

## **Progress on the Multifunctional Range Receiver for SGSLR**

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### **1. Introduction**

NASA's Space Geodesy Satellite Laser Ranging System (SGSLR) is a single photon sensitive system operating at a laser fire rate of 2 kHz designed to replace the current network of conventional, multiphoton, low repetition rate (<20 Hz) SLR stations, such as the MOBILE LASER (MOBLAS) and Transportable Laser Ranging Systems (TLRS) and associated University-operated stations in Texas and Hawaii. With a more than two order of magnitude increase in laser repetition rate, the time required to generate millimeter-accuracy normal points is greatly reduced and the ability to track a few dozen active satellites is greatly enhanced. However, with pulse energies on the order of a mJ, the expected satellite return rate is highly dependent on satellite range, atmospheric attenuation at low satellite elevation angles, as well as system parameters such as pulse energy, beam divergence, and telescope pointing error.

In this paper, we describe a multifunctional, multichannel range receiver which simultaneously:

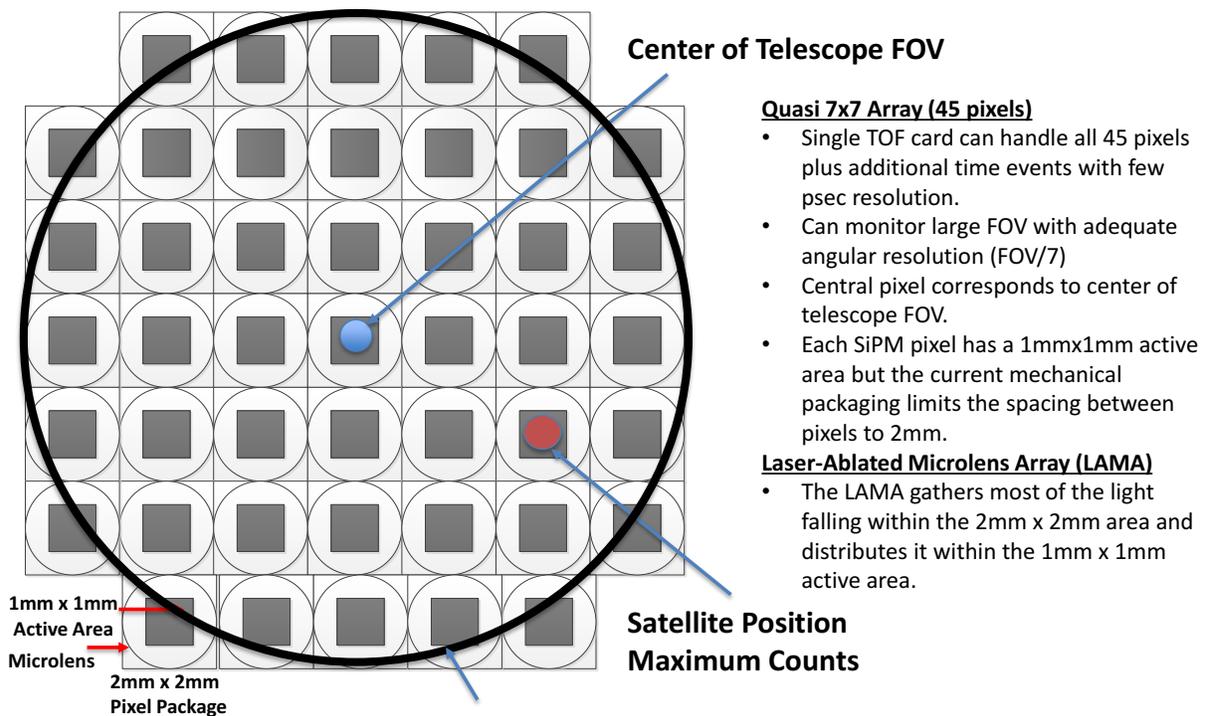
1. Serves as an accurate and self-calibrating Event Timer (ET) for photon start/stop events and other timing signals;
2. Provides a high resolution measurement of the satellite angular position relative to the telescope optical axis which is then used to correct for telescope pointing error;
3. Acts as an Electronic Spatial Filter which eliminates the vast majority of noise counts and therefore greatly reduces potential noise-induced bias in the range measurement for weak links.
4. Can utilize Segmented Anode Microchannel PhotoMultiplier Tubes (MCP/PMTs) or arrays of Silicon PhotoMultiplier (SiPMs) as the detector.

