# NGSLR System Overview

*Introduction to the NGSLR System*

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**Version 1.0**

January 2014

NASA-NGSLR-Overview

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# Acknowledgements

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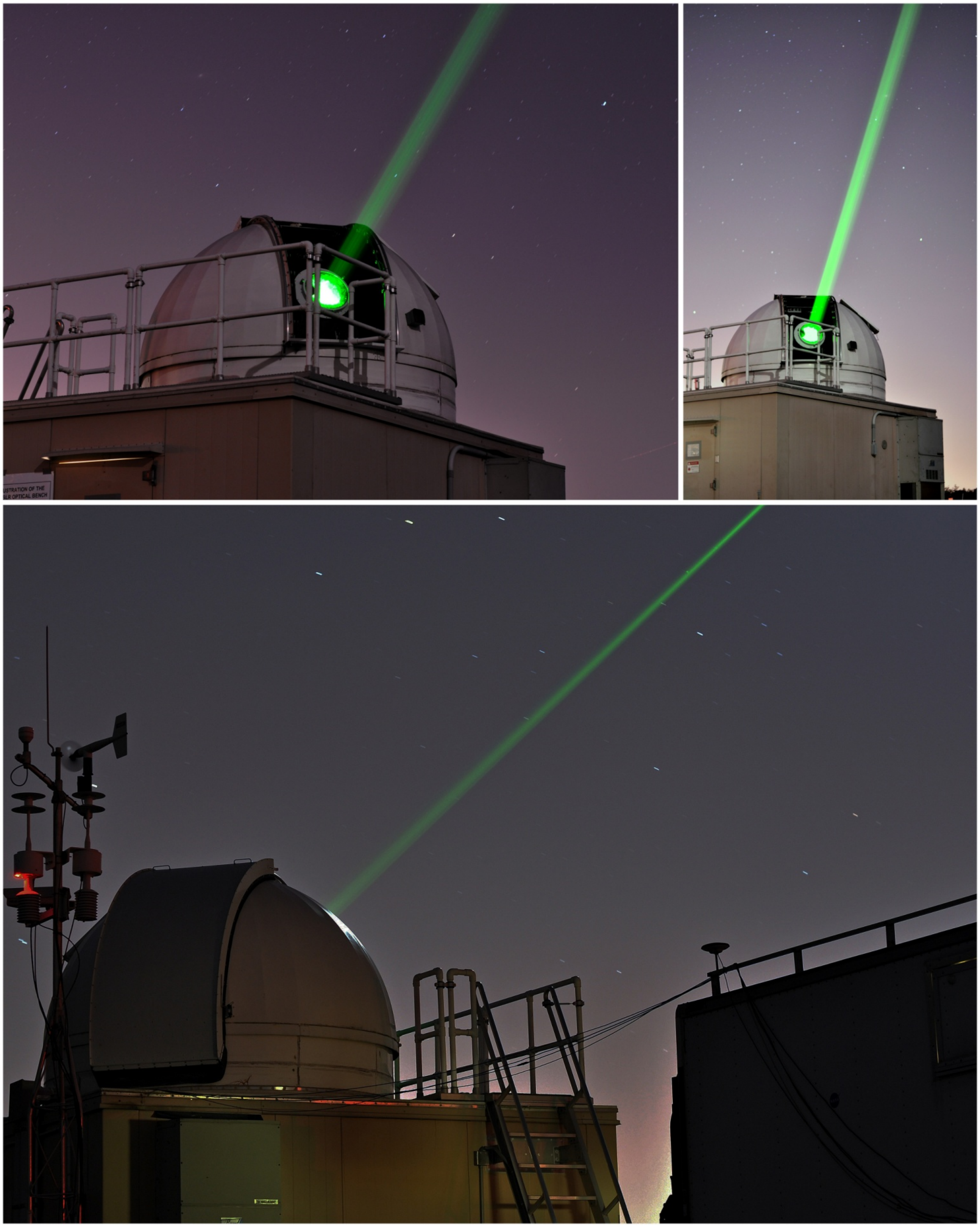
*The development of NGSLR (formerly SLR2000) is funded through the Science Mission Directorate at NASA Headquarters. This prototype is being developed by the Space Geodesy Project at Goddard Space Flight Center in cooperation with the Laser Remote Sensing Laboratory, both part of the Solar System Exploration Division at Goddard.*



***NGSLR during Ranging Operations***

# 1 Introduction

The National Aeronautics and Space Administration (NASA) has been involved in Satellite Laser Ranging (SLR) since October 31, 1964, when the world's first laser ranging returns from the Explorer-22 satellite (BE-B) were detected at the Goddard Optical Research Facility (now the Goddard Geophysical and Astronomical Observatory or GGAO). Since that time, NASA SLR operations have grown to include a global network of stations that track nearly 30 international spacecraft missions ranging from an altitude of 300 km to approximately 20,000 km. These stations contribute data to the International Laser Ranging Service (ILRS) where it is used to support geodetic and geophysical research. NASA's legacy SLR systems have provided valuable data for many years, but are costly to operate and maintain, and will not be able to satisfy projected performance requirements in the near future. Budgetary constraints, increasing precision requirements, and the need to track increasing numbers of retroreflector equipped satellites are steering SLR system design toward smaller, more automated tracking systems.

The Next Generation Satellite Laser Ranging station (NGSLR) is the prototype for a semi-automated, single photon, high repetition rate satellite laser ranging station scheduled to be deployed around the world in the coming decade. It will serve as a replacement for NASA's aging MOBLAS (MOBile LASer) and TLRS (Transportable Laser Ranging System) series SLR systems, which have been in service since the late 1970's. Pointing precision of the NGSLR system is about 1 arcsecond. The absolute shot to shot range accuracy to LAGEOS is about 1 centimeter with a normal point (time averaged) range precision of about 1 millimeter. Additional features include semi-automated tracking, compact design, lower operation and replication costs, and increased reliability. When fully operational, the system will provide continuous, 24 hour tracking coverage to Earth orbiting satellites equipped with passive retroreflector arrays.

In addition to the normal two-way satellite laser ranging, the NGSLR system is capable of supporting other types of laser ranging, including one and two-way asynchronous transponder ranging (Degnan, 2002). Currently, the NGSLR prototype is supporting one-way laser ranging to the Lunar Reconnaissance Orbiter (LRO), an uplink only range where NGSLR records the laser fire times, and the spacecraft records the receive events. Analysts form ranges after the pass by correctly associating fires with receive events. Further details on the LRO operations at NGSLR can be found in the manual "Laser Ranging to the Lunar Reconnaissance Orbiter (LRO) from NASA's Next Generation Satellite Laser Ranging Station" (NASA-NGSLR-OPS-LRO), or in various papers and presentations including: Zuber, et al. (2010); Mao et al. (2010); Clarke et al. (2008); Mallama (2008); McGarry et al. (2008); McGarry & Zagwodzki (2009).

## 1.1 Development of the Next Generation System

The original concept behind NGSLR was first proposed by John Degnan in 1994 as *SLR2000*, an autonomous and eye-safe SLR system. The focus of this endeavor was to develop an innovative station that could provide 24 hour tracking coverage, while reducing the cost of the SLR technique by increasing reliability, standardization and automation. This novel approach was based on over 30 years of experience developing and operating SLR systems at the Goddard Space Flight Center, and was designed to significantly reduce operations costs and possibly reduce replication costs by as much as an order of magnitude.

### 1.1.1 Proving Design Feasibility

During the first several years of NASA funding, prototypes of several critical components were developed to prove feasibility of the new concept. These included:

- A sensitive, high-speed, quadrant micro-channel plate photomultiplier for simultaneous ranging and pointing correction (Degnan 1999; McGarry, Zagwodzki, et al. 2002).
- Oscillator-only (Degnan and Zayhowski 1998) and oscillator/amplifier (Isyanova et al. 2002) versions of a multi-kilohertz microchip-laser based transmitter.
- A "smart" meteorological station which included an upgraded all-sky cloud sensor (Degnan and McGarry 1997; Mallama and Degnan 2002).
- A multi-kHz rate Range Gate Generator (Degnan, et al. 2003).
- A multi-kHz rate Event Timer with 1 mm resolution (Degnan, et al. 2003).

Once the key specifications on these advanced components were largely met, attention then turned to the detailed engineering design of the system and its components.

### 1.1.2 Technical Goals

The following comprise the current technical goals of the system:

- Semi-autonomous operations
- 24 hours tracking of LEO, LAGEOS and GNSS satellites (with ILRS approved retro-reflectors)
- Accuracy and stability at the MOBLAS level or better
- 1 mm normal point precision on LAGEOS
- Integration of the LHRS radar for all ranging operations
- Increased reliability (Mean Time Between Failures (MBTF) > 4 months)

### 1.1.3 Design of the Prototype

Legacy NASA SLR stations require operators to determine system viability, avoid direct contact of the laser beam with aircraft and ground personnel, and select the objects to track. The NGSLR prototype replaces much of the operator functions with automated processes. The system fires low energy pulses (~1 mJ) at a 2 kHz rate and performs single photon detection, which ensures return rates similar to those from traditional higher transmit energy, lower repetition rate SLR systems (4-10 Hz). NGSLR took a fresh approach in making the time-of-flight measurements to satellites. In the past, low repetition rate NASA systems (typically 5 Hz) operated with a single pulse in flight, enabling time interval unit measurement. Because these were single stop systems, the threshold was always set well above the noise and strong signal was always desired. For over 30 years, the NASA MOBLAS systems operated with high Signal to Noise Ratio (SNR) to prevent false detection. Supporting this philosophy of high SNR was the fact that transit time jitter of the early photomultiplier tubes (which contributed significantly to the RMS jitter) dropped off with an increase in signal. The installation of the micro-channel plate photomultiplier tubes (MCP PMTs) in NASA's systems in the 1980's changed the playing field significantly. The transit time jitter of the MCP PMT, even at the single photoelectron level, contributed less than 3 mm to the overall system RMS (Degnan, 1985). The implications are that systems can operate at the single photoelectron level as accurately as the multi-photon level. Hence, a SNR <1 is tolerable while enabling a reduction in laser pulse energy. In addition, the laser pulse repetition frequency (PRF) can be increased to aid in acquisition and closed loop racking. This paradigm shift in operational philosophy required the development of new instrumentation, hardware, and control algorithms to realize system operation.

One of the major challenges during the design of the system was to develop a low cost approach that could meet the above technical requirements and provide for future flexibility. This demanded using COTS/MOTS components where possible, and was implemented in several key areas such as the shelter, lasers, most of the components of the Timing and Frequency system, the Laser Hazard Reduction system (LHRS), a majority of the meteorological instrumentation, and many components on the redesigned Optical Bench.

The current system includes a more powerful COTS laser capable of ultra-short pulse/high repetition rate operation, a high bandwidth/high quantum efficiency detector, and an optical bench designed to seamlessly integrate the various automated components. Successful automation of the system includes coordinated operation of critical components such as the laser, beam blocks, ND filters, motorized optics, motorized shutters, and the star camera with the various software and hardware components that control them. The recently upgraded design has resulted in improved alignment and optical isolation, further improving the operation of the system.

