Technological Challenges

of SLR Tracking of GNSS Constellations

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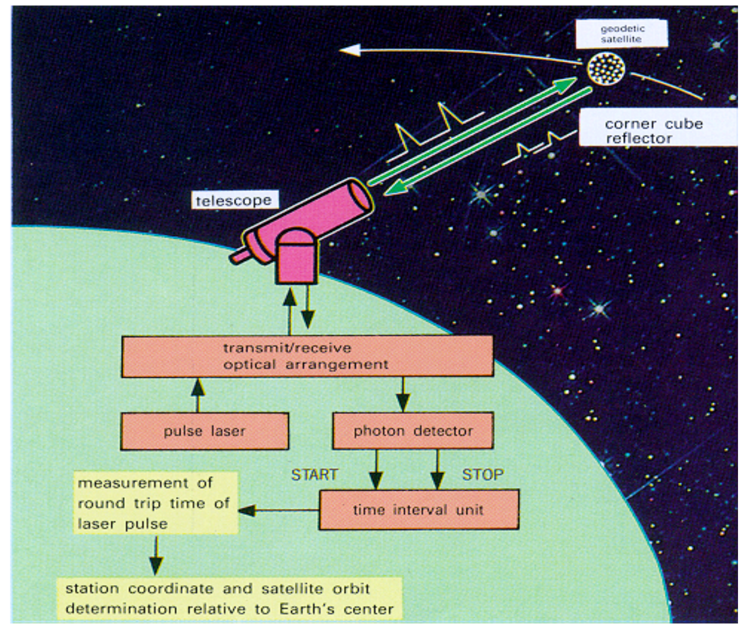
Satellite Laser Ranging Technique

Precise range measurement between an SLR ground station and a retroreflector-equipped satellite using ultrashort laser pulses corrected for refraction, satellite center of mass, and the internal delay of the ranging machine.

- Simple range measurement
- Space segment is passive
- Simple refraction model
- Night/Day Operation (Not on GNSS)
- Near real-time global data availability
- Satellite altitudes from 400 km to synchronous satellites, and the Moon
- Cm satellite Orbit Accuracy
- Able to see small changes by looking at long time series



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

SLR Data are formed into Normal Points

- Full rate data is consolidated into normal points at the stations prior to shipment to the data centers;
- Normal points originated with lunar ranging back in the late 1960’s;
- SLR normal points span time intervals as short as 5 seconds for very low satellites to 5 minutes for GNSS satellites.
- Normal point intervals are chosen to keep the orbital perturbation effect insignificant during the normal point interval;
- All of the analyses are done with normal points except for engineering studies on system performance and diagnoses.