### **2. Technical Approach**

The telescope Field-of-View (FOV) is imaged onto a single photon sensitive array detector having a rapid recovery time per pixel to prevent a solar photon or dark noise count from disabling the detector prior to a satellite return. Detector options include a segmented anode Microchannel Plate PhotoMultiplier Tube (MCP/PMT) or a Silicon Photomultiplier (SiPM). The latter was chosen for SGSLR because of its relatively low cost and short acquisition time, but current packaging of individual SiPM pixels measure 2mm on a side. However, since the active area is only 1mm x 1mm, a Laser Ablated Microlens Array (LAMA) must be placed in front of the detector to capture almost 100% of the pixel FOV and focus it into the active area. The

timing receiver time tags and stores all of the counts (signal plus noise) and transfers the collected data to the system computer for post-processing.

The expected noise count rates within each pixel are quite small due to a typical sub-microsecond range gate and an extremely small pixel FOV. Since the satellite is a star-like point source in the receiver FOV, the returns over a short integration period add to the count in the single pixel in which they typically fall (although in rare instances they may temporarily fall at the boundaries of 2 or 4 pixels thereby splitting the signal contribution). In addition, the satellite returns are temporally correlated with each other satellite returns, thereby allowing the receiver to statistically determine the pixel (or pixels) containing the satellite returns within a short period of time (red circle in Figure 1). The position of the signal pixel within the array in turn provides the angular correction which centers the telescope FOV on the satellite (blue circle in Figure 1).



**Figure 1: The SiPM array used in the SGSLR receiver consists of 45 pixels which share the total solar and dark noise counts while typically only one pixel records the satellite returns. The 1 mm x 1mm gray squares within the 2mm x 2 mm white squares represent the active area within each pixel. To avoid a 75% loss in signal count, a Laser-Ablated Microlens Array (LAMA), represented by the circles and the areas between them, captures almost all of the incident photons within a 2mm x 2mm white square and directs them to the 1mm x 1mm gray active area.**

In order to best utilize all of the pixels in the acquisition and tracking phases of the satellite, the receiver FOV should match the transmit beam divergence. This ensures that, if the satellite is illuminated by the laser beam, some returns will be recorded as well as the satellite's angular position within the receiver FOV. Transmitter divergence is controlled by varying the curvature

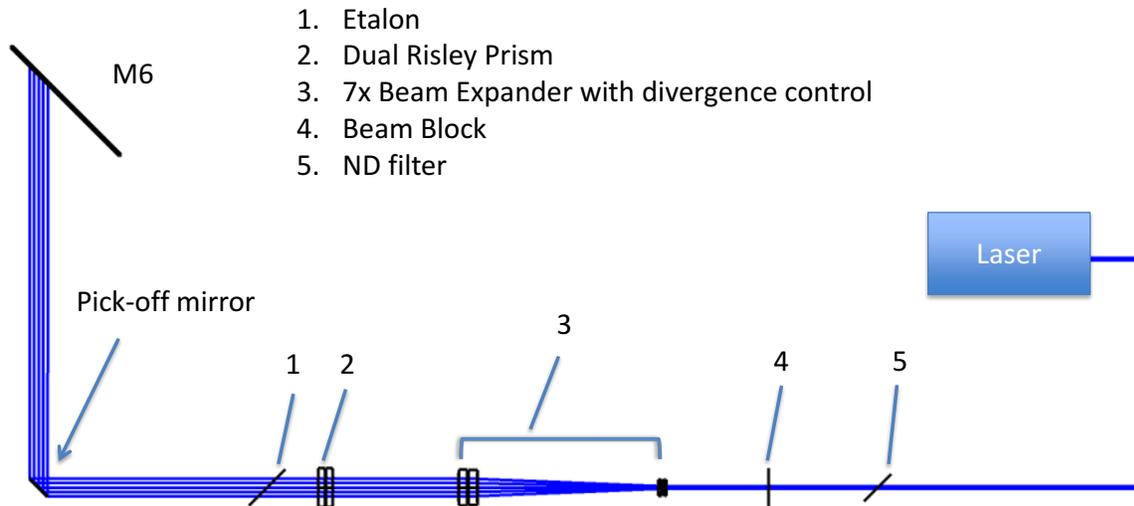
of the laser phase front using a variable beam expander in the transmit path as in Figure 2. In addition, SGSLR has a software controlled Dual Risley Prism (DRP) device which provides a transmitter point-ahead such that, when the telescope is pointed at where the satellite was one light transit time ago, the DRP points the transmit beam to where the satellite will be one light transit time later. This places the peak of the Gaussian transmit beam on the satellite, thereby maximizing the satellite illumination and received signal rates.