For further information on the development and testing of the individual subsystems and software packages, please refer to the NGSLR references in Appendix C, many of which can be found in the Proceedings of the International Workshops on Laser Ranging. The full proceedings for all workshops can be found online at:

http://ilrs.gsfc.nasa.gov/about/reports/index.html

### 1.1.4 Demonstrated Tracking Capability and Data Collection

The NGSLR prototype is currently operational and is located at the Goddard Geophysical and Astronomical Observatory (GGAO), which is part of NASA's Goddard Space Flight Center (GSFC). The system routinely remains stable to within +/- 1.5 mm during hour long ground calibrations. While NGSLR is quite different from legacy NASA stations like MOBLAS and TLRS, the final data products will be the same with an accuracy that is equal to or better than those from current NASA SLR systems. Over the past year, NGSLR has taken over 280 passes of data, during both day and night tracking, demonstrating robust daylight tracking capability to retroreflector equipped satellites in low earth orbit (LEO), to LAGEOS-1 and LAGEOS-2 (~6000 km), and to GNSS satellites (~20,000 km). The system has successfully completed a collocation with MOBAS-7, demonstrating ranging agreement between systems. Details of the collocation results can be found in various presentations and papers given at the 18$^{th}$ International Laser Ranging Workshop in Japan (November 11-15, 2013).

## 1.2 Documentation Goals

This document captures the configuration of the system during the collocation with MOBLAS-7 in the summer of 2013. It is intended to familiarize the reader with the NGSLR system and to serve as an aid in navigating the project documentation in a quick and efficient manner. Although available in hard copy, it is preferable to view the documentation electronically, as this will allow the reader to take advantage of software features unique to the electronic version such as embedded links, bookmarks, and topical search capability.

# 2 Basic System Operation

NGSLR is capable of automatically acquiring and tracking satellites using a set of predictions downloaded on a daily basis. The software controls the configuration of the system in various modes such as satellite tracking, ground calibration, star assessment, and star calibration. Weather, visibility, and cloud coverage are also monitored automatically by the software. These features greatly decrease the operator workload, and streamline the tracking process. The operator is still required to be on site due to laser safety requirements, as well as to interact with several systems that have yet to be automated. These tasks include manually re-enabling the laser after an aircraft has been detected, closing the dome before the onset of inclement weather, powering up/down equipment, verifying safety systems, and serving as a backup to the radar-based aircraft avoidance system, known as the LHRS. An operator control interface is provided using a laptop running the Remote Access Terminal (RAT) software, which allows the operator to adjust system parameters and modify the tracking schedule. A messaging system (Daily Diary) records the operation of the system during the last 24 hours, serving as an aid in troubleshooting system problems.

## 2.1 Satellite Predictions and Scheduling

NGSLR will perform day and night ranging to LEO to GNSS altitudes, with the majority of tracking coming from segments of GNSS and LAGEOS passes. LEO objects, when tracked, will typically be tracked for the full pass due to the short duration of these events. Tracking is directed and coordinated using a schedule that is developed off site and stored on the Crustal Dynamics Data Information System (CDDIS). The schedule is comprised of a seven day, satellite prioritized, interleaved list that maximizes tracking on all ILRS satellites. It lists all available targets for a site, listing a primary target to be tracked along with a set of secondary targets that can be tracked. Each satellite is assigned a tracking priority by the ILRS which typically decreases with increasing orbital altitude and orbital inclination. Adjustments to the priority are made by the ILRS for satellites that require support for active missions, post launch intensive tracking, or for missions that have greater importance within the analysis community.

Satellite predictions are available from various prediction providers, and are stored on CDDIS in the Consolidated Prediction Format (CPF). Software for NGSLR picks up the predictions from providers that are believed to be the best for each satellite. The preferred provider can change at any time and not affect the operations at NGSLR.

This schedule and the corresponding satellite predictions are retrieved at a set time during each day for use by the tracking computer. Ground calibrations are automatically interleaved between satellites in the schedule at 1 to 1 ½ hour intervals. Ground calibrations are short data segments to ground targets which measure the system delay for post processing range data correction. Star calibrations are currently selected by the operator and are performed approximately every 1 to 2 weeks (or on an as needed basis) and are used to correct the mount model to maintain accurate system pointing.

## 2.2 Satellite Laser Ranging Operations

NGSLR will spend the majority of its day acquiring and tracking satellites using the schedule. Laser Ranging occurs for scheduled passes as cloud conditions and ILRS restricted tracking parameters* permit. Exceptions include the following conditions where the dome must be closed in order to protect sensitive equipment:

- Precipitation of any kind
- Sustained gusts of greater than 40 mph (17.8 m/s)
- Temperatures that are above 122° F (50° C) or below 14° F (-10° C)

**

**Some missions define whether they will allow satellite tracking at a particular time. See the ILRS website for more information on tracking restrictions at: [http://ilrs.gsfc.nasa.gov/](http://ilrs.gsfc.nasa.gov/)*

### 2.2.1 Data Collection Cycle

NGSLR automatically follows the schedule, with the system cycling back and forth between ground calibrations and satellite passes (Figure 2-1). The schedule begins with ground calibration, followed by a 1-1 ½ hour block of passes that consist of satellites in a variety of orbital paths and altitudes. Any single pass could last from 2 minutes up to 1 hour. Regardless of the satellite, tracking is never performed below 20° in elevation due to FAA laser safety restrictions.

| | |
|---|---|
| | **Power up system** |
| Data Collection | Initial Ground Calibration |
| | Set of Satellite Passes |
| | Ground Calibration |
| | Set of Satellite Passes |
| | Ground Calibration |
| | Set of Satellite Passes |
| | Ground Calibration |
| | Set of Satellite Passes |
| | Ground Calibration |
| | Set of Satellite Passes |
| | Ground Calibration |
| | Set of Satellite Passes |
| | Ground Calibration |
| | Set of Satellite Passes |
| | Final Ground Calibration |
| | **Shut Down System** |

**Figure 2-1: Typical shift showing the data collection cycle**

*Please note that back to back shifts do not require shutdown and startup cycles between them.*

Ground Calibrations determine the system delay. This technique measures the difference between the theoretical time it should take for light to travel through the atmosphere to the target and back (as determined by the surveyed range corrected by refraction), and the time that is actually measured by the system. This system delay time is removed from satellite range measurements to produce an accurate product. In order to have an accurate estimate of the system delay, any differences in the path length between ground calibration and satellite tracking must be known and accounted for. In addition, the return rate of the ground calibrations must match the return rates from the satellites.

Once the first ground calibration of the shift is complete, the system can then move on to the first set of satellite passes, tracking each according to its priority on the schedule. During the day, sun avoidance is done automatically by the system, driving the telescope around the sun or choosing another target if necessary. At night, star assessments are performed prior to nighttime satellite passes in order to provide the best acquisition probability. Upon completion of the set of passes, a final ground calibration is performed to capture the system delay. Once the data collection cycle is complete, the operator either hands it off to the next operator, or shuts down the system until the next shift.

Every 1 to 2 weeks, the system performs a star calibration to correct the mount model for accurate pointing. This requires that the system have a fairly clear nighttime sky so that enough stars can be clearly captured by the Star Camera. The system uses the Sky Camera system, which determines the clarity of the sky using an infrared image of the sky. If these criteria are met, NGSLR uses the FK5 star data file for star pointing predictions, and data received from USNO (via the `iers.dut` file) for Earth orientation parameters, and chooses stars between $3^{rd}$ and $4^{th}$ magnitudes for consistency in the star centroid calculations. The star calibration software points the telescope at each star in the list, calculates the centroid of the star, centers the star and records the biases, taking about 30-40 minutes to complete 50 stars. The system then performs a least squares fit of the bias data to the mount model to generate an updated set of mount model coefficients, which is used to correct the pointing during satellite tracking.

## 2.3 NGSLR Data Post Processing

The NGSLR Post Processing Software performs post tracking data processing and analysis, creation of data products, and data product delivery. Satellite data is stored until post ground calibration data has been processed. The software will then process the raw data files in the time order of their creation.

The calibration data is processed using an iterative sigma multiplier filter on range returns which have been corrected for the system delay (as calculated from recent ground calibrations) and stored in a database. The atmospheric refraction, and any optics that are in calibration path but not the satellite path, are also accounted for in the range corrections.

The satellite data post processing begins by splitting the raw data files into individual satellite pass files. The full rate observed minus calculated (O-C) range residuals are computed by subtracting the predicted range, atmospheric refraction, and system delay from the measured range. The system delay is determined by averaging the system delays from the closest in time ground calibrations before and after the satellite pass.

The pass observations are initially filtered using the real-time software's signal flag. The signal flag is set by the on-site signal processing software and determined during the real-time tracking of the satellites. This signal is a sub-set of the all the signal returns received from the satellite. The post-processing software starts with the real-time returns, and then includes all returns in a range space window and time (epoch) space window near the real-time signal. The process ensues that nearly all potential signal returns are included in the analysis while eliminating obvious noise returns.

This set of observations is input into the normal point software. The normal point software's main function is to generate the ILRS data product (CRD normal points). The normal points are formed by first generating full rate residuals from a predicted satellite orbit, then smoothing and filtering the residuals using various techniques including an iterative least squares polynomial. After the residuals have been filtered, the normal points are formed by averaging the accepted range observations in each normal point time bin and time tagging the normal with the median time observation in the bin. Normal points that pass quality control standards are output in the CRD format, compressed and delivered to the ILRS data center once per hour. The full rate observations used to generate the normal points are also output in the CRD format, but are retained at GGAO for future reference.

