Space Geodesy Satellite Laser Ranging

SGSLR

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For more information see:
NASA's satellite laser ranging systems for the twenty-first century
Journal of Geodesy, https://doi.org/10.1007/s00190-018-1191-6

Goddard Astronomy Club lunchtime presentation

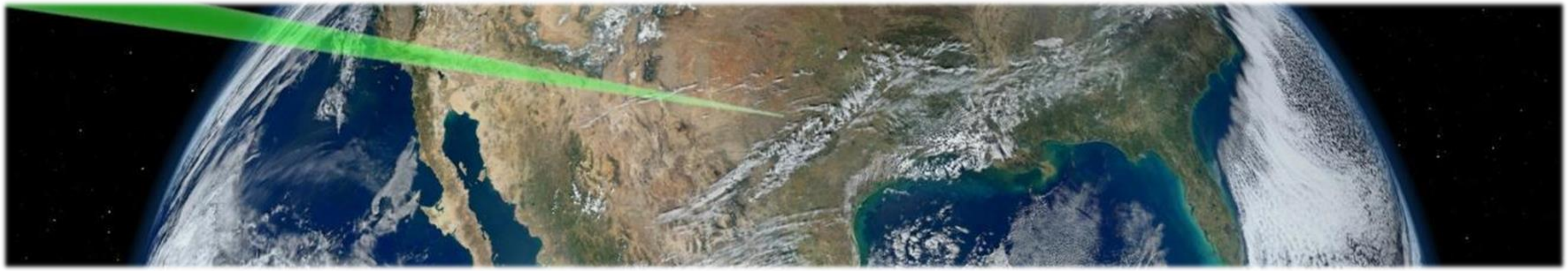
Abstract

For over 40 years, NASA's global network of satellite laser ranging (SLR) stations has provided a significant percentage of the global orbital data used to define the International Terrestrial Reference Frame (ITRF). The current NASA legacy network is reaching its end-of-life and a new generation of systems must be ready to take its place. Scientific demands of sub-millimeter precision ranging and the ever-increasing number of tracking targets give aggressive performance requirements to this new generation of systems. Using lessons learned from the legacy systems and the successful development of a prototype station, a new network of SLR stations, called the Space Geodesy Satellite Laser Ranging (SGSLR) systems, is being developed. These will be the state-of-the-art SLR component of NASA's Space Geodesy Project.

This presentation will give some background on the Space Geodesy Project and NASA's legacy SLR network, but will highlight the initial development and testing of the SGSLR system at Goddard's Geophysical and Astronomical Observatory (Goddard's area 200). We will discuss the build and testing of the system, show pictures of the new facility and subsystems, and point out the future global deployment locations.

Outline of Presentation

- Brief history of Satellite Laser Ranging (SLR)
- International Laser Ranging Service (ILRS)
- NASA's Space Geodesy Project
- SGSLR technical overview
- First three SGSLR deployments



Satellite Laser Ranging History

Satellite Laser Ranging History

- NASA's Satellite Laser Ranging (SLR) effort started over 50 years ago with the first successful laser ranging to the Beacon Explorer B satellite on October 31, 1964 at the Goddard Space Flight Center in Greenbelt, Maryland.

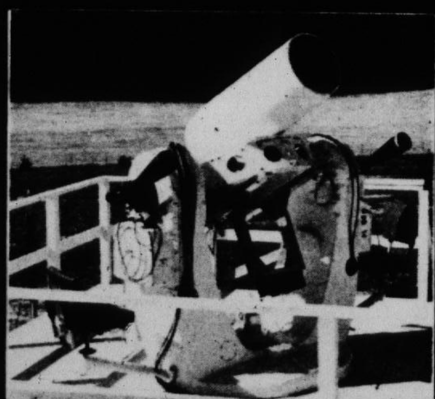
- Since then SLR has become an international effort with over 30 countries participating. There are currently over 100 satellites in orbit carrying retro-reflector arrays for ground tracking by SLR stations.

- In addition, a small subset of stations range to the retro-reflector arrays left on the moon's surface by the Apollo astronauts.

The First SLR Measurements

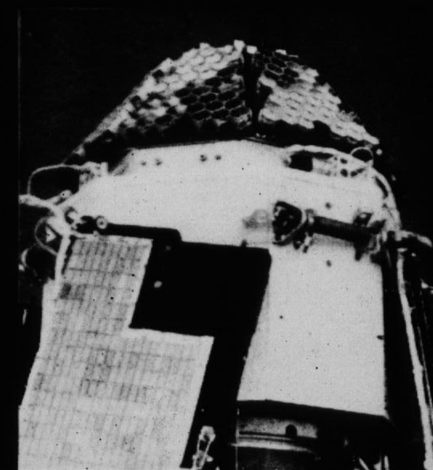
GSFC records first SLR returns ever on Oct 31, 1964
(GSFC team lead by Henry Plotkin)

SATELLITE LASER RANGING - 1964



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

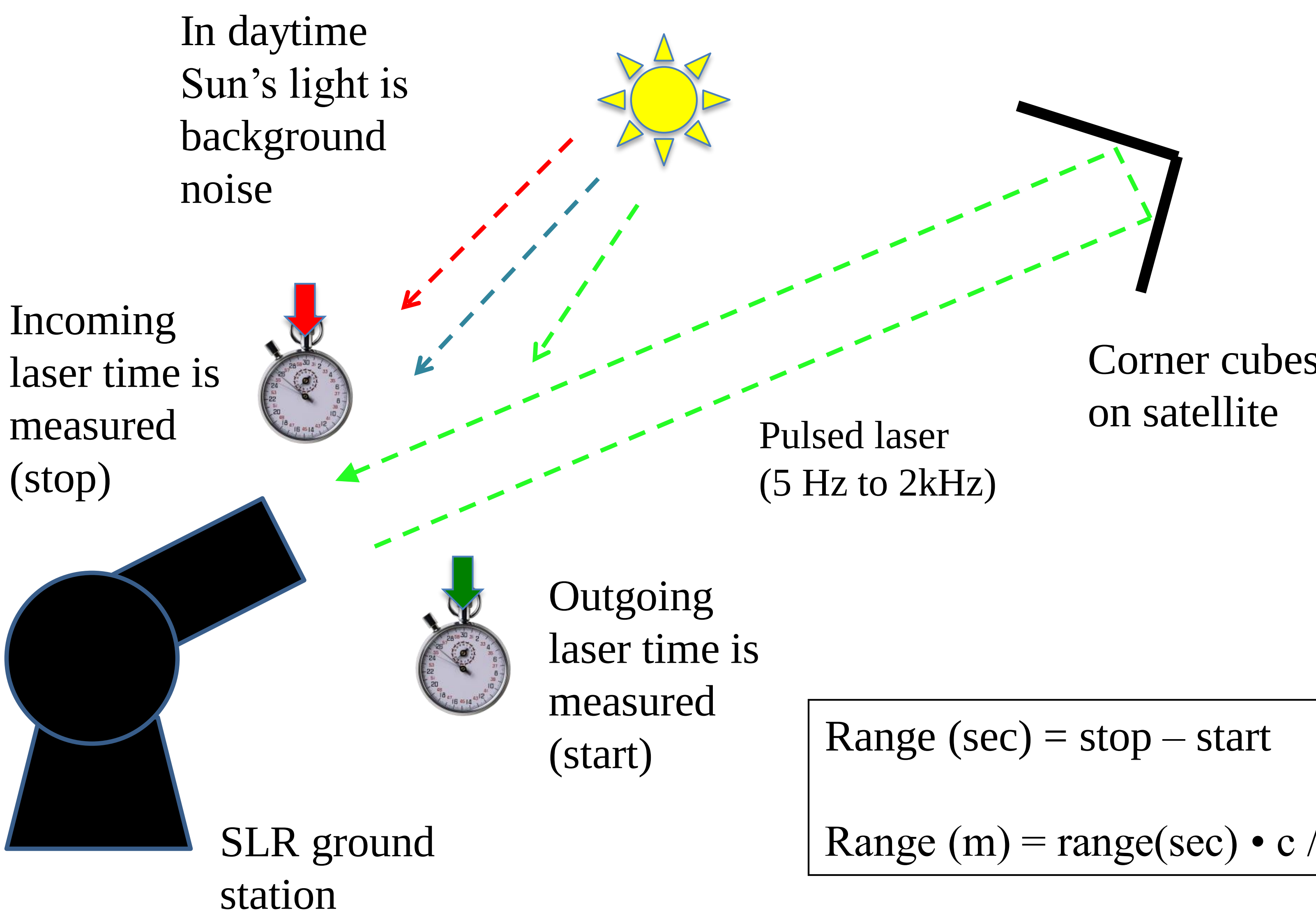
GODLAS



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

BE-B: first satellite with retro-reflectors

Laser Ranging Measurement



Range (sec) = stop – start

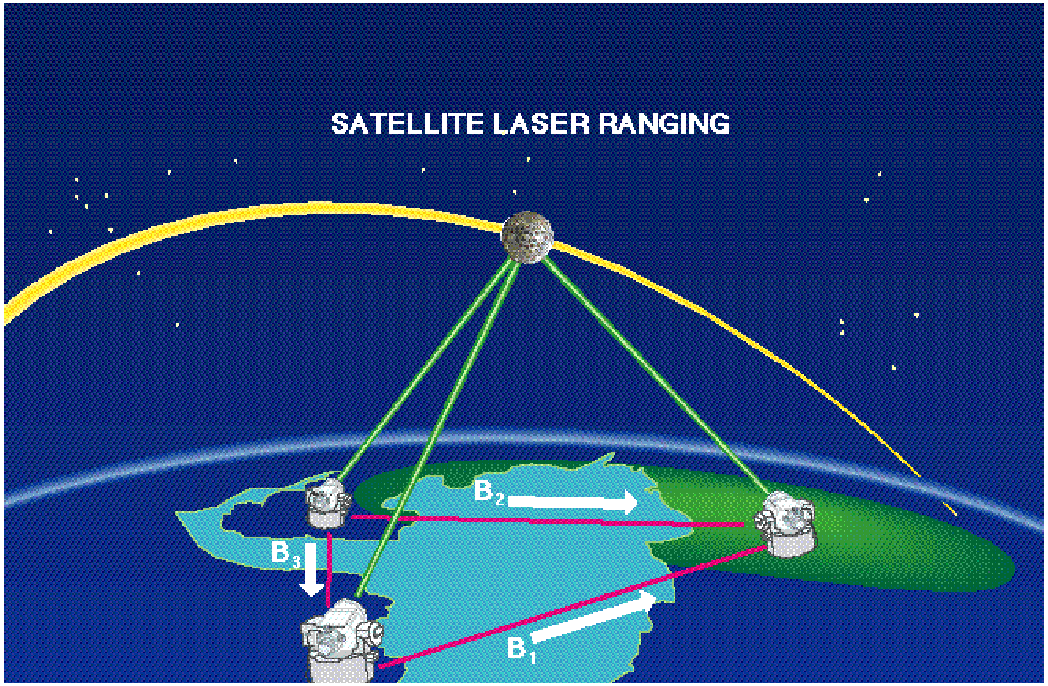
Range (m) = range(sec) • c / 2

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) as well as geosynchronous and the Moon**
- **Centimeter accuracy satellite orbits**

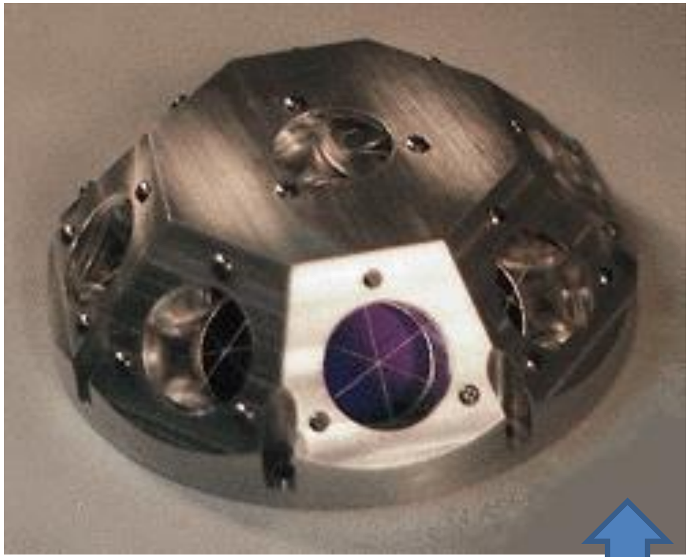
  ~ 1-2 cm (LAGEOS) & ~2-3 cm (GPS)



SLR generates unambiguous centimeter accuracy orbits!

