The Expanding Core and Co-location Space Geodesy Network and the Importance of High Latitude Sites.

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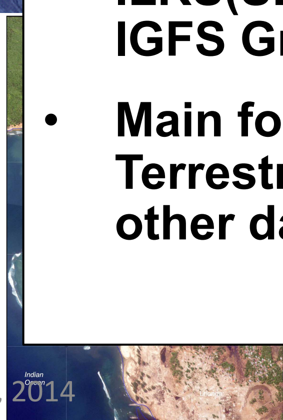
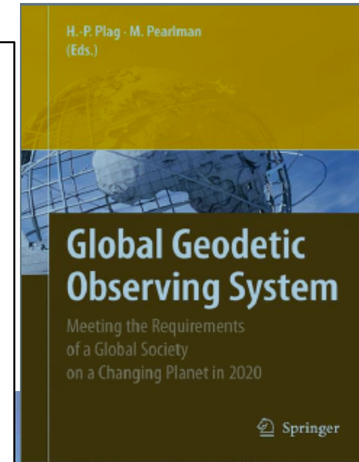
GGOS

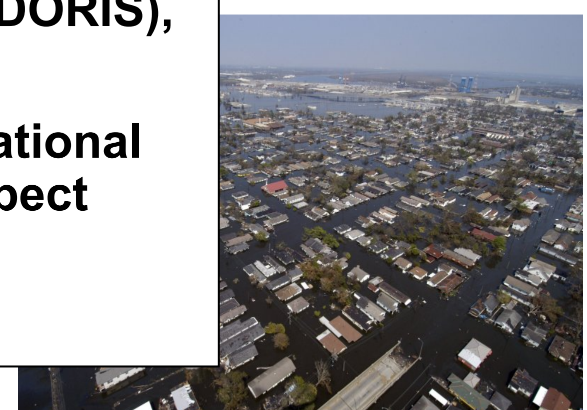
Fifth Symposium on Polar Science
2 -5 December 2014
Tokyo, Japan

Global Geodetic Observing System (GGOS)



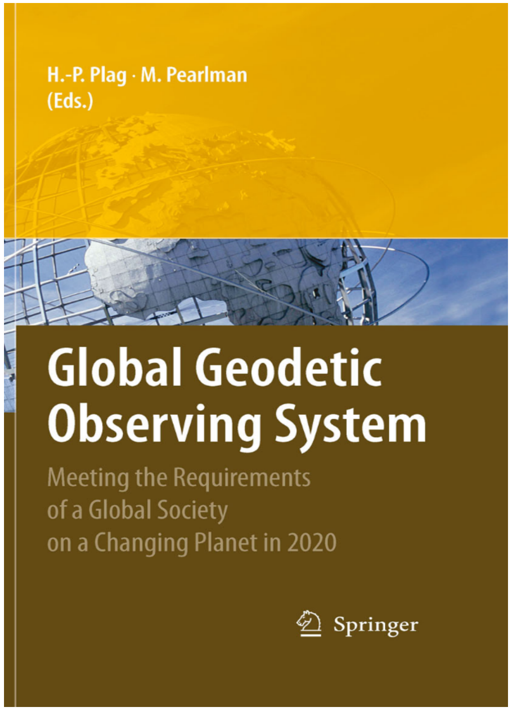
- Established by the IAG to integrate the three fundamental areas of geodesy (Earth's shape, gravity field, and rotation), to monitor geodetic parameters and their temporal variations in a global reference frame with a target relative accuracy of 10E-9 or better (See GGOS 2020)
- **Provide products & services with the geodetic accuracy necessary to address important geophysical questions and societal needs,** and to provide the robustness and continuity of service which will be required of this system in order to <u>meet future needs and make intelligent decisions</u>
- **Constituted mainly from the Services – ILRS(SLR), IVS(VLBI), IGS(GNSS), IDS(DORIS), IGFS Gravity Field), IERS, etc.**
- **Main focus at the moment is the International Terrestrial Reference Frame, but we expect other data products to emerge**





GGOS 2020 Book (2009)

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



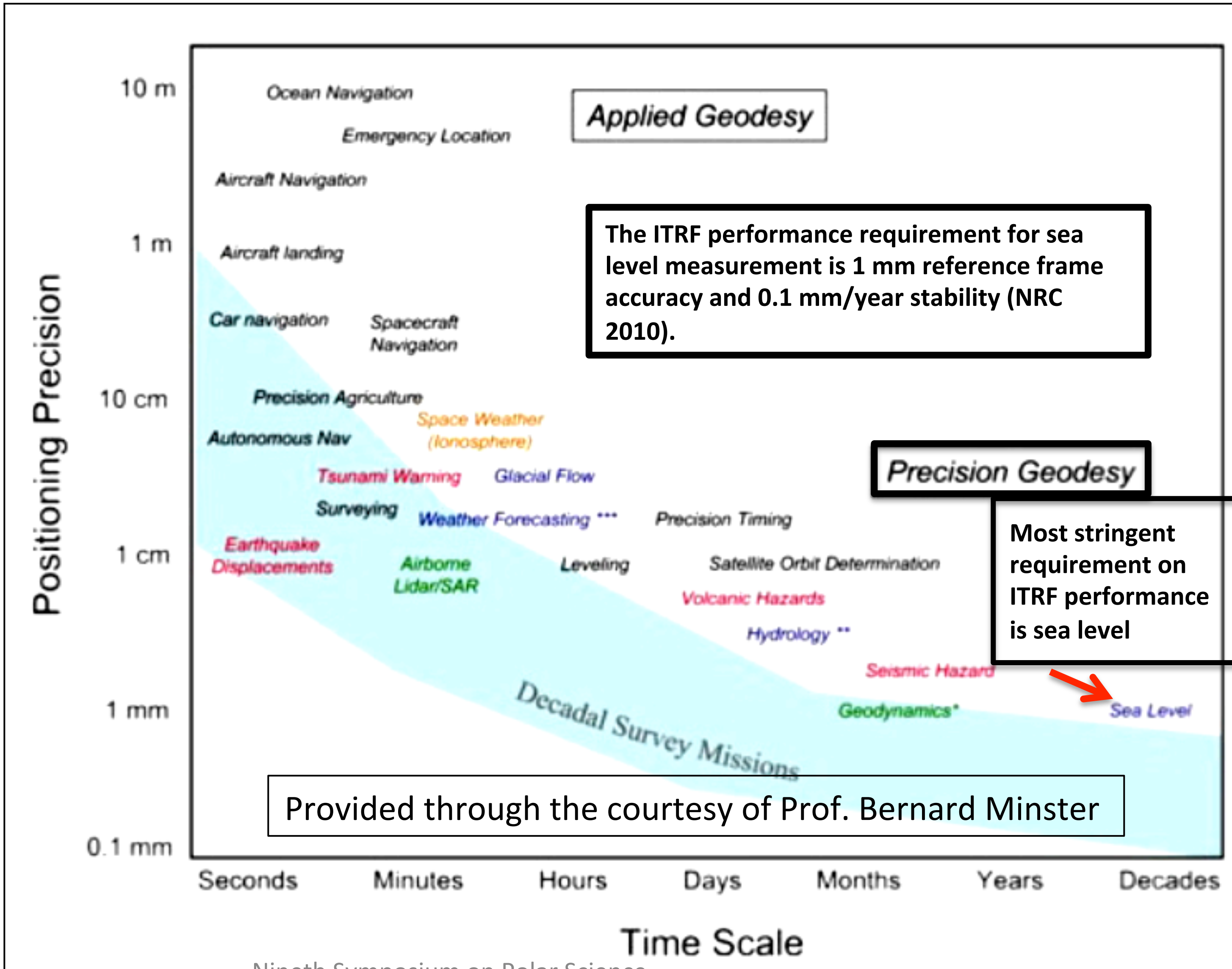
Content: main arguements for GGOS

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

Practical Applications of Space Geodesy

US National Research Council Study

- **Geodesy** is the science of the Earth's shape, gravity and rotation, including their evolution in time.
- **Techniques** used to observe the geodetic properties of the Earth **provide the basis for the International Terrestrial Reference Frame (ITRF)**
- The **ITRF** is the foundation for virtually all **airborne, space-based, and ground-based Earth observations**, and is fundamentally important for **interplanetary spacecraft tracking and navigation.**



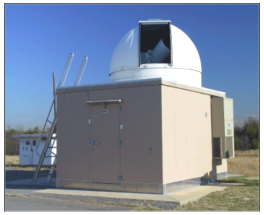
GGOS Reference Frame Requirement

- **Basis upon which we measure change over space, time, and evolving technology**
- **Most stringent requirement from sea level rise:**
  - **"accuracy of 1 mm, and stability at 0.1 mm/yr"**
  - **This is a factor 10-20 beyond current capability**
- **Accessibility: 24 hours/day; worldwide**

  Users anywhere on the Earth can position their measurements in the reference frame
- **Space Segment:**
  - **LAGEOS, LARES, GNSS, DORIS, Quasars to define the reference frame**
- **Ground Segment (Core Sites):**
  - **Global distributed network of "modern technology", co-located SLR, VLBI, GNSS, DORIS stations locally tied together with accurate site ties**
  - **Dense network of GNSS ground stations to distribute the reference frame globally to the users**

VLBI	NGSLR	GNSS	DORIS	Vector Tie
				

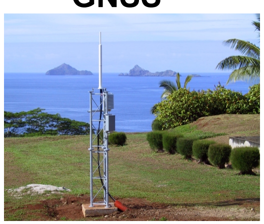
Why a Core Site?



SLR

VLBI

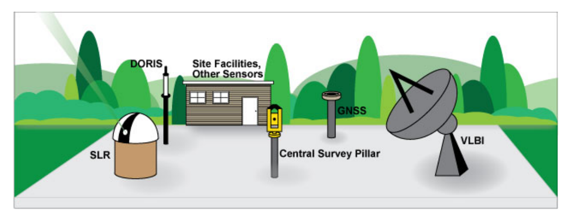
GNSS



DORIS

- A ground site with co-located SLR, VLBI, GNSS and DORIS (where available) so that their measurements can be related to sub-mm accuracy
- Why do we need multiple techniques?
  - 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 (Co-location) allows us to take advantage of the strengths and mitigate the weaknesses



What does each technique provide to the Reference Frame

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

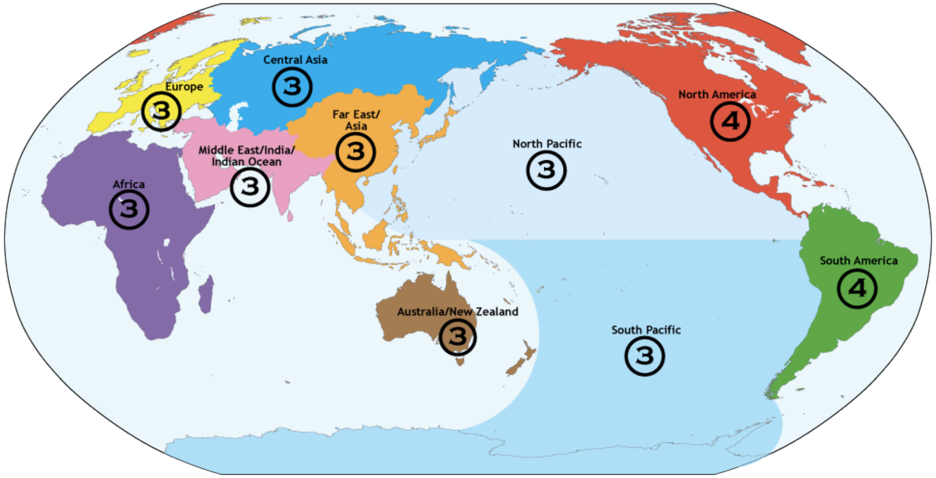
Simulation Studies to Scope the Network

(impact on the Reference Frame)

(Erricos Pavlis)

Simulation studies show:

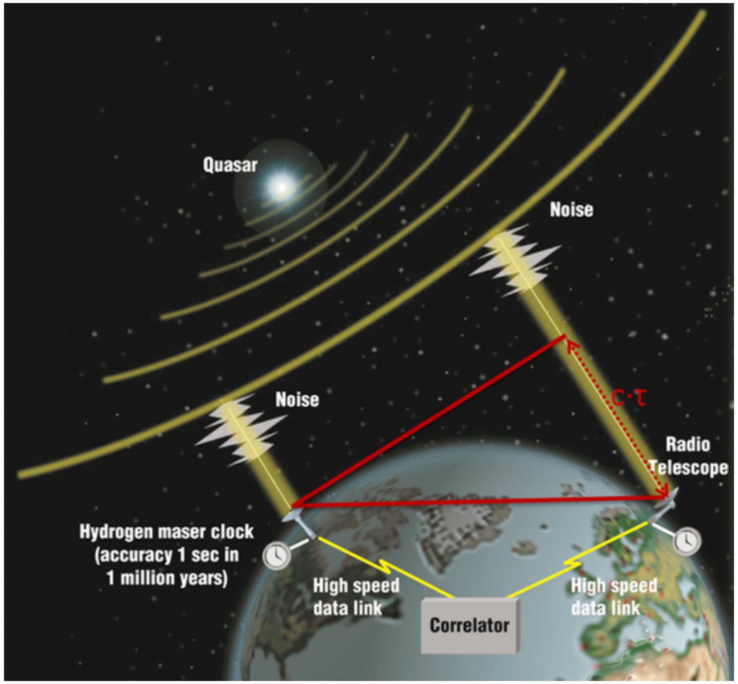
- ~32 globally distributed, well positioned, new technology, co-location sites will be required to define and maintain the reference frame;
- ~16 of these co-location stations must track GNSS satellites with SLR to calibrate the GNSS orbits which are used to distribute the reference frame.



