NASA's Satellite Laser Ranging Systems for the 21st Century

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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 (SGP). Each of SGSLR's nine subsystems has been designed to produce a robust, kilohertz laser ranging system with 24/7 operational capability and with minimal human intervention.

SGSLR's data must support the aggressive goals of the Global Geodetic Observing System (GGOS), which are 1 millimeter (mm) position accuracy and 0.1 mm per year stability of the ITRF.

This paper will describe the major requirements and accompanying design of the new SGSLR systems, how the systems will be tested, and the expected system performance.

1 Introduction and Background

The NASA SGP (Merkowitz et al 2016) supports current and future geodetic science needs by maintaining and operating a global network of Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), and Global Navigation Satellite Systems (GNSS) ground stations. The data produced by the global network are used for a variety of products, including: the definition of the ITRF.

Many of the geodetic stations are decades old and are not capable of meeting future requirements. The US National Research Council (NRC) Committee on Earth Science and Applications from Space warned in 2007 that: "The geodetic infrastructure needed to enhance or even to maintain the terrestrial reference frame is in danger of collapse" (Decadal Survey 2007).

Measurement of changes in the mean sea level will require a Terrestrial Reference Frame with an accuracy of 1 mm and stability of 0.1 mm per year, a factor of 10-20 beyond current capabilities (Gross et al 2009). To meet this need, NASA is building and deploying co-located next generation geodetic stations to new and existing sites around the globe. In 2013 the prototype SLR system, NASA's Next Generation Satellite Laser Ranging (NGSLR) system, was tested and verified at NASA's Goddard Geophysical and Astronomical Observatory in Greenbelt, Maryland (McGarry et al 2013). The NGSLR satellite data was directly compared to the NASA Network standard, MOBLAS-7, examined for stability and precision, and scrutinized for any anomalies by directly comparing simultaneous range data. This was a highly successful verification of the performance of the NGSLR system and proved that NGSLR is a viable SLR system design that meets the SLR accuracy and stability requirements.

NGSLR also successfully demonstrated many of the next generation requirements, including ranging performance and partial automation. This prototype is the foundation for the new SGSLR system design.

NASA SLR is part of the International Laser Ranging Service (ILRS) (Pearlman et al 2002)[1] which includes approximately forty laser ranging stations, distributed around the world, many of which are being upgraded to meet new generation requirements (Wilkinson et al 2018). The ILRS stations track more than ninety satellites from Low Earth Orbit (LEO) to the geosynchronous orbit altitude as well as retro-reflector arrays on the surface of the Moon (Pearlman et al 2018). SLR systems use short laser pulses to measure the two-way range to a satellite from the origin (or invariant point) of the system to the target. ILRS systems range primarily to satellites equipped with retro-reflector arrays. The primary science product from SLR systems is the normal point, which is a time and range that represent all ranges during a specific period of time. The period of time

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[1] https://ilrs.cddis.eosdis.nasa.gov

is satellite dependent and can range from five seconds to five minutes. A more detailed description of how normal points are generated is given at the ILRS website.[2]

2 Requirements

The SGSLR system is being designed to satisfy system requirements that are mandated from NASA Headquarters and flow through the Space Geodesy Project requirements. They are a response to the 2007 NRC Decadal Survey, SGP network simulations, and a need to reduce future operating costs. The Decadal Survey and network simulations drive the requirements for data quality and quantity, the ability to track most satellites around the clock, and the capability to operate at most locations on the Earth. The need to reduce costs drives the requirements for automation, robustness, ease of maintenance and upgrade, and system longevity. The importance of automating SLR system operation while increasing performance to exceed all of the ILRS stations, with the exception of the top performers, cannot be over emphasized and is not a simple requirement to fulfill. Increasing performance of the entire NASA Network to meet the ITRF goals is very important, but being able to do this with systems that will be able to operate within future funding requirements is crucial to the future of NASA SLR.

SGSLR will be able to track satellites during daylight as well as night for all satellites with altitudes from 300 km to geosynchronous, provided their retro-reflector arrays satisfy the ILRS guidelines for optical cross-section. The basic SGSLR design will be able to operate in environments from arctic to tropical, with only minor modifications to the system for locality.

The ILRS uses the LAGEOS satellites (Appleby 2016) to determine system performance. The time of the measurements must be known to better than 100 ns from UTC. The SGSLR requirements for normal points include LAGEOS bias stability over an hour (<1.5 mm RMS), LAGEOS bias stability over a year (< 2 mm RMS), and precision over one month (< 1.5 mm RMS). These requirements represent the capabilities of the current best stations in the ILRS. The ITRF performance will benefit significantly from 10+ systems with a standard design, excellent performance, all operating in the same manner, and with a good geographic distribution around the world. Simulations (Pavlis 2008) using an SLR Network of stations with these characteristics show that this performance will result in the required ITRF accuracy and stability.

The SGSLR system must be capable of local and remote operation, and eventually full automation. Local operations will support the initial deployment and allow for local technicians to operate the system and aid in diagnosing problems. Remote operation will allow for the operation of the stations from a central facility as needed. Remote operation is a step towards automation but will remain a capability and is expected to be used for tracking difficult targets (such as newly launched satellites), special experiments, and for diagnosing and resolving station issues. Full automation is expected to result in lower operating costs, uniformity of operation, and a much larger data volume. SGSLR has an annual data volume requirement that is similar to the best performing SLR stations in the world. Simulation analysis indicates that SGSLR's expected data volume will exceed that.

The SGSLR systems will send in science, housekeeping and engineering data to the SGP central facility, i.e. the Space Geodesy Network Operations Center (SGNOC), on a routine basis. Science data (normal points) will be transmitted to the SGNOC hourly. Housekeeping and engineering data will flow more frequently. The SGNOC will monitor, trend and archive the data received. Operators at the SGNOC will be able to remotely control each SGSLR system individually and will also be able to send commands to all of the stations.

The SGSLR systems will have a modular design which will allow for quick repairs by onsite technicians, thus reducing system down time. With selective upgrades to the subsystems over the years, the systems are expected to perform optimally for decades.

Range data is measured from the system's invariant point. The origin or invariant point of an SLR azimuth/elevation gimbal system is the theoretical point where the azimuth and elevation axes meet. In reality, the azimuth and elevation axes get very close (0.25 mm) but never physically meet. On SGSLR this point is defined as the fiducial mark on the tertiary mirror as shown in Figure 3. Surveys of the system location are made to external reference markers on the gimbal. To meet GGOS requirements, the location of this invariant point must be very stable and known to better than 1 mm, relative to external reference markers, for all pointing angles and temperatures. SGSLR is the first SLR system with a goal to meet this difficult requirement.

3 Automation

In the future each SGSLR station will be able to operate independently, making decisions on safety and performance. All housekeeping, engineering and science data will flow in to the SGNOC where it will be monitored by software, as well as by humans. Through the SGNOC, operators will be able to take full control of each SGSLR system as needed. Separate from full system control, the SGNOC will also be able to command the SGSLR systems similarly to commanding of a spacecraft instrument.

