AN OVERVIEW OF SLR2000 ENGINEERING PROGRESS AND POTENTIAL FUTURE UPGRADES

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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.

The SLR2000 system concept was first proposed in 1994 [Degnan, 1994], but significant funding for the SLR2000 project was not provided by NASA until August 1997. The first detailed overview of the SLR2000 system and technical approach was presented at the 1997 Fall Europto Meeting in London, UK [Degnan and McGarry, 1997], updated at the 11th International Workshop on Laser Ranging in Deggendorf, Germany [Degnan, 1998] and once again at the 1999 Fall Europto meeting in Florence, Italy [Degnan, 1999]. The reader is referred to these earlier publications 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 are available online along with photos of the various subsystems. The present paper will concentrate on hardware progress made since the 1999 Florence meeting. Although significant progress was also made on the system software, this will not be addressed in the present article.

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 [Degnan, 1998; Donovan et al, 2000a]; (2) a moderate power microlaser transmitter [Degnan and Zayhowski, 1998]; (3) a "smart" meteorological station [Mallama et al, 2000]; (4) a high speed range gate generator [Degnan, 1998]; and (5) a high speed, high 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.

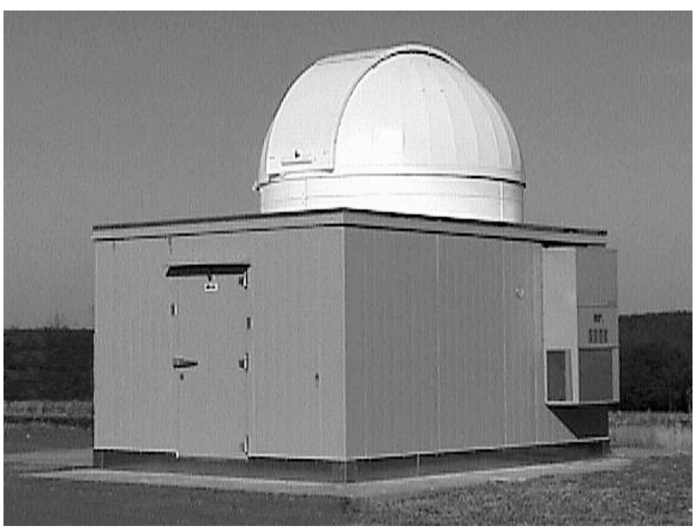
As of this writing, prototypes of all SLR2000 components and subsystems have either been developed or are well into the detailed design/ build phase. The primary driver on schedule is a fixed level of funding available each year to support SLR2000 development. During the past year, we have largely completed the design and fabrication of the three most expensive subsystems - the shelter, the tracking mount, and the telescope. The optical transceiver design is essentially complete, but fabrication and integration were postponed to the current year due to insufficient funds. Full system field tests are expected to begin in the last half of 2001.

2.0 RECENT HARDWARE DEVELOPMENTS

2.1 Environmental Shelter and Dome

The SLR2000 system is protected by the environmental shelter and azimuth tracking dome shown in Figure 1a. 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 motorized open slit (shutter) and azimuth drive. Both are under computer control and the dome azimuth drive is slaved to the tracking mount azimuth. 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 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, 2000b]. 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.



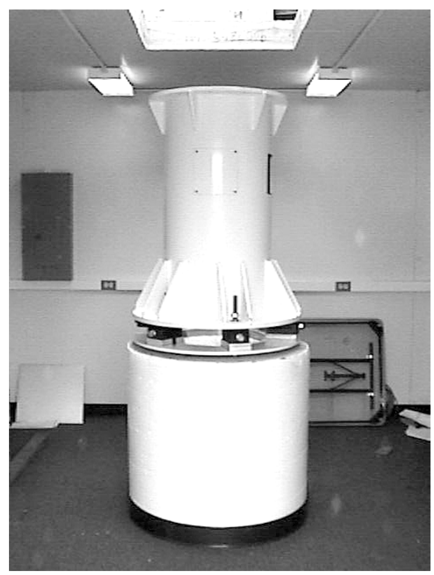


Figure 1: (a) Exterior view of the prototype SLR2000 shelter with 3 meter tracking dome at the Goddard Space Flight Center; (b) interior view of the shelter showing the stainless steel riser (with three adjustable feet for leveling) on top of the cylindrical concrete monument.

