Current Trends and Challenges in Satellite Laser Ranging

Michael R. Pearlman[1,] Graham M Appleby[2], Giuseppe Bianco[3], Carey Noll[4], Erricos Pavlis[5],

1 Harvard-Smithsonian Center for Astrophysics, Cambridge MA, United States
2 NERC Space Geodesy Facility, Herstmonceux, UK,
3 Centro di Geodesia Spaziale "G. Colombo", Agenzia Spaziale Italiana, Matera, Italy,
4 NASA Goddard Space Flight Center, Greenbelt MD, United States,
5 University of Maryland, Baltimore MD, United States

Based on a talk "Appleby et al" given at the
Ninth IVS General Meeting,
Johannesburg, South Africa in 2016

ILRS

3rd General Meeting of the AOV
November 9 – 10, 2018
Canberra, Australia

Outline

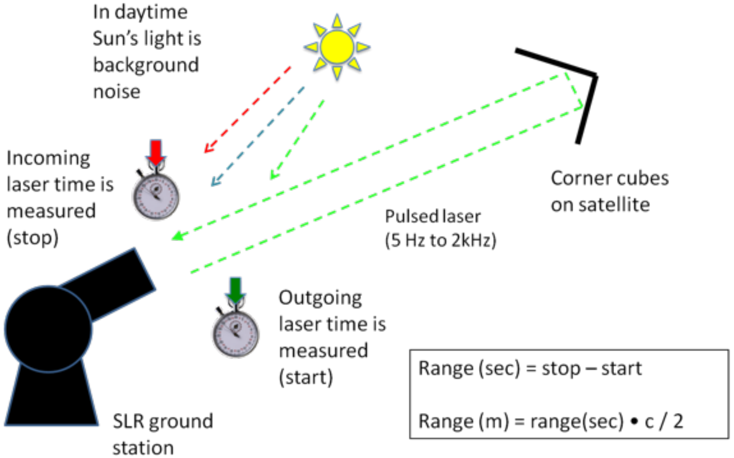
- Review of the technique of Satellite Laser Ranging (SLR)
- Current trends in SLR and the changing technology
- Applications
- Space segment
- Expanding constellations needing SLR
- New sites
- Scale difference among the space geodesy techniques
- International Laser Ranging Service
- Role within GGOS

Laser Ranging

- In the era of the Global Geodetic Observing System (GGOS), high-quality multi-technique sites are crucial:
- The space-observational Services, the **IDS**, **IGS**, **ILRS** and **IVS** together supply the data and products to meet the GGOS Mission;
- Major goals are determination and maintenance of the **terrestrial reference frame** and determination and monitoring of the **Earth's gravity field**;
- Realised through:
  - inter-technique site ties (CORE and Co-location stations);
  - combination of analysis products (site position, velocity, Earth orientation); and
  - tracking support for gravity missions
- Precise orbit determination crucial for altimetry and other missions with scientific impact

Satellite Laser Ranging (SLR)

- SLR directly measures the range between the ground station and passive retroreflectors on satellites using very short laser pulses, corrected for refraction, satellite center of mass, and the internal delay of the ranging machine.
- The output data are “normal points” which are full rate data averaged over short intervals.
- The state of the art is normal points with a few mm precision and sub-centimeter-level accuracies;
- Stations tracks from 300 km to 22,000+ km in day & night;
- Each station tracks independently but the network can be scheduled together (set priorities) to optimize tracking;
- Near real-time data availability through the CDDIS and EDC.



- Sub-cm accuracy orbits
- Long-term stable station positions
- Unambiguous centimeter time series

Laser Ranging activities are organized under the International Laser Ranging Service (ILRS)

- The ILRS provides global satellite and lunar laser ranging data and their derived data products to support research in geodesy, geophysics, Lunar science, and fundamental physics. This includes data products that are fundamental to the International Terrestrial Reference Frame (ITRF), which is established and maintained by the International Earth Rotation and Reference Systems Service (IERS).

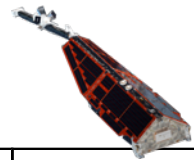
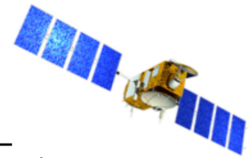
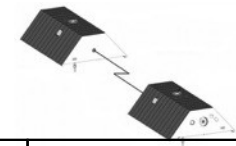
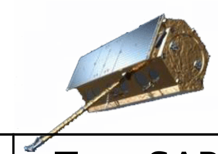
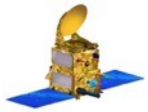
- The ILRS is one of the space geodetic services of the International Association of Geodesy (IAG) and is a member of the IAG's Global Geodetic Observing System (GGOS). The Services, under the umbrella of GGOS, provide the geodetic infrastructure necessary for monitoring global change in the Earth system *(Beutler and Rummel*, *2012)*.

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
  - Earth to Earth and Earth to space time transfer
  - Space debris tracking for reentry prediction
- More than ~180 Space Missions Supported since 1970
- Four Missions 'Rescued' in the Last two Decades

Sample of SLR Satellite Constellation

LEO Satellites

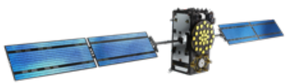
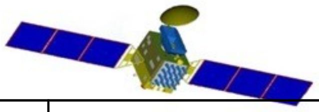
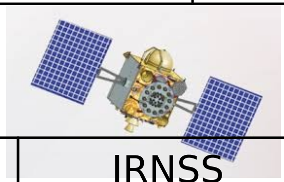
Satellite	Swarm	Jason-2/3	GRACE	TerraSAR-X	SARAL
Inclination	92°	66°	89°	66°	98.55°
Perigee ht. (km)	720	1,336	450	1,350	814

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

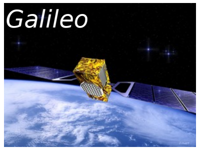
GNSS/GEO Satellites

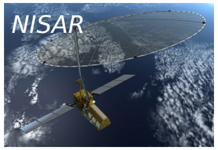
    

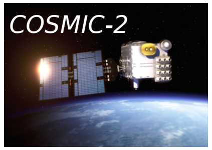
Satellite	GLONASS	Galileo	Beidou	IRNSS	QZS
Inclination	65°	56°	55.5°	29°	45°
Perigee ht. (km)	19,140	23,220	42.161	42,164	32,000

