SLR2000: PROGRESS AND FUTURE APPLICATIONS

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1.0 INTRODUCTION

SLR2000 is an autonomous and eyesafe single photon-counting satellite laser ranging station with an expected single shot range precision of about one centimeter and a normal point precision better than 3 mm. The system will provide continuous 24 hour tracking coverage. Replication costs are expected to be on the order of $1M per system, and the system will be about 75% less expensive to operate and maintain than current manned systems. Computer simulations have predicted a daylight tracking capability to GPS and lower satellites. Computer and hardware simulations have demonstrated the ability of our current correlation range receiver and autotracking algorithms to extract mean signal strengths as small as 0.0001 photoelectrons per pulse from solar background noise during daylight tracking [Degnan, 2002a].

The SLR2000 system concept was first proposed in 1994 [Degnan, 1994a], but significant funding for the SLR2000 project was not provided by NASA until August 1997. The first detailed overview of the SLR2000 system concept and proposed technical approach was presented at the 1997 Fall Europto Meeting in London, UK [Degnan and McGarry, 1997]. Technical updates on system evolution and progress can be found in the proceedings of the past two SLR workshops in Deggendorf, Germany [Degnan, 1998] and Matera, Italy [Degnan, 2000]. Detailed papers on individual subsystems, algorithms, or software packages can also be found in past and present workshop proceedings. The reader is referred to these earlier system overviews and to the subsystem references therein for additional detail. The SLR2000 project also maintains a web site at the following URL address:

http://cddisa.gsfc.nasa.gov/920_3/slr2000/slr2000.html

Most SLR2000-related hardware and software publications and presentations are available online along with photos and test results for the various subsystems. The present paper will provide an overview of the current hardware approach and status. Recent progress on the SLR2000 software development is reported elsewhere in these proceedings. [McGarry et al, 2002a].

During the first year of funding, prototypes of several "enabling" components, without which the system is not feasible, were successfully developed. These include: (1) a sensitive, high speed, quadrant microchannel plate photomultiplier for simultaneous ranging and pointing correction [Degnan, 1998; Donovan et al, 2000a; McGarry et al, 2002b]; (2) oscillator-only [Degnan and Zayhowski, 1998] and oscillator/amplifier [Isyanova et al, 2002] versions of a microchip-laser based transmitter; (3) a "smart" meteorological station which includes an upgraded all-sky cloud sensor [Mallama et al, 2002]; (4) a multi-kHz rate range gate generator [Degnan, 1998]; and (5) a multi- kHz rate, 1 mm resolution event timer [Degnan, 1998]. Once the key specifications on these advanced components were largely met and system feasibility had therefore been established, attention then turned to the detailed engineering design and procurement of more conventional elements of the system such as the shelter and protective dome, arcsecond precision tracking mount, telescope, and optical transceiver. The principal challenge during this phase was to choose reliable but low cost approaches to meeting our technical requirements and goals.

As of this writing, prototypes of the essential SLR2000 components and subsystems have been developed, successfully tested at the subsystem level, and integrated into the prototype system. Field alignment and testing has begun.

2.0 SUBSYSTEM OVERVIEWS

2.1 Environmental Shelter and Dome

The SLR2000 system is protected by the environmental shelter and azimuth tracking dome shown in Figure 1. The facility sits on a stable concrete pad. The walls, roof, and floor of the shelter are assembled from prefabricated sheets manufactured by the Bally Corporation and are typically used in building refrigeration boxes. Each wall panel is 10 cm thick and consists of thermally insulating material sandwiched between two aluminum outer surfaces, which can be painted or otherwise treated to withstand harsh environments. Besides their excellent insulation and durability, the panels provide a relatively dust free environment and are easy to assemble onsite via interlocking connectors. The 3 meter diameter fiberglass dome, manufactured by Technology Innovations Inc., has a custom motorized open slit (shutter) and azimuth drive designed by Honeywell Technology Solutions Inc. (HTSI). Both are under computer control and the dome azimuth drive is slaved to the tracking mount azimuth.

The telescope and tracking mount are housed within an open dome during operations and hence are exposed to the ambient atmosphere. An open dome was chosen over a closed dome in order to avoid fogging and condensation on the dome window and possible increases in beam divergence due to lensing caused by thermal gradients between the exterior and interior faces of the nominally flat window. Protection of the dome interior from the elements is accomplished by temperature, wind and precipitation sensors tied into the dome activators. The electronics room is thermally isolated from the open dome area by a removable ceiling is and maintained at a nominal 23^{o}C by a dual heater/air conditioning system for low operating loads and redundancy. This stabilizes the temperature of critical elements in the optical transceiver and timing electronics and provides a comfortable workplace for visiting maintenance personnel.