- Major Challenge
- Will require time, significant resources, and strong international participation

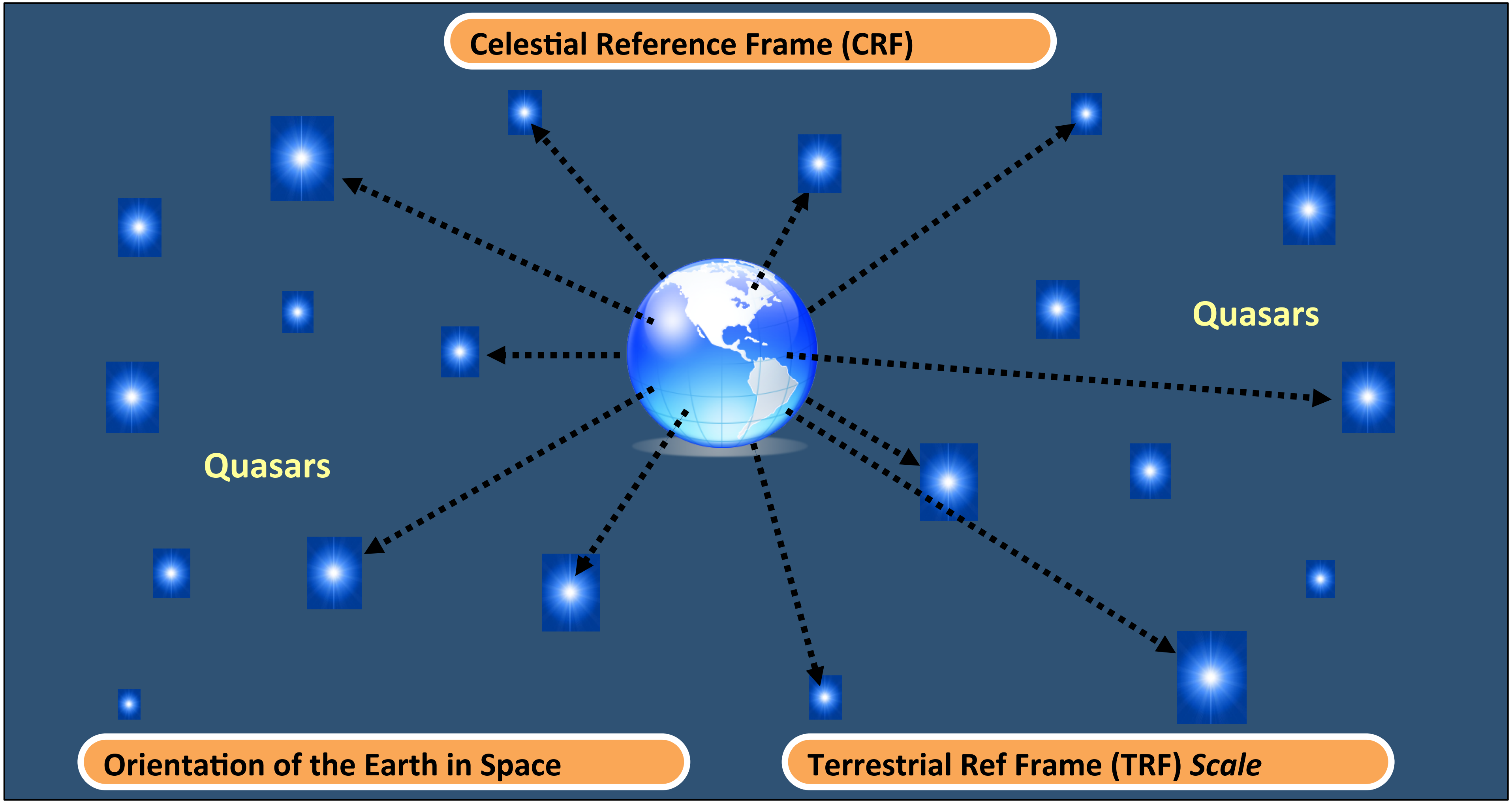
Very Long Baseline Interferometry

- VLBI is a geometric technique that measures the time difference between the arrival at two Earth-based antennas of a radio wavefront emitted by a distant quasar.
- Using large numbers of time difference measurements from many quasars observed with a global network of antennas, VLBI determines the **inertial reference frame** defined by the quasars and simultaneously, the precise positions and velocities of the antennas.

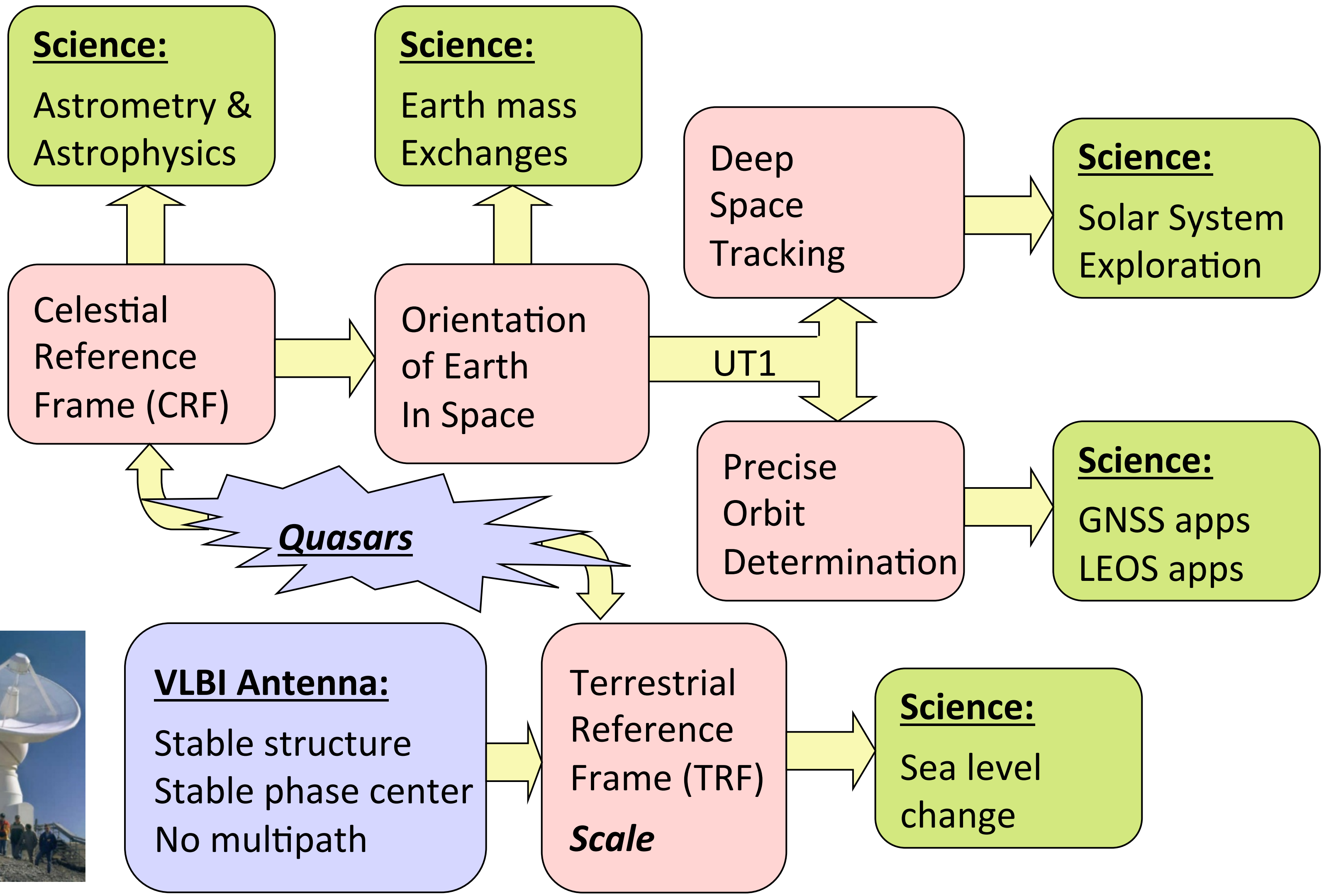


- Since the antennas are fixed to the Earth, their locations track the **instantaneous orientation of the Earth in the inertial reference frame.**
- Relative changes in the antenna locations from a series of measurements indicate tectonic plate motion, regional deformation, and local uplift or subsidence.
- The current uncertainty of the delay observable is ~10-15 ps and the precision is 4 ps.

Role of VLBI in Geodesy



Role of VLBI in Science



Next Generation VLBI: VGOS
VLBI Global Observing System

Features:

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

Implies:

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

New VGOS radio telescopes

Ny-Alesund (NO)

Courtesy L. Langkaas

Zelenchukskaya (RU)

Courtesy
A. Ipatov

Ishioka (JP) Courtesy Y. Fukuzaki

Badary (RU)

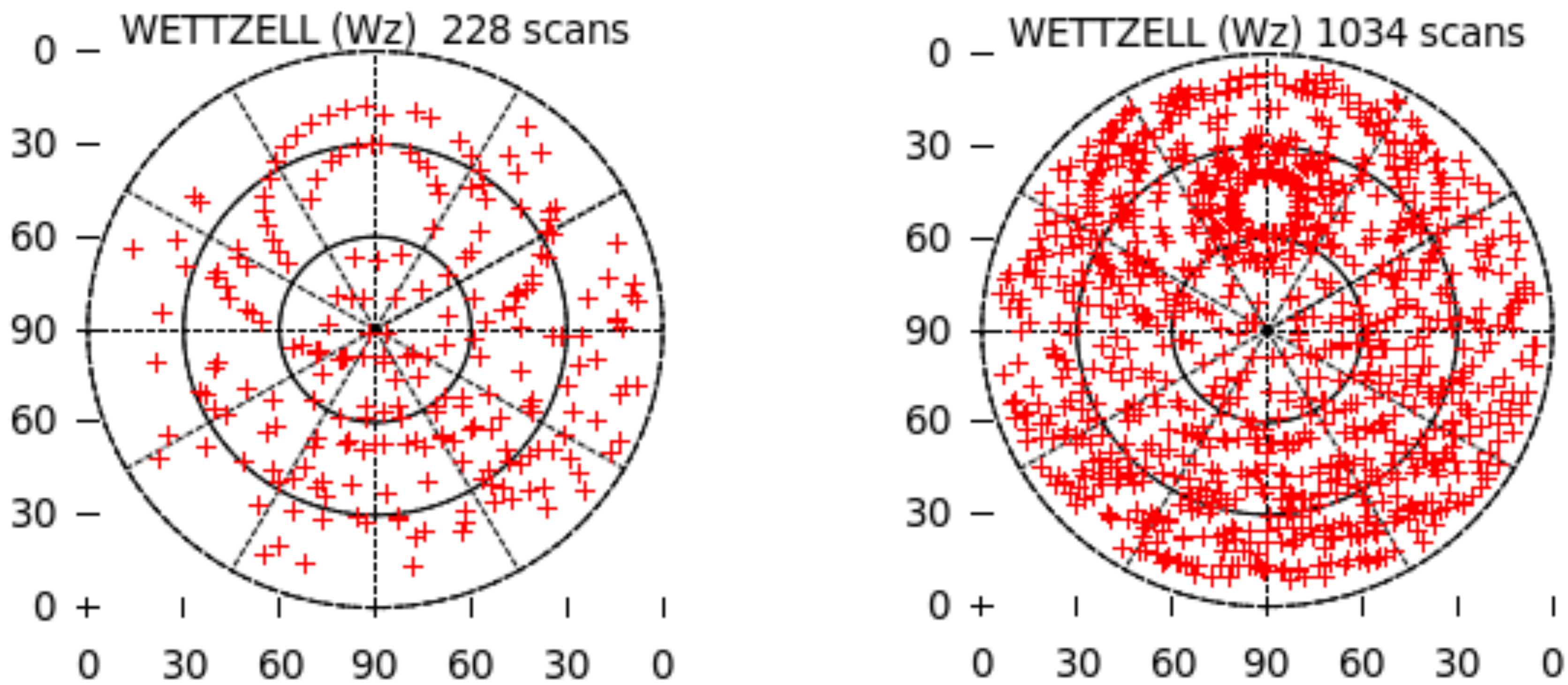
Courtesy
A. Ipatov

GGAO (US)

Courtesy A. Niell

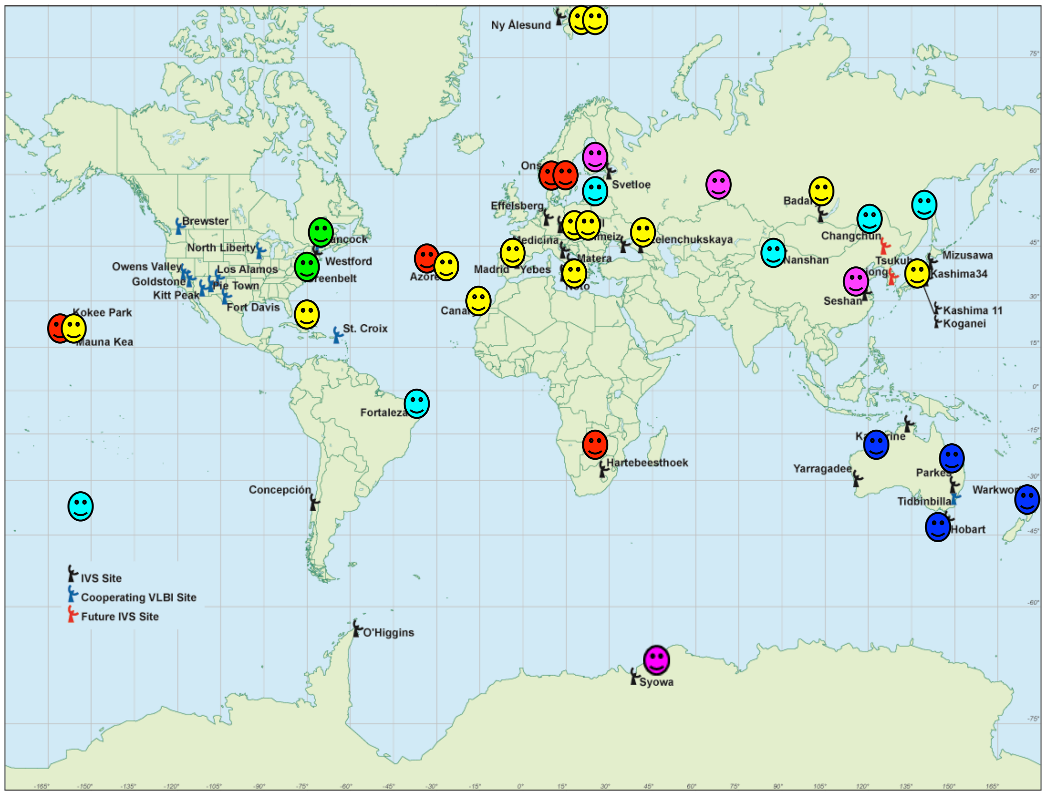
Next Generation VLBI: VGOS
VLBI Global Observing System

- dense sampling of local sky for optimal estimation of atmosphere parameters



VGOS World

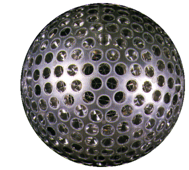
New VGOS radio telescopes for the IVS



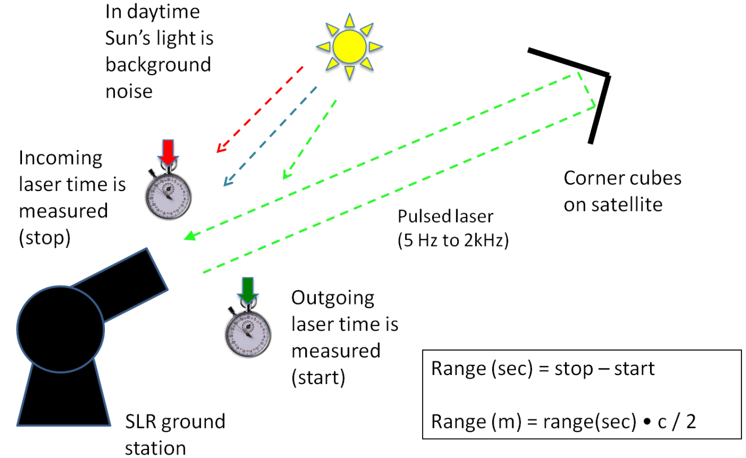
- operational
- under construction
- funded
- proposal submitted
- planning phase
- planning phase upgrade

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

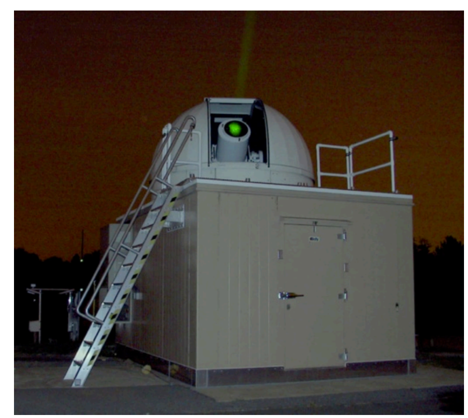
Satellite Laser Ranging



- Satellite Laser Ranging directly measures the range between the ground station and the satellite using very short laser pulses, corrected for refraction, satellite center of mass, and the internal delay of the ranging machine.
- The state of the art is sub millimeter precision average measurements (called normal points) with centimeter level accuracies;
- Can track satellites from 300 km to 22,000+ km in day & night;
- Each station tracks independently but a network of stations an be scheduled together (set priorities) to optimize tracking;
- Requires only a passive retroreflector on the satellite;
- Near real-time data availability through the CDDIS and EDC.