Many new Missions

- Network routinely tracked 100+ satellites in 2018
- In last year, new, approved missions included:
  - S-NET (4 cubesats/testing inter-satellite communication)
  - Sentinel-3B (altimeter mission/restricted tracking)
  - GRACE-FO (2 satellites/gravity measurements)
  - Tiangong-2 (Chinese spacecraft)
  - Beidou-3M (4 GNSS satellites)
  - PAZ (SAR mission)
  - ICESat-2 (laser altimetry mission/restricted tracking)
  - Astrocast Precursor (2 cubesats/engineering testing)
  - GNSS (Galileo, GLONASS, IRNSS)
- Future missions:
  - Additional GNSS: BeiDou/Compass, Galileo, etc.
  - LightSail-2, COSMIC-2, HY-2C, SWOT, NISAR





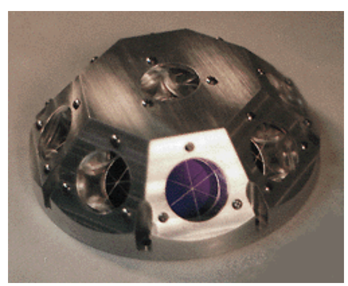


Space Segment
Retroreflector Arrays

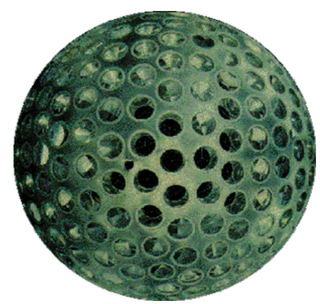
- Arrays need to accommodate velocity aberration
- Common use of the “pyramid or GFZ arrays” for LEO satellites – nearly COTS; particular design depends upon the satellite’s altitude and tracking requirement;
- Issue of ILRS Standard Specification for GNSS satellites of effective area of 100 million square meters;
- Adaptation of the GNSS standard to Synchronous satellites;
- Denser arrays with smaller cubes helps reduce return signal rms

Grace

Jason



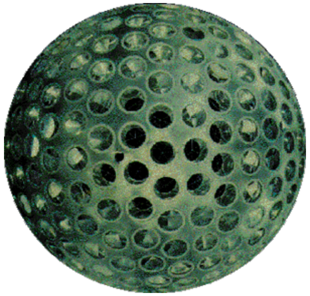
LAGEOS

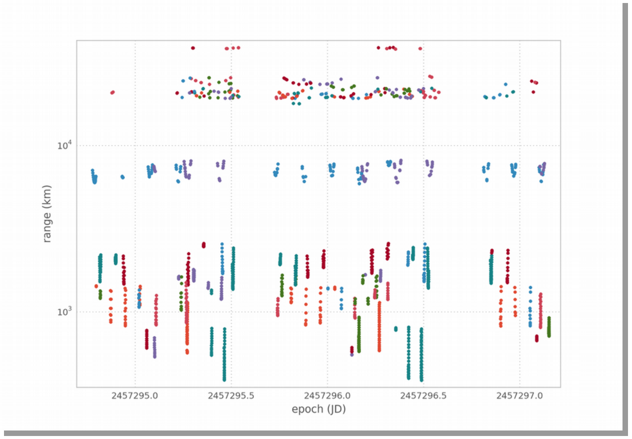


Beidou

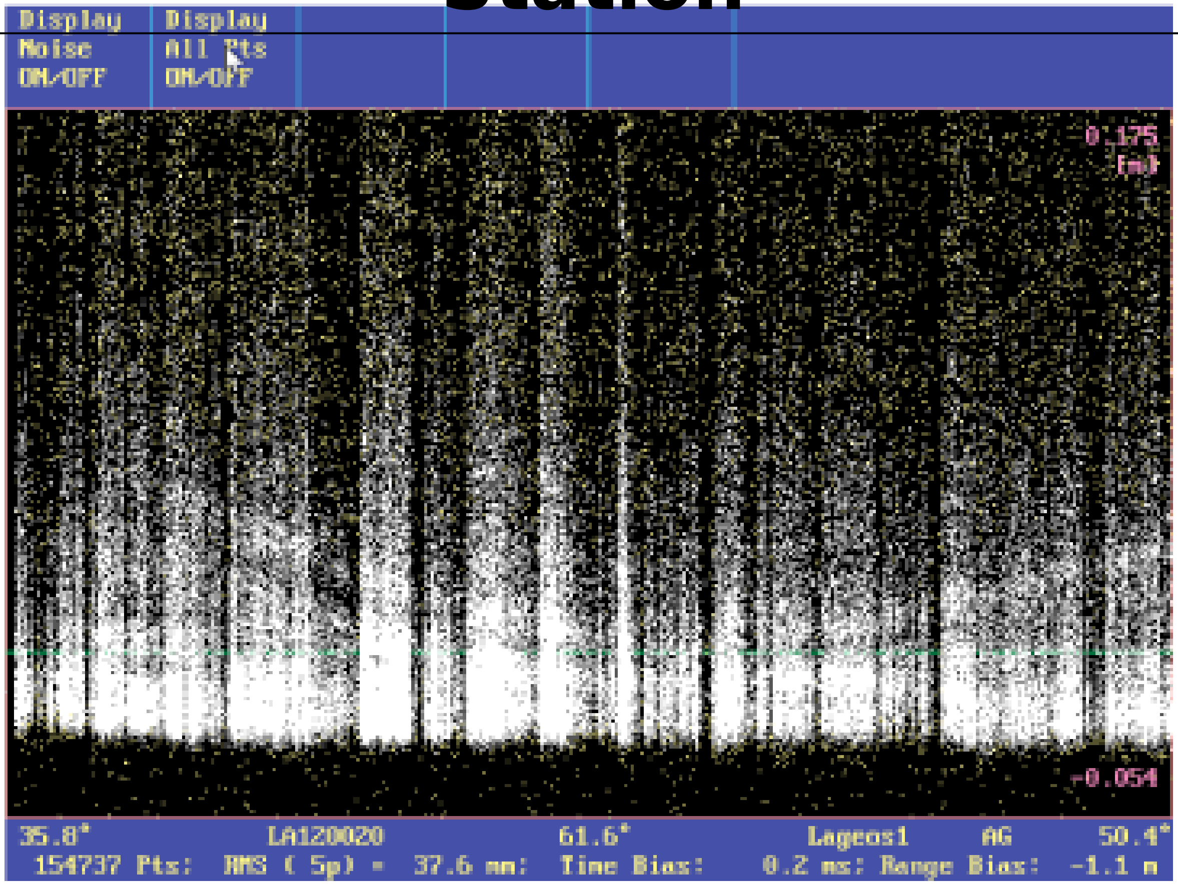
Current trends in SLR

- SLR systems: lower energy, higher repetition rates (kHz)
- Single photon sensitive detectors (geodetic satellites)
- Shorter normal point intervals (take data more quickly) and faster slewing for increased pass interleaving
- Real-time data evaluation for real-time decision making
- Automated to autonomous operation with remote access
- Stations with two SLR systems to help address the workload (e.g., Hartebeestoek)
- Environmental monitoring and awareness for instrument integrity and safety
- Real-time network communication and information sharing among stations
- Denser arrays with smaller cubes helps reduce return signal rms