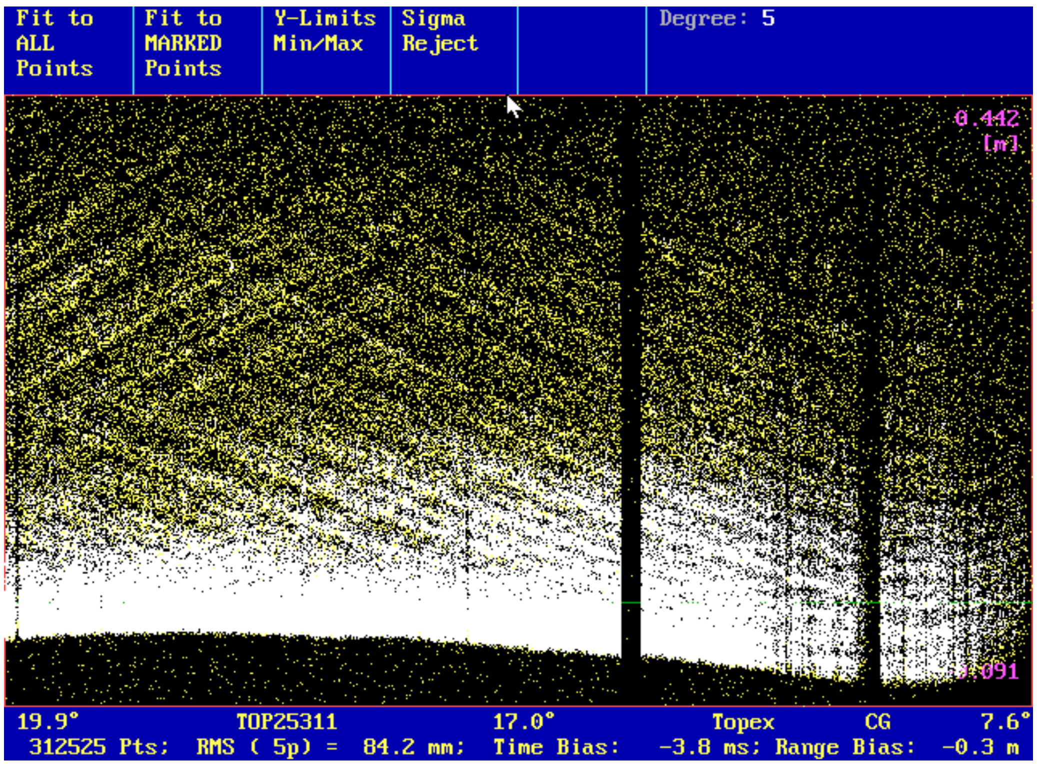
Technology Challenges
to SLR Ranging to GNSS Satellites

- Getting enough laser photons on the satellite;
- Collecting enough photons back at the ground station;
- Separating the desired returning photons from the undesired photon noise (daylight ranging);
- Having sufficient range accuracy;
- Connecting SLR with other co-located space techniques (ground survey);
- Having sufficient geographic coverage.

Getting Enough Photons on the Satellite

- Laser Output
  - Typical legacy lasers (older systems)
    - 5 – 10 pulses per second;
    - pulse energies from millijoules to 100’s of minutes;
    - pulse widths in the range of 100 – 200 ps;
  - Newer high repetition systems (100 to 2 KHz) with narrow pulse width (35 ps):
    - same average power, but some statistical benefit;
    - faster satellite acquisition and data accumulation;
    - more satellites tracked.
    - enhanced interleaving of passes;
    - cornercubes can be resolved in some cases;
    - data processing more complicated; pattern must be interpreted or modeled;
    - These laser are installed or being installed at Graz, Herstmonceux, Changchun, Wuhan, Kunming, and TROS.

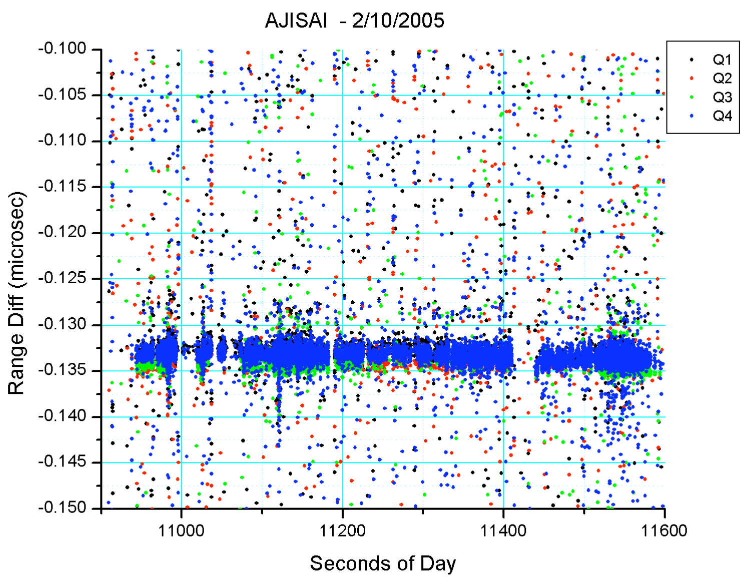
2 Kilohertz returns from Graz Station (using few ps pulse width)