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[2] https://ilrs.cddis.eosdis.nasa.gov/data_and_products/data/npt/index.html

Full automation will allow for continuous operations with only brief periods each week for software and hardware maintenance. This will result in higher data volume and will greatly reduce the impact of global data volume drops during weekends and holidays. In addition, since all SGSLR systems will be operated in the same way, the differences in the data due to human operator choices will be eliminated. This will provide a more consistent data set from all SGSLR systems.

The activities now performed by human operators at the legacy systems will be replicated by the SGSLR hardware and software. These include selection of targets to track, recognition of satellite signal, optimization of tracking, calibration of pointing and ranging, re-enabling of the laser after a laser safety subsystem disable, determination of when the weather allows opening of the dome, recognition of where cloud cover in the sky is located, monitoring of the subsystem and system statuses, and responding to problems. Problems that cannot be resolved by the system itself will result in alert texts and emails being sent to both the SGNOC personnel and the local technicians who will be on call at all times.

Challenges in the path to full automation include: changing Federal Aviation Administration (FAA) regulations in the U.S. to remove the need for a human operator to re-enable the laser; ensuring that the system IT Security is capable of protecting the system and its data from intrusion and corruption; developing a sophisticated cloud recognition algorithm for use by the software to determine where in the sky to select targets; and working through all of the decision paths and hazard analysis needed for an automated system to ensure all safety and security issues are anticipated.

4 Implementation

SGSLR consists of nine major subsystems which are pictured in the block diagram of Figure 1. Each subsystem is described below with an explanation of how each is contributing to meeting the system requirements.

4.1 Gimbal and Telescope

The Gimbal and Telescope Assembly (GTA) selected for the SGSLR is a 50 cm clear aperture Cassegrain Optical Telescope Assembly (OTA) integrated into a highly accurate pointing gimbal as shown in Figure 2. The GTA has been uniquely designed and built by Cobham Integrated Electronic Solutions in Lansdale, Pennsylvania and is the subsystem responsible for transmitting the system's laser pulses to the satellite and collecting the return light.

The GTA consists of an elevation over azimuth gimbal with maximum tracking velocities of 10 degrees per second in azimuth and 2 degrees per second in elevation. This system will be capable of tracking stars and satellites from Low Earth Orbiting up to Geosynchronous altitude with a better than 3 arc second RMS pointing accuracy and with a minimal keyhole near zenith. The gimbal tracking error between commanded and actual angles will be less than 1 arc second RMS over a second. The GTA will be able to slew at rates greater than 20 degrees per second to support interleaving of satellites and an ambitious tracking schedule.

The measured range to the satellites is referenced to the origin of the system which is the invariant point (IP) of the GTA (Figure 3). The IP location is established during the fabrication and integration of the OTA to the tracking gimbal. As the GTA is rotated throughout its full Azimuth (continuous rotation clockwise and counter-clockwise) and Elevation (-5 degrees to 185 degrees from horizontal) angles, the IP will remain within a 1 mm sphere with knowledge to 0.1 mm. In addition, the IP location is referenced to three external datums on the gimbal that relate knowledge of the IP to 0.1 mm and allow for measurement of the IP by an external survey. Movement of the origin with temperature changes has been modeled by STOP (Structural, Thermal, Optical) analysis and will allow a determination of location of the invariant point at any operational temperature.

The STOP analysis allowed the GTA design to be refined to a high degree, resulting in a very structurally symmetric mechanical design. The steel structure of the GTA symmetrically expands so that the IP X and Y location moves less than 0.083 mm throughout the -40°C to +50°C temperature range. Movement in the Z axis has been modeled through STOP analysis and will be verified through precision surveys and laboratory verification of GTA subassemblies. Temperature sensors located throughout the GTA will provide inputs to the GTA structural model and result in precise knowledge of the IP. Precision assembly, followed by laboratory measurement of the IP, will allow knowledge to within a 1 mm diameter sphere of the IP as the GTA is rotated throughout the full range of motion in azimuth and elevation.

The integrated GTA has been designed to meet the full temperature range required for operation at all locations in the Space Geodesy Network, ranging from -40°C to +50°C. The GTA is expected to be extremely stable and hold its pointing calibration for several months.

To keep the optical system clean, the entrance and exit of the system has optical windows. The GTA interfaces to a steel riser that mates the GTA to the isolated concrete telescope pier within the operational shelter and provides the light path to the Optical Bench. Optical alignments for the GTA are accomplished though datums accurately placed on each optic of the Coudé path and several fixtures that can be placed in front of both optical windows at the top and bottom of the GTA optical system.

4.2 Optical Bench

The SGSLR optical bench is illustrated in Figure 5. It is designed to house and rigidly maintain the alignment of the various optical subsystems to each other and to the GTA.

The subsystems on the transmitter side include: (1) the 2 kHz, 50 picosecond (ps) FWHM frequency doubled Nd:YAG laser transmitter, (2) a programmable beam expander which controls the size and divergence of the transmitted beam, (3) a Risley Prism pair which points the transmitter ahead of the receive telescope such that the peak of the Gaussian transmitter profile always falls on the satellite for maximum signal return rate and minimum normal point integration times, and (4) a small insertion mirror which couples the transmitter into a small fraction of the annulus between the primary and secondary mirrors in the monostatic GTA. The small insertion mirror (T4 in Figure 5) minimizes the receiver obscuration loss and helps to protect the single photon sensitive detector array from laser backscatter. The insertion mirror is placed off-axis to ensure that laser reflections off powered elements (lenses, mirrors) having curved surfaces in the GTA do not have a direct path back to the receiver. In addition, all flat optics (e.g. optical windows) in the GTA are tilted and/or wedged with respect to the optical axis. As an additional precaution, the interior walls of the telescope and Coudé path are blackened to suppress stray light. Additional protection of the receiver is provided by a variable spatial filter in the receiver path, i.e., R2 in Figure 5. These types of backscatter protections were found to work quite well in the much more difficult predecessor NGSLR system in which, for eye safety reasons, the transmitter and receiver shared the entire telescope aperture via a complex combination of Faraday rotators and other polarizing elements on the optical bench which offered many more opportunities for backscatter into the receiver.

Also in the transmit path, a portion of the outgoing pulse are: (1) sampled and carried by optical fiber to one channel of the multichannel range receiver to start the pulse time-of-flight measurement; and (2) directed to a beam profiler to monitor the transmitter far field shape and divergence. The transmitter path also includes Laser Safety Subsystem controlled ND filters and beam blocks to respectively reduce signal strengths during ground target calibrations and to eliminate potential optical hazards to aircraft or ground personnel detected by the Laser Safety Subsystem.

Referring again to Figure 5, the components on the receiver side include: (1) an achromatic 3.75x beam reducing telescope, R1, which feeds both the narrowband range receiver array and the wideband star camera used in star calibrations, (2) a 1-to-1 beam expander with a motorized iris at the central focus, R2, to control the receiver FOV; and (3) a motorized telephoto lens, R3, capable of optimally matching the receiver FOV to the transmitter beam divergence to aid in satellite acquisition and tracking as described in the next subsection. Additional elements in the receive path include: (1) two oppositely oriented linear ND filters, R5, to control receive signal strength; and (2) shutters to block the receiver and/or star camera. The use of two linear ND filters is intended to eliminate the intensity gradient across the received beam profile introduced by a single linear ND filter. The shutters are not utilized during satellite operations and are included to shield the sensitive detectors from unwanted light when the system is not actively tracking satellites.