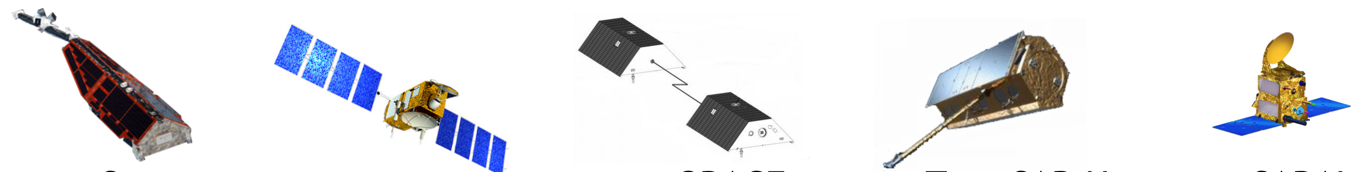


- Unambiguous centimeter accuracy orbits
- Long-term stable time series



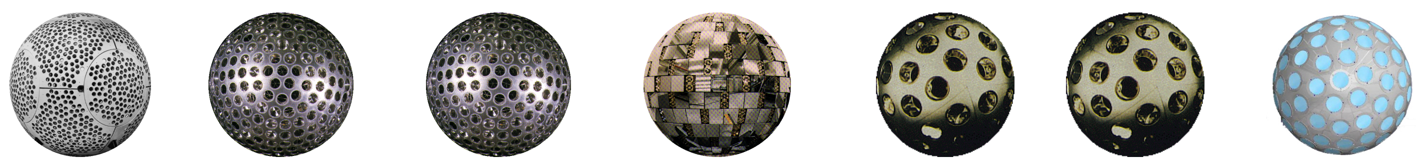
Sample of SLR Satellite Constellation

LEO Satellites



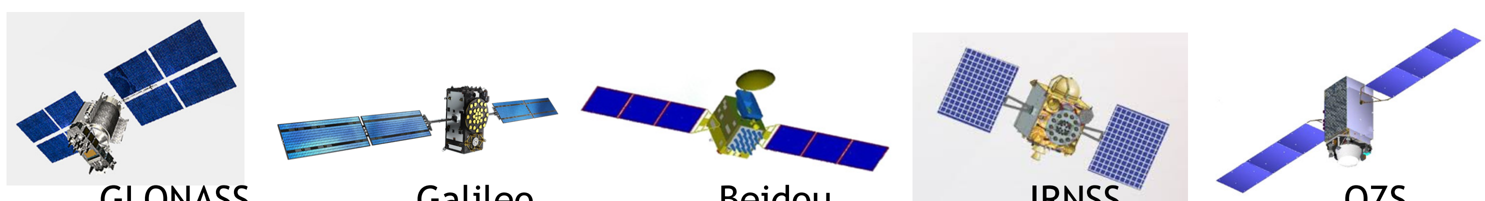
Satellite	Swarm	Jason-2	GRACE	TerraSAR-X	SARAL
Inclination	92°	66°	89°	66°	98.55°
Perigee ht. (km)	720	1,336	450	1,350	814

Geodetic Satellites



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

GNSS/GEO Satellites



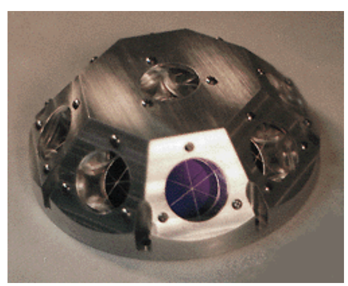
Satellite	GLONASS	Galileo	Beidou	IRNSS	QZS
Inclination	65°	56°	55.5°	29°	45°
Perigee ht. (km)	19,140	23,220	42.161	42,164	32,000

Retroreflector Arrays

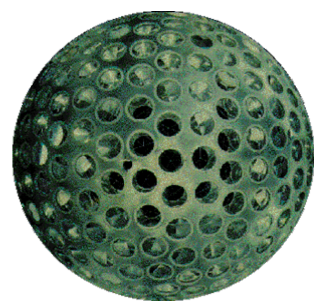
- Common use of the "pyramid OR GFZ arrays" for LEO satellites – nearly COTS; particular design depends upon the satellites altitude and tracking requirement;
- Issue of ILRS Standard Specification for GNSS satellites of effective area of 100 million square meters;
- Adaptation of the GNSS standard to Synchronous satellites;
  - IRNSS constellation, Beidou (Compass), QZS

Champ

Jason



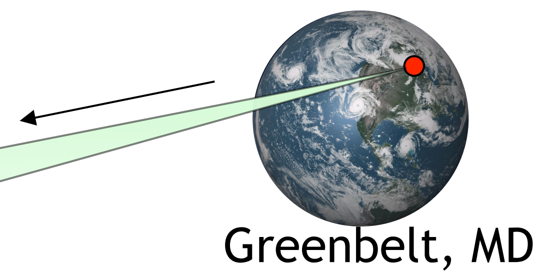
LAGEOS

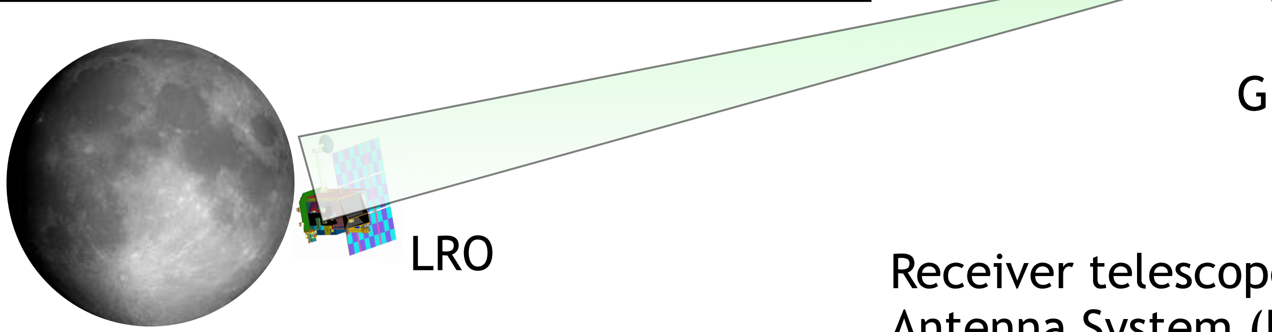


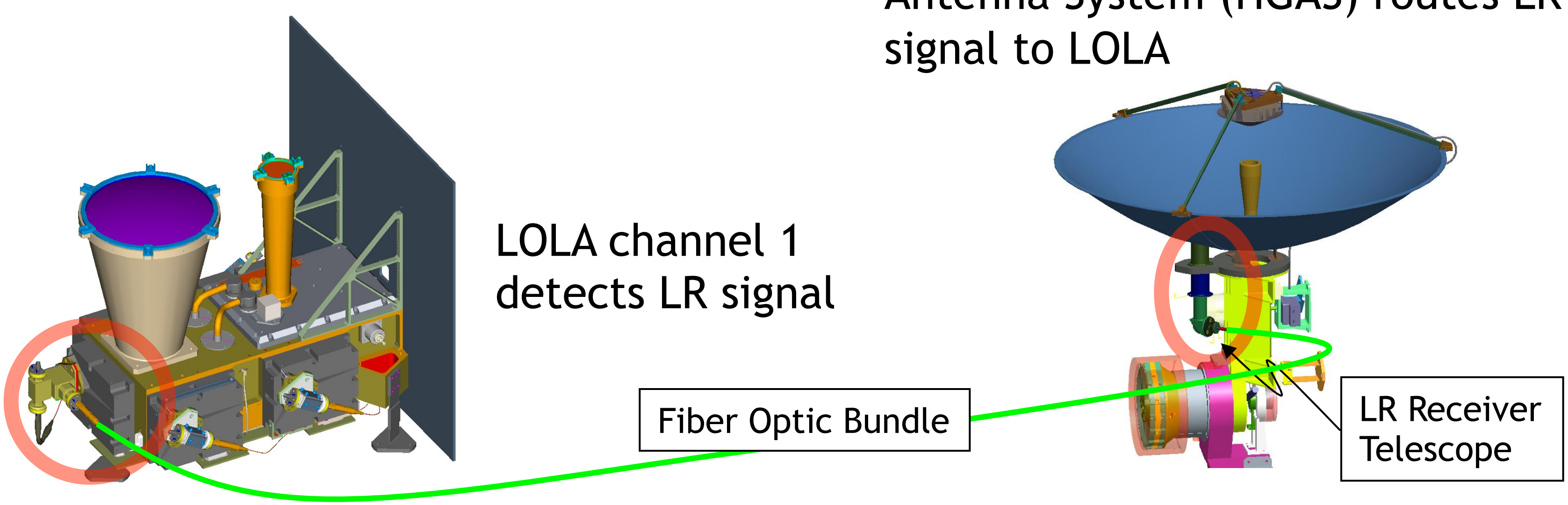
Beidou

LRO Laser Ranging

- Transmit 532nm laser pulses at 28 Hz to LRO
- Time stamp departure and arrival times
- Five year campaign





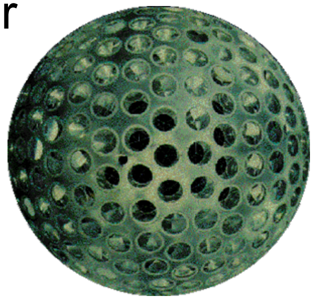


SLR Science and Applications

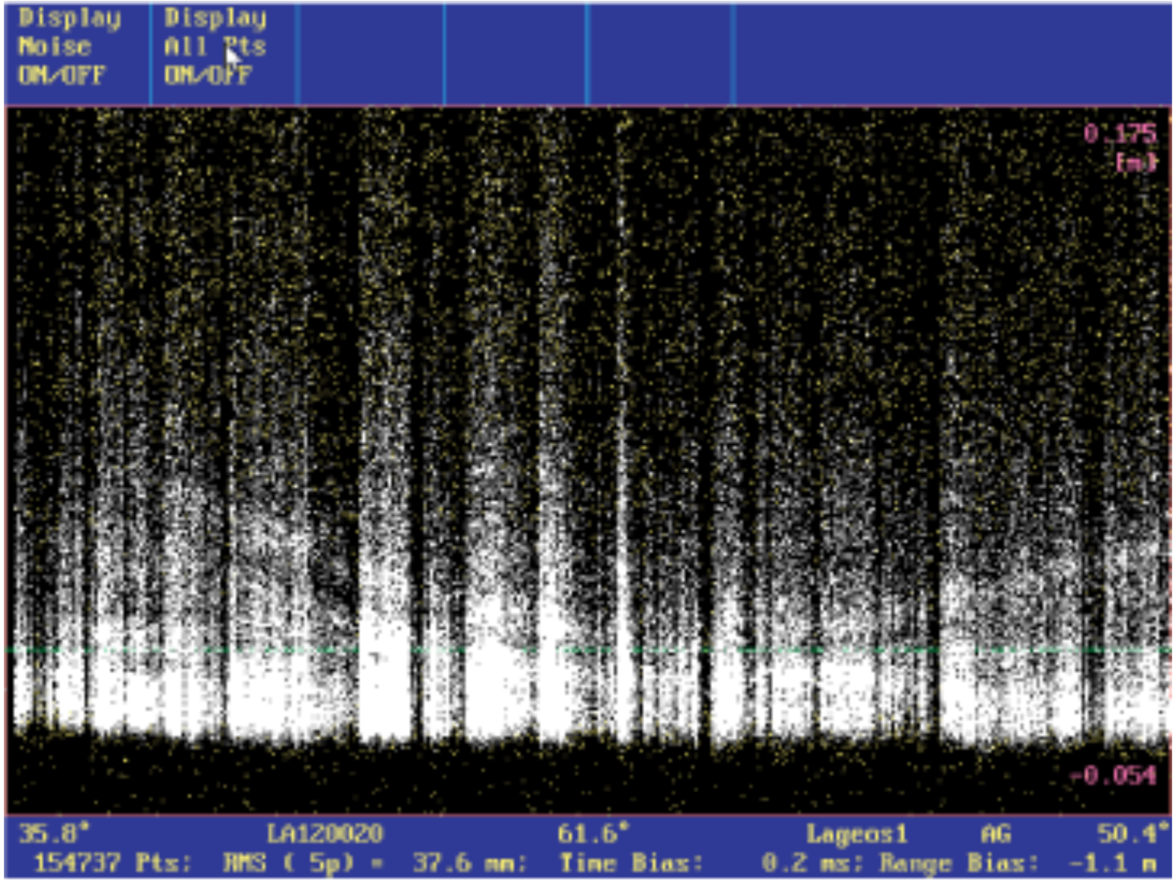
- Measurements
  - Precision Orbit Determination (POD)
  - Time History of Station Positions and Motions
- Products
  - **Terrestrial Reference Frame (Center of Mass and Scale)**
  - Plate Tectonics and Crustal Deformation
  - Static and Time-varying Gravity Field
  - Earth Orientation and Rotation (Polar Motion, length of day)
  - Orbits and Calibration of Altimetry Missions (Oceans, Ice)
  - Total Earth Mass Distribution
  - Space Science –Satellite Dynamics, etc.
  - Relativity Measurements and Lunar Science
- More than ~150 Space Missions Supported since 1970
- Four Missions Rescued in the Last Decade

