SGSLR: Development of a New Generation of Satellite Laser Ranging Stations

NASA GSFC Geodesy & Geophysics Laboratory Seminar
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Code 61A

Geodetic Infrastructure: Sounding the Alarm

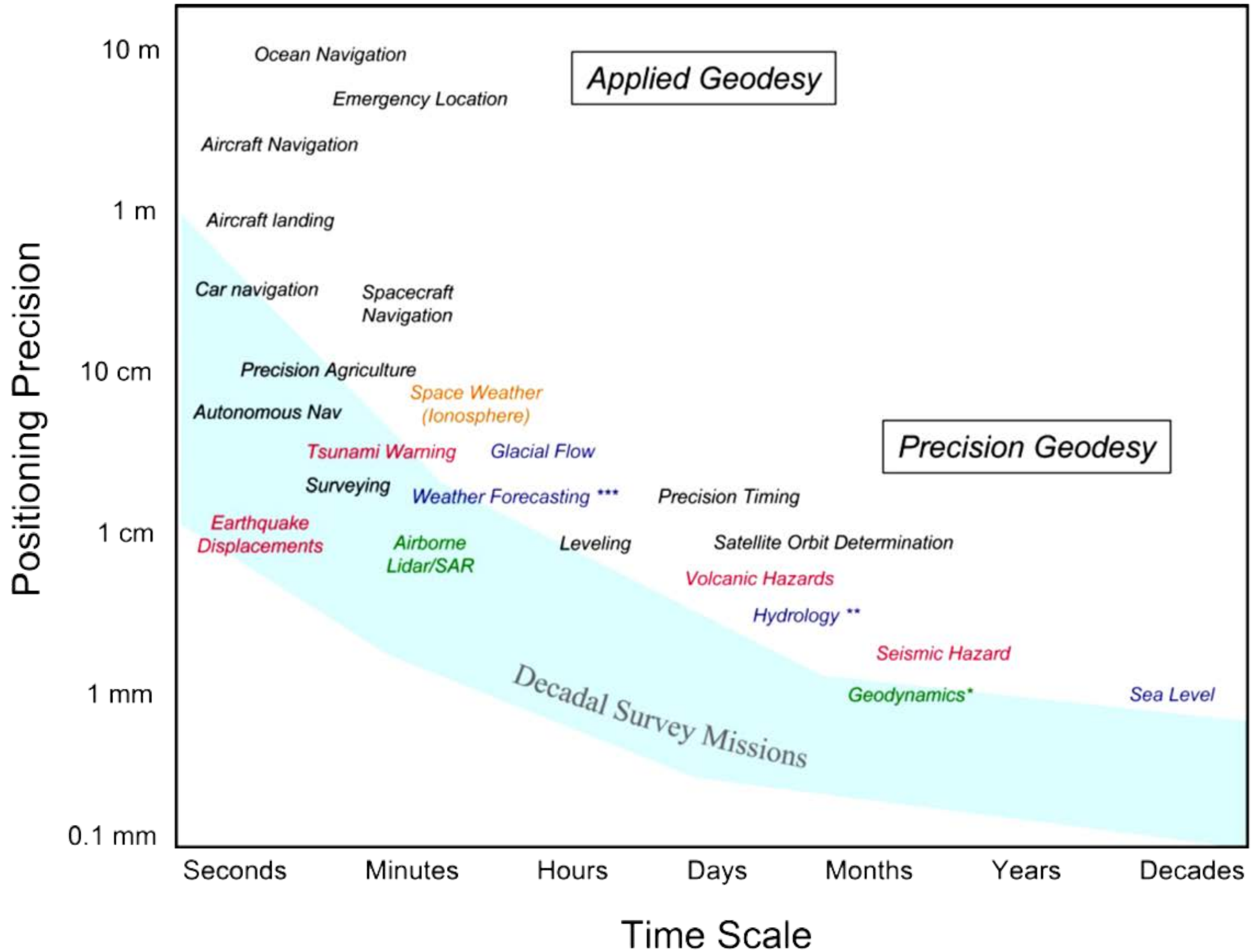
"The geodetic infrastructure needed to enhance or even to maintain the terrestrial reference frame is in danger of collapse ... Improvements in accuracy and economic efficiency are needed… [The terrestrial reference frame] provides the foundation for virtually all space-based and ground-based observations in Earth science and studies of global change, including remote monitoring of sea level, sea-surface topography, plate motions, crustal deformation, the geoid, and time-varying gravity from space."

-2007 Earth Science Decadal Survey,
Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond

"Underpinning all spaceborne observations is an accurate terrestrial reference frame, which is critical for accurate positioning and navigation of all satellite and aircraft missions, especially now that it is necessary to reliably integrate data from constellations of satellites. Notably, ground networks (VLBI, SLR, and GPS) remain an essential component for reliable, sustained quantification of this terrestrial reference frame. Consequently, a major Earth observing priority for the next decade is to maintain and improve the terrestrial reference frame."

- Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space (2018)

Geodetic Applications and Requirements



National Research Council. Precise Geodetic Infrastructure: National Requirements for a Shared Resource. Washington, DC: The National Academies Press, 2010.

NASA’s Space Geodesy Project (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	DORIS
			

Components of SGP

VLBI
- Orientation of ITRF with respect to ICRF
- ITRF Scale

SLR
- Origin of ITRF (Earth's CM)
- ITRF Scale
- Position spacecraft in ITRF ("Orbits")

GNSS
- Precise monitoring of Polar Motion and Rotation Rate
- Position spacecraft in ITRF ("Orbits")
- Position instruments on Land and Sea (Tide Gauges and Buoys, Geodetic Instruments)

DORIS
- Position spacecraft in ITRF ("Orbits")
- Enhances global distribution of ITRF Station positions and velocities

Technique Connectivity (Station Co-Location)

Fully Define ITRF

VTS: ITRF Performance Improvement

Origin, Scale, Orientation

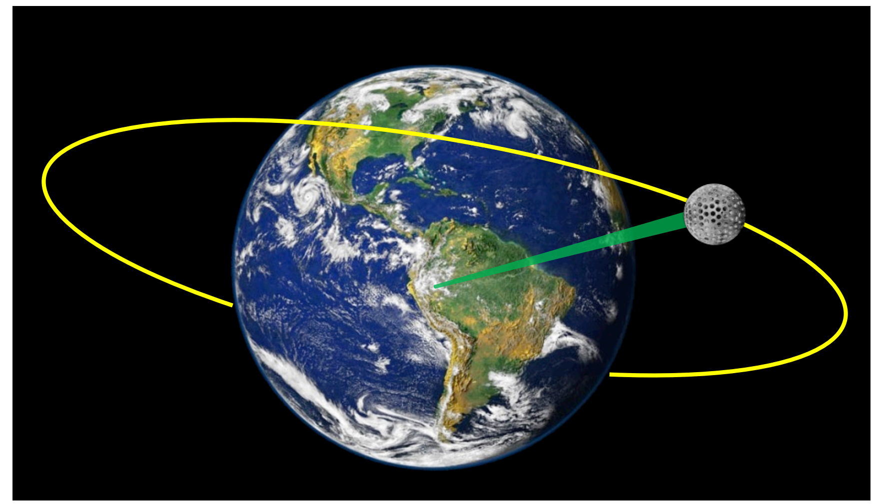
Low-Density Global Distribution

High-Density Global Distribution

Satellite Laser Ranging Technique

Observable: The precise measurement of the roundtrip time-of-flight of an ultra-short (< 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), Geosynchronous and the Moon
- Centimeter accuracy satellite orbits



SLR generates unambiguous centimeter accuracy orbits!

NASA Legacy Stations - MOBLAS and TLRS

- Built and operated since the early 80's
- 5 MOBLAS Stations and 2 TLRS stations around the world
- 5 – 10 Hz laser repetition rate, multiphoton signal
- Limited automation
- Requires a local station operator
- Dedicated personnel keep them productive

NGSLR to SGSLR

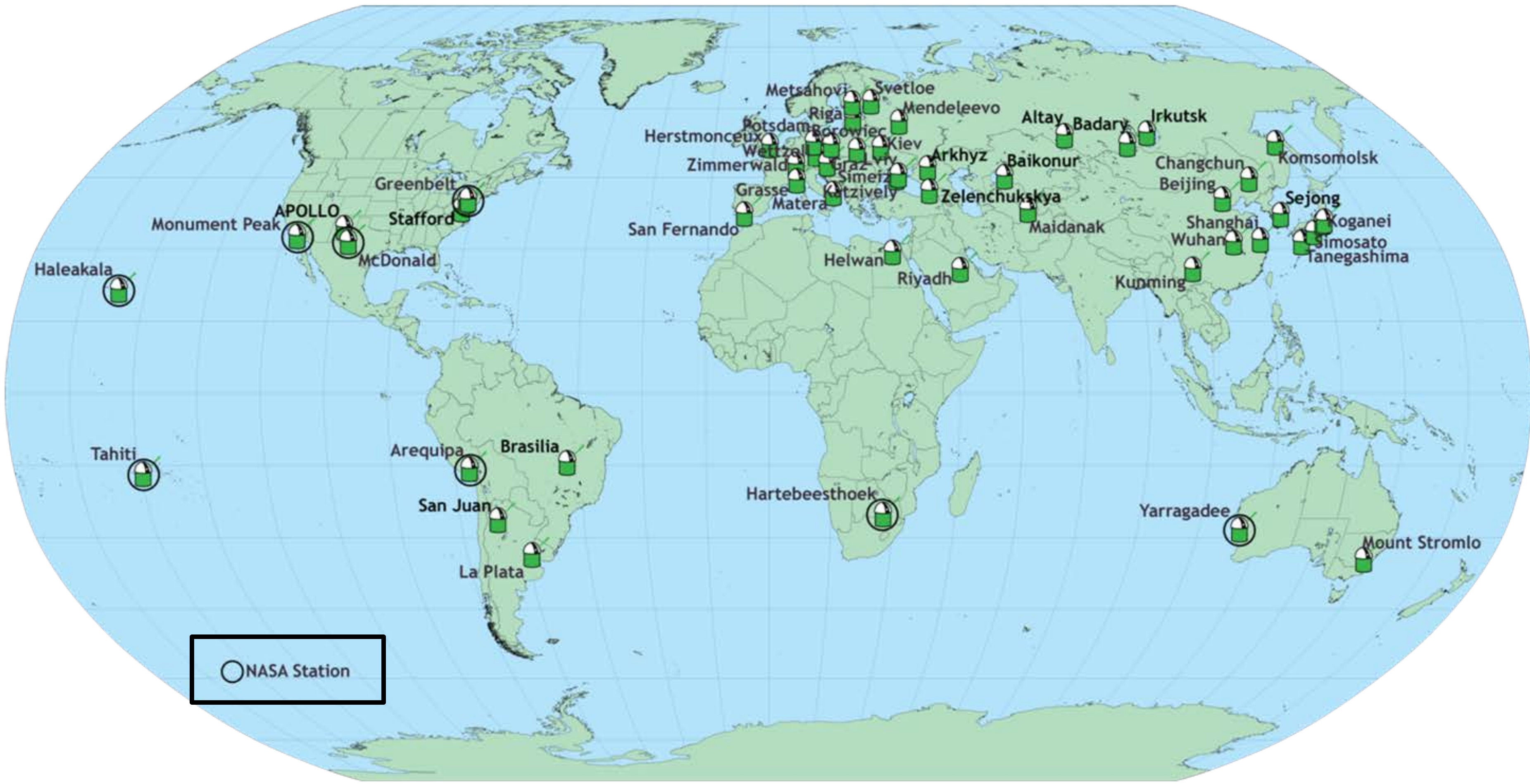
- NGSLR – Next Generation SLR Prototype
  - Kilohertz Ranging
  - Semi-autonomous
  - Single Photon Ranging – controlled by return rate
  - Successful collocation with MOBLAS-7 in 2013
- SGSLR – SGP SGSLR Station
  - NGSLR Features plus…
  - 1 mm normal point precision for LAGEOS
  - Stability at the 1 mm level over an hour
  - Fully Autonomous 24/7 hour ranging
  - As COTS as practical

