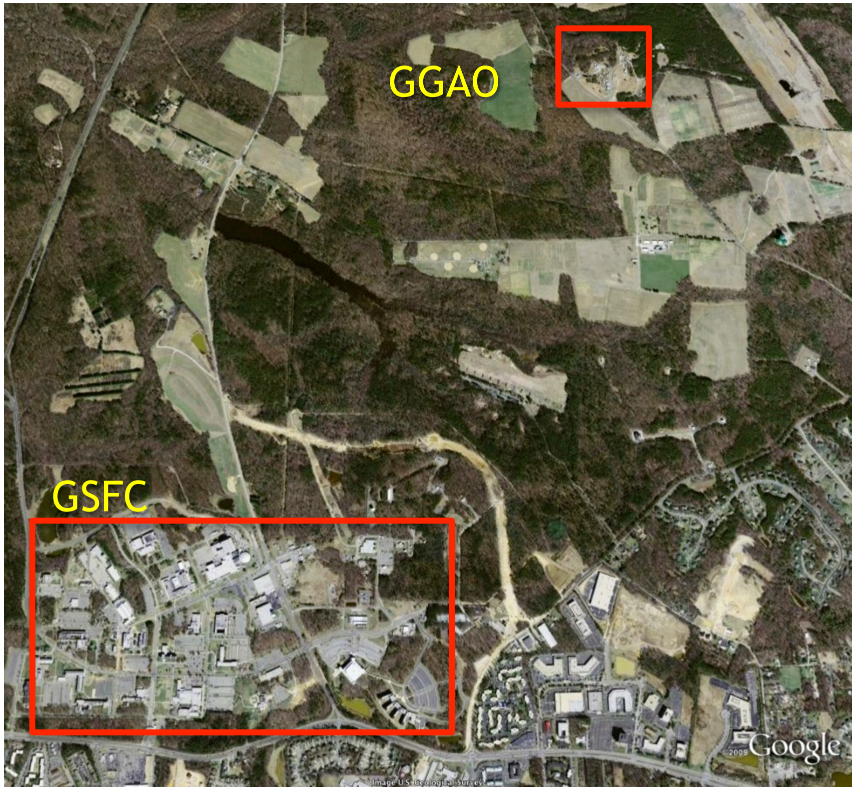
- Goddard led in partnership with JPL and participation from the Smithsonian Astrophysical Observatory and the University of Maryland.

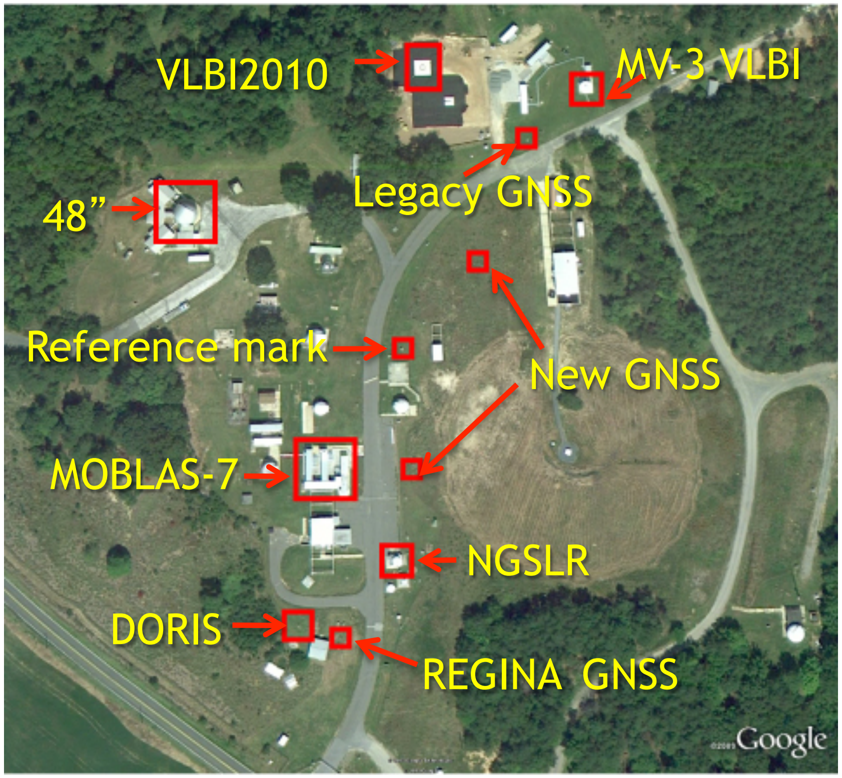
- Goals:
  - Establish and operate a prototype next generation space geodetic station with integrated next generation SLR, VLBI, GNSS (and DORIS) systems, along with a system that provides for accurate vector ties between them.
  - Develop a Project Implementation Plan for the construction, deployment and operation of a NASA network of similar next generation stations that will become the core of a larger global network of modern space geodetic stations.