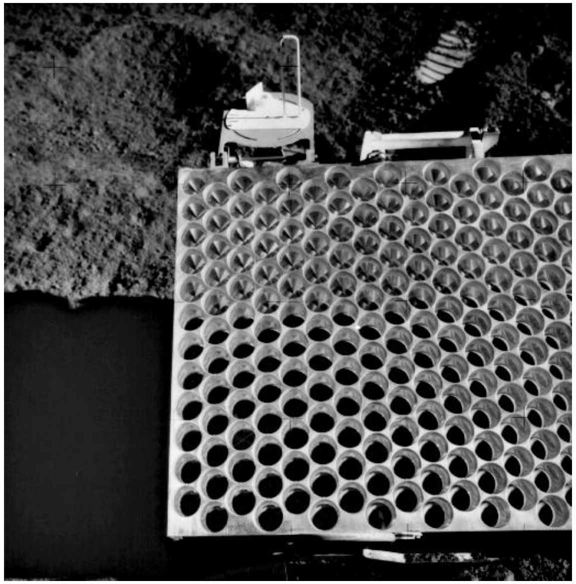
Corner Cube Reflectors and Arrays

Retro-Reflector Array (RRA): GPS 35,36
- **32 solid cubes – each 28mm**
- **Aluminum coated reflective surfaces**
- **Array shape: planar square**
- **Array size: 239 x 194 x 37 mm**
- **Array mass: 1.27 kg**

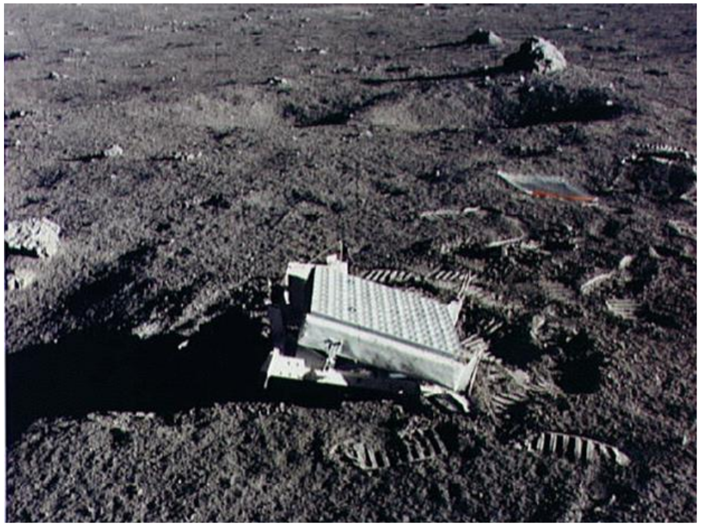


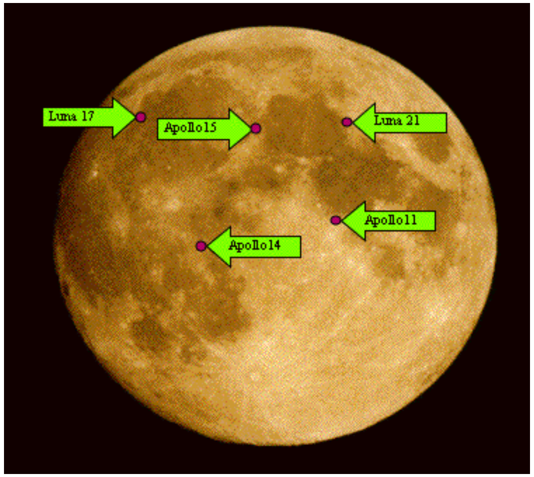
Retro-Reflector Array (RRA): JASON (GFO, ADEOS-II)
9 solid cubes – each 32 mm
Research grade radiation resistant suprasil quartz
Silver coated
Array shape: hemispherical (16cm diameter)
Array mass: 731 gm

Lunar Laser Ranging



- 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 station (MLRS) successfully ranged continuously since 1970s until recently.





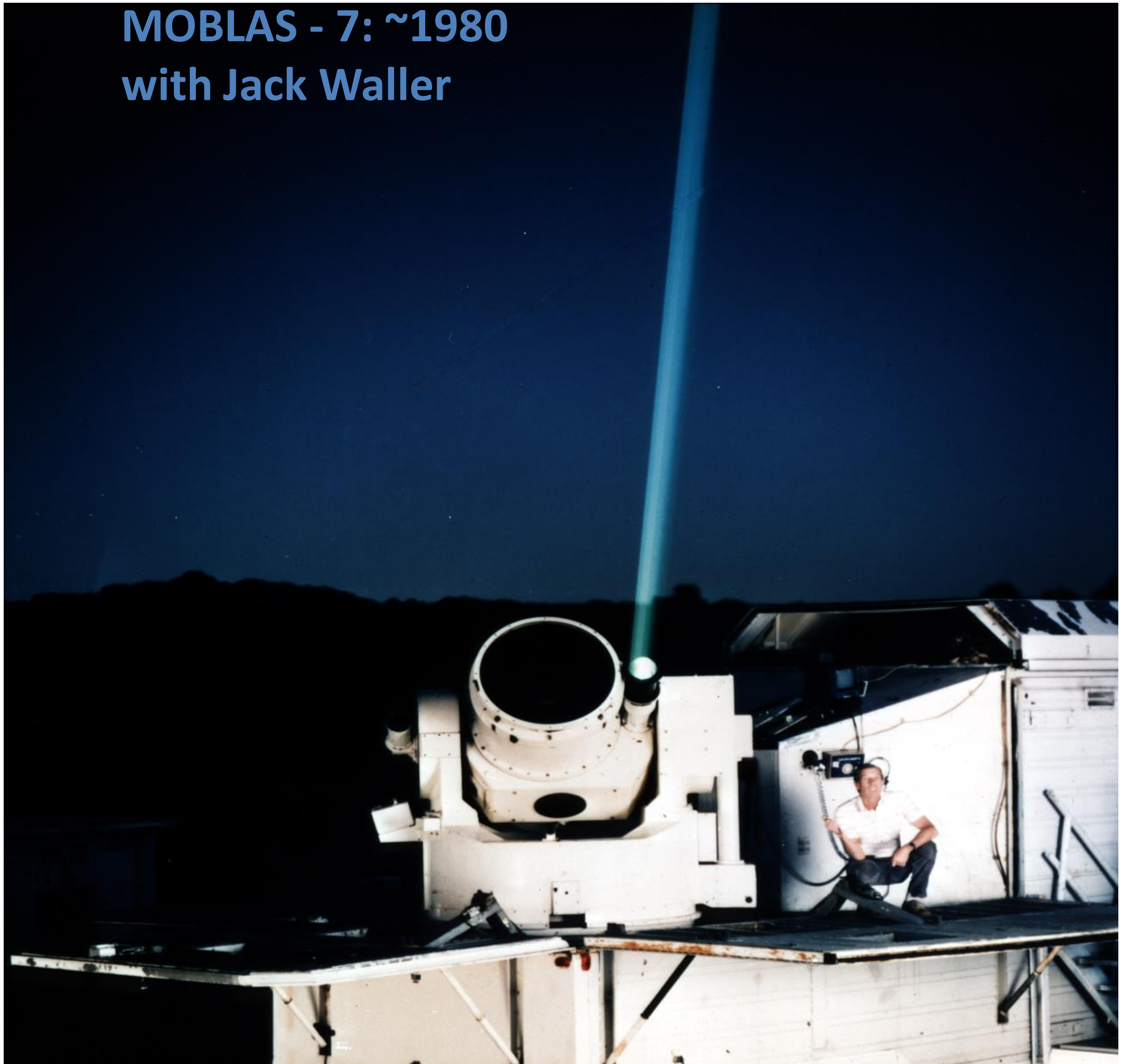
Goddard Geophysical and Astronomical Observatory (GGAO), aka area 200

GGAO = GORF (Goddard Optical Research Facility) = optical site = area 200

Picture circa 1980

- Located ~ 3 miles from GSFC in middle of BARC on Springfield Road.
- Contains all four Geodetic Techniques (aka GGOS core site).
- 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.

MOBLAS-7 at GGAO



-MOBLAS systems built ~1980 by Contraves (telescope & mount), and BFEC (electronics).

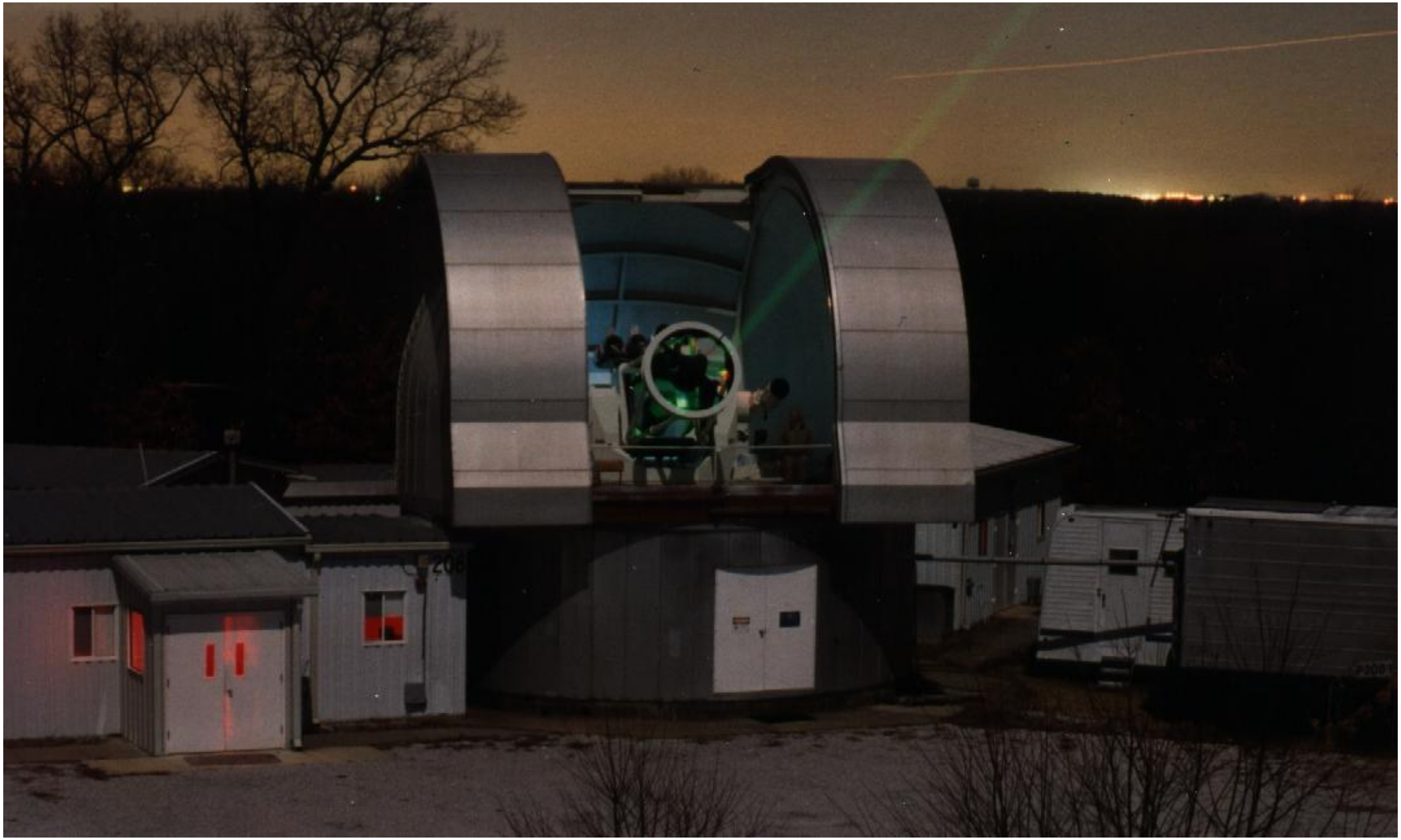
- 76 cm (30”) diameter telescope.

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

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

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

1.2 m Telescope Facility at GGAO



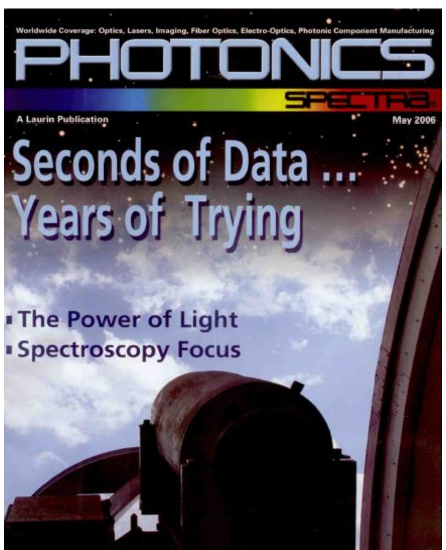
1.2 m Telescope Facility Accomplishments

- Built in 1973-74 by GSFC. Gimbal/Telescope by Kollmorgen Corporation. Multi-user facility with arcsecond precision tracking capability.

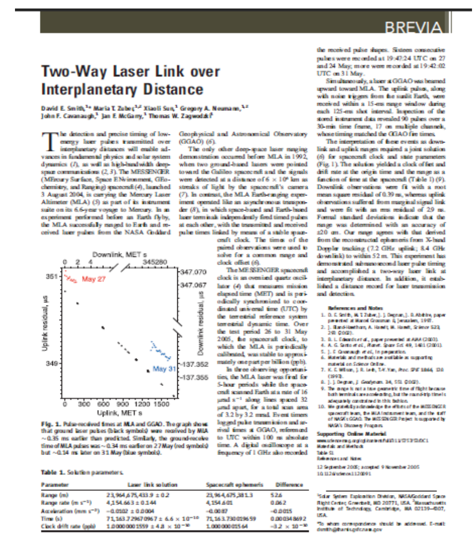
- R&D Facility used by many groups at NASA & Universities.

- Two-way in-cruise calibration of the Mercury Laser Altimeter (MLA) onboard the MESSENGER spacecraft at 24 Mkm (2005).

- One-way on-orbit successful laser ranging to the Mars Observer Laser Altimeter (MOLA) onboard the MGS spacecraft orbiting Mars at 80 Mkm (2005).



- Multiple two-way on-orbit calibration of the Lunar Orbiter Laser Altimeter (LOLA) onboard the LRO spacecraft orbiting the Moon (2009 through 2014).



BREVIA

Two-Way Laser Link over Interplanetary Distance

David E. Smith,[1*] Maria T. Zuber,[1,2] Xiaoli Sun,[1] Gregory A. Neumann,[1,2] John F. Cavanaugh,[1] Jan F. McGarry,[1] Thomas W. Zagwodzki[1]

The detection and precise timing of low-energy laser pulses transmitted over interplanetary distances will enable advances in fundamental physics and solar system dynamics (1), as well as high-bandwidth deep-space communications (2, 3). The MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) spacecraft (4), launched 3 August 2004, is carrying the Mercury Laser Altimeter (MLA) (5) as part of its instrument suite on its 6.6-year voyage to Mercury. In an experiment performed before an Earth flyby, the MLA successfully ranged to Earth and received laser pulses from the NASA Goddard Geophysical and Astronomical Observatory (GGAO) (6).

