# Current Trends in Satellite Laser Ranging

Graham Appleby[1], Georg Kirchner[2], Jan McGarry[3]
Thomas Murphy[4], Carey Noll[3], Erricos Pavlis[5], Michael Pearlman[6], Francis Pierron[7]

1 *NERC Space Geodesy Facility, Herstmonceux, UK*
2 Space Research Institute, Austrian Academy of Sciences, Graz, Austria
3 *NASA Goddard Space Flight Center, Greenbelt, MD, USA*
4 *University of California, San Diego, La Jolla, CA, USA*
5 GEST, *University of Maryland, Baltimore, MD, USA*
6 *Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA*
7 *Observatoire de la Cote d'Azure/CERGA, Grasse, France*

# Laser Ranging

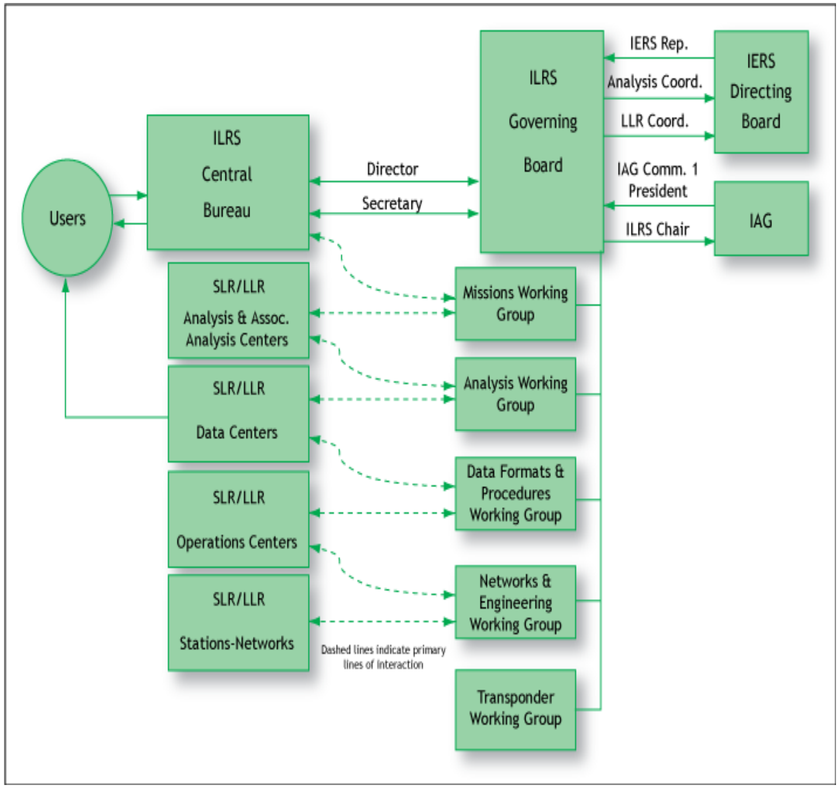
- In the era of the Global Geodetic Observing System (GGOS), high-quality multi-technique sites are crucial:
- The space-observational Services, the **IDS**, **IGS**, **ILRS** and **IVS** together supply the data and products to meet the GGOS Mission;
- Major goals are determination and maintenance of the terrestrial reference frame and determination and monitoring of the Earth's gravity field;
- Realised via inter-technique site ties and combination of analysis products (site position, velocity, Earth orientation) and tracking support for gravity missions
- For ITRF 2008:
  - geodetic laser ranging provided geo-centre and scale;
  - geodetic VLBI provided scale

# International Laser Ranging Service

Established in 1998 as a service under the
International Association of Geodesy (IAG)

The ILRS:

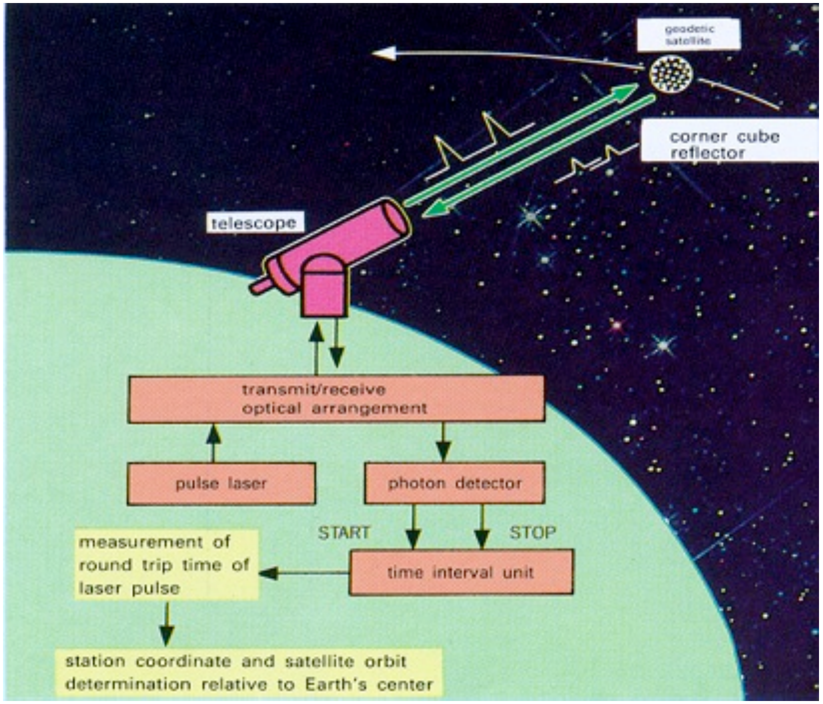
- Collects, merges, analyzes, archives and distributes satellite and lunar laser ranging data to satisfy user needs
- Encourages the application of new technologies to enhance the quality, quantity, and cost effectiveness of its data products
- Produces standard products for the scientific and applications communities:
  - **Including weekly combined station coordinate solutions and daily EOPs from its Analysis Centres**
- Includes 75 agencies in 26 countries



# 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
- Near real-time global data availability
- Satellite altitudes from 400 km to synchronous satellites, and the Moon
- Satellite Orbit Accuracy ~1cm
- Able to see small changes by looking at long time series