International Laser Ranging Service: Goals

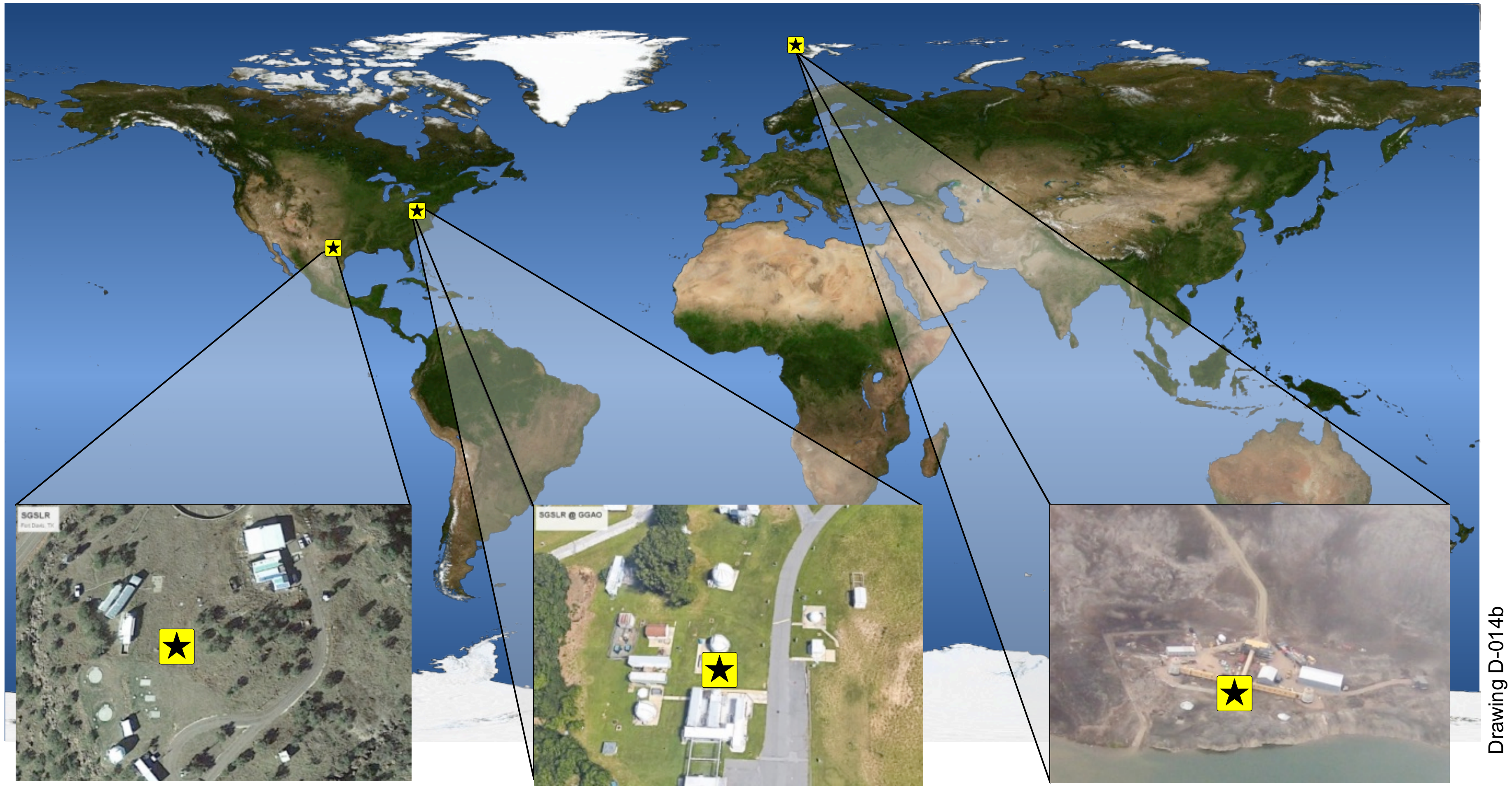
- To provide global satellite and lunar laser ranging data and their related products to support geodetic and geophysical research activities.
- To promote research and development activities in all aspects of the satellite and lunar laser ranging technique.
- To provide the International Earth Rotation and Reference Systems Service (IERS) with products important to the maintenance of an accurate 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

International Laser Ranging Service



Planned SGSLR Locations



McDonald Observatory, TX (MGO)

Greenbelt, MD (GGAO)

Ny-Ålesund, Norway (NGO)

Science Data Products

- Normal Point data is the standard ILRS data product and the primary science data product (level-1). A Normal Point is a combination of range measurements spanning a period of time which is a function of satellite altitude.
- SGSLR will follow the ILRS standards for Normal Point generation utilizing the Herstmonceux Algorithm. Refer to the following link for a description: http://ilrs.gsfc.nasa.gov/data_and_products/data/npt/npt_algorithm.html
- Normal Points will be automatically generated and subject to the following quality control checks on-site.
  - Use a minimum number of observations and single shot RMS to filter potential invalid normal points.
  - Use the skew and kurtosis to filter anomalous normal points.
- Qualified Normal Points will be automatically delivered to the Space Geodesy Network Operations Center (SGNOC).
- Full rate data will also be delivered to the SGNOC

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

Data Requirements

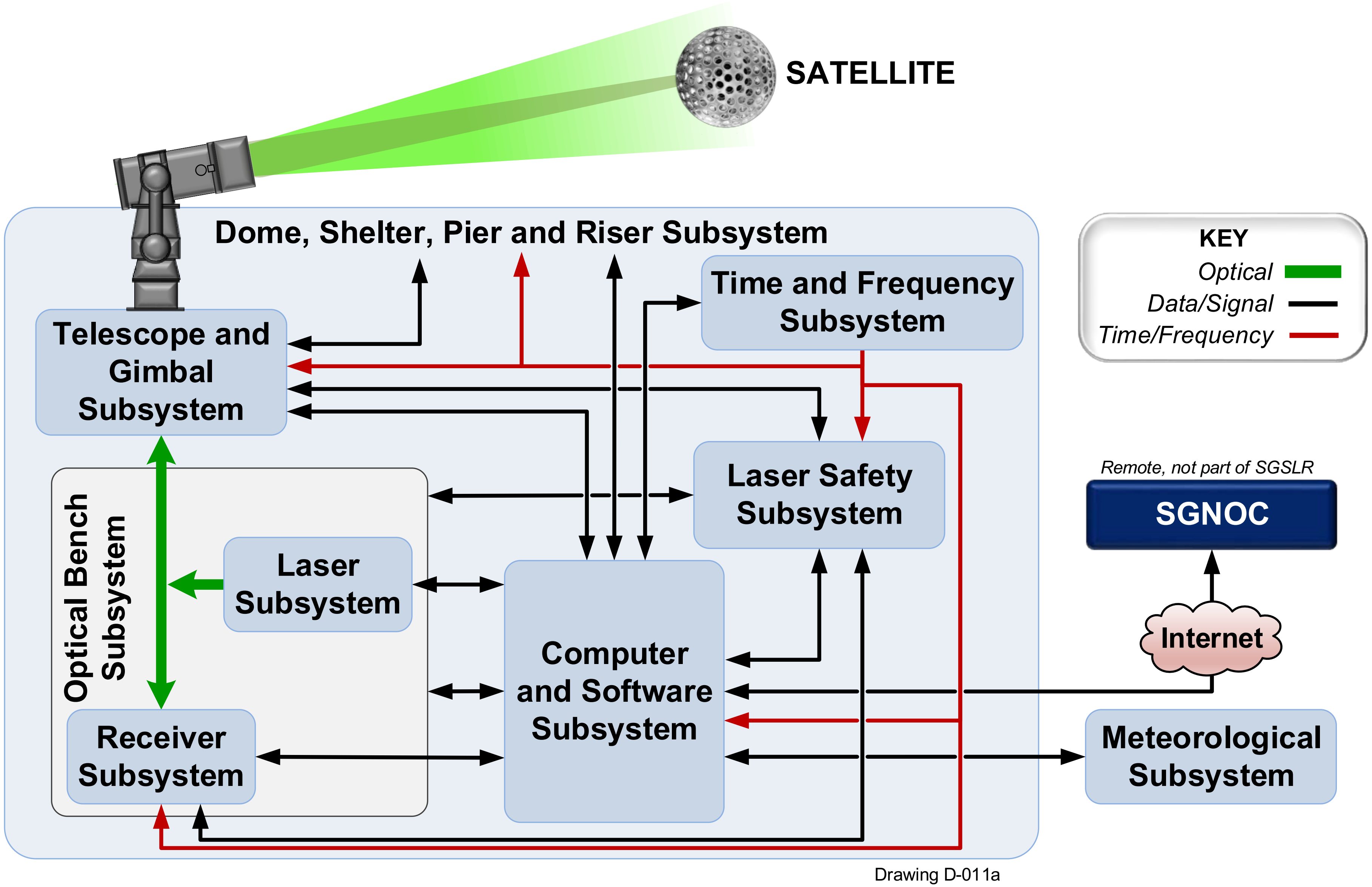
Quality Requirements

- Data precision for LAGEOS Normal Points shall be < 1.5 mm when averaged over a one month period
- The LAGEOS Normal Point range bias shall be stable to 1.5 mm over 1 hour
- Over 1 year the RMS of station's LAGEOS Normal Point range biases shall be < 2 mm
- Normal Point time of day shall be accurate to < 100 ns RMS
- SGSLR Stations shall not introduce any unquantified biases into the legacy SLR network