The only other deep-space laser ranging demonstration occurred before MLA in 1992, when two ground-based lasers were pointed toward the Galileo spacecraft and the signals were detected at a distance of 6 × 10⁶ km as streaks of light by the spacecraft's camera (7). In contrast, the MLA Earth-ranging experiment operated like an asynchronous transponder (8), in which space-based and Earth-based laser terminals independently fired timed pulses at each other, with the transmitted and received pulse times linked by means of a stable spacecraft clock. The times of the paired observations were used to solve for a common range and clock offset (6).

The MESSENGER spacecraft clock is an ovenized quartz oscillator (4) that measures mission elapsed time (MET) and is periodically synchronized to coordinated universal time (UTC) by the terrestrial reference system terrestrial dynamic time. Over the test period 26 to 31 May 2005, the spacecraft clock, to which the MLA is periodically calibrated, was stable to approximately one part per billion (ppb).

In three observing opportunities, the MLA laser was fired for 5-hour periods while the spacecraft scanned Earth at a rate of 16 μrad s⁻¹ along lines spaced 32 μrad apart, for a total scan area of 3.2 by 3.2 mrad. Event timers logged pulse transmission and arrival times at GGAO, referenced to UTC within 100 ns absolute time. A digital oscilloscope at a frequency of 1 GHz also recorded the received pulse shapes. Sixteen consecutive pulses were recorded at 19:47:24 UTC on 27 and 24 May; more were recorded at 19:42:02 UTC on 31 May.

Simultaneously, a laser at GGAO was beamed upward toward MLA. The uplink pulses, along with noise triggers from the sunlit Earth, were received within a 15-ms range window during each 125-ms shot interval. Inspection of the stored instrument data revealed 90 pulses over a 30-min time frame, 17 on multiple channels, whose timing matched the GGAO fire times.

The interpretation of these events as downlink and uplink ranges required a joint solution (6) for spacecraft clock and state parameters (Fig. 1). The solution yielded a clock offset and drift rate at the origin time and the range as a function of time at the spacecraft (Table 1) (9). Downlink observations were fit with a root mean square residual of 0.39 ns, whereas uplink observations suffered from marginal signal link and were fit with an rms residual of 2.9 ns. Formal standard deviations indicate that the range was determined with an accuracy of ±20 cm. Our range agrees with that derived from the reconstructed ephemeris from X-band Doppler tracking (7.2 GHz uplink; 8.4 GHz downlink) to within 52 m. This experiment has demonstrated subnanosecond laser pulse timing and accomplished a two-way laser link at interplanetary distance. In addition, it established a distance record for laser transmission and detection.

Fig. 1. Pulse-received times at MLA and GGAO. The graph shows that ground laser pulses (black symbols) were received by MLA ~0.35 ms earlier than predicted. Similarly, the ground-receive time of MLA pulses was ~0.34 ms earlier on 27 May (red symbols) but ~0.14 ms later on 31 May (blue symbols).

Table 1. Solution parameters.

Parameter	Laser link solution	Spacecraft ephemeris	Difference
Range (m)	23,964,675,433.9 ± 0.2	23,964,675,381.3	52.6
Range rate (m s⁻¹)	4,154.663 ± 0.144	4,154.601	0.062
Acceleration (mm s⁻²)	−0.0102 ± 0.0004	−0.0087	−0.0015
Time (s)	71,163.72967 0967 ± 6.6 × 10⁻¹⁰	71,163.730019659	0.000348692
Clock drift rate (ppb)	1.0000000 1559 ± 4.8 × 10⁻¹⁰	1.00000001564	−3.2 × 10⁻¹⁰

References and Notes

1. D. E. Smith, M. T. Zuber, J. J. Degnan, J. B. Abshire, paper presented at Marcel Grossman 8, Jerusalem, 1997.
2. J. Bland-Hawthorn, A. Hazell, M. Hazell, Science 523, 248 (2002).
3. B. L. Edwards et al., paper presented at AIAA (2003).
4. A. G. Santo et al., Planet. Space Sci. 49, 1481 (2001).
5. J. F. Cavanaugh et al., in preparation.
6. Materials and methods are available as supporting material on Science Online.
7. K. E. Wilson, J. R. Lesh, T.-Y. Yan, Proc. SPIE 1866, 138 (1993).
8. J. J. Degnan, J. Geodynam. 34, 551 (2002).
9. The range is not a true geometric time of flight because both terminals are accelerating, but the round-trip time is adequately constrained in this fashion.
10. We gratefully acknowledge the efforts of the MESSENGER spacecraft team, the MLA instrument team, and the staff of NASA's GGAO. The MESSENGER Project is supported by NASA's Discovery Program.

Supporting Online Material
www.sciencemag.org/cgi/content/full/311/5757/53/DC1
Materials and Methods
Table S1
References and Notes

12 September 2005; accepted 9 November 2005
10.1126/science.1120091

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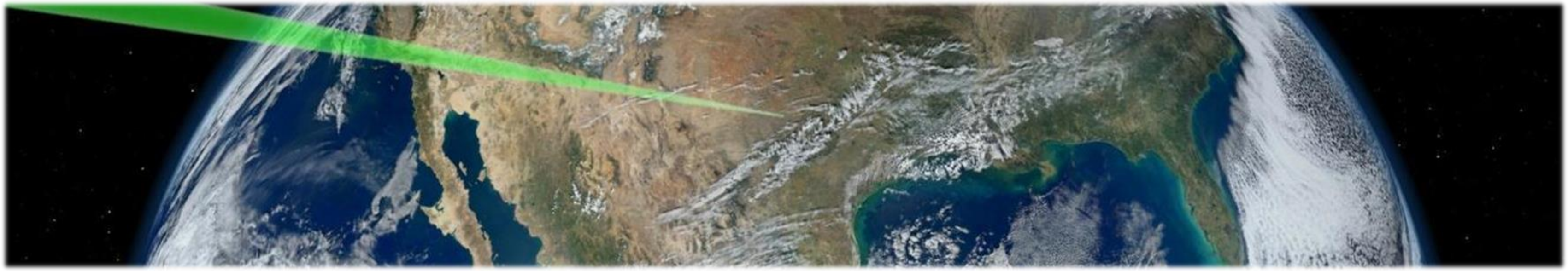
NGSLR – Prototype for SGSLR

NGSLR is a high repetition rate single photon detection laser ranging system capable of tracking cube corner reflector (CCR) equipped satellites in Earth orbit. Started in the late 1990s this system successfully demonstrated the performance requirements through a collocation with MOBLAS-7 in 2013.

In addition NGSLR was the primary station for ranging to the Lunar Reconnaissance Orbit (LRO) from 2009 until September 2014.

System Features:

- 1 to 2 arcsecond pointing/tracking accuracy
- Track CCR equipped satellites to 20,000 km altitude, 24/7 operation
- Reduced ocular, chemical, electrical hazards
- Semi automated tracking features
- Small, compact, low maintenance, increased reliability
- Lower operating/replication costs



International Laser Ranging Service (ILRS)

International Laser Ranging Serivice

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).

NASA Goddard runs the **Central Bureau** of the ILRS. The Central Bureau is responsible for overseeing global operations of the international stations.

https://ilrs.cddis.eosdis.nasa.gov/

International Laser Ranging Service Goals

- To provide global satellite and lunar laser ranging data and their related products to support geodetic and geophysical research activities.
- To promote research and development activities in all aspects of the satellite and lunar laser ranging technique.
- **To provide the International Earth Rotation and Reference Systems Service (IERS) with products important to the maintenance of an accurate International Terrestrial Reference Frame (ITRF).**
- To develop the global standards and specifications and encourage international adherence to its conventions.
- To specify laser ranging satellite priorities and tracking strategies required to maximize network efficiency.
- To provide a forum for the exchange of laser ranging technology, operational experience, and mission planning.

NASA SLR is a leader in the ILRS

ILRS

ILRS Performance Standards

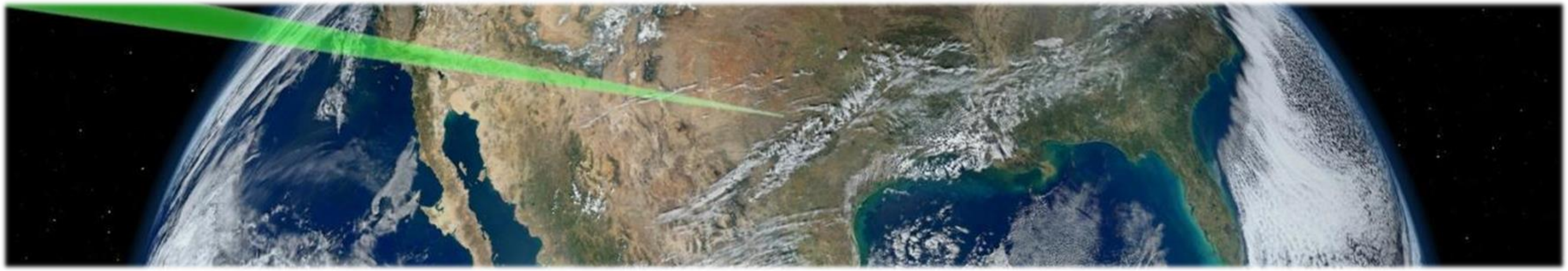
- The ILRS uses the LAser GEOdynamics Satellites (LAGEOS) to determine ground system performance

  https://ilrs.cddis.eosdis.nasa.gov/missions/satellite_missions/current_missions/lag1_general.html

- LAGEOS satellites (1 and 2) are spherical satellites with 426 retro-reflector cubes uniformly distributed about the surface
- Very stable ~6000 km altitude orbits
- Satellite ephemeris is known to < 1 cm
- 40+ years on orbit for first LAGEOS
  - LAGEOS 1 launched 1976
  - LAGEOS 2 launched 1992

International Laser Ranging Service

Eight of these stations are part of NASA's Current Legacy Network



Space Geodesy Project (SGP)

Space Geodesy

- **Geodesy** is the science of accurately measuring and understanding three fundamental properties of the Earth: its geometric shape, its orientation in space, and its gravity field— as well as the changes of these properties with time

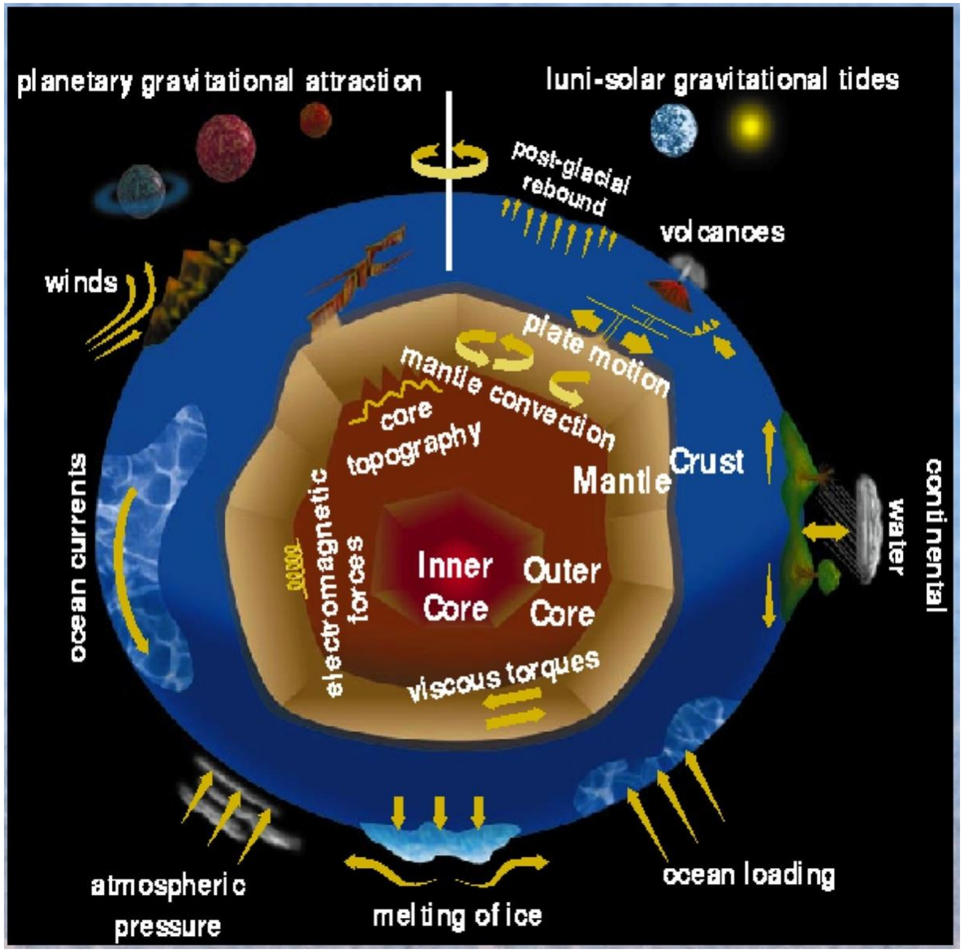
- **Space geodesy** is geodesy by means of sources external to Earth, including artificial satellites, quasars, and lunar retroreflectors.