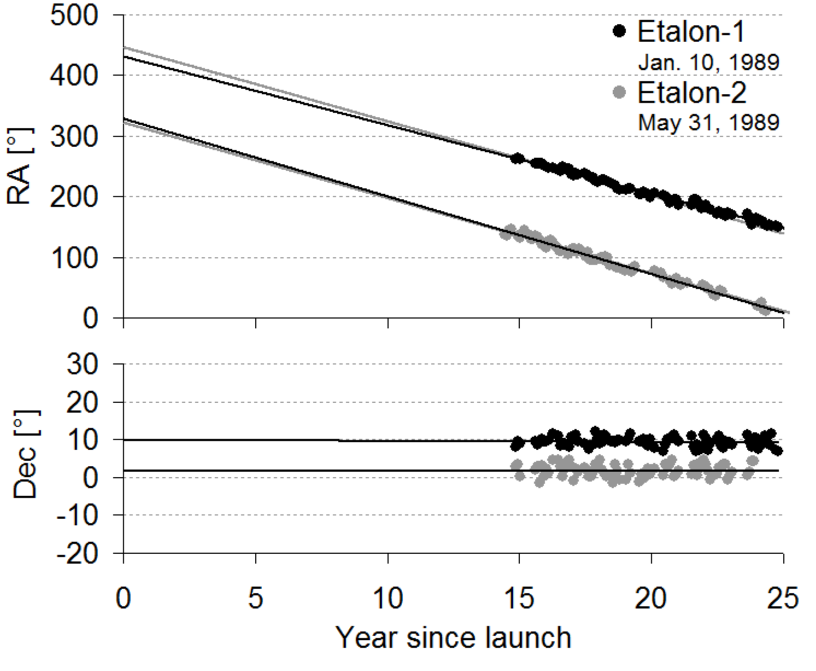
LAGEOS Pass from Graz Station



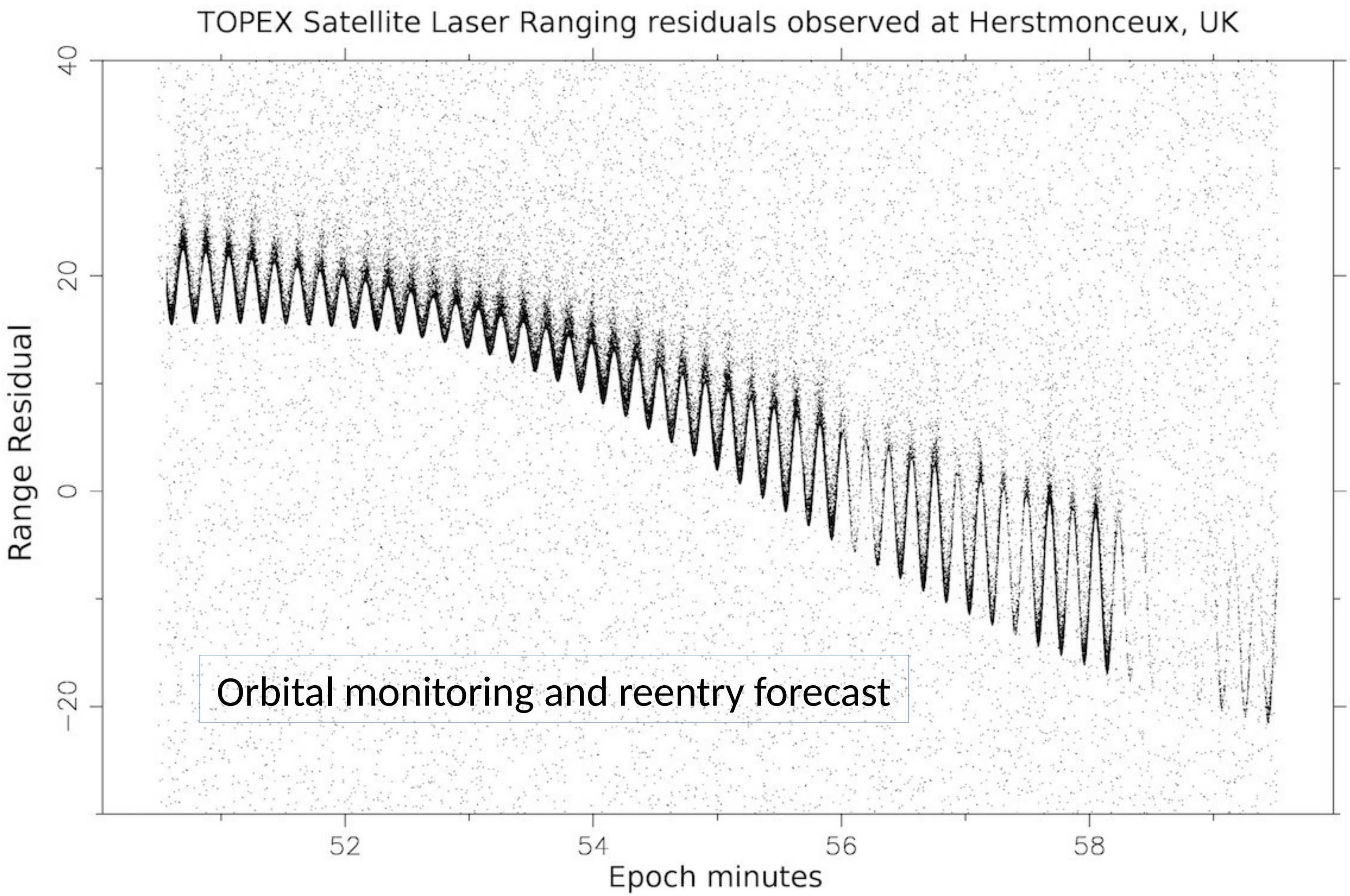
High repetition rate, **short pulse** lasers allow us to see retroreflector array details