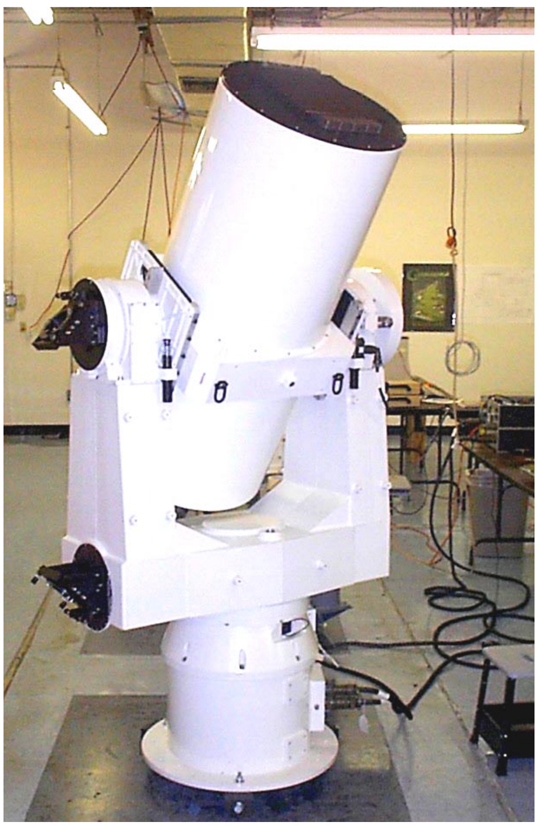
Outside ambient air and heated air from the electronics room are dehumidified and mixed to maintain the telescope slightly above external ambient when the dome is closed in order to minimize thermal gradients and prevent water condensation upon opening the dome. Inexpensive security devices automatically detect, record, and report threats to system security via Internet and/or recorded telephone messages. These include motion and intrusion sensors and surveillance cameras for detecting and reporting unauthorized personnel in the vicinity, thermal sensors for detecting heat pump failure, power/voltage monitors, etc. [Donovan et al, 2000]. Key security components, such as the computer and selected sensors, are protected by UPS, and the safe default mode for key subsystems will be "Power Off" in the event of a power failure.

Figure 1: Exterior view of the prototype SLR2000 system with 3 meter tracking dome at the Goddard Space Flight Center. The telescope can be seen in the dome slit.

2.2 Telescope and Precision Tracking Mount

The prototype arcsecond precision tracking mount was built by Xybion Corporation in Clearwater, Florida. During factory acceptance testing in November 2001, a mass simulator was used in place of the actual telescope. These tests were repeated with the simulator at GSFC following delivery of the mount in January 2002. A final set of tests was performed with the actual telescope in February 2002 with similar results. A wide variety of satellite passes were simulated during testing, and the command-vs-actual angles were recorded and plotted. Except in rare cases of high angular velocity near PCA, the system typically met the one arcsecond requirement as in Figure 2. A more extensivedescription of the test results can be found in a companion article by Patterson and McGarry in these proceedings.

The telescope and the optical path in the yoke arm of the mount are independently purged with clean dry air and sealed via O-rings to keep the path free of contaminants and atmospheric water vapor. Inflatable bladders attached to the sealed volumes compensate for internal pressure changes over the large operating temperature range. Condensation control at the exit window of the telescope and at the telescope/yoke interface windows is accomplished via temperature and humidity sensors plus heater elements, which raise the affected optical components a few degrees above ambient. Electrical connections for the sensors and heaters are provided via slip rings.