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

# SLR Science and Applications

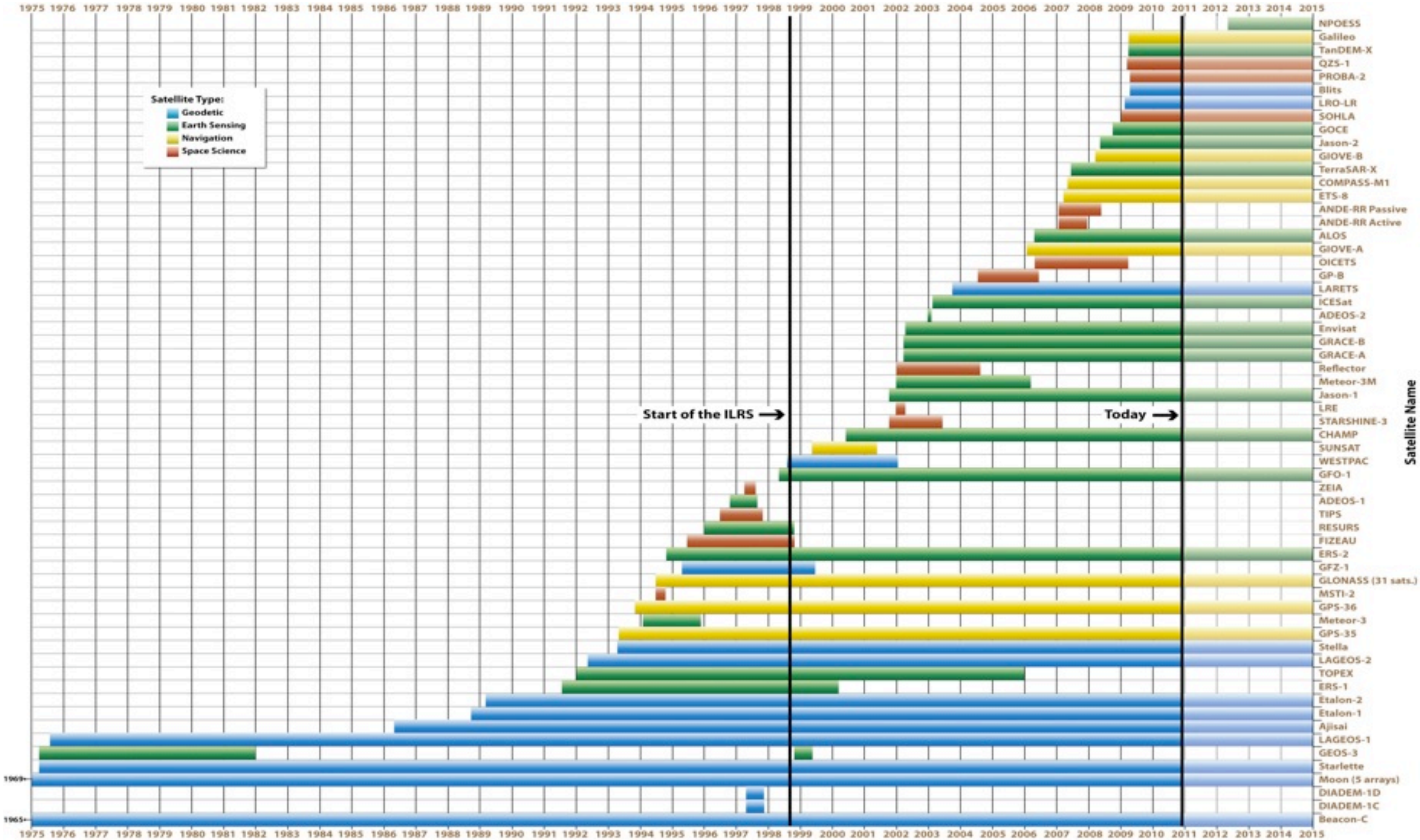
- Measurements
  - Precision Orbit Determination (POD)
  - Time History of Station Positions and Motions
- Products
  - Terrestrial Reference Frame (Center of Mass and Scale)
  - Plate Tectonics and Crustal Deformation
  - Static and Time-varying Gravity Field
  - Earth Orientation and Rotation (Polar Motion, length of day)
  - Orbits and Calibration of Altimetry Missions (Oceans, Ice)
  - Total Earth Mass Distribution
  - Space Science - Tether Dynamics, etc.
  - Relativity Measurements and Lunar Science
- More than 60 Space Missions Supported since 1970
- Five Missions Rescued in the Last Two Decades

# ILRS Tracking Network


~30 global stations provide tracking data regularly
Most of the SLR stations co-located with GNSS; some also with VLBI, DORIS, and Gravity measurements

# Selected SLR Stations Around the World

# Missions supported by the ILRS



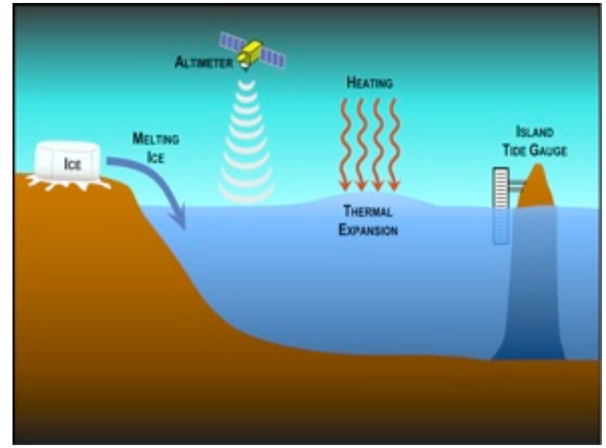
# Sample of SLR Satellite Constellation

## (Geodetic Satellites)

| | Etalon-I & -II | LAGEOS-1 | LAGEOS-2 | Ajisai | Starlette | Stella | Larets |
|---|---|---|---|---|---|---|---|
| Inclination | 64.8° | 109.8° | 52.6° | 50° | 50° | 98.6° | 98.2° |
| Perigee ht. (km) | 19,120 | 5,860 | 5,620 | 1,490 | 810 | 800 | 691 |
| Diameter (cm) | 129.4 | 60 | 60 | 215 | 24 | 24 | 20 |
| Mass (kg) | 1415 | 407 | 405.4 | 685 | 47.3 | 47.3 | 23.3 |