High repetition-rate stations:

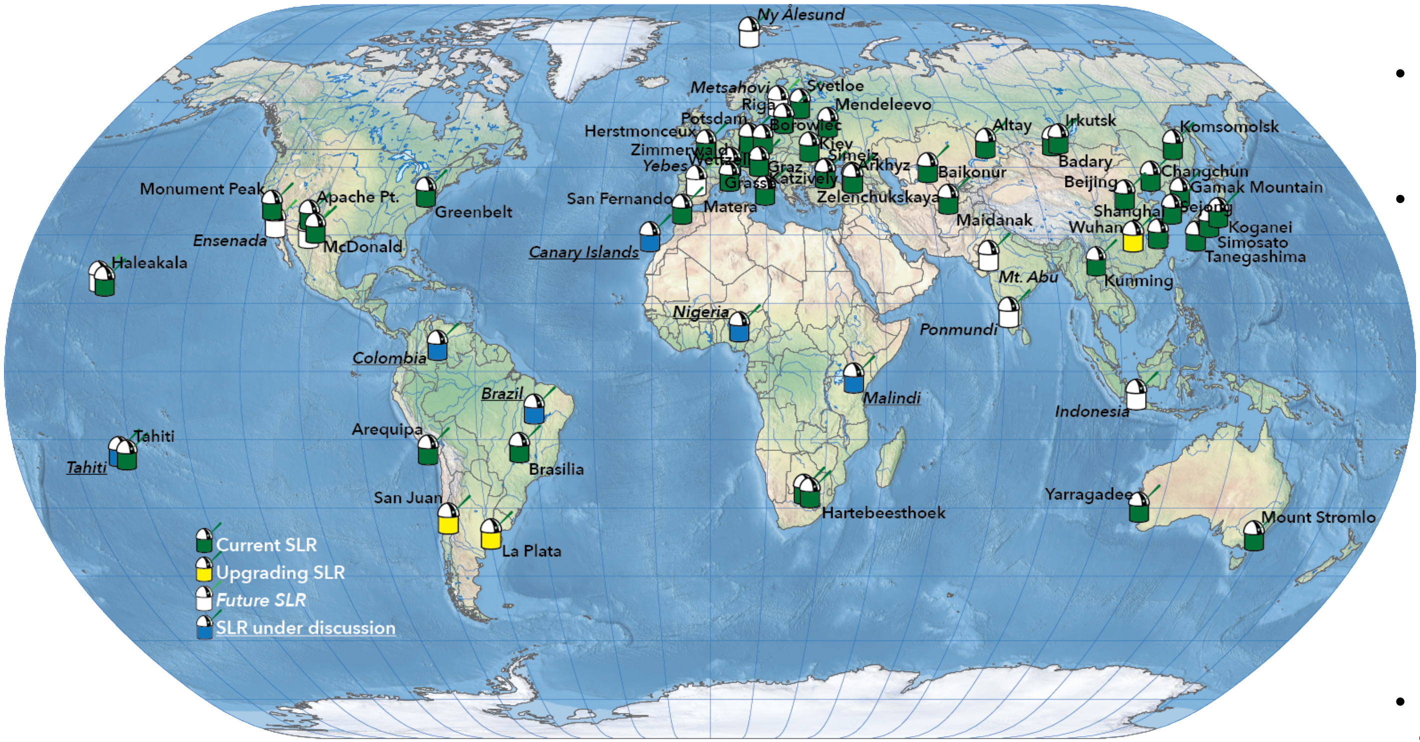
- Leading to impressive diagnostics of satellite attitude
  - Most of the geodetic spheres have had spin vectors measured as functions of time:
  - e.g. D. Kucharski et al, Etalon-1 and -2, *ASR* 2014