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

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

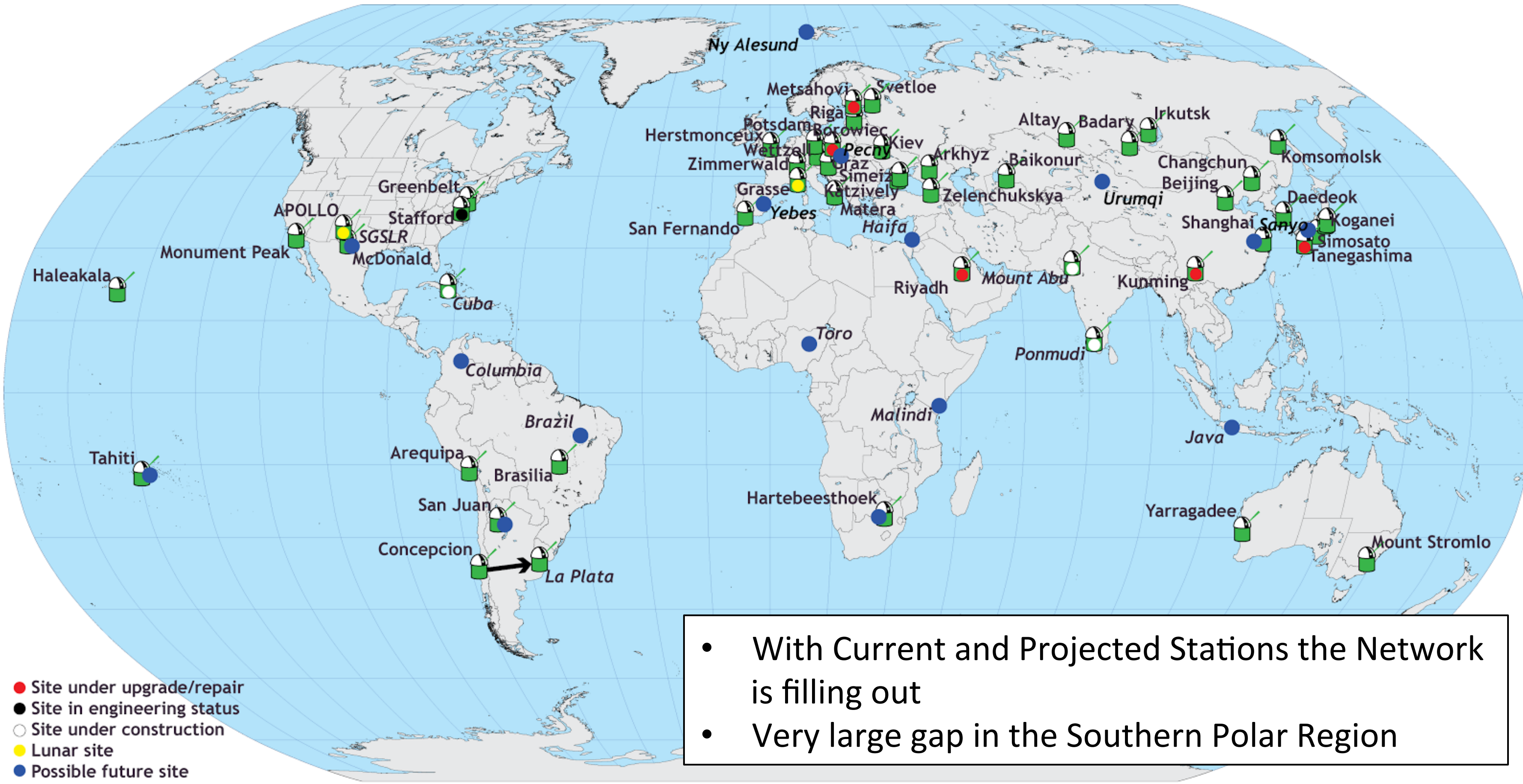


LAGEOS Pass from Graz Station



High repetition rate, short pulse lasers allow us to see retroreflector array details

Projected SLR Network



- With Current and Projected Stations the Network is filling out
- Very large gap in the Southern Polar Region

New Generation GNSS Receiver

- Multi-constellation receiver (GPS, Galileo, GLONAS, COMPASS, etc)
- Installed with deep-drilled brace monuments;
- Registered for the IGS

Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)

- Global network of ~57 stations.
- DORIS receivers are used on altimeter (TOPEX, Jason1, Jason2, ENVISAT, Cryosat-2) and remote sensing (SPOT) satellites; Future Missions: Jason-3, SWOT & SENTINEL-3.

Two Recent Initiatives

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

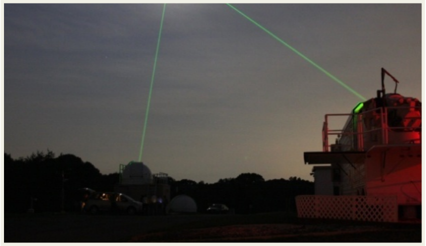
The development of the foreign segment of the Russian SLR network

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

- staions is ready **- next generation stations**

NASA's Space Geodesy Project

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



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

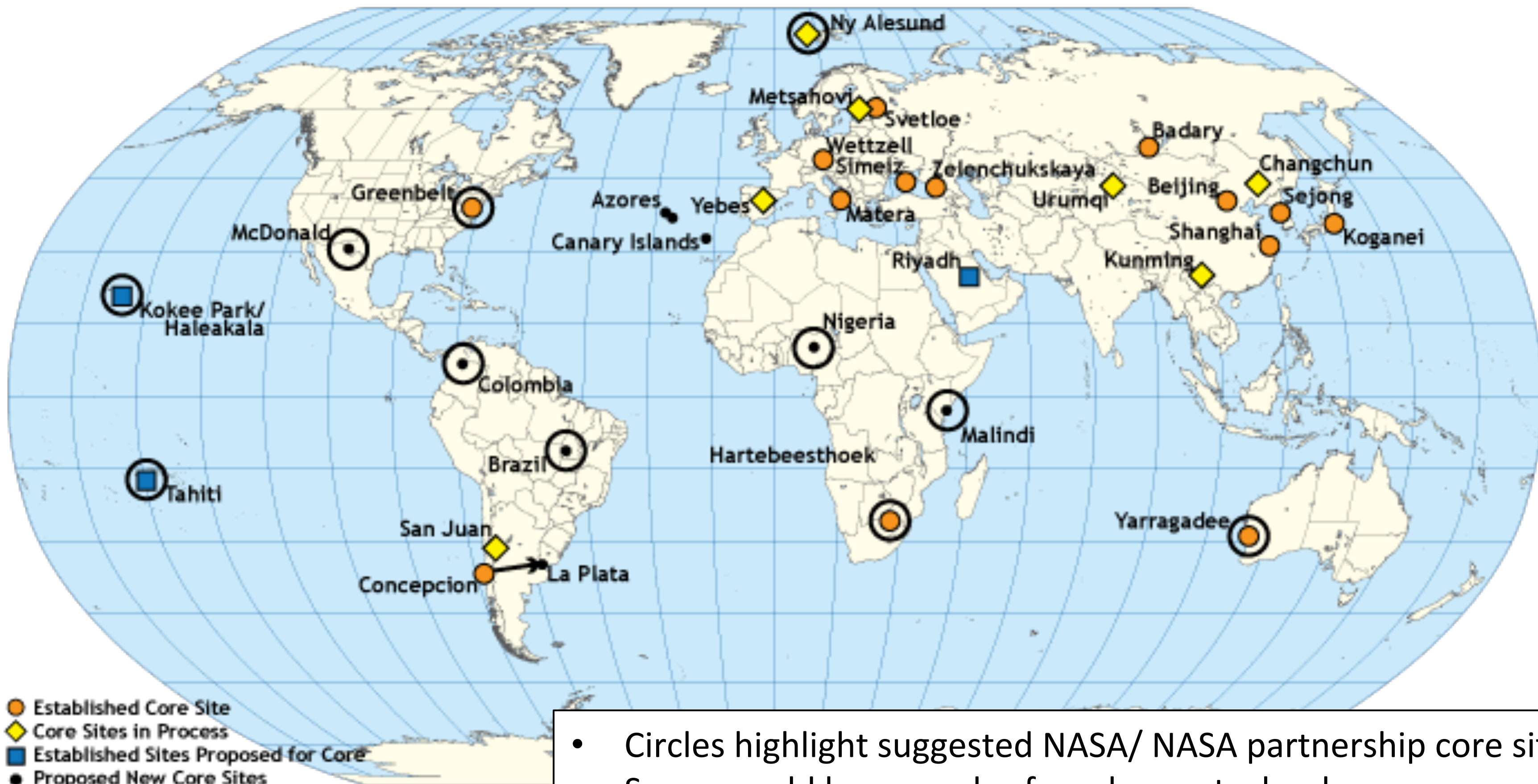
Next Generation Satellite Laser Ranging (NGSLR)

Very Long Baseline Interferometry (VLBI)

Global Navigation Satellite System (GNSS)

Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)

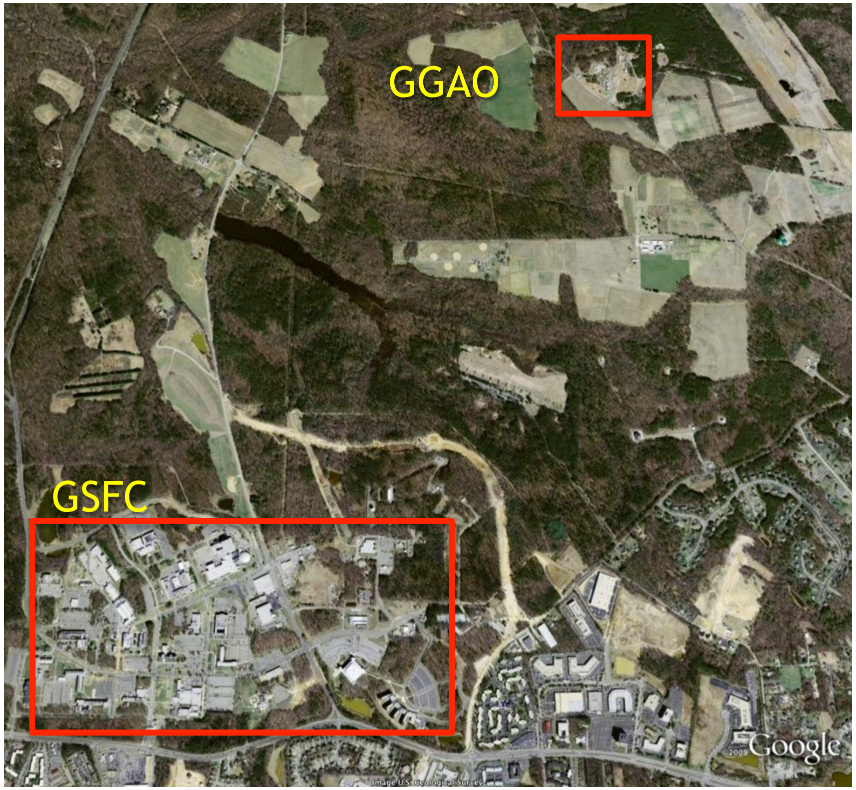
Current and Projected Core Sites

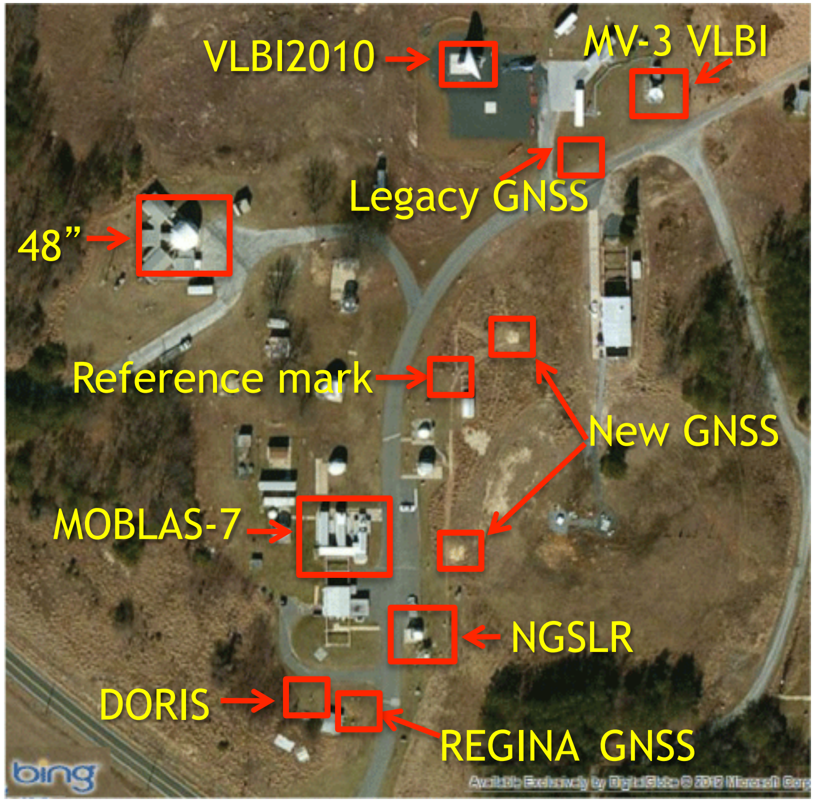


- Circles highlight suggested NASA/ NASA partnership core sites
- Some would be upgrades from legacy technology
- Some would be new sites to fill geographic gaps

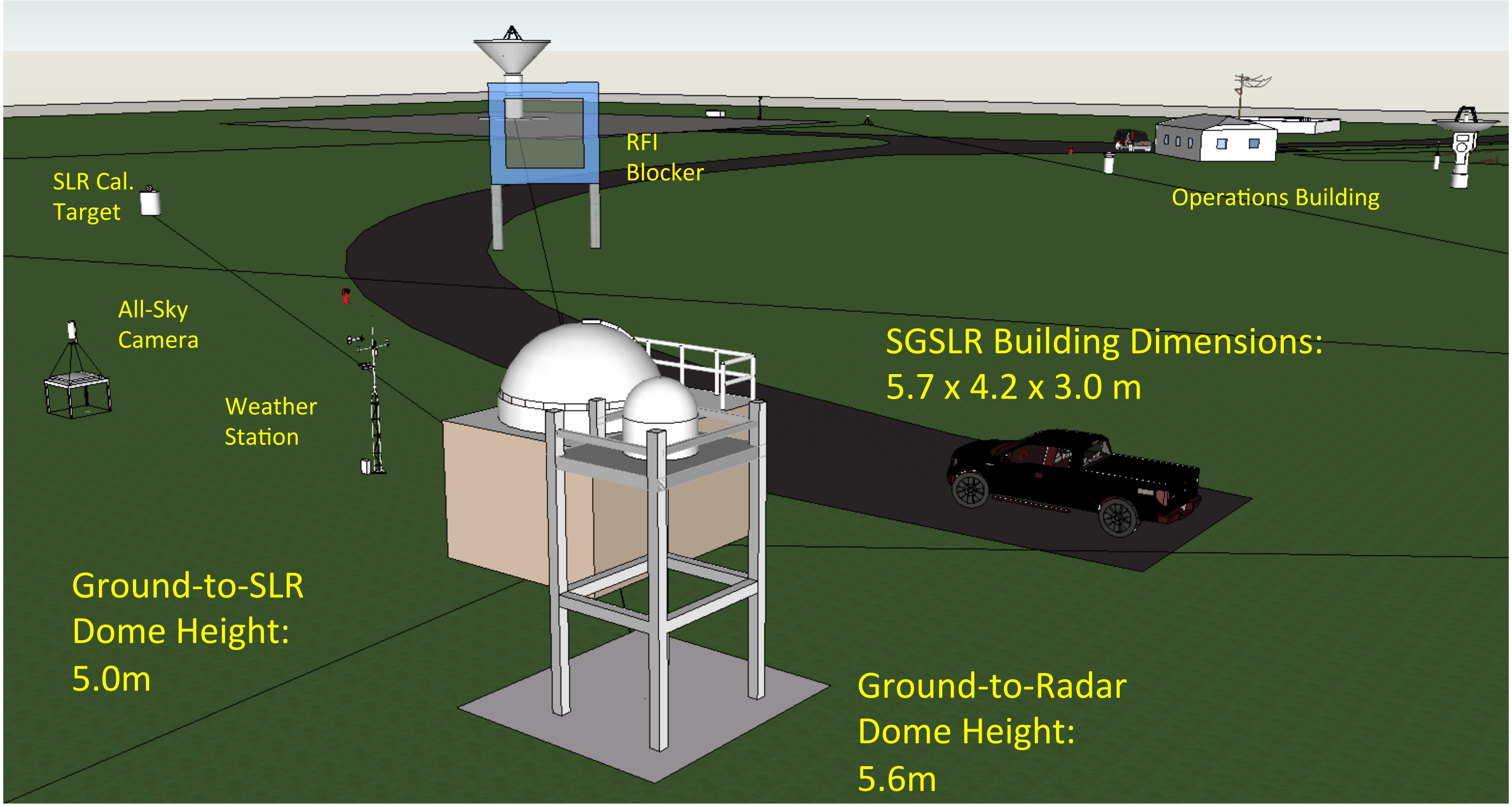
Prototype Geodetic Station at GGAO

- Goddard Geophysical and Astronomical Observatory (GGAO) 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.