# The Geodetic Reference Frame Requirement

Measurement of sea level change is one of the primary science drivers

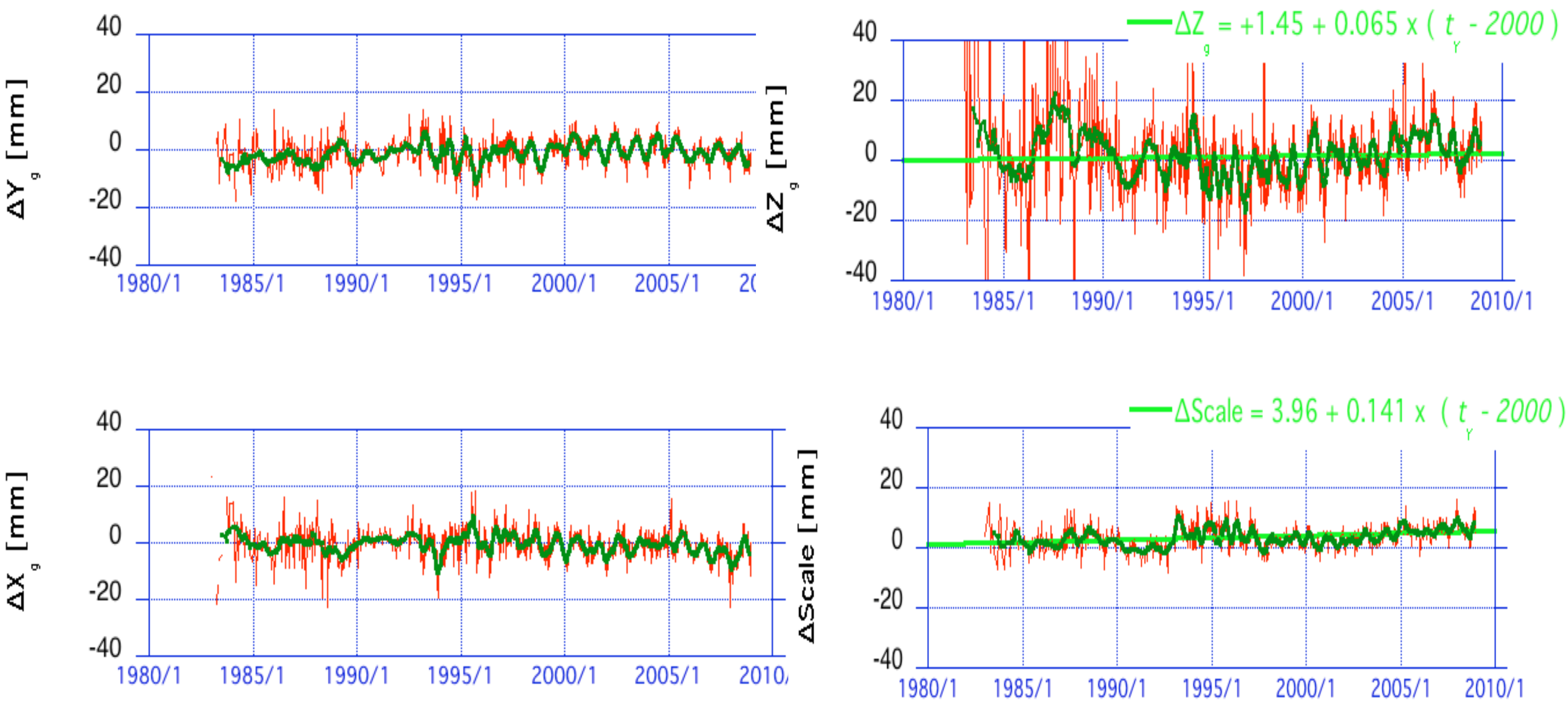



## <1 mm reference frame accuracy

## < 0.1 mm/yr stability

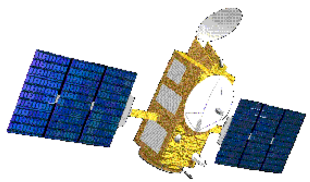
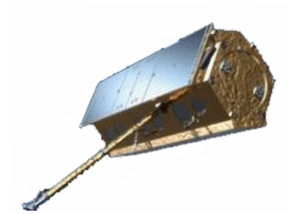
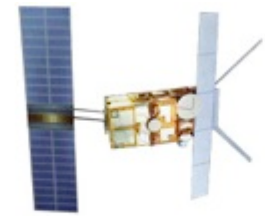
i.e. a factor of 10-20 improvement over current ITRF performance as demonstrated by SLR results for ITRF2008 Origin and Scale variations:

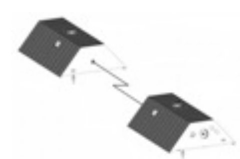
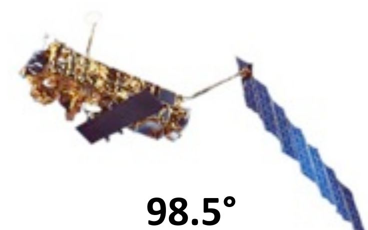
# ITRF2008 Origin and Scale Variations from SLR



# Sample of SLR Satellite Constellation

## (Support for Precise Orbit Determination)

| | Jason-2 | Terra-SAR-X/ TanDEM-X | ERS-2 |
|---|---|---|---|
| |  |  |  |
| **Inclination** | **66°** | **97.4°** | **98.5°** |
| **Perigee ht. (km)** | **1,336** | **514** | **785** |
| **Mass (kg)** | **300** | **1,230** | **2,516** |

| | GOCE | GRACE | Envisat |
|---|---|---|---|
| |  |  |  |
| **Inclination** | **96.7°** | **89°** | **98.5°** |
| **Perigee ht. (km)** | **295** | **450** | **796** |
| **Mass (kg)** | **1050** | **432/sat.** | **8,211** |

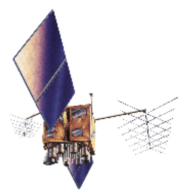
# Growing Need for SLR measurements on the GNSS Constellations

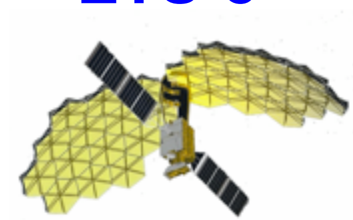
- **Geoscience**
  - Improve the Terrestrial Reference Frame (colocation in space)

  - Improve LEO POD via GNSS tracking of SLR-calibrated GNSS orbits
    - Altimeter satellites

- **GNSS World**
  - Provide independent Quality Assurance: - The GNSS orbit accuracy cannot be directly validated from the GNSS data itself;
  - Assure interoperability amongst GPS, GLONASS, Galileo, COMPASS
  - Insure realization of WGS84 reference frame is consistent with ITRF
  - SLR is NOT required for use in routine / operational RF-derived orbit and clock products
- **GNSS Support** is set to become more demanding, with GALILEO, GPS...