Quantity Requirements

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

Internal Interface Overview



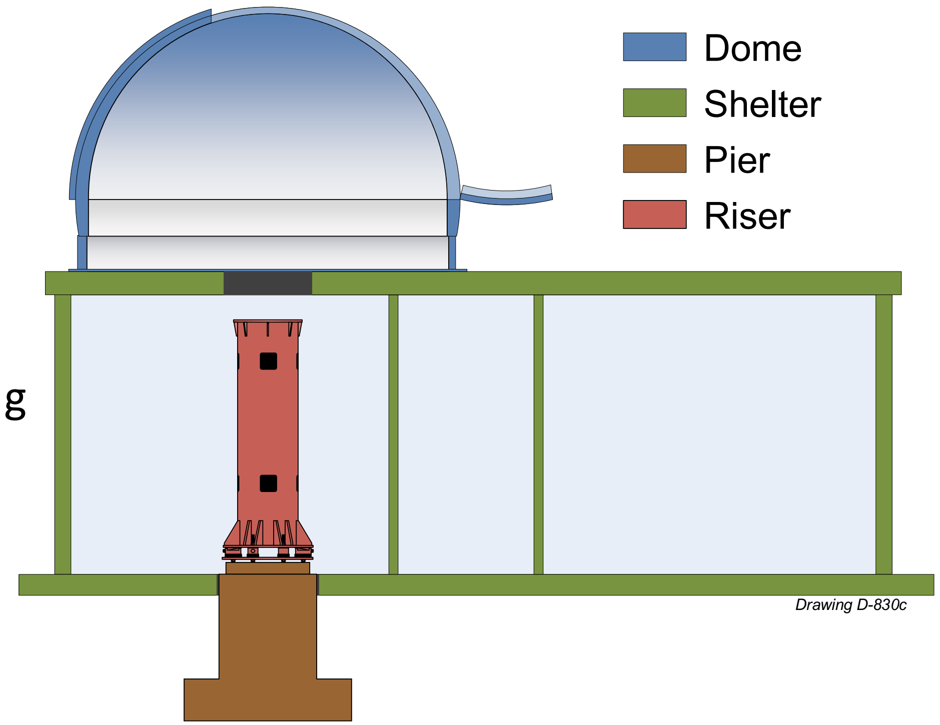
SGSLR's Nine Major Subsystems

- **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

DSPR Subsystem

- Key Specifications
  - Dome – Baader Planetarium
    - ~ 4 meter diameter
    - Supports work inside dome during bad weather

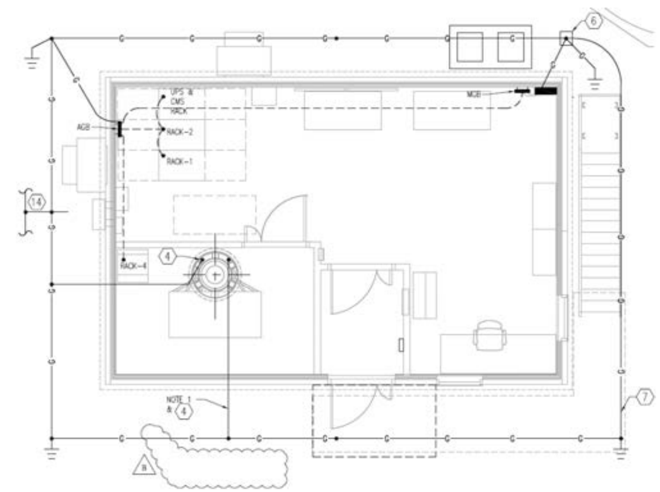
  - Shelter
    - COTS prefabricated concrete building
    - 20’ wide x 30’ long x 10’ high
    - Partitioned into three areas (Vestibule, Operations, Laser)
  - Pier
    - Steel reinforced concrete, single pour
    - ~ 3’ in diameter cylinder on top of a stable foundation
    - No direct contact between the pier and the shelter (vibration isolation)

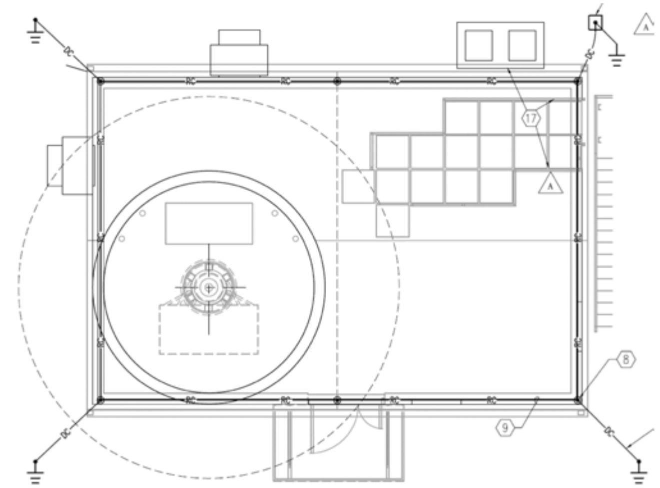


  - Riser
    - 1 meter in diameter by 2 meters in height

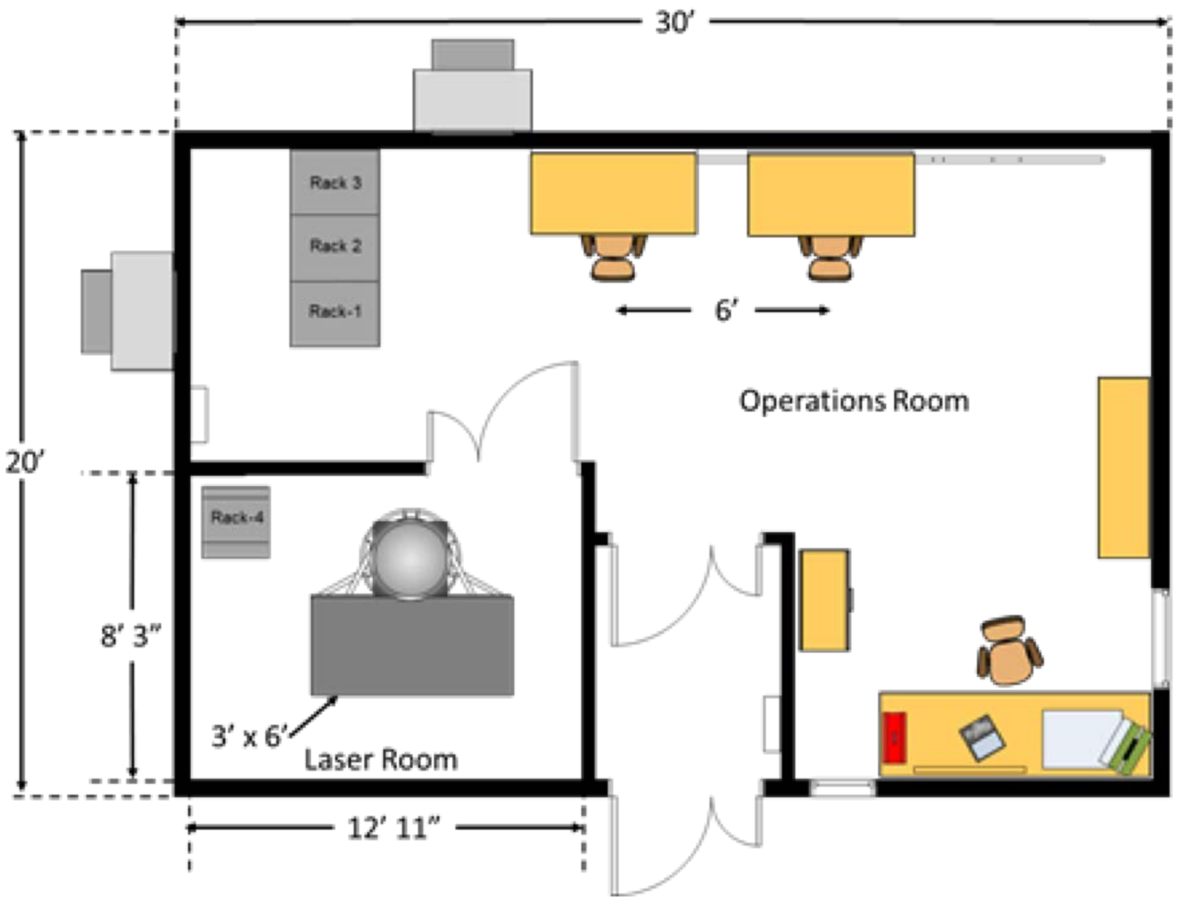
Lightning Protection

- Counterpoise ground field
- Air terminals
- Main Power UPS
- Surge/spike arrestor system
- Fiber optic external data interfaces





DSPR Subsystem



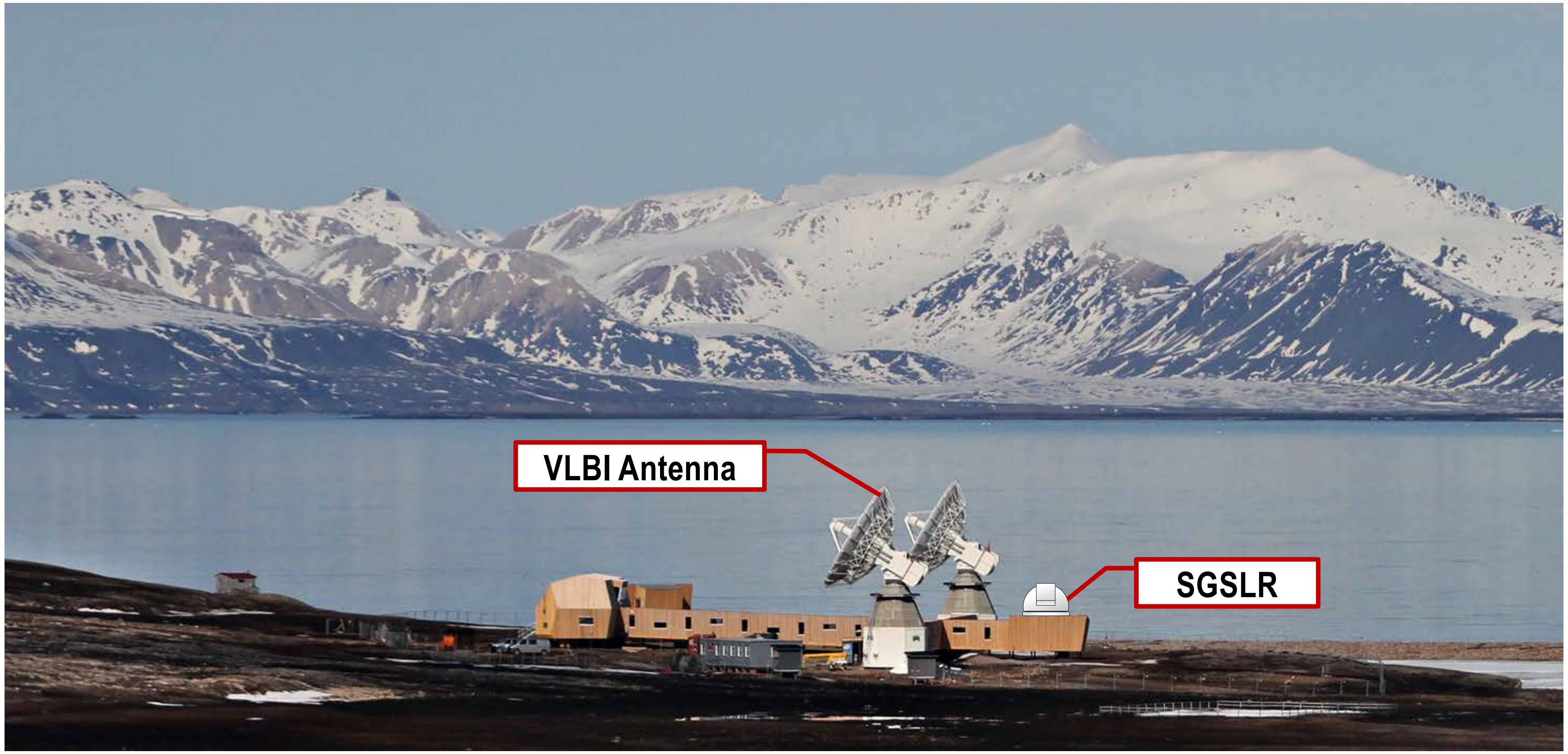
DSPR Subsystem

- Shelter constructed at GGAO in March, 2019
- Dome installed at GGAO in May, 2019