Space Geodesy

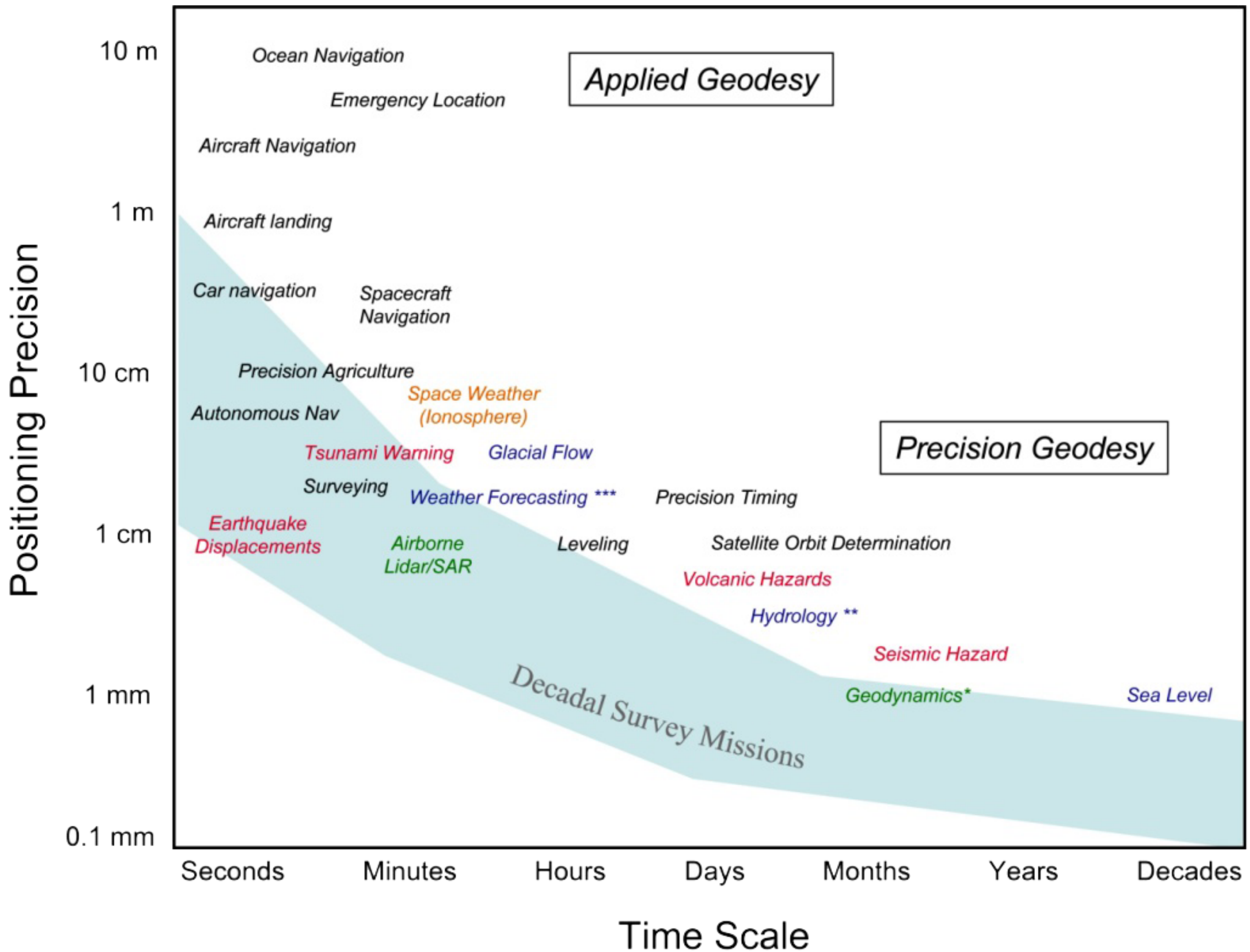
The Earth as we perceive it

https://space-geodesy.nasa.gov

The dynamic Earth as it is



Space Geodesy Provides Positioning, Navigation, and Timing Reference Frames and Earth System Observations



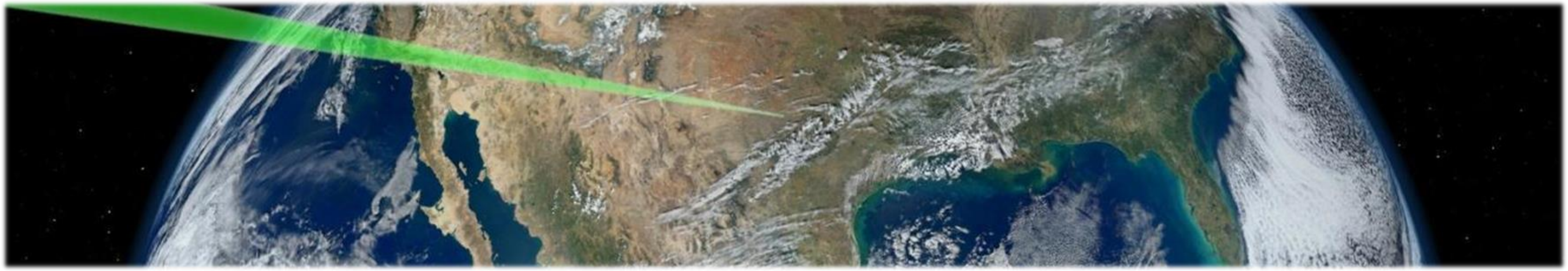
NASA's Space Geodesy Program (SGP)

- New NASA initiative started at the end of 2011 in response to the Earth Science Decadal and the National Research Council study "Precise Geodetic Infrastructure."
- Encompasses the development, operation, and maintenance of a Global Network of Space Geodetic technique instruments, a data transport and collection system, analysis and the public disseminations of data products required to maintain a stable terrestrial reference system.
- Comprises ongoing tasks that include:
  - The operation and management of NASA's existing global geodetic network and analysis systems, and the delivery of Space Geodetic products.
  - Operation of the prototype next generation space geodetic site at NASA Goddard with integrated next generation SLR, VLBI, GNSS, and DORIS stations, along with a system that provides for accurate vector ties between them.
  - Plan and implement the construction, deployment and operation of a NASA network of similar next generation stations that will become the core of a larger global network of modern space geodetic stations.
  - Development and delivery of retro-reflector arrays for the next generation GPS III satellites.
  - Modernization of NASA's space geodesy analysis systems in support of NASA Earth Science requirements.

VLBI	SLR	GNSS	Vector Tie
			

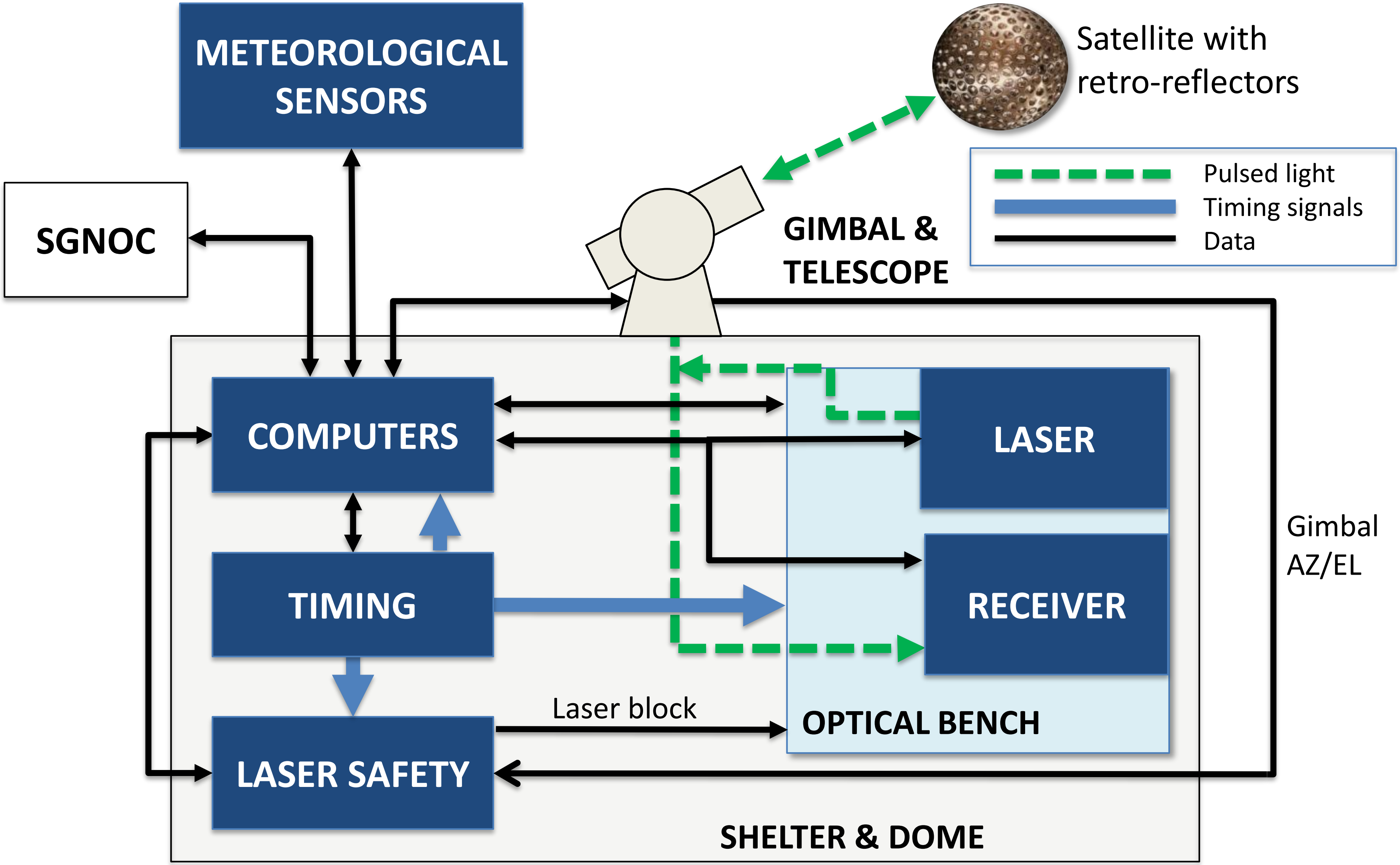
NASA Satellite Laser Ranging (SLR)

- **GSFC/SGP operates five SLR stations:**
  - GGAO, Greenbelt, Maryland,
  - McDonald Observatory, Fort Davis, Texas (Univ. of Texas at Austin),
  - Monument Peak, Mount Laguna, California,
  - Haleakala, Maui, Hawaii (Univ. of Hawaii, Institute for Astronomy),
  - Arequipa, Peru (Universidad Nacional de San Agustin (UNSA)).
- **GSFC/SGP supports three partner stations:**
  - Tahiti, French Polynesia (CNES, Univ. of French Polynesia),
  - Hartebeesthoek, South Africa (NRF, Hartebeesthoek Radio Observatory),
  - Yarragadee, Australia (Geoscience Australia).
- **GSFC maintains the archival and distribution of the worldwide SLR data using the Crustal Dynamics Data Information System (CDDIS).**



SGSLR Technical Overview

SGSLR Simplified Block Diagram



SGSLR's Nine Major Subsystems

- **Timing & Frequency (T&F)**
  - GPS tie to USNO – heart beat of system
  - Monitoring of timing using 2nd GPS
  - Monitoring info supplied to software
- **Meteorological (MET)**
  - Pressure, Temperature, Humidity for data quality
  - Horizontal Visibility, Precipitation, Wind, Sky Clarity for automation
- **Telescope and Gimbal**
  - Gimbal & Telescope Assembly **(GTA)** – pointing and tracking
  - Visual Tracking Aid – used by operator
- **Optical Bench (OB)**
  - Transmit path, Receive path, Star Camera, Motion Control
  - Software can automatically configure for all modes
- **Laser**
  - Provides health & diagnostic information to Software
  - Repetition rate controlled by software
- **Laser Safety (LSS)**
  - NASA/ANSI compliant, Failsafe, Redundant, Highly responsive
  - Provides information to Software on actions it takes and reasons why
- **Receiver**
  - Sigma Space Range Receiver **(SSRx)** – Precise signal timing coupled with angular offset info to optimize pointing
  - Range Control Electronics **(RCE)** – sets range window and laser fire rate
- **Dome, Shelter, Pier, Riser (DSPR)**
  - Provides clean stable environment and protection from weather
  - Software controls power through UPS units and can shut everything down
- **Computer and Software (C&S)**
  - Ties all subsystems together for manned, remote, and automated operations

Level 3 Requirements: Data Quality/Quantity

Quality Requirements

- **SLBP3.1**

  Data precision for LAGEOS Normal Points shall be < 1.5 mm when averaged over a one month period

- **SLBP3.2**

  The LAGEOS Normal Point range bias shall be stable to 1.5 mm over 1 hour

- **SLBP3.3**

  Over 1 year the RMS of station's LAGEOS Normal Point range biases shall be < 2 mm

- **SLBP3.5**

  Normal Point time of day shall be accurate to < 100 ns RMS

- **SLBP3.8**

  SGSLR Stations shall not introduce any unquantified biases into the legacy SLR network