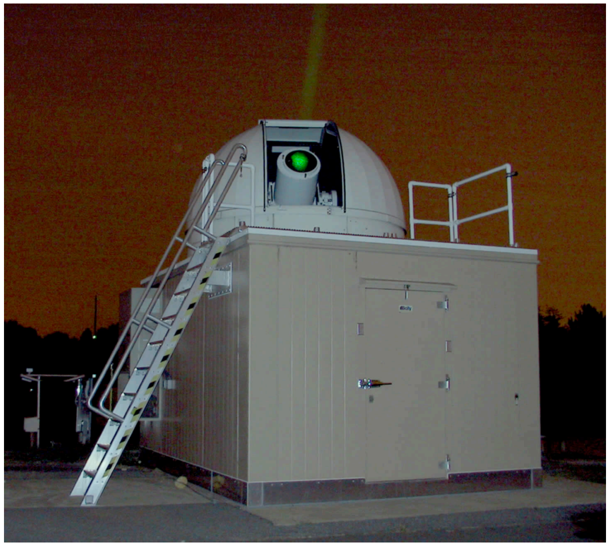


- Using 30 ps laser, 2 KHz laser
- Very high resolution
- Single cube resolution
- More complicated data analysis

Getting Enough Photons on the Satellite

- Newer high repetition systems (2 KHz) with wider pulse widths (300 ps) at NASA GSFC (NGSLR):
  - averaging is done in ranging machine itself prior to submission;
  - less single point precision, but simple data interpretation;
  - higher eye safety damage threshold, an issue for consideration for fully automated systems;
  - Quadrant detector for real-time tracking updates.





International Laser Ranging Service

Getting Enough Photons on the Satellite

- **Output beam divergence**
  - reasonably good lasers have near diffraction limited, output beam divergence
  - depends on telescope aperture size and quality of pointing.
  - SLR systems use blind pointing (with good predictions), but searching means less data and few satellites tracked.
  - stability of the mount and accuracy of pointing is really the limitation.

Pointing accuracy at the level of a few arcsec

Collecting Enough Photons back at the Ground Station -1

- Telescope aperture – function of cost and system configuration
- Performance of the array
  - properties of the corner cubes
    - size and material of the cube;
    - Back-coating or total internal reflection;
    - vertex offset angle (to accommodate velocity aberration); and
    - thermal mounting conditions (thermal gradients can degrade optical properties).
  - structure of the array
    - array size (number of cubes),
    - shape (as compact as practicable),
    - accessibility (is the array obstructed), and
    - thermal conditions.

Collecting enough photons back at the ground station - 2

- Uncoated cubes (total internal reflection) have a larger cross-section, but a narrower field of view; which lends itself very well to the higher satellites with flat arrays.
- Uncoated cubes have a polarization effect that could influence range accuracy if provisions are not made at the ground system.
- With the exception of Lageos 1 and 2 and more recently ETS-8 and COMPASS – 3M, all of the present ILRS tracked satellites have back-coated corner cubes.
- The vector offset between the “optical center” of the array and the satellite center of mass must be known:
  – Any error in this vector measurement will be included in the range measurement and will introduce a bias;
  – Accurate vector measurements require good engineering drawings and accurate models of how satellite center of mass will change over time in flight are essential.

Retroreflector Arrays

on MEO and HEO Satellites

(provided by Dave Arnold)