DSPR Subsystem

- Shelter constructed at MGO in November, 2019
- Dome installed at MGO in January, 2020

Site Layout: Ny-Ålesund

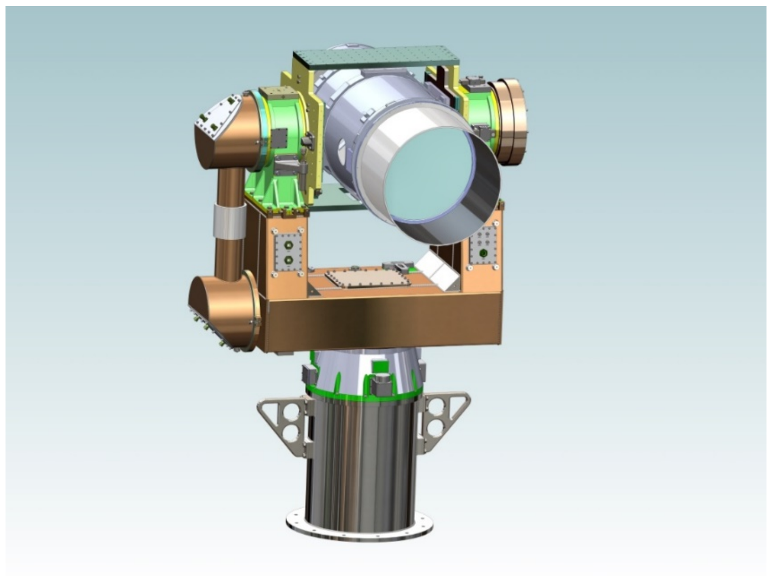


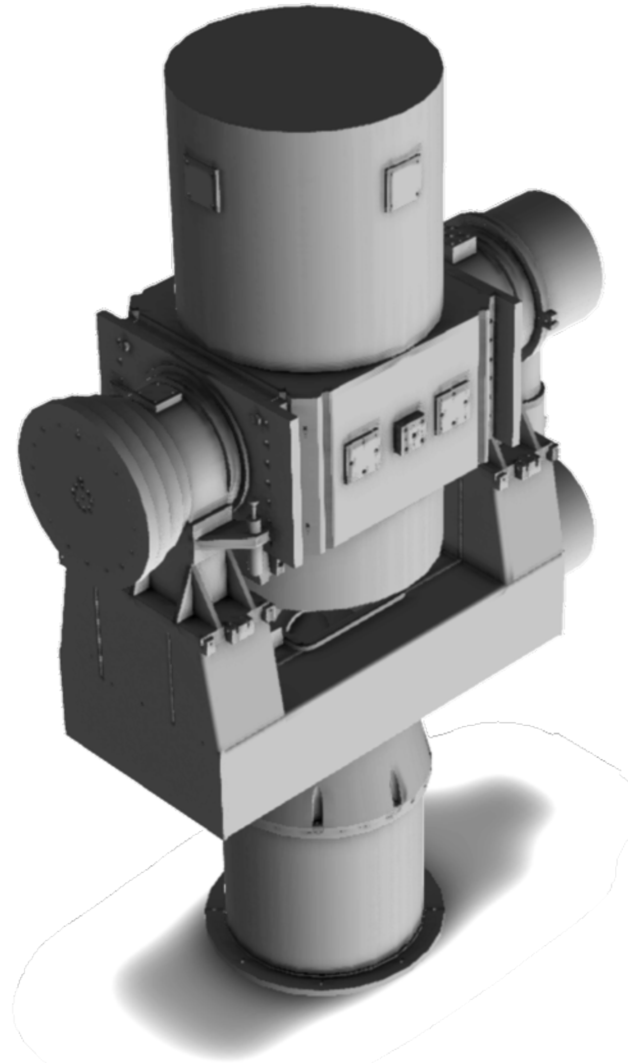
NOTES:

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

Telescope and Gimbal Subsystem

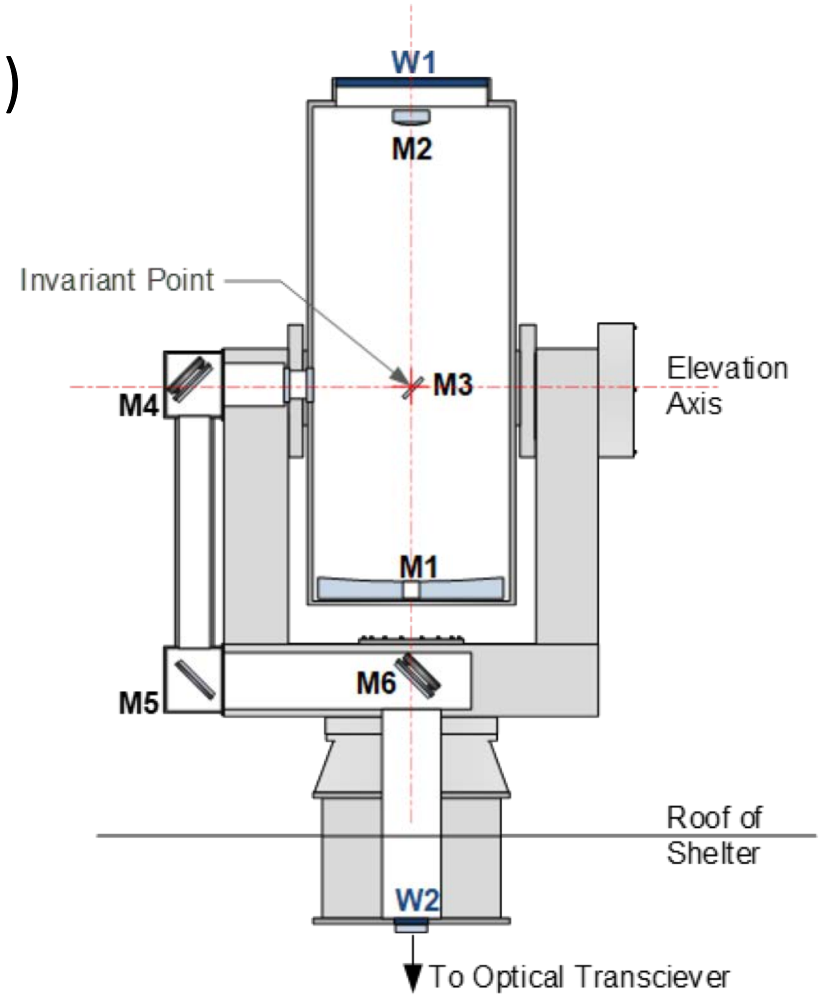
- Vendor: Cobham
- GTA Details
  - Elevation over Azimuth Gimbal
  - 0.5 meter Clear Aperture Telescope
  - Ritchey–Chrétien Telescope Design
- Single Telescope-Gimbal vendor





Telescope and Gimbal Subsystem

- Key Specifications
  - Azimuth — 0° to 360° (continuous)
  - Elevation — 7° to 90° (tracking)
  - Absolute Pointing — ≤ 3 arcsec RMS*
  - Jitter — ≤ 1 arcsec
  - Azimuth \ Elevation Velocity — 0 to 5°/sec
  - Azimuth \ Elevation Acceleration — 0 to 5 °/ sec^2
  - Invariant Point Knowledge — ≤ 1 mm in 3D space
  - Slew Rate — 20°/sec
  - Operational Range — -40°C to +50°C
  - Operational wind velocity — ≤40 mph**
  - Optical Coating Wavelength — 532 nm, 1064 nm



*after modeling from star calibration

** with dome protection

Invariant Point

- Origin of the SGSLR system which is the theoretical point used by the Science Community to define the location of the SLR system. It is the location where the theoretical azimuth and elevation axes meet.
- The time of the laser pulse as it crosses the invariant point is the theoretical start of the range time measurement. The time of the laser pulse as it crosses the invariant point on its return from the satellite is the theoretical stop of the range time measurement. Thus the distance to the satellite is measured from the invariant point.
- The actual origin of the GTA can move around as the azimuth and elevation angles move and as the temperature changes. To work toward achieving ranging measurements accurate to the millimeter level, the invariant point of the system must be known at all times to within 1 millimeter. The VTS system will be monitoring external points on the gimbal and can determine movement of these points. It is important to understand the movement of the invariant point with respect to these external points (by measurement or modeling), so that the Science Community can fully determine the system's origin at all times.

Telescope and Gimbal Subsystem

- Status of build
  - 3 Gimbals are constructed and undergoing testing (star calibrations and pointing)
  - Construction of first telescope is nearing completion