Space Debris: T/P

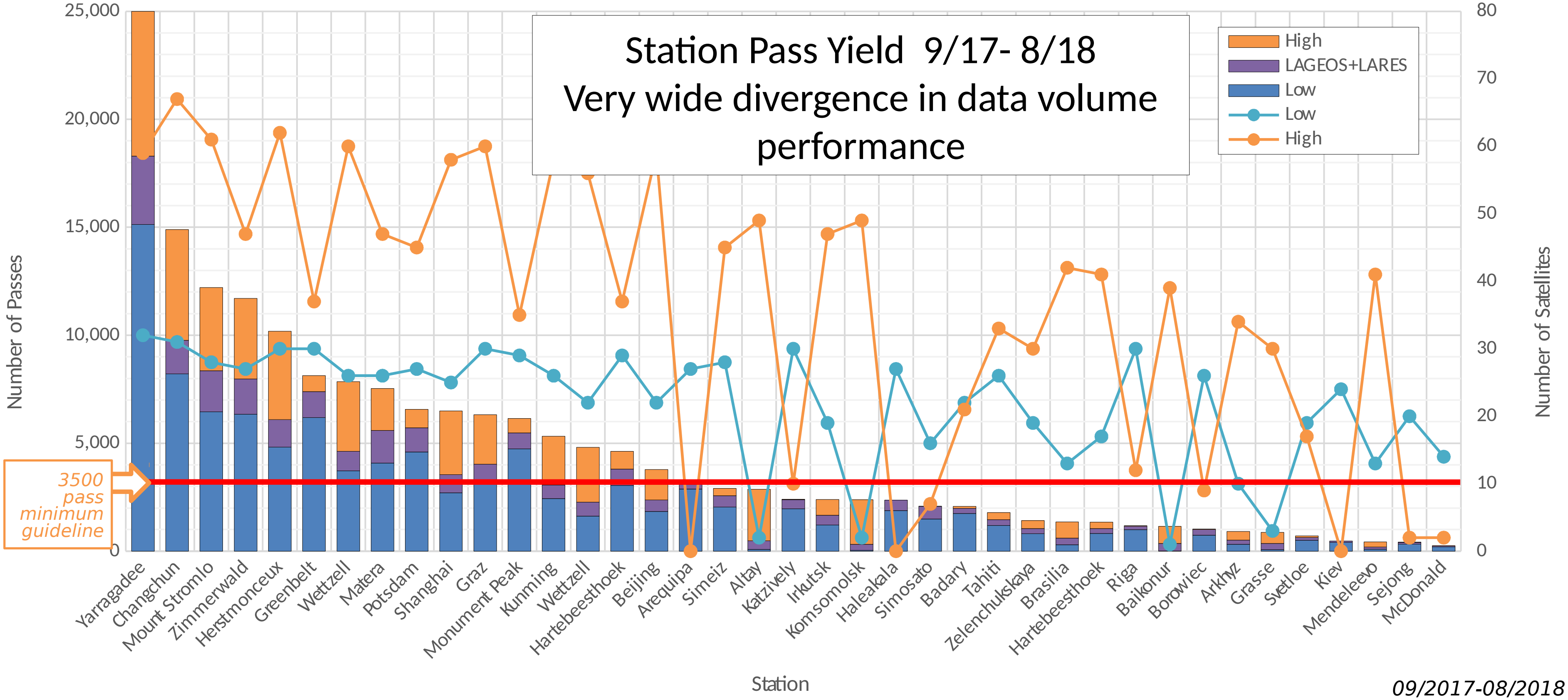


ILRS network



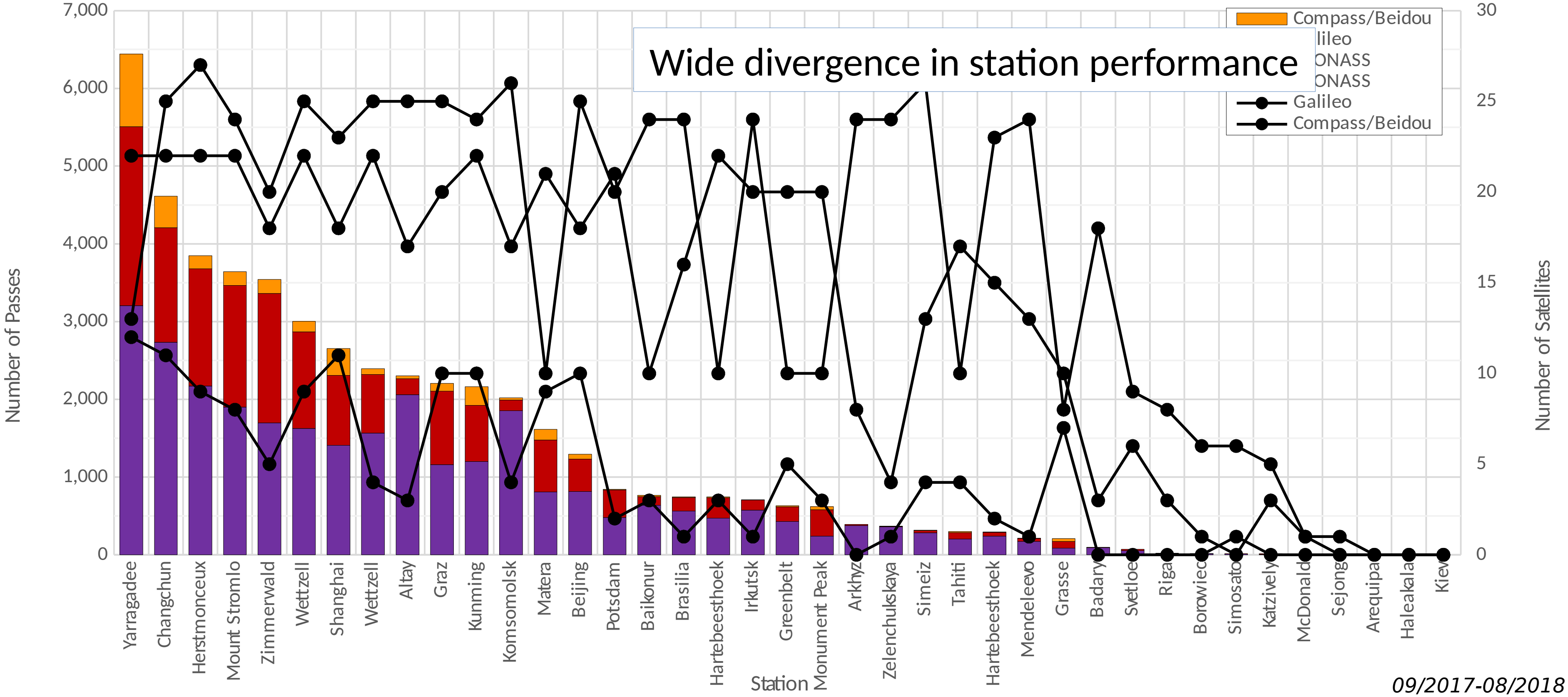
- BKG AGGO in setup at La Plata Observatory (Argentina)
- New stations underway:
  - Russia: Ensenada (Mexico), Java (Indonesia), Gran Canary (Spain)
  - NASA/NASA affiliated: McDonald, Halekala (USA), and Ny Ålesund (NMA, Norway)
  - Others: Metsahovi (Finland), Mt. Abu and Ponmundi (India), and Yebes (Spain)
- Upgrades underway at some stations
- First co-location of Russian and NASA SLR laser systems established at Hartebeesthoek, South Africa);