4.3 Receiver Subsystem

The heart of the SGSLR receiver subsystem is a 45 pixel array detector (7x7 array with the 4 inactive corners removed) as in Figure 6. Each pixel is a single photon sensitive Silicon Photomultiplier (SiPMT) measuring 2 mm x 2 mm with a central 1mm x 1 mm active area containing hundreds of single stop SiAPDs terminated at a single anode which is, in turn, input to one channel of a multichannel timing receiver. Additional timing channels are available for time-tagging other signals requiring high timing precision. A Laser-Ablated Microlens Array (LAMA) placed in front of the detector array ensures that the vast majority of the received photons are directed to the active region of the pixel. The large number of SiAPDs per pixel gives each channel a multistop capability with near zero (~2 nsec) deadtime limited by recovery times in the receiver electronics. The multichannel timing unit uses threshold detection to time-stamp, with few picosecond precision, all single photon events (noise or signal) in each channel. Although the telescope spot size is designed to fit within a single pixel, the laser return may occasionally fall on a pixel border resulting in a sharing of signal photons between 2 or 4 pixels. The channel recording the most events (noise plus signal) provide the angular offset of the satellite from the telescope optical axis to the system computer. The gimbal motor is then directed to drive and maintain the maximum signal on the central pixel to ensure that the peak of the Gaussian transmit beam is incident on the satellite, the satellite return rate is maximized, and the normal point integration time minimized.

The receiver optical train also includes a translatable telescopic lens (R3 in Figure 5) which allows the receiver FOV seen by the array to match the transmitter beam divergence. This minimizes solar noise while aiding satellite acquisition since a pixel viewing a sky element outside the transmitter beam divergence cannot contribute to the location of the satellite. The reduction in solar noise background is further reinforced by a one-to-one beam expander with a computer-controlled iris at the central focal plane (also designed to roughly match the transmitter beam divergence) and a high transmission (>70%) narrowband (0.3 nm FWHM) spectral filter.

Ultimately, dark counts and solar noise are filtered out in the usual way using the spatial and temporal correlation of the satellite returns within the signal pixel(s), but with as little as 2.2% (1/45) of the normal solar noise background if a single detector were to view the entire receiver FOV. The dark counts per SiPMT pixel can be as low as 30 kHz at the recommended bias voltage or as high as 300 kHz with higher bias voltage (for increased photon detection efficiency) and/or operating temperatures. In any event, the mean dark count rate is < 0.15 pe per pixel per pulse for a typical range gate of 0.5 µs.

Although the SiPMTs and multichannel receivers have been used successfully in a number of airborne Single Photon Lidars (SPLs) built by Sigma Space, they have not yet been fully evaluated for mm accuracy SLR applications. As a result, the prototype SGSLR transmitter and receiver are currently undergoing testing to an external calibration target in order to determine the overall range accuracy and stability. We are presently favoring a mode of operation in which the outer pixels are used to rapidly acquire the satellite and then confine the satellite returns to the central pixel(s) (Degnan et al 2016b). This ensures that the dual Risley prisms in the transmit path are always centering the laser beam on the satellite and maximizing the return rate, which is especially important for the higher satellites. In the event that the range accuracy goals are not met with the new hardware, we have the option to substitute, via an annular mirror, an alternate stop detector and timer for the central stop pixel that has already met the required timing accuracy, such as the MicroChannel Plate PhotoMultiplier (MCP/PMT) used previously in collocation tests with MOBLAS-7 (McGarry et al 2013). The outer pixels would continue to guide the telescope onto the satellite.

4.4 Laser Subsystem

The Laser Subsystem is responsible for providing stable, narrow pulse width, Gaussian laser pulses used for ranging operations. Components of the subsystem include the laser and an air-water chiller for temperature control.

The RGL-532 laser, designed and manufactured by Photonics Industries, is a COTS integrated all-in-one package of optics and control electronics, which fits entirely on the optical bench. It consists of a frequency doubled Nd:YAG, in a master oscillator / power amplifier (MOPA) configuration. Characteristics of the laser include: a Gaussian diffraction limited beam, 50 ps temporal pulse width (FWHM), 2.5 milliJoule (mJ) per pulse at 532 nm, and a variable, externally triggered repetition rate (capable of single shot to 4 kHz with a nominal operational rate of 2 kHz). There is a 2% RMS pulse energy stability specification, important for limiting time walk due to amplitude variation.

The Computer and Software Subsystem interfaces with the laser via an Ethernet connection. Commands and monitoring information are via simple HTTP POST/GET methods. The laser is externally triggered to fire via a TTL signal supplied by the Range Control Electronics. To prevent collisions between transmitted laser pulses and the return light from the satellite, the Computer and Software Subsystem must adjust the laser fire rate during satellite passes from approximately 1.9 to 2 kHz. The chiller is controlled and monitored via an RS232 interface. In the event of a hardware fault, lasing will be inhibited in order to prevent damage.

4.5 Laser Safety Subsystem

The primary function of the Laser Safety Subsystem (LSS) is to ensure the safe operation of indoor and outdoor laser energy propagation by preventing hazardous energy levels of exposure to persons within the SGSLR shelter, in surrounding areas outside of the shelter, and aircraft. The LSS is comprised of an aircraft detection system, and an in house built Laser Interlock System that receives laser energy inhibit signals from various monitoring sensors including the radar. The Laser Hazard Reduction System (LHRS), a pedestal mounted radar system used to detect aircraft, is comprised of a solid-state radar that transmits coherent X band energy and operates at >500 Hz rate. The pedestal is an X-Y gimbal using self-contained, direct drive rotary drives that are very low maintenance and offer very smooth and accurate operations. The LHRS is slaved directly to the GTA ensuring the radar pedestal always points in the direction of the of the transmitted laser energy. A Field Programmable Gate Array (FPGA) based control unit is used to accept the GTA pointing information, position the radar pedestal, monitor radar transmit energy as well as the overall health of the aircraft detection system, and provide status information to the Computer and Software Subsystem. “Watchdog timers” are used to monitor FPGA operations for any processor malfunctions. The LHRS is capable of detecting aircraft covering the entire range of the SGSLR Nominal Ocular Hazard Range (NOHD). The failsafe design will ensure that any issues with the LHRS will cause the LSS to inhibit the transmission of laser energy.

The Laser Interlock (LI) is an FPGA based electronic system that accepts inputs from various sensors including door position monitors, footpads, motion sensors, personnel activated emergency stop switches, and the aircraft detection system. Activation of these sensors will cause the LI to inhibit the transmission of laser energy through the use of multiple beam blocks, attenuators and an electronic inhibit for the laser trigger. The LI also uses “watchdog timers” to monitor processor operations and provide a failsafe design and safe the system.