# GNSS Satellite Constellation (High Earth Orbit)

| | GLONASS | GPS | COMPASS | GIOVE | ETS-8 |
|---|---|---|---|---|---|
| Inclination | 65° | 64.8° | 55.5° | 56° | 0° |
| Perigee ht. (km) | 19,140 | 20,195 | 21,500 | 23,920 | 36,000 |
| Mass (kg) | 1,400 | 930 | 2,200 | 600 | 2,800 |

# GNSS laser ranging

- Particularly challenging for stations because of distance:
  - Up to 24,000 km for GIOVE/ GALILEO
- Imperative that laser reflector arrays have sufficient radar cross-section to support day/ night ranging
- ILRS recommendation to LRA industry: $100 \times 10^6$ $m^2$
- Collaboration with array Test Facility in Frascati
  - Potential for development of novel arrays

# What technology/modelling developments are on-going within the current ILRS Network

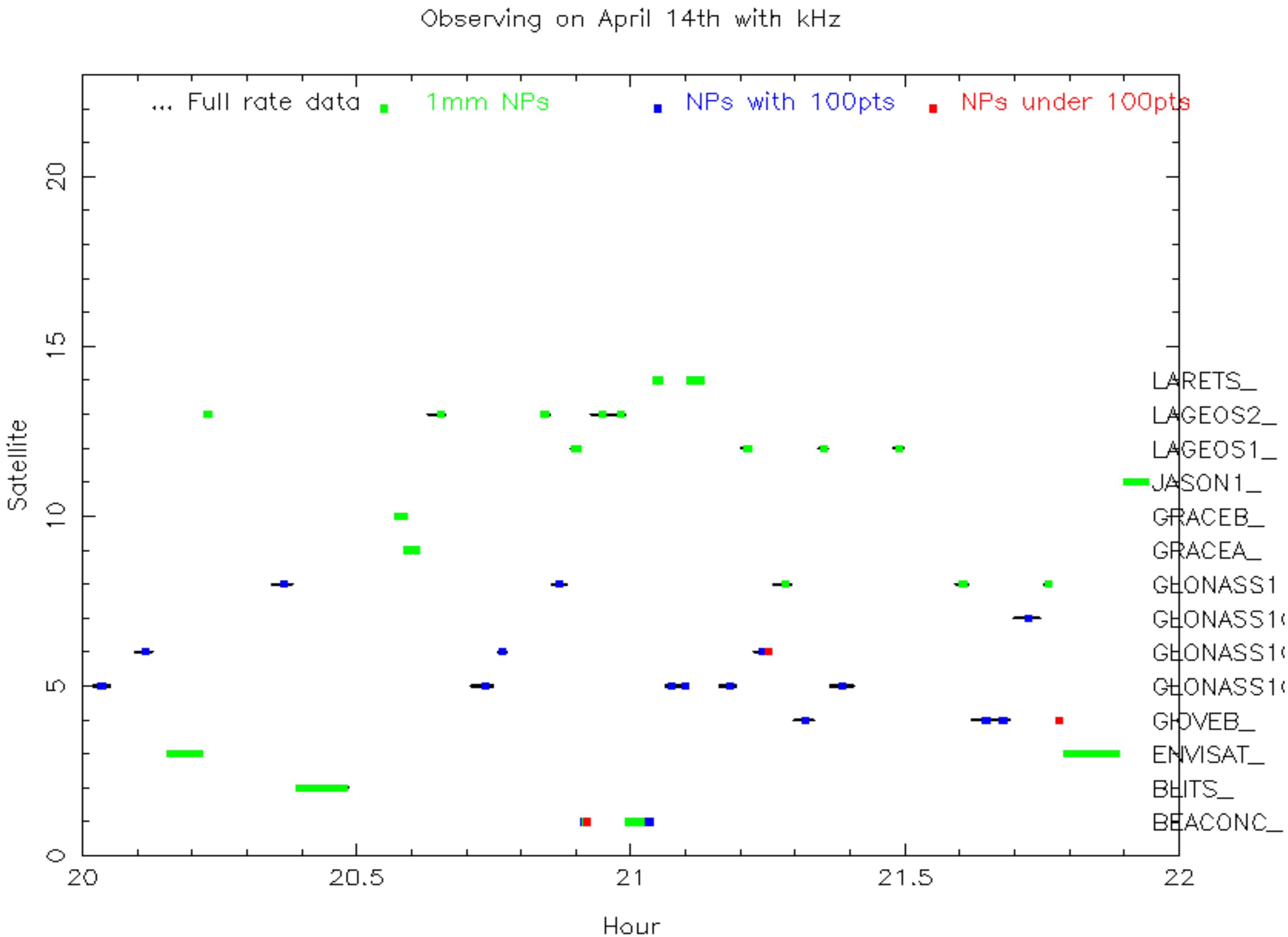
- To address this need for improvement and to expand the technique into new applications:

- 2 kHz operation:
  - to increase data yield and hence normal-point precision
  - improve efficiency of satellite interleaving
  - new science from attitude-monitoring
- Eye-safe operations and auto tracking
- Automation (unattended operation)
- Event timers with near-pico-sec resolution
- Evaluation of hardware-induced observational error
- Improved modelling of satellite mass-centre corrections
- **Some examples**:

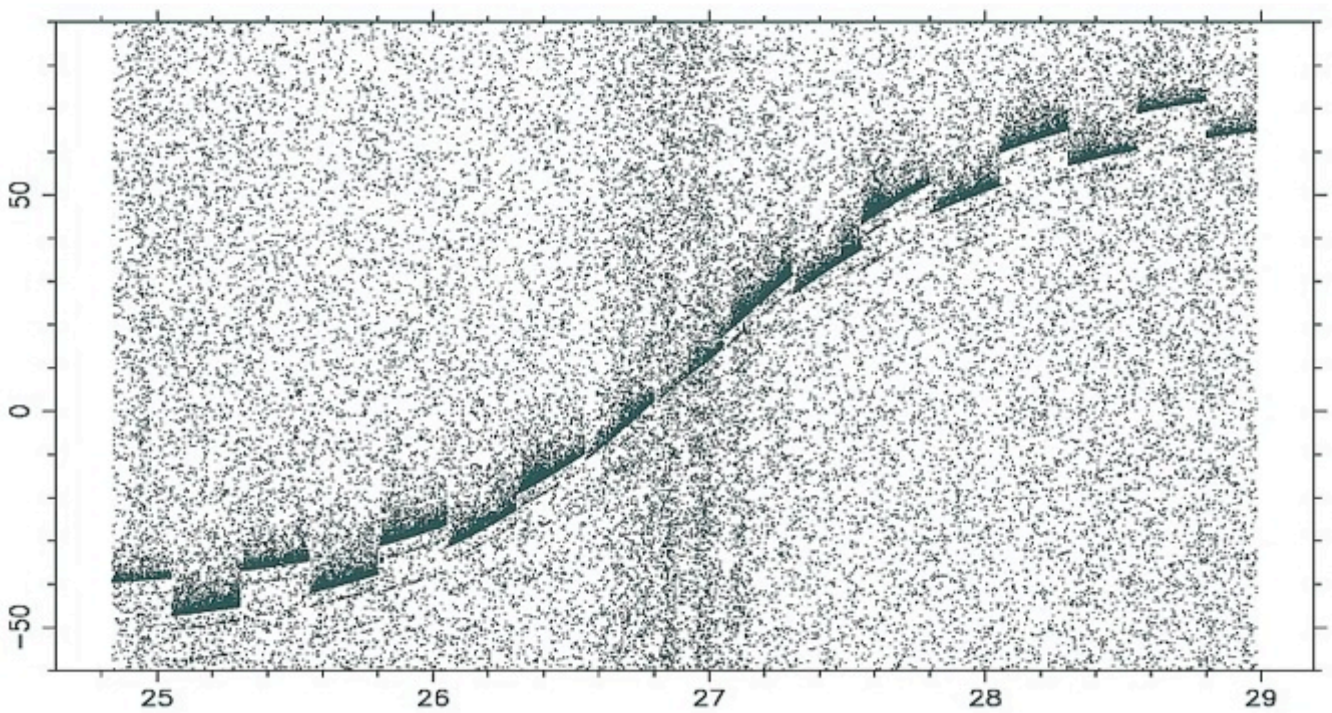
# High repetition-rate, automation

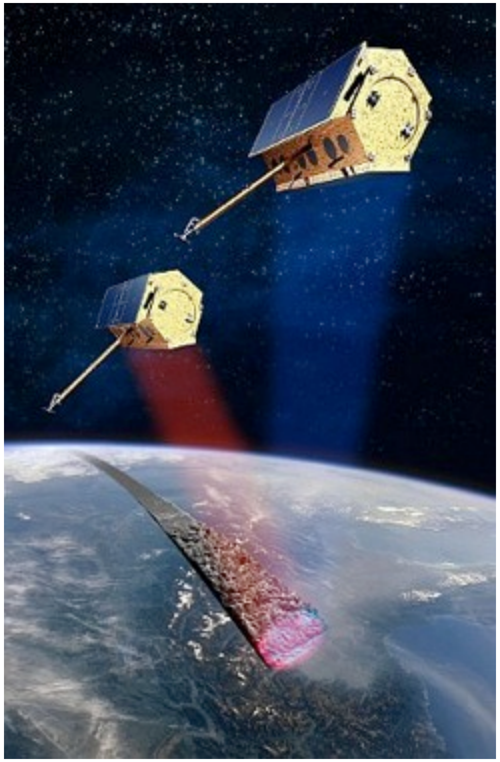
- Prototype Automated SLR System at NASA Goddard Space Flight Center;
- some other ILRS stations have upgraded to kHz repetition rates:
- Improved ranging precision through need to upgrade event timers
- Other benefits:

# Experiment to obtain 1mm precision per NP



# Very rapid switching between TanDEM-X and TerraSAR-X

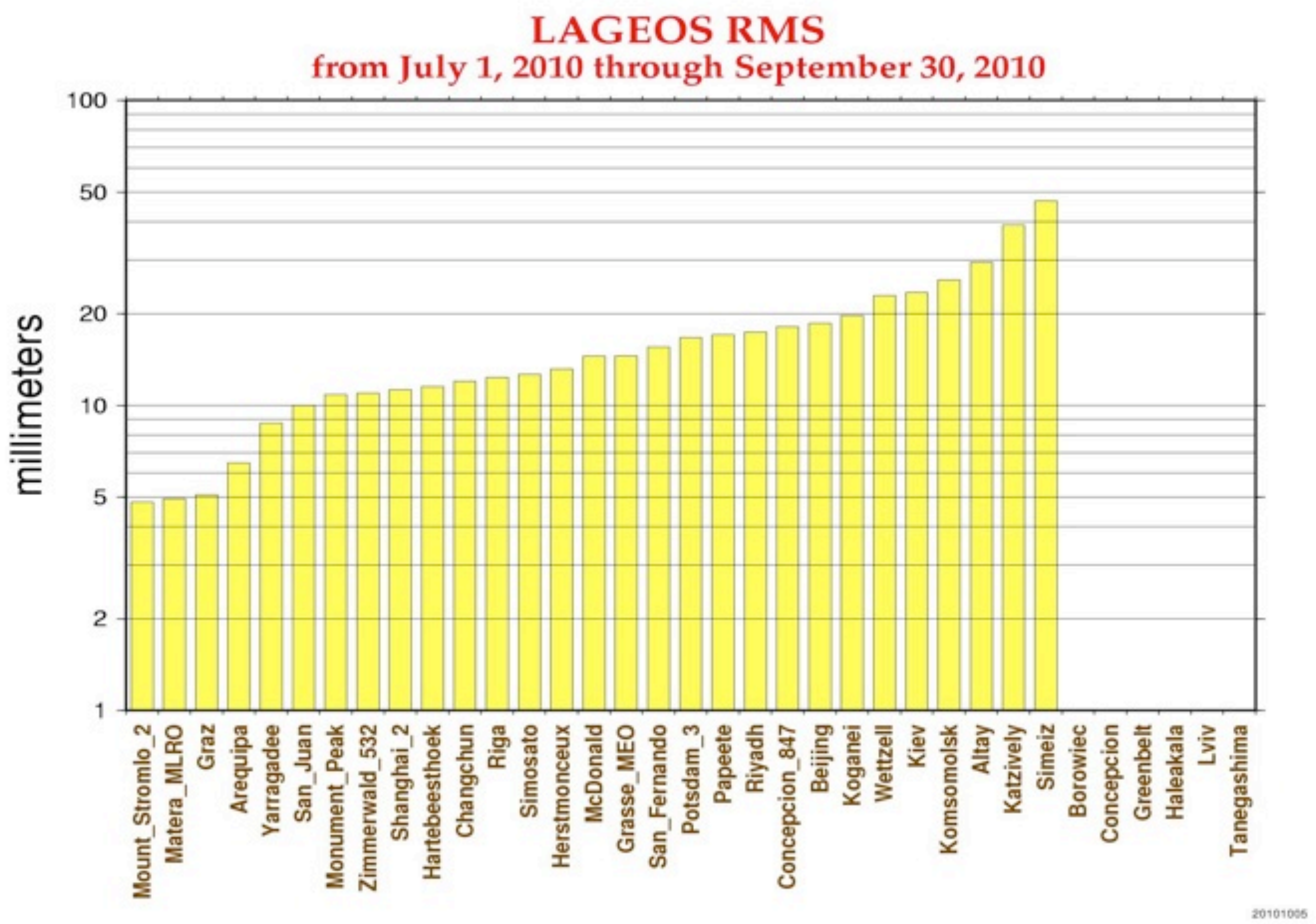


# Ranging accuracy

- Even more important than rapid acquisition and pass-interleaving is range accuracy, especially for the geodetic satellites;
- Dependent upon:
  - Ranging system technology – time of flight measurement, laser pulse-length
  - Accuracy of survey to calibration board
  - Ability to model accurately the **centre-of-mass** corrections for a non-homogeneous network:

# Range data quality assessment by ILRS - single-shot precision



# Magnitude of CoM effect

- Depending upon the stations' technology, there is a range of appropriate CoM values;

- For LAGEOS the total range is **~6mm**
- For ETALON the total range is **~5cm**

- Note that station technology is also **time-dependent**
- We have developed a table of CoM corrections
  - station- and time-dependent.
- Will be tested and used in next re-analysis.

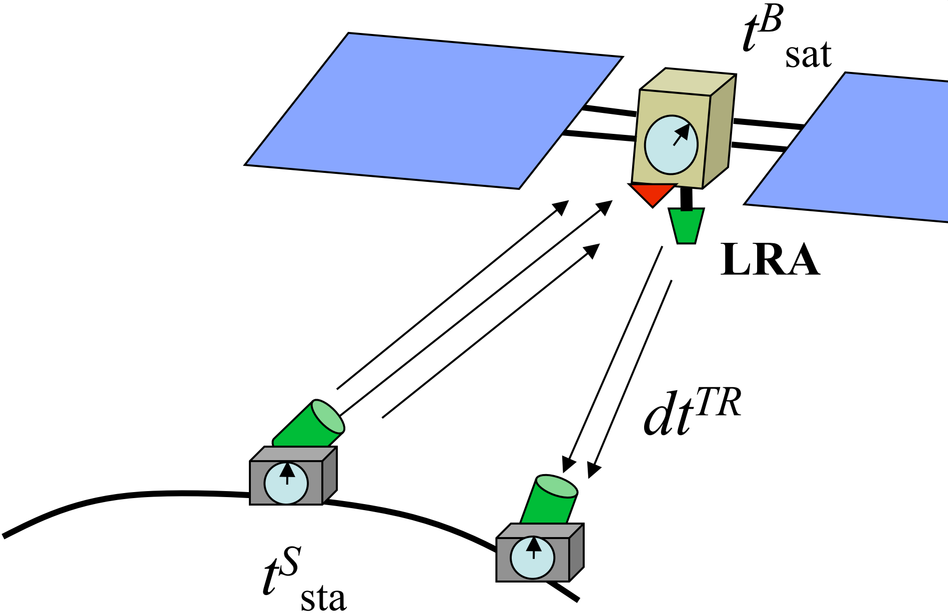
# New applications

- Especially for the more versatile SLR stations, a number of novel missions:

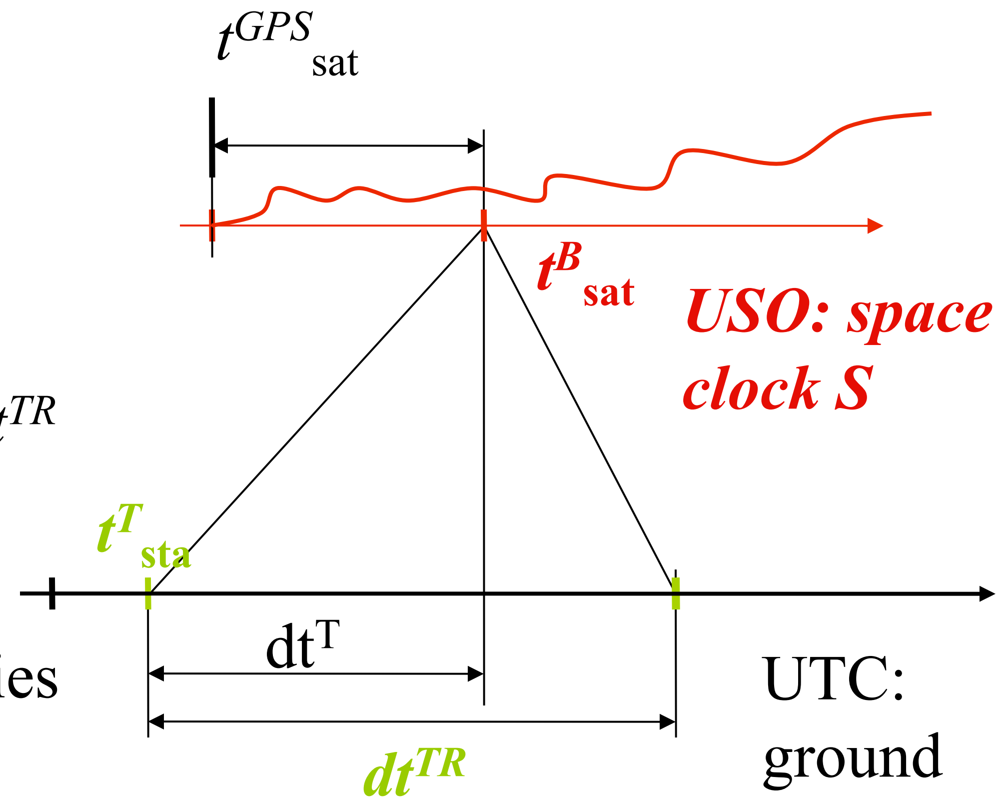
- Time Transfer by Laser Link (T2L2, CNES)
- Lunar Reconnaissance Orbiter (LRO, NASA)