Station performance: passes



09/2017-08/2018

Station performance: GNSS

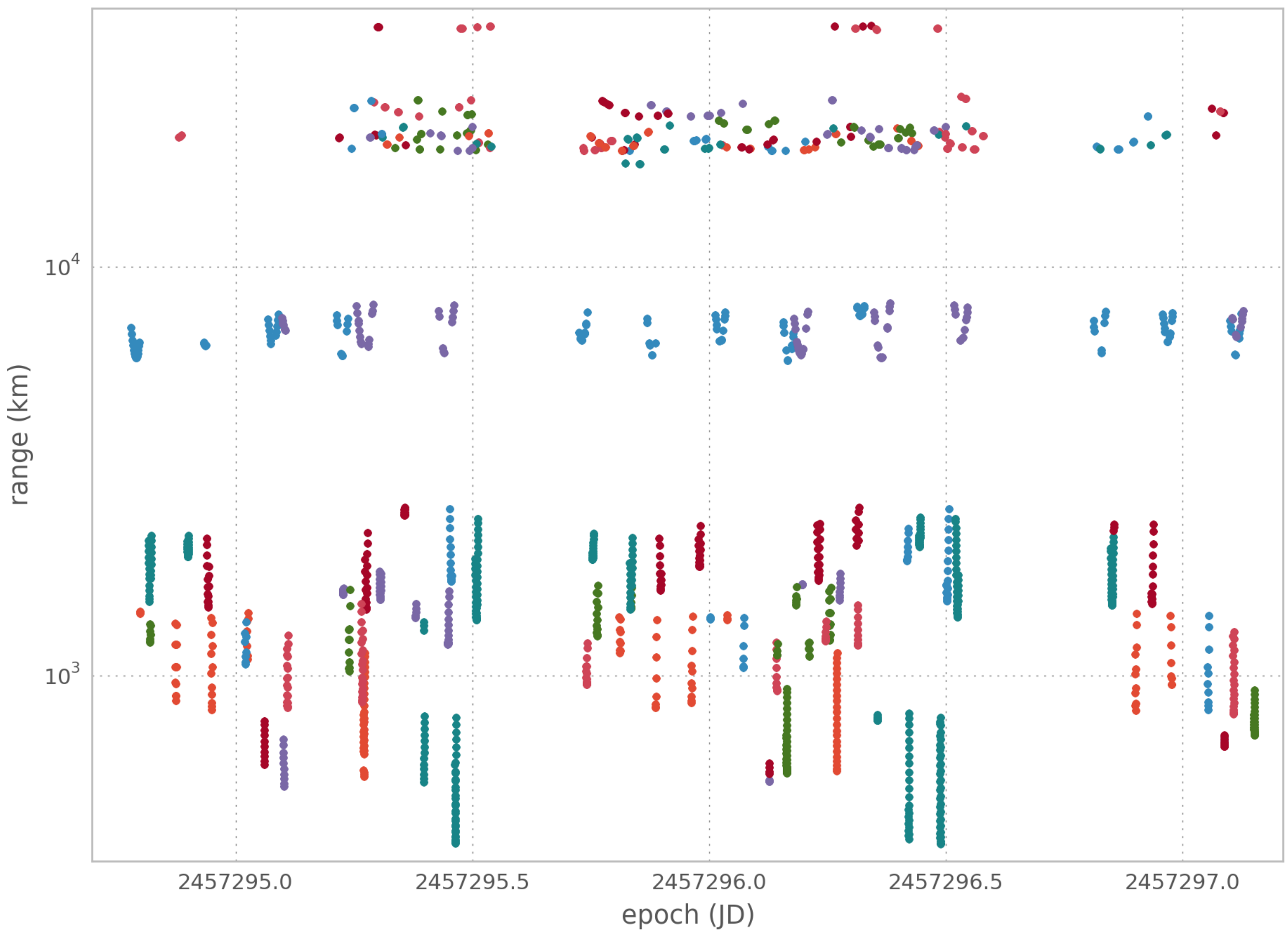


09/2017-08/2018

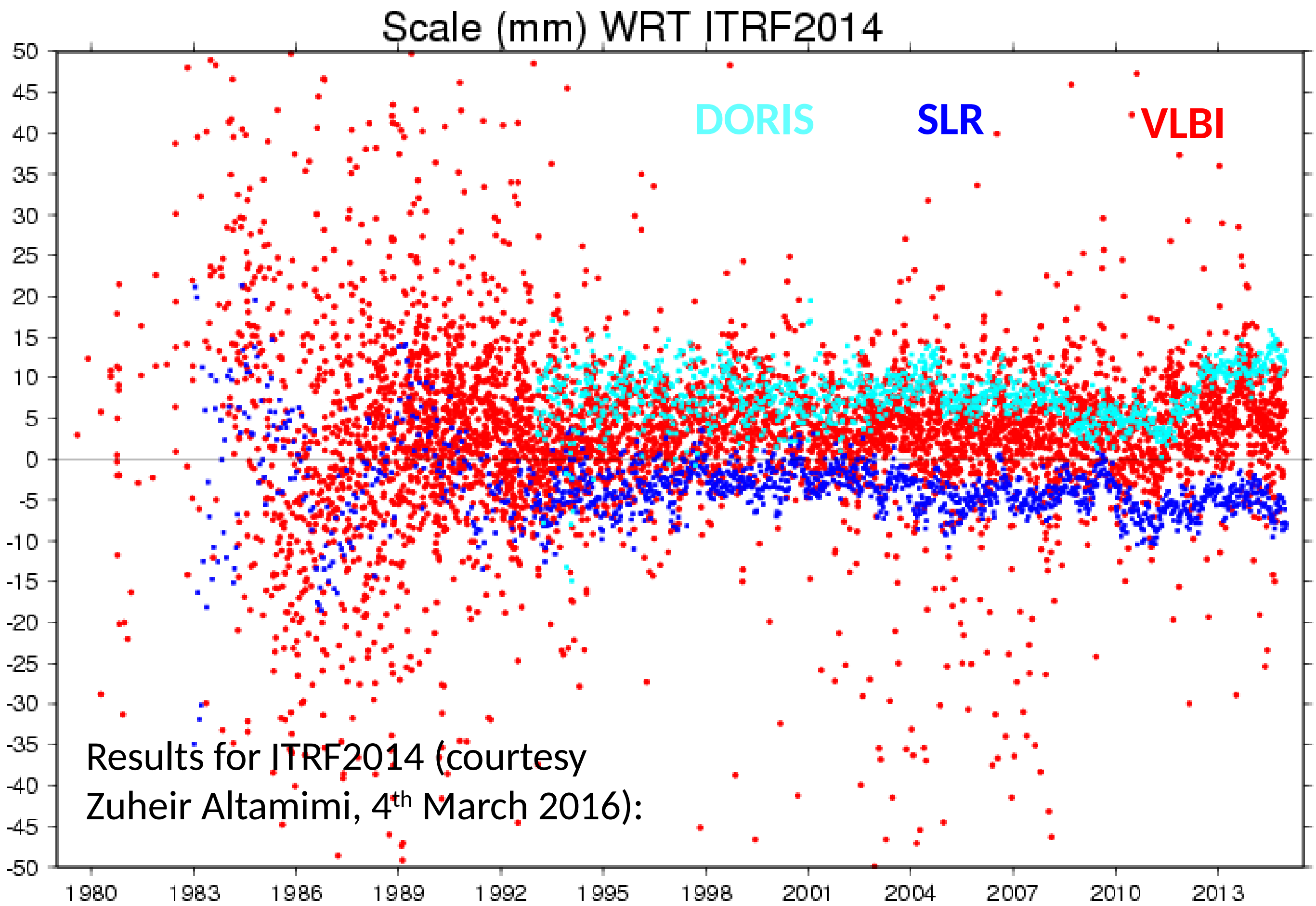
Increasing numbers of satellites

- Particularly demanding are the expanding constellations of GNSS satellites
- The missions and the data users want as much laser tracking data as possible
- The ILRS in consultation with the IGS and the ICG is looking at different strategies to try to provide better capability for GNSS while not compromizing the other users