The LSS meets the criteria, requirements, and processes established in the NASA GPR 1860.2 Laser Radiation Protection, the ANSI Z136.1 Safe Use of Lasers, the ANSI Z13.6 Safe Use of Lasers Outdoors, the SAE ARP5572 - Control Measures for Laser Safety, and the very stringent SAE AS6029A - Performance Criteria for Laser Control Measures Used for Aviation Safety. All SGSLR operations will also be compliant with all aviation requirements for the transmission of laser energy through navigable airspace both within the United States abiding by the FAA AC70-1 Outdoor Laser Operations and International requirements as applicable. The overall design of the LSS and compliance with national and international safety standards will allow the SGSLR to support total automated operations.

4.6 Time and Frequency

An enhanced, flexible Time and Frequency Subsystem has been designed in order to meet the science and future automation requirements of the SGSLR system. Assembled from commercial, off the shelf (COTS) equipment, the subsystem features ease of both maintenance and replacement of components. Centered around an improved, state of the art GPS-steered Rubidium time and frequency standard, this subsystem generates and distributes 1PPS, 10 MHz and IRIG-B time codes to all other SGSLR subsystems as required. The Microsemi S650, successor to the time proven XLi, with an improved accuracy of 15 ns RMS to USNO, is being evaluated as the central time and frequency source.

The arrival time of the 1PPS and IRIG-B timecodes at the various subsystems is within a few nanoseconds of each other and is characterized and recorded as part of the integration testing. Distribution of IRIG-B time codes to other subsystems allows precise time tagging of operational and alarm events for logging and troubleshooting.

The distribution equipment features redundant signal inputs in order to utilize alternate signal sources that may be available onsite. An internal measurement scheme utilizing independent GPS receivers constantly monitors the subsystem and provides data to the Computer and Software Subsystem to assess the accuracy of the timing signals. Additional front rack panel input/output connections allow access to the timing signals as well as the measurement system for troubleshooting and short-term scientific experiments.

The Time and Frequency Subsystem is equipped to meet the remote operation and future automation requirements of the SGSLR system. Key components of the Time and Frequency signal chain and measurement system can communicate status and alarm conditions, allowing the Computer and Software Subsystem to monitor and take appropriate actions if necessary. This data will also be provided to the SGNOC on a routine basis for monitoring station health, trending, and archiving.

4.7 Meteorological Subsystem

The Meteorological Subsystem measures environmental conditions close to the SGSLR system invariant point that are critical to developing accurate range data for satellite laser ranging. The subsystem also provides significant inputs to the system health and safety during automated operations. The Paroscientific MET4A unit measures barometric pressure, temperature, and relative humidity which provide input to the mathematical models used for atmospheric refraction correction to the science data (Degnan 1993). The barometric pressure measurement range is 500 to 1100 hPa with an accuracy of ±0.08 hPa; the temperature measurement range is -40°C to +50°C with an accuracy of ±0.1 degrees C; the humidity measurement range is 0 to 100% non-condensing, with an accuracy of ±2% (at 25 C). Barometric pressure, temperature, precipitation (Vaisala FS11P), wind speed and direction (Vaisala WMT703), and cloud coverage are used to provide data for system automation and protection. This information is passed to the Computer and Software Subsystem to determine when the system operates due to the local weather conditions.

4.8 Dome and Shelter

The Dome, Shelter, Pier, and Riser (DSPR) Subsystem, as shown in Figure 4, includes the components which enclose, protect and support SLR operations. The dome, manufactured in Germany by Baader Planetarium, is 4.2 meters in diameter and will contain and protect the telescope, gimbal, and associated hardware while allowing transmission and reception of light during operations. The shelter contains, protects, powers, and provides climate control for the optical bench, laser and all of the electronics as well as providing work space for support personnel. The pier is a stable concrete cylinder, isolated from the shelter foundation, which supports the riser. The riser is a hollow steel structure on top of the pier that serves as the interface between the optical bench and the GTA. The DSPR has been designed to handle a wide variety of environmental conditions ranging from the arctic to the desert.

During normal operation, the dome will be slaved to the GTA azimuth. The Computer and Software Subsystem has complete control of the dome shutter. In the event of precipitation, the Computer and Software Subsystem will close the shutter. Another key feature of the dome is a fast rotation rate of up to 18° per second which allows it to keep up with the gimbal for most movement.

The shelter dimensions are 20’ x 30’ (with the ability to easily size down to 20’ x 20’) and include a vestibule to help cut down on dirt along with a separate area for the laser and optical bench. Precision climate control of the shelter is monitored and controlled by the Computer and Software Subsystem. The laser area of the shelter has a tighter temperature control loop of ±1.5 degrees C. Additional environmental monitoring of the shelter that support automation includes temperature, humidity, water ingress at select locations, airflow sensors, fire protection, and light control. An additional security system will incorporate cameras, motion sensors, etc. In addition, the Computer and Software Subsystem can shut down subsystems/equipment as needed along with the entire SGSLR system through the use of the DSPR Uninterruptable Power Supplies (UPS). The shelter also provides a fiber optic interface to external signals coming to and from the shelter, which serves as added protection from potential lightning hits. Other measures taken to protect against lightning strikes include the use of best practices for grounding, the use of surge protection, and air terminals on the roof of the shelter.

4.9 Computers and Software

The SGSLR Computer and Software Subsystem controls, calibrates, and monitors all SGSLR subsystems and the system as a whole. The Computer and Software Subsystem links all other subsystems together by controlling all subsystem moveable optical devices during operations, directing all subsystem traffic in real-time (including telescope pointing), calculating real-time time tags by combining range and epoch timing measurements, and making all real-time operational decisions. The software is also responsible for transferring and storing data, post-processing the range measurements by generating the science data, and communicating with the SGNOC.

The software provides for system automation by making real-time decisions based on weather conditions, sky conditions and satellite availability. It prioritizes tasks for tracking operations and sets acquisition parameters that produce optimum return rates. Automation also requires that the software be capable of monitoring all hardware that protects the system, humans and aircraft by determining and reporting system and subsystem statuses, and recording and reporting routine activities to the SGNOC. The system will send alerts when necessary, and employ remediation processes, when possible, in an attempt to correct anomalies. The software will also be capable of providing modes for engineering troubleshooting or repair by allowing for diagnostic control and simulation. The software is designed to support local, remote, and fully automated operations (McGarry et al 2017).

The SGSLR computer architecture includes a combination of real-time and non-real-time CPU's and virtual machines. The real-time machine is using the Ubuntu operating system with the Xenomai real-time extension. The system sits behind a managed switch (firewall) and requires two-factor authentication. It also employs data encryption through a VPN for data transfers outside of the system.

Security is of crucial importance in the design and development of automated systems. It is very important that SGSLR be secure both physically and through the internet. Information Technology (IT) Security must protect against intrusion from unauthorized users, corruption of the computers from malware, disabling of internet access, and corruption or disruption of the data delivered to the SGNOC. The SGSLR team is working with NASA experts to develop an approach that will allow SGSLR to perform and communicate as needed while protecting it from unauthorized access, system and data corruption, and internet and/or data disruption.