  – Stations with high-accuracy clocks and frequency standards (H-maser) particularly valuable to the missions

# T2L2 Timing Experiment




$t^R_{sta} = t^S_{sta} + dt^{TR}$



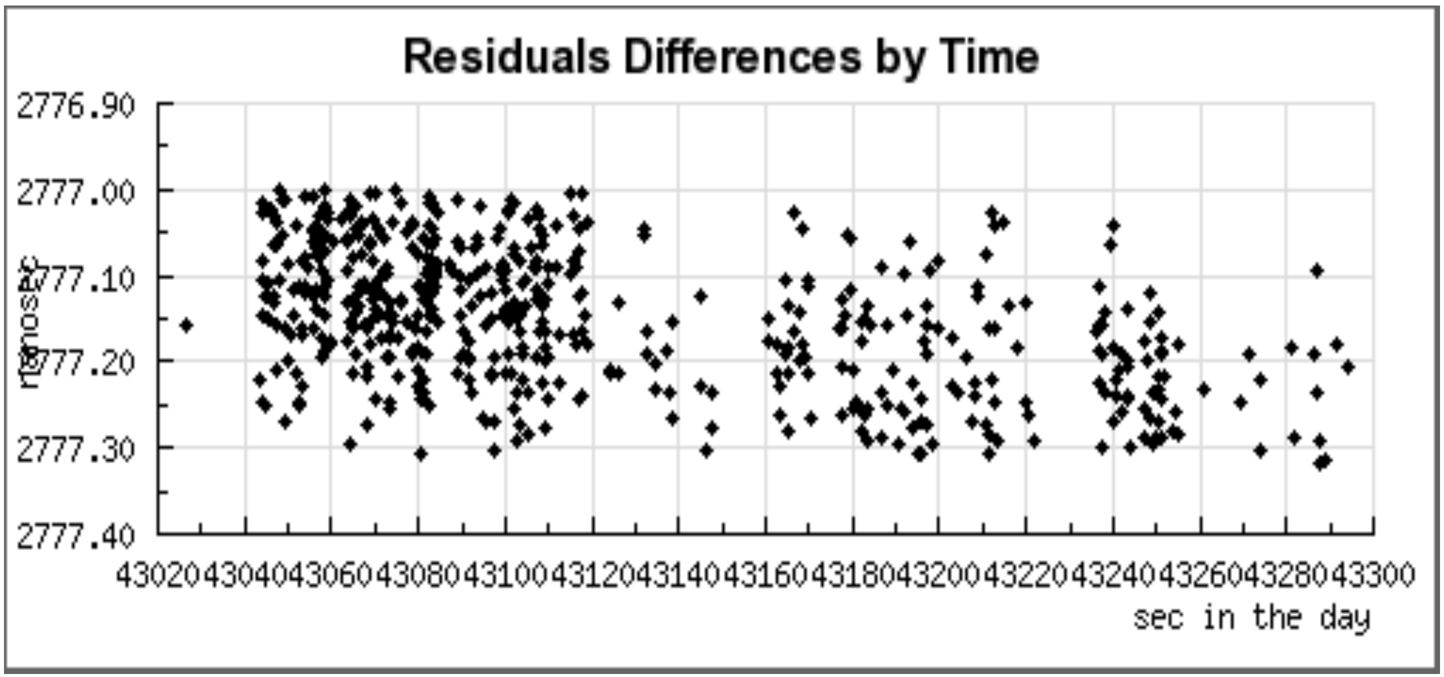

$t^S_{sta}$, $dt^{TR}$, $t^B_{sat}$ : measured quantities = « triplet »

(dt$^T$ is computed from $dt^{TR}$)

$$X_A = (t_S + t_R)/2 - t_B + \tau_{Relativity} + \tau_{Atmosphere} + \tau_{Instrument}$$

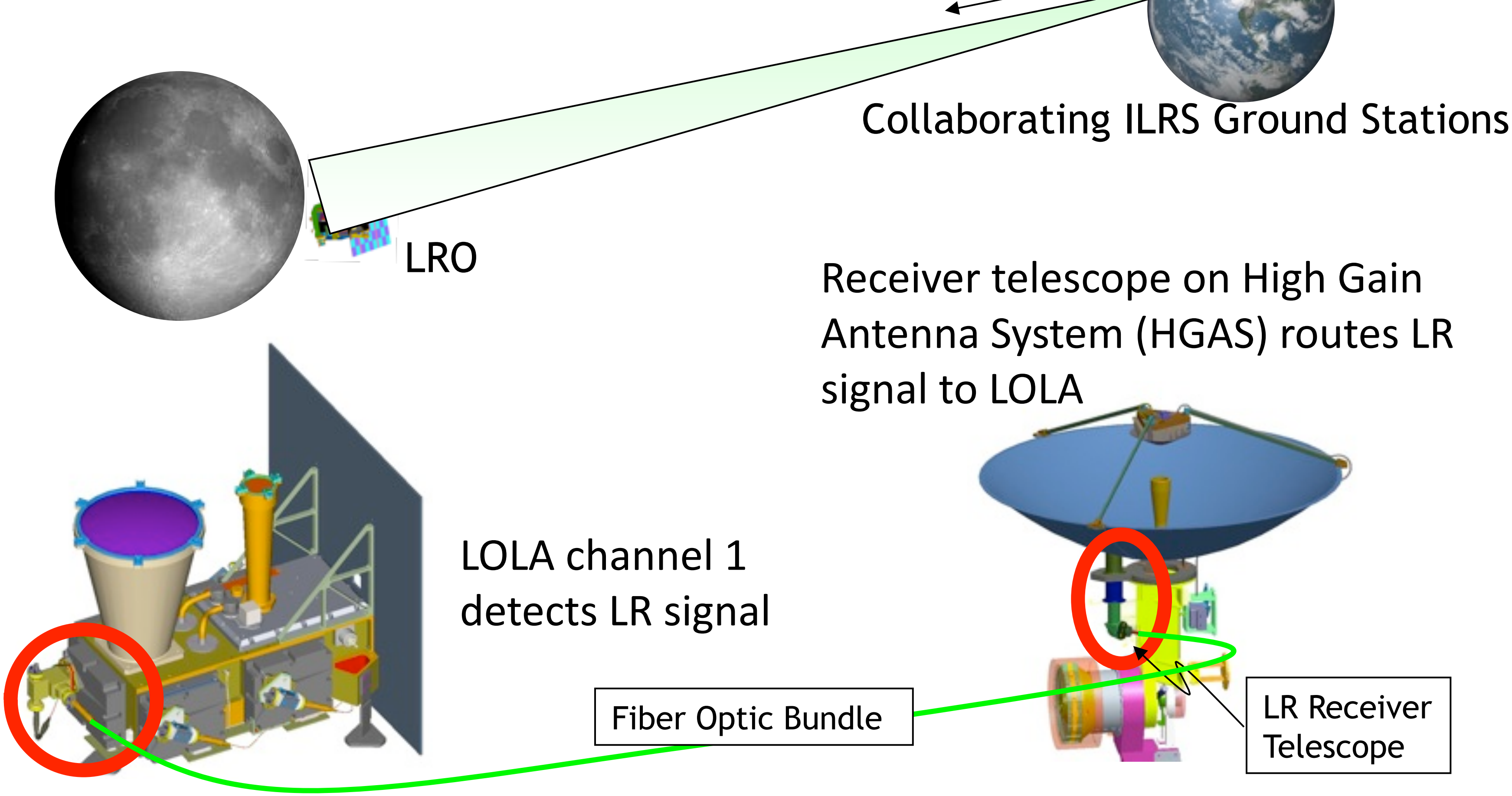
# Two-station time-transfer at ~200ps level of precision.

**Date : 20101119     Station #1 : 7845     Station #2 : 7840.  5-minute common data**
**(Samain, *et al*. CNES, OCA)**



# LRO Laser Ranging

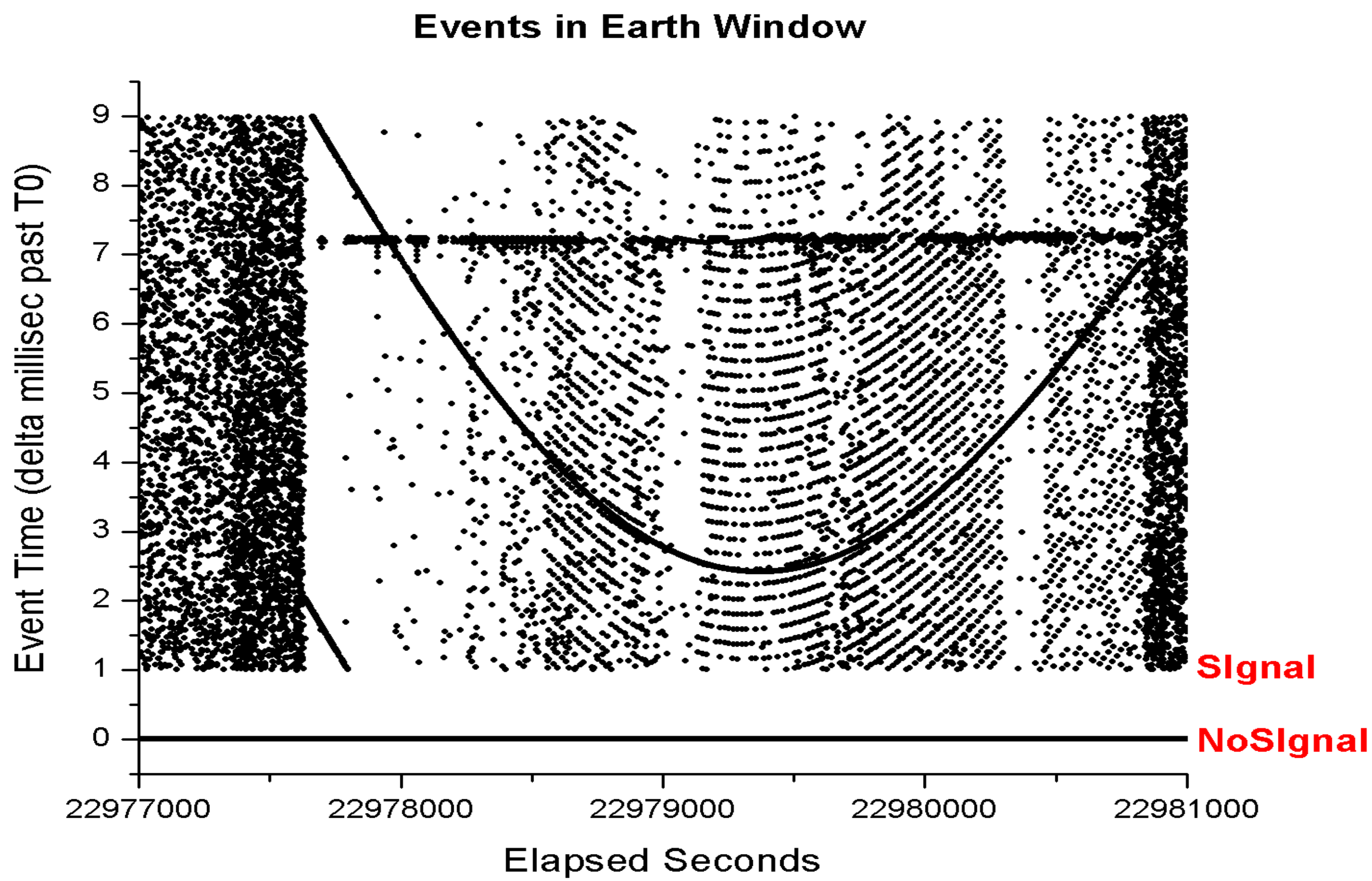
- Transmit 532nm laser pulses at 28 Hz to LRO
- Time stamp departure and arrival times



# LRO Ranging progress

- Some 750 hours of 'ranging' from up to seven ILRS stations
- Recently a number of simultaneous tracking sessions by 2 and 3 stations:
  - NGSLR, McDonald and Monument Peak
- Agreements between the stations and NASA being extended for further two years

# LRO Ranging: 3-station simultaneous tracking in LRO range window



# Summary

- ILRS organisationally effective
- Open to new challenges and missions:
  - Continuing need to improve data quality;
  - Upgrade ageing systems;
  - Improve geographic distribution
  - Effective support for transponder missions
    - T2L2, LRO, future Mars/Phobos/Deimos probe
- Improving Lunar Ranging capability, but yet to become routine for stations