SGSLR Range Control Electronics Design and Implementation

Evan Hoffman[1], Donald Patterson[2], Howard Donovan[2], Jan McGarry[1], Bart Clarke[2]

1 – NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

2 – KBRWyle, Columbia, Maryland, USA

Abstract

Here we discuss the SGSLR range control electronics (RCE). The purpose of the RCE is to provide temporal data filtering through the generation of range windows and report relevant data back to the analysis software. Timing and inter-subsystem dataflow requirements/rationales are presented. The SGSLR will be a high repetition rate, monostatic system, with a high data volume requirement. As a result, a method has been developed to minimize collisions between the transmit and receive paths, as well as a mechanism within the RCE to protect the receiver during collisions. The theory behind the design and the benefits and improvements over the heritage system are discussed. We also touch on the design implementation; advances in hardware technology have allowed us to construct an RCE with almost all commercial off-the-shelf materials.

Introduction

The Space Geodesy Satellite Laser Ranging (SGSLR) systems are the new SLR systems being designed and constructed to replace the current aging NASA SLR network. The new design is being developed with the aim of full automation, ease of maintenance, modularity, and high data volume. Within the overall system design, the range control electronics (RCE) is one such piece of hardware which demonstrates these concepts.

The practice of generating timing windows, or gates, for SLR ranging measurements is certainly not new. The NASA network, as well as the international SLR network as a whole, has been doing so for decades. Each network has its own custom approach to window generation in both an algorithmic and a physical hardware/software sense. This usually results in a product that is suited to the station's configuration at the time of construction, but is costly to build, and has to be maintained and protected from obsolescence by the station itself or a single vendor.

While there are other solutions available, there are no fully commercial off-the-shelf (COTS) products available to SLR stations for SLR range generation. SGSLR's design uses COTS building blocks that conform to industry standards, which make modifications due to obsolescence as inexpensive and painless as possible. Advances in FPGA speed, performance, and reliability allow the core of the gate generation functions to be coded in a standard hardware description language, giving the design portability and flexibility.

Temporal Filtering

The primary function of the RCE is to provide temporal filtering. Satellite laser ranging has a significant number of noise sources which affect the accuracy and precision of the range measurement. These include things such as detector and timer noise, stray light in the optical path, and scattered atmospheric light. Since the orbital position of the tracked satellite is generally known within meters, it is possible to put upper and lower bounds on its predicted range. Using these bounds, an electronic gate signal is sent to the detector and/or timing equipment, outside of which any signal or noise is suppressed. The gate width can be narrowed to suppress a greater amount of noise, or widened if orbital predictions are poor.

The gate has the effect of reducing the probability of so-called “false alarms”, i.e., noise that is interpreted as signal. The probability can be expressed as [1]:

$$P_{FA} = 1 - e^{-a_L T}$$

$$a_L = \frac{n_b (n_b \tau)^{L-1}}{(L-1)!} \left[\sum_{K=0}^{L-1} \frac{(n_b \tau)^K}{K!} \right]^{-1}$$

with P_{FA} the probability of a false alarm, L the photoelectron threshold level, n_b the mean solar background noise rate, τ the impulse response of the detector, and T the width of the gate. In systems configured for single photon detection, a_L will reduce to the mean solar noise background rate.

Temporal filtering also reduces the data rate required by the data recording equipment. The worst case mean solar background noise rate estimated for SGSLR with a 14 arcsecond field of view is 13 MHz [2]. Using that calculation for different fields of view and different gate widths, a worst case scenario data rate was calculated for the candidate multi-pixel receiver. With the widest planned gate of 10 microseconds and the widest planned field of view of 60 arcseconds, the data rate from the receiver (in full daylight) is about 29 megabytes per second. An ungated signal would require a data rate of over 1 gigabyte per second.

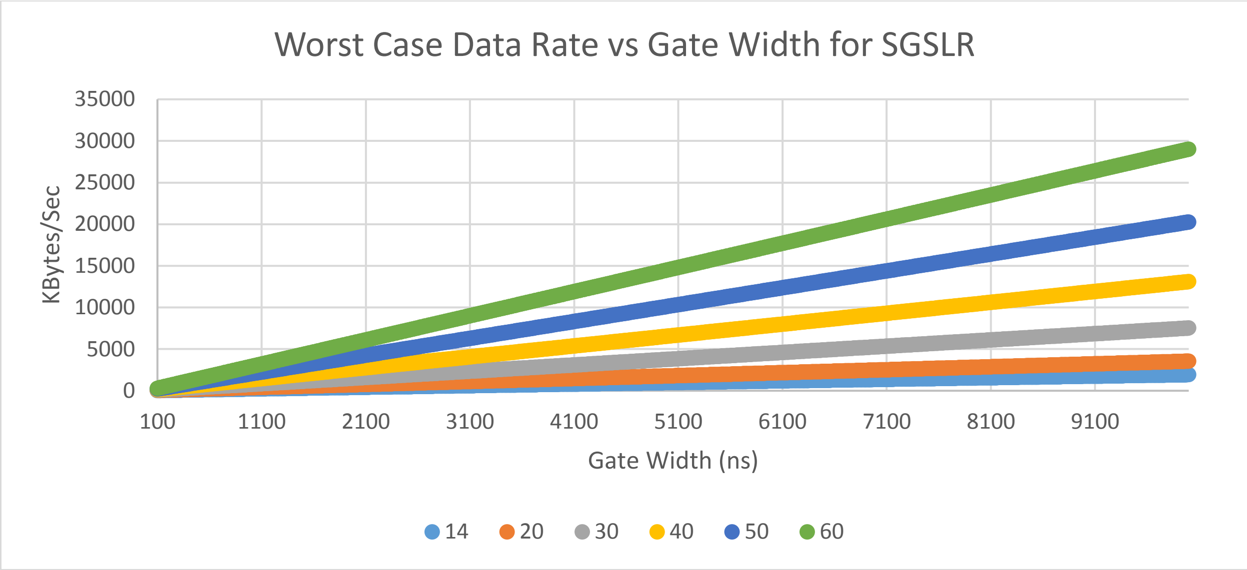

Figure 1- Worst case data rates for the proposed SGSLR receiver, for different gates widths and receiver field of views (FOV is in arcseconds).