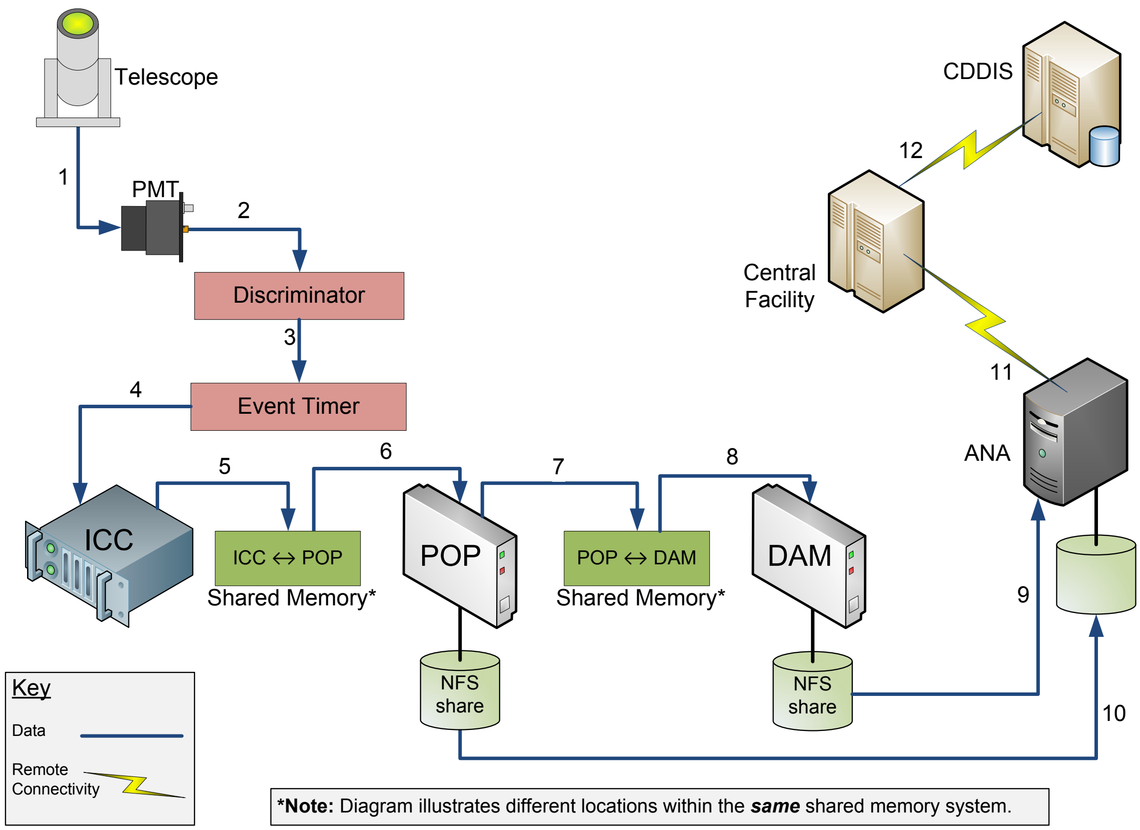



**Figure 2-2: Diagram illustrating the flow of ranging data**

1. Laser returns along with background noise arrive through the telescope.
2. PMT detects photon(s) and sends analog signal to the discriminator.
3. Discriminator converts the analog signal to a logic pulse and sends it to the Event Timer.
4. ICC reads values from the Event Timer buffer every 500µs.
5. ICC sends data to POP every 500µs.
6. POP collects the data from ICC and stores in a circular buffer.
7. POP performs signal processing on the data in the circular buffer every frame (4 to 30 seconds, satellite dependent).
8. POP appends data from each frame to a unique set of logx_*.asc and logx*.bin files under the /logx directory.
9. Once logging is completed (may be multiple passes), POP puts the name of the logx file in shared memory and sets the data ready flag.
10. The **overseer** program, running on DAM, uses the name of the logx file to create a blank logx file on its NFS share.
11. Running on ANA, **process_log** monitors DAM's NFS share for new files, indicating that a logx file is ready to be copied from the POP Network File System (NFS) share.
12. The actual logx file is copied to ANA and processing begins.
13. Once processing is complete, *.npt files are sent to a central facility where the data is collected up and sent on to CDDIS.

# 3 Main Components of NGSLR

The NGSLR prototype can be divided into eleven major subsystems that perform unique functions within the system (Figure 3-1). Control of the system is centralized in the Computer and Software system, which provides a console for an operator via a graphical user interface. Each subsystem, along with a brief introduction, is listed below. These include:

1) Shelter and Dome
2) Telescope
3) Tracking Subsystem
4) Optical Bench
5) Laser Subsystem
6) Computer and Software
7) IO Chassis
8) Time & Frequency
9) Range Receiver
10) Weather
11) Laser Hazard Reduction System (LHRS)

Details on all of these subsystems can be found in the NGSLR Hardware Manual (NASA-NGSLR-HWR-Manual).

*Figure 3-1 (below) illustrates the interconnectivity of the system and the delegation of responsibilities among the devices.*

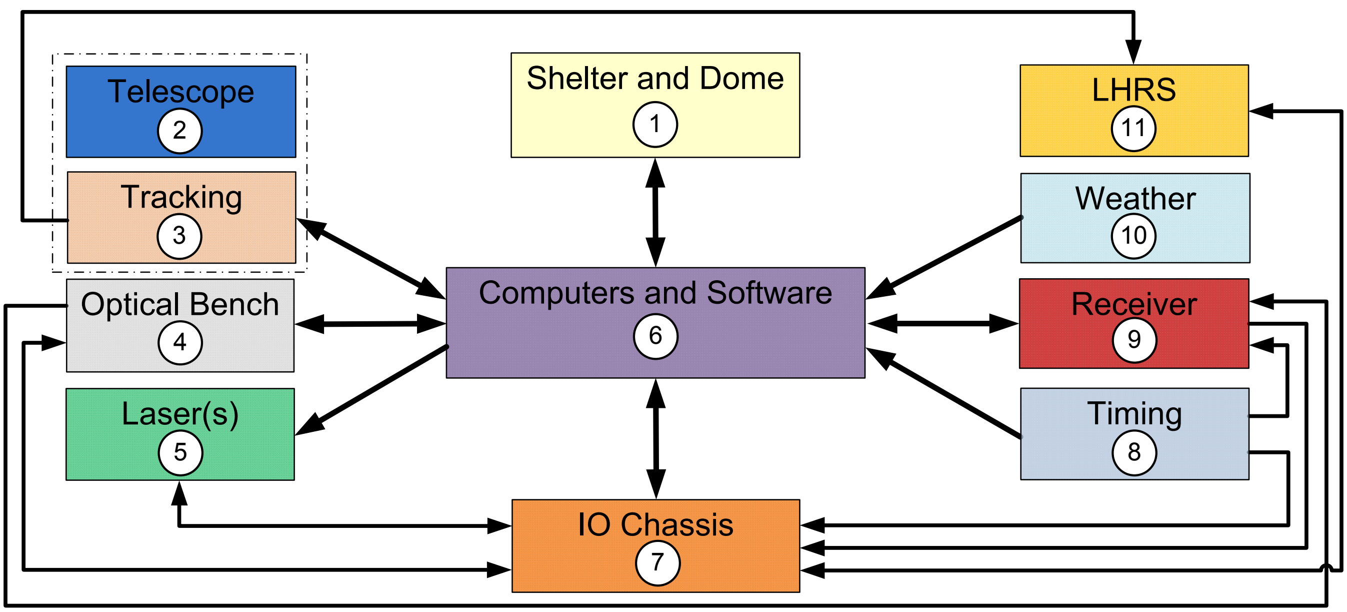



**Figure 3-1: The eleven major systems of NGSLR**

## 3.1 Shelter and Dome

The shelter is a modular structure that provides a temperature controlled environment for the equipment (Figures 3-2 and 3-3). It supports a motorized, 10’ diameter, fiberglass observatory dome which protects the telescope and gimbal system. The dome rotates with the telescope, as the azimuth control system is slaved to the telescope via the software. Access to the telescope and dome is provided by a stairway accessible catwalk mounted on top of the shelter.

**Figure 3-2: Front of NGSLR Shelter and Dome**

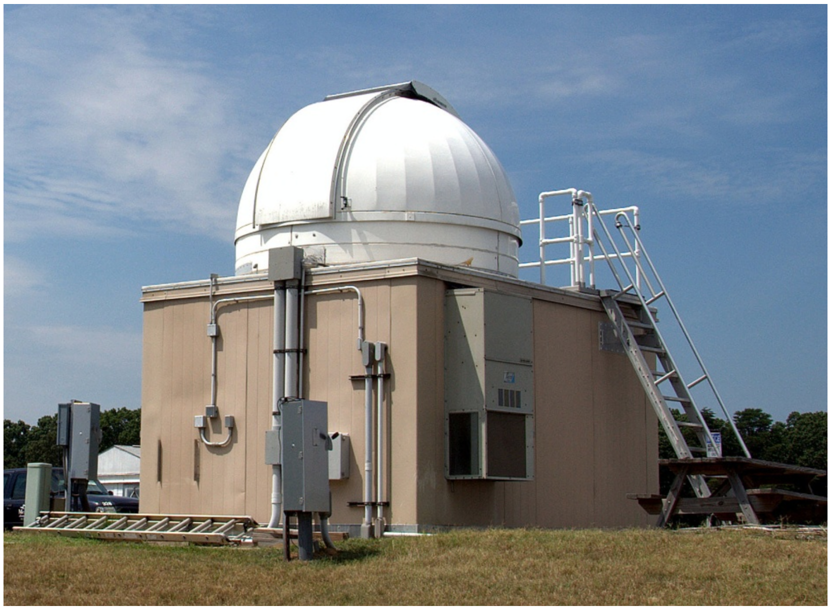


**Figure 3-3: Back ¾ view of the NGSLR Shelter**

The interior is divided up into two major sections, the control area and the laser operations area as shown in Figure 3-4. The control area allows authorized personnel access to the operator console and the equipment rack without requiring eye protection during operations (Figure 3-5). The laser operations area is an enclosed area for the optical bench which confines stray laser energy and assists in maintaining a clean environment for the optics. Personnel in this area are required to wear eye protection when the laser is operational. Air within this area is maintained at a slight positive pressure to discourage the entry of unfiltered air.