Telescope and Gimbal Subsystem

SGSLR Team Gimbal Testing at vendor facility

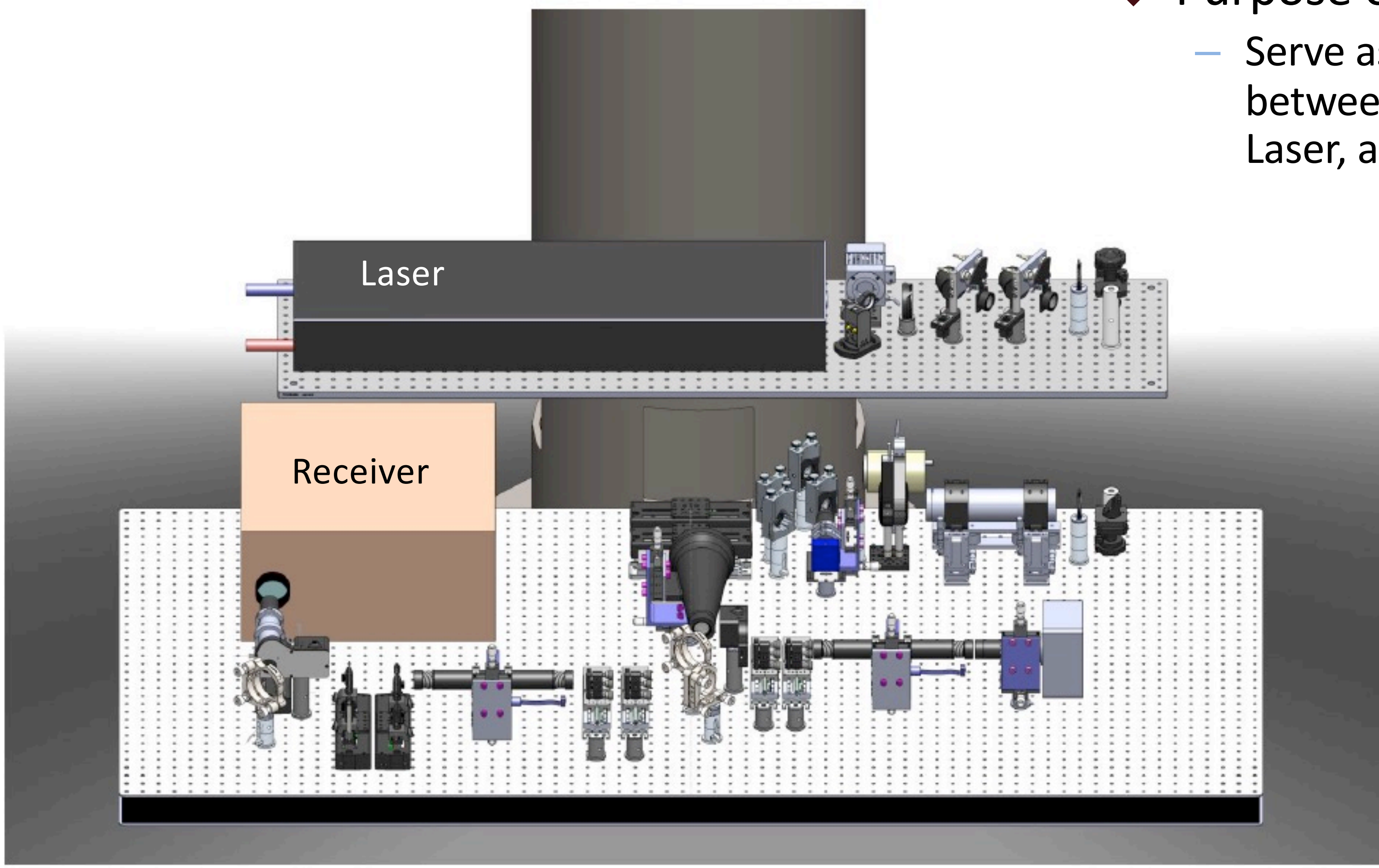
Gimbal and Mass Simulator being lowered into SGSLR, September 2019

Gimbal and Mass Simulator at GGAO

Time and Frequency Subsystem

- Key Specifications
  - 10 MHz Frequency Reference Stability (GPS Steered Rubidium)
    - @ 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
- Subsystem has been constructed and tested

Optical Bench Subsystem



- Purpose of subsystem
  - Serve as the optical interface between the Telescope and Gimbal, Laser, and Receiver Subsystems

- Transmit Path
- Receive Path
- Star Camera Path

Optical Bench Subsystem

- Key Specifications
  - Photonics Industries Laser Parameters
    - Divergence range 0.4 to 1.5 mR
    - Beam diameter range 1.5 to 2.0 mm
    - Maximum laser energy 2.5 mJ @ 532 nm
  - 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 (Covers ~10 pixels)

Meteorological Subsystem

- ## 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

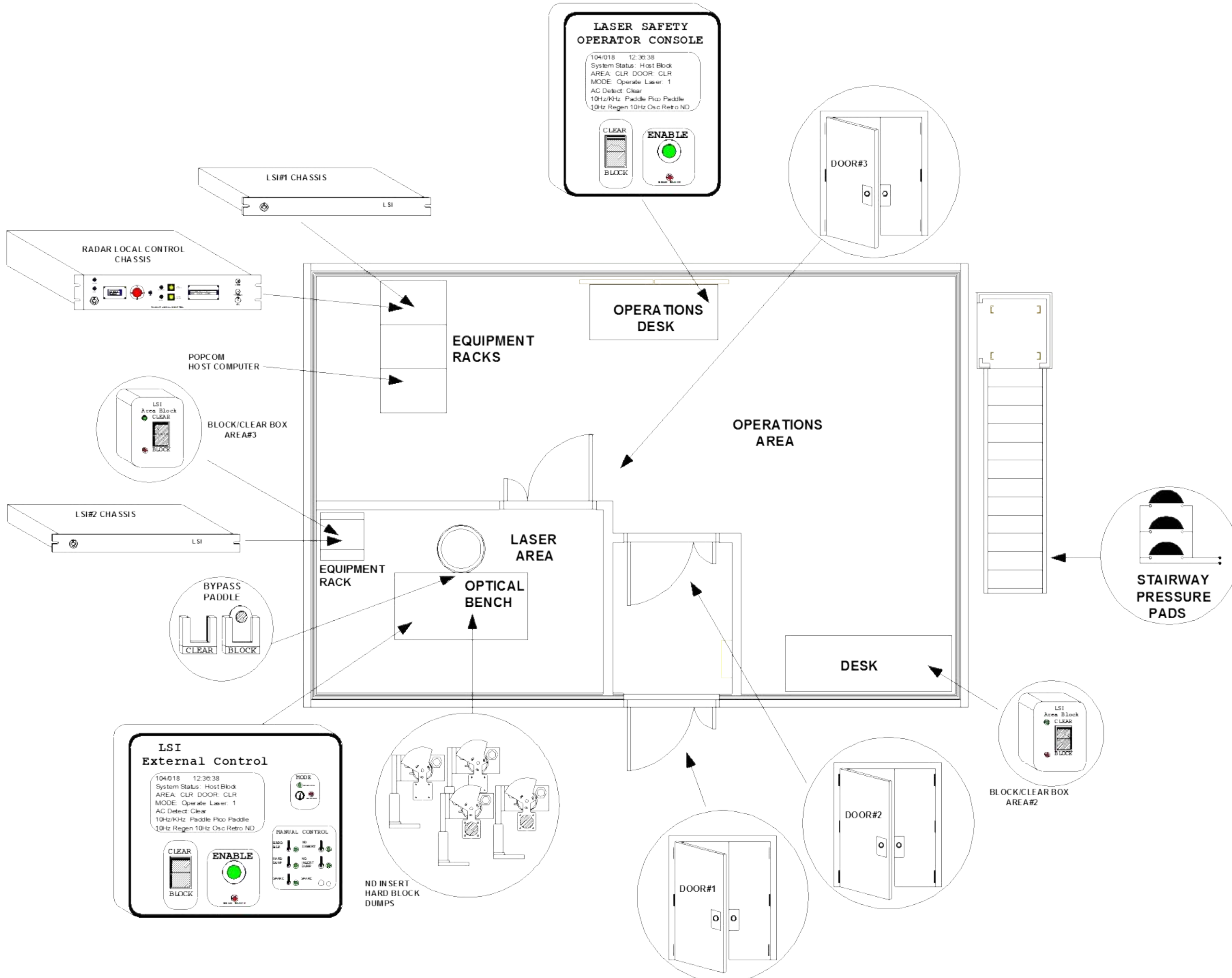
Accuracy of these measurements are directly related to range measurement accuracy!

Laser Safety Subsystem

- Aircraft Avoidance Radar and Interlocks
- Key Features
  - Fails Safe Design/Implementation
  - Co-aligned and directly slaved to the telescope and gimbal
    - Constantly monitors airspace in direction of laser energy
  - Radar power level monitored
  - Radar pedestal level monitor
  - Cable interfaces
  - Watchdog timers used for μP operations
  - Redundancy
    - Laser Trigger Inhibit
    - Beam Blocks/Optical Attenuators
  - Weekly LHRS and LI verification
    - Check individual interlocks (door, pressure pads, buttons)
    - Verify radar detection off of ground target
    - Verify beam block operation

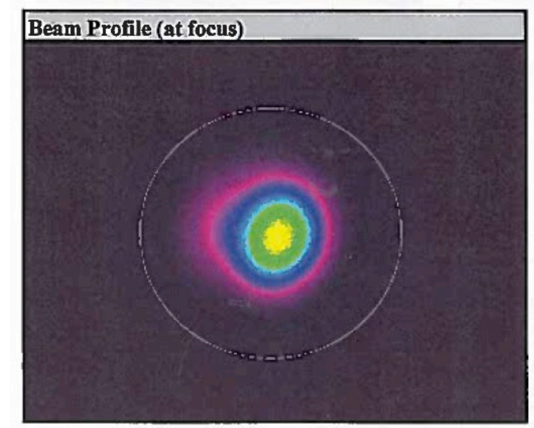
Laser Safety Subsystem

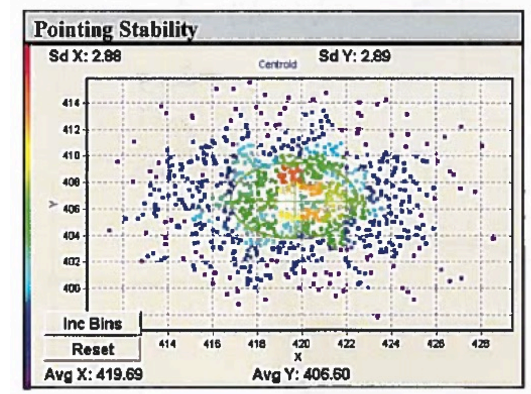
Interlocks



Laser Subsystem

- Key Specifications
  - Wavelength 532 nm
  - Pulse Energy 2.5 mJ
  - Average Power 5.0 W
  - Beam Divergence < 1 mR
  - Beam Diameter 1.7 mm
  - Pulse Width 50 ps
  - Repetition Rate Single Shot to 5 kHz
  - Spatial Mode TEM_{00}
  - Pulse to Pulse Stability < 2% RMS
  - Long Term Stability < 2 % (8h ±3°C)
  - Beam pointing Stability < 50 µRad





Receiver Subsystem

SSRx Key Specifications

- 7x7 SenSL Detector Array
  - 2 mm Pixel size
  - ~65 kHz noise per pixel
  - High QE
  - Negligible dead space
- Sigma Space Timer Card
  - 52 Channels with single shot precision of 3.45 ps
    - 45 multi-stop event channels
  - Dead time per channel (ns)

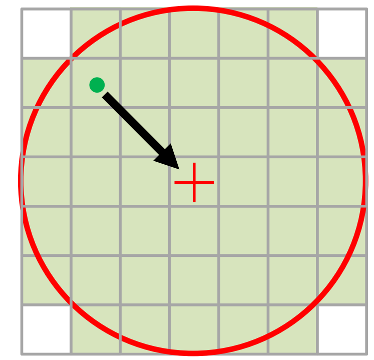
45 stop event channels	3.39
Laser Fire	< 60
1 PPS from GPS	< 60
1 PPS from Maser	< 60
Range Gate Start	< 60
Spare Fire	< 60
Spare Detector	3.39
Spare 1 PPS	< 60

RCE Key Specifications

- Range Window (RW)
  - Delay Range — 4 nsec. to 500 msec.
  - Window Width — 4 nsec. to 10 μsec.
  - Dual Output — TTL, 50 Ohm BNC
- Range Window/Window (W/W)
  - W/W — Centered on RW
  - W/W Width — Based on RW
  - Dual Output — TTL, 50 Ohm BNC
- Laser Fire
  - Pulse Repetition Interval (PRI)
    - 500, 500.5, 501, 502, 504, 510, 520, 530 μsec.
  - Pulse Width — 10 μsec.
  - Dual Output — TTL, 50 Ohm BNC
- Blanking
  - Selectable 100 nsec. - 100 μsec. before/after start diode