View from Space Geodesy SLR (SGSLR)



Approximate building dimensions shown

Sejong Site (South Korea)

- VLBI, GNSS and Gravimeter : NGII (National Geographic Information Institute)
  - In testing
- SLR : KASI (Korea Astronomy & Space Science Institute)
  - Operational at KASI HQ in Daejeon,
  - To be relocated to Sejong site in late 2014

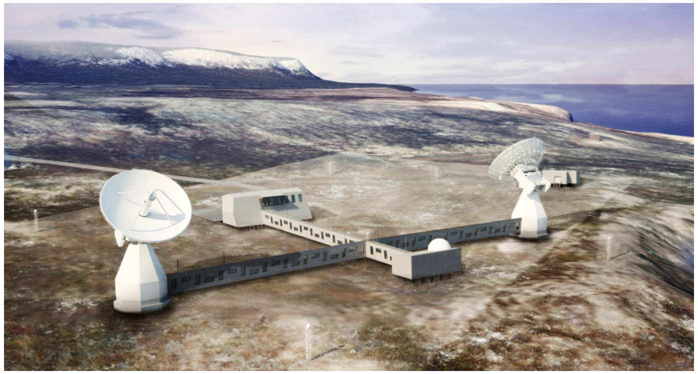
- 40cm Rx and 10cm Tx telescope
- 2kHz repetition rate
- 2.5mJ/pulse and 50ps pulse width
- Aircraft detection using a radar

- 22m Cassegrain antenna
- Rx frequency : 2, 8, 22 and 43GHz
- Aperture efficiency : ~60%
- GNSS receiver and Gravimeter

Ny Alesund Core Site

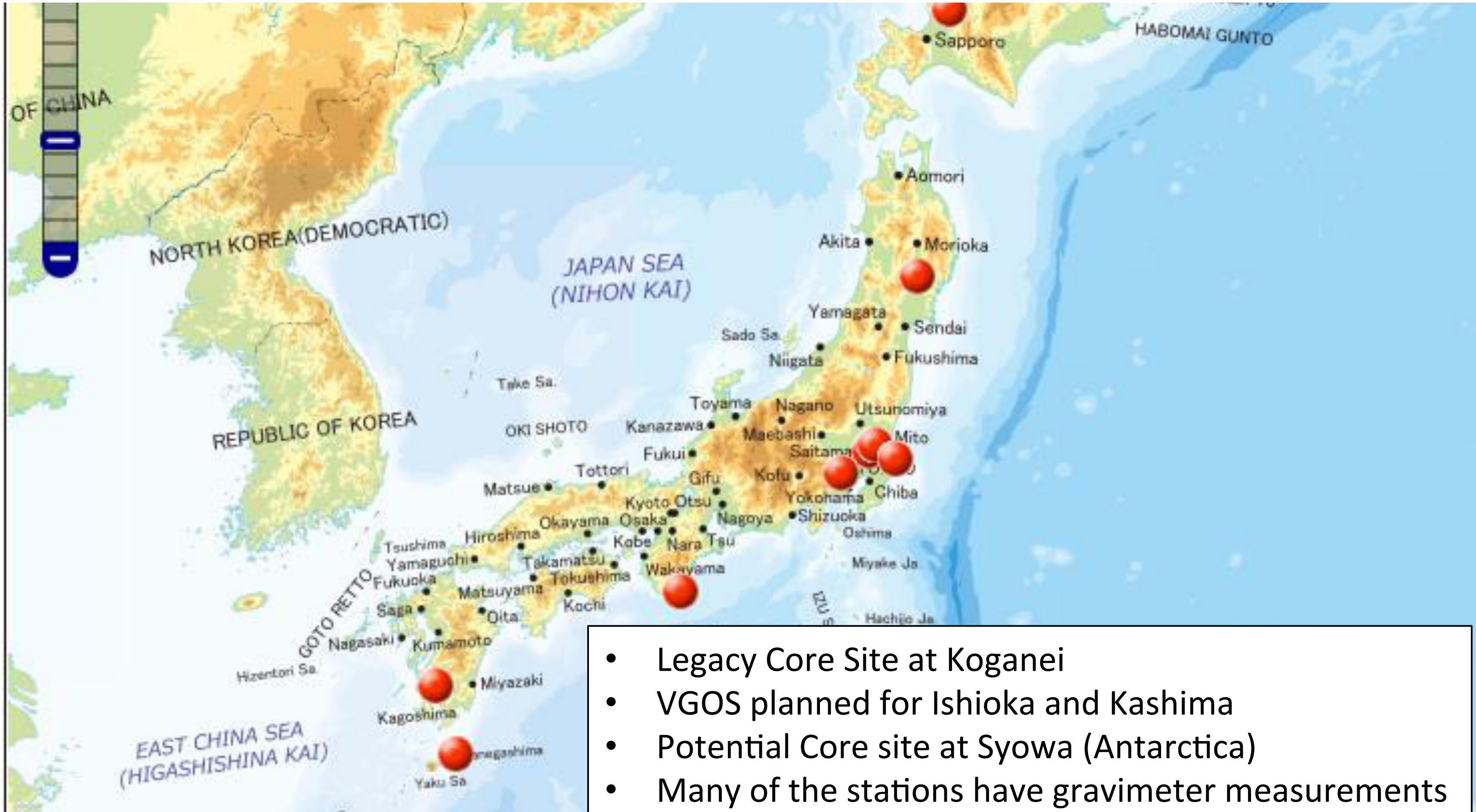
(From Ina Elsrud, PM)

- Planned to be a core station including VLBI, SLR, GNSS, DORIS, absolute gravity- and super conducting gravity meter
- Extreme interest because of the very high latitude (~80 Deg)
- Site infrastructure work is now underway
- 2018 - two VGOS telescopes, GNSS, DORIS and gravimeters
- 2020 – SLR
- 2021 – Closeout of the legacy VLBI after 3 year parallel run



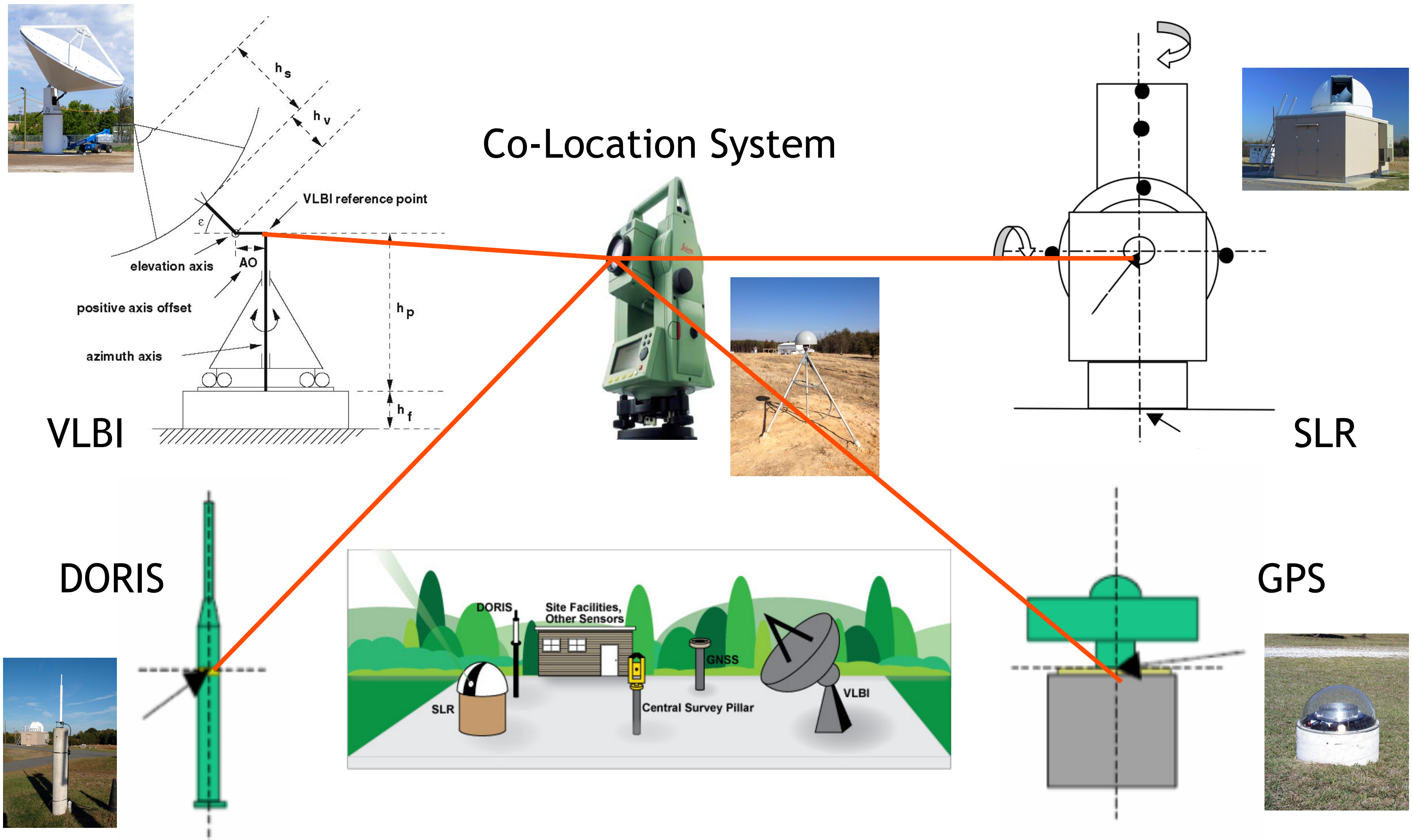
Map of Sites in Japan

Response to GGOS CfP



- Legacy Core Site at Koganei
- VGOS planned for Ishioka and Kashima
- Potential Core site at Syowa (Antarctica)
- Many of the stations have gravimeter measurements
- Joined the GGOS Network through the CfP

Local Ground Survey is an Essential Part of Co-location



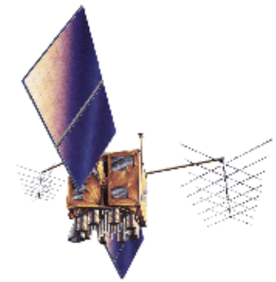
Co-location in Space

Compass

GNSS/SLR

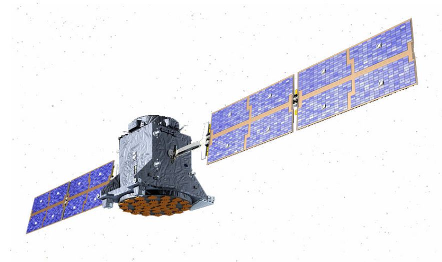
GLONASS

GNSS/SLR



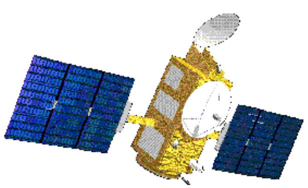
GPS

GNSS/SLR



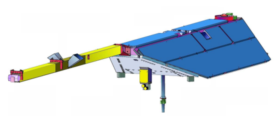
GIOVE/Galileo

GNSS/SLR



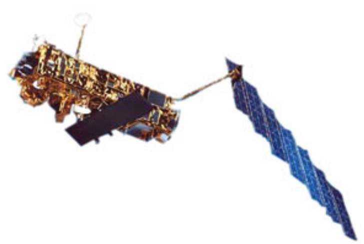
Jason

DORIS/GNSS/SLR



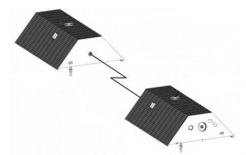
CHAMP

GNSS/SLR



Envisat

DORIS/SLR



GRACE

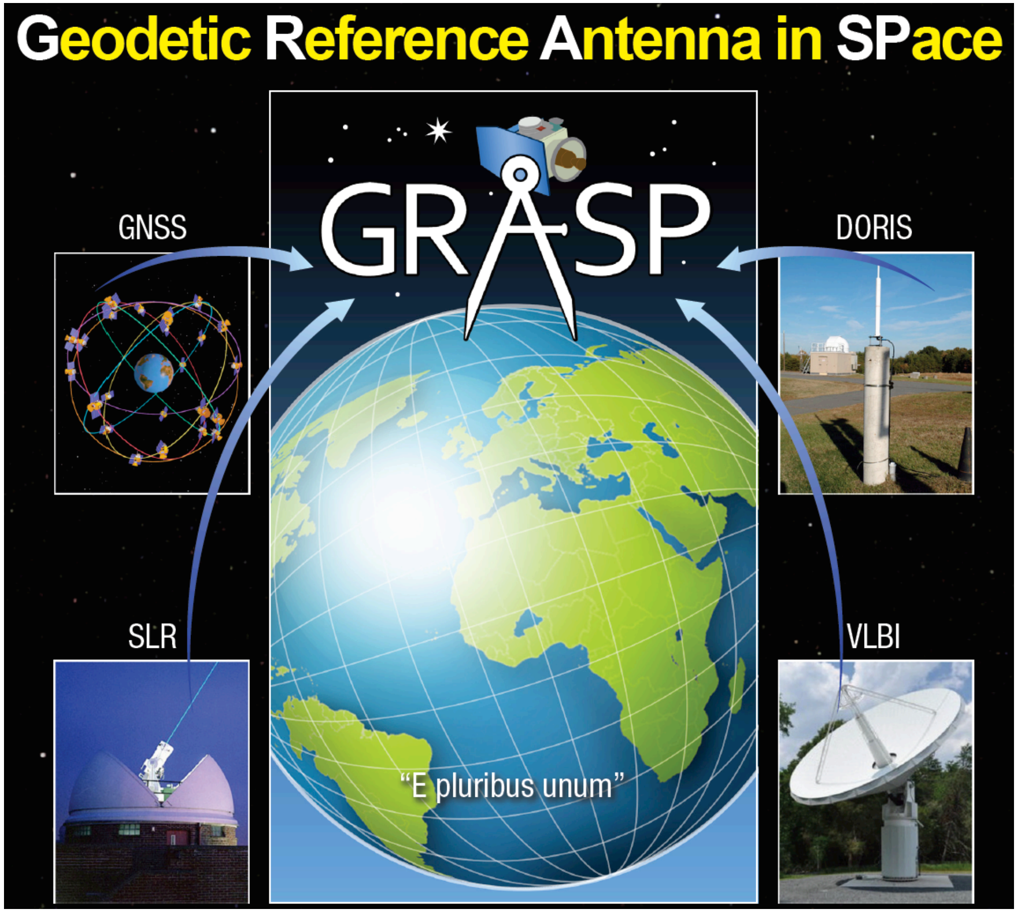
GNSS/SLR

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

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

[1] Jet Propulsion Laboratory

[2] University of Colorado, Boulder



Reality

Recognizing that:

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

As a result:

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

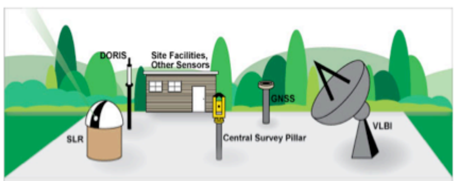
But – many groups are taking the initiative to join, build and upgrade

GGOS Site Requirements Document

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

Global Geodetic Observing System (GGOS)

Site Requirements
for
GGOS Core Sites



August 1, 2011

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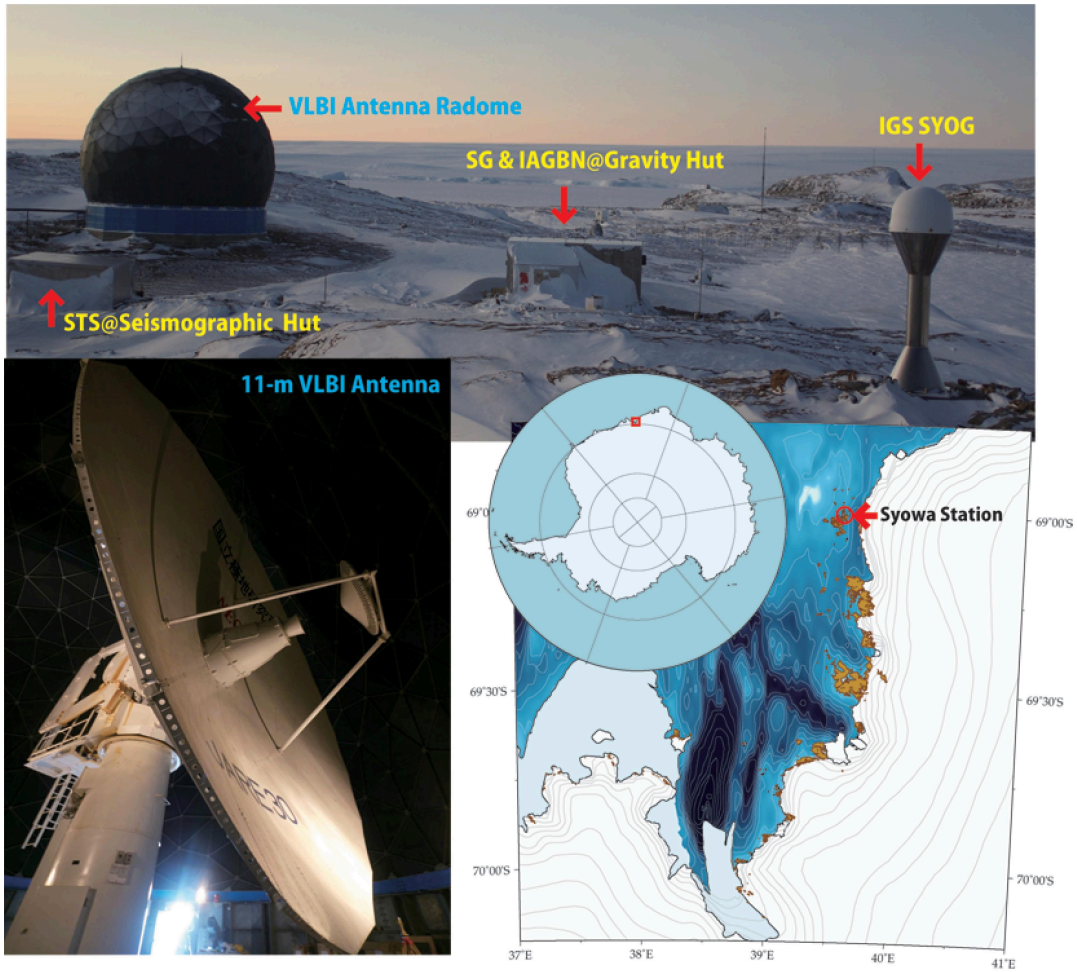
- Introduction and Justification
  - What is a Fundamental Station?
  - Why do we need the Reference Frame?
  - Why do we need a global network?
  - What is the current situation?
  - What do we need?
- Site Conditions
  - Global consideration for the location
  - Geology
  - Site area
  - Weather and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

- The Question of Syowa

Syowa: Location and Future Plans



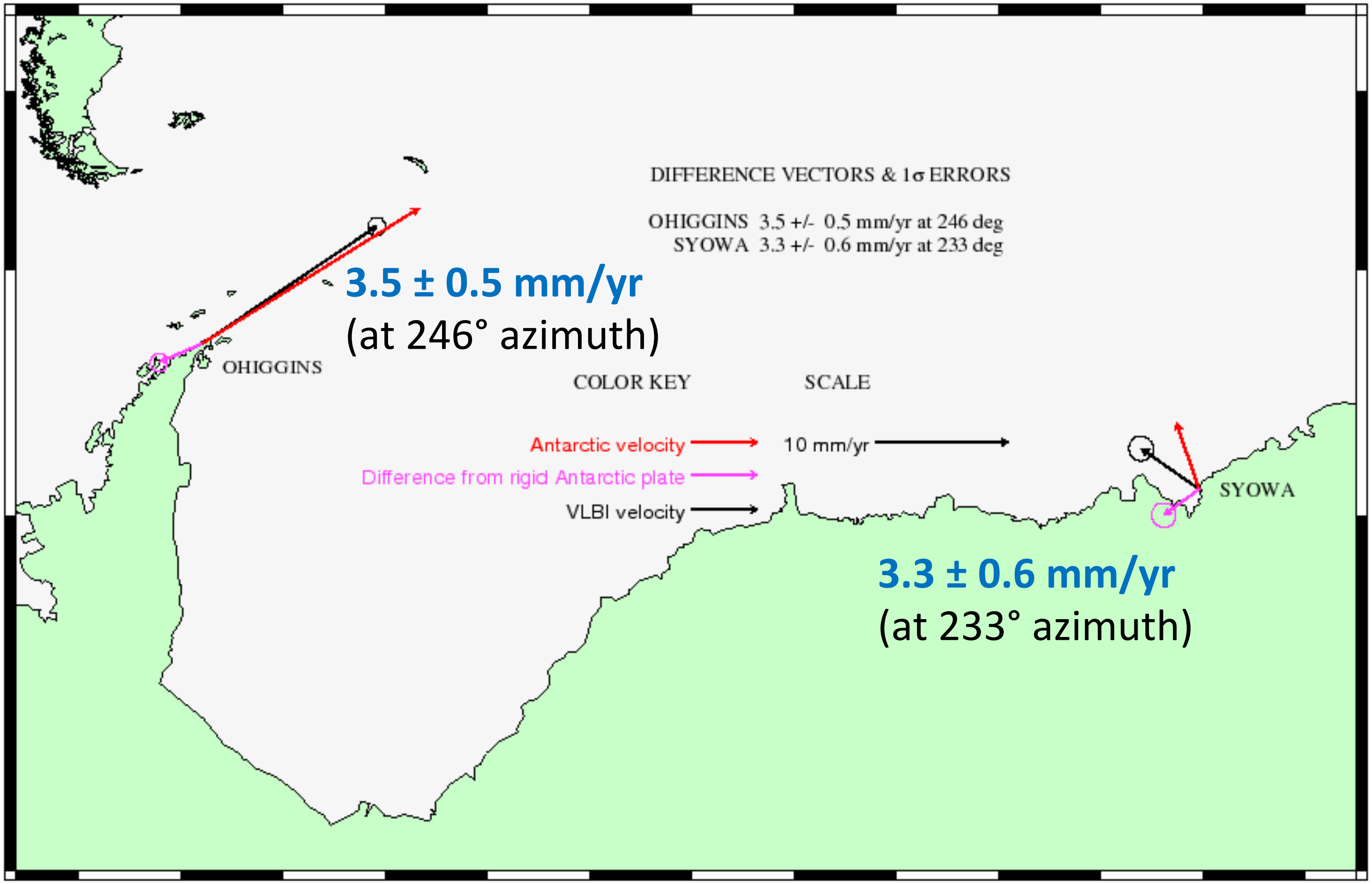
- Legacy 11-m VLBI antenna to be dismantled in period December 2015 through February 2016
- Proposal submitted for building a VGOS-type antenna after 2017

Courtesy of Aoyama et al., IVS 2013 Annual Report

Possible future VGOS subnet in the South

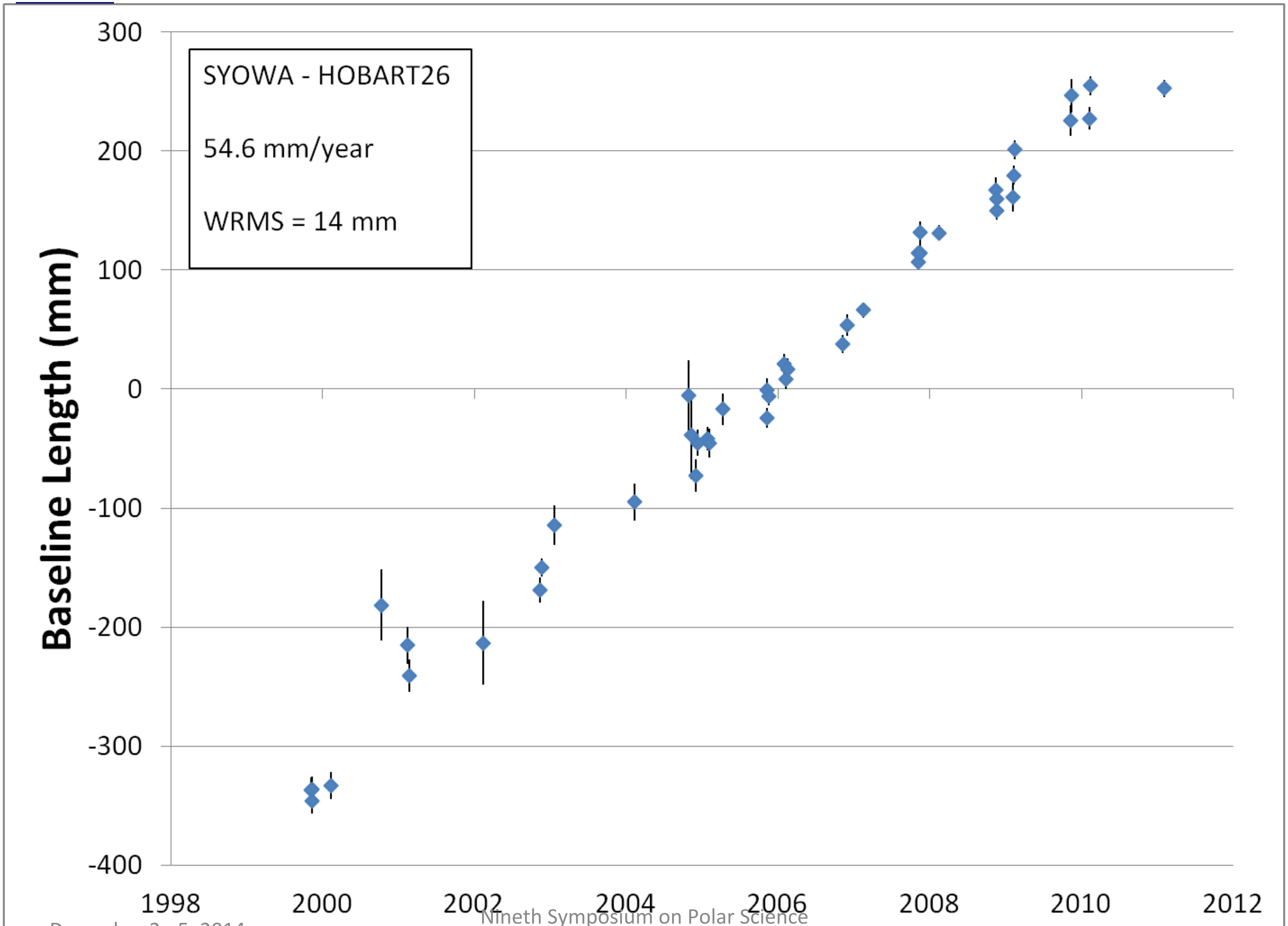
Upgrading of Syowa VLBI to VGOS is very important