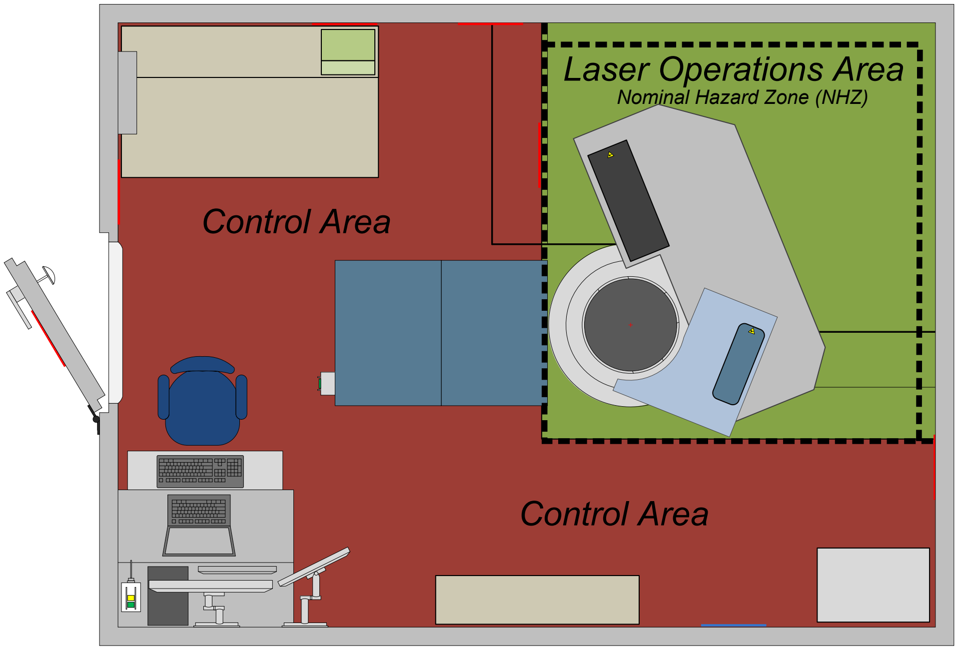



**Figure 3-4: Layout of the NGSLR Shelter**

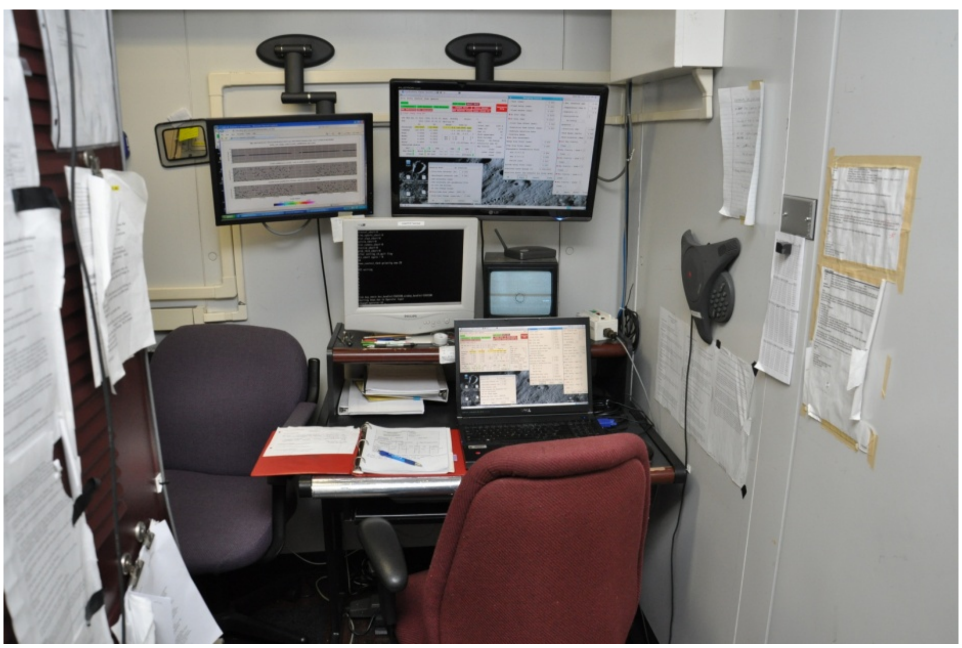


**Figure 3-5: View of the Operator Console**

## 3.2 Telescope Assembly

The telescope assembly includes the telescope and the coelostat. The telescope is a 40 cm, coudé focus, off-axis design that is used for both transmission and reception of the signal (Figure 3-6). The off-axis design was originally chosen to allow the transmitter and receiver to share the entire telescope aperture during eye safe operations. The telescope is connected to a coelostat built into the telescope mount which directs light between the telescope and the optical bench. Special care is taken to ensure that the coelostat light path is parallel with the mechanical axis of the telescope.

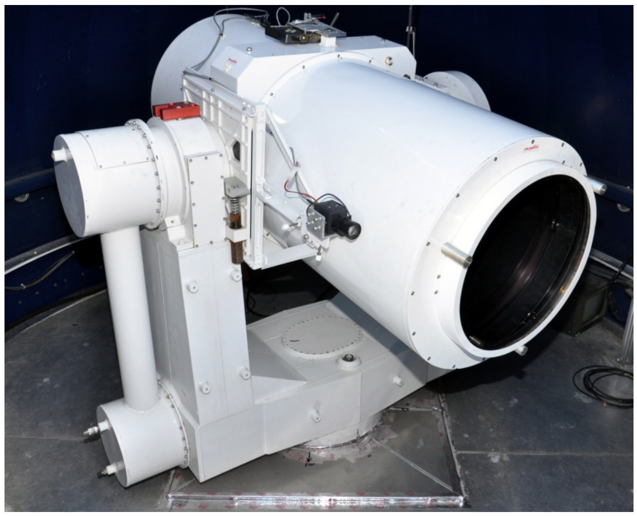


**Figure 3-6: NGSLR Telescope in Az/El Tracking Mount**

## 3.3 Tracking Subsystem

The custom built Azimuth-Elevation (AZ/EL) tracking system is comprised of a mount and mount controller (Figures 3-7 and 3-8). These are capable of arcsecond level pointing while tracking at speeds up to several degrees per second. Pointing ranges from -3° to 183° in elevation while azimuth rotation is unlimited. The controller is driven via velocity commands at 50 Hz as directed by the **I**nterface **C**ontrol **C**omputer (ICC).

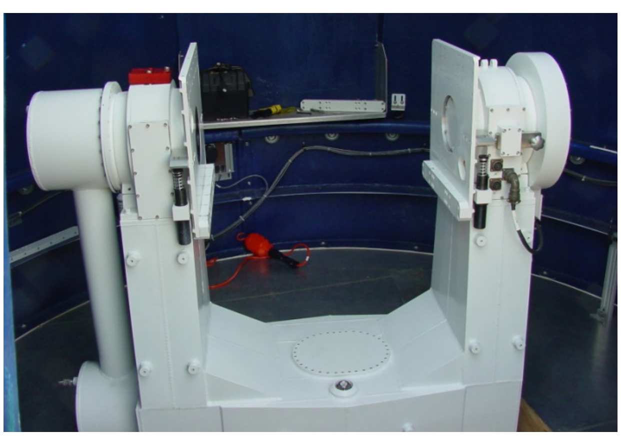


**Figure 3-7: Azimuth/Elevation Mount and Coelostat (left side) prior to the installation of the Telescope.**


**Figure 3-8: Controller for the mount, located in the equipment rack behind the operator**

## 3.4 Optical Bench

The optical bench maintains the position, spacing, and alignment of all the optical components before the coelostat (Figure 3-9). Devices include the laser head(s), turning mirrors, lenses, prisms and other similar items related to the transmission and detection of the laser. Several devices on the optical bench are controlled remotely by the DAM computer and adjust the point-ahead of the laser transmitter, the band pass filter, the rotary ND wheels and the receiver field of view. Automated safety devices such as beam blocks, shutters, and ND filters (for ground calibration) are also situated on the SLR optical bench, controlled by the IO Chassis (See Section 3.7).

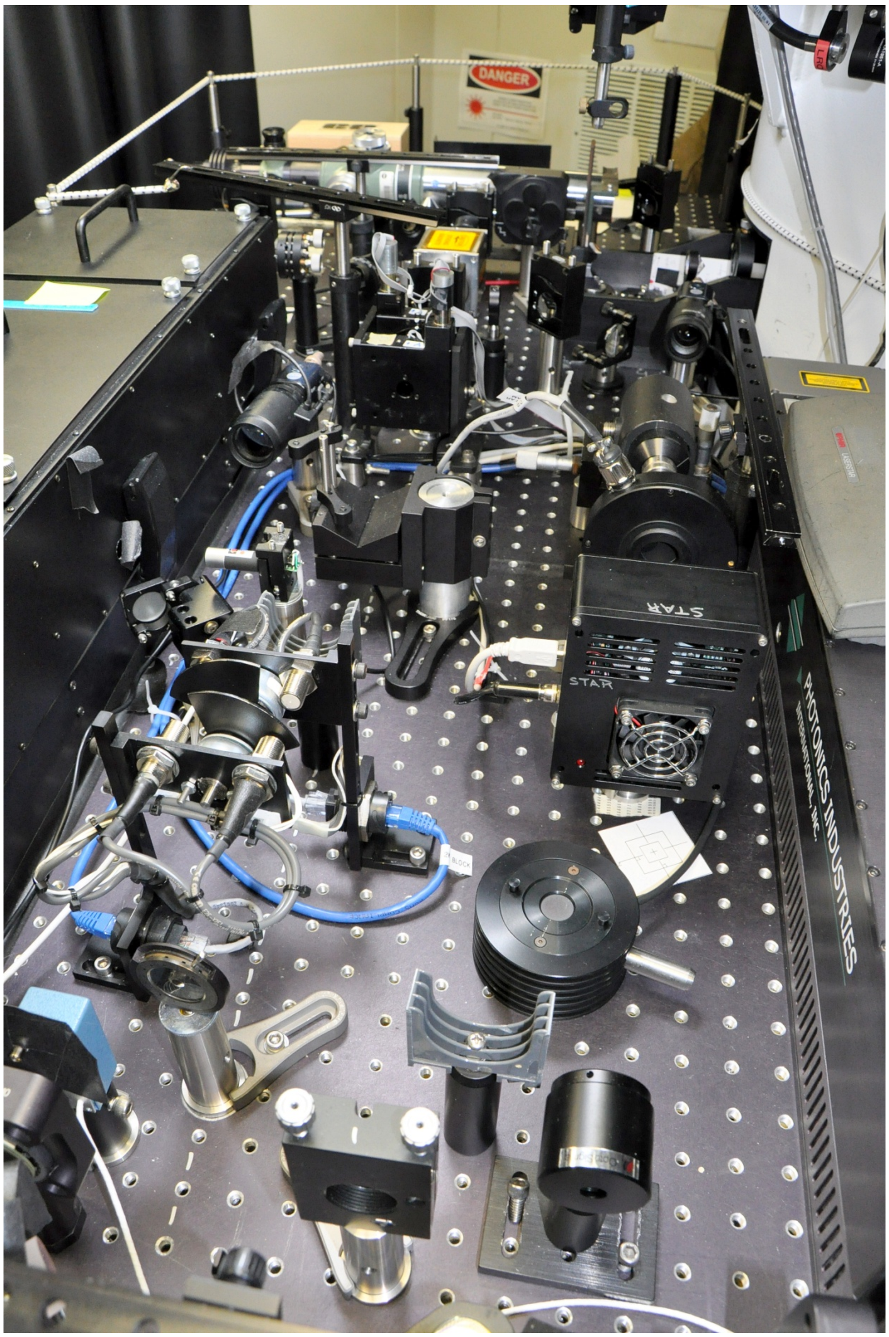



**Figure 3-9: View of the SLR Optical Bench during development**

## 3.5 Laser Subsystem

The NGSLR system uses different lasers for SLR and LRO operations. The SLR laser is a pulsed 532 nm laser used for two-way ranging to satellites (Figure 3-10). The 2 kHz repetition rate is adjusted over a narrow range to avoid interference between the outgoing and incoming light at the sensitive single photon detector. SLR laser output energy at the laser is 1.0 mJ/pulse, with a pulse width of 50 ps (FWHM). The LRO laser, used for one-way ranging to the Lunar Reconnaissance Orbiter, is a 28 Hz / 532.2 nm laser with a 5.5 ns pulse-width and an output energy at the laser of ~ 40 mJ/pulse (Figure 3-11). It is inserted into the telescope optical system after the SLR laser optics and thus is unaffected by changes to the SLR optical bench.