5 Expected System Performance

5.1 Data quality and link calculations

The variance of the Probability Distribution Function (PDF) for single photon returns from a satellite is obtained by summing the variances introduced by all of the contributing elements such as the laser, detector, Event Timer, and satellite impulse response. The single shot range RMS for an SGSLR system ranging to LAGEOS is estimated to be about 280 ps, or 42 mm (Degnan 2016a). This is obtained by computing the sum of the variances, σ^2, and computing the square root using the following values for the 50 ps FWHM laser pulsewidth (σ_L = 21 ps): impulse response of the SENSL detector (σ_D = 267 ps), the event timer as an integrated part of the receiver (σ_{ET} < 23 ps), and the pulse spreading caused by LAGEOS (σ_S = 77 ps). The normal point RMS is reduced by $\sqrt{N}$ where N is the number of measurements per normal point. Thus, obtaining a normal point variance of 1 mm requires a minimum of N = 2209 measurements, which, at a 2 kHz fire rate, can be generated within the ILRS allotted time of 120 seconds with a LAGEOS return rate of only 0.92%.

Analysis of the SGSLR link budget shows a quick integration time to achieve 1 mm normal point precision (Degnan 2016a). The analysis considers a comprehensive list of factors such as detector efficiency, telescope pointing bias and jitter, laser power, optics efficiency, atmospheric transmission, atmospheric turbulence and target speckle. Atmospheric turbulence/speckle effects include beam wander, beam spread, and scintillation. Figure 7 shows integration times for 1 mm normal point precision on LAGEOS. In extremely clear conditions the integration time is below 10 seconds at 10 degrees elevation. This elevation angle represents a worst case. Even in light fog, at 20 degrees elevation angle and above, the precision can still be obtained within the 2 minute LAGEOS normal point time. Figure 8 shows the integration times on a GNSS target. The analysis suggests robust tracking for targets from Low Earth Orbiting to GNSS altitudes.

SGSLR has a requirement for precision normal points to LAGEOS to be less than 1.5 mm averaged over one month, but is expected to achieve 1.0 mm. Under normal operations, the return rate will be kept under 10% to ensure the vast majority of detections will be at the single photon level, avoiding biases caused by multi-photon detection. At the 10% return rate, a LAGEOS normal point will reach a precision of 1 mm in about 10 seconds of ranging. Recently, it has been shown analytically (Degnan 2017) that accurate and unbiased normal points can be achieved at much higher return rates if one replaces conventional threshold detection approaches with centroid detecting circuits as used in some advanced microwave radars.

In addition, range biases must be stable to 1.5 mm over one hour and less than 2 mm over the course of a year. Contributions to the range bias include the angle dependent time walk (invariant point location), ground target stability, system delay instability between calibrations, refraction correction error due to barometric pressure inaccuracy, and amplitude variations in start and stop channels combined with threshold detection. Collocation between the NASA SLR network standard, MOBLAS-7, and the prototype NGSLR station has demonstrated that error sources do not contribute more than a 1.7 mm range bias (McGarry et al 2014). The collocation technique is described in Section 6, Verifying the Performance.

During normal operations, the system will be calibrated every one to two hours in order to compensate for possible changes in system delay. SGSLR will have three ground targets available, each surveyed and external to the system. One of the targets will function as a primary calibration reference, while the others will be used to periodically measure angle-dependent bias.

Calibration of the delay from the fire time measurement to the time the laser crosses the origin of the system (telescope invariant point) will be performed for each SGSLR system. Based on the experience with calibrating the fire delay on NGSLR for LRO-LR we expect the accuracy of this measurement to be better than 1 ns (Sun et al 2013).

5.2 Data Volume

Simulations show that a fully automated and deployed SGSLR will contribute a significant portion of the global laser ranging coverage. Table 1 shows estimated values for SGSLR annual data volume and precision ranging down to 10 degrees elevation at Yaragadee, Australia and 20 degrees elevation at Greenbelt, Maryland. High performing stations in the SLR network are included in the table for comparison, as well as the SGSLR requirement. Simulations used existing satellite pass schedules to determine target opportunities. The ILRS satellite priority list was used to select the satellites for simulated tracking at any given time. Tracking at SGSLR was assumed to be 24 hours a day and 365 days a year. Normal points generation was assumed to take the full normal point period for each satellite. The maximum number of possible normal points was counted for each satellite segment in the schedule. This normal point number was then reduced by 50% for weather outages at Greenbelt and 14% for weather outages at Yarragadee. A further 15% reduction in annual normal point count was used to represent maintenance periods. Finally the remaining normal point count was reduced by 60% to represent missed acquisitions, sun avoidance, aircraft avoidance, and other tracking related issues. The 60% reduction in normal point data appears to be very conservative, however, our approach to estimating the data volume was validated by the successful estimation of the data volume for two current SLR systems, Graz and Yarragadee for the same time period of Table 1.

Estimated data volumes shown in the chart do not take into account interleaving (ending a normal point when the desired precision is achieved and moving to another satellite to maximize the number of normal points). Therefore, the totals can be considered a lower bound.

6 Verifying the Performance

SGSLR will be tested throughout all phases of the system development, build, integration, and deployment. Final verification of the Space Geodesy requirements will occur at the system level at Goddard's Geophysical and Astronomical Observatory. Ranging data will be collected and analyzed against orbit generated data from the global SLR community to determine precision and stability. Ranging measurements will also be compared against the NASA SLR Network Standard Station, MOBLAS-7, to assess the system accuracy in a test method called collocation.

Although the long term requirements, including data quantity, can only be verified after the deployment and during the commissioning phases of operations, NASA has developed the collocation technique. This is a unique system quality verification method for SLR systems that has proven to be an important system level test, not only to verify the system performance, but also to transfer the exceptional NASA system performance to each station deployed around the globe. Collocation is a method of direct comparison testing developed by NASA in the 1980's and is used to identify SLR system ranging anomalies by utilizing a purely geometric technique to isolate station dependent, systematic ranging errors from other external sources of systematic errors. The process directly compares ranging data from two or more SLR systems in close proximity (<600 meters, preferably <60 meters) at the sub-centimeter level by quasi-simultaneously ranging to common retro-reflector equipped satellites[3]. The completed collocation is the final step for the SGSLR system quality performance and design validation.

The collocation test provides a unique opportunity to identify SLR problems by isolating station-dependent systematic ranging errors at the few millimeter level from other major sources of systematic errors including atmosphere, orbit modeling, station location, or orbital errors. The collocation period also establishes a documented benchmark of the SGSLR laser ranging capability, and has helped NASA SLR

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[3] https://ilrs.cddis.eosdis.nasa.gov/network/system_performance/co-location_history.html

in the past achieve uniformity and consistency of performance across the Network.

7 Current Status and Future Plans

The SGSLR subsystems are currently at various stages of design and build. The GTA has a fully matured design and three GTA units are being built. Factory Acceptance Testing of the first unit is expected by early 2019. The preliminary Time and Frequency Subsystem is being built and tested. The Optical Bench Subsystem design recently passed an Engineering Peer Review where it was reviewed by subject matter experts from both NASA and the Naval Research Laboratory. The Receiver Subsystem prototype is undergoing testing on ground targets at NASA. The laser, dome and meteorological equipment are all COTS instrumentation and procurement of all of these for the first SGSLR system is underway. The aircraft avoidance radars for both Texas and Goddard are being built. The software design is being worked and follows from the software originally written for and used at NGSLR.

