An Overview of Satellite Laser Ranging (SLR)

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NASA / GSFC / 694

June 2012

NGSLR Team

John Annen (automation lab lead, hardware development) - GSFC/694
Jack Cheek (software lead, sysadmin, real-time software) - SigmaSpace
Bart Clarke (software: OD, SLR data analysis, signal processing) - Honeywell
John Degnan (lasers, SLR theory, original SLR2000 concept) - SigmaSpace
Bud Donovan (hardware lead, deputy NGSLR lead, laser safety) – Honeywell
Felipe Hall (documentation lead) – Honeywell
Evan Hoffman (hardware development & sustaining engineering) - Honeywell
Julie Horvath (config control & collocation lead, i/f with ILRS) - Honeywell
Tony Mann (software: unix sysadmin, device drivers) - Honeywell
Jan McGarry (NGSLR lead, algorithm & software development) - GSFC/694
Alice Nelson (hardware development & sustaining engineering) - Honeywell
Don Patterson (hardware develop., sustaining & system engineering) - Honeywell
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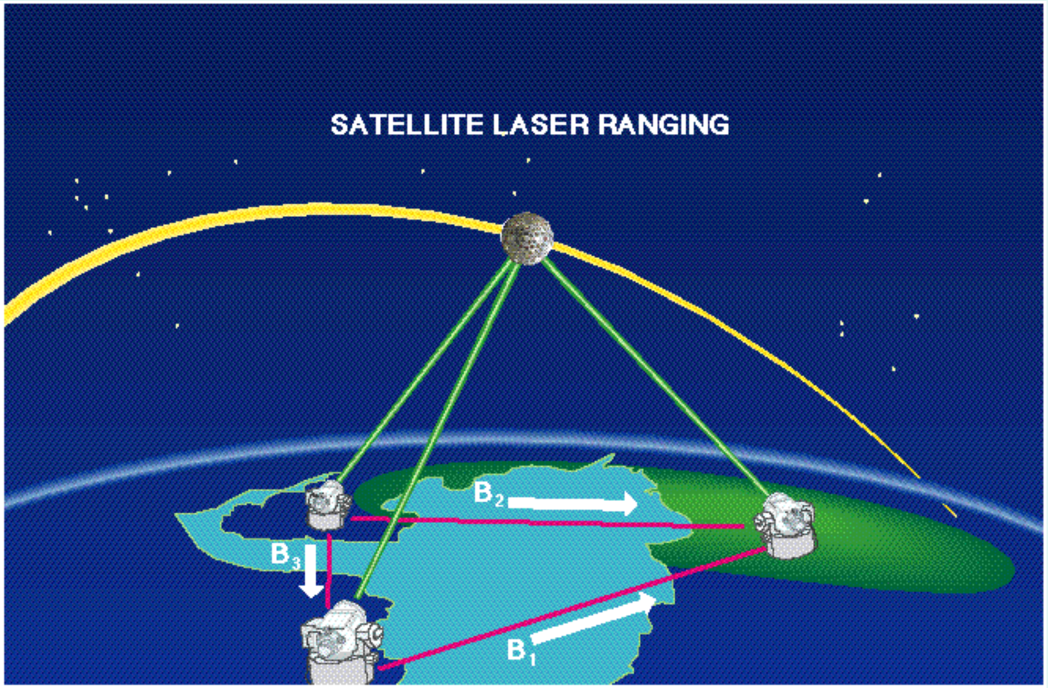
Mark Torrence (SLR analysis) - SGT
Tom Varghese (system engineering) – Cybioms
Scott Wetzel (cross-SGP integration) - Honeywell
Tom Zagwodzki (system engineering) - Cybioms

Satellite Laser Ranging Technique

Observable: The precise measurement of the roundtrip time-of-flight of an ultrashort (< 500 psec) laser pulse between an SLR ground station and a retroreflector- equipped satellite which is then corrected for atmospheric refraction using ground-based meteorological sensors.

- **Unambiguous time-of-flight measurement**
- **1 to 2 mm normal point precision**
- **Passive space segment (reflector)**
- **Simple refraction model**
- **Night / Day Operation**
- **Near real-time global data availability**
- **Satellite altitudes from 300 km to 22,000 km (GPS, GLONASS) and the Moon**
- **Centimeter accuracy satellite orbits**

  ~ 1-2 cm (LAGEOS) & ~2-3 cm (GPS)



SLR generates unambiguous centimeter accuracy orbits!

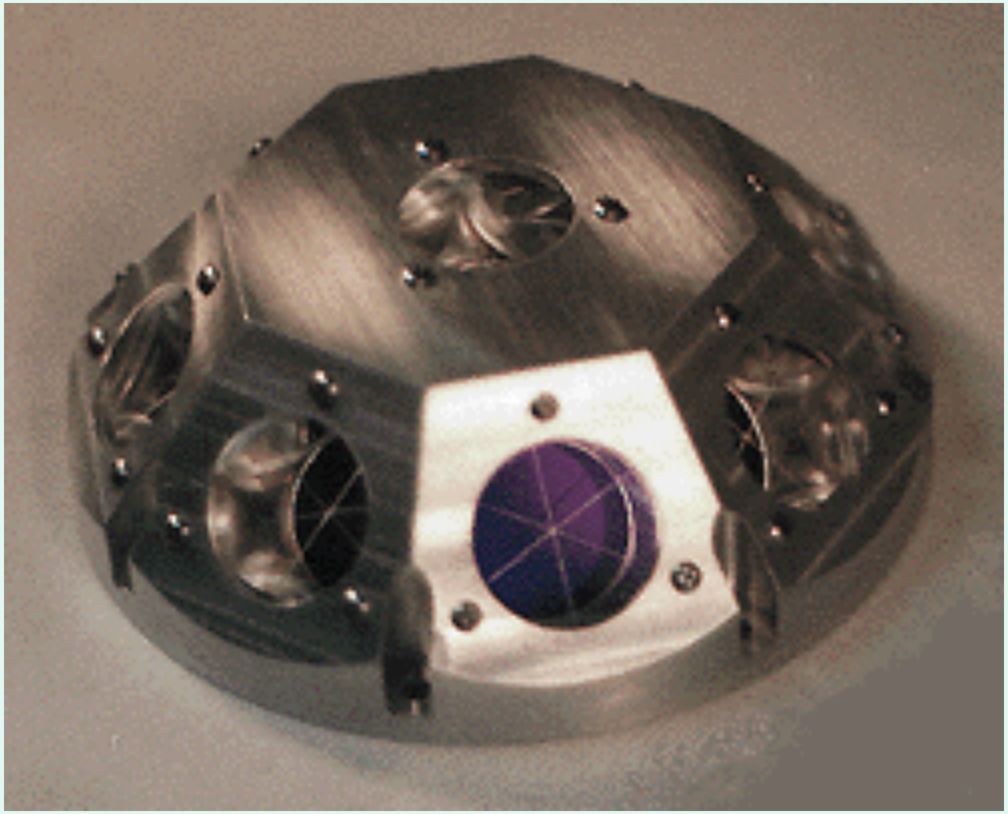
SLR Retro-Reflector Array (RRA): GPS 35,36

32 cubes – each 28mm
Aluminum coated reflective surfaces
Array shape: planar square
Array size: 239 x 194 x 37 mm
Array mass: 1.27 kg

Solid cubes

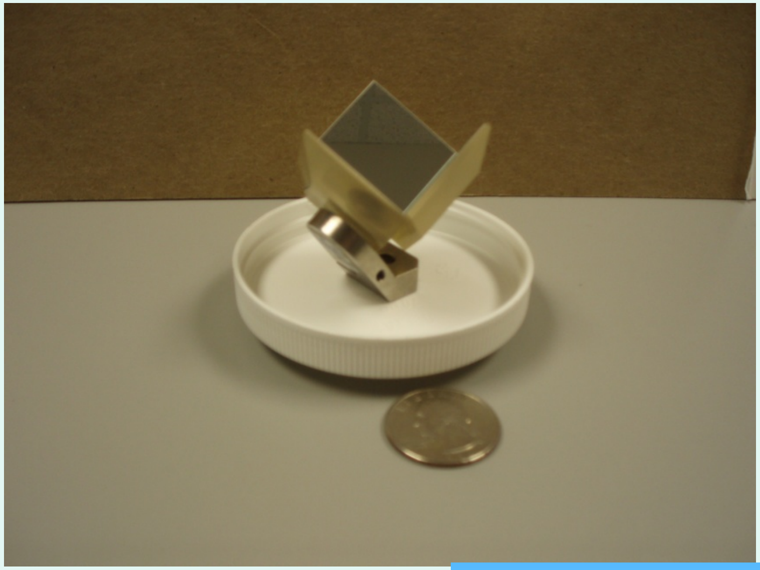
Retro-Reflector Array (RRA): JASON (GFO, ADEOS-II)

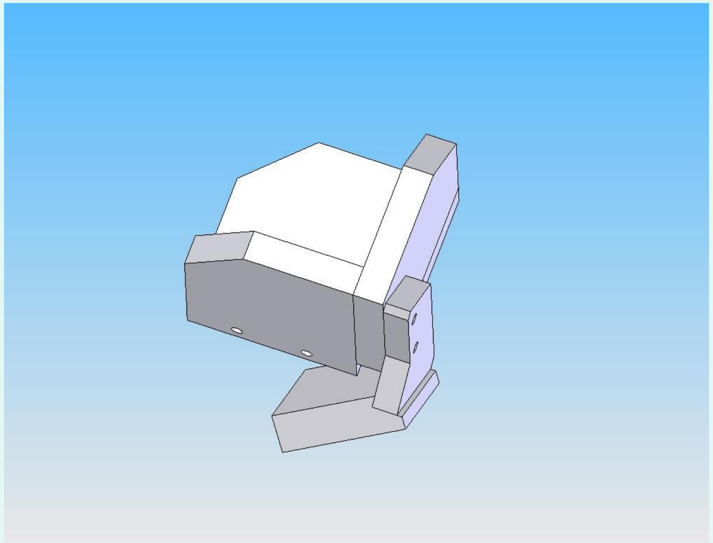
9 cubes – each 32 mm - 1 nadir pointing and 8 on sides
Research grade radiation resistant suprasil quartz, silver coated
Arrray shape: hemispherical
Array size: 16cm diameter
Array mass: 731 gm