Site Motion: Syowa and O'Higgins

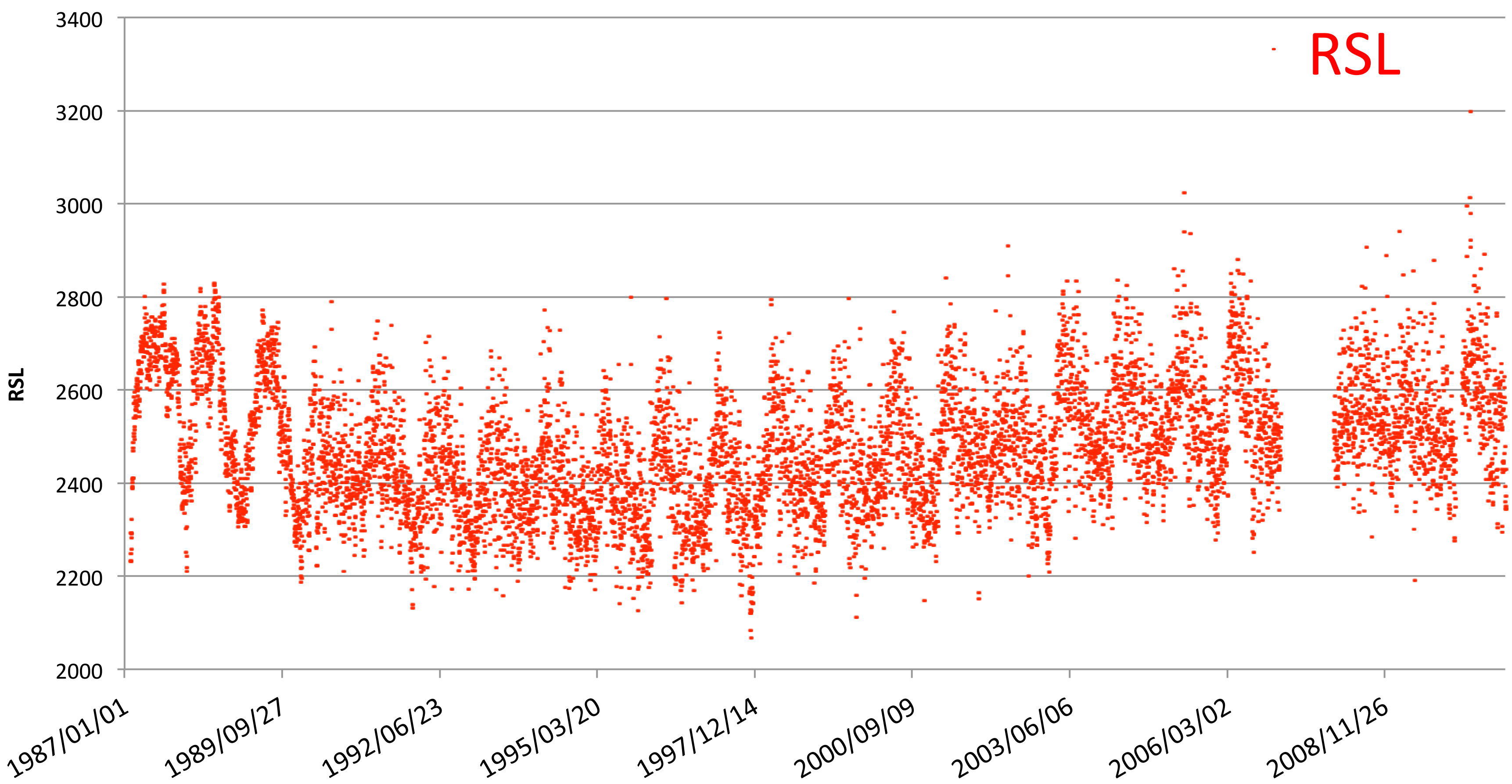


Goddard Space Flight Center VLBI solution KB 2011an version 01
NUVEL1A-NNR reference frame. 1σ (realistic) error ellipses.

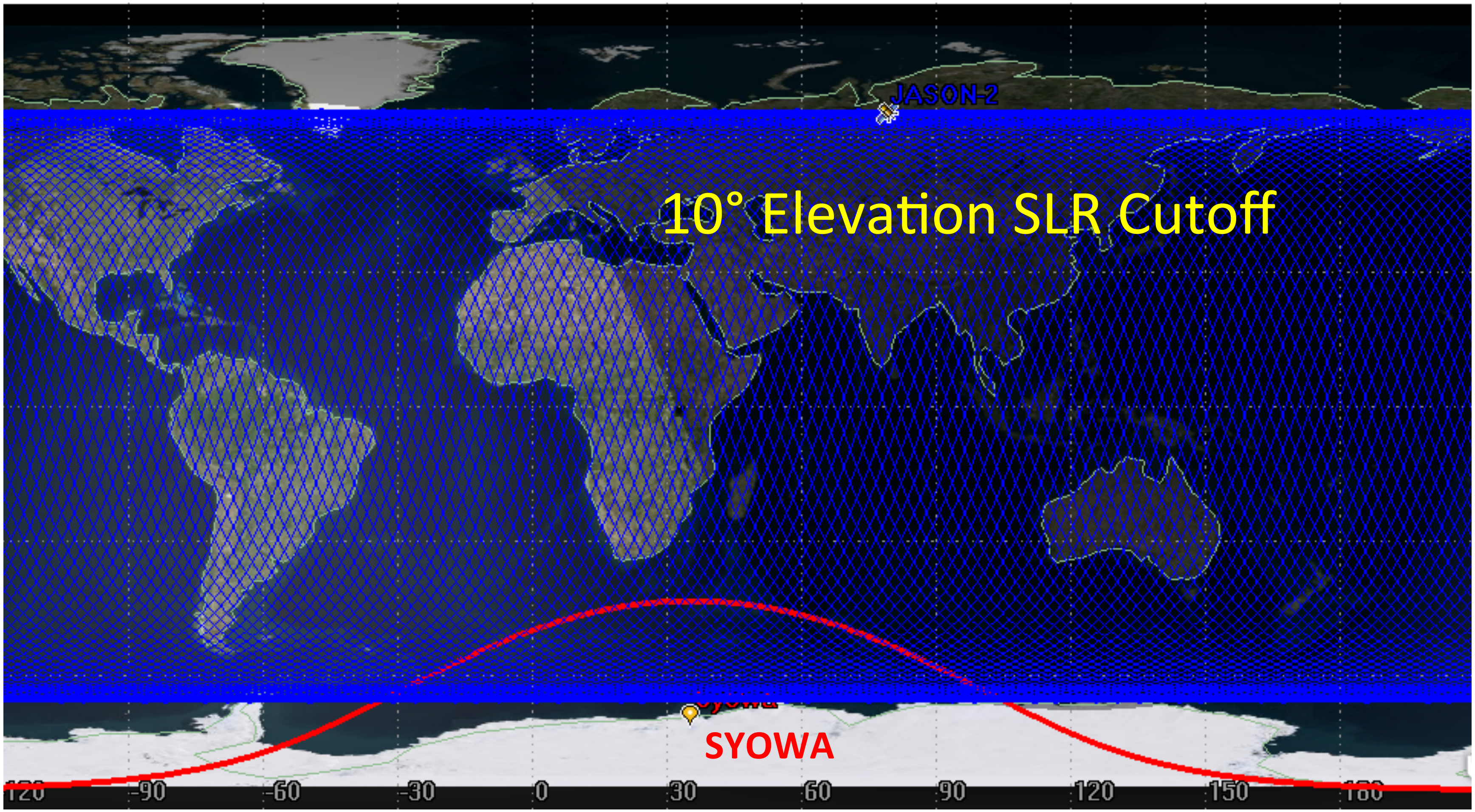
solution year: 2011


SYOWA - HOBART26
54.6 mm/year
WRMS = 14 mm
Baseline Length (mm)
300
200
100
0
-100
-200
-300
-400
1998
2000
2002
2004
2006
2008
2010
2012