SGSLR SSRx Overview

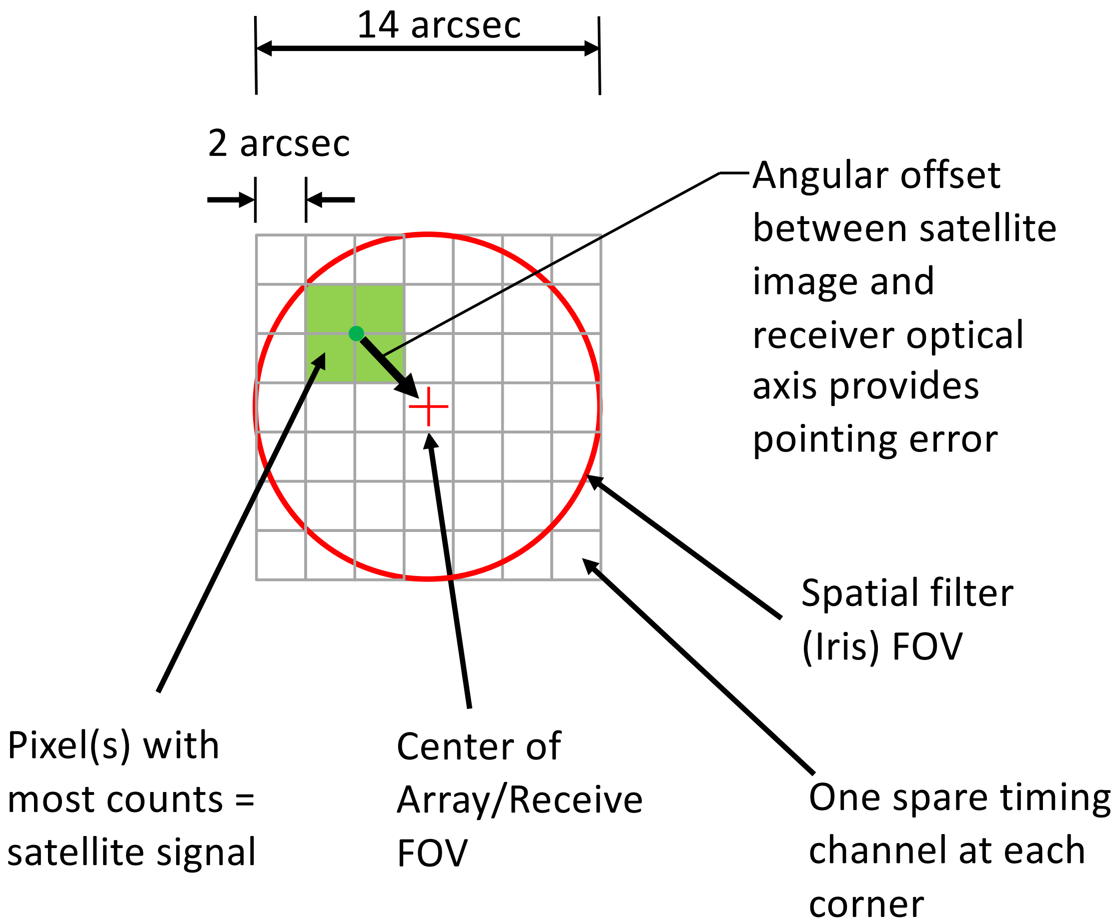
- Provide Closed Loop Tracking
  - 7x7 pixelated detector array
  - 4 pixels in corners unused
  - Count # of events in each pixel to determine satellite location
  - Signal location used by C&S subsystem to correct angular position to maximize return signal strength



- 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

Determining Pointing Error and Eliminating Noise - 7x7 Array



Since noise is distributed uniformly over the entire pixel array, and 4 corner pixels may see some signal, this implies that at least 41 of 45 pixels, or 91% of the noise counts can be discarded, thereby greatly reducing the potential for noise induced range bias errors in weak links.

Sigma Space Receiver (SSRx)

Event Timer: Sigma Space Photon Counting Electronics

- Used in ICESat-2 ATLAS instrument
- Specifically designed for multi-pixel array timing
- Used for altimetry, but our SLR requirements are more exacting

Photon Detection: Array of Silicon Photomultipliers

- Array configuration provides spatial information
- Allows operation in single photon mode
- Much more robust than conventional PMT
- <u>MUCH</u> more economical
- Noisier than our old PMT friend but…
    - Maybe we can deal with it? Lets find out!

SSRx Testing

Subset of Success Criteria for our testing:

- Single shot standard deviation from the ground target(s) similar to or better than NGSLR's (< 4 cm).
- Mean ground calibration data normal point precision similar to or better than NGSLR's within 120 seconds (< 0.5 mm).
- Standard Deviation of ground calibration normal point data < 1.5 mm over 1 hour.

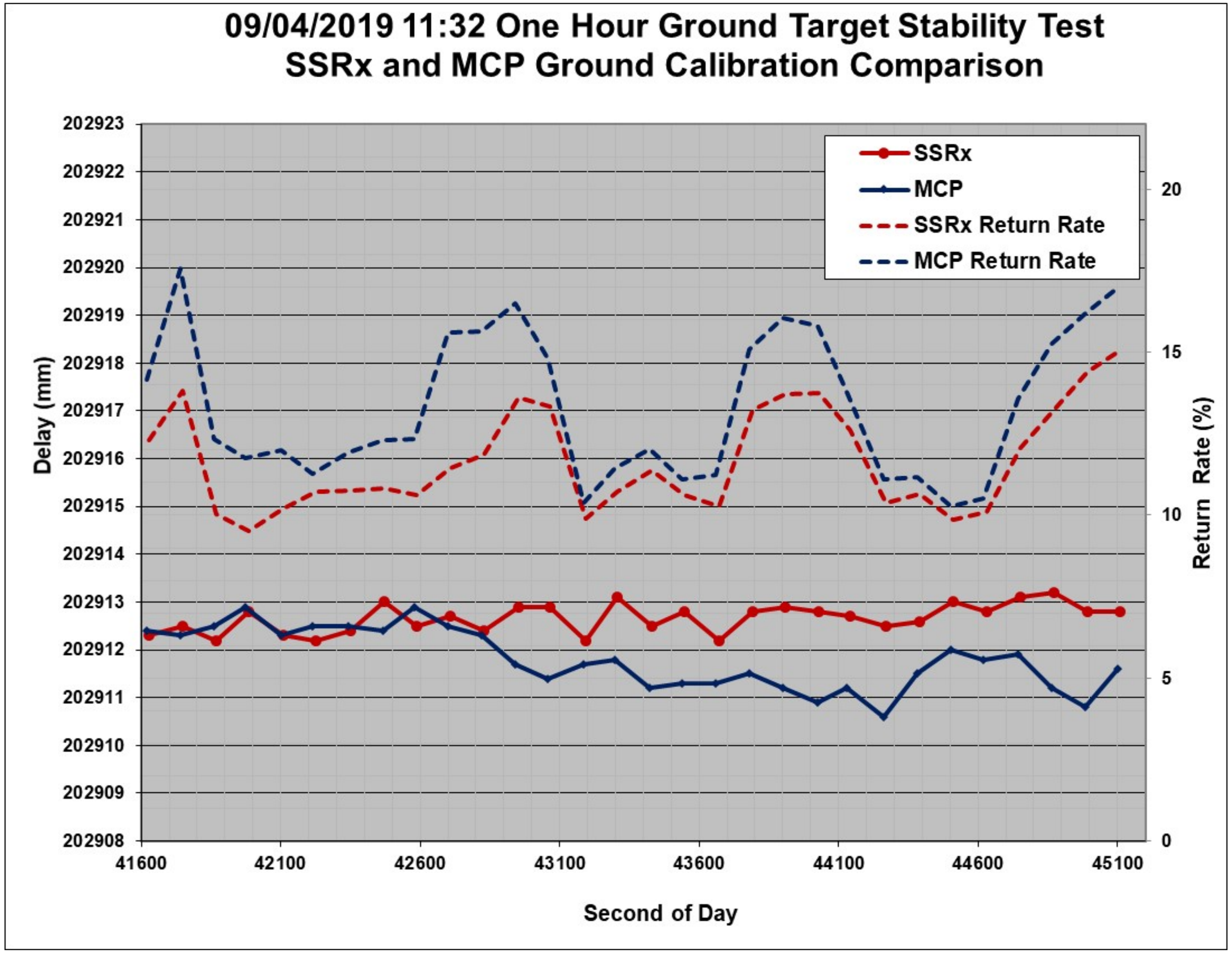
Let’s compare the SSRx side-by-side with a conventional PMT-Constant Fraction Discriminator setup, to see how it holds up.

Lessons Learned: Constructing a good test setup is hard. Constructing a test setup to measure at the millimeter level while isolating the test subject is really really hard.

Pulse Amplitude Correction

- Instead of measuring pulse amplitude directly to correct for bias, we can measure pulse width and approximate pulse amplitude very closely
- Can be done with **no extra circuitry**, simply tag both rise and fall of photon detection pulse
- Tested with various return rates and results are very promising, allowing for higher return rate scenarios