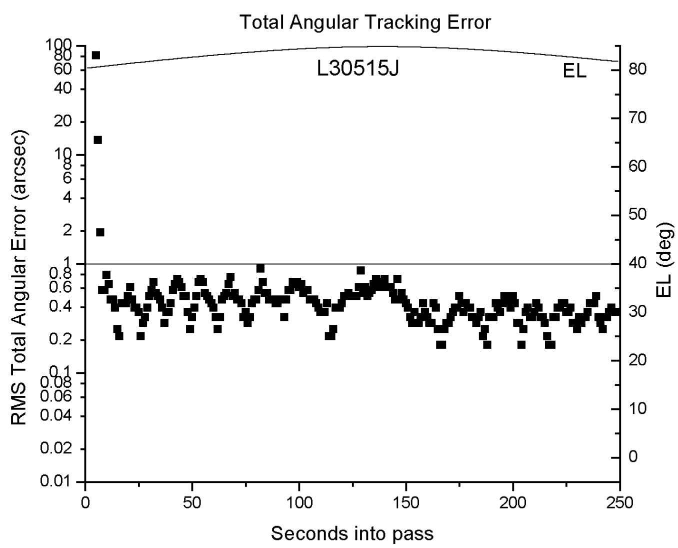


Figure 2: Prototype SLR2000 tracking mount integrated with telescope mass simulator during factory testing and tracking performance under a simulated moderate elevation LAGEOS pass near PCA. The horizontal line in the graph corresponds to a one arcsecond tracking error.

The prototype telescope uses a custom-designed off-axis all reflective telescope designed to operate over a wide temperature range (20 to 120^{o} F). An off-axis design was chosen to permit the transmitter and receiver to share the full telescope aperture and to avoid optical “shadowing” of the satellite in the far field that might be caused by a central obscuration [Klein and Degnan, 1974], as in more conventional Cassegrain designs. The telescope incorporates various design elements (invar rods, low thermal expansion Zerodur optical substrates, etc.) to passively maintain system alignment and focus over a wide temperature range. In addition, active control of the focus is provided within the optical transceiver. The latter includes a computer-translatable lens and CCD camera, which can check and correct the focus periodically by imaging stars and minimizing their spatial extent in the focal plane. The CCD camera is also used to perform periodic star calibrations to compensate for mechanical sag in the mount or telescope via a mathematical mount model.

2.3 Optical Transceiver

An early goal of the SLR2000 transceiver was to develop a totally passive technique by which the full aperture of the primary could be shared by the transmitted and received beams with negligible optical loss. This proved to be an elusive goal, and several passive approaches were examined and abandoned for various technical reasons. However, we believe we have now developed a novel, totally passive (i.e. has no electronic or mechanical parts), transmit/receive concept to accomplish this task. This new "switch" concept, shown in Figure 3, allows the transmitter and receiver to share the entire primary aperture, operates at arbitrarily high laser repetition rates, protects the transmitter from back reflections in the forward optics, and has low loss in either the transmit or receive mode even when interrogating depolarizing target satellites such as LAGEOS 1 and 2, which use uncoated Total Internal Reflection (TIR) retroreflector prisms.