NASA plans to deploy up to 10 SGSLR systems over the next 10+ years replacing legacy SLR systems and adding sites with a strong impact to the ITRF as indicated by the Pavlis network simulations. Merkowitz has described the priorities for the SGSLR deployment (Merkowitz et al 2018) and the first stations will be going to the McDonald Observatory in Texas, Ny-Ålesund in Norway, Goddard in Maryland, and Haleakala in Hawaii.

The build and testing of the first two systems will help mature the design and work out any issues. These two systems are expected to require a longer period of development and testing than subsequent systems.

The McDonald site development is already underway and this SGSLR system will be deployed there in 2020. The Norwegian system is expected to be deployed to Ny-Ålesund, Svalbard by 2022. With sufficient funding the remaining SGSLR systems could be deployed yearly starting in 2023.

8 Conclusions

When deployed, SGSLR stations will provide NASA with an advanced, robust, and eventually fully automated SLR Network, which will support future science needs and provide critical data for the generation of a very precise, highly stable International Terrestrial Reference Frame. Costs for operations and maintenance of these systems are expected to be significantly less than for the current SLR Network. These systems will perform better than most stations in the current global SLR Network in terms of data precision, stability and quantity. They will be able to operate in most locations around the world and are being designed to last for decades.

9 Acknowledgments

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Keywords:

Space Geodesy, laser ranging, SLR, SGSLR, ITRF, ILRS

Illustrations and Tables

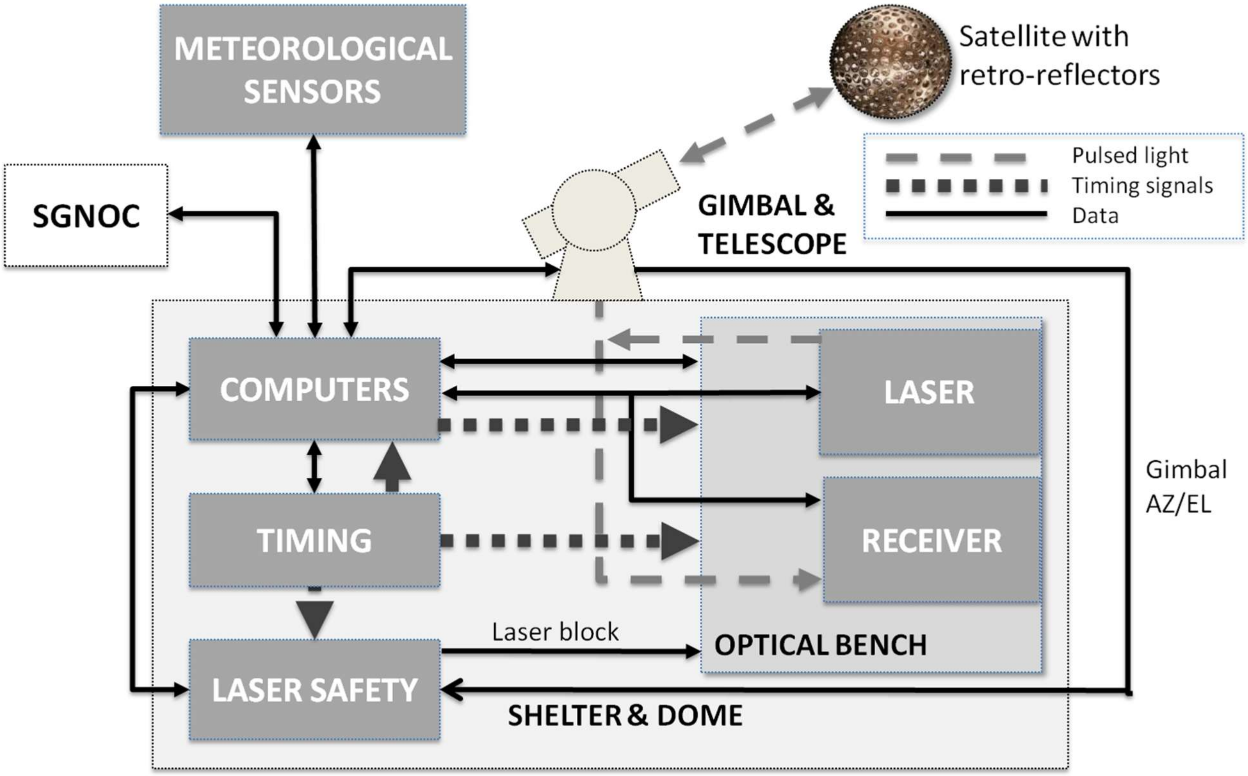


Fig. 1 Simplified block diagram of the SGSLR subsystem interfaces

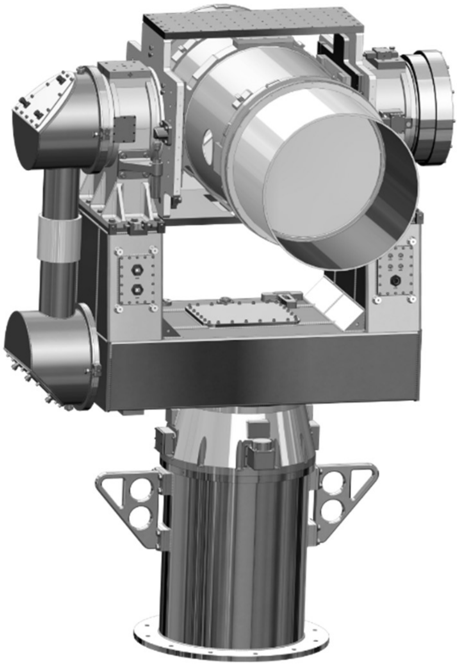


Fig. 2 Cobham gimbal and telescope assembly

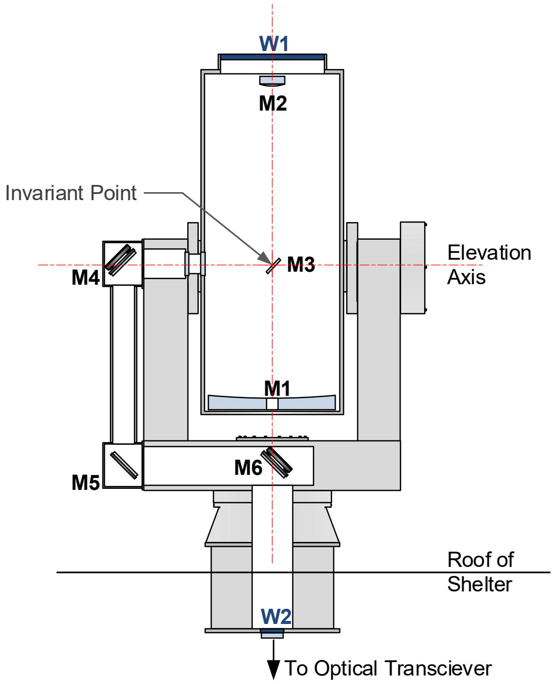


Fig. 3 GTA Coudé path showing the Invariant point location on the tertiary (M3)