In practice, some stations are very busy



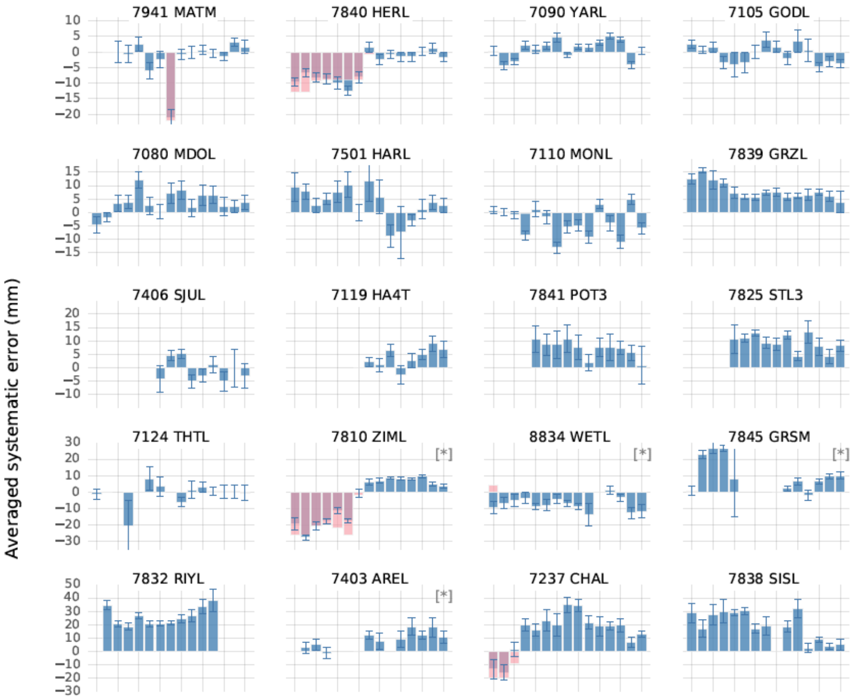
All VLBI, SLR & DORIS Scales wrt ITRF2014



Persistent systematic difference in scales determined by SLR and VLBI;
VLBI vs SLR Scale Difference : 1.37 (± 0.10) ppb; Scale rate negligible

Systematic difference in scales determined by SLR and VLBI;

- At least part of the cause appears to be systematic issues in the measurement data, and perhaps site-tie and global distribution issues;
- ILRS Activities underway:
  - Station Systematics modeling (Erricos)
  - Center of mass correction on the geodetic satellites (Jose Rodriguez)
  - Atmospheric loading; other loading, etc.
- So far – we see a reduction in the difference of about 50% (Very promising)



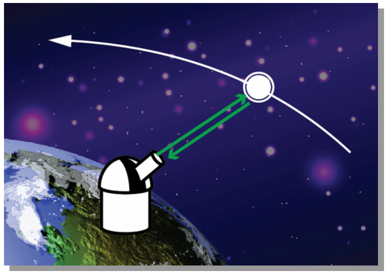
Satellite Laser Ranging

Summary

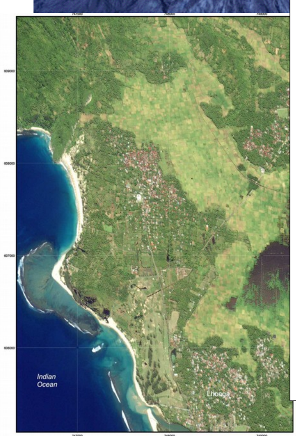
- Challenging program with very important science and societal benefits
- Technologies are maturing; new technologies are on the horizon
- Global distribution is essential; success needs the enhanced networks that will depend on partnerships
- Very large opportunity for participation in analysis and scientific research
- Need to engage young scientists and students

Challenges

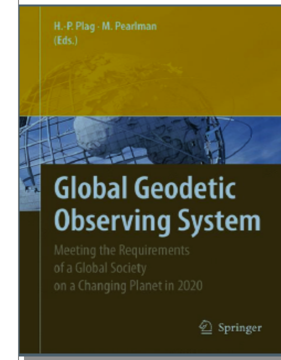
- Many geographic gaps, primarily in Latin America, Africa, and Oceania
- Mix of new and old technologies and levels of financial support
- Lack of standardization in system hardware and operations
- Local limitations: weather, personnel, budget, etc.
- Data systematics issues
- Large number of missions asking for support

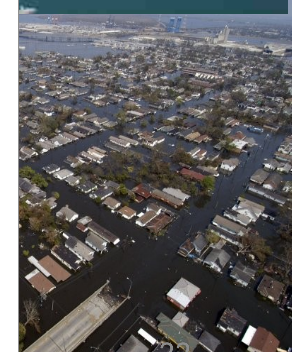


Global Geodetic Observing System (GGOS)



- Established by the IAG in 2004 to be its Observing System
- Vision: Advancing our understanding of the dynamic Earth system by quantifying our planet's changes in space and time to:
  - Advance Earth Science (Earth, oceans, ice, atmosphere, etc)
  - Help us better understand the processes
  - Help us make intelligent societal decisions
- Mode of Operation: Works with the IAG components (IGS, ILRS, IVS, IDS, IGFS, IERS, IAG commissions, etc.) to provide the geodetic infrastructure necessary for monitoring the Earth System and Global Change:
  - observations needed to monitor, map, and understand changes in the Earth's shape, rotation, and mass distribution;
  - the TERRESTRIAL REFERENCE FRAME and CELESTIAL REFERENCE FRAME for measuring and consistently interpreting key global change processes;
  - Other data products that require integration among measuring techniques: Unified height systems, Unified sea level model, Natural hazard warning tools, etc
- The reference frames are developed through the multi-technique space geodesy networks (IVS, ILRS, IDS, and IGS)