VLBI	NGSLR	GNSS	Vector Tie
			

Goddard Geophysical and Astronomical Observatory (GGAO)

- Goddard Geophysical and Astronomical Observatory is located 5 km from Goddard Space Flight Center in the middle of the Beltsville Agricultural Research Center. GGAO is one of the few sites in the world to have all four geodetic techniques co-located at a single location.

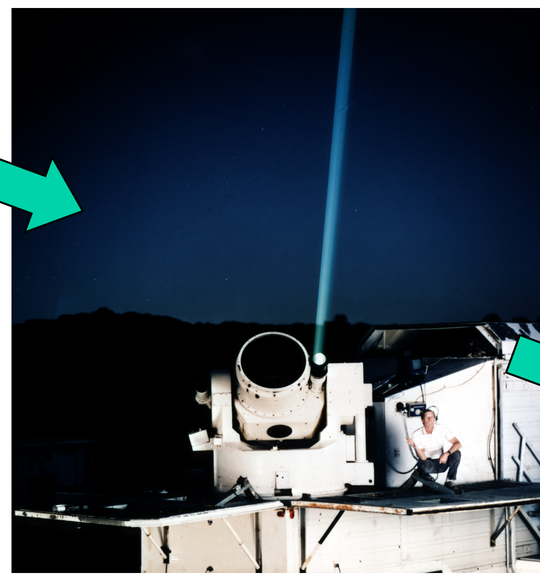




SLR at GGAO: Past, Present, Future

- GGAO is home to NASA's SLR activities. Developed at Goddard in the early 1960's as a very accurate tracking technique for satellites carrying retro-reflectors, SLR is now practiced in over 30 countries.
- Continuous set of GGAO SLR data since 1964

Past: GODLAS

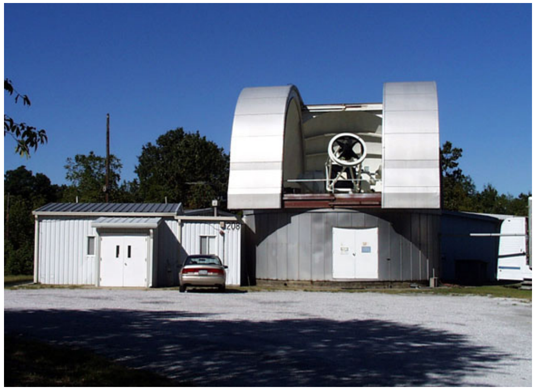


Present: MOBLAS-7

Future: Next Generation Satellite Laser Ranging (NGSLR)

SLR at GGAO

- GGAO is home to NASA's SLR activities. Developed at Goddard in the early 1960's as a very accurate tracking technique for satellites carrying retro-reflectors, SLR is now practiced in over 30 countries
- Two SLR stations at GGAO, MOBLAS-7 and NGSLR, support the laser ranging activities of the International Laser Ranging Service (ILRS), *http://ilrs.gsfc.nasa.gov*; the 1.2M telescope performs R&D activities
- "NGSLR (NASA's Next Generation SLR) performs one way (uplink only) ranging to the Lunar Reconnaissance Orbiter (LRO), providing 10 cm accurate ranges used in the determination of onboard clock drift and aging, and eventually for use in more precise orbit determination
- The 1.2 meter telescope is performing periodic on-orbit calibrations of the Lunar Orbiter Laser Altimeter (LOLA) onboard LRO; three successful on-orbit calibrations have been performed so far
- <u>Reference & citation</u>:
  Pearlman, M.R., Degnan, J.J., and Bosworth, J.M., The International Laser Ranging Service, *Adv. Space Res.* , 30(2), pp. 135-143, 2002. DOI:10.1016/S0273-1177(02)00277-6.