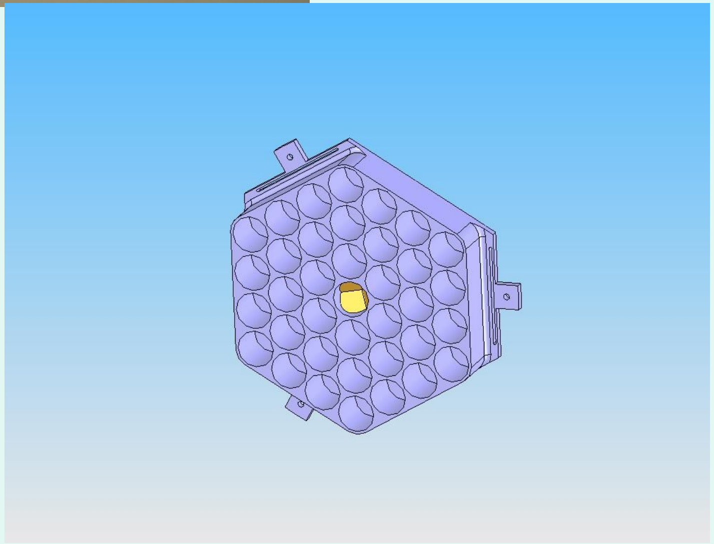


Solid cubes

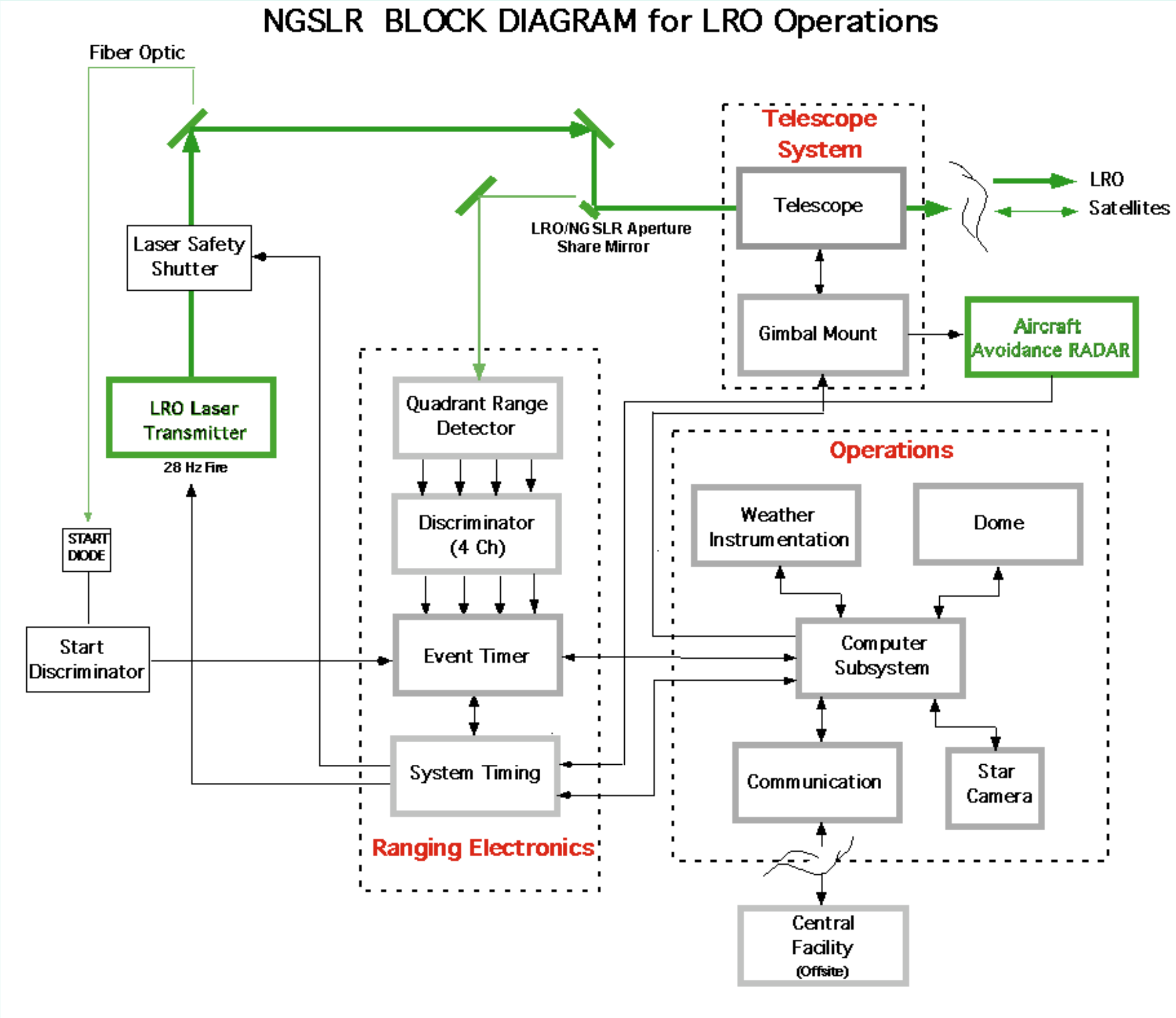
Hollow Corner Cubes







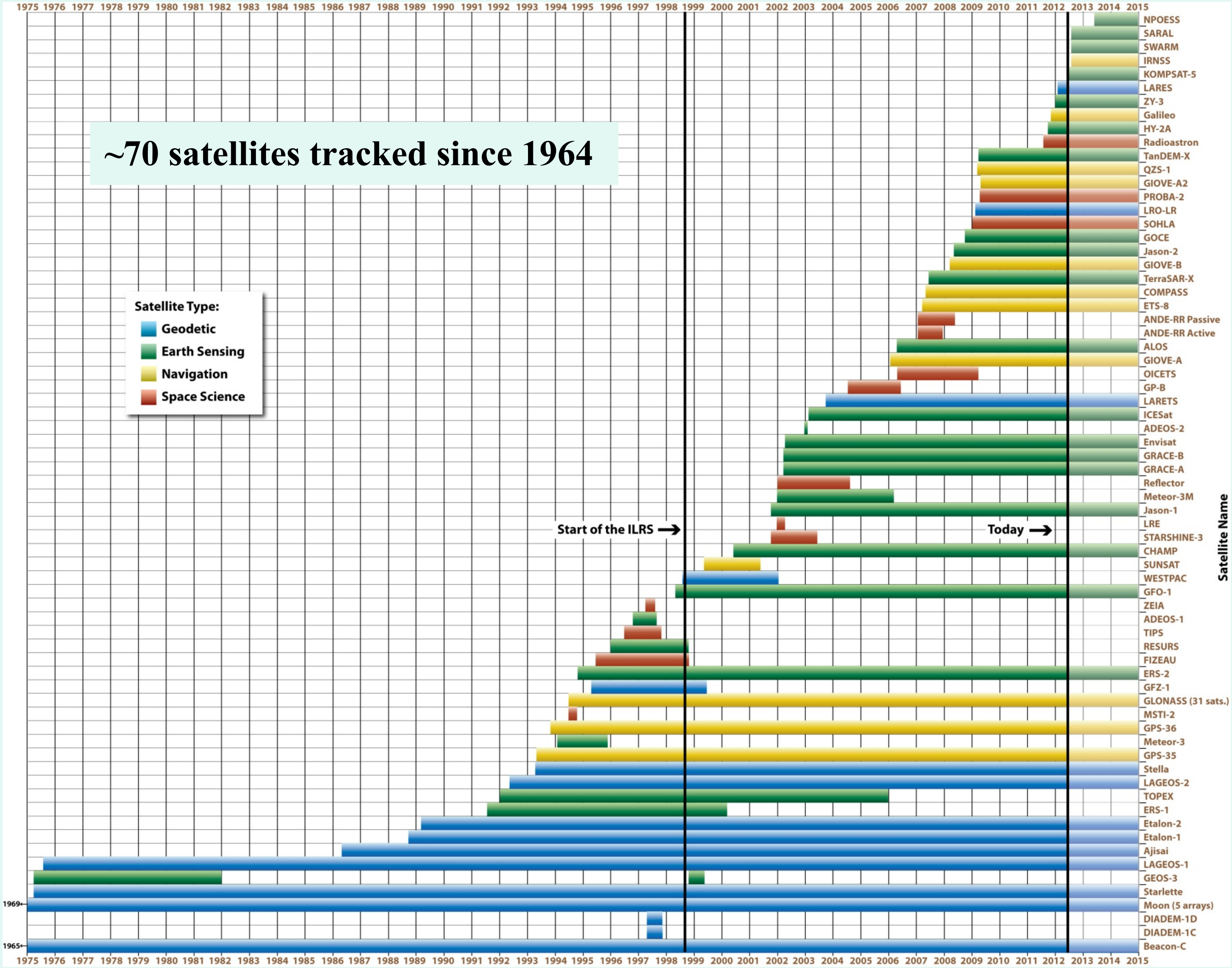
NGSLR Block Diagram



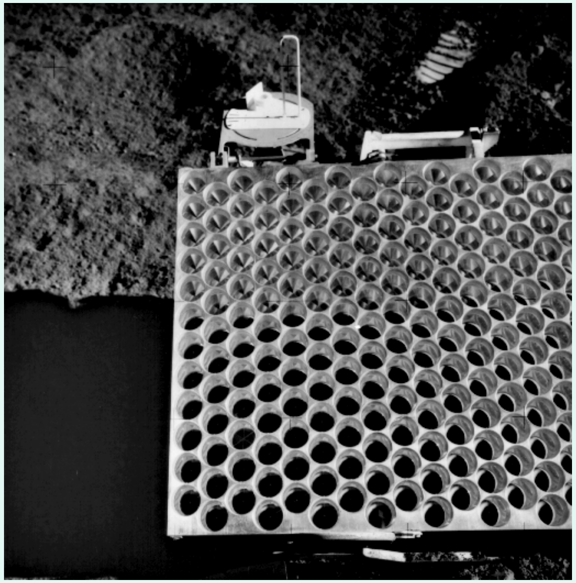
Science Applications of Satellite and Lunar Laser Ranging

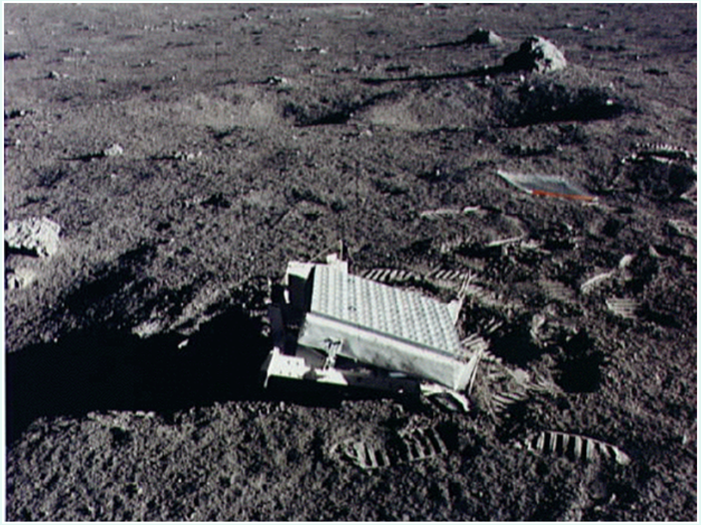
- Earth Gravity Field
  - Static medium to long wavelength components
  - Time variation in long wavelength components
  - Mass motions within the solid Earth, oceans, and atmosphere
- Lunar Physics (LLR)
  - Centimeter accuracy lunar ephemerides
  - Lunar librations (variations from uniform rotation)
  - Lunar tidal displacements
  - Lunar mass distribution
  - Secular deceleration due to tidal dissipation in Earth's oceans
  - Measurement of $G(M_E + M_M)$
- General Relativity
  - Test/evaluate competing theories
  - Support atomic clock experiments in aircraft and spacecraft
  - Verify Equivalence Principle
  - Constrain β parameter in the Robertson-Walker Metric
  - Constrain time rate of change in G
- Future Applications
  - Global time transfer to 50 psec to support science, high data rate link synchronization, etc (French T2L2 Experiment)
  - Two-way interplanetary ranging and time transfer for Solar System Science and improved General Relativity Experiments (Asynchronous Laser Transponders)
- Terrestrial Reference Frame (SLR)
  - Geocenter motion
  - Scale (GM)
  - 3-D station positions and velocities (>50)
- Solar System Reference Frame (LLR)
  - Dynamic equinox
  - Obliquity of the Ecliptic
  - Precession constant
- Earth Orientation Parameters (EOP)
  - Polar motion
  - Length of Day (LOD)
  - High frequency UT1
- Centimeter Accuracy Orbits
  - Test/calibrate microwave navigation techniques (e.g., GPS, GLONASS, DORIS, PRARE)
  - Support microwave and laser altimetry missions (e.g., TOPEX/Poseidon, ERS 1&2, GFO-1, JASON, GLAS, VCL)
  - Support gravity missions (e.g. CHAMP, GRACE, Gravity Probe B)
- Geodynamics
  - Tectonic plate motion
  - Regional crustal deformation

Space Missions Tracked by SLR



Lunar Laser Ranging (LLR) to retro-reflectors

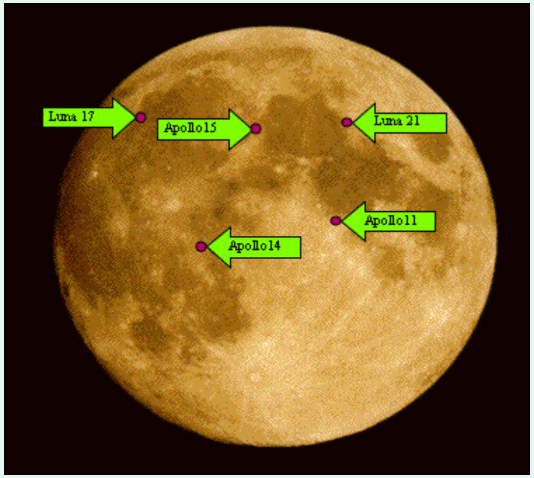




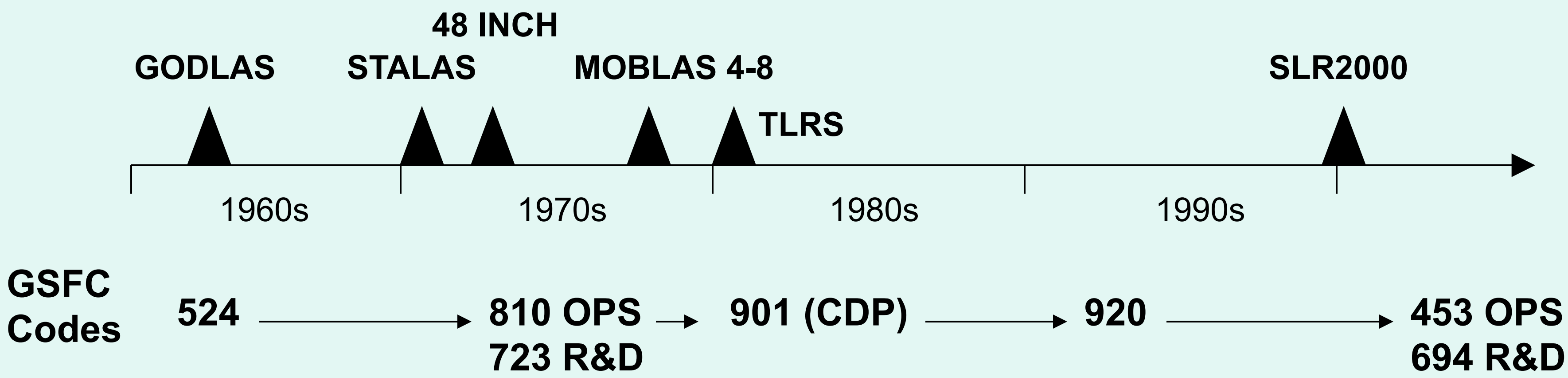
• There are 5 retro-reflectors arrays: 3 Apollo and 2 Luna.

• Apollo RRA's have 3.8 cm cubes. Apollo 11 & 14 have 100, Apollo 15 has 300.

• Regularly tracked by only a few stations. NASA funded University of Texas (MLRS) has successfully ranged continuously since 1970s. Ranges are accurate to a few centimeters.



SLR at GSFC



GSFC invented and developed Satellite Laser Ranging and continues to advance SLR R&D, however, there have been many contributors to SLR over the years, including SAO & U.Texas in U.S. and many international groups.