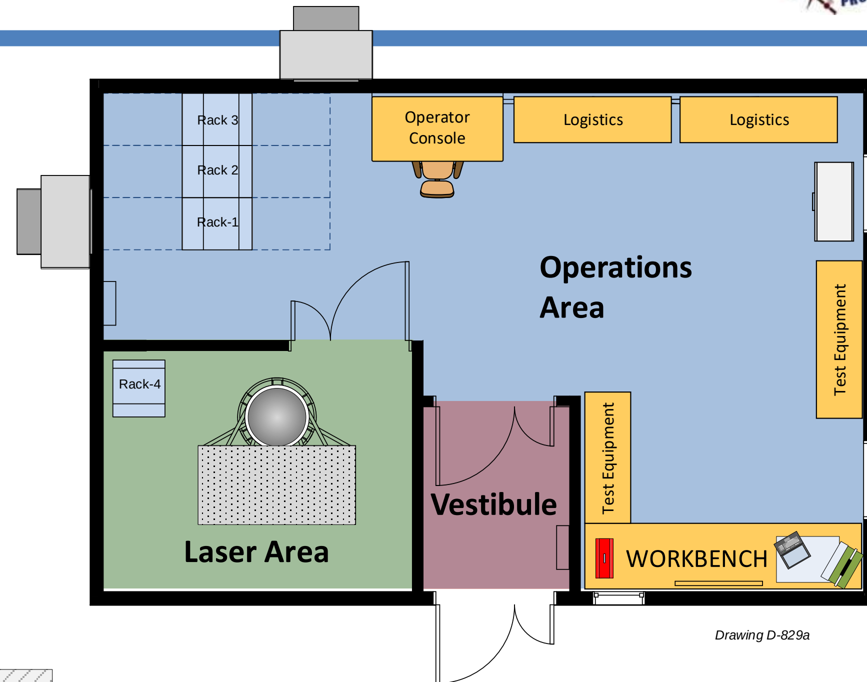
Quantity Requirements

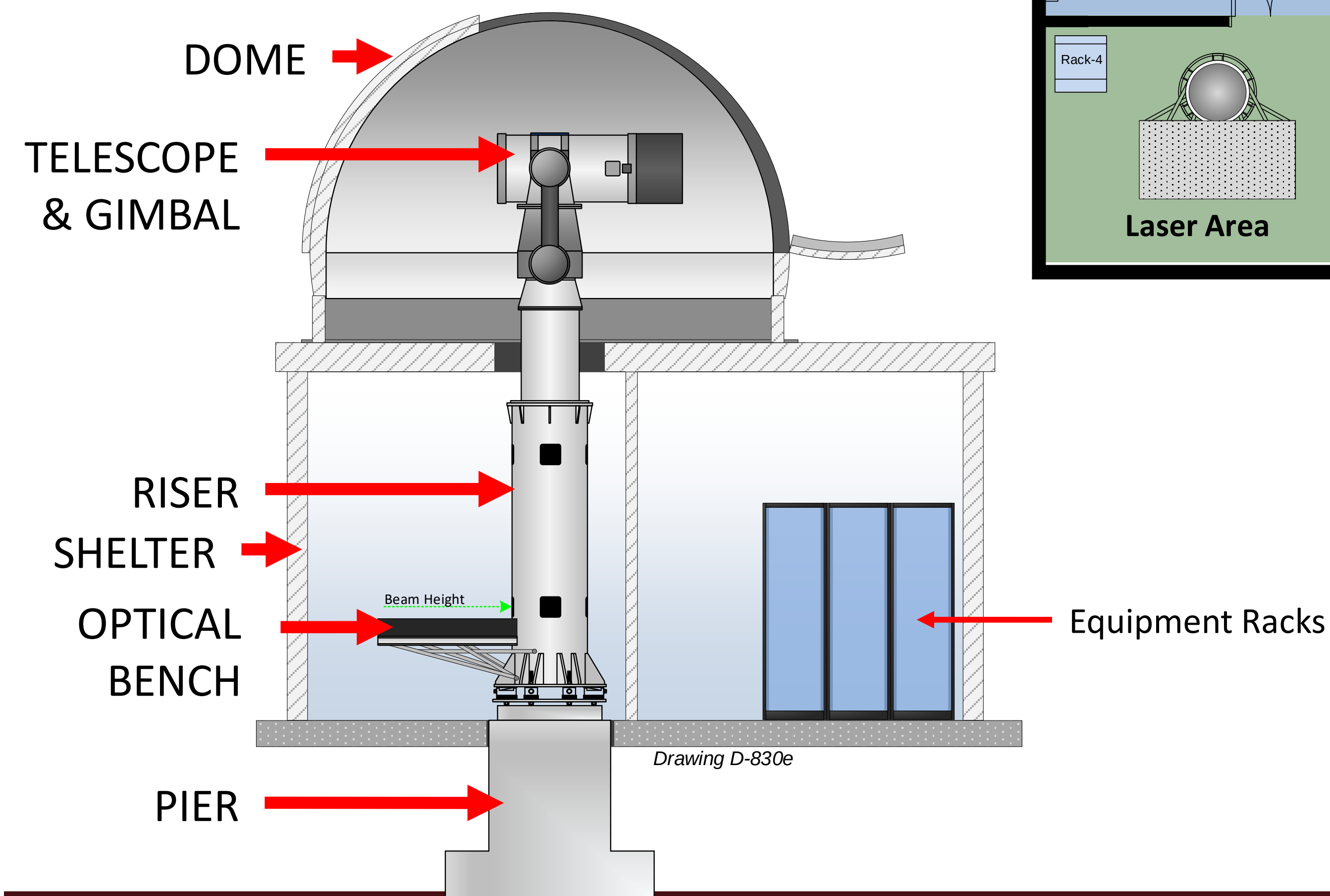
- **SLBP3.4**

  SGSLR Station shall be capable of producing an annual volume of 45,000 LEO, 7,000 LAGEOS and 10,000 GNSS Normal Points

Cross-section of SGSLR Shelter

- Vibration isolation between pier and shelter
- 20’ x 30’ x 10’ shelter
- 4.2 m dome

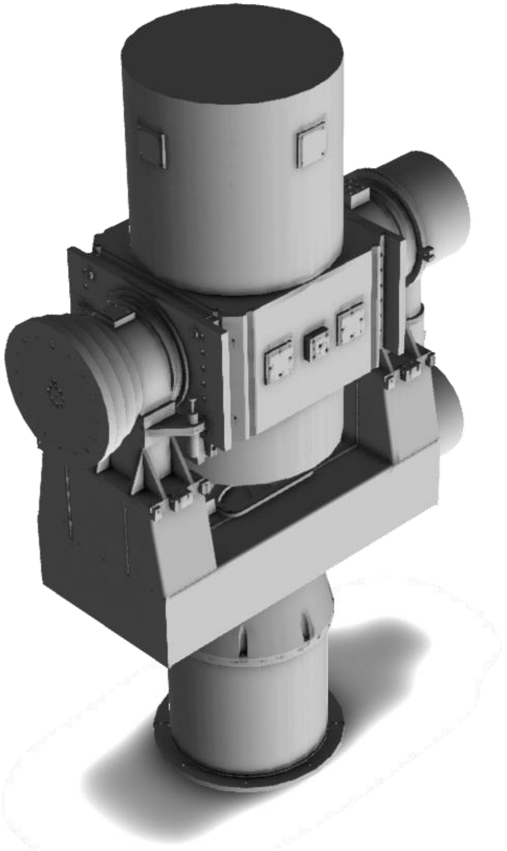




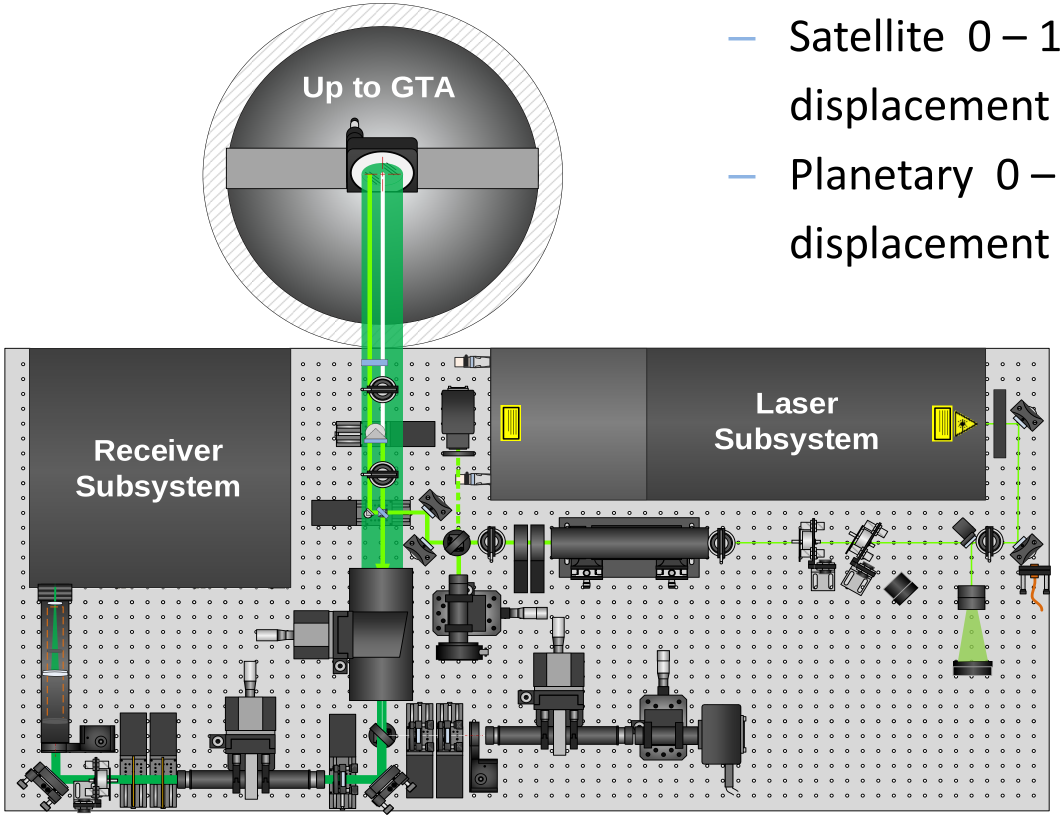
Telescope & Gimbal

Specification	Current Best Estimate
Type:	Ritchey–Chrétien
Aperture Size:	0.5 meters
Jitter:	1 arcsec RMS
Absolute open loop pointing:	3 arcsec RMS
Invariant Point:	1mm in 3D space
Tracking Az Velocity: **Tracking Az Acceleration:** **Tracking El Velocity:** **Tracking El Acceleration**	0°– 10°/sec 0°– 1°/sec^2 0°– 2°/sec 0°– 0.5°/sec^2
Slew Az Velocity: **Slew Az Acceleration:** **Slew El Velocity:** **Slew El Acceleration:**	75°/sec 30°/sec^2 75°/sec 30°/sec^2

Specifically designed for SGSLR



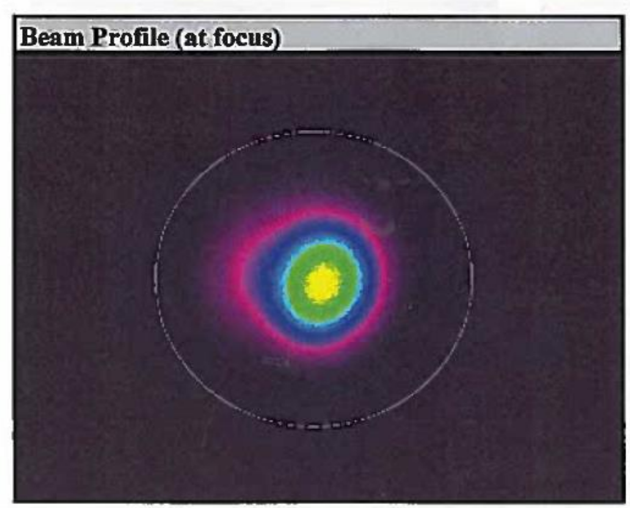
Optical Bench Subsystem

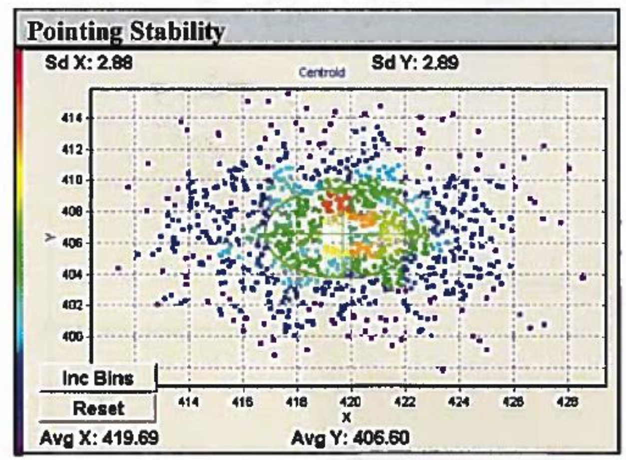


- Transmit path optical transmission > 90.8%
- Transmit Divergence out of the Telescope
  - 6 – 30 arcseconds full angle
- Point Ahead – GTA out of the Telescope
  - Satellite 0 – 11 arcseconds beam angular displacement in any direction
  - Planetary 0 – 60 arcseconds beam angular displacement in any direction
- Receive path optical transmission 77% (night) 54% (day)
- Receiver FOV from the Telescope
  - 14 to 60 arcseconds
- Star Camera FOV from the Telescope
  - 2 arcminute FOV
  - Spot size 2 arcseconds

Laser Subsystem

- **Photonics Industries RGL-532-25**
  - Wavelength: 532 nm
  - Pulse Energy: 2.5 mJ
  - Beam Divergence: < 1 mR
  - Beam Diameter: 1.7 mm
  - Pulse Width: 50 ps
  - Repetition Rate: Single Shot to 5 kHz
- Externally triggered at varying frequencies of 1887 Hz – 2000 Hz (500 – 530 µs between shots) to avoid transmit/receive collisions