The Function of the RCE

Along with its primary function of window generation, SGSLR's RCE has the following functions: generation of a laser fire command to externally trigger the laser to fire, measurement of the delay between the fire command and the actual firing of the laser (via a start diode), the suppression of a window creation ("blanking") directly before and after the laser is fired, and implementation of range-dependent pulse repetition frequencies (PRF) to prevent collisions between transmit and receive signals. Each of these functions is described below.

Laser Fire Command: SGSLR must be able to control the timing of the laser firing in order to facilitate other processes based on this timing, such as precise window placement. The RCE receives laser fire commands from the computer/software subsystem and implements them as a TTL pulse based on its internal clock, which is disciplined by the station's timing subsystem. The laser fire commands precisely placed in time based on the PRF calculation done by the computer/software subsystem (explained in more detail below).

Command to Fire Delay: There is a delay between the TTL pulse being received by the laser electronics and the actual firing of the laser, due to electronic and laser cavity delays. A photodiode on the optical bench (also used as the 'start' pulse for the time of flight measurement) sends its signal back to the RCE when it detects light from the optical output window of the laser. This signal is used to adjust the gate to the predicted range based on the actual laser firing time.

Blanking: SGSLR is a monostatic, high repetition rate system. As such, there are multiple pulses in flight at any given time, with transmitted pulses and received pulses sharing a common path. There are instances when the timing of a range window will coincide with the firing of the laser. The receiver must be protected from laser backscatter during firing, both from the optical bench and the atmosphere. To achieve this, window creation is suppressed a given amount of time before and after a laser fire command. This is known as ‘blanking’.

Range-Dependent PRF: For a given pulse repetition frequency, or pulse repetition interval (PRI) in the time domain, there is a set of ranges in which every returned pulse will coincide with a laser fire command, allowing no detection. This can be a minor nuisance for fast moving targets, or a major data limiter for slow moving targets such as GNSS satellites. In order to maximize data volume, the pulse repetition frequency switches between a set number of values to avoid these collisions. The offset from the nominal PRI (500 microseconds in the case of SGSLR) can be calculated as [3]:

$$\frac{T_B}{k_{min}} \leq \delta T \leq \frac{T_0 - T_B}{k_{max}}$$

T_B is the total blanking time, T_0 is the nominal PRI, k_{min} and k_{max} are the minimum and maximum pulses in flight respectively, and δT is the offset from the nominal PRI. If more than two PRI’s are necessary, a multiple of δT is used.

The number of PRI’s required, n, can be derived from the number of total pulses in flight, and the total blanking time, and can be expressed as:

$$n \geq \left(\frac{T_B}{T_0 - T_B}\right) \frac{k_{max}}{k_{min}} + 1$$

An illustration of three pulses in flight is shown in Figure 2.

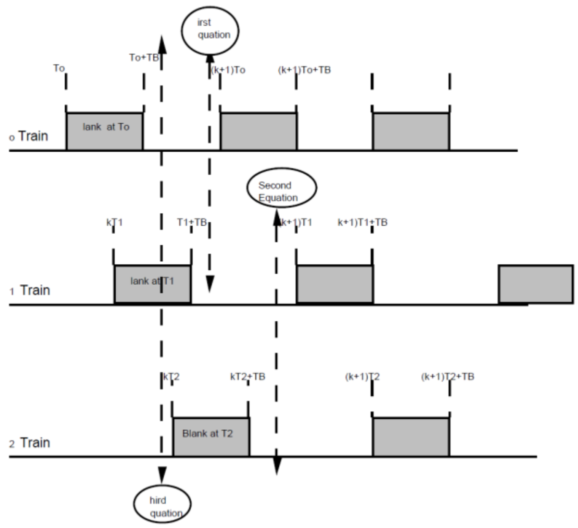

Figure 2- Example figure with three different PRFs, figure from [2]

For SGSLR, we will be using 2 PRI's for all tracking; the nominal PRI and one delta PRI. Table 1 shows example delta PRIs for various targets.

Satellite	**Ranges (km)**	**PRI value (microseconds)**
GEO	30000-50000	500.5
GNSS+	10000-30000	501
LAGEOS	3900-15000	502
MID	1200-4000	504
LEO	450-1300	510
GOCE	200-500	520

Table 1- PRI Variation with Range

More information about this process, including derivations, can be found in "System/Usage Impact of Operating the SLR2000 at 2 kHz." By Titterton et al., in the proceedings of the Eleventh Workshop on Laser Ranging.

RCE as a Component of SGSLR

SGSLR is divided into 9 separate subsystems. The receiver subsystem is responsible for the detection of light from the satellite and the time-of-flight measurement (see Figure 2). The RCE is a component of this subsystem.