Comprehensive SGSLR link analyses [1] suggest that a full beam divergence of 28 arcsec is adequate to maintain a high rate of return for LAGEOS and LEO satellites without imposing heavy demands on the pointing accuracy requirements of either the receive telescope or transmitter DRP assembly. For GNSS and higher HEO satellites, a full beam divergence of 14 arcsec would be recommended for most of the pass. In all cases, heavy atmospheric transmission losses at low elevation angles ( $<20^\circ$ ) or under less than optimum conditions might prompt the use of a narrower divergence angle to increase return rates as monitored by the system computer. Thus, if the receiver FOV (defined by the large black circle in Figure 1) were to match the transmitter divergence (defined as the angular distance between the  $1/e^2$  intensity points of the Gaussian spatial profile and containing 87% of the total laser energy), the angular resolution of the individual pixels would be 4 arcsec and 2 arcsec for the low and high satellites respectively.

The T/R angular offset is a maximum when tracking at station zenith and a minimum when tracking at the lowest elevation angle ( $10^\circ$ ). The maximum and minimum T/R angular offsets are listed for representative satellites in Table 1, where we note that the T/R half FOV in Table 1 is larger than the Max/Min T/R offset in all cases. Thus, even with an absent or inexact T/R offset correction, the satellite image would fall well within the 2 sigma radius of the Gaussian transmit beam, which contains 87% of the total laser energy.

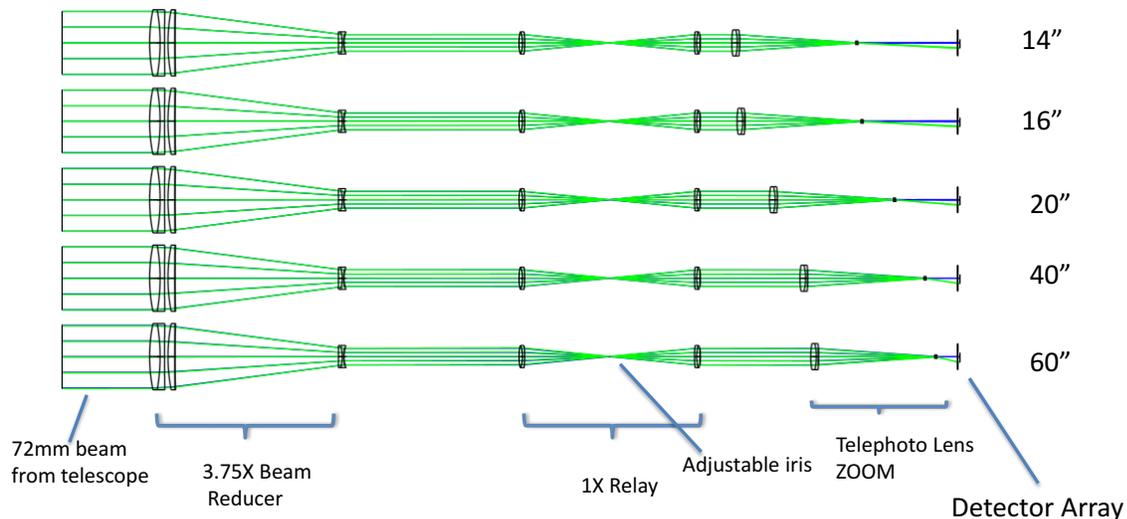
Satellite	Altitude, km	Max/Min T/R Offset (arcsec)	T/R Half FOV (arcsec)
Starlette	950	10.13 to 5.22	14
LAGEOS	6000	7.78 to 6.70	14
GNSS	20,000	5.33 to 5.18	7
GEO	35,790	4.21 to 4.16	TBD