Test Results – Stability over an Hour



MCP STDDEV = 0.51 mm
SSRX STDEV = 0.29 mm

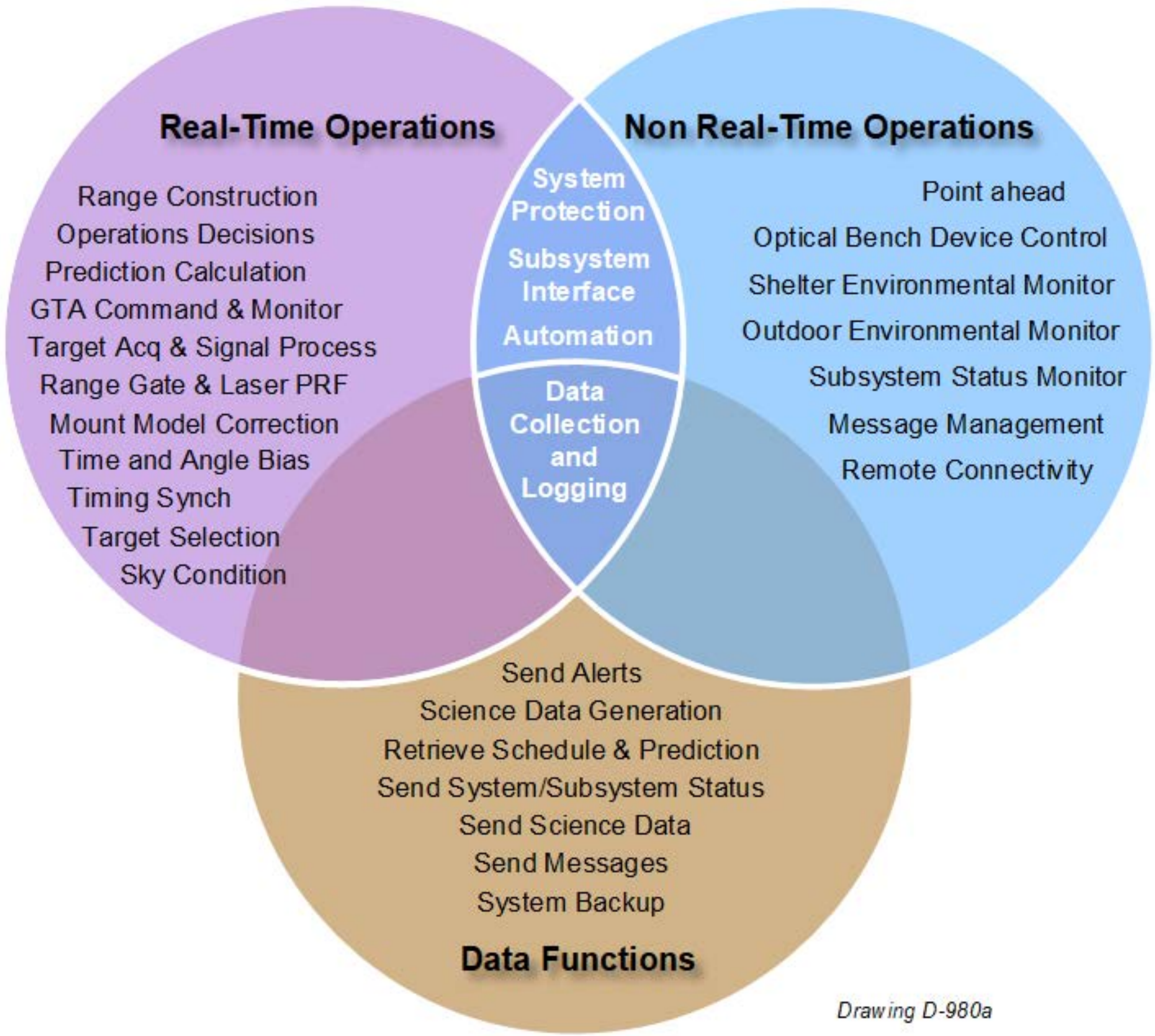
For 2 minute normal points, this dataset showed 0.29 mm standard deviation between the normal points over an hour after pulse width correction!

This is not cherry-picked, most datasets were under 0.5 mm for this statistic.

SSRx Testing

- SGSLR's proposed receiver survived its round of testing intact
- Both the SiPM array and developed Sigma Space timer technology meets and/or exceeds its requirements and compares very favorably to conventional SLR detector technology
- Pulse Width correction works very well to remove range walk due to pulse amplitude variation, eliminating our needs for constant fraction discriminators
- Testing still needed to characterize correction techiquine for multi-retroflector return profiles

Software Main Functions



Software Design / Main Functions

DAM

Optical Bench Device Commanding
- Risley Prisms
- Beam Expander
- ND Filters
- FOV device
- Iris device
- Daylight filters
- Shutters

Message Handling
Remote Access Management
Meteorological Data Collection
Hardware and Environmental Monitoring
System and subsystem safety and health monitoring
Laser Configuration

Linux

POPCOM

Operational Decision Making
- Target Selection
- Target Acquisition and Signal Identification
- Time and Angle Bias
- Meteorological Conditions

Data Collection and Logging
Raw Data Formation
Time Interrupt Handling
Dome and Shutter Control
Mount Model Correction
GTA Commanding and Monitoring
Receiver Commanding and Monitoring
Range Gate & Laser PRF Determination

Linux *(Realtime)*

LOCAL/REMOTE

RAT

System Interface
- Monitoring
- Operational Control
- Troubleshooting

Linux

VIRTUAL MACHINE

CAMERA

Sky clarity (All Sky Camera)
Centroid calculation (Star Camera)
Laser monitoring
- Beam Profiler
- Power Meter

CNS Clock configuration

Windows 10

ANA

Data Processing
Prediction and Schedule Retrieving
Science Data Generation and Delivery

Linux

KEY

- Computer
- Software Function
- Grouping as listed

ADMIN

System Backup
IT Security Logging

Linux

Drawing D-981a

Automation

- SGSLR will be built for full Automation (No human operator)
- Phased Approach: Local -> Remote -> Autonomous
- System Software must provide for fully automated Satellite Tracking, Ground Calibration, and Star Calibration capability by controlling hardware real-time:
  - GTA pointing
  - Range Gate windows
  - Laser Fire
  - Optical Bench and optics optimization:
    - Star Camera
    - Beam divergence
    - ND Filters
    - Daylight Filters
    - Receiver FOV
    - Iris

Completed at NGSLR
Partially completed at NGSLR
New for SGSLR

Automation (2)

- System Software must provide for fully automated Satellite Tracking, Ground Calibration, and Star Calibration capability by making real-time operator decisions:
  - Target selection
    - Satellite Targets, Ground Targets, Stars, Real-Time Satellite Interleaving, VTS
  - Closed Loop Tracking
    - Satellite search
    - Signal recognition
    - Bias pointing signal optimization
  - Batch Commanding
  - Sky condition decisions
  - Sun Avoidance
  - Restricted Satellite Tracking
  - Real-Time communication with VLBI
  - System Protection
    - Beam Blocks
    - Camera and Receiver Shutter
    - Dome Shutter
    - System Shutdown

Completed at NGSLR
Partially completed at NGSLR
New for SGSLR

Automation (3)

- The SGSLR system software must provide automated system data post processing, and real-time and non real-time system monitoring capability by:
  - Retrieval of prediction and restricted tracking
  - Data transfer to SGNOC
  - Science data generation (Herstmonceux algorithm) in ILRS format
  - Generation of Engineering and analysis data
  - Environmental Monitoring
  - Subsystem Status
  - Error Handling and Alert notification

Completed at NGSLR
Partially completed at NGSLR
New for SGSLR

Expected Performance against Global Station Performance

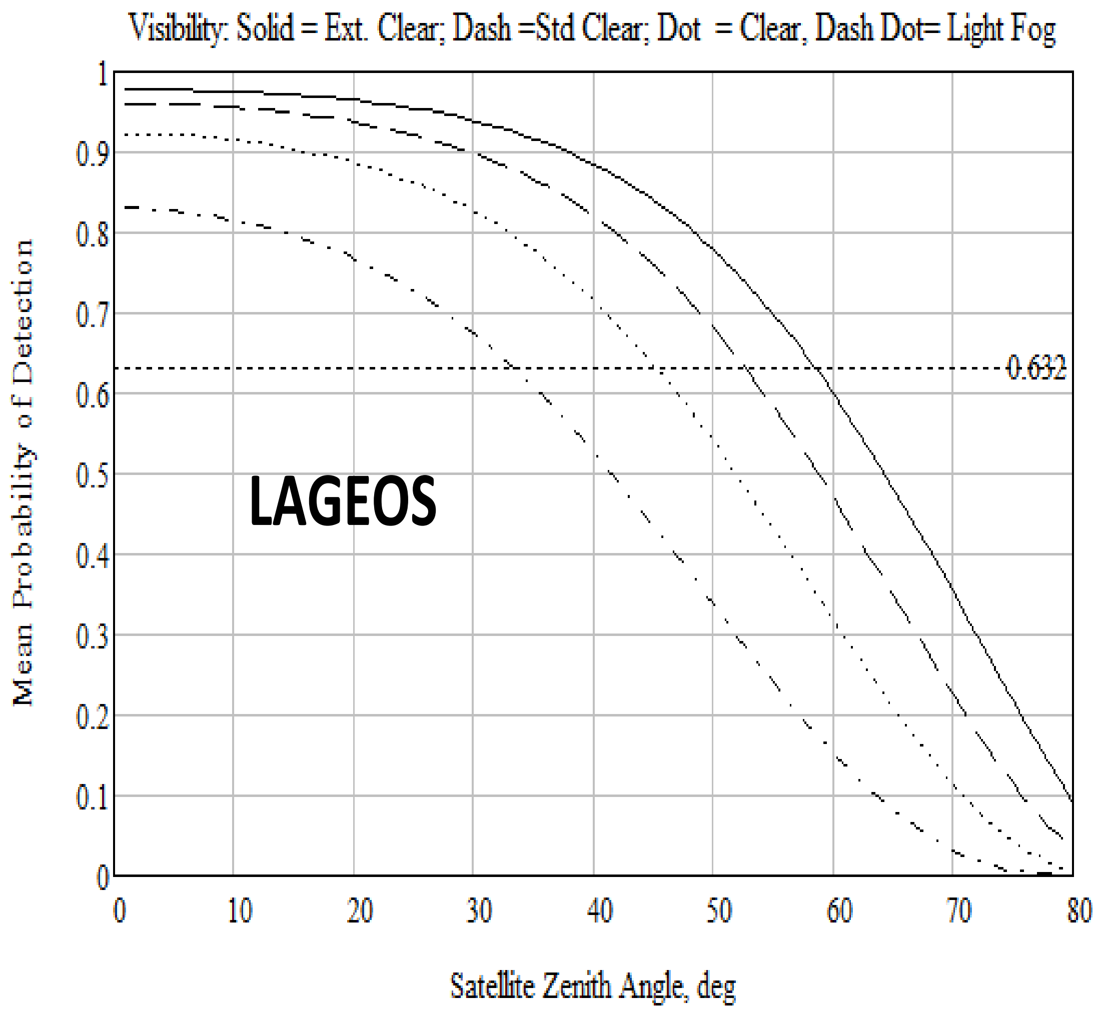
Data volume from ILRS Global Report Card: April 2013 thru March 2014