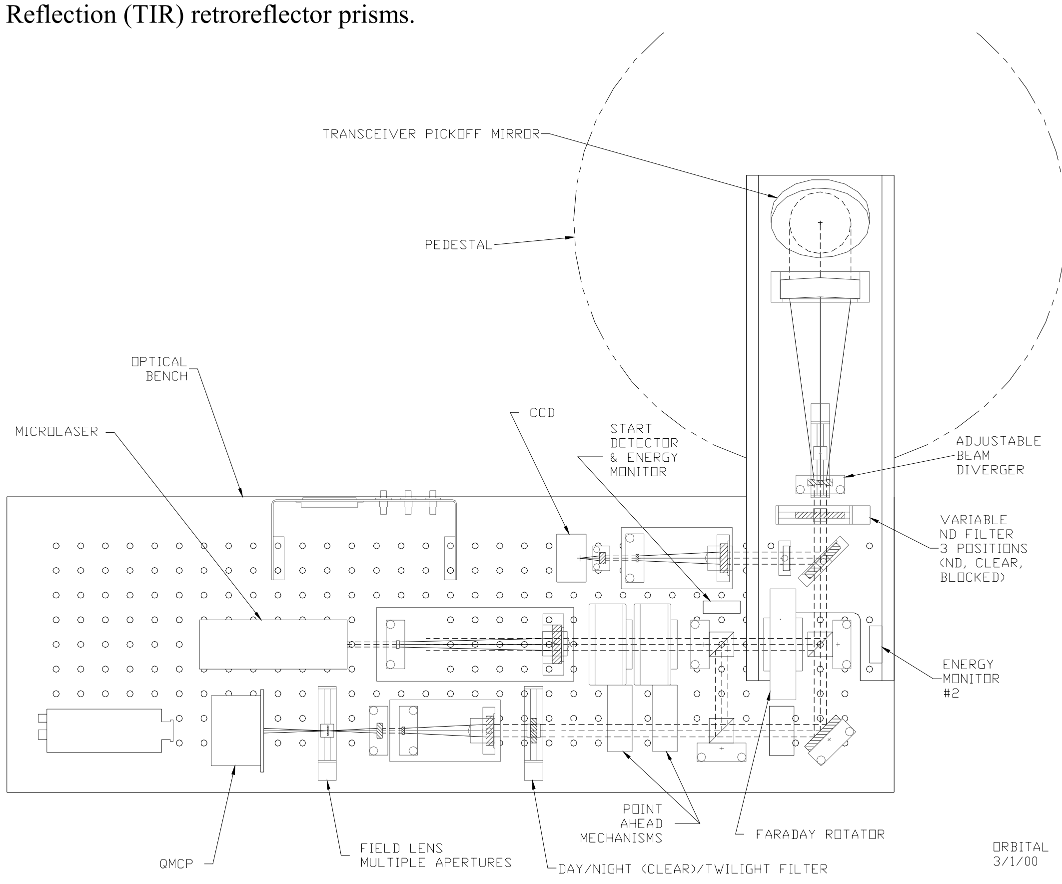


Figure 3: SLR2000 optical transceiver design.

On the transmitter side, the microlaser beam is expanded by a ten power telescope and passes through two serial, stepper-motor driven Risley prisms which steer the narrow laser beam slightly off the receiver axis to allow for point-ahead compensation on the satellite. Analysis has shown that the transmit and receive fields-of-view can be offset by as much as 11 arcseconds (about one transmitter beam full-width) for the current constellation of satellites. The p-polarized beam passes through the input polarizer and is rotated to s-polarization by the Faraday Rotator/ half wave plate combination so that pulses reflect off the second (exit) polarizer into the telescope path. The beam divergence can be adjusted, based on satellite altitude, by a computer-controlled diverging lens in the intermediate telescope. The transmit beam can also be attenuated during ground target calibration via a computer-controlled Neutral density (ND) filter (which also attenuates the receive beam by the same amount).

On the receiver side, the exit polarizer splits the received photons into two channels based on polarization. The p-polarized photons pass through the exit polarizer, reflect off the 45 degree mirror, pass through a glass compensator block (which equalizes the time delay in the s and receiver channels), and then pass through the final polarizing cube into the remainder of the receiver chain, which includes a narrowband filter, variable spatial filter, and quadrant detector. After reflecting off the exit polarizer, the received s-polarized photons retrace the transmit path, but, due to the non-reciprocal behavior of the Faraday Isolator and half-wave plate combination, they retain their s-polarization on the return transit. As a result, they are reflected off the entrance polarizer and are recombined with the p-polarized photons at the final (third) polarizing cube.

A CCD camera in a third leg of the transceiver aids in performing star calibrations and mechanical mount modeling in addition to maintaining system focus over a wide temperature range using the computer controlled diverging lens.

To enhance and ensure the alignment stability of the overall optical system, the transceiver optical bench is rigidly attached to the stainless steel riser, which also supports the tracking mount and telescope, as in Figure 4.