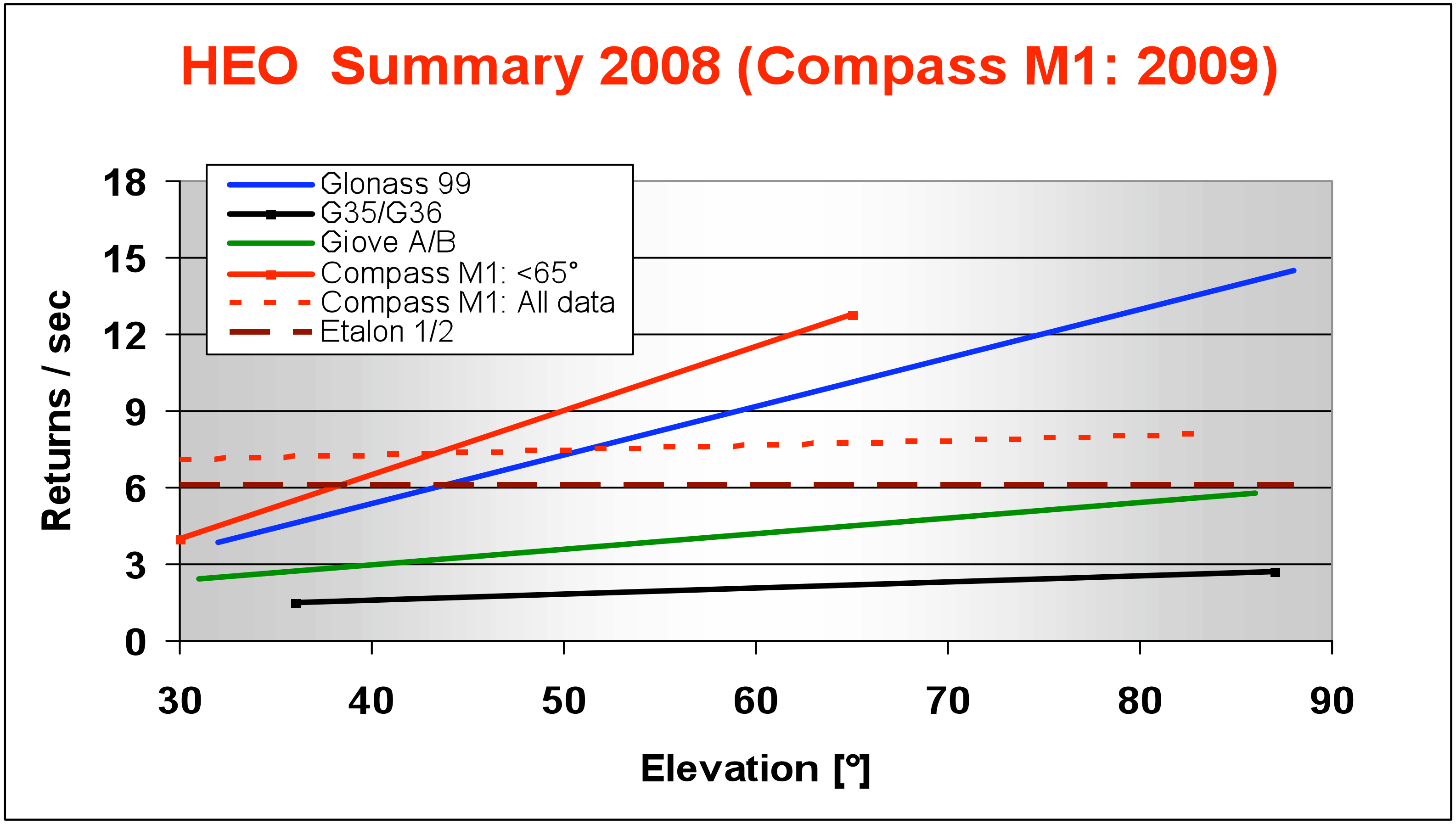
Satellite	Altitude (MM)	Effective Cross Section (MSqM)	Relative Return Signal Strength			
			Zenith	30 deg	45 deg	60 deg
Lageos1/2 *	5.8	15	1.0	1.0	1.0	1.0
Etalon1/2	19	55	.032	.037	.044	.058
GLONASS	19	80	.046	.054	.065	.084
GPS 35/36	20	20	.009	.011	.013	.018
COMPASS *	21.5	80	.028	.033	.041	.054
GIOVE-A	23.9	45	.010	.012	.015	.021
GIOVE-B	23.9	40	.009	.011	.014	.018
ETS-8 *	36	140	.006	.008	.010	.014
* Sphere	** Galileo Test Satellite		*** Synchronous			