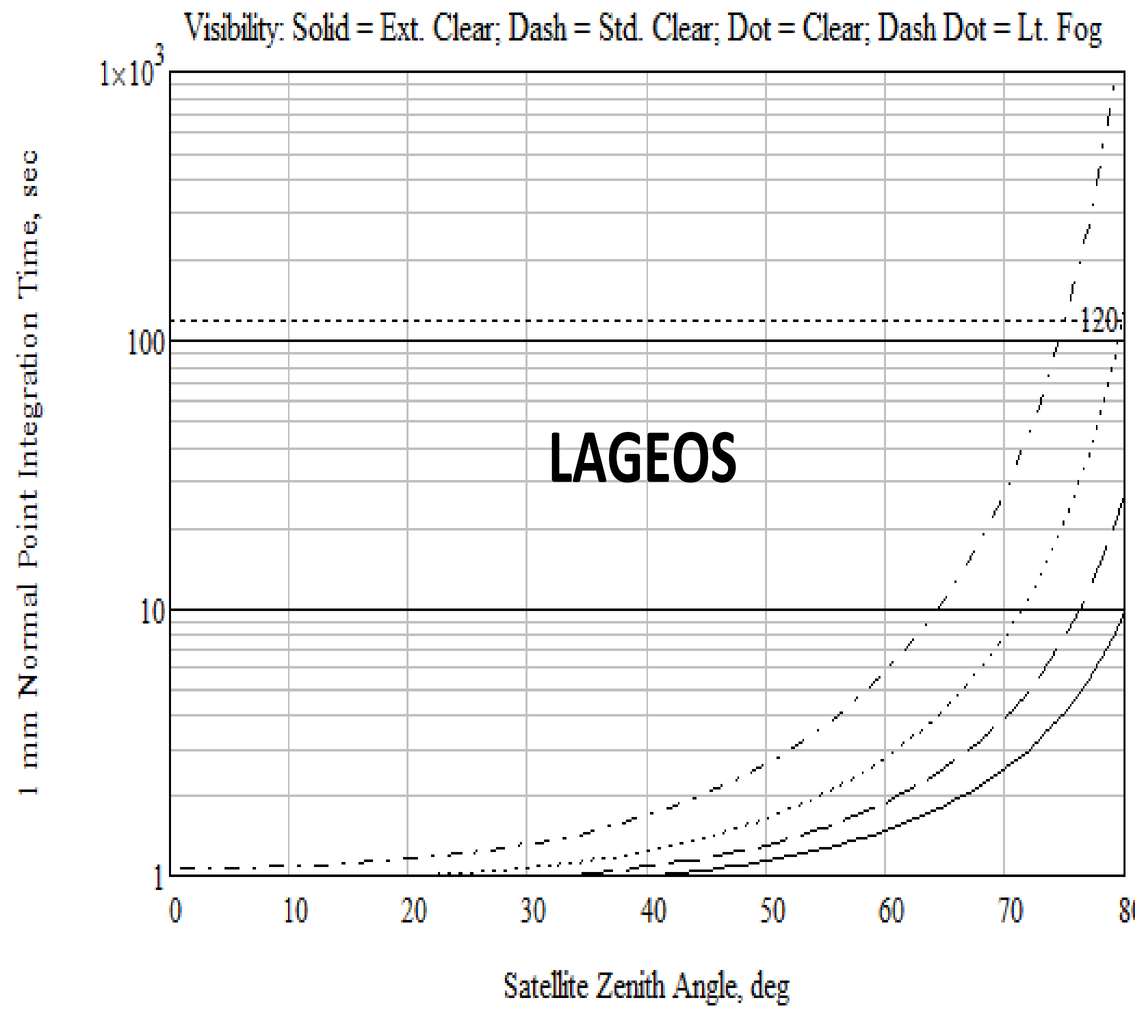
Site ID	Station Number	LEO NP Totals	LAGEOS NP Totals	High NP Totals	LAGEOS Average Precision (mm)	JCET Long Term Stability (mm)
YARL[1]	7090	176,683	20,634	21,986	1.9	2.5
GODL[2]	7105	76,554	7,666	3,052	2.0	3.5
CHAL	7237	69,438	7,235	14,735	0.8	4.1
STL3	7825	78,089	7,218	3,984	1.9	1.5
GRZL	7839	75,714	5,468	18,016	0.2	1.8
HERL	7840	38,592	7,018	6,069	1.9	1.2
WETL	8834	46,509	5,053	12,683	1.6	3.0
SGSLR(20°)	@7105	53,400	7,400	12,200	<1.5	<1.8
SGSLR(10°)	@7090	200,000	18,500	26,400	<1.5	<1.8
Requirement		45,000	7,000	10,000	<1.5	<2.0

Projected SGSLR annual NP data volume[3]:
(20°) 50% weather outage, 16% other outage, 40% data collection when active, min 20° elevation
(10°) 14% weather outage, 16% other, 40% data collection when active, min 10° elevation

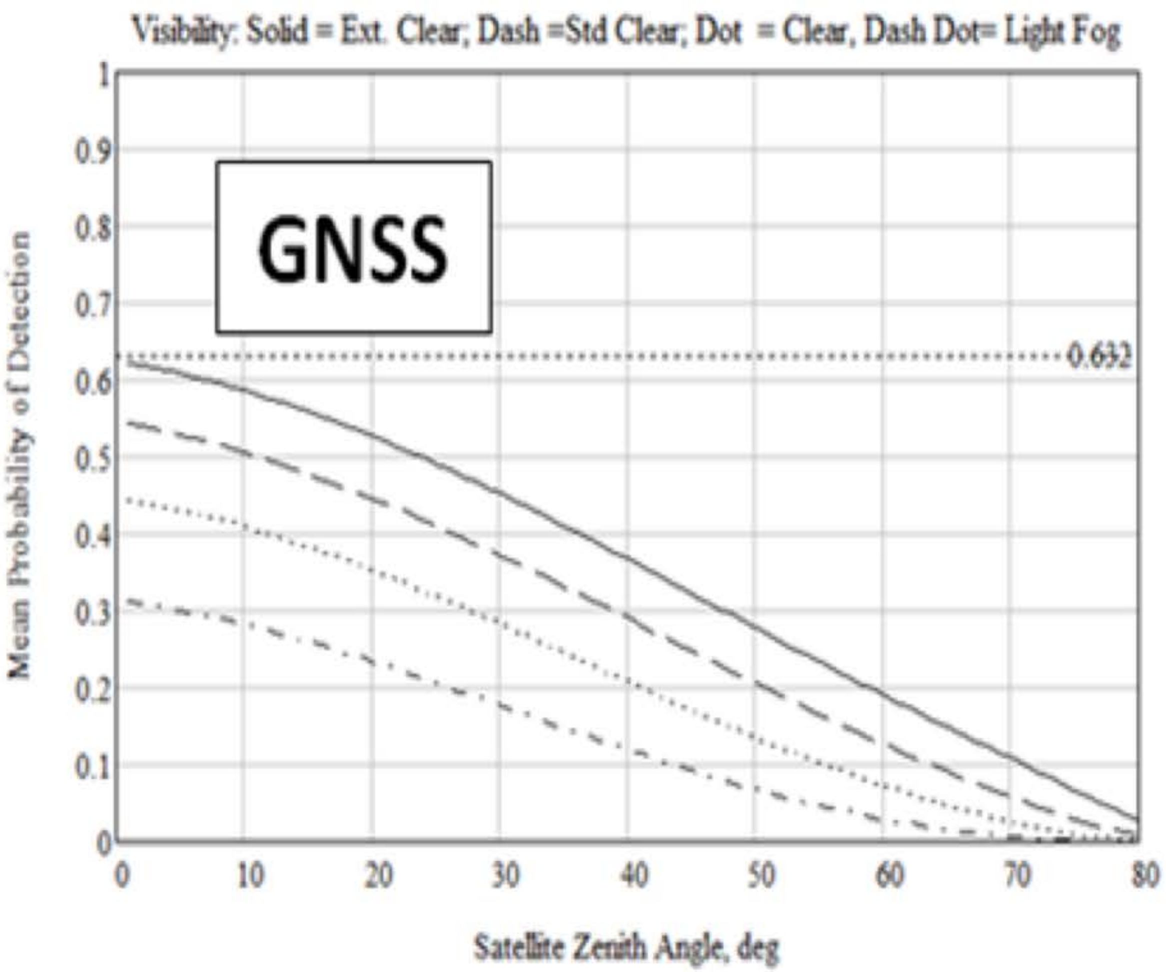
[1]**YARL has 14% weather outage and tracks to 14° elevation**
[2]**GODL has 50% weather outage and tracks down to 10° elevation**
[3]**Precision and stability numbers for SGSLR are based upon SGSLR analysis and NGSLR performance**

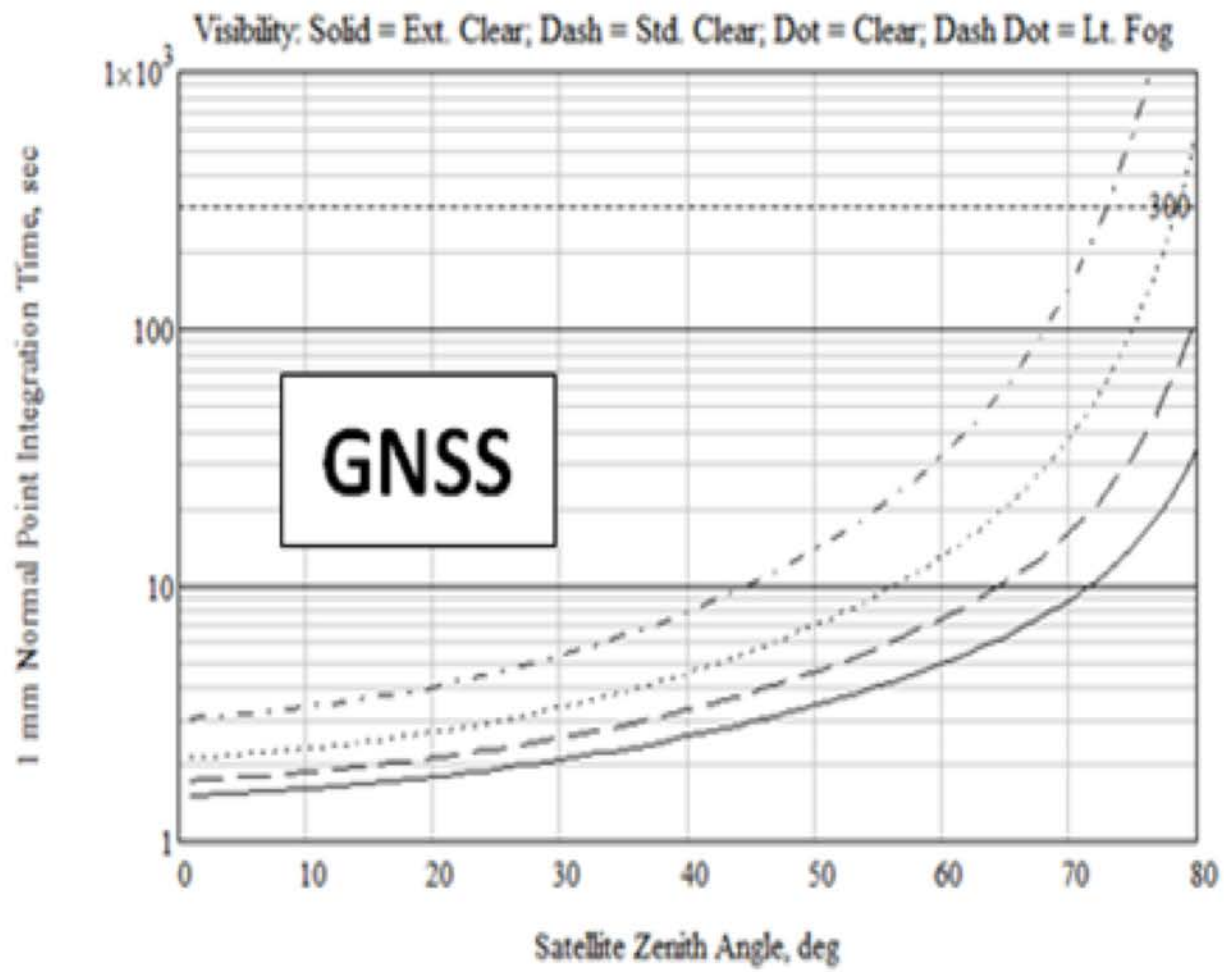
LAGEOS Integration Times





GNSS Integration Times





Summary

- Geodetic network is aging and in dire need of repair and refresh
- SGSLR will be a large part of a much needed refresh and improvement of the geodetic network, replacing the heritage network
- SGSLR concentrates on development towards autonomous 24/7 tracking and millimeter precision to LAGEOS (data volume and precision)
- Innovate design lends itself to autonomous tracking
- Construction underway at GGAO, MGO, and NGO

Thanks!