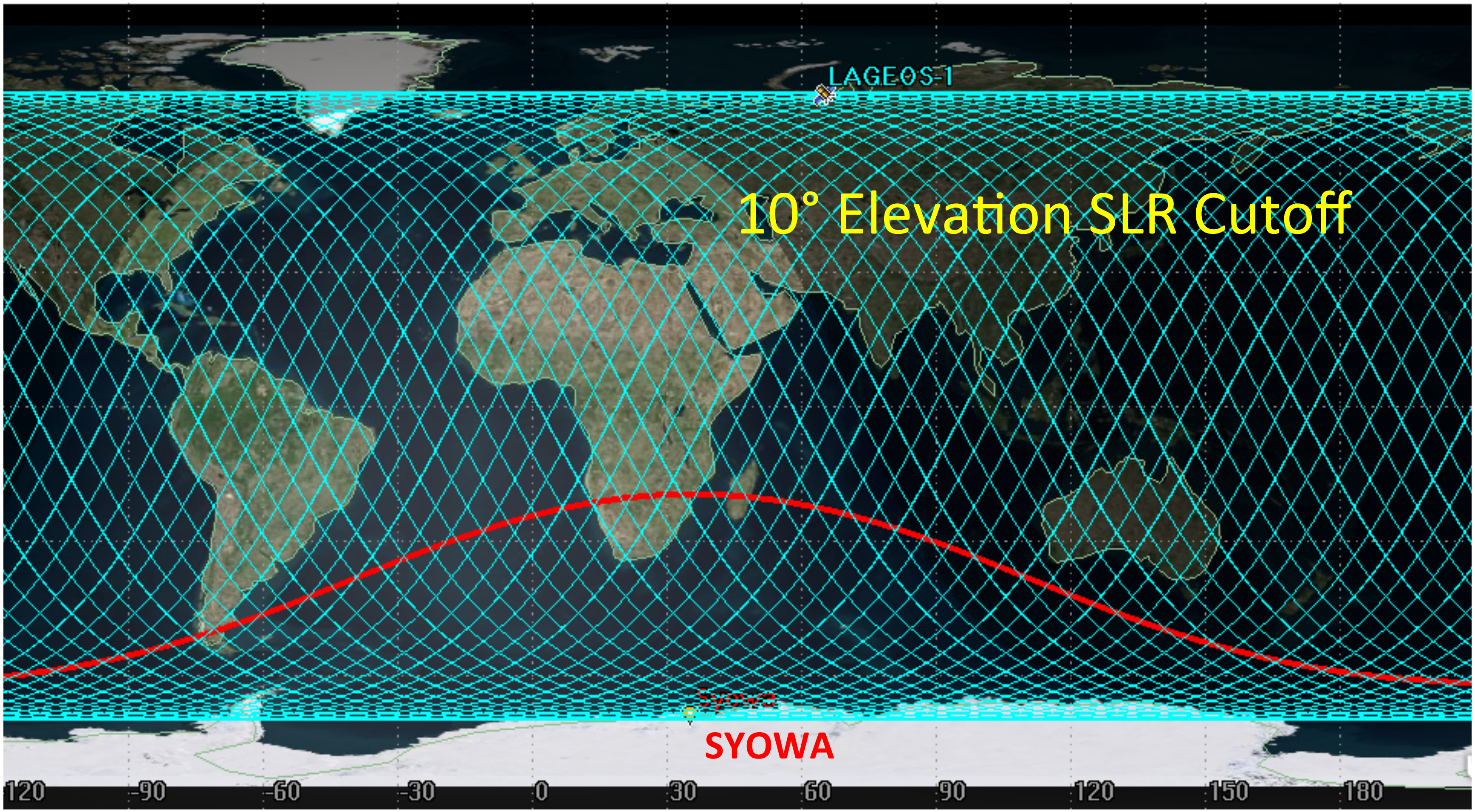
Relative Sea Level Time Series



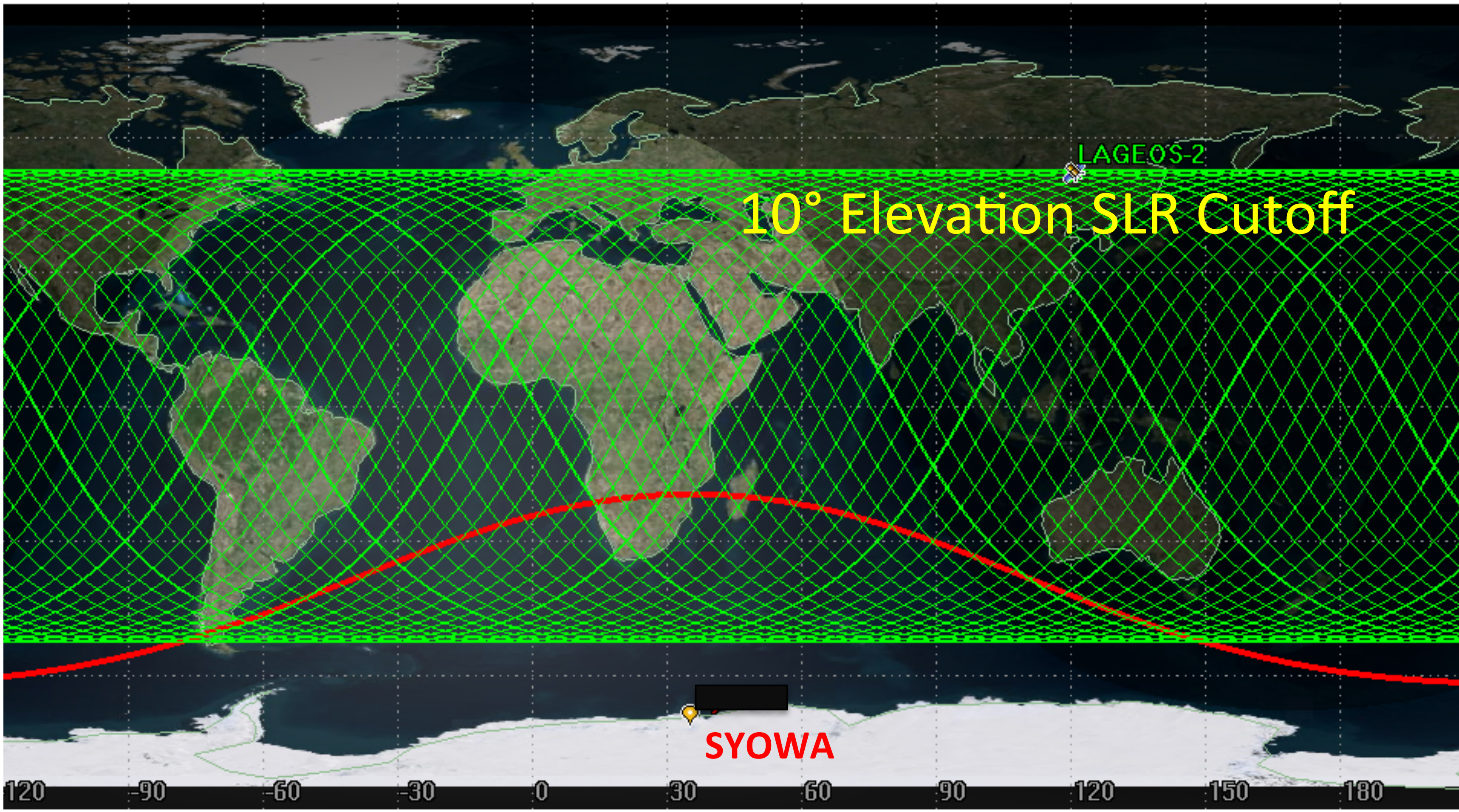
JASON-2 (Mean T/P) Groundtrack



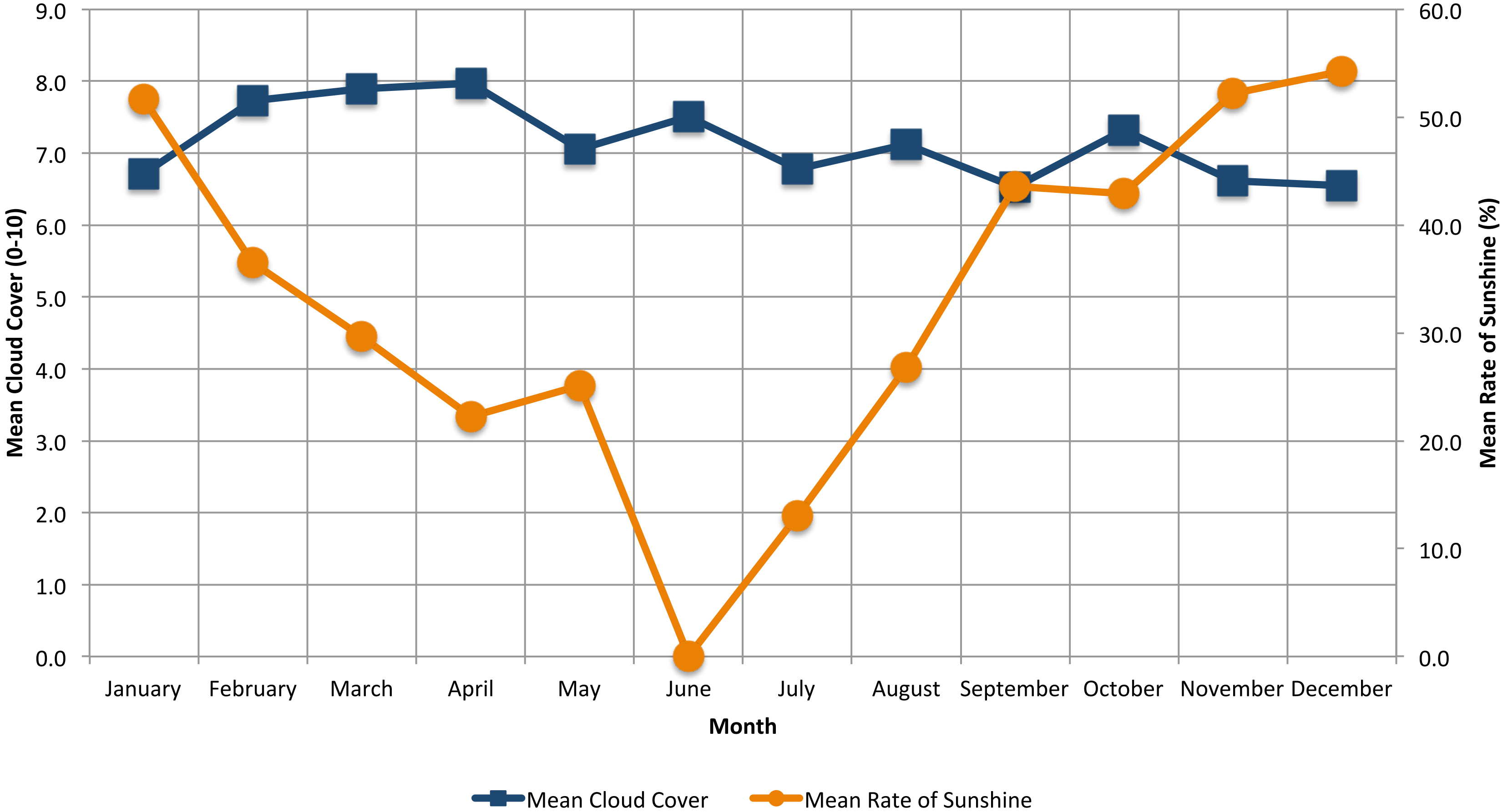
LAGEOS-1 Groundtrack



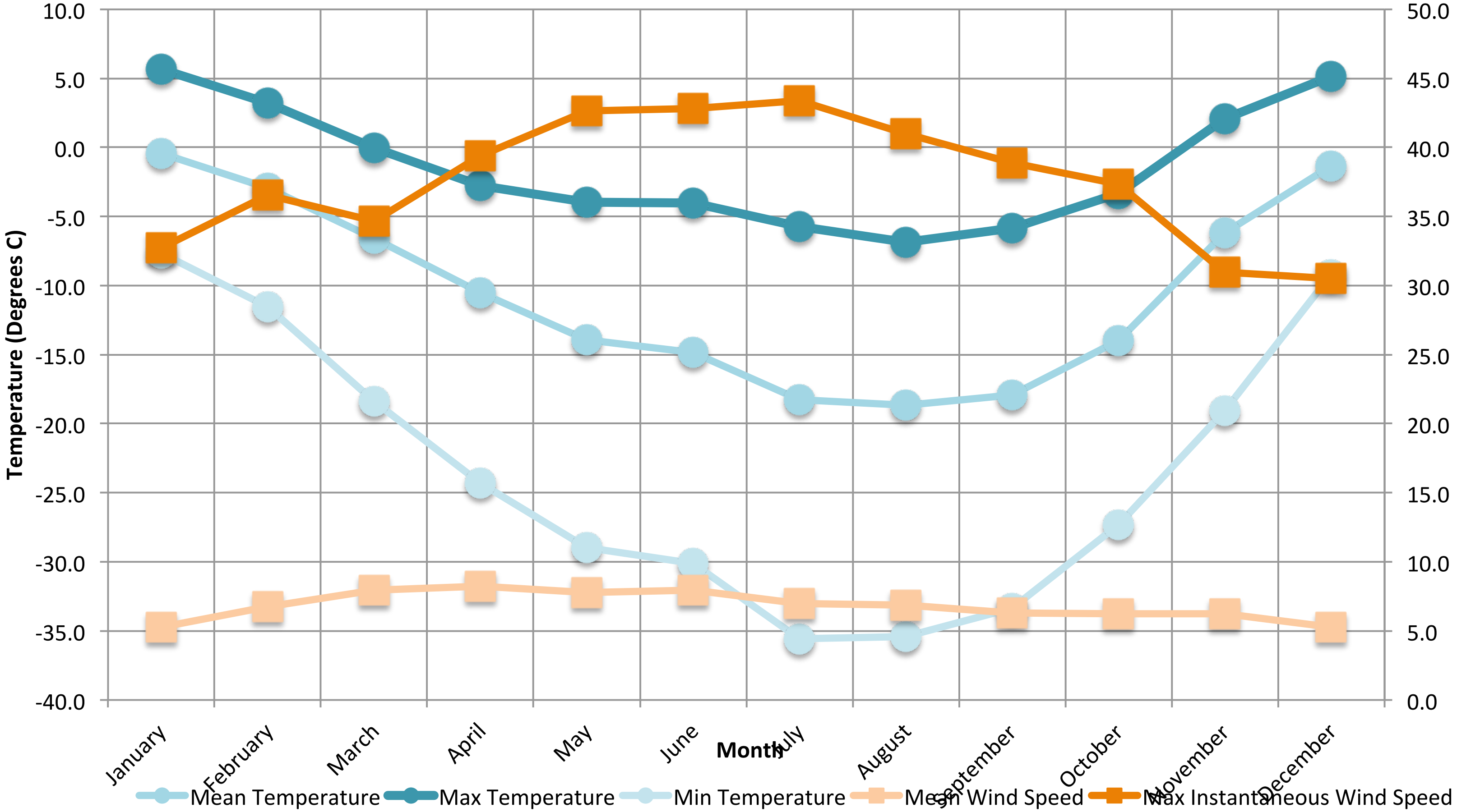
LAGEOS-2 Groundtrack



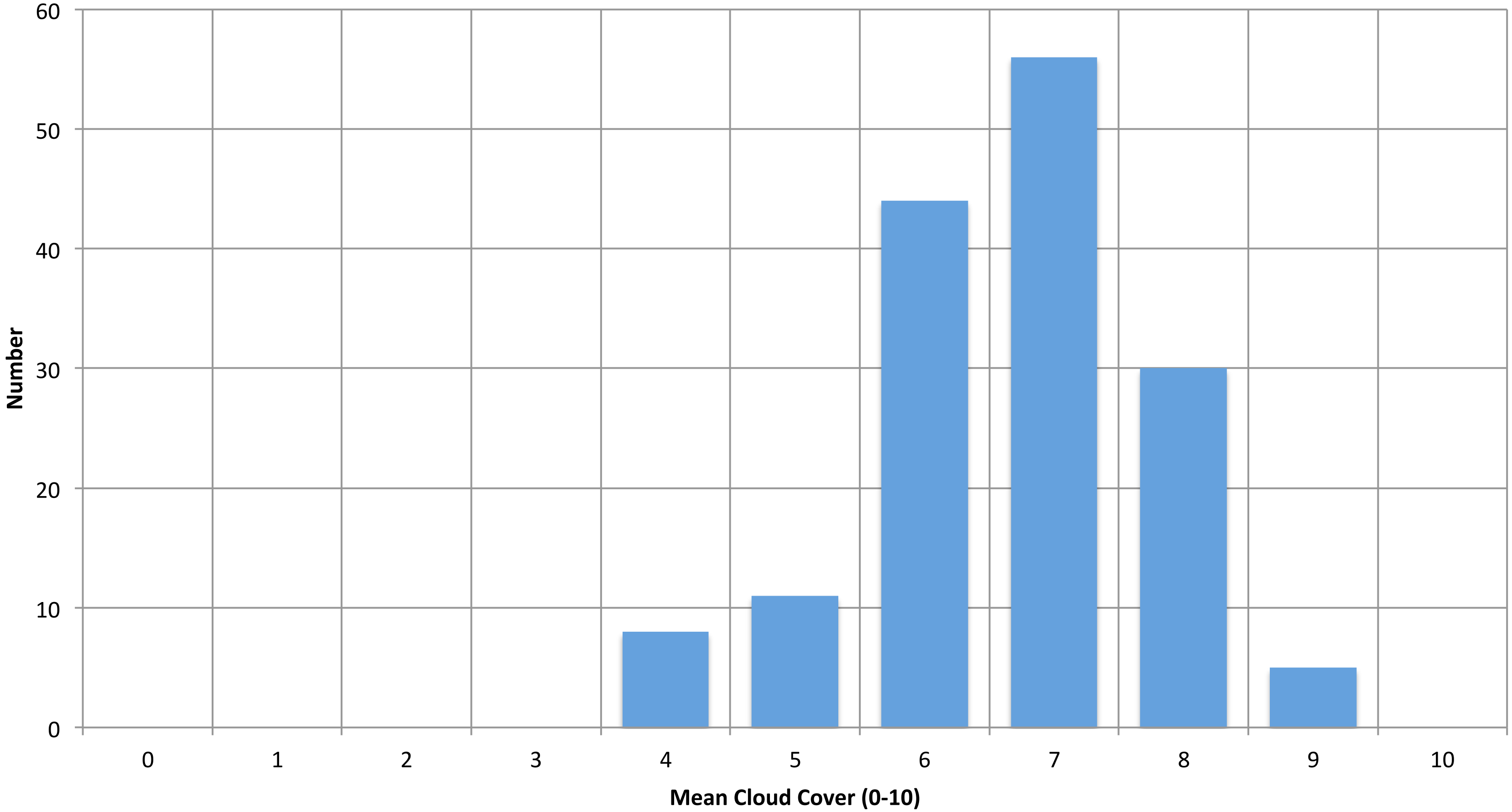
Mean Cloud Cover and Sunshine Syowa



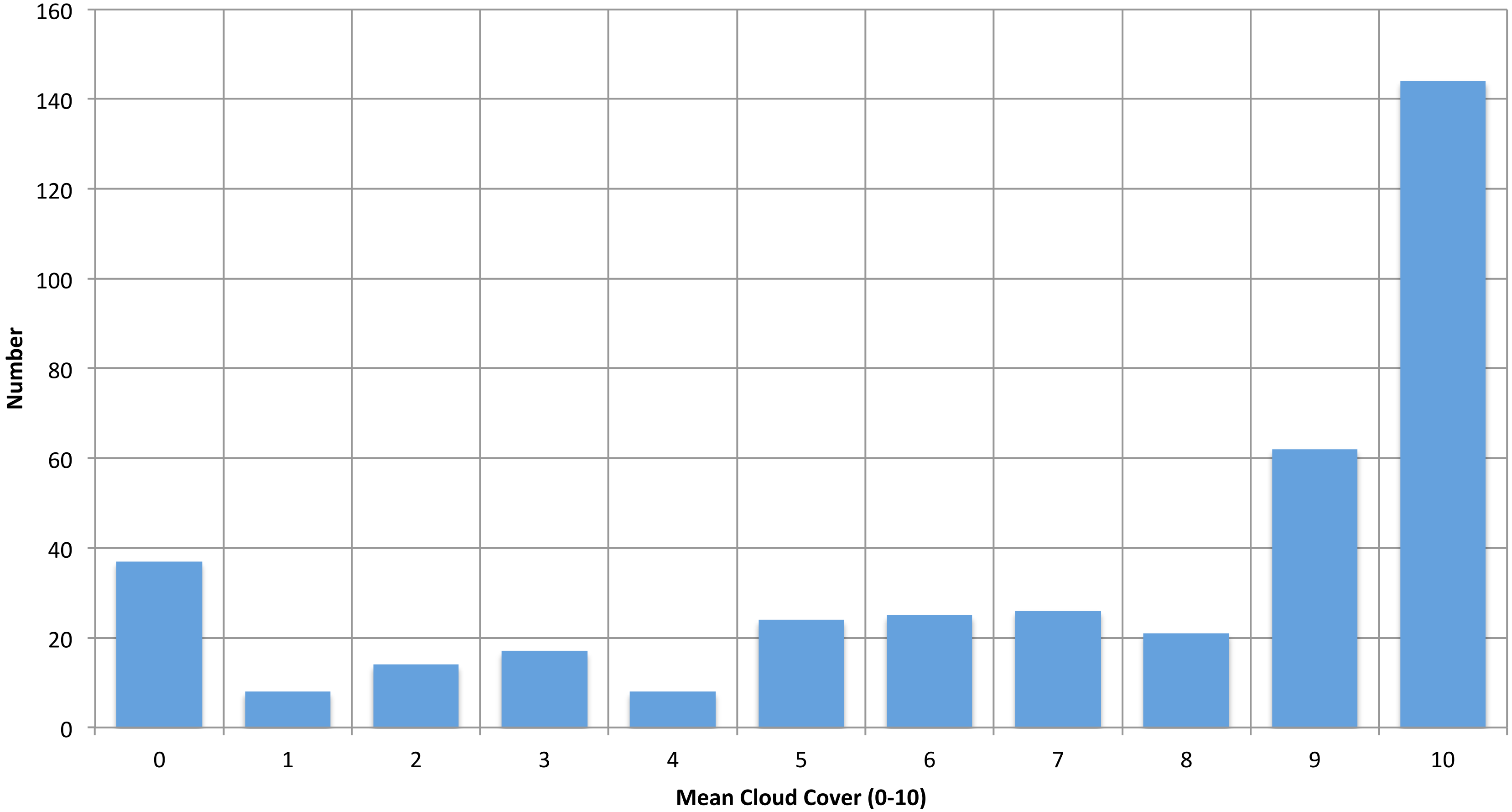
Temperature and Wind Speed
Syowa



Syowa Monthly Mean Cloud Cover 2014 -2013



Distribution of Daily Cloud Cover for 2013 Syowa



Syowa

- Unique location from the coverage point of view
- Need to look very closely on the impact of weather on the SLR