•Glonass with a very large array and COMPASS with uncoated cubes run about 3 times as large as signal strengths from GPS and GIOVE satellites

•GNSS signal strengths run from 3 – 8% of that from Lageos;

Ranging Tests form the Graz Stations
2 KHz Laser shows similar results

(provided by Georg Kirchner)



GPS Tracking Campaign

(25-Mar-2008 through 26-May-2008)

Site Name	Station #	No. Passes	No. Normal Points
Beijing	7249	1	3
Changchun	7237	2	8
Graz	7839	28	251
Greenbelt	7105	2	4
Herstmonceux	7840	23	77
Katzively	1893	1	6
Koganei	7308	2	9
Matera	7941	1	6
McDonald	7080	10	42
Monument Peak	7110	4	9
Mount Stromlo	7825	11	40
Riyadh	7832	20	99
San Juan	7406	60	375
Simeiz	1873	2	50
Tanegashima	7358	29	149
Wettzell	8834	18	79
Yarragadee	7090	70	267
Zimmerwald	7810	15	61
Totals:	18 stations	299	1535

33 Passes/week

Where do we stand?

- "The best" stations
  - range to LAGEOS in both daytime and night-time;
  - range GLONASS at night with some success in daylight;
  - range to GIOVE-A at night
- A few stations range to GPS 35/36 at night;
- Some stations are upgrading hardware and operational procedures to improve performance

ILRS Retroreflector Standard for GNSS satellites

(Revision September 28, 2007)

- Retroreflector payloads for GPS, GLONASS, and COMPASS satellites should have an “effective cross-section” of 100 million sq. meters (5 times that of GPS-35 and -36) for GNSS satellites;
- *Added Recommendation: Retroreflector payloads for satellites such as Galileo in higher orbits should scale the “effective cross-section” to compensate for the R**4 reduction in signal strength;*
- The parameters necessary for the precise definition of the vectors between the effective reflection plane, the radiometric antenna phase center and the **center of** mass of the spacecraft be specified and maintained with mm accuracy.

Separating the desired returning photons from the undesired photon noise (daylight ranging);

- Requires careful filtering and signal discrimination to avoid being overtaken by daylight noise.
  - narrow receiver field of view (again pointing accuracy dependence),
  - spectral filtering,
  - temporal filtering (range gate). With good predictions, which should certainly be achievable with operating GNSS satellites, range gates may be set down at a few 100 nsec.
  - multi-stop timers that can record several returns (signal and noise) for later discrimination (for systems that use fast recovery detectors (PMT's).

Sufficient Range Accuracy

- Accuracy is influenced by system parameters such as pulse repetition rate, pulse width, etc;
- Unmodeled system errors will corrupt range measurements and aliased scientific results;
- Careful and comprehensive calibration combined with good engineering design and practices are critical.

The real issue: overcoming systematic errors

Connecting SLR with other Co-located Space Techniques

Ground Survey Techniques

- **Fundamental problem with the co-location** is the measurement of the vector between the invariant reference points (intersection of axes, GPS antenna reference points, etc.) on the co-located instruments;
- **Invariant points are almost always inaccessible** and the determination of these vectors includes a survey between accessible points on each instrument plus extrapolations to points that are not directly accessible.;
- Extrapolation process includes careful examination of engineering drawings, laboratory measurements, dynamic local surveys, etc. **Small motions** may be corrupting measurements and subsequently our data products;
- Current ground survey techniques can provide closure to properly configured ground monuments to mm accuracies, but these measurements -tend to be **very expensive and infrequent**.