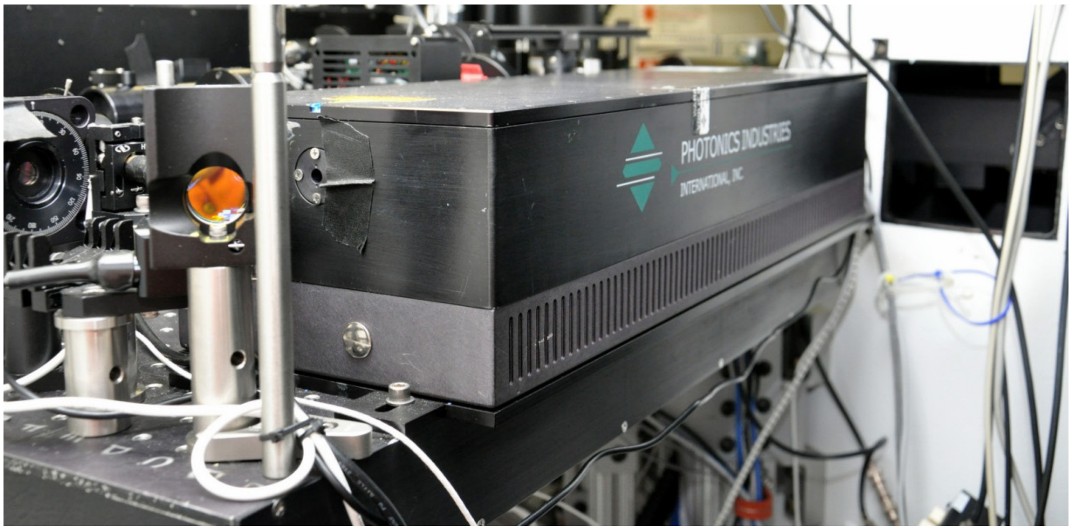



**Figure 3-10: SLR Laser as installed on the SLR Optical Bench**

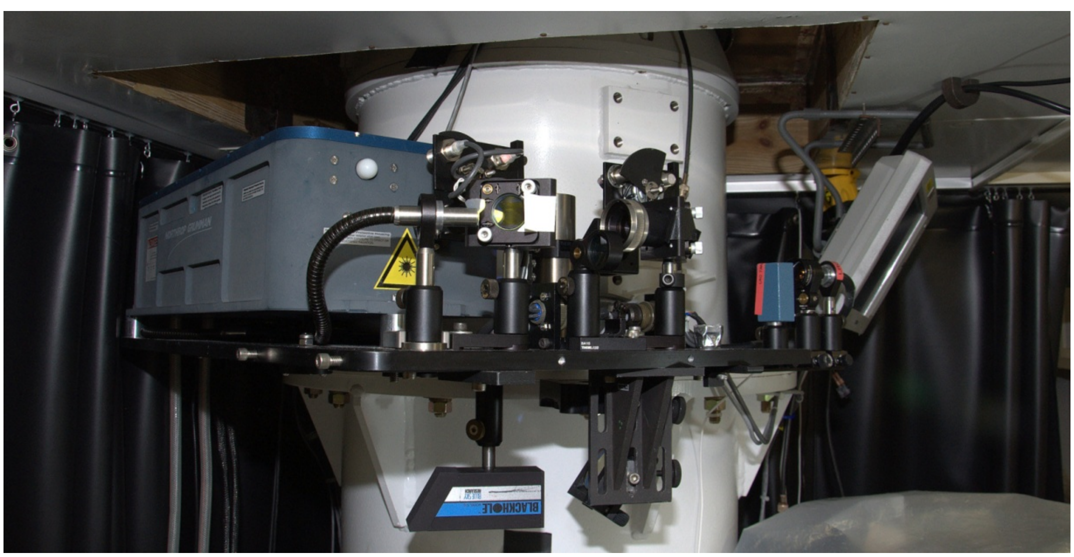


**Figure 3-11: LRO Laser and LRO Optical Table mounted on the Telescope Pier above the SLR Optical Bench**

## 3.6 Computer and Software

Numerous computers control the NGSLR system. These include: the **I**nterface **C**ontrol **C**omputer (ICC), the **P**seudo **Op**erator (POP), the **D**evice **A**ccess **M**anager (DAM), the data **Ana**lysis computer (ANA), the **Cam**era computer (CAM), and the **R**emote **A**ccess **T**erminal (RAT) (Figure 3-12).

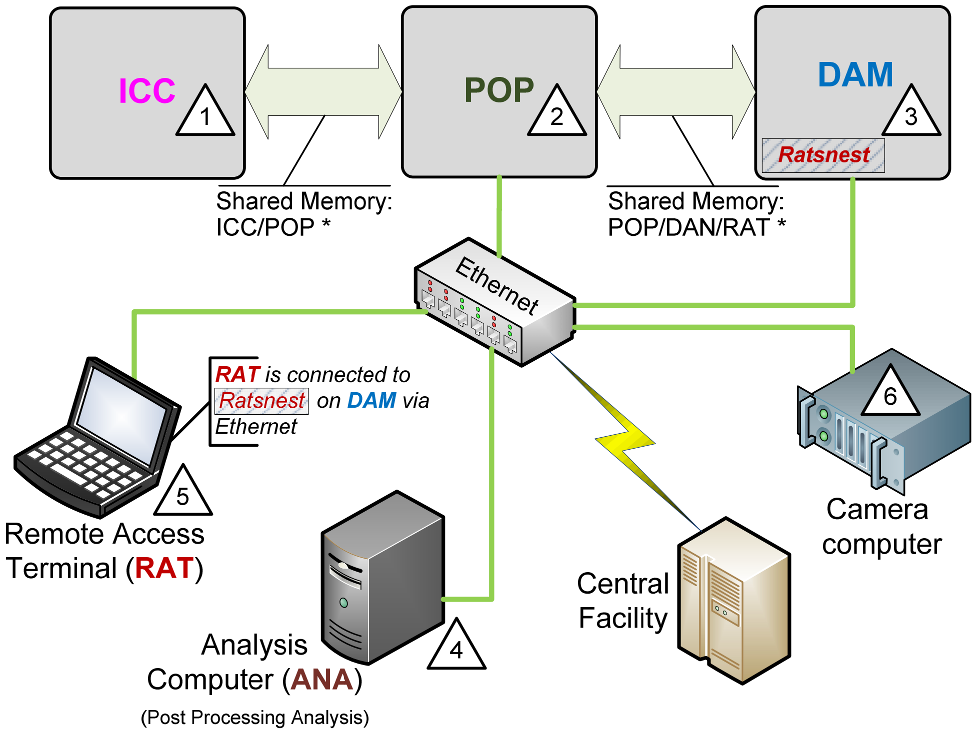



**Figure 3-12: The six main computers that comprise the NGSLR computer system**

### 3.6.1 Interface Control Computer (ICC)

The **ICC** performs real-time input and output functions to hardware devices via interface cards. No data processing is actually performed on the ICC; all data is passed to and from POP via shared memory. This DOS based system runs on a Pentium class processor with a mixed ISA/PCI bus. Software tasking is driven by 2 kHz interrupts from the timing system via a timing and digital interface card.

### 3.6.2 Pseudo Operator Computer (POP)

**POP** makes most of the operator decisions, controls the VME hardware interface to the IO Chassis, and passes data to and from DAM via NFS and shared memory. As with the ICC, the software tasking is driven by a 2 kHz interrupt from the timing system. POP runs under LynxOS on a single board Pentium computer hosted on the VMEbus Chassis.

### 3.6.3 Device Access Manager Computer (DAM)

**DAM** is responsible for controlling the motorized optics on the SLR optical bench, providing an area for ANA to deposit predictions and schedules from the remote Central Facility (which will be utilized by POP), hosting a remote interface for the RAT system and collecting meteorological information. DAM operates under LynxOS on a single board Pentium computer hosted by the VME bus Chassis.

### 3.6.4 Data Analysis Computer (ANA)

**ANA**, the data analysis computer, is responsible for post processing and data delivery. Ranging data is sent through three processing systems: Calibration, Satellite, and Normal Point, which produce the final data product in ILRS Normal Point format. These files are uploaded to a central distribution facility on an hourly basis for use by the scientific community. ANA runs on a desktop computer using Fedora Linux.

### 3.6.5 Remote Access Terminal

**RAT** allows one operator to remotely control, configure and troubleshoot all major systems over the NASA intranet. The RAT software resides on a laptop running Fedora Linux, and allows the operator to display data graphically on the monitor, and run the NGSLR system. RAT connects through a secure internet connection to a service on DAM, which provides access to information on the other NGSLR systems.

### 3.6.6 Camera Computer

The **Camera** computer is a Windows XP (SP3) based system which configures the SLR laser for alignment or tracking operation, controls the beam profiler, and controls the two camera systems used on NGSLR (the Sky and Star cameras). Images from these cameras are passed to the other NGSLR computers via NFS mounted files. In addition, the Camera computer also displays the LRO-LR real-time website, used by operators during LRO operations. The SLR laser is configured for operation using a custom software package developed to simplify operation of the laser. The beam profiler is operated using GUI based software provided by the manufacturer, while the two cameras are controlled by custom software written by the NGSLR development team. The first camera is a CCD that is mounted on the SLR optical bench and is used to perform star calibrations. The second, a thermal infrared camera located outside of the NGSLR facility, is used to determine cloud cover over the full hemispherical sky.

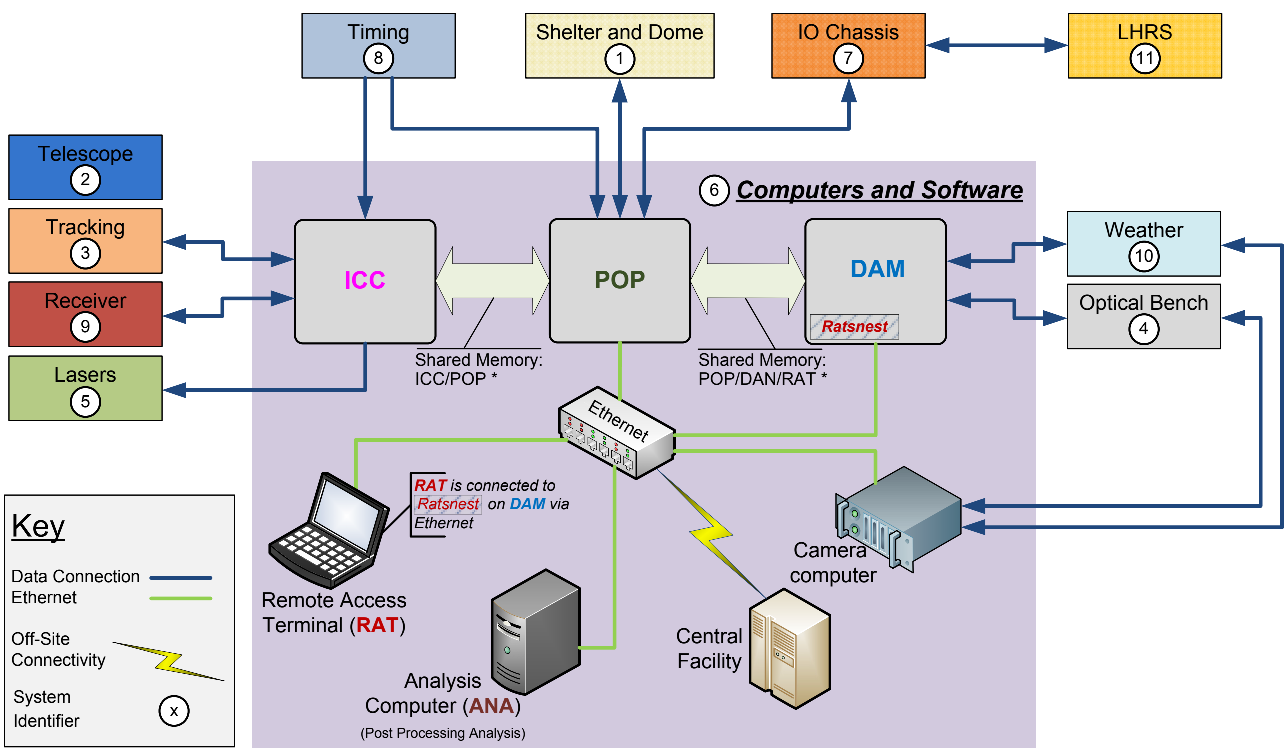



**Figure 3-13: NGSLR Computer System Connectivity Diagram**

## 3.7 IO Chassis

The IO Chassis is a custom built, multi-function safety and signal processing device. It controls the operation of laser beam blocks and ND filters dependent on the status of external safety devices (such as the LHRS) and/or commands from the POP Computer (Figure 3-14). In addition, it controls and distributes the gating signals for the detector and discriminator during tracking and ground calibration, and passes the firing signals for the SLR and LRO lasers, all of which are sent from the ICC computer. Both the blanking circuit for SLR operations and the 28 Hz LRO laser fire circuitry are housed in the IO chassis.