**Table 1: The maximum and minimum offsets between the transmitter and receiver FOVs for several representative satellites at different orbital altitudes are determined by the angular velocity of the satellite as seen by the station and the two-way pulse time-of-flight (TOF). Note that the half FOV in the final column is greater than the offsets in column 3, implying that the satellite will be illuminated by the laser even if the transmitter point ahead is in error or not applied at all.**



**Figure 2: The SGSLR transmitter path includes a variable beam expander (3) which controls the curvature of the transmitter phase front and defines the final beam divergence without significantly modifying the beam diameter. A Dual Risley Prism (DRP) assembly (2) provides a point ahead correction designed to place the peak of the Gaussian spatial profile on the satellite. An off-axis injection mirror directs the beam through the annulus of the receive telescope.**

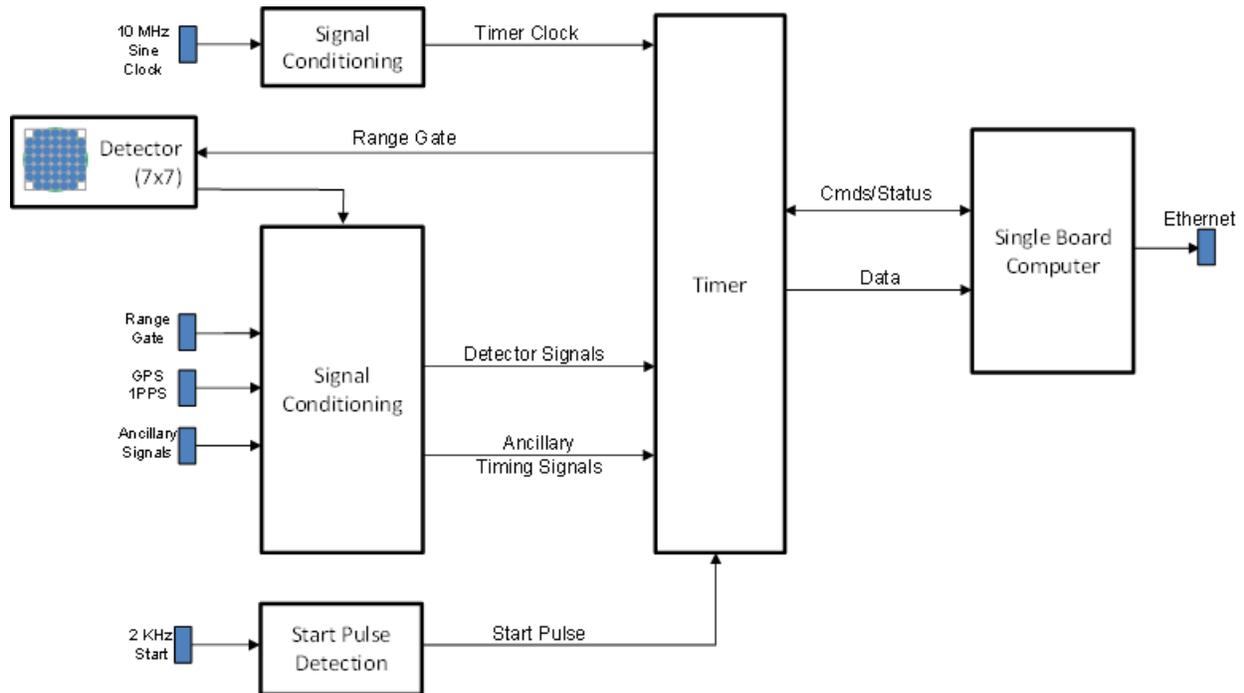
Figure 3 provides a block diagram of the proposed SGSLR receive path which includes a variable telephoto lens which allows the receiver FOV to be matched to the chosen laser beam divergence. The focused spot is expected to be slightly less than 1 mm, the dimension of the active area within the pixel.