Connecting SLR with other Co-located Space Techniques

Ground Survey techniques

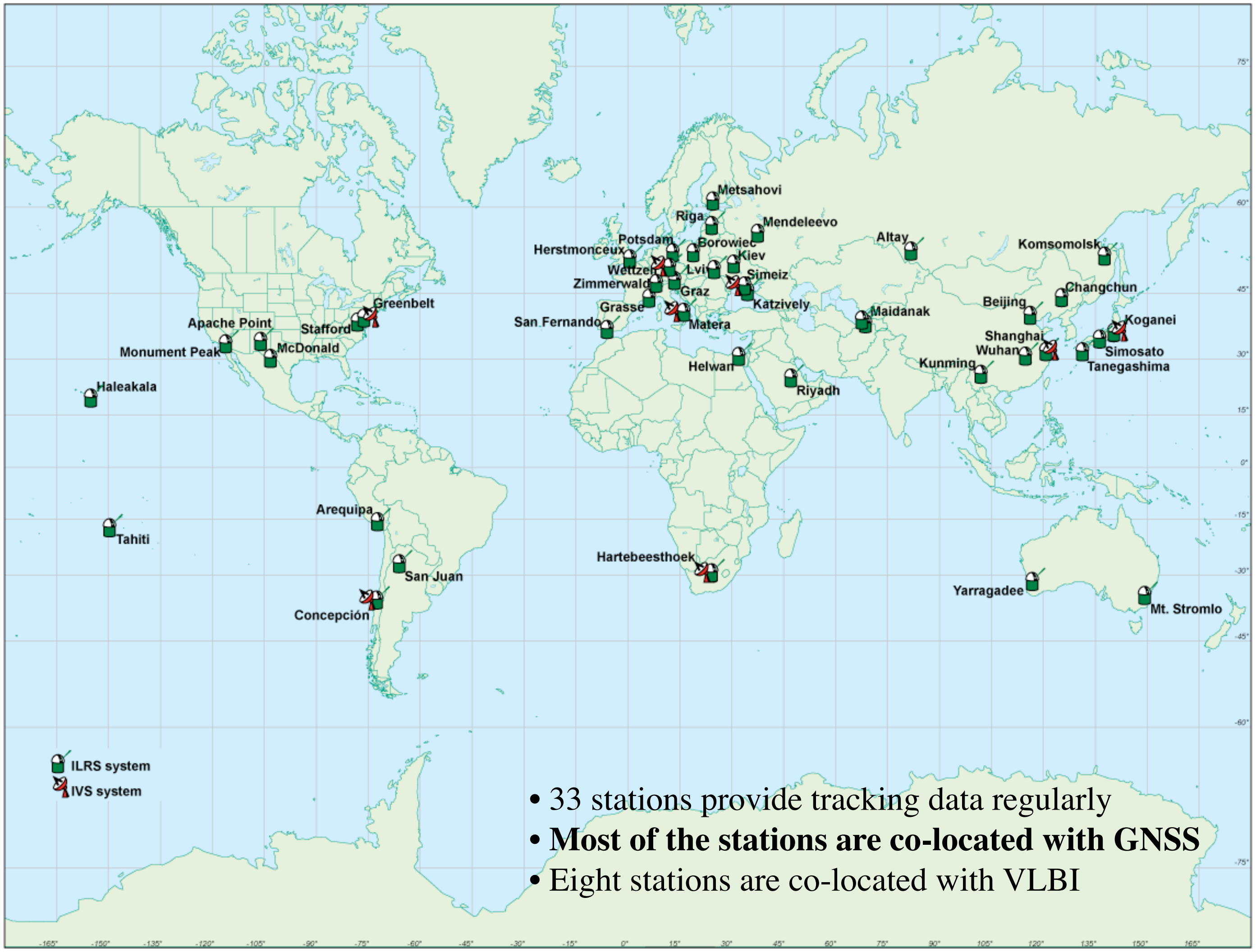
- We need to develop an economical approach that will measure or even monitor the inter-system vectors with sufficient spatial accuracy and temporal resolution to support reference frame requirements now projected at 1 mm accuracy and 0.1 mm/year stability.
- A promising solution at the moment is based on ground based surveys using commercially available Robotic Total Station (RTS) survey systems and a local network of ground reference pillars,