**Figure 3-14: Front faceplate of IO Chassis**

## 3.8 Time and Frequency

SLR tracking operations require accurate station time keeping to ensure that satellite ranges are accurately time tagged, and require an accurate frequency source for high precision range measurements (Figure 3-15). Station time keeping is maintained by a GPS steered Rubidium atomic clock, while a hydrogen maser provides a stable 10 MHz frequency source.

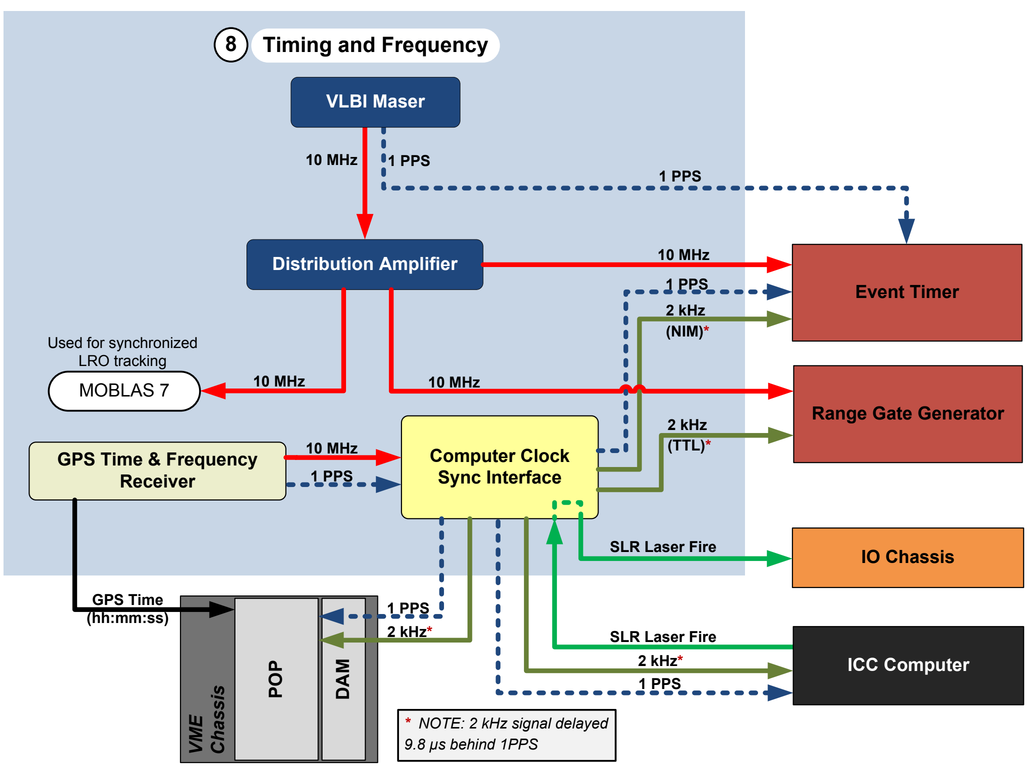



**Figure 3-15: Timing and Frequency System Connectivity**

## 3.9 Range Receiver

The Range Receiver subsystem detects and time tags returns, provides gating for the detector, and controls the programmable delays for the system. Critical components include a micro-channel plate photomultiplier tube, signal amplifier, timing discriminator, Event Timer (ET), gating module and the Range Gate Generator (RGG) as shown on Figure 3-16. These components form an essential part of the signal detection system where synchronization is crucial to proper system operation.

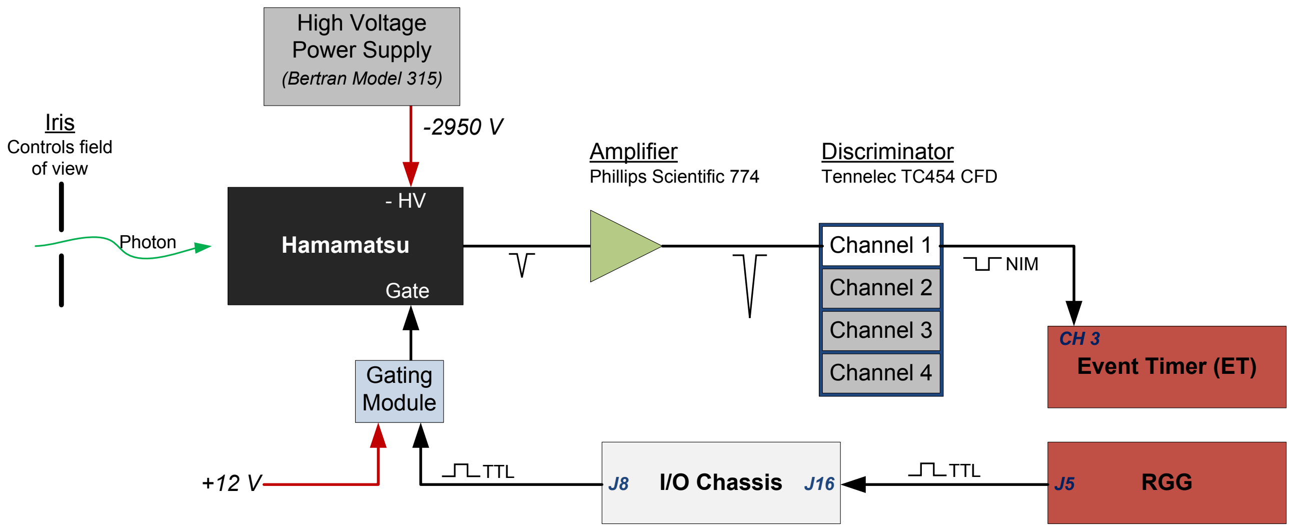



**Figure 3-16: Range Receiver Block Diagram**

## 3.10 Weather

The weather system uses COTS meteorological instruments that measure pressure, temperature, relative humidity, precipitation, horizontal visibility, and wind velocity (Figure 3-17). Pressure, temperature, and relative humidity readings are used to compute atmospheric corrections to the measured range based on the Marini-Murray model (Marini and Murray, 1973). In addition, the weather system hosts the Sky Camera, an in-house developed, thermal infrared instrument which monitors cloud cover and determines whether tracking is possible in a particular region of the sky (Mallama and Degnan, 2002).

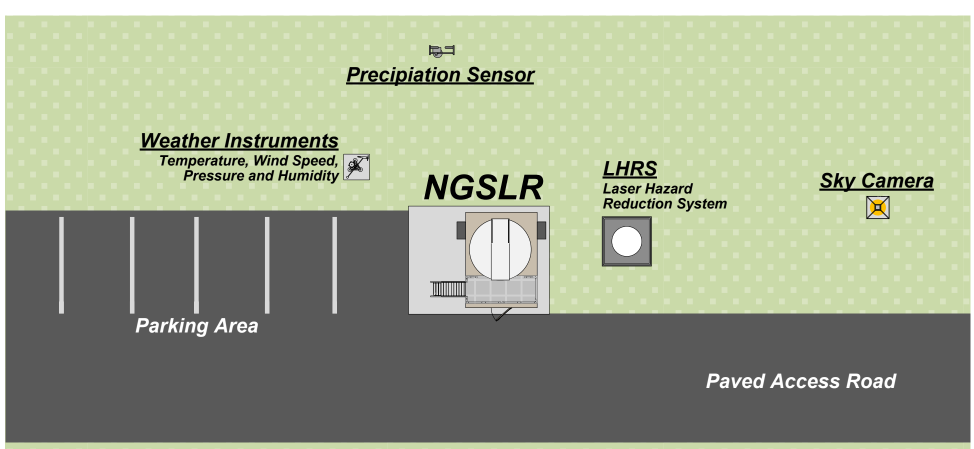



**Figure 3-17: Overhead layout of weather instrumentation**

## 3.11 Laser Hazard Reduction System (LHRS)

The Laser Hazard Reduction System (LHRS) is a laser safety radar system needed for aircraft avoidance. Housed on an elevated platform approximately 30 feet from NGSLR, the radar is slaved to the pointing of the telescope and the laser (Figure 3-18). When an aircraft is detected within a 3 degree diameter cone surrounding the laser beam, a beam block is activated to interrupt the laser transmit path, effectively cutting off the transmission of the beam (Figure 3-19). Due to FAA regulations, the insertion of the beam block must be manually acknowledged by the operator after each occurrence in order to re-enable the transmission of the laser. The radar operates in an environmentally controlled dome, as directed by a control unit located in the NGSLR shelter.

**Figure 3-18: The NGSLR shelter (left) with the LHRS tower on the right**

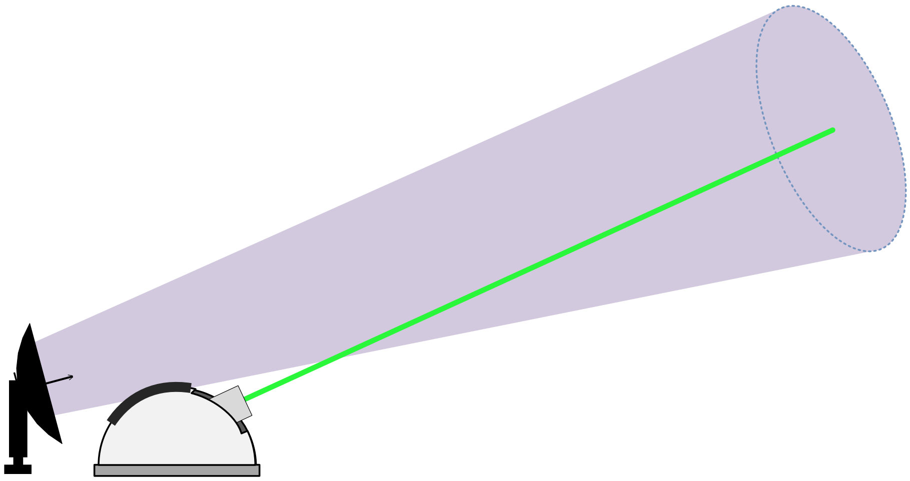


**Figure 3-19: Conceptual diagram of the cone of radar energy from the LHRS that surrounds the laser**

# Appendix

## Appendix A: Acronyms

| Acronym | Definition |
|---|---|
| AZ/EL | Azimuth/Elevation |
| CCD | Charge Coupled Device |
| CDDIS | Crustal Dynamics Data Information System |
| COTS | Commercial Off The Shelf |
| CPF | Consolidated Prediction Format |
| CRD | Consolidated Laser Ranging Data Format |
| FAA | Federal Aviation Administration |
| FWHM | Full Width at Half Maximum |
| GGAO | Goddard Geophysical and Astronomical Observatory |
| GNSS | Global Navigation Satellite System |
| GPS | Global Positioning System |
| GUI | Graphical User Interface |
| ILRS | International Laser Ranging Service |
| IO | Input / Output |
| ISA | Industry Standard Architecture |
| LAGEOS | Laser Geodynamics Satellite |
| LEO | Low Earth Orbit |
| LHRS | Laser Hazard Reduction System |
| LRO | Lunar Reconnaissance Orbiter |
| LRO-LR | Lunar Reconnaissance Orbiter - Laser Ranging |
| MCP | Micro-Channel Plate |
| MOBLAS | Mobile Satellite Laser Ranging System |
| MOTS | Modified Off The Shelf |
| MTBF | Mean Time Between Failure |
| ND | Neutral Density |
| NFS | Network File System |
| NGSLR | Next Generation Satellite Laser Ranging |
| PCI | Peripheral Component Interconnect |
| PMT | Photo Multiplier Tube |
| PRF | Pulse Repetition Frequency |
| RMS | Root Mean Square |
| SLR | Satellite Laser Ranging |
| SNR | Signal to Noise Ratio |
| TLRS | Transportable Laser Ranging System |
| USNO | United States Naval Observatory |