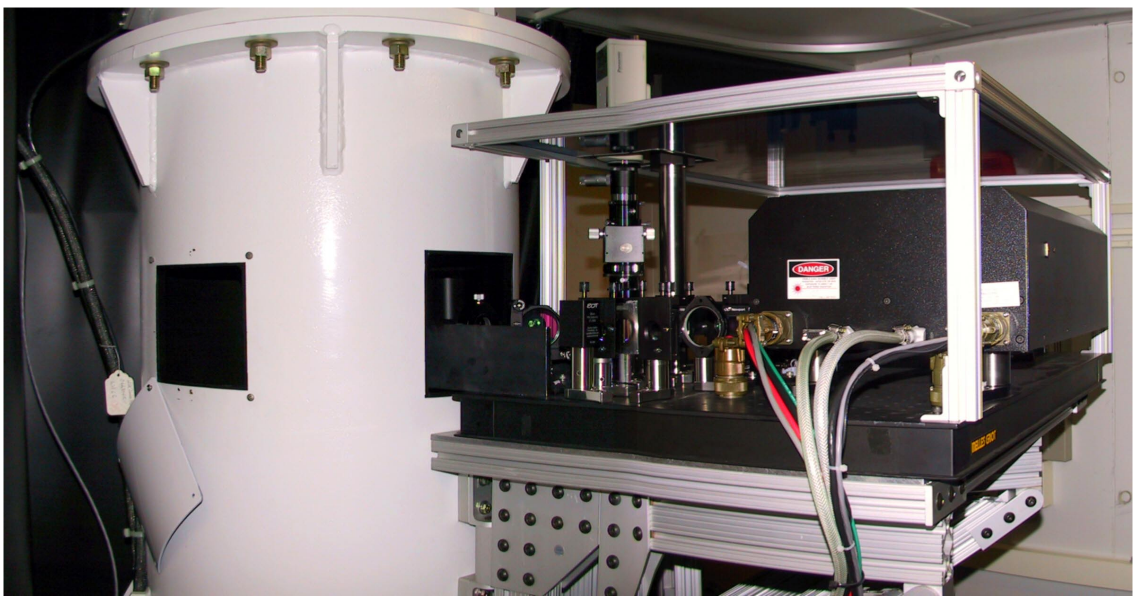


Figure 4: Transceiver optical bench attached to the stainless steel riser assembly. The water-cooled “brassboard” transmitter is mounted on the right side of the bench in the photo whereas the receiver optical elements are mounted on the left of the bench.

2.4 Microlaser Transmitter

The frequency-doubled microlaser transmitter, operating in the visible at a wavelength of 532 nm and a repetition rate of 2 kHz, must produce approximately 130 μJ of energy at the telescope aperture. This is the maximum energy that can be passed through the 40 cm transmit/receive telescope at this repetition rate without exceeding the U.S. eye safety limit for visible Q-switched lasers. Because of anticipated losses in the optical train, the actual laser must produce about 220 μJ of green light at the source. Our pulsewidth goal of 150 picoseconds or less at 532 nm was driven by an attempt to roughly match the pulsewidth of the modelocked MOBLAS transmitter and quadrant photomultiplier. At the Matera workshop, we reported on the characteristics of a prototype water-cooled microlaser oscillator/amplifier system, which came very close to meeting our technical specifications [Degnan, 2000] and is pictured in Figure 4. We have continued our transmitter development to further increase the output energy, reduce the pulsewidth, and replace water-cooling with an air-cooled system. The status of that development is reported elsewhere in these proceedings [Isyanova et al, 2002]

3.0 FURTHER UPGRADES AND APPLICATIONS

Beyond the development of the basic SLR2000, we have been investigating potential future upgrades and applications of the system. At the Matera workshop [Degnan, 2000], we discussed the possibility of taking advantage of bias-free photon-counting range measurements and kilohertz laser fire rates and comparing the normal points at two wavelengths to compute the atmospheric refraction delay. This upgrade would require the addition of a second wavelength channel to the receiver.

The feasibility of utilizing SLR2000 as an Earth station in a two way laser transponder link for precise interplanetary ranging and time transfer was also developed over the last three workshops. Detailed mathematical models and operational scenarios have been developed and applied to a two-way Earth-Mars link in a recent Journal article [Degnan, 2002]. Since the Data Formats and Procedures Working Group of the ILRS is already developing prediction formats for supporting future transponders, the principal modification would be to extend the range of the transmitter point ahead capability in SLR2000 from the current 11 arcseconds to about 45 arcseconds.

NASA headquarters has recently directed GSFC to investigate the feasibility of using SLR2000 as the ground terminal in a space-to-ground laser communications link while simultaneously ranging to retroreflectors onboard the spacecraft. The motivation for initiating this activity comes from an emerging suite of new Earth sensors which require substantial information bandwidths for high speed data transfer to the ground. These include hyperspectral imagers, Interferometric Synthetic Aperture Radars (In-SAR), and 3D imaging lidars. SLR2000 is already designed to perform the majority of field operations needed for an automated laser communications station and has a sufficiently large telescope to accommodate high bandwidths transmitted from Earth orbit. For example, it automatically assesses local weather and cloud cover conditions and performs necessary system and personnel health and safety functions. In addition, SLR tracking provides a highly accurate orbit for rapid spacecraft acquisition, independent confirmation of target satellite acquisition via the retroreflector returns, and a visible beacon for the spaceborne communications terminal to lock onto. A simple wavelength splitter within the SLR2000 optical transceiver would divert the incoming communications photons to a separate optical receiver. It is hoped that such a diversification of SLR2000 functions would attract new users and additional funding for a global multifunction network.

The development schedule as been impacted by is a fixed level of funding available each year to support SLR2000 development and unforeseen delays in the delivery and integration of the prototype tracking mount and telescope.

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