2.2 Telescope and Precision Tracking Mount

The contract for the arcsecond precision tracking mount was awarded to Xybion Corporation in Clearwater, Florida, in late August 1999 following a competitive bid. Mount fabrication was completed in June 2000. Figure 2a shows the mount integrated with the telescope mass simulator during factory testing, which is presently ongoing to meet the stringent tracking specifications of $\pm$ one arcsecond. The telescope and tracking mount are housed within an open dome during operations and hence are exposed to the ambient atmosphere. The tracking mount is rigidly attached to the top of the stainless steel riser in Figure 1b.

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.

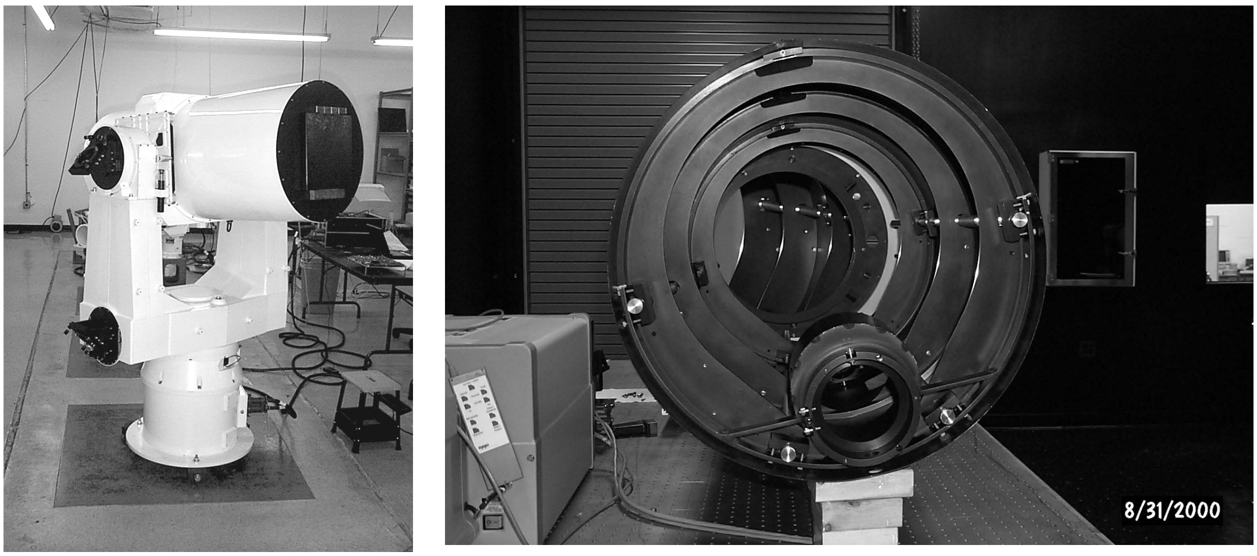


Figure 2: (a) Prototype SLR2000 tracking mount integrated with telescope mass simulator during factory testing; (b) SLR2000 prototype telescope during final assembly.

The prototype telescope, shown during final assembly in Figure 2b, uses a custom-designed off-axis all reflective telescope designed to operate over a wide temperature range (20 to 120^{o} F). The 40 cm diameter Zerodur primary can be seen at the rear of the photo with the secondary mirror mount protruding from the lower front of the assembly, just right of center. Also visible in the photo are the ends of four stabilizing invar rods. An off-axis design was chosen to permit the transmitter and receiver to share the full telescope aperture and to avoid optical problems caused by a central obscuration, 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. 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, 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.

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 beam slightly off the receiver axis to account for point-ahead on the satellite. 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. 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 compensator block (which matches the s-channel time delay), 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.