  See http://ilrs.gsfc.nasa.gov/docs/TLS_2008Workshop_Report.pdf

Geodetic Reference Antenna in Space (GRASP)

- Inverts the survey problem and determine the inter-technique vectors through co-location on space with a multi-technique equipped satellite;
- Being developed at JPL; would take advantage of measurements taken directly to the technique reference points and could be done continuously.
- Envisioned as a low cost micro-satellite, specifically designed to support mm-level calibration and stability between the electromagnetic/optic phase centers of its radio and optical sensors, nominally a GPS, receiver, an SLR retroreflector, a VLBI transceiver, and a DORIS receiver.
- Preliminary analysis of the GRASP mission calls for orbital altitudes of approximately 2000-2500 km, to minimize atmospheric drag mismodeling, no moving parts on the satellite to optimize solar pressure modeling and extend the satellite lifetime.

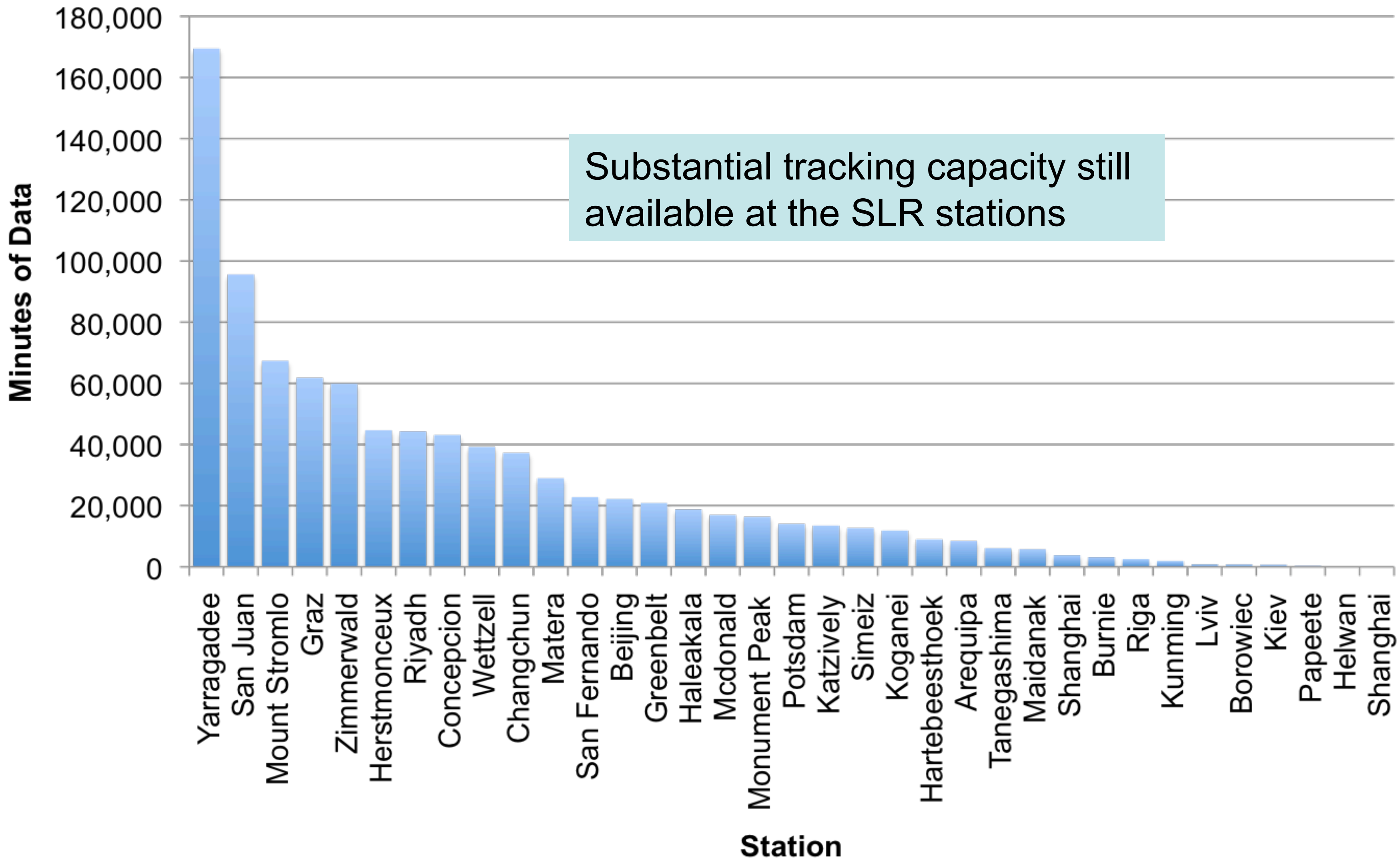
ILRS Network



- 33 stations provide tracking data regularly
- **Most of the stations are co-located with GNSS**
- Eight stations are co-located with VLBI

ILRS Network Tracking

01-Jul-2007 through 30-Jun-2008



Status of the SLR Network

- Over the last decade the SLR network has expanded most notably in the Southern Hemisphere;
- There are still large geographic gaps in particular in Africa and the Indian Ocean;
- Geographic gaps in the network, but it should not be too much of a problem with GNSS satellites;
- Programs such as GGOS are focusing on these gaps with an eye toward bringing new groups into space geodesy activities to help fill the existing gaps;
- Mix of legacy (in some cases decades old) and modern systems; however the older systems in many cases perform well;
- Performance differences between stations; some in their present condition will not contribute;
- Many stations undergoing upgrades to improve tracking capability.

Selected SLR Stations Around the World

The Next Generation SLR Systems

The next generation systems will operate with:

- higher repetition rate (100 Hz to 2 kHz) lasers to increase data yield and improve normal point precision;