Next Generation Satellite Laser Ranging System (NGSLR)

NGSLR is a high repetition rate single photon detection laser ranging system capable of tracking cube corner reflector (CCR) equipped satellites in Earth orbit. The concept of NGSLR was developed by J. Degnan (GSFC, retired) in the 1990s. Technical development continues at Goddard. The system has demonstrated tracking of Earth orbit satellites with altitudes from 300 km to 20000 km.

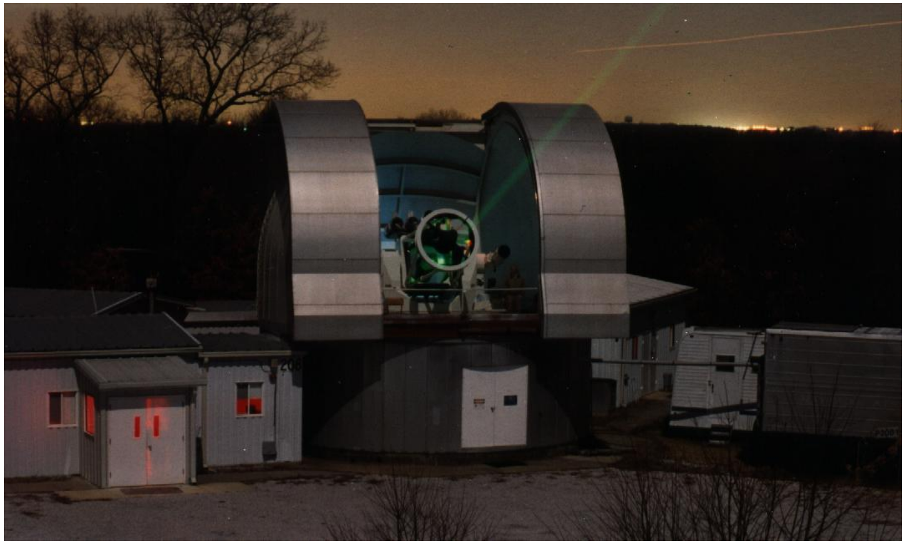
Achievements & Status:

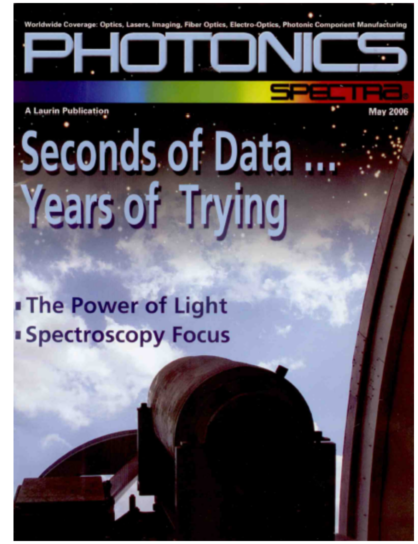
- Successfully tracked most of ILRS satellites.
- LEO, LAGEOS 1 & 2, and GNSS have all been successfully tracked in both daylight and night.
- Starting intercomparison testing with MOBLAS-7.
- Assembling new optical bench to support use of 2.5 mJ, 2 kHz Photonics Industries laser.

System Features:

- 1 to 2 arcsecond pointing/tracking accuracy,
- Track CCR equipped satellites to 20,000 km altitude, 24/7 operation,
- Reduced chemical & electrical hazards,
- Semi automated tracking features,
- Small, compact, low maintenance, increased reliability,
- Lower operating/replication costs.

48"(1.2 Meter) Telescope Facility at GGAO





- Multi-user facility built in 1973-74
- Arc-second precision tracking telescope
- Has supported many GSFC experiments including:
  - Mercury Laser Altimeter (MLA) Earthlink 2-Way Laser Ranging
  - MLA onboard MESSENGER at distance of 24 Mkm (Smith, Zuber, Sun, Neumann, Zagwodzki, McGarry): May 2005
  - Mars Orbiter Laser Altimeter (MOLA) Earthlink 1-Way Laser Ranging.
  - MOLA onboard MGS orbiting Mars at ~80 Mkm (Smith, Abshire, Sun, Zuber, Neumann, Zagwodzki, McGarry): Sep 2005
  - LOLA on-orbit calibration, 2-way laser ranging (Smith, Zuber, Zagwodzki, McGarry, Sun, Liiva, Neumann): Aug & Sep 2009