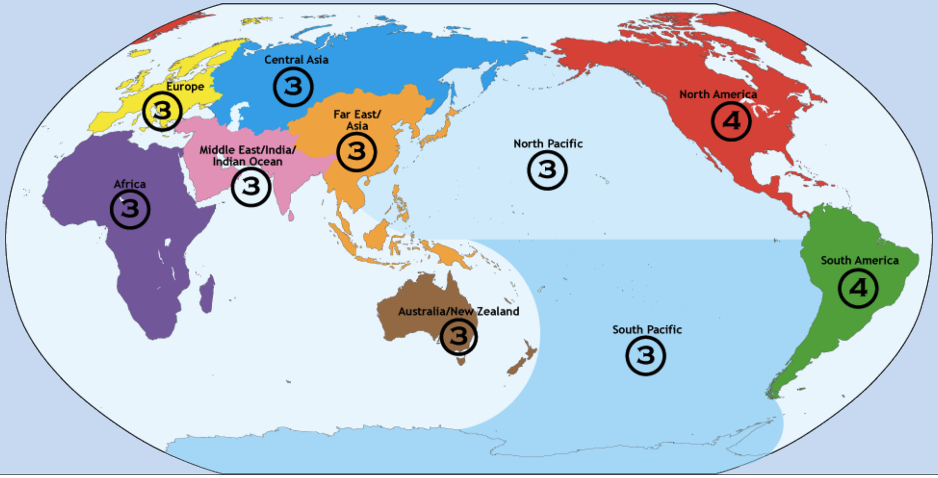
Early Simulation Studies to Scope the Network

(impact on the Reference Frame)

(Erricos Pavlis)

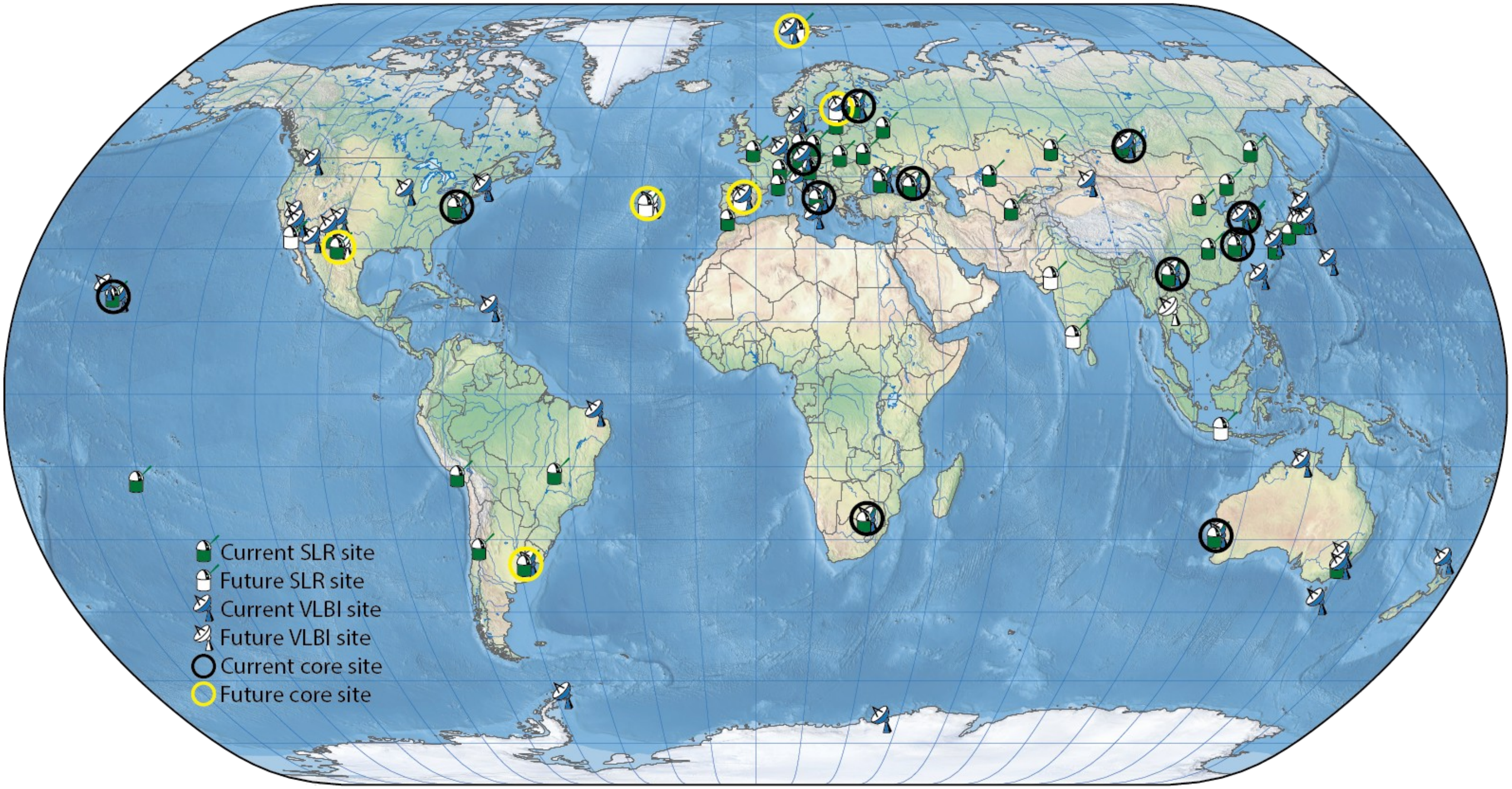
Early simulation studies showed the we needed:

- ~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.



- **Design Initiative, but it a major Challenge**
- **Will require time, significant resources, and strong international participation**
- **Now we recognize that it will be a combination of core and colocation sites with apple geographic distribution.**

Present and Projected CORE Sites
2020 – 2022 Timeframe



UN Adopted its first Geospatial UN Resolution

- **Global Geodetic Reference Frame (ITRF and ICRF combination) for Sustainable Development (GGRF) resolution - *No. A/69/L.53* -**
- **adopted by the United Nations General Assembly on 26th of Feb, 2015**
- **co-sponsored by 52 Member States including Japan**

- … first resolution recognizing the importance of a globally coordinated approach to geodesy – the discipline focused on accurately measuring the shape, rotation and gravitational field of planet Earth.
- The General Assembly resolution, *A Global Geodetic Reference Frame for Sustainable Development*, outlines the value of ground-based obserations and remote satellite sensing when tracking changes in populations, ice caps, oceans and the atmosphere over time.

Thank you for the opportunity to participate in the

3rd General Meeting of AOV