# Appendix B: System Specifications

## NGSLR System Specifications

| Major Systems | Vendor | Model | Description | Characteristics |
|---|---|---|---|---|
| **(1) Shelter and Dome** | | | | |
| **Shelter** | Bally Refrigerated | Custom Item | Modular Building | Modular insulated shelter |
| | | | *Dimensions (L x W x H)* | 11' 7" x 15' 5" x 8' 8" |
| | | | | |
| **Dome** | Technical Innovations | PD-10 | Astronomical Dome | 10' diameter fiberglass dome |
| | HTSI | Custom Item | Azimuth Control System | Rotational Accuracy: ~0.25° Stationary Targets / < 5° High Velocity |
| | | | *Max. Velocity* | ~15°/s |
| | | | | |
| | HTSI | Custom Item | Shutter Control System | Battery Powered / Charged via Solar Panel |
| | | | | |
| **System Power Requirements** | - | - | - | Three Phase |
| | | | | 208 VAC Phase to Phase |
| | | | | 120 VAC Phase to Neutral |
| | | | | 100 Amps |
| | | | | 50-60 Hz |
| | | | | Earth ground less than 25 ohms |
| | | | | |
| **Heating, Cooling and Ventilation** | Bard | WA191-A05 | HVAC Cooling Package | Cooling Capacity: 18,300 BTUH |
| | | | | Power requirements: (230/208 VAC; 1 Phase; 30 A) |
| | Bard | EHWA02-A05 | HVAC Heater Package | Heating Capacity: 5 kW |
| | | | | Power requirements: (230/208 VAC; 1 Phase; 30 A) |
| | | | | |
| **(2) Telescope** | | | | |
| **Telescope** | Orbital Sciences | Custom Item | | 40 cm off-axis reflector |
| | | | | |
| **Coelostat** | Xybion | Custom Item | | Unlimited rotation in azimuth, -3° to 183° in elevation |
| | | | | |
| **(3) Tracking Subsystem** | | | | |
| **Mount** | Xybion | SPS Series 2715 | Motorized Mount | Azimuth / Elevation |
| | | | *Command Type* | Velocity Feed Forward |
| | | | *Command rate* | 50 Hz (Via serial connection) |
| | | | *Range of Motion* | Unlimited rotation in azimuth, -3° to 183° in elevation |
| | | | *Maximum Velocity* | 20°/s (both axes) |
| | | | *Maximum Acceleration* | 20 °/s² |
| | | | *Tracking errors* | ~ 1 arcseconds RMS each axis |
| | | | | *Note: Xybion was bought out by Cobham Sensor Systems in 2003* |
| | | | | |
| **(4) Optical Bench** | | | | **50% Transmit/Receive Efficiency** |
| *This list only includes critical items on the optical bench, presented in the same order as on the NGSLR Optical Bench Drawings* | | | | |
| ***Operational Equipment*** | | | | |
| **1/2 Wave Plate** | CVI/Melles Griot | QWPO-532-05-1-R10 | Polarization Control | Rotation of laser polarization |
| **Thin Film Plate Polarizer** | Precision Photonics | P01405-DY | Re-direct S component | Direct S component to Beam Dump |
| **Beam Dump** | Opto-Sigma | 119-0770 | Absorb S component | Black anodized aluminum cylinder |
| **Start Diode** | Monsanto | MD-2 | Laser Fire Time | Diode detector with 0.5 ns rise time |
| **Beam Expander** | CVI | CWBX-7.0-4X-532 | Expands outgoing beam | 4X power optic |
| **Risley Prism Optics** | CVI Laser | W2-IF-1024-C-532 | Point ahead optics (2) | Transmitter point-ahead: ≤ 30 arcseconds |
| | | | *Wedge angle* | 30 arcminutes ±5 arcminutes |
| | National Aperture | MM-4M-R | *Rotary Stage (2)* | Provides rotational positioning of Risleys |
| **Etalon Optic** | CVI/Melles Griot | ET-25.4-0.25-UV-532-95 | Beam Splitting Optic | AR coated for 532 nm |
| **Telescope Focus** | | | Focus / 3X Beam Expander | Lens assembly (2 lenses), negative lens is adjustable in position |
| **Band Pass Filter** | Barr Filters | CWL:532.ONM | Filters in receive path only | 532.1 nm, 0.3 nm (FWHM) |
| **Receive ND Wheels** | Thorlabs | NDC-25C-2 | 0-2 ND Gradient Filters (2) | Each attenuates signal during ground calibration |
| **Telephoto Lens** | Special Optics | - | Iris Focus | 850 mm (EFL) lens takes collimated beam and focuses it at the iris |
| **Field of View (Iris)** | Sigma Space Corp. | Custom Item | Field of View | 11 arcseconds / 16 arcseconds / 25 arcseconds |
| **MCP Shutter** | JML Optical | - | Protects the MCP | Electromechanical shutter |

# NGSLR System Specifications

| Major Systems | Vendor | Model | Description | Characteristics |
|---|---|---|---|---|
| ***Alignment Equipment*** | | | | |
| **Wide field of view Camera** | WATEC | WAT-902H | Alignment Aid | Able to view the full telescope FOV |
| **Star Camera Beam Reducer** | Special Optics | 52-25-5XA-532/1064 | Reduces Star Field Image | Reduces beam to a size usable by the Star Camera |
| **Star Camera Shutter** | JML Optical | - | Protects the Star Camera | Electromechanical shutter |
| **Star Camera** | SBIG | ST-402ME | Focus and Alignment | CCD camera used for system alignment and focus reference |
| | | | *Description* | Low noise, high QE camera |
| | | | *Lens* | 1" focal length lens for the Star Camera |
| | | | *CCD Size* | 765 x 510 pixels |
| | | | *Sensitivity* | < 8th magnitude stars |
| | | | *Interface* | USB 2.0 |
| **Auto Collimator** | Keuffel & Esser | 71-2022 | Collimated Light Source | Used by the Star Camera as the focus reference for the system |
| | | | | |
| **(5) Laser Subsystem** | | | | |
| **SLR Laser** | Photonics Industries | RGL-532-2.5 | Used for SLR Operations | Main SLR Laser, two way ranging |
| | | | *Wavelength* | Doubled Nd:YAG (532 nm) |
| | | | *Polarization* | Horizontal (Ratio >100:1) |
| | | | *Fire Rate* | Variable (Optimized for 2 kHz) |
| | | | *Pulse Width* | ~50 ps (FWHM) |
| | | | Pulse to pulse stability | < 2% RMS |
| | | | *Maximum Pulse Energy* | ~2.8 mJ/pulse |
| | | | *Maximum Average Power @ 2 kHz* | ~5.6 W |
| | | | *Operating Pulse Energy* | 1 mJ/pulse |
| | | | *Average Operating Power@ 2 kHz* | 2 W |
| | | | *Beam Diameter* | ~2.5 mm |
| | | | *Full-Angle Far-Field Divergence* | 0.9 mrad |
| | | | *Pointing Stability* | 4.6 μrads, 7.8 μrads (x,y) |
| | | | $M^2$ | 1.47 |
| | | | | |
| **LRO Laser** | Northrop Grumman | NPL-002-QTGP-0010 | Used for LRO Operations | LRO Laser, one way ranging |
| | | | *Wavelength* | Doubled Nd:YAG (532 nm) |
| | | | *Polarization* | Linear |
| | | | *Fire Rate* | 28 Hz |
| | | | *Pulse Width* | 5.5 ns (FWHM) |
| | | | *Maximum Pulse Energy* | 50 mJ/pulse |
| | | | *Maximum Average Power @ 28 Hz* | 1.4 W |
| | | | *Operating Pulse Energy* | 40 mJ/pulse |
| | | | *Average Operating Power@ 28 Hz* | 1.12 W |
| | | | *Beam Diameter* | 9 mm |
| | | | *Full-Angle Divergence* | <1.6 mrad |
| | | | | |
| **(6) Computers/SW** | | | | |
| **VME Chassis** | GE/FANUC | - | Main Chassis | 6U Double slot Eurocard format |
| | GE/FANUC | 7851RC Card | Pseudo Operator | System automation, data handling and coordination |
| | | | *Operating System* | LynxOS |
| | | | *Processor* | Pentium IV (2.2 GHz) |
| | | | *RAM/HD* | 1 GB SDRAM/60 GB (IDE) |
| | GE/FANUC | 7851RC Card | Device Access Manager | Device management and control |
| | | | *Operating System* | LynxOS |
| | | | *Processor* | Pentium IV (2.2 GHz) |
| | | | *RAM/HD* | 1 GB SDRAM/60 GB (IDE) |
| | GE/FANUC | 7459 Card | Additional Storage(2) | Single slot CD-RW (IDE) and 80 GB hard drive (IDE) |
| | GE/FANUC | 5810 Card | PCI-VME Bus Adapter | PCI-VME bus adapter via single mode fiber |
| | GE/FANUC | 400-206 Card | Dual Port 8 MB RAM | Optional memory card for 5810 |
| | GE/FANUC | 6015 Card | Serial Port Expansion(3) | Hosts (4) serial ports per card |
| | GE/FANUC | 2510b Card | Parallel I/O | Hosts (2) 64-pin DIN connectors |
| | GE/FANUC | 4514a Card | Analog/Digital I/O | 16 channel, 12 bit analog I/O card with analog to digital converter |