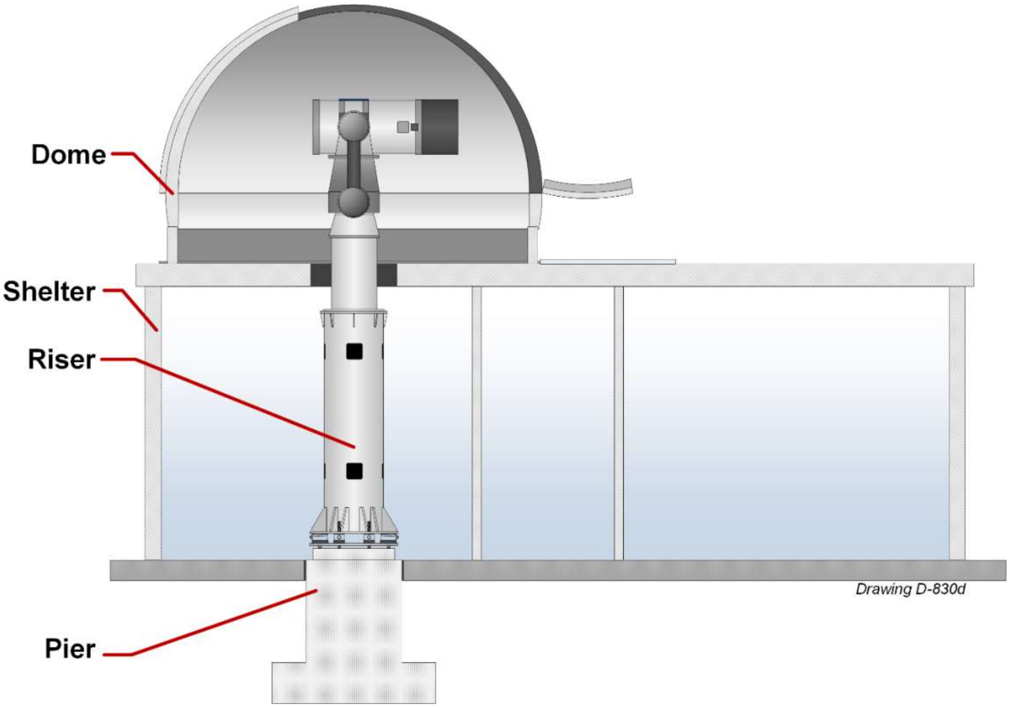


Fig. 4 Dome Shelter Pier Riser (DSPR) diagram showing major components

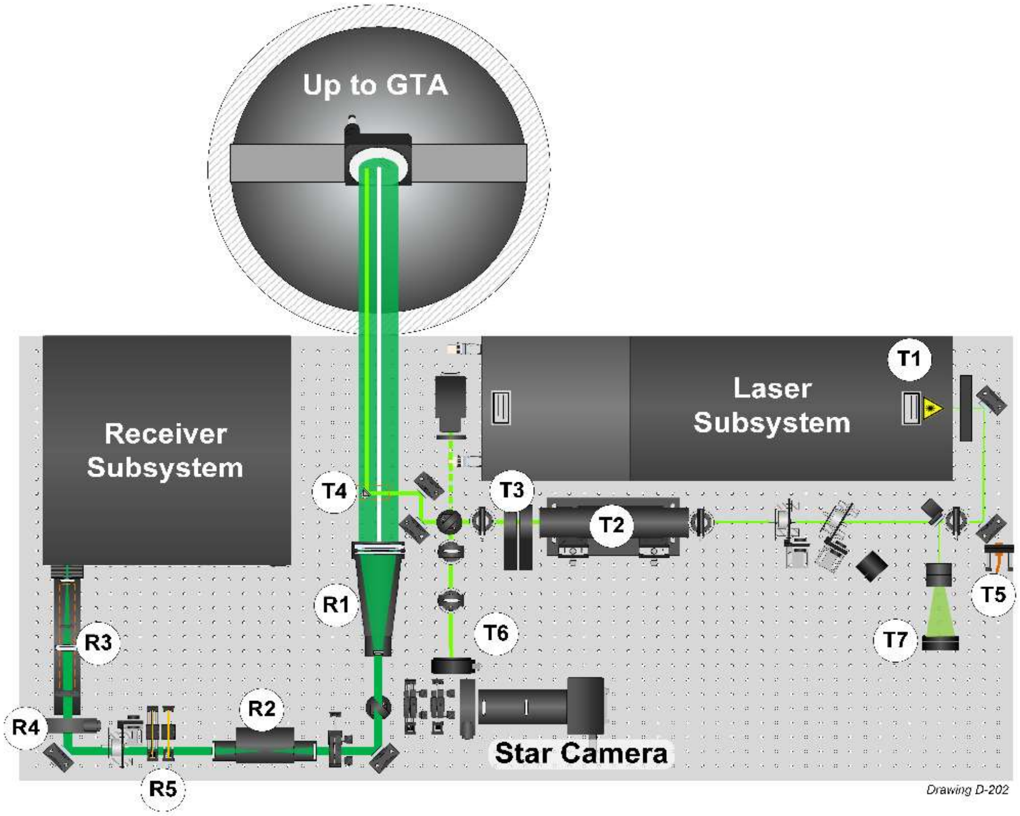
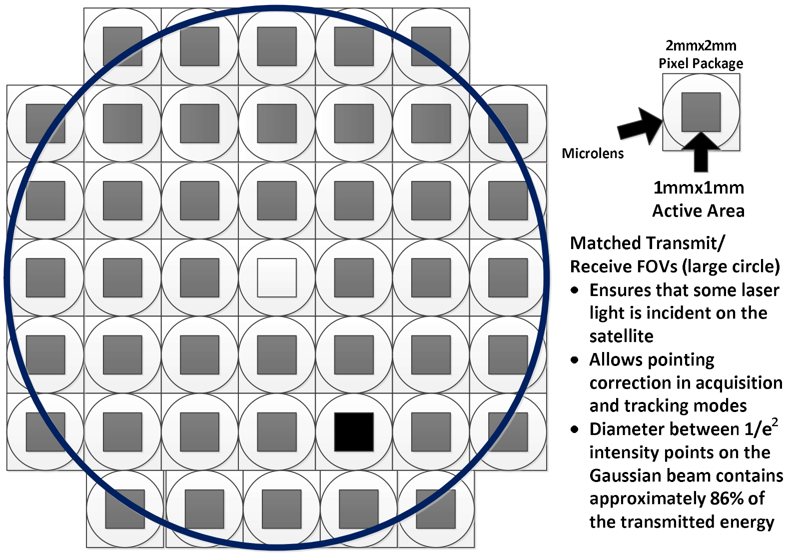


Fig. 5 Optical Bench block diagram. The optics in the transmitter path are T1 (the laser), T2 (beam expander, 7.4x with divergence control), T3 (Risley prism pair), T4 (insertion mirror), T5 (start diode), T6 (beam profiler), and T7 (power meter w/diverging optics). The optics in the receiver path are R1 (3.75x beam reducing telescope), R2 (beam expander with motorize IRIS to control the FOV), R3 (telephoto lens), R4 (detector shutter), and R5 (ND filters)