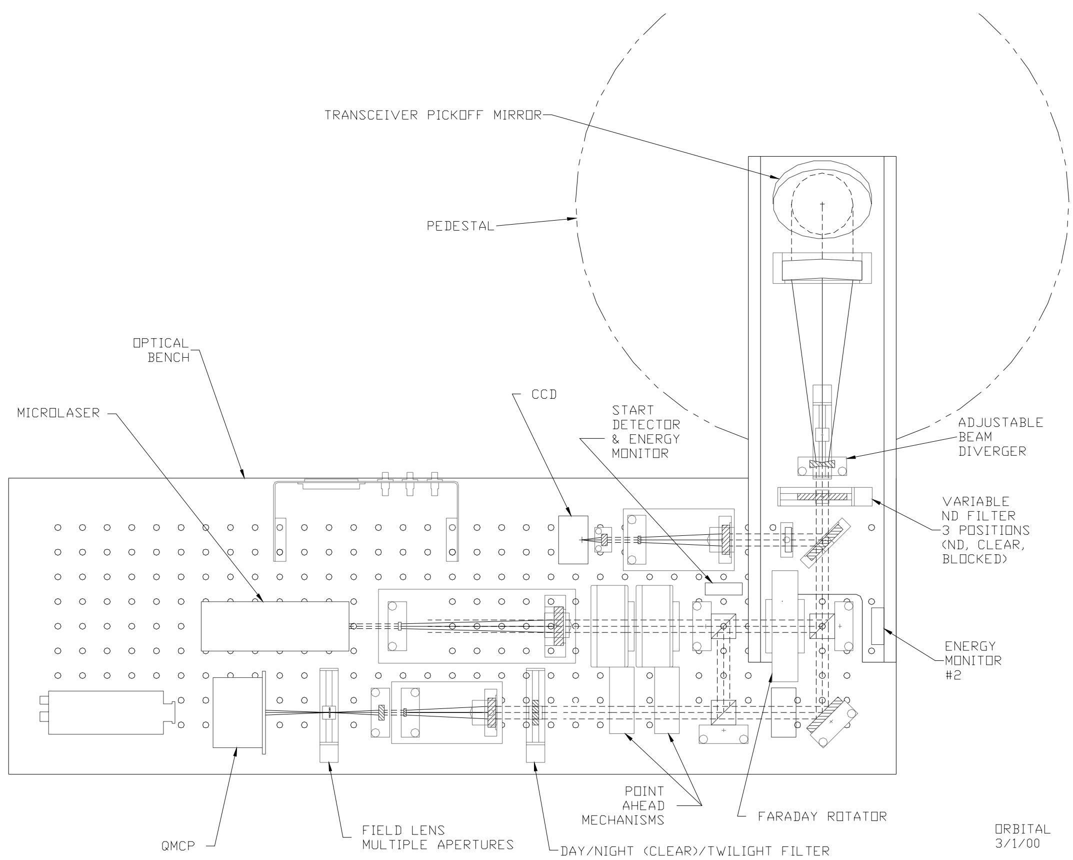


Figure 3: SLR2000 optical transceiver design.

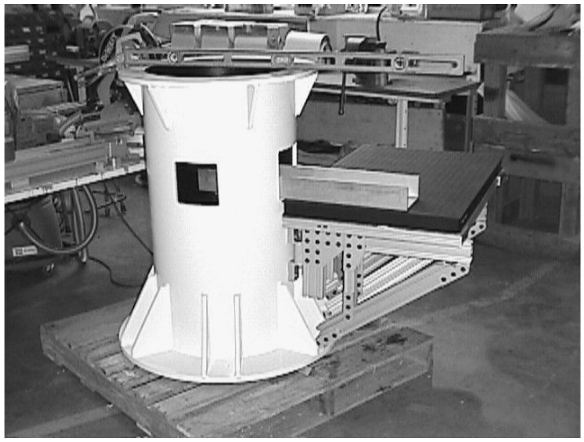


Figure 4: Transceiver optical bench attached to the riser assembly.

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 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. The pulse width goal of 150 picoseconds or less at 532 nm is driven by an attempt to match the pulsewidth of our current modelocked MOBLAS transmitter.

A NASA-funded program at MIT Lincoln Laboratories produced a diode-pumped high power Nd: YAG microchip oscillator [Degnan and Zayhowski, 1998], but it was later determined that this approach lacked flexibility in meeting conflicting microlaser specifications on pulsewidth, energy and repetition rate. Thus, we have reverted to the baseline design of a diode-pumped, passively Q-switched, Nd:YAG microchip laser oscillator followed by a passive, CW diode-pumped multipass amplifier. A prototype transmitter was recently developed through a Phase II Small Business Innovative Research (SBIR) program at Q-peak Inc. and was delivered to NASA in August 2000 [Isyanova et al, 2000]. The prototype Nd:YAG microchip oscillator is end-pumped by a quasi-CW 1 Watt fiber-coupled diode operating at 808 nm and produces 3.2 μJ, 400 psec pulses at a 2 kHz rate. The oscillator pulse then makes six passes through a passive Nd:YVO_4 amplifier, transversely-pumped from opposite sides of the slab by two linear CW diode arrays. The amplifier increases the pulse energy to 335 μJ. A Type I LBO doubling crystal in a temperature-stabilized oven produces 400 mW (200 μJ @ 2 kHz) of average laser power at 532 nm for a conversion efficiency of 60%. The final output beam is highly gaussian with an M^2 value of 1.17 and 1.14 in the horizontal and vertical planes respectively.