VLBI at GGAO

- MV-3 system was originally a mobile VLBI station supporting the Crustal Dynamics Project that began in 1980
- Mobile system made measurements in western U.S., Alaska, and Europe.
- Since 1993, MV-3 has been a fixed site at GGAO and part of the global network supporting the International VLBI Service for Geodesy and Astrometry (IVS), http://ivscc.gsfc.nasa.gov
- MV-3 now serving as a testbed facility for NASA VLBI R&D, including VLBI2010 development
- Reference & Citation:
  W. Schlüter, D. Behrend, The International VLBI Service for Geodesy and Astrometry (IVS): current capabilities and future prospects, J Geod, 81(6–8), pp. 379–387, 2007. DOI: 10.1007/s00190-006-0131-z

VLBI 2010

VLBI2010 is an enabling technology upgrade to the existing global geodetic VLBI network. It was developed by Working Group 3 of the International VLBI Service for Geodesy and Astrometry (IVS). Technical development continues at Goddard and MIT Haystack Observatory.

Achievements & Status:

- Demonstrated 60% aperture efficiency.
- Demonstrated 5 deg/sec azimuth slew rate.
- Demonstrated broadband data collection at a rate of 8 Gbps and a 4 ps group delay uncertainty for the GGAO-Haystack baseline.
- On-track to completing system by April 2013.

System Features:

- 12-m / 5 deg per sec / 8 Gbps enables improved troposphere sampling with acceptable SNR for observation by worldwide VLBI network.
- Standardization and commercial-off-the-shelf availability of many key components will lead to lower operation and replication costs.
- Selectable RF band placement will better tolerate radio frequency interference and allow compatibility with legacy S/X systems.
- Improvement in group delay will enable ~1mm position determination when the VLBI2010 technology is incorporated in the expanded global network.

GNSS at GGAO

- GGAO host several legacy and modern multi-constellation GNSS (GPS, GLONASS, Galileo) antennas and receivers
- Data publicly available from CDDIS.
- Receivers are key contributors to the International GNSS Service (IGS), http://igscb.jpl.nasa.gov.
- JPL provides installation and infrastructure support for receiver, antenna, and data download.
- GGAO also used for engineering tests of various GNSS antennas.
- <u>Reference & Citation:</u>

Dow, J.M., Neilan, R. E., and Rizos, C., The International GNSS Service in a changing landscape of Global Navigation Satellite Systems, Journal of Geodesy (2009) 83:191–198, DOI: 10.1007/s00190-008-0300-3