- photon-counting detectors to reduce the emitted laser energies by orders of magnitude and reduce optical hazards on the ground and at aircraft (some are totally eye-safe);
- multi-stop event timers with few ps resolutions to improve low energy performance in a high solar-noise environment; and
- considerably more automation to permit remote and even autonomous operation;

Many systems will operate at single photon levels with

- Single Photon Avalanche Diode (SPAD) detectors or
- MicroChannel Plate PhotoMultiplier Tubes (MCP/PMIs).

Some systems are experimenting with two-wavelength operations to test atmospheric refraction models and/or to provide unambiguous calibration of the atmospheric delay.

A Possible Plan for Multiple GNSS Tracking

- Assumptions:
  - Satellites carry the enhanced array (factor of 5 increase in effective cross section);
  - Precise Center of Mass information including the change with fuel consumption required for all spacecraft;
  - Many network stations will be using enhanced systems (e.g. KHz ranging, improved detection,) in the 2013 timeframe for improved performance on weak targets;
  - Increased automation and data interleaving procedures at the field stations will increase ranging efficiency;
- Concepts for an Operational HEO Plan:
  - Support GPS, Galileo, and GLONASS; COMPASS; and possibly other;
  - Pointing predictions based on on-board GPS data and SLR data for improved pointing particularly in daylight using real-time communication;
  - Decrease Normal Point intervals (from 5 minutes) as data volume increases, thereby increasing tracking capacity;
  - Three segments per pass (ascending, middle, descending);
  - Data available for analysis immediately after each pass;
  - Network tracking roster organized for at least 16 GNSS satellites at a time (at least one satellite per orbital plane per system);
  - Tracking cycles set for 30 – 60 days (to cover all satellites within a 12 month period);
  - Greater stress on daylight tracking;
  - Flexible tracking strategies; organized in cooperation with the agencies involved and the requirements for the ITRF;