3.0 FEASIBILITY OF TWO COLOR RANGING IN PHOTON-COUNTING MODE

Beyond the development of the basic SLR2000, we are looking at a potential two-color upgrade as well as adapting the SLR2000 system for interplanetary ranging through the use of transponders. The transponder application is discussed elsewhere [Degnan, 2000a; Degnan, 2000b].

In order to achieve 3 mm absolute range accuracy using two color ranging at the second and third harmonics of the Nd:YAG laser (532 and 355 nm), one must perform differential timing at the 2 psec level. Even with averaging, high SNR systems equipped with conventional PMT/discriminator or SPAD configurations and operating at low laser fire rates have not, and probably will not, achieve the necessary temporal resolution within a typical normal point. Streak cameras are complex and expensive; they typically require the light to be focused into a slit and optical delay lines for pre-triggering of the camera. Furthermore, single shot paired waveforms from the usual multicube target array tend to be highly uncorrelated at the two wavelengths (e.g, exhibiting different numbers of peaks, etc.), making the Differential Time Of Flight (DTOF) difficult to measure [Zagwodzki et al, TBD]. This is true even for spherical geodetic targets such as Starlette and LAGEOS. Stefan Reipl at Wettzell [Reipl, TBD] has attempted to overcome this problem by averaging over several streak camera waveforms, but the amount of averaging possible is limited by the low fire rate in typical high SNR systems.

At the outset of the SLR2000 program, we did not believe that a two color version was possible. High repetition rate, photon-counting instruments such as SLR2000 cannot hope to perform two color measurements on a single shot since the single photon returns can come from anywhere within the return waveforms for the different wavelengths, resulting in poor temporal resolution in the DTOF (especially for multicube targets). In 1992, however, the Hearstmonceux SLR group observed that, following the fit of single photon range data to multiple orbits, the distribution of range residuals had high correlation with the expected satellite signature, which is a single-peaked function for the spherical geodetic satellites [Appleby, 1992]. This was illustrated for a variety of satellites using low repetition rate, photon-counting receivers and multiple satellite passes. It was later demonstrated theoretically that, in the limit of low mean signal strength (<< 1 pe) and photon counting, the distribution of range residuals should closely follow the satellite signature convolved with the laser pulsewidth which, for laser pulsewidths short relative to the target impulse response, is essentially the satellite signature [Degnan, 1994].

Since the atmosphere changes from pass to pass, one would like to collect a large number of two-color, single photon measurements within a single normal point on a single pass. The SLR2000 system, firing at a rate of 2 kHz, transmits 240,000 pulses within a single two minute LAGEOS normal point. Depending on satellite elevation angle and atmospheric conditions, several thousand to several tens of thousands of single photon range measurements are expected within each LAGEOS normal point. Higher numbers of measurements per normal point can be obtained from lower satellites. The average satellite impulse response should be nearly identical at the two wavelengths except possibly for a very small systematic shift in the reflection center due to slightly different indices of refraction in the retroreflectors. Thus, in principle, the centroid of the distributions at each wavelength can then be accurately estimated within picoseconds and a DTOF computed.

4.0 CONCLUDING REMARKS

By September 2001, we hope to finalize the SLR2000 subsystem and software development, complete the assembly and integration of the prototype SLR2000 system, and begin field testing. Software status is reviewed elsewhere in these proceedings [McGarry et al, 2000]. From a hardware perspective, we will be concentrating on the fabrication and integration of the remaining subsystems (optical transceiver, security system) and further upgrading the transmitter and meteorological station. This will be followed by a period of extensive field testing, with replication of a dozen or more systems beginning approximately October 2002.

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