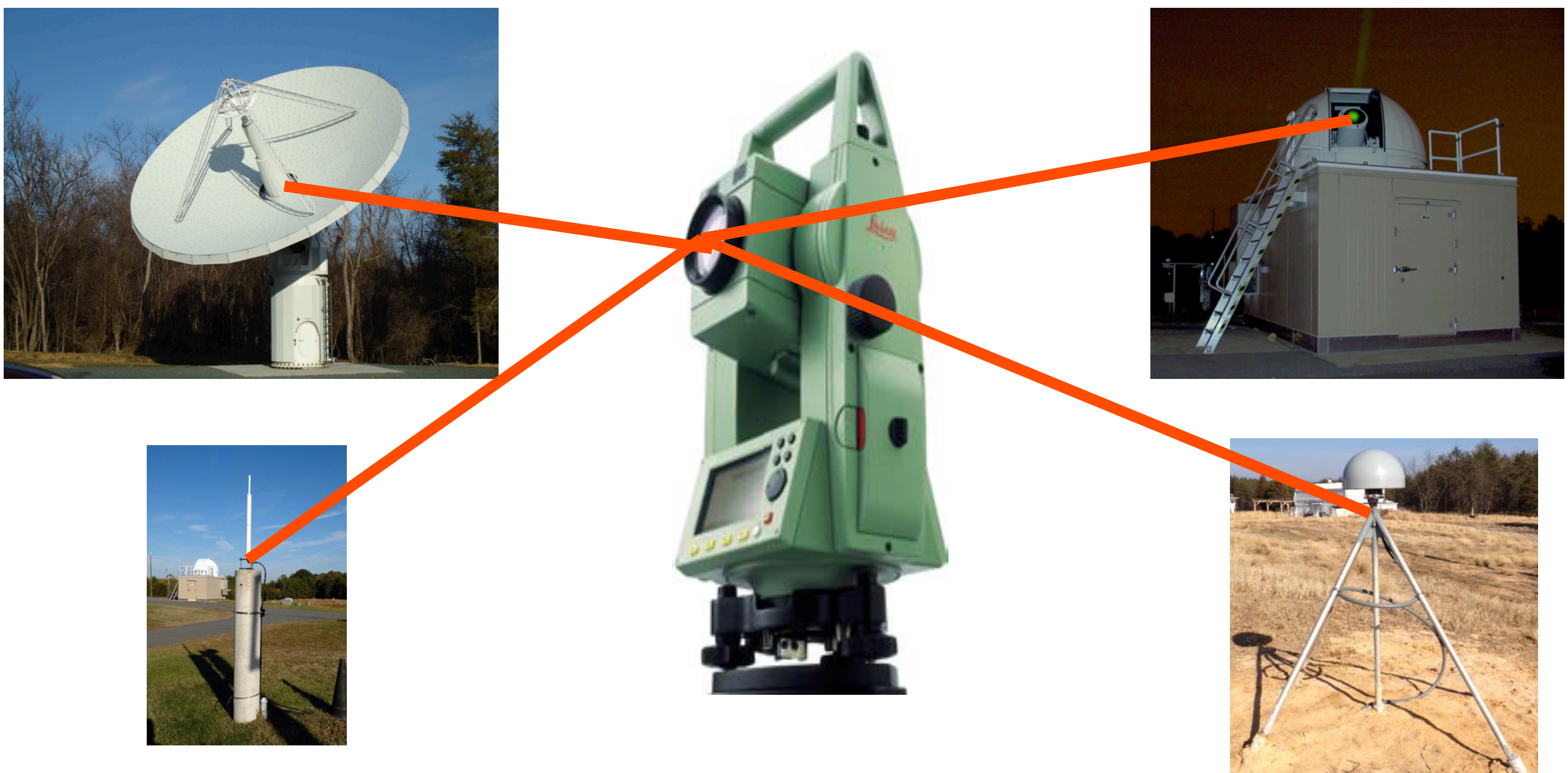
DORIS at GGAO

DORIS Global Network

- GGAO DORIS beacon part of a global network of ~57 stations
- DORIS@GGAO since June 2000
- Beacons emit at 2 Ghz and 400 Mhz; the observable is dual-frequency 1-way Doppler
- DORIS receivers are located on altimeter (TOPEX/Poseidon, Jason, ENVISAT) and remote sensing (SPOT) satellites; future satellites include: Cryosat-2, Jason-3, SWOT & SENTINEL-3
- DORIS data are used for Precision Orbit Determination, and contribute to IERS reference frame realizations
- International DORIS Service URL: *http://ids.cls.fr*
- Reference & Citation: Tavernier, G., Fagard, H., Feissel-Vernier, M., et al., The International DORIS Service: Genesis and early achievements, *J. Geod. 80(8-11)*, pp. 403-417, 2006. DOI: 10.1007/s00190-006-0082-4.

Co-location Vector Monitoring

- Automated measurement of inter-instrument vectors is an essential aspect of an integrated space geodesy station.
- Measurements provide closure between terrestrial reference frames derived from different space geodesy techniques.
- Tests of technologies and currently available systems underway at GGAO.



Project Status Summary

- Prototype station is currently on-budget and on-schedule for a July 2013 completion.
- An implementation plan is currently being developed to upgrade the current NASA sites and establish new sites with our international partners.
- On-going discussions with existing and potential international partners, including Brazil, Columbia, Norway, South Africa, and Australia.

Acronyms

- CDDIS Crustal Dynamics Data Information System
- DORIS Doppler Orbitography and Radio-positioning by Integrated Satellite
- GGAO Goddard Geophysical and Astronomical Observatory
- GGOS Global Geodetic Observing System
- GNSS Global Navigation Satellite System
- LAGEOS LAser GEOdynamics Satellite
- LEO Low Earth Orbit
- NGSLR Next Generation Satellite Laser Ranging
- RTS Robotic Total Station
- SAO Smithsonian Astrophysical Observatory
- SGP Space Geodesy Project
- SINEX Solution INdependent EXchange format
- SLR Satellite Laser Ranging
- UMBC University of Maryland, Baltimore County
- VLBI Very Long Baseline Interferometry