# NGSLR System Specifications

| Major Systems | Vendor | Model | Description | Characteristics |
|---|---|---|---|---|
| **ICC Chassis** | Trenton Technology | TR-P2LX | Command and Control | Pentium running DOS 6.22; ISA/PCI bus |
| | | | *Processor* | Intel Pentium II (233 MHz) |
| | | | *RAM* | 64 KB (Maximum usable due to the use of DOS) |
| | | | | |
| **ANA** | Dell | Optiplex 380 | Data Processing | Fedora 12 (LINUX) (32 bit) |
| | | | *Processor* | Intel Core 2 Duo, E7600 (3.02 GHz) |
| | | | *RAM/HD* | 4GB RAM/250 GB |
| | | | | |
| **Camera** | Superlogics | SL-R4U-MB-775 | HW Interface for Operator | Windows XP SP3 |
| | | | *Processor* | Pentium IV (2.2GHz) |
| | | | *RAM/HD* | 256 MB RAM/80 GB |
| | | | | |
| **RAT** | Dell | Precision M6400n | Operator Console | Fedora 10 (LINUX), (32 bit, 4 GB RAM) |
| | | | *Processor* | Intel Core 2 Duo, P8700 (2.53GHz) |
| | | | *RAM/HD* | 8 GB RAM/160 GB |
| | | | | |
| **Languages (All systems)** | | | | Assembly Language, C, FORTRAN, Perl, Python, UNIX scripts |
| **(7) IO Chassis** | | | | |
| **IO Chassis** | HTSI | Custom Item | Multi-function Device | Controls and manages safety devices |
| | | | | |
| **(8) Time & Freq** | | | | |
| **Station Time (GPS)** | Symmetricom | XL-DC | System Time | |
| | | | *Frequency/Timing Stability* | $3 \times 10^{-12}$ over 1 day |
| | | | *Oscillator Stability* | $2 \times 10^{-6}$ (When the unit is not locked on satellites) |
| | | | *Core Receiver Frequency* | 1575.42 MHz (L1 signal) |
| | | | *Accuracy* | GPS Time ±150 ns |
| | | | *GPS Antenna Input (1)* | BNC connector |
| | | | *1 PPS Output (1)* | BNC connector |
| | | | *5 MHz Output (4)* | BNC connector |
| | | | *10 MHz Output (4)* | BNC connector |
| | | | *IRIG-B OUT (1)* | BNC connector |
| | | | *IRIG-B IN (1)* | BNC connector |
| | | | | |
| **Hydrogen Maser** | Symmetricom | MHM 2010 | Primary Frequency Source | Located remotely; Connected via fiber link |
| | | | *Accuracy* | $3.0 \times 10^{-14}$ over two hours (estimated) |
| | | | *10 MHz Output (2)* | 1 V (RMS), 50 ohm, 13 dBm |
| | | | *5 MHz Output (2)* | 1 V (RMS), 50 ohm, 13 dBm |
| | | | *1 PPS Output (1)* | Amplitude: 3 V, 2 µs wide Jitter, < 10 ps RMS |
| | | | | |
| **Cesium Frequency Standard** | Symmetricom | 4310B | Secondary Frequency Source | |
| | | | *Accuracy* | $4.5 \times 10^{-13}$ over two hours |
| | | | *Input/Outputs* | Input: 1 PPS Sync / Outputs: 1 PPS, 5 MHz, 10 MHz, 10 MHz TTL |
| | | | | |
| **Coax to Fiber Transceiver** | Symmetricom | 144-691-(1/2) | Transmits/Receives 10 Mhz | - |
| | | | | |
| **Coax to Fiber Transceiver** | Symmetricom | 144-693-(1/2) | Transmits/Receives 1 PPS | - |
| | | | | |
| **Distribution Amplifier** | Symmetricom | 6502B | Distributes 10 MHz | RF Distribution (Used for 10 MHz signal) |
| | | | *Input (2)* | BNC Input, (50 Ω), Frequency Range: 0.1 to 10 MHz |
| | | | *Outputs (10)* | BNC Output, Frequency Range: 0.1 to 10 MHz |

# NGSLR System Specifications

| Major Systems | Vendor | Model | Description | Characteristics |
|---|---|---|---|---|
| **(9) Range Receiver** | | | | |
| **Detector** | Hamamatsu | R5916U-64 | Signal Photon Detector | Microchannel Plate Photomultiplier Tube (MCP PMT) |
| | | | *Quantum Efficiency* | 25% (min), 35% (typ), 42% (as measured) |
| | | | *Rise Time* | 200 ps mm |
| | | | *Fall Time* | 700 ps |
| | | | *I.R.F (FWHM)* | 110 ps |
| | | | *Supply Voltage* | -2800 to -3000 |
| | | | | |
| **Amplifier** | Phillips Scientific | 774 | Signal Amplifier | Fast rise time amplifier |
| | | | *Wideband Performance* | 100 KHz to 1.8 GHz |
| | | | *Fixed Voltage Gain* | 50 |
| | | | *Rise time* | 180 psec |
| | | | *Insertion Delay* | Typically 1.0 nsec |
| | | | | *Note: Information from 2009 manual* |
| | | | | |
| **Discriminator** | Tennelec | TC 454 | SLR Signal Discriminator | Constant Fraction Discriminator |
| | | | *Count rate capability* | 200 MHz |
| | | | *Dynamic Range* | 1000:1 |
| | | | *Typical Walk* | ±30 ps for 100:1 Dynamic Range |
| | | | | *Note: Company now owned by Canberra; Information from 2009 manual* |
| | | | | |
| **Discriminator** | Phillips Scientific | 6915 | LRO Signal Discriminator | Constant Fraction Discriminator |
| | | | | |
| **Event Timer** | HTSI | Custom Item | Time-tag Events | |
| | | | *Resolution* | 1.5 ps |
| | | | *RMS* | 30 ps |
| | | | *Deadtime* | 50 nsec |
| | | | *Inputs [NIM] (12)* | SMA connector |
| | | | *Other Inputs* | 10 MHz, 2 kHz, 1 PPS |
| | | | | |
| **Range Gate Generator** | HTSI | Custom Item | Controls Programmable Delays | |
| | | | *Precision* | 30 ps |
| | | | *Step* | 30 ps |
| | | | *TTL Channels (4)* | SMA connector |
| | | | *NIM Channels (2)* | SMA connector |
| | | | *Inputs* | 2 kHz, 10 MHz |
| | | | | |
| **(10) Weather** | | | | |
| **Pressure/Temp./Humidity** | Paroscientific | MET4 | Measurement Accuracy | |
| | | | *Pressure* | ±0.08 hPa from 500 hPa to 1100 hPa |
| | | | *Temperature* | ±0.2 °C from -50°C to +60°C |
| | | | *Humidity* | ±2% Humidity at 25°C |
| | | | | |
| **Wind** | Belfort/Young | Model 05103 | Measurement Accuracy | |
| | | | *Wind Speed* | 0-100 m/s ±0.3 m/s |
| | | | *Wind Direction* | 360° ± 3° |
| | | | | |
| **Precipitation/Visibility** | Vaisala | Model FD12P | Measurement Accuracy | |
| | | | *Visibility Measurement*<br>*Threshold of Detection*<br>*Intensity* | 10 m - 50 km<br>0.05 mm/h (within 10 min)<br>0-999 mm/h |
| | | | | |
| **SkyCamera** | Jenoptik | VarioCAM | Specifications | Infrared (8-13 µm) Camera in NEMA 4 enclosure |
| | | | *Detector* | 320 x 240 pixel resolution |
| | | | *Image Coverage* | 1.3° of the sky per pixel, down to 10° Elevation |
| | | | *Calibration* | -50°C to 100°C (special order) |
| | | | *Interface* | Fire Wire (IEEE 1394) |
| | PerkinElmer | Custom Item | *Hemispherical Mirror* | Rhodium coating (0.050-0.060 in thick) |

# NGSLR System Specifications

| Major Systems | Vendor | Model | Description | Characteristics |
|---|---|---|---|---|
| **(11) LHRS** | | | | |
| **Laser Hazard Reduction System** | HTSI | LHRS Radar | | |
| | | | *Type* | Azimuth / Elevation |
| | | | *Azimuth Range* | Unlimited |
| | | | *Elevation Range* | -2° through 182° |
| | | | *Maximum Slew Velocity* | ~15°/s |
| | | | *Transmitter Center Frequency* | 9410 MHz ±30 MHz |
| | | | *Minimum Detection Range* | ~200 m |
| | | *Maximum system capability for target detection* | | ~42 km for a 20 $m^2$ target (calculated value) |

# Appendix C: Published Papers on NGSLR


Appleby, G., G. Kirchner, J. McGarry, T. Murphy, C. Noll, E. Pavlis, and M. Pearlman. (2010). "Current Trends in Satellite Laser Ranging." American Geophysical Union, Fall Meeting, San Francisco, California, December 13-17. Abstract: G14B-05.

Bauer, S., J. Oberst, H. Hussmann, P. Glaser, U. Schreiber, D. Mao, G. Neumann, et al. (2012). "Reduction and analysis of one-way laser ranging data from Wettzell ground station to LRO." International Technical Laser Workshop 2012, Frascati, Italy, November 5-9.

Behrend, D., J. Gipson, C. Ma, and J. McGarry. (2011). "GGAO as an Integrated Geodetic Site." European Geosciences Union: Spring Meeting, Vienna, Austria, April 3-8. Abstract: EGU2011-14126.

Clarke, C., J. Degnan, J. McGarry, and E. Pavlis. "Processing Single Photon Data for Maximum Range Accuracy." 18th International Laser Ranging Workshop, Fujiyoshida, Japan, November 11-15. Abstract: 13-0413.

Clarke, C., J. Horvath, J. McGarry, C. Noll, D. Carter, G. Neumann, and M. Torrence. (2008). "Laser Ranging (LR) Lunar Reconnaissance Orbiter (LRO) Data Flow and Scheduling." Proceedings of the 16th International Laser Ranging Workshop, Poznan, Poland, October 12-17.

Degnan, J. (2000). "An Overview of SLR2000: Engineering Progress and Potential Future Upgrades." Proceedings of the 12th International Workshop on Laser Ranging, Matera, Italy, November 13-17.

Degnan, J. (1999). "Engineering Progress on the Fully Automated, Photon-Counting SLR2000 Satellite Laser Ranging Station." Laser Radar Ranging and Atmospheric Lidar Techniques II, Europto Proceedings, Vol. 3865, Florence, Italy, September 20-21: pp. 75-82.

Degnan, J. (2002). "Optimization of the Correlation Range Receiver Parameters in SLR2000." Proceedings of the 13th International Workshop on Laser Ranging, Washington, DC, October 7-11.

Degnan, J. (2008). "Ray Matrix Analysis for the Real Time Control of Automated SLR2000 Optical Subsystems." Technical Report (Revised), Sigma Space Corporation, Lanham, MD.

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Degnan, J. (1998). "SLR2000 Project: Engineering Overview and Status." Proceedings of the 11th International Workshop on Laser Ranging, Deggendorf, Germany, September 21-25.

Degnan, J., and D. Caplan. (2006). "Performance of a Liquid Crystal Optical Gate for Suppressing Laser Backscatter In Monostatic Kilohertz SLR Systems." Proceedings of the 15th International Workshop on Laser Ranging, Canberra, Australia, October 15-20.

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