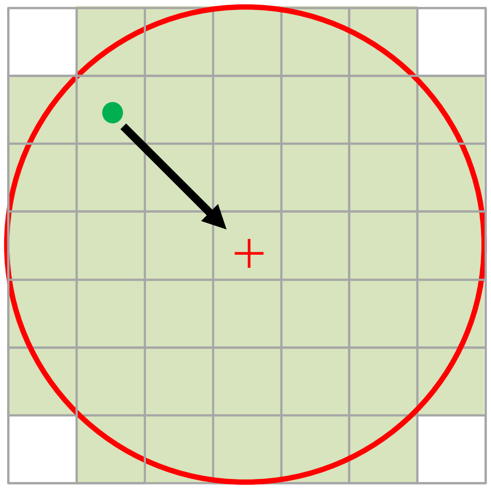


Receiver Subsystem

- **SigmaSpace Receiver (SSRx)**
  - Detects and time tags start (transmit) and stop (receive) ranging events
  - Precisely relates ranging events and ancillary signals to UTC
- **Range Control Electronics (RCE)**
  - **Generate** a gate that ‘windows’ a Satellite OR Calibration (Ground/Internal) corner cube return for sensor detection in the Receiver Subsystem
  - **Generate** a ‘Laser Fire’ Command signal BUT not at the same time a window signal appears

SGSLR SSRx Overview

- Provide Closed Loop Tracking
  - 7x7 pixelated MCP-PMT detector array
  - 4 pixels in corners unused
  - Count # of events in each pixel to determine satellite location
  - Signal location used by C&S subsystem to correct angular position to maximize return signal strength



- Make Precise, High Resolution Timing Measurements
  - Start Events: Single measurement per shot
  - Stop Events: Multi-stop, low dead-time
  - Ancillary Events (e.g., 1 PPS)

- Selection based on proven heritage hardware from aircraft and space-flight designs

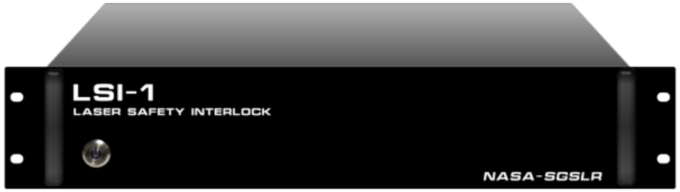
Time and Frequency Subsystem

- Key Specifications
  - 10 MHz Frequency Reference Stability
    - @ 1 Second $\leq 7 \times 10^{-11}$
    - @ 1 Day $\leq 2 \times 10^{-12}$
  - IRIG-B Accuracy
    - DCLS 200 ns of UTC
    - AM 10 µS of UTC
  - 1 PPS Accuracy 15 ns to UTC
  - Monitoring Accuracy
    - Time Resolution: 12.2 ps LSB, 48 bit range
    - Jitter: < 10 ns/second

Laser Safety Subsystem

Key Specifications

- LSI (Laser Safety Interlock)
  - Failsafe & Redundant
  - Multiple Safety Sensor Inputs (Footpads, Door Sensors, Laser Kill Switches, etc.)
  - Reaction time
    - Laser Fire Disable ~50 ms
- LHRS (Laser Hazard Reduction System) - radar
  - Transmit Frequency 9410 MHz
  - Transmit Power 25 W
  - Range 45 km for a 20 sq-m target
  - Drive Rate
    - Azimuth 20°/second
    - Elevation 20°/second
  - Pointing Accuracy ± 0.05°
  - Dish diameter 48”
  - Repetition Rate 1000 Hz
  - Pulse
    - Pulse length 40 ns
    - Chirp length 2-96 µs



Meteorological Subsystem (1 of 2)

◆ Key Specifications

- Barometric Pressure Measurement
  - Range: 500 to 1100 hPa
  - Accuracy: ±0.08 hPa
- Temperature Measurement
  - Range: -40°C to +60°C
  - Accuracy: ±0.1°C
- Humidity Measurement
  - Range: 0 to 100% non-condensing
  - Accuracy: ±2% at 25°C
- Precipitation:
  - Device measures multiple types of precipitation: rain, freezing rain, fog, haze (dust, smoke, sand) and clear conditions
  - Precipitation detection sensitivity: 0.05 mm/h or less, within 10 minutes
  - Intensity Measurement Range: 0.00 – 999 mm/h

Meteorological Subsystem (2 of 2)

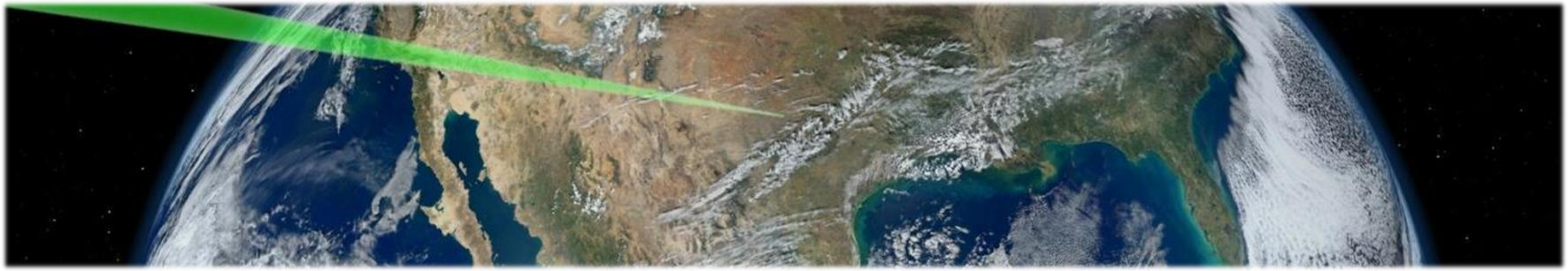
- **Key Specifications**
  - Wind Speed Measurement
    - Range: 0 – 75 m/s
    - Accuracy: ±0.1 m/s or 2% of reading *(whichever is greater)*
    - Resolution: 0.01 m/s
  - Wind Direction Measurement Range: 0 - 360^{o}
    - Accuracy: $\pm 2^{o}$
    - Resolution: 0.01^{o}
  - Sky Camera
    - Field of View: 180^{o} x 180^{o}
    - Pixel Scale: 5.4 arcmin/pixel
  - Temperature Range for Operation/Survival
    - Operating Temperature: -40°C to +50°C
    - Survival Temperature: -40°C to +50°C

Computer and Software Subsystem

- Purpose of subsystem
  - Support local and remote operations
  - Command/control, calibrate, and monitor the system
  - Link all other subsystems together
  - Transfer and store data, process ranging data, perform operational decision making, generate and deliver science data product, and communicate with the SGNOC
  - System Automation
- SGSLR deployment be phased in local, remote, and automated operation stages
- Final Phase SGSLR will support automated 24/7 operations

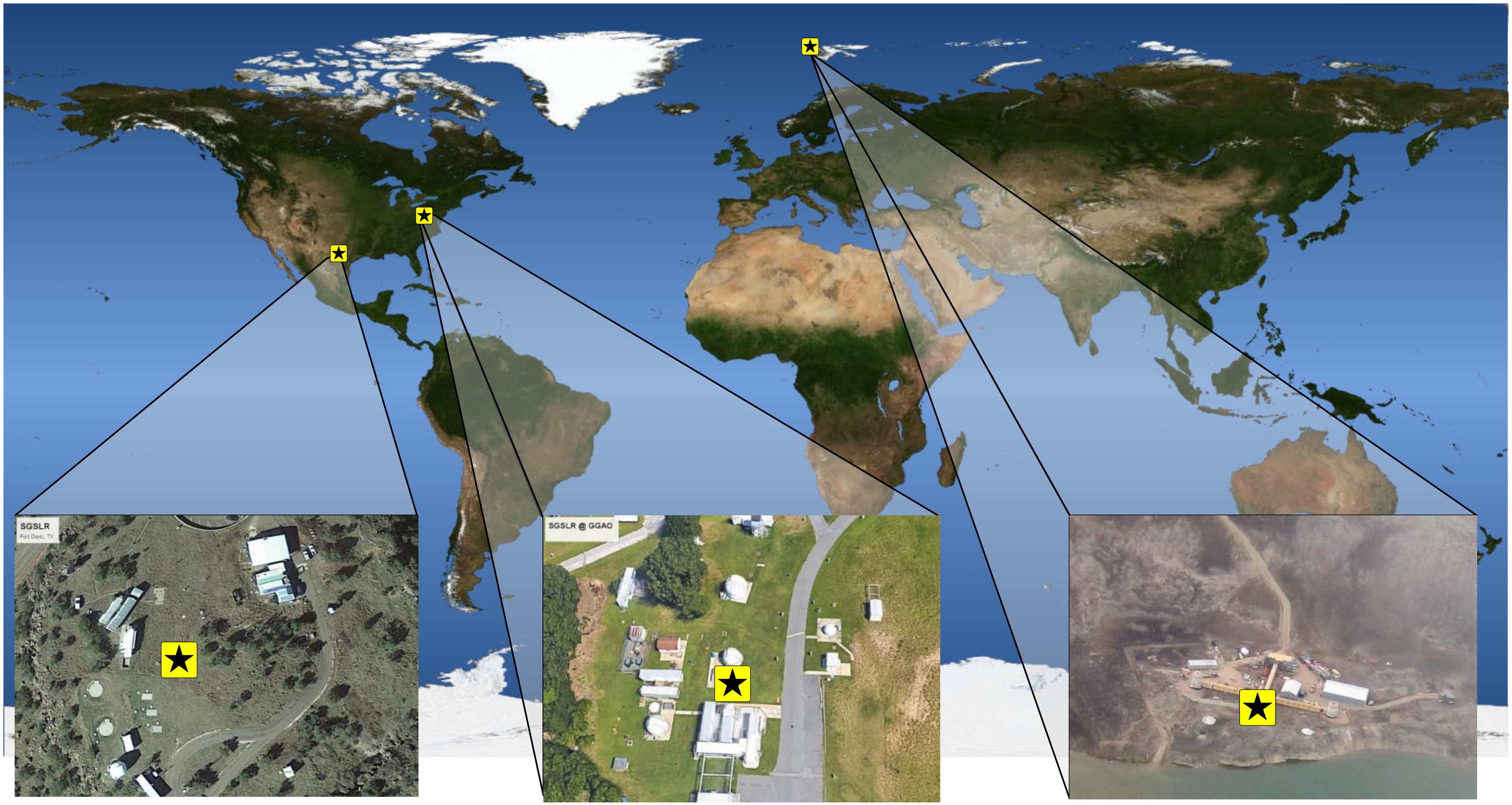
SGSLR Facilities at GSFC

- Building 28 W120G
  - Limited access lab (smartcard needed) with no windows
  - Designed for laser testing & characterization
  - Optical benches will be built here
- 1.2 meter telescope facility (located at GGAO)
  - Hardware lab is being used for receiver testing
  - Telescope can and has been used for:
    - Ground target ranging using SGSLR prototype receiver
    - Testing GTA FAT camera configuration by tracking stars and sunlit satellites
  - Software lab is being used for SW development/testing
- SGSLR test & verification facility (located at GGAO)
  - Facility currently being built
  - Will be used for GTA SAT, SGSLR I&T, and System Verification (including collocation with MOBLAS-7)



First Three SGSLR Deployments

SGSLR Sites



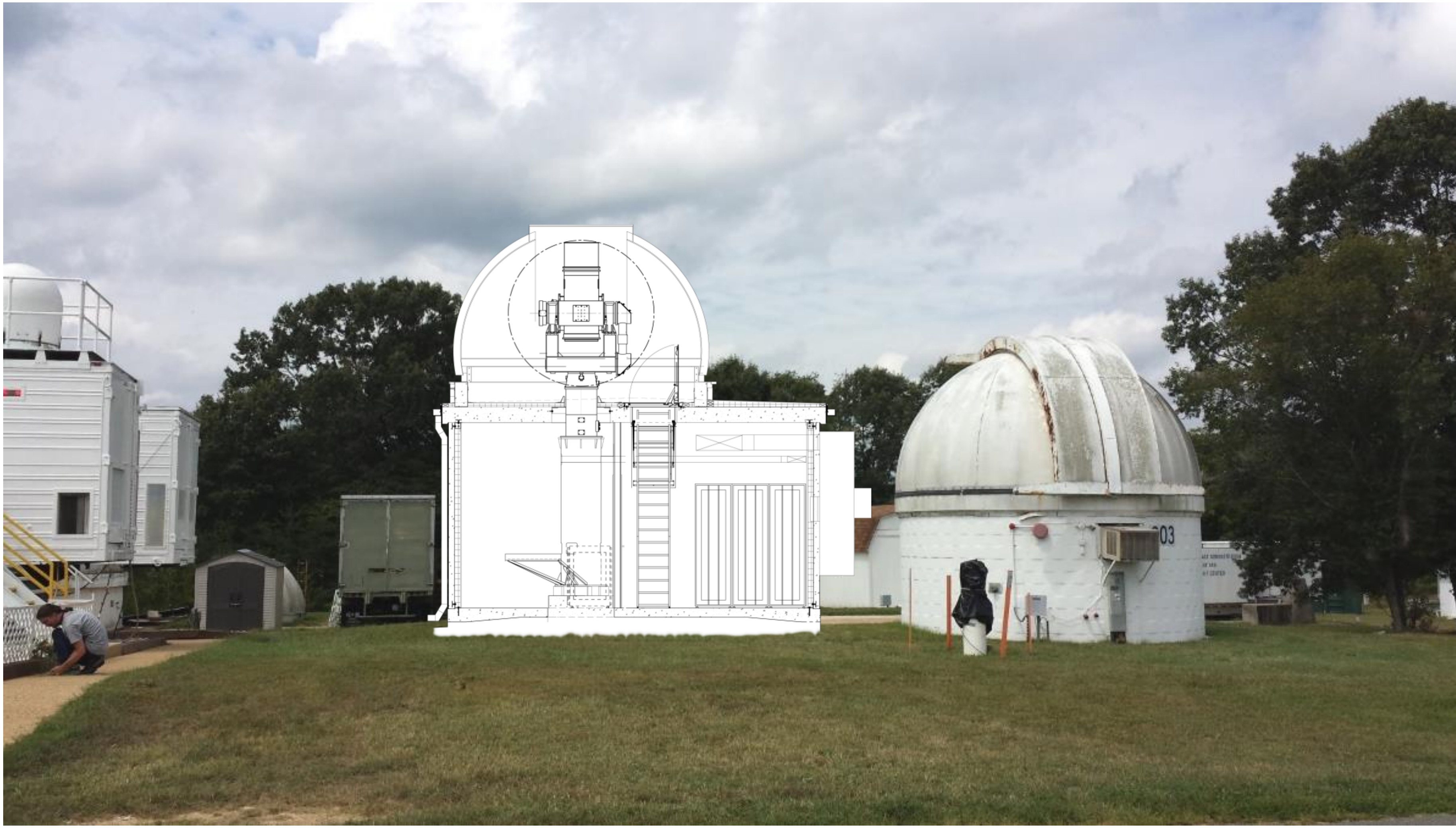
McDonald Observatory, TX
(MGO)