**Figure 3: Proposed SGSLR receive path which includes a motorized adjustable field stop(iris) and telephoto lens which allows the receiver FOV to be matched to the transmitted laser divergence over a wide range (14 to 60 arcsec), thereby ensuring that laser returns from the satellite will be seen by the detector array.**

If the DRP and diffraction limited telescope are both pointing properly, the satellite returns will always be centered within the array. If the DRP pointing is slightly off, however, the receiver will still center the telescope on the satellite, but the satellite will not be located precisely at the peak of the Gaussian transmit beam with a corresponding small reduction in signal return rates.

Figure 4 is a simplified block diagram of the overall SGSLR receiver which, in addition to timing events generated by the receiver array, also timetags the laser start pulse, range gate, GPS, and other ancillary signals. Timing data is transferred to a single board computer which identifies the signal pixel(s) based primarily on the number of counts per pixel observed in a given interval, filters out the vast majority of the noise, and passes the relevant data via Ethernet to the system computer. It also relays commands and status information with the system computer.



**Figure 4: A greatly simplified block diagram of the overall SGSLR Receiver**

### 3. SUMMARY

The proposed receiver provides an accurate measure of the magnitude and direction of the angular error between the satellite and the telescope optical axis while simultaneously serving as a Multichannel Event Timer, providing 45 channels of multistop ranging data, each having recovery times less than 2 nsec following a photon event and event timing precisions of a few picoseconds. Maximum utility during satellite acquisition and tracking is obtained by matching the transmitter and receiver FOVs, where the transmitter divergence is controlled by a programmable beam expander and the receiver FOV is controlled by an adjustable iris and a programmable telephoto lens. This ensures that some fraction of the outgoing laser light impinges on the satellite providing some rate of return which increases as the pointing bias is driven to zero, where the peak of the Gaussian beam profile falls on the satellite.

The design can accommodate segmented anode MicroChannel Plate PhotoMultipliers Tubes (MCP/PMTs) as well as Silicon PhotoMultipliers (SiPMs). Based on in-house experiments, the SiPMs appear to perform comparably to MCP/PMTs with regard to detection efficiencies and pulsewidths but are significantly less expensive and have relatively short acquisition times and long operational lifetimes. Unlike MCP/PMT's, however, current SiPM packaging requires the use of a Laser-Ablated Microlens Array (LAMA) which captures most of the light incident on the 2mm x 2mm square and directs it to the 1mm x 1mm active area of the pixel. The multistop capability and low deadtime characteristics of a given pixel is due to the fact that the active area contains hundreds to thousands of individual single stop SiAPDs, all connected to a common anode, and the receiver optical train is designed to fill the 1mm x 1mm active area.

In general, we expect the satellite signal to fall into one, two, or four pixels out of 45. By simply rejecting the noise counts in the other pixels, one can eliminate between 91 and 98% of the noise counts in near real time. Thus, the Sigma Space SGSLR receiver acts as a highly effective Electronic Spatial Filter. Figure 5 is a photo of the prototype which is currently undergoing field tests at NASA's NGSLR facility in Greenbelt, MD.



**Figure 5: Photo of the SGSLR receiver prototype. The 3U EMI shielded enclosure measures 42.5 cm x 40.6 cm x 13.3 cm.**

## References

J. Degnan, An Upgraded SGSLR Link Analysis Which Includes the Effects of Atmospheric Scintillation and Target Speckle, 20<sup>th</sup> International Workshop on Laser Ranging, Potsdam, Germany, October 2016, <http://cddis.gsfc.nasa.gov/lw20>.