Goddard Geophysical and Astronomical Observatory (GGAO) formerly Goddard Optical Research Facility (GORF)

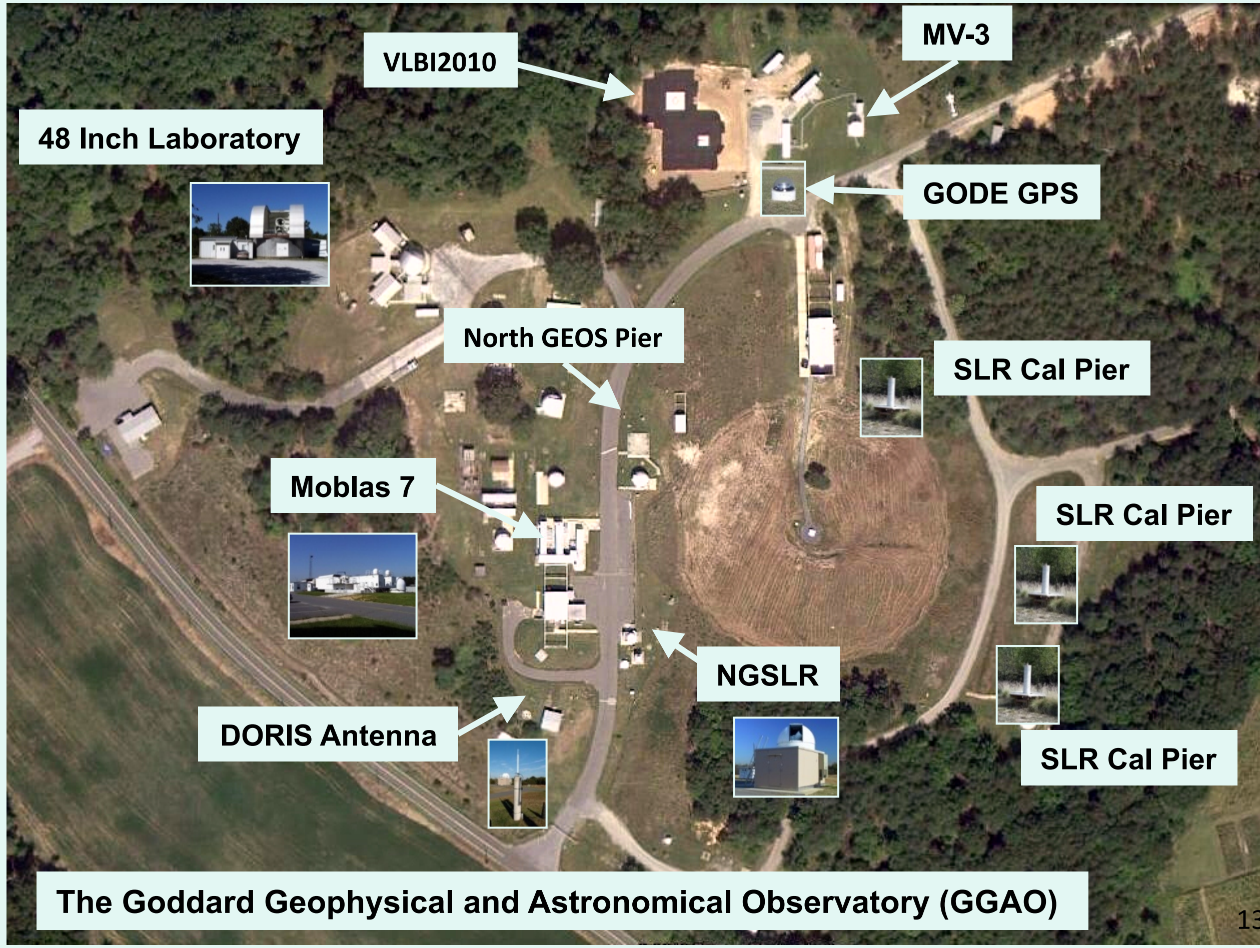
- Located ~ 3 miles from GSFC in middle of BARC on Springfield Road.

- Home to MOBLAS-7, 48” telescope, VLBI MV3, GPS, and numerous other facilities and experiments.

- GGAO has been the site of all NASA SLR system development, testing and collocations. The Italian MLRO system, the Saudi SALRO, and other ILRS systems have also been developed and tested at site.

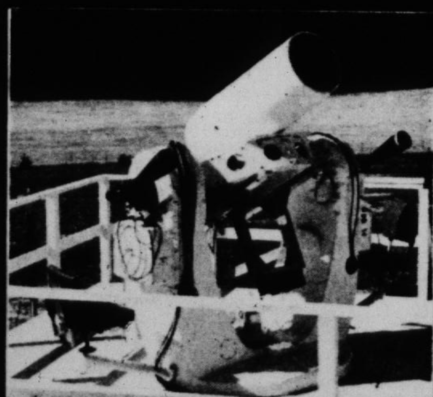
NASA GSFC GGAO Fundamental Station

- GSFC GGAO currently one of only a few Fundamental Stations in the SLR community.
- SLR (NGSLR), VLBI (VLBI2010) and GPS facilities being developed and integrated into the Fundamental Station concept.
- These techniques will be tied with a survey technique developed to monitor the site ties on a regular basis.



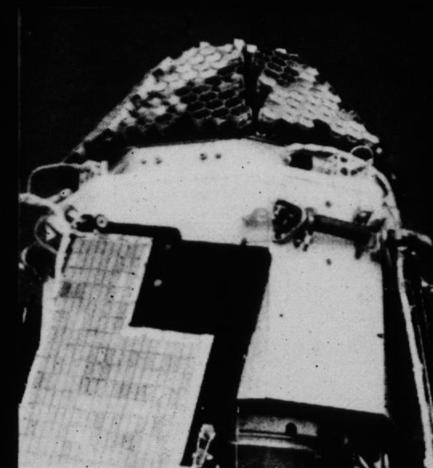
GSFC records first SLR returns ever on Oct 31, 1964
(GSFC team lead by Henry Plotkin)

SATELLITE LASER RANGING - 1964



TRANSMITTING LASER AND RECEIVING TELESCOPE, MOUNTED ON A MODIFIED NIKE-AJAX RADAR PEDESTAL.

GODLAS

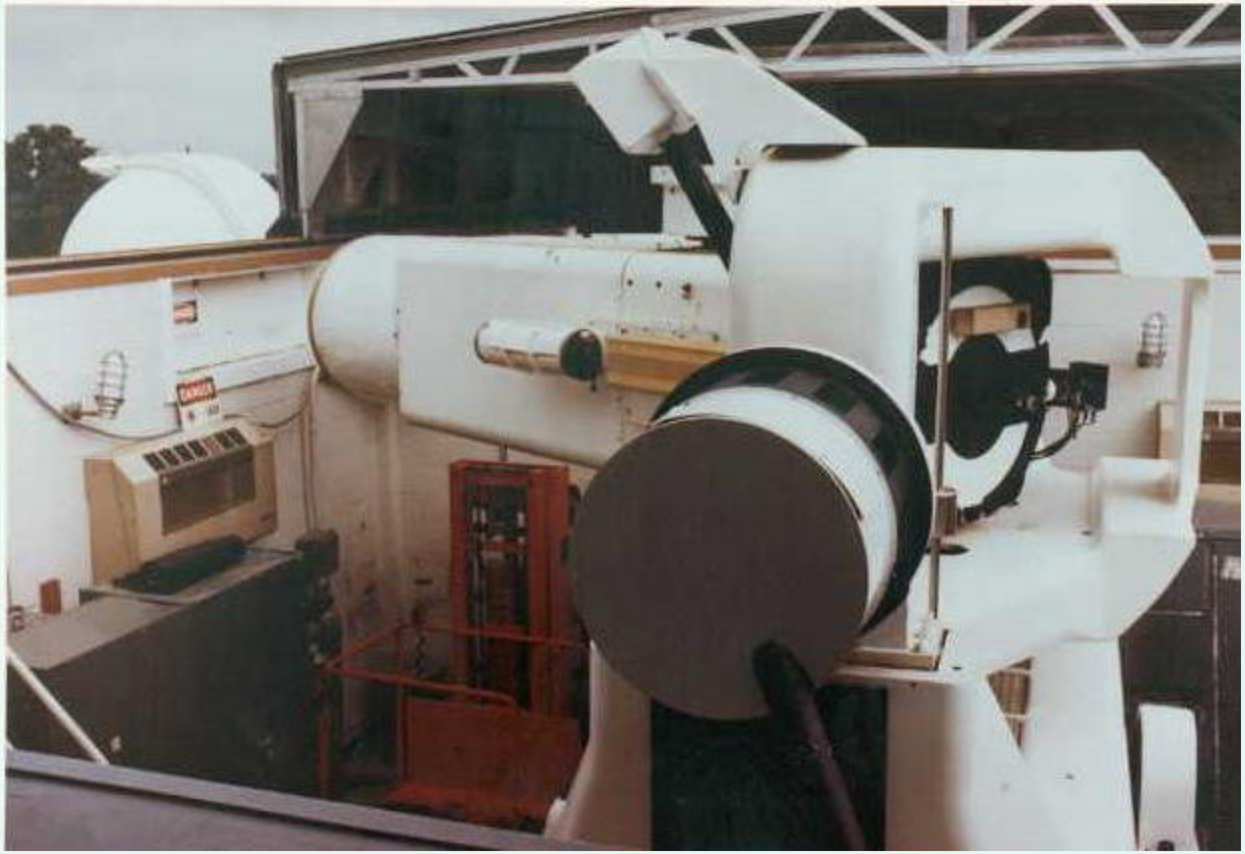


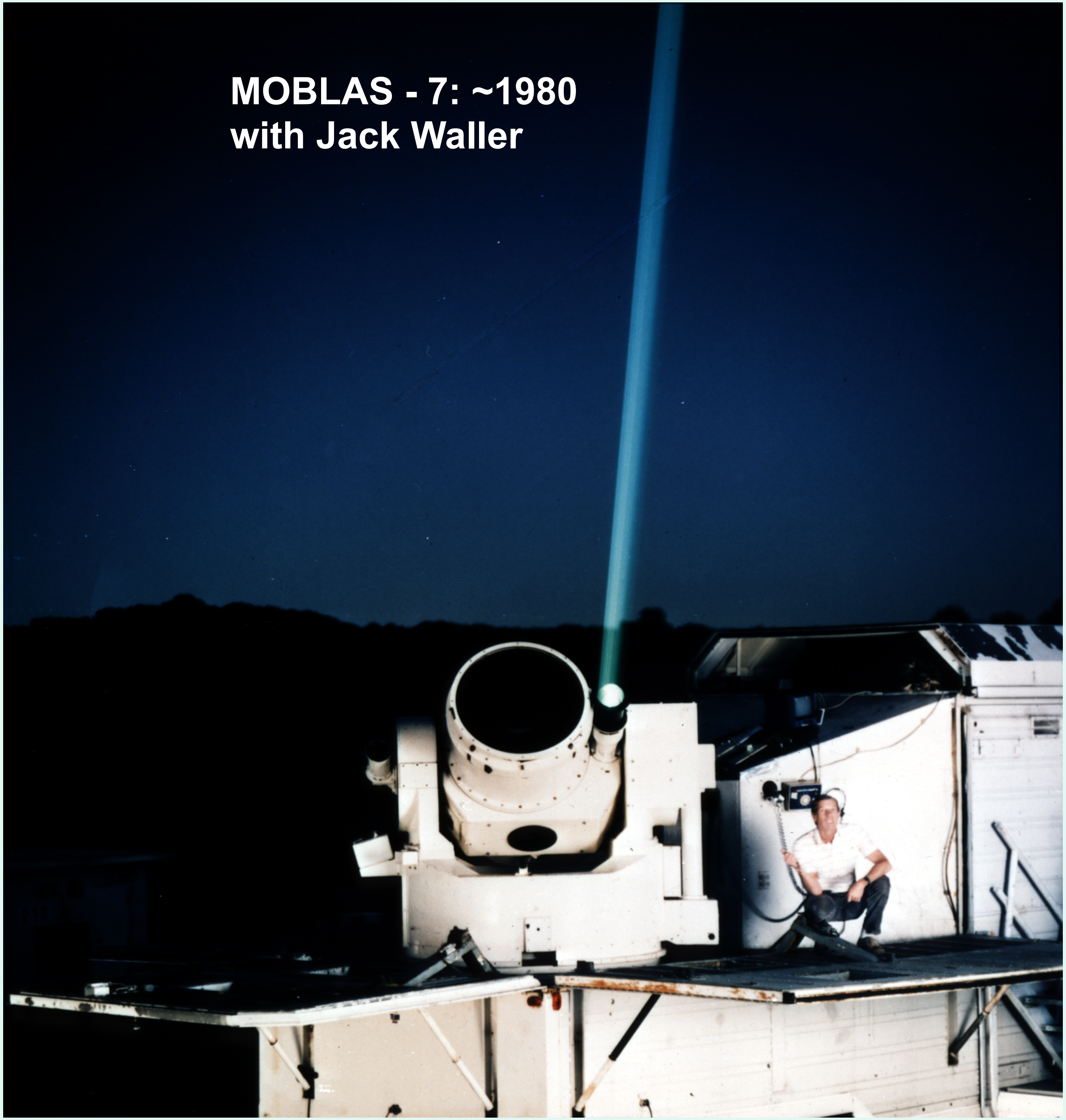
THE BEACON EXPLORER-B SATELLITE WITH ARRAY OF CUBE-CORNER REFLECTORS.

BE-B: first satellite with retro-reflectors

STALAS

- Developed in early 1970s as a "stationary laser" system at GORF.
- X-Y mount with 61cm (24") telescope.
- Initial system had 1 Hz ruby (694nm) laser.





-Systems built in 1978 by Contraves (telescope & mount), and BFEC (electronics).

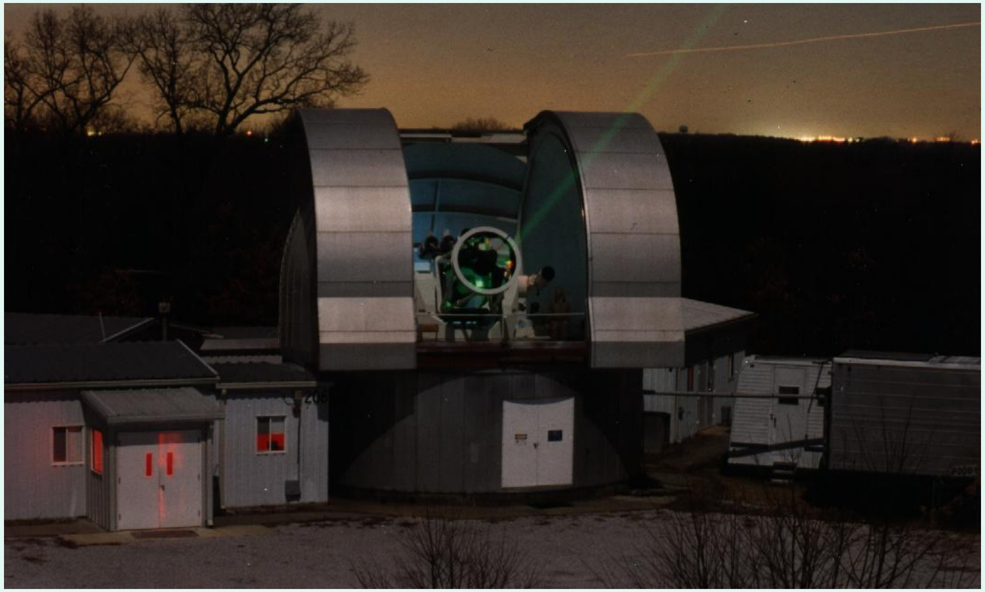
- 76 cm (30”) diameter telescope.

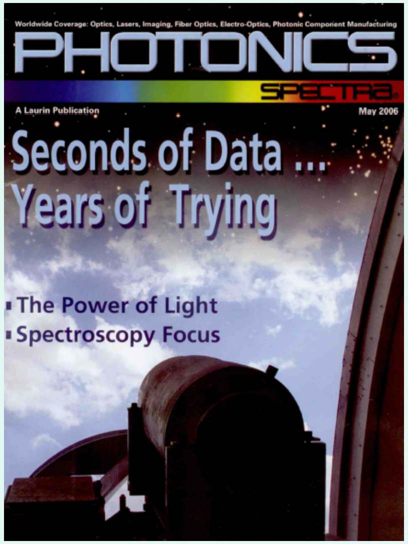
- Laser (now): 4,5,10Hz, 532nm, 100mJ.

-5 systems, all still operating, now located in:

California (Mon.Peak)
Australia
South Africa
Maryland (GGAO)
Tahita.

On-orbit Calibration of LOLA from NASA's 1.2 m Telescope





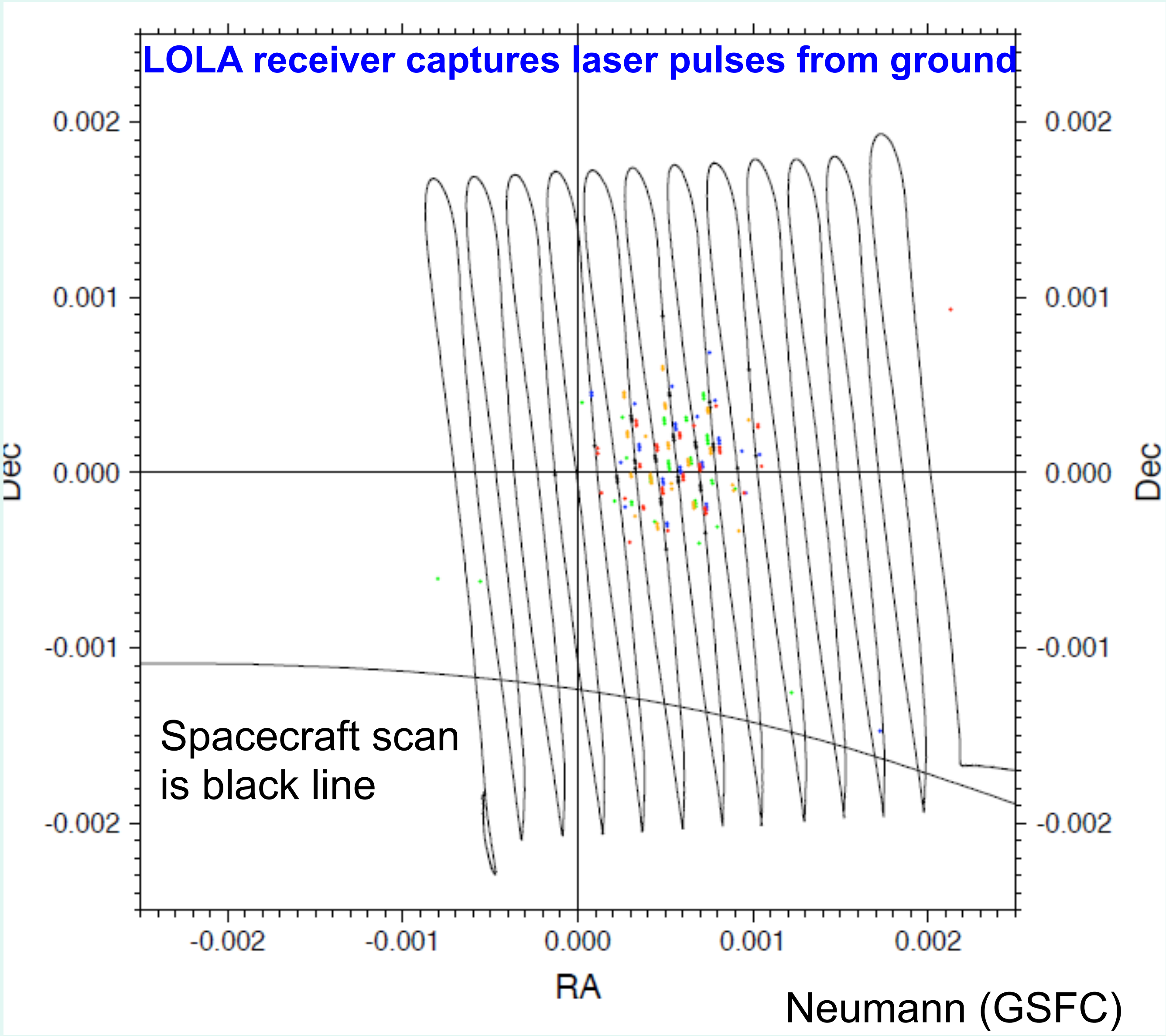
Multi-user facility built in 1973-74. Arcsecond precision tracking telescope.

Has supported many experiments including in 2005:
- **2-way ranging to Mercury Laser Altimeter (MLA) on MESSENGER (24 Mkm), and**
- **1-way ranging to Mars Orbiter Laser Altimeter (MOLA) on MGS (orbiting Mars at 80 Mkm).**

Successful on-orbit calibration of LOLA (2-way ranging) in 2009: 8/25, 9/13, 9/14.

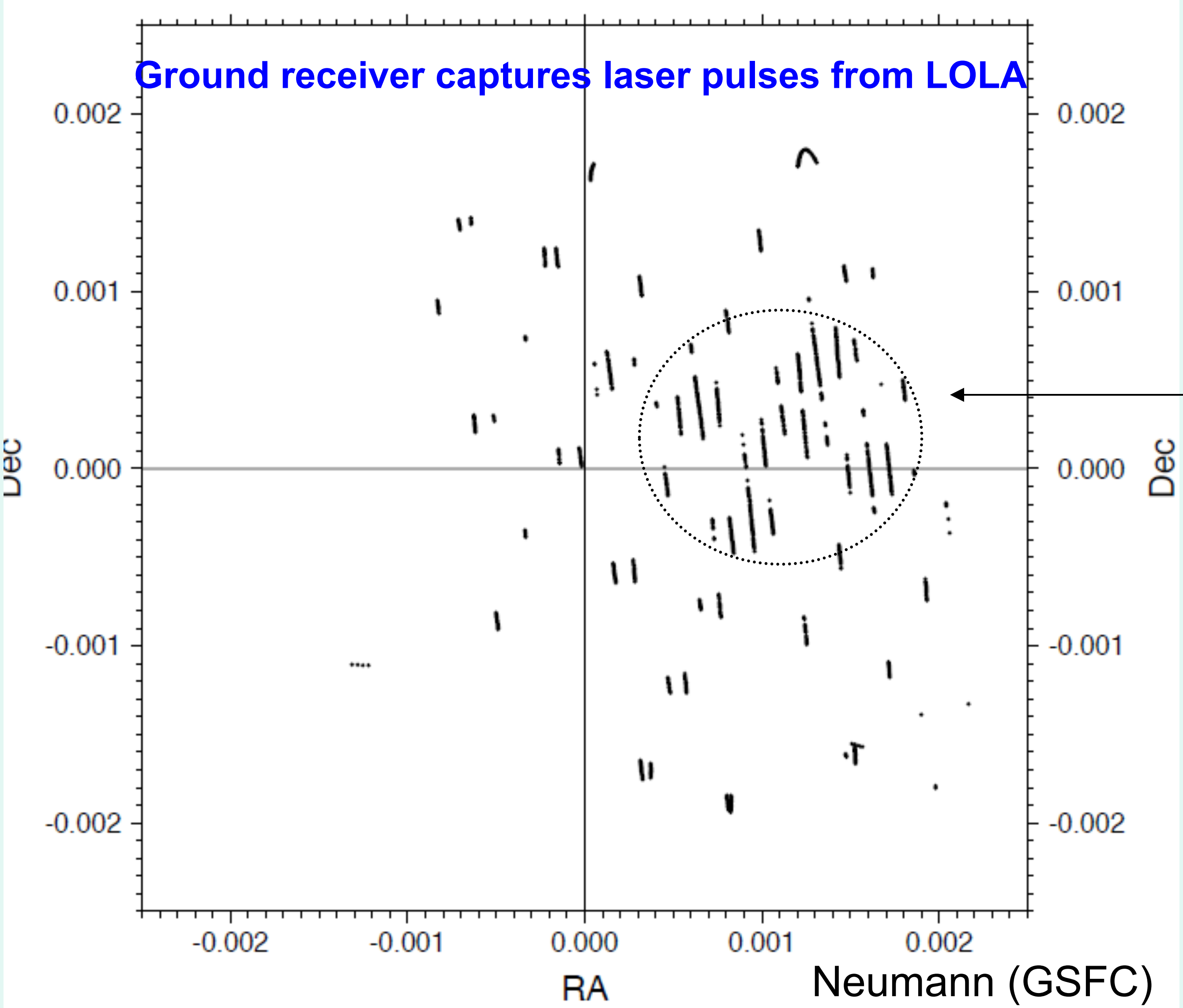
Very Preliminary Analysis of Sep 13 Scan

Plot of LOLA received events on scan location

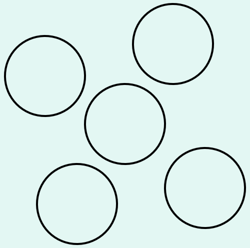


Very Preliminary Analysis Sep 13 Scan

Plot of ground received events on LRO scan location



5 laser spots can be seen:



Neumann (GSFC)

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:

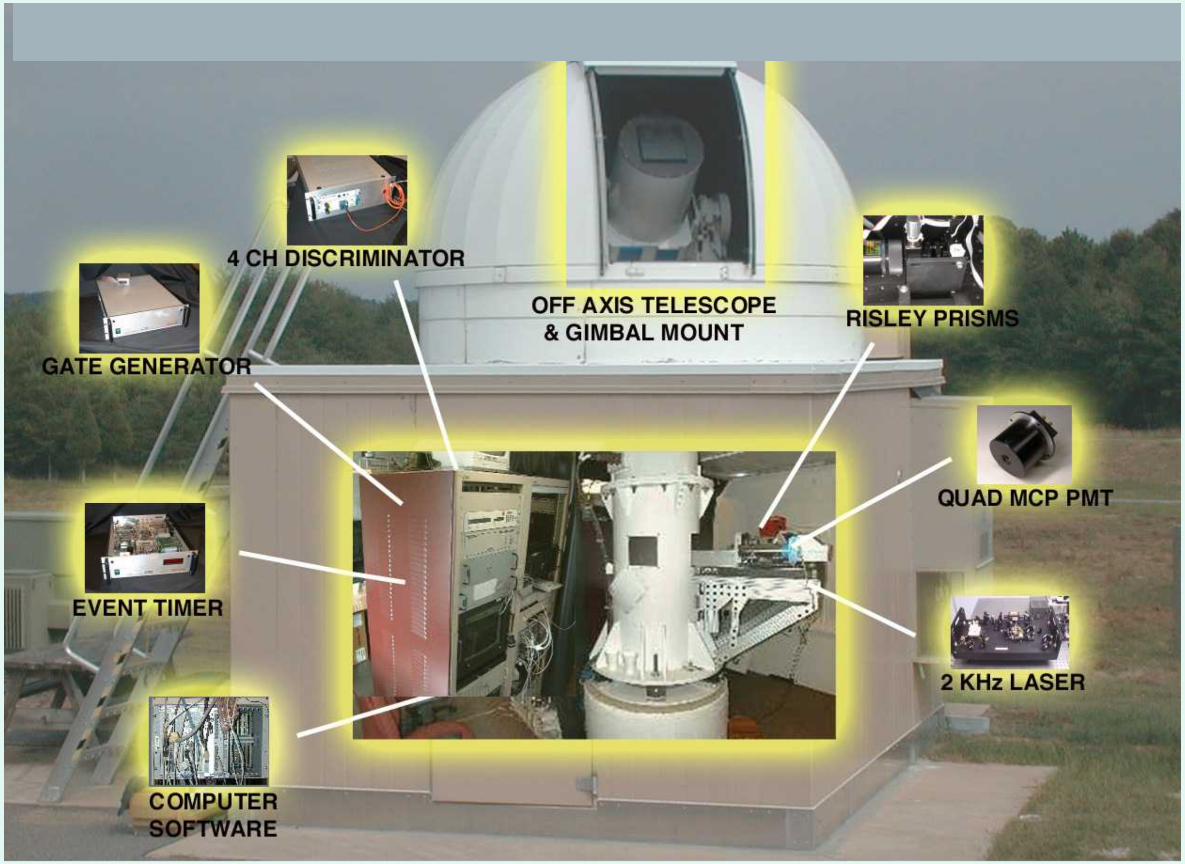
- Successfully tracked most of ILRS satellites.
- LEO, LAGEOS 1 & 2, and GNSS have all been successfully tracked in both daylight and night.
- Starting intercomparison testing with MOBLAS-7.
- Assembling new optical bench to support use of 2.5 mJ, 2 kHz Photonics Industries laser.

System Features:

- 1 to 2 arcsecond pointing/tracking accuracy,
- mm precision LAGEOS normal points,
- 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.

NGSLR Major Subsystems

1. Time & Frequency	6. Tracking
2. Telescope	7. Receiver
3. Transceiver (Optical) Bench	8. Computer and Software
4. Laser	9. Weather Instrumentation
5. Laser Hazard Reduction System (LHRS)	10. Shelter and Dome



NGSLR System Characteristics

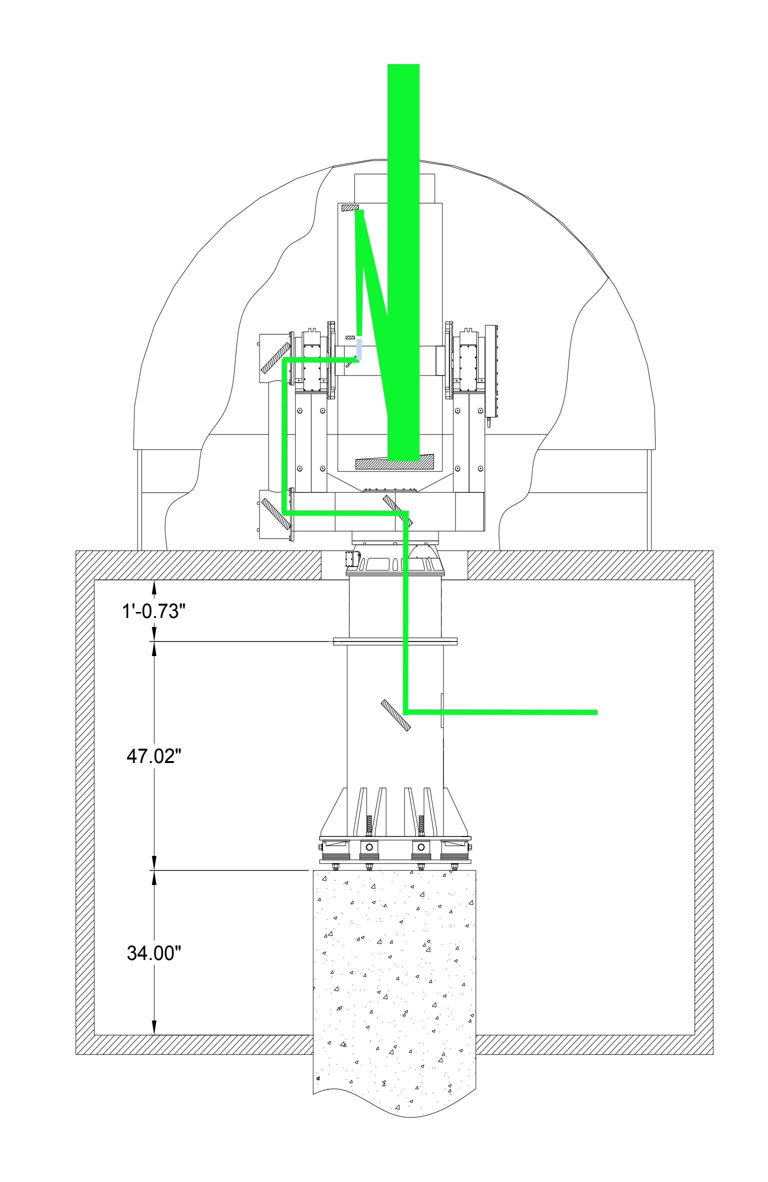
- **Telescope:**

- 40 cm Telescope Aperture Off-Axis Parabola
- No Central Obscuration

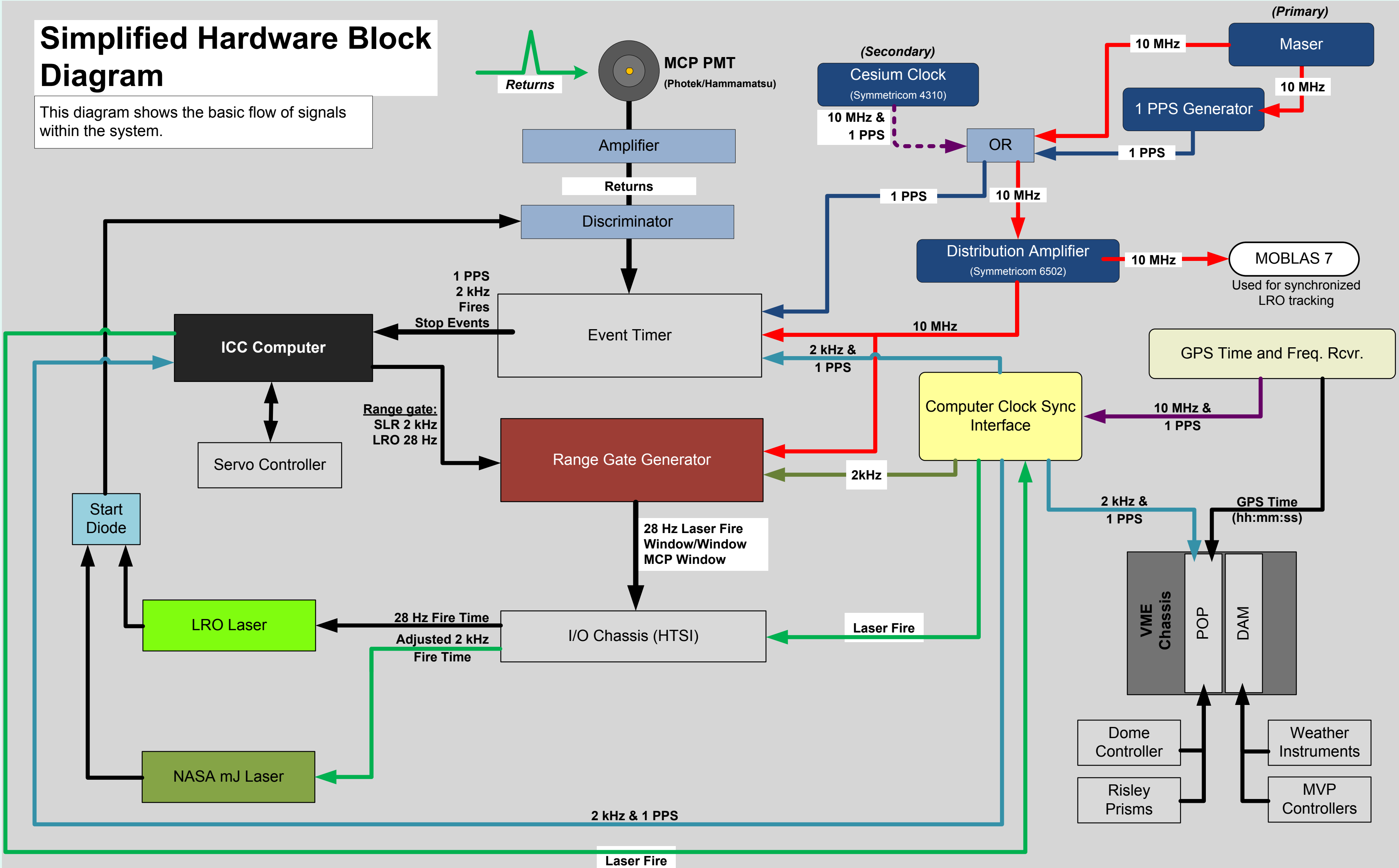
- **Tracking:**

- AZ/EL with 1 arcsec RMS gimbal pointing accuracy

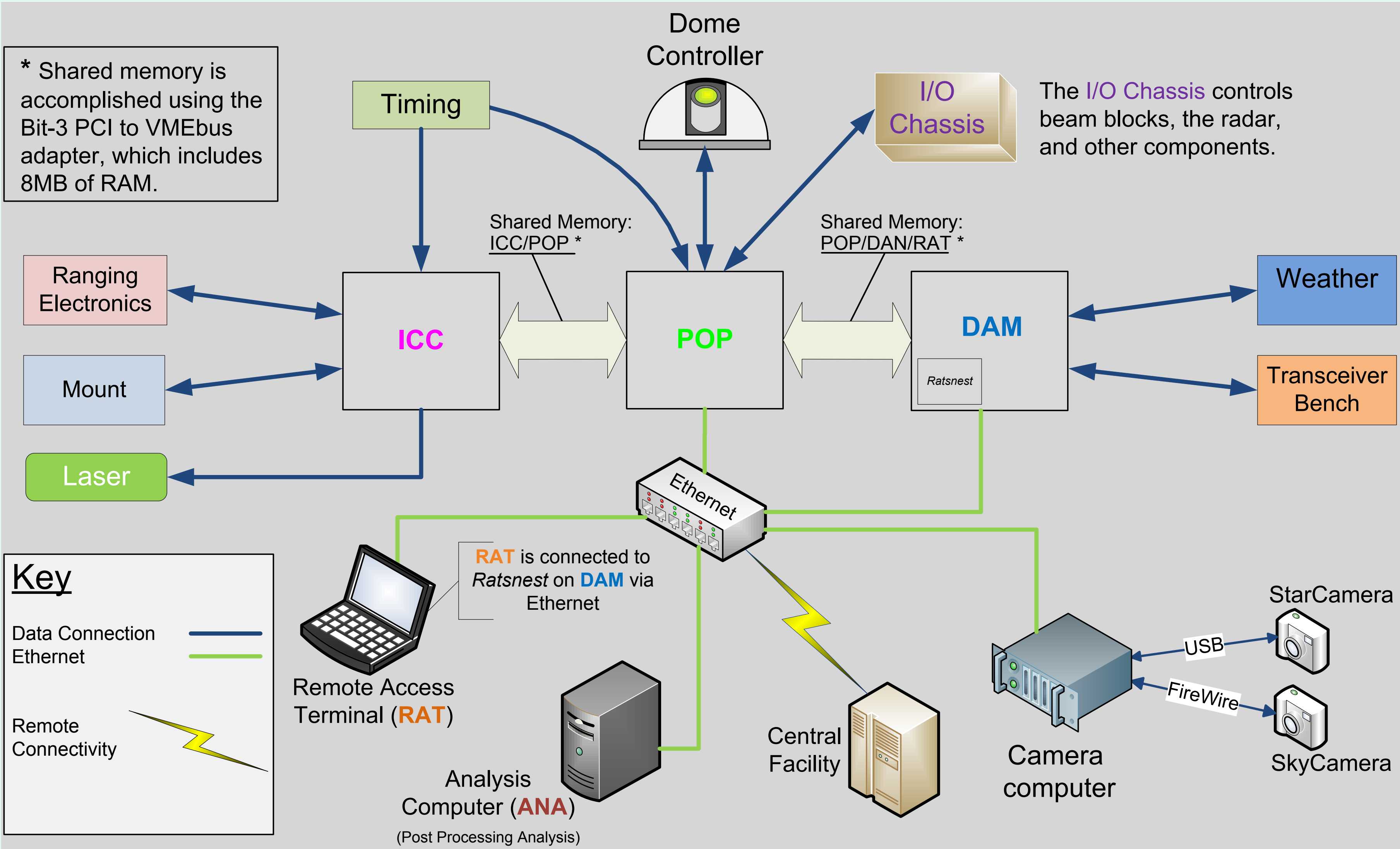
- **Transceiver Bench:**
  - Common Optics for Transmit and Receive
  - Passive Transmit/Receive Switch
  - Risley Prism Point-Ahead of Transmit
- **Laser:**
  - Subnanosecond pulse, 2 kHz
  - Asynchronous PRF, software controlled
  - Divergence control by software
- **Receiver:**
  - High QE, GaAsP Microchannel Plate Photomultiplier
  - Constant Fraction Discriminators
  - GPS-synchronized Rubidium Oscillator /Time and Frequency Receiver
  - Picosecond Precision Event Timer
- **Weather:**
  - Day/Night All-Sky Cloud Sensor (thermal)
  - Wind Monitor
  - Surface Pressure, Temperature, and Humidity Monitors
  - Visibility/Precipitation Sensor



NGSLR System Block Diagram



NGSLR Computer Interfaces



Daylight Ranging to GNSS (GLONASS-109)

- First successful NGSLR daylight ranging to a GNSS satellite (GLONASS-109) occurred on April 2, 2012.

- Plot shows measured minus predicted ranges. Green dots show all returns (most are background noise); blue dots are signal picked out by real-time software.

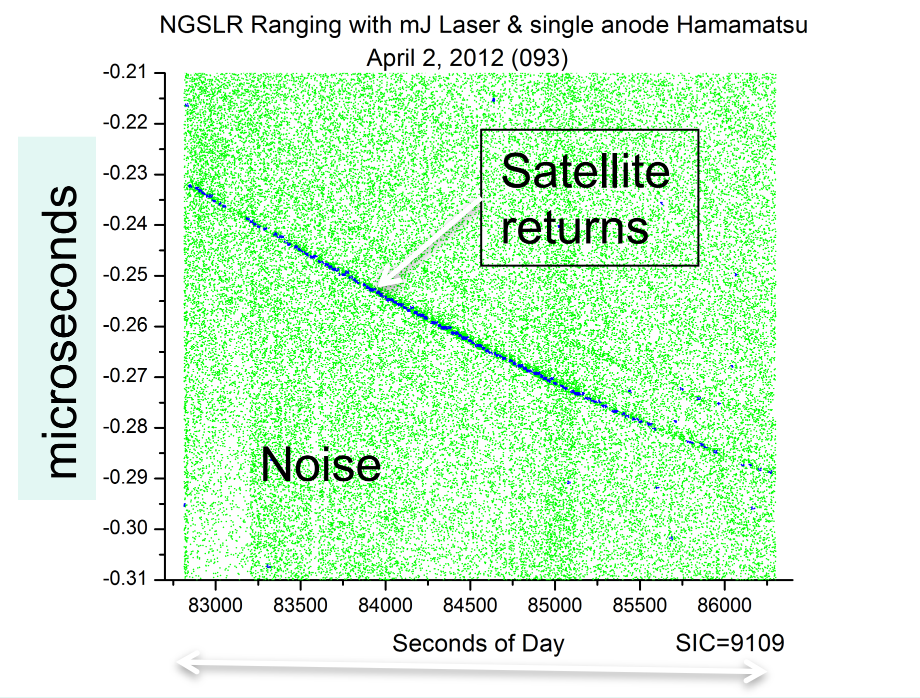
- GLONASS are Russian GNSS satellites orbiting at altitude of ~ 19,000 km. Due to high altitude and response of retro-reflector array, they are difficult to track in daylight for most ILRS stations.

- NGSLR ranged with NASA mJ laser transmitting 500 μJ/pulse, 6 arcsec beam divergence, and 43% QE Hamamatsu detector.

- Normal Point RMS of pass was 3.4 mm.

GLONASS-109

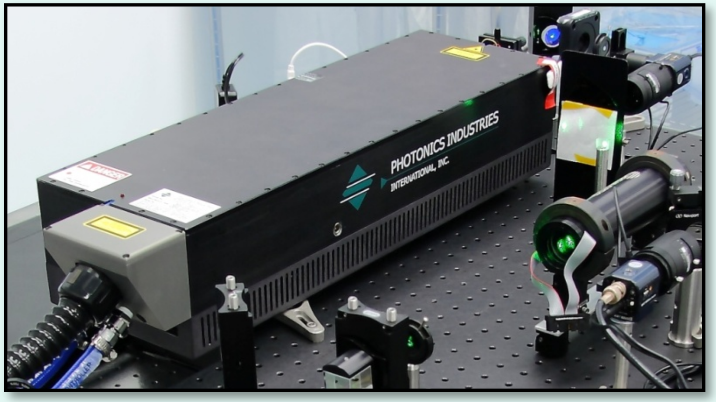
NGSLR Measured minus Predicted Ranges



~ 1 hour pass

NGSLR: New Photonics Industries Laser

Parameter	Reported by PI	Measured
Pulse Energy	2.76 mJ	2.7 mJ
Wavelength	532 nm	532.19 nm (measured IR at 1064.38)
Far Field Beam Divergence	1.13 mrads	0.856 mrads avg, 0.672 x 1.007 mrads
Near Field Spot Diameter	2.92 mm @ 1000 mm	2.5 mm x 3.4 mm @ 1350 mm
Pointing Stability	<5 urads	4.6 urads x 7.8 urads (full angle)
Pulse Width	~50 ps	< 150 ps (equipment limitations)
Transmitter Delay	Not Specified	336 ns
Warm Up Time (energy level)	<15 minutes to reach 100%	90% @ 8 seconds, 95% @ 70 seconds, 100% @ 12 minutes



8 hours performance test gave good results.

NGSLR: New Optical Bench Design

Drawing Key

Operational Equipment

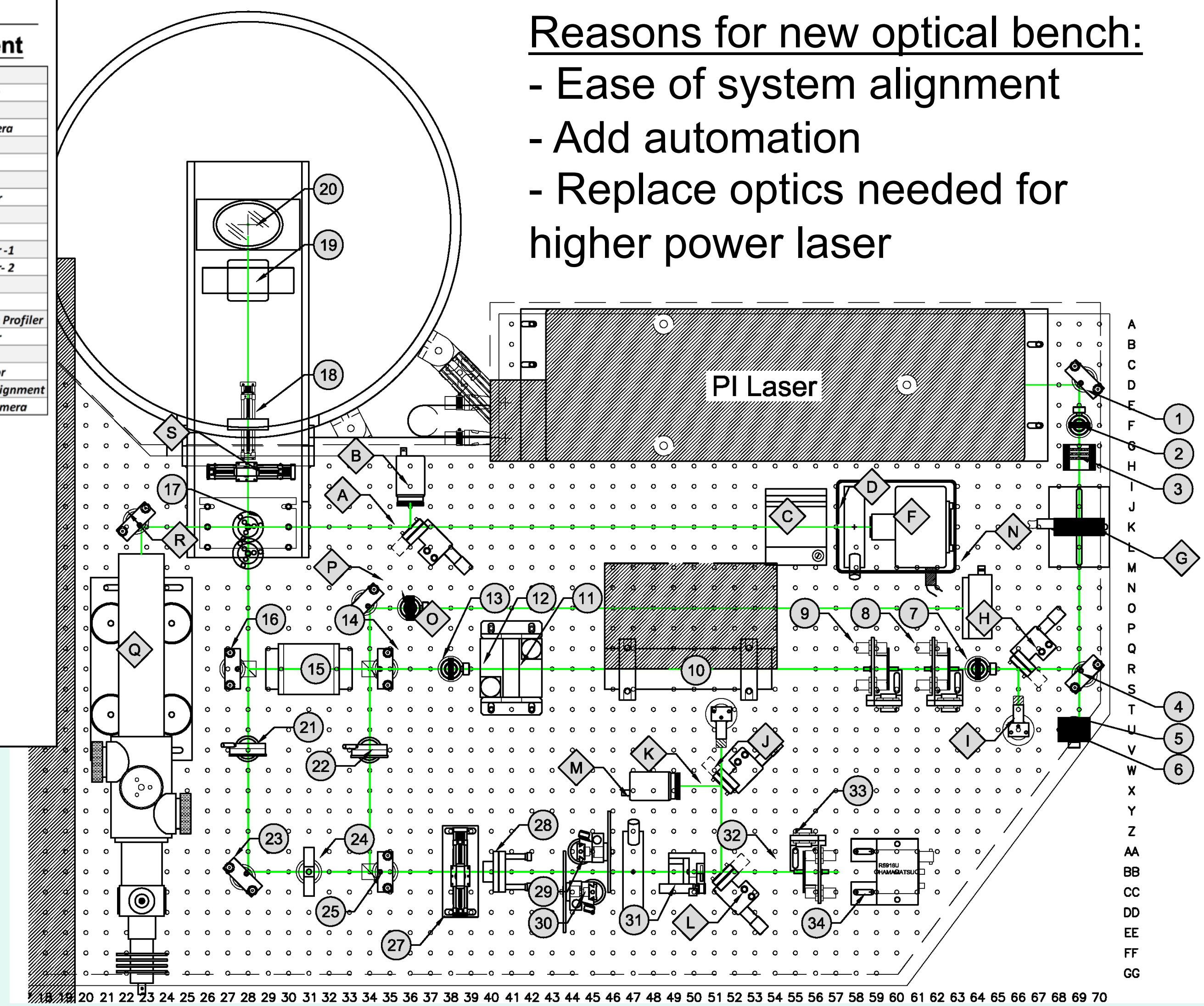
1	Turning Mirror - T1
2	Alignment Iris 1
3	Transmit ND Filter 1
3a	1/4 Wave Plate
3b	Brewster Window
3c	Beam Dump
4	Turning Mirror - T2
5	Start Diode ND Filter
6	Start Diode
7	Alignment Iris 2
8	Transmit Beam Block
9	Transmit ND Filter 2
10	Transmit 8X Beam Expander
11	Risley Prism 1
12	Risley Prism 2
13	Alignment Iris 3
14	Glan-Taylor Prism 1
15	Faraday Rotator
16	Glan-Taylor Prism 2
17	Etalon Beam Splitter
18	Negative Lens - 3X Beam expander
19	Positive Lens - 3X Beam expander
20	Pit Mirror
21	Liquid Crystal Rotator 1
22	Liquid Crystal Rotator 2
23	T/R switch turning Mirror
24	Optical Path Compensator
25	Glan-Taylor Prism 3
26	Turning mirror -R2
27	Bandpass Filter
28	Telephoto lens
29	Rotary ND wheel 1
30	Rotary ND wheel 2
31	Iris to control field of view
32	Uniblitz Shutter for MCP
33	Receive ND Filter
34	Mount for MCP
35	Light Tight Box MCP

Alignment Equipment

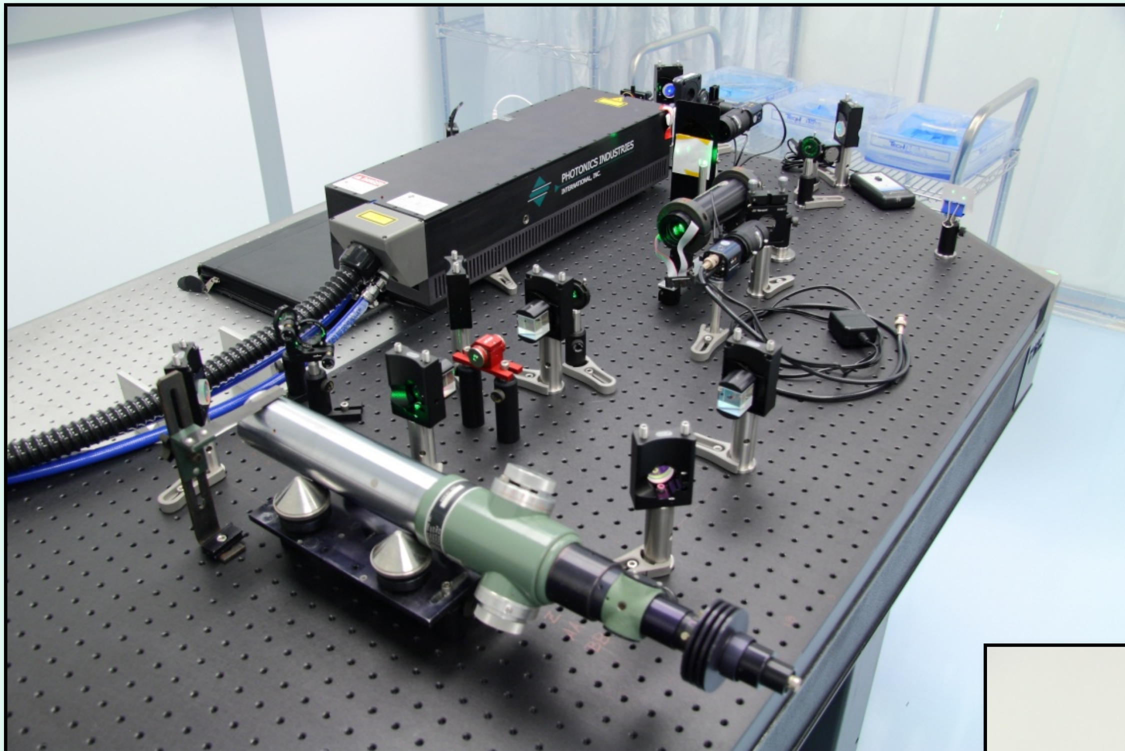
A	Wide field of view Camera
B	Wide field of view Flip Mirror
C	Star Camera Beam Reducer
D	Uniblitz Shutter for Star Camera
E	unused
F	Star Camera
G	Power Meter
H	Transmit Aligment Flip Mirror
I	Transmit Alignment laser
J	Receive Alignment laser
K	Receive Alignment Flip Mirror -1
L	Receive Alignment Flip Mirror- 2
M	Receive Path Camera
N	Beam Profiler
O	Long Focal Length lens- Beam Profiler
P	Turning Mirror -Beam Profiler
Q	K&E Autocollimator
R	Autocollimator Turning Mirror
S	Flip corner cube for System Alignment
T	Light tight box for the Star Camera

Reasons for new optical bench:

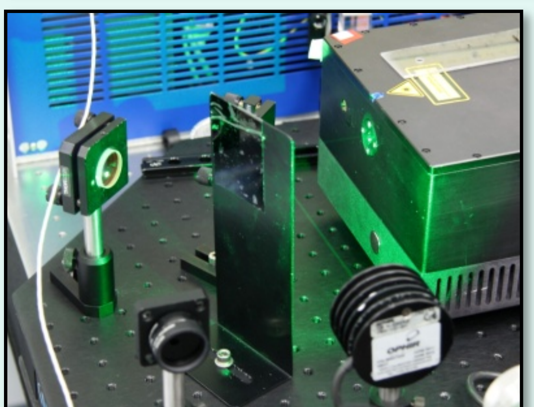
- Ease of system alignment
- Add automation
- Replace optics needed for higher power laser



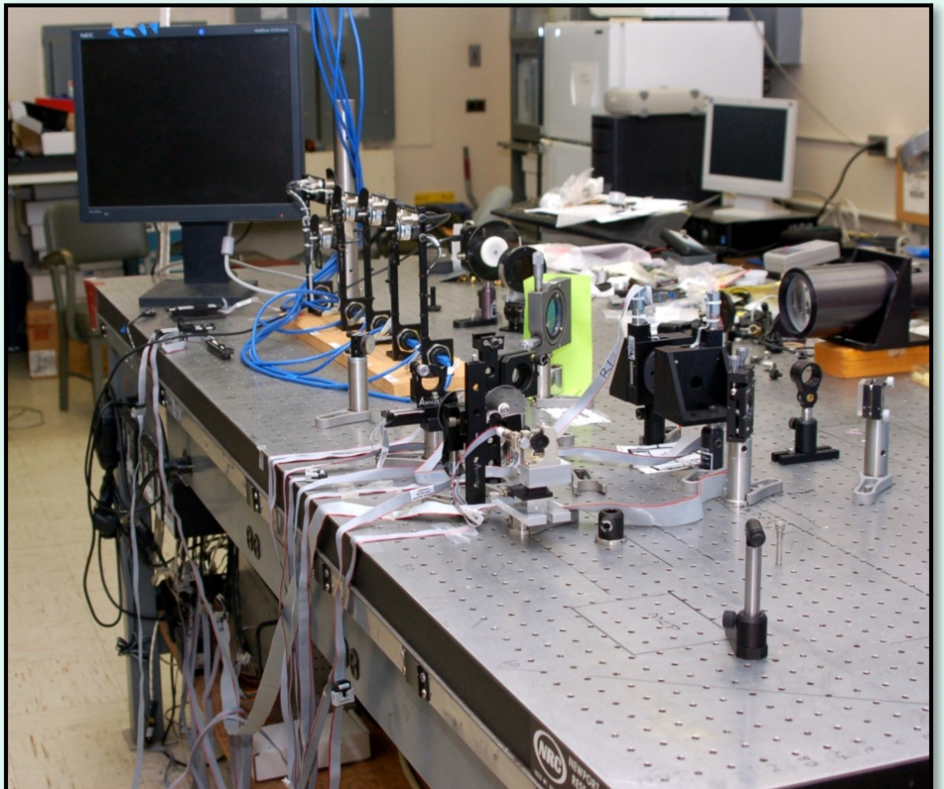
NGSLR: Optical Bench in B33 Cleanroom

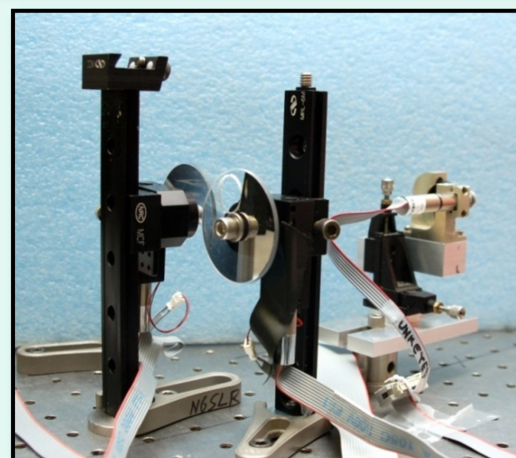


Just starting the optical bench layout. PI laser is at the far end of the bench.

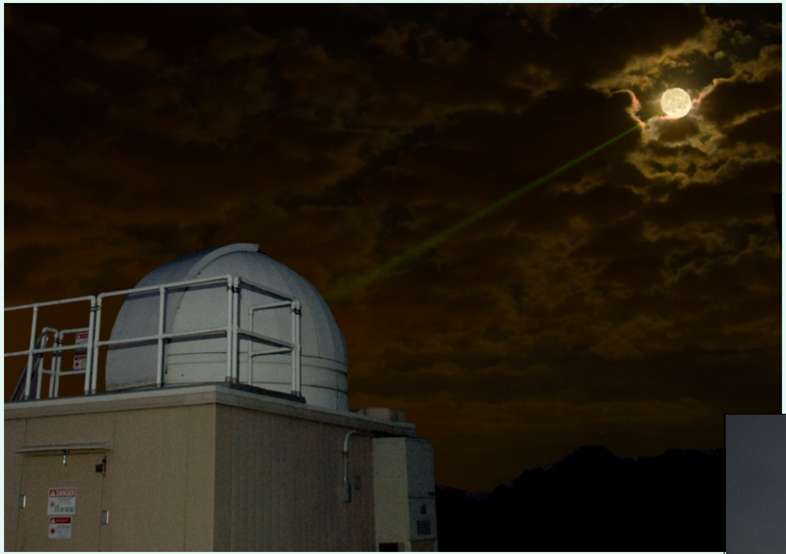


NGSLR : IO Chassis Testing at 48” Lab





LRO-LR at GGAO



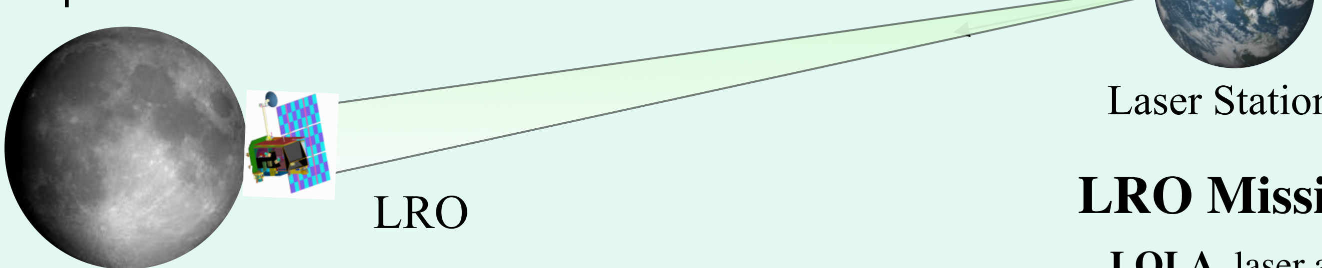
- Laser Ranging (LR) to LRO from NGSLR operationally 7 days a week.
- LR is 1-way laser uplink. Feedback via LOLA housekeeping data in semi-real-time.
- LR provides data for precision LRO orbit determination (used with S-band tracking).

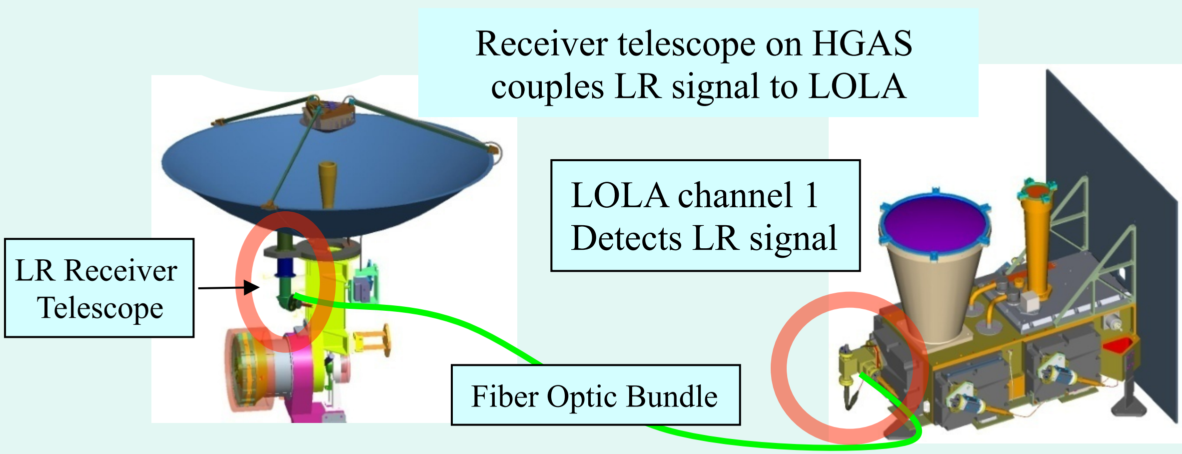
“Back to the Moon”
LRO Public Tour
(August 1, 2009)

Lunar Reconnaissance Orbiter (LRO) – Laser Ranging (LR) Overview

Sub-network of ILRS will support LRO for one-way laser ranging

- Transmit 532 nm laser pulses at =< 28Hz to LRO
- Time stamp departure times at ground station
- Event arrival times recorded by LOLA
- Compute relative 1-way range to LRO from the two pieces of data





LRO Mission Includes:

LOLA, laser altimeter

LROC, camera

LAMP, Lyman alpha telescope

LEND, neutron detector

DIVINER, thermal radiometer

CRATER, cosmic ray detector

mini-RF, radar tech demo

Laser Ranging (LR) to the Lunar Reconnaissance Orbiter (LRO)

Achievements & Status:

- Have collected over 2000 hours of LRO-LR data in the 2.5+ years since launch.

- Have many 2, 3 and even 4-way simultaneous passes collected over last two years. Preliminary analysis of 3-way geometric solution for orbit performed – waiting on better station geometry to complete.

- Have some days with almost complete 24 hour coverage.

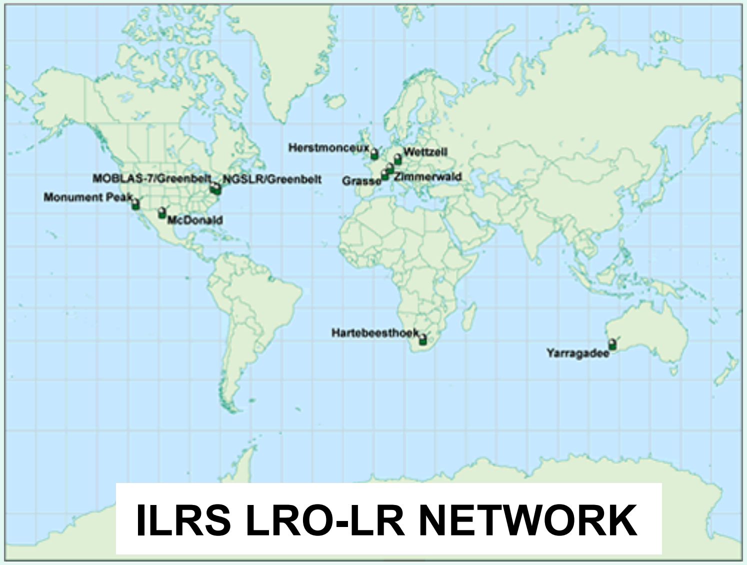
- Lasercom experiment using LRO by Sun & Skillman was successfully completed.

Planned & in-progress work:

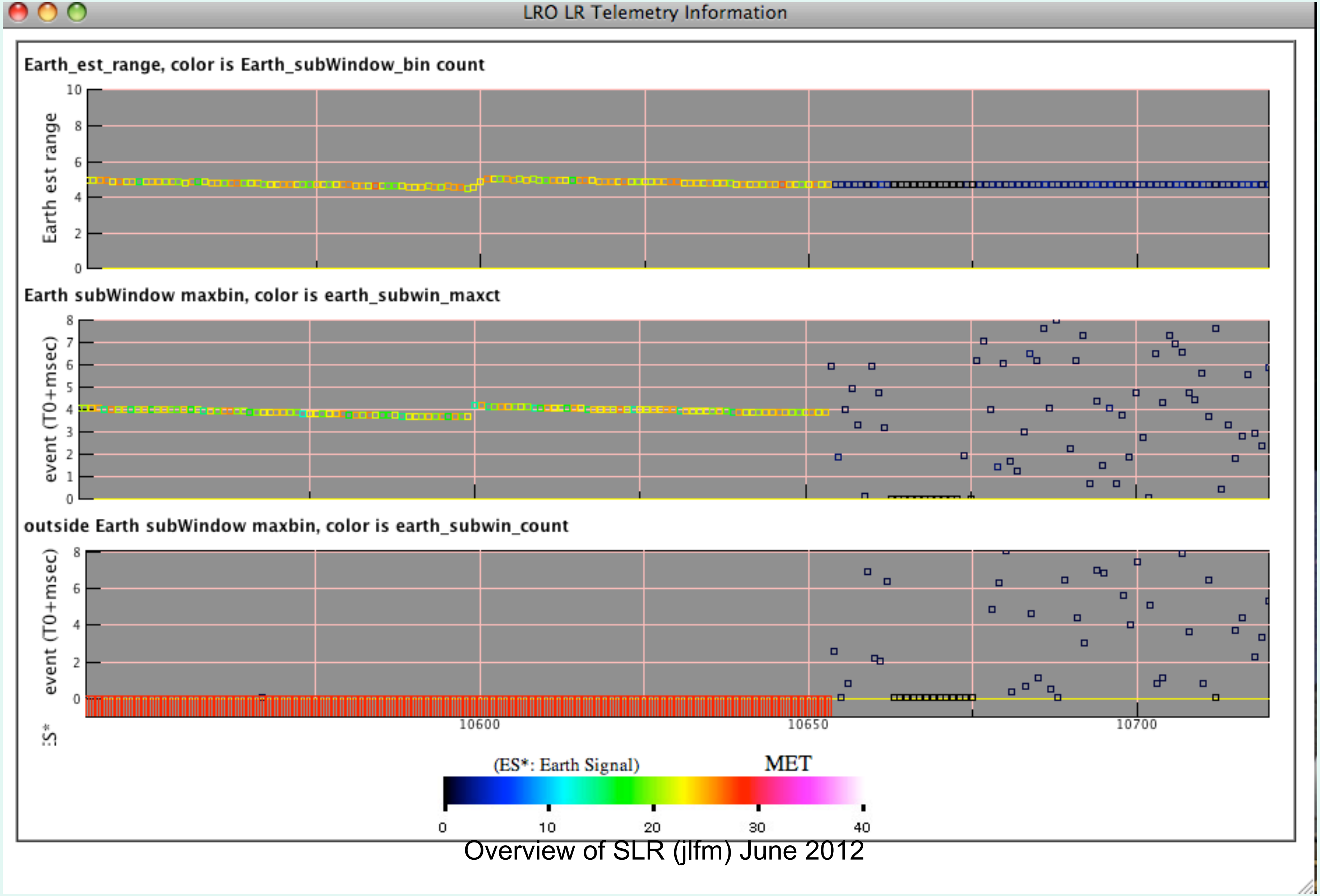
- 3-way simultaneous ranging between Europe, NGSLR and Hartebeesthoek.

- Completion of precise orbit determination using LR.

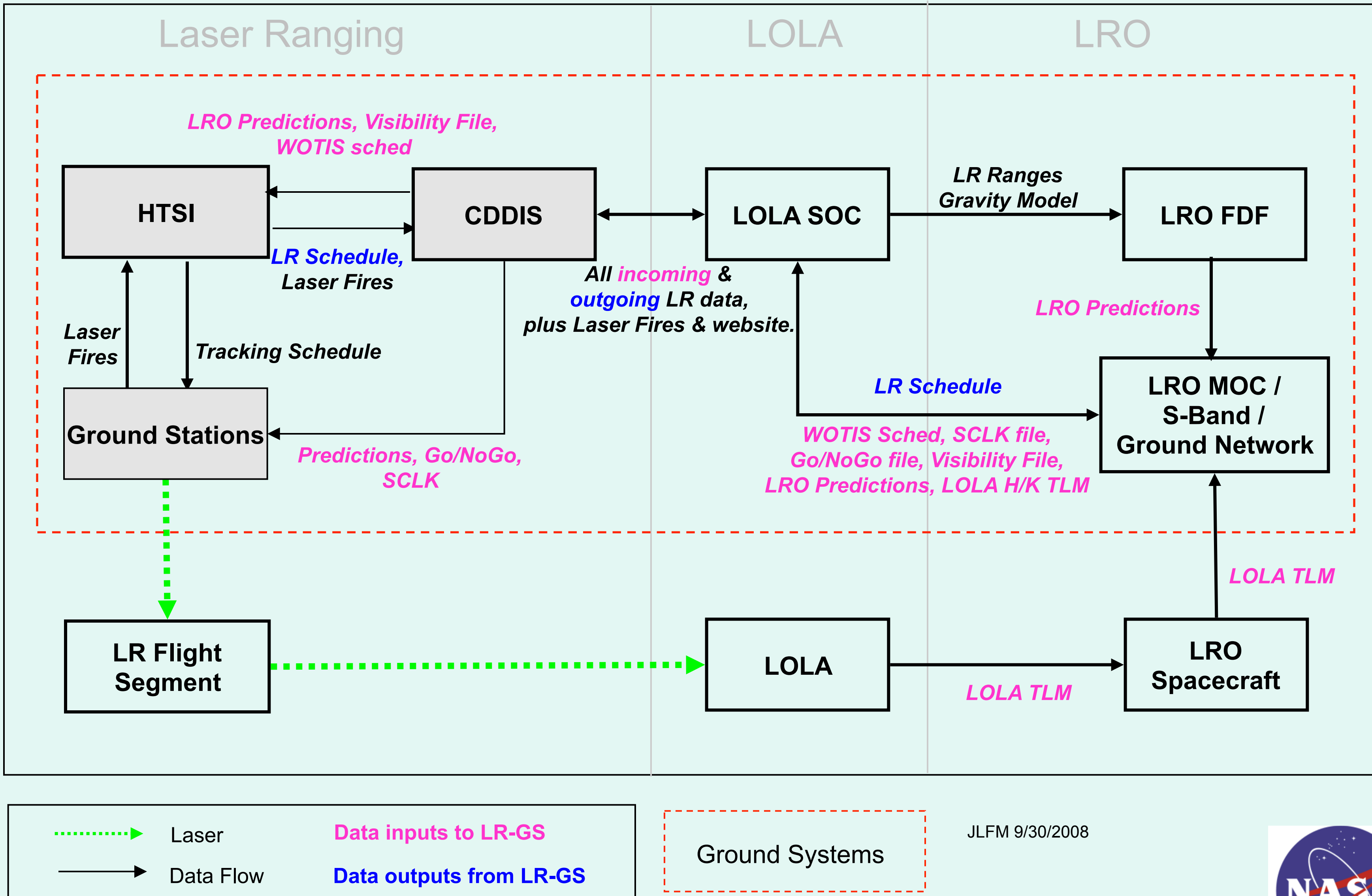
- Time transfer experiment:
    (1) NGSLR to MOBLAS-7, then
    (2) NGSLR to Wettzell.



Real-time LRO-LR telemetry website



Laser Ranging Network Block Diagram

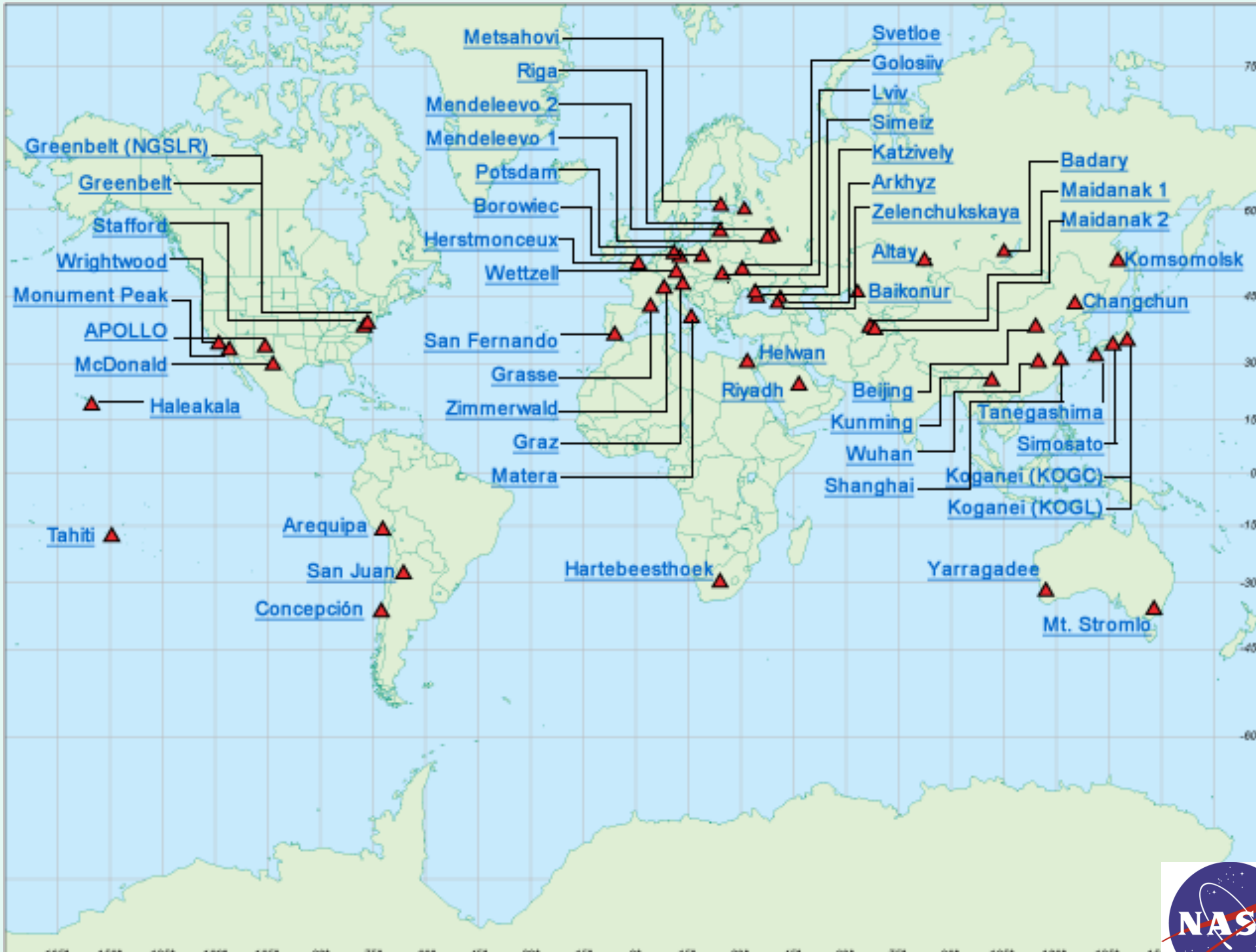


JLFM 9/30/2008

NASA SLR is part of the **International Laser Ranging Service (ILRS)**

The International Laser Ranging Service (ILRS) began in 1998 and provides global satellite and lunar laser ranging data and their related products **to support geodetic and geophysical research activities as well as IERS products important to the maintenance of an accurate International Terrestrial Reference Frame (ITRF).** The service develops the necessary global standards/specifications and encourages international adherence to its conventions. The ILRS is one of the space geodetic services of the International Association of Geodesy (IAG).

GSFC has been chosen to run the **Central Bureau** of the ILRS. The Central Bureau is responsible for overseeing global operations of 40 international stations



Metsahovi
Riga
Mendeleevo 2
Mendeleevo 1
Potsdam
Borowiec
Herstmonceux
Wettzell
San Fernando
Grasse
Zimmerwald
Graz
Matera
Greenbelt (NGSLR)
Greenbelt
Stafford
Wrightwood
Monument Peak
APOLLO
McDonald
Haleakala
Tahiti
Arequipa
San Juan
Concepción
Hartebeesthoek
Svetloe
Golosiiv
Lviv
Simeiz
Katzively
Arkhyz
Zelenchukskaya
Altay
Baikonur
Helwan
Riyadh
Badary
Maidanak 1
Maidanak 2
Komsomolsk
Changchun
Beijing
Kunming
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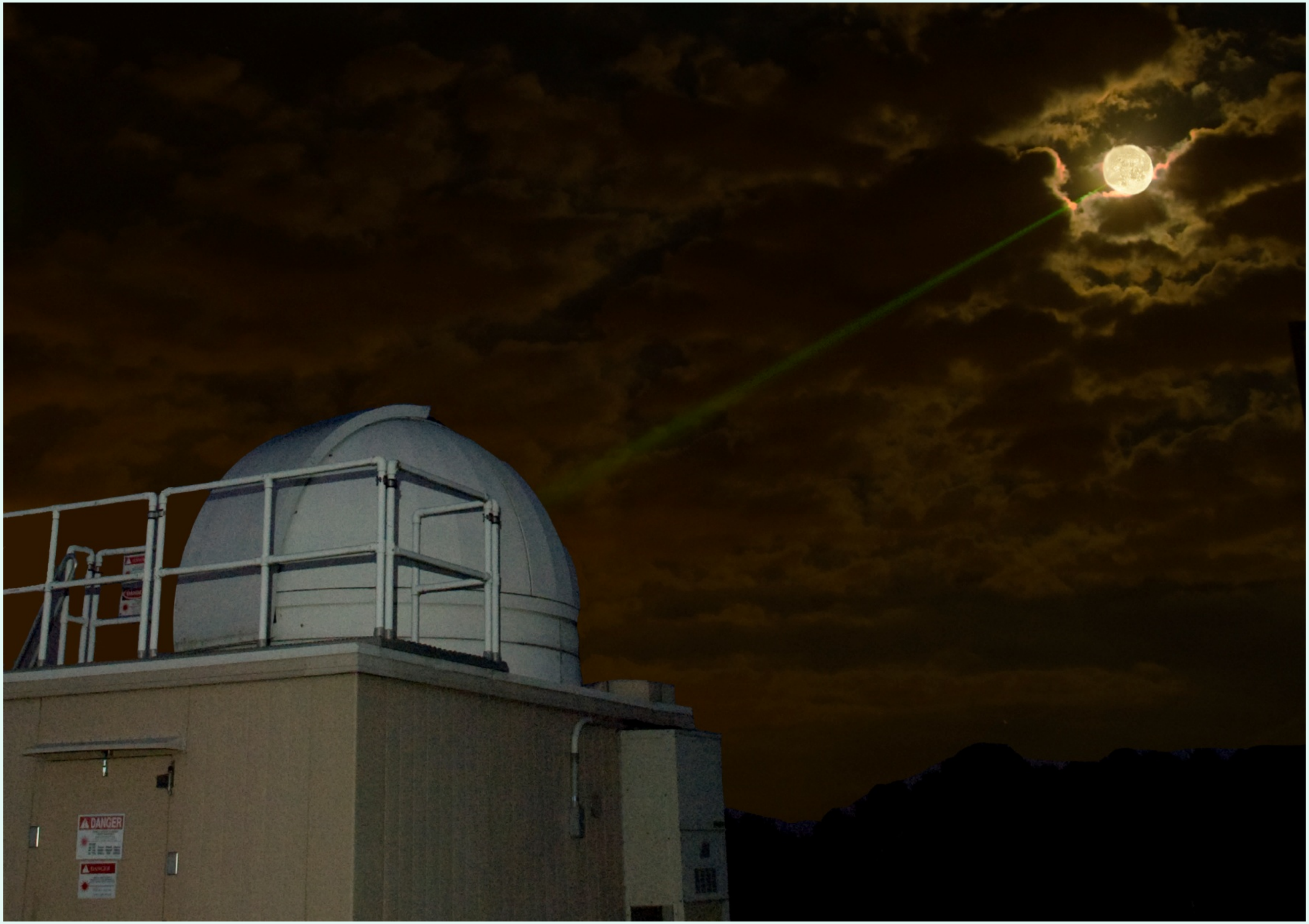
Simosato
Koganei (KOGC)
Koganei (KOGL)
Yarragadee
Mt. Stromlo


DANGER
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