Matched Transmit/
Receive FOVs (large circle)

- Ensures that some laser light is incident on the satellite
- Allows pointing correction in acquisition and tracking modes
- Diameter between $1/e^2$ intensity points on the Gaussian beam contains approximately 86% of the transmitted energy

Fig. 6 The SGSLR Detector Array is placed in the image plane of the telescope, and consists of 45 independent, 2 mm x 2 mm, single photon sensitive Silicon Photomultipliers (white squares), each of which has a 1 mm x 1 mm active area (grey squares) at the center, which collects light from a different portion of the sky within the overall receiver Field of View. A matching array of 45 laser-ablated micro lenses (circles), captures almost all of the light falling within a given 2 mm x 2 mm pixel and transfers it to the active area. During target acquisition and tracking, the telescope axis (center white pixel) is pointed to the receive light from the satellite. If the telescope is pointed incorrectly, there will either be no return or the signal will fall in an off center pixel (represented by the black square). Since each pixel subtends a known angle, the telescope pointing can be corrected to bring the signal to the center of the array.

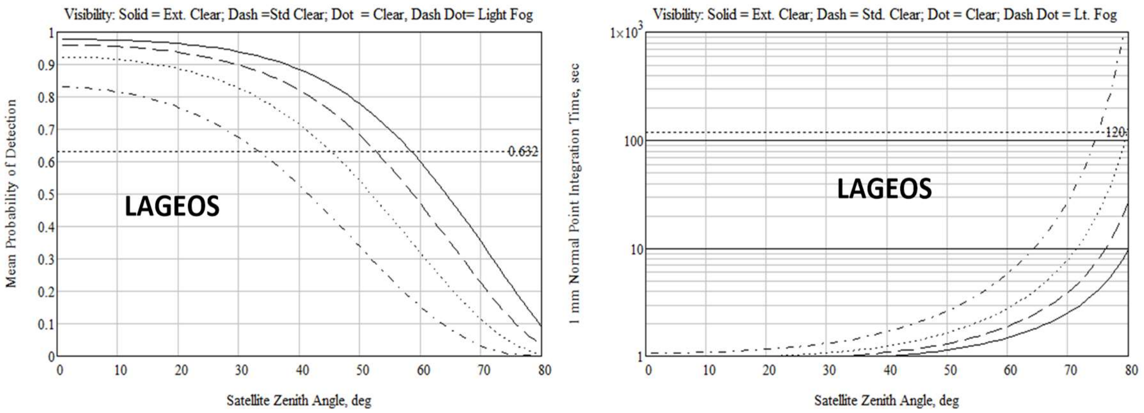


Fig. 7 Integration times to achieve 1 mm normal point precision on LAGEOS under various atmospheric conditions (right plot). The left plot shows the corresponding probability of detection. The horizontal line at 0.632 corresponds to the probability of detecting a mean signal level of 1 photoelectron (pe) with a 1 pe threshold. The horizontal dashed line at 120 seconds in the right plot represents the normal point integration time allotted to LAGEOS by the ILRS.

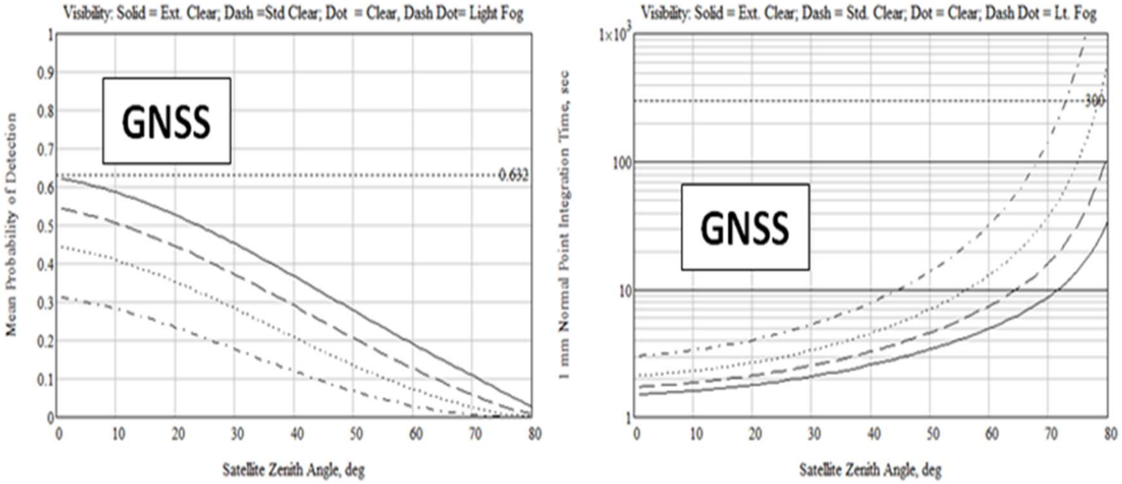


Fig. 8 Integration times to achieve 1 mm normal point precision on GNSS satellites under various atmospheric conditions (right plot). The left plot shows the corresponding probability of detection. The horizontal line at 0.632 corresponds to the probability of detecting a mean signal level of 1 pe with a 1 pe threshold. The horizontal line at 300 seconds in the right hand plot represents the normal point integration time allotted to GNSS satellites by the ILRS.

Site ID	Location	LEO NP Totals	LAGEOS NP Totals	High NP Totals	LAGEOS Average Precision (mm)	JCET Long Term Stability (mm)
YARL	Yarragadee, Australia	176,683	20,634	21,986	1.9	2.5
GODL	Greenbelt, MD USA	76,554	7,666	3,052	2.0	3.5
CHAL	Changchun, China	69,438	7,235	14,735	0.8	4.1
GRZL	Graz, Austria	75,714	5,468	18,016	0.2	1.8
HERL	Herstmonceux, Gr Britain	38,592	7,018	6,069	1.9	1.2
WETL	Wettzell, Germany	46,509	5,053	12,683	1.6	3
SGSLR(20°)	**Greenbelt, MD USA**	**55,000**	**7,600**	**12,500**	**<1.5**	**<1.8**
SGSLR(10°)	**Yarragadee, Australia**	**200,000**	**18,500**	**26,000**	**<1.5**	**<1.8**
Requirement		**45,000**	**7,000**	**10,000**	**<1.5**	**<2.0**

Table 1 Comparison of SGSLR estimated data volume, precision and stability with actual data from high performing ILRS stations for the period April 2013 through March 2014. SGSLR data volume was estimated through simulation for two locations with differing minimum elevation angle limits. Interleaving of passes for SGSLR was not taken into account, and conservative numbers were used for system down time and tracking success, thus this table should be considered a lower bound on SGSLR's data volume capability. Precision and stability for SGSLR were taken from actual NGSLR performance during the extended collocation period. SGSLR's performance is expected to be better. Requirements given in the last row are from the SGSLR requirements which are explained in section 2. JCET is the Joint Center for Earth Systems Technology at the University of Maryland Baltimore County.