Greenbelt, MD
(GGAO)

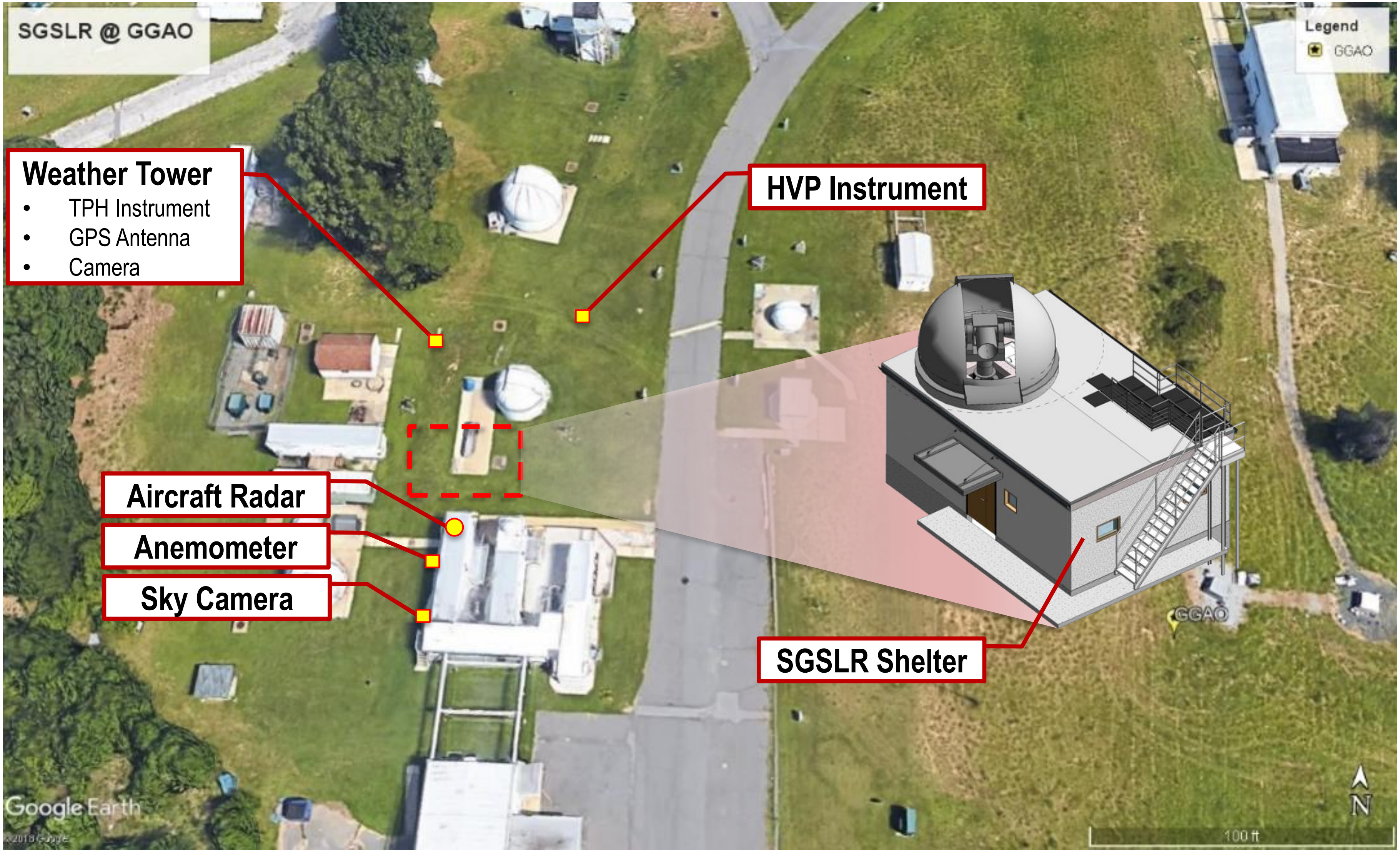
Ny-Ålesund, Norway
(NGO)

Drawing D-014b

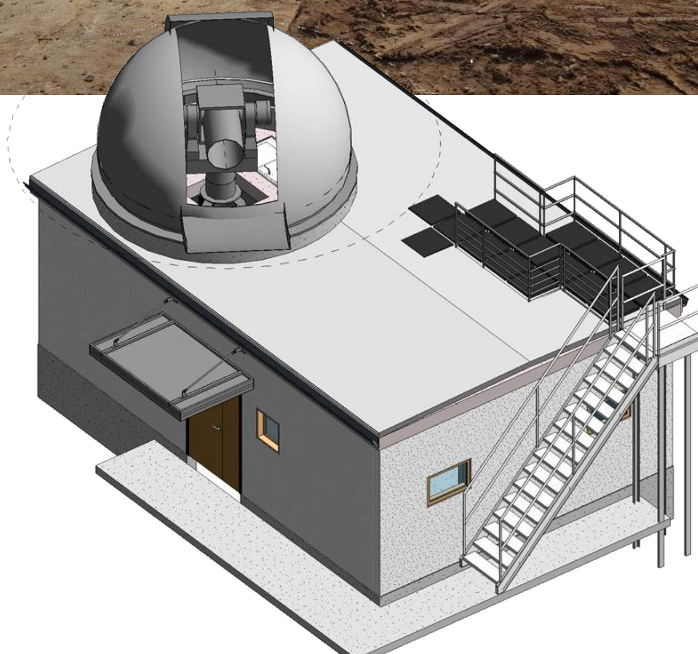
Site Layout: GGAO



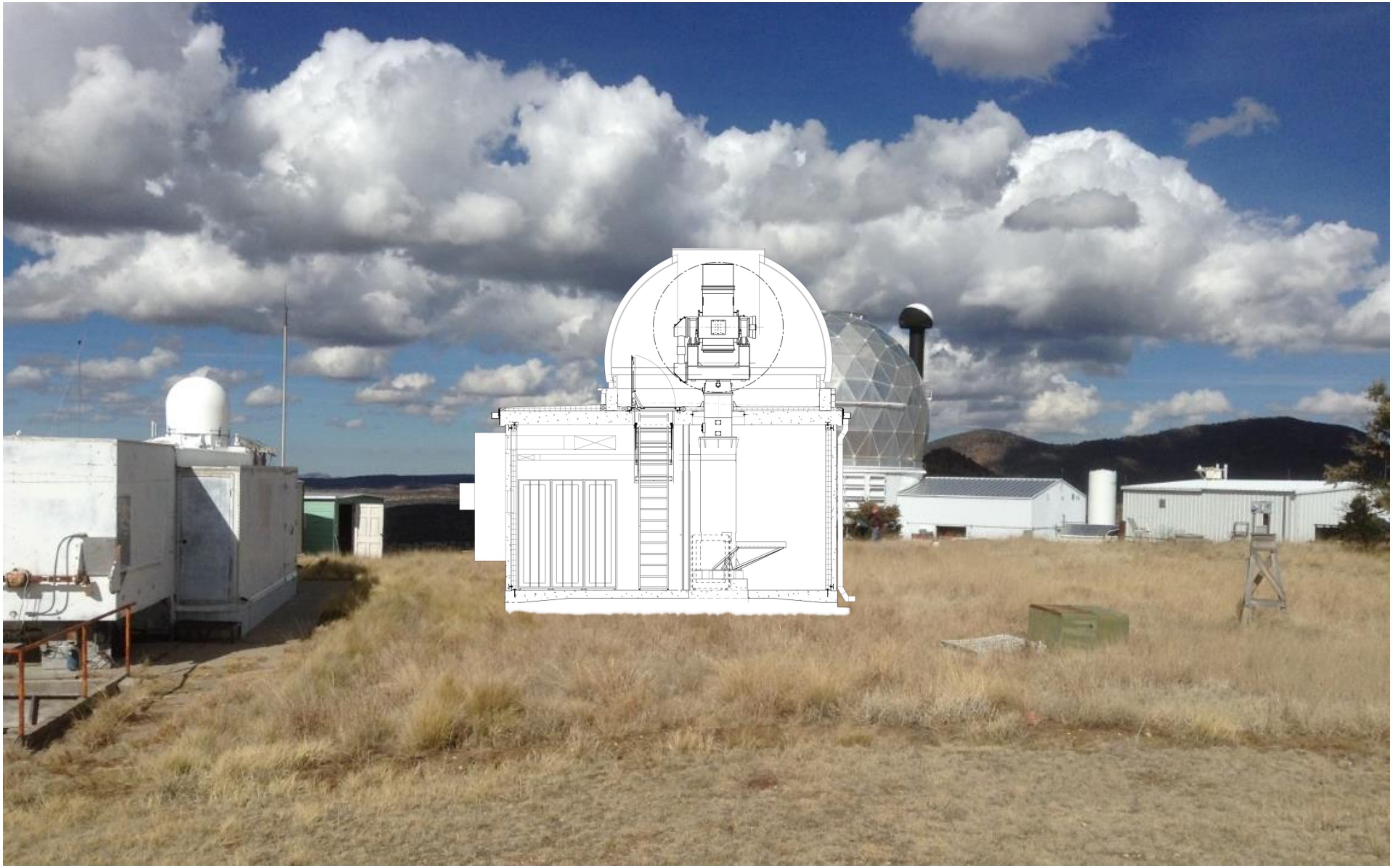
Site Layout: GGAO



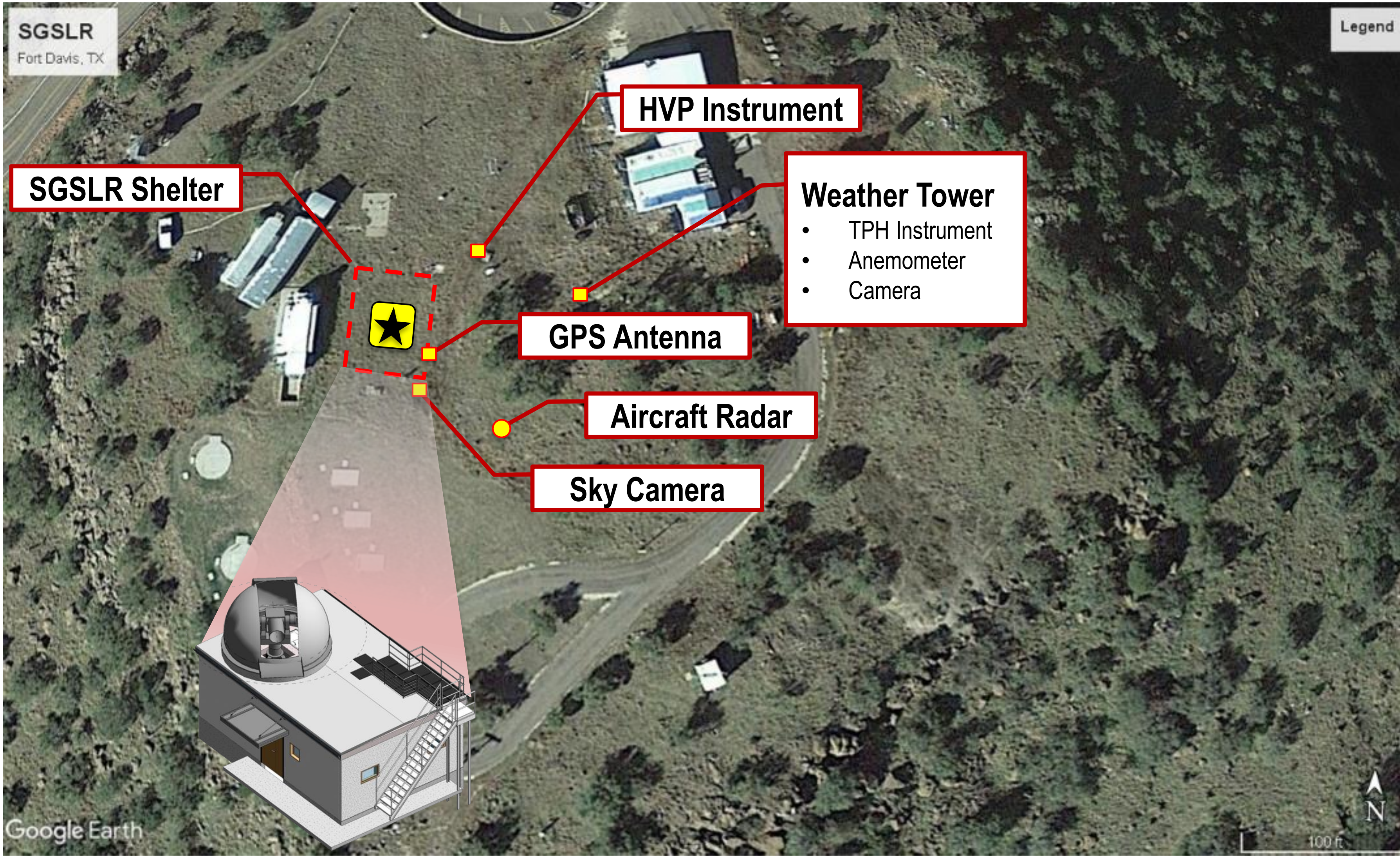
GGAO Shelter Being Built



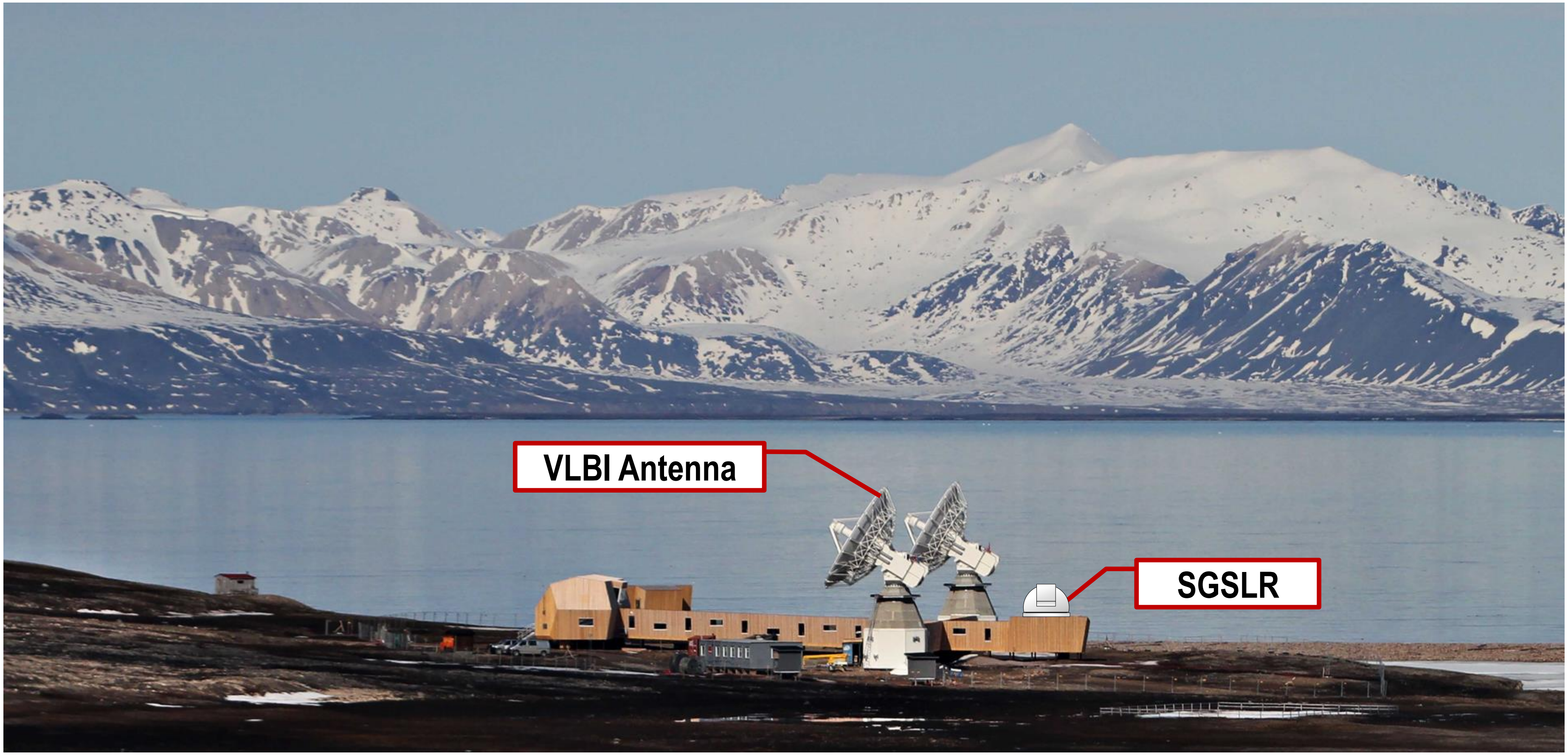
Site Layout: McDonald Observatory



Site Layout: McDonald Observatory

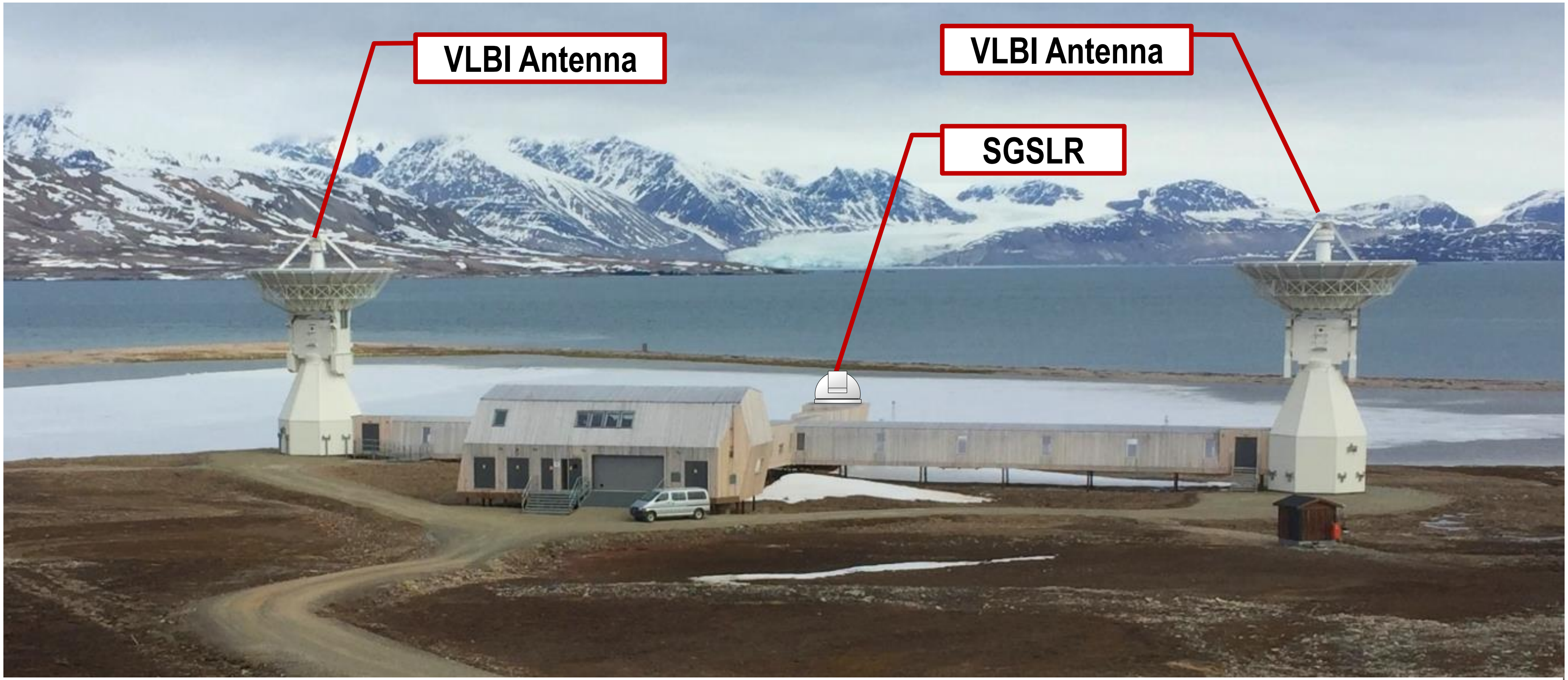


Site Layout: Ny-Ålesund



NOTES:
- Shelter already constructed; Dome not yet installed
- Unique shelter design
- Co-located with VLBI

Site Layout: Ny-Ålesund



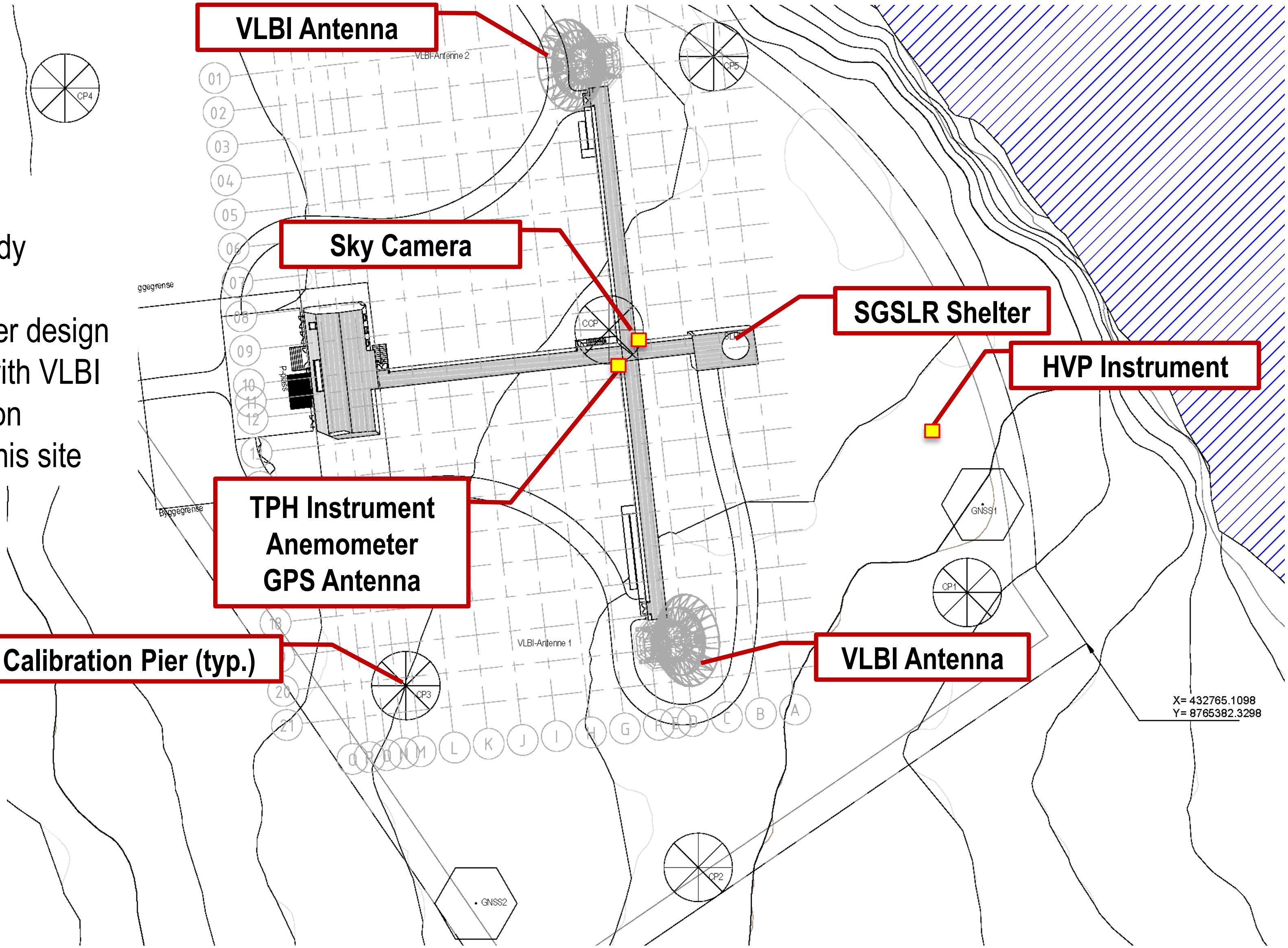
NOTES:

- Shelter already constructed; Dome not yet installed
- Unique shelter design
- Co-located with VLBI

Site Layout: Ny-Ålesund

NOTES:

- Shelter already constructed
- Unique shelter design
- Co-located with VLBI
- Arctic Location
- No radar at this site



Comparison of Subsystems by Site

Subsystem	GGAO	MGO	NGO
Telescope and Gimbal	*Baseline Design*	*Baseline Design*	*Baseline Design*
Time and Frequency	*Baseline Design*	*Baseline Design*	*Baseline Design*
Optical Bench	*Baseline Design*	*Baseline Design*	*Baseline Design* **Optical bench height based on NGO riser**
Meteorological	*Baseline Design*	*Baseline Design*	*Baseline Design*
Laser Safety	*Baseline Design*	*Baseline Design*	*Baseline Design* **Aircraft detection method, no radar allowed - NMA assessing detection method**
Laser	*Baseline Design*	*Baseline Design*	*Baseline Design*
DSPR	*Baseline Design*	*Baseline Design*	NMA built shelter **(smaller)** **Pier and Riser Height Different.** **UPS will convert local power.**
Receiver	*Baseline Design*	*Baseline Design*	*Baseline Design*
Computer & Software	*Baseline Design*	*Baseline Design*	*Baseline Design*
Network Architecture	*Baseline Design*	*Baseline Design*	*Baseline Design*

Standardized design can be applied to most locations

SUMMARY

- Satellite Laser Ranging was first successfully performed at NASA Goddard in 1964 (at what is now GGAO).
- NASA Goddard has a continuous history of successful SLR activities since 1964.
- The Goddard Geophysical and Astronomical Observatory has played and will continue to play a major role in NASA SLR.
- The SLR part of the new Space Geodesy Network will be SGSLR which is designed to fulfill rigorous requirements for data accuracy, stability, and quantity.
- Testing and verification of each SGSLR system will take place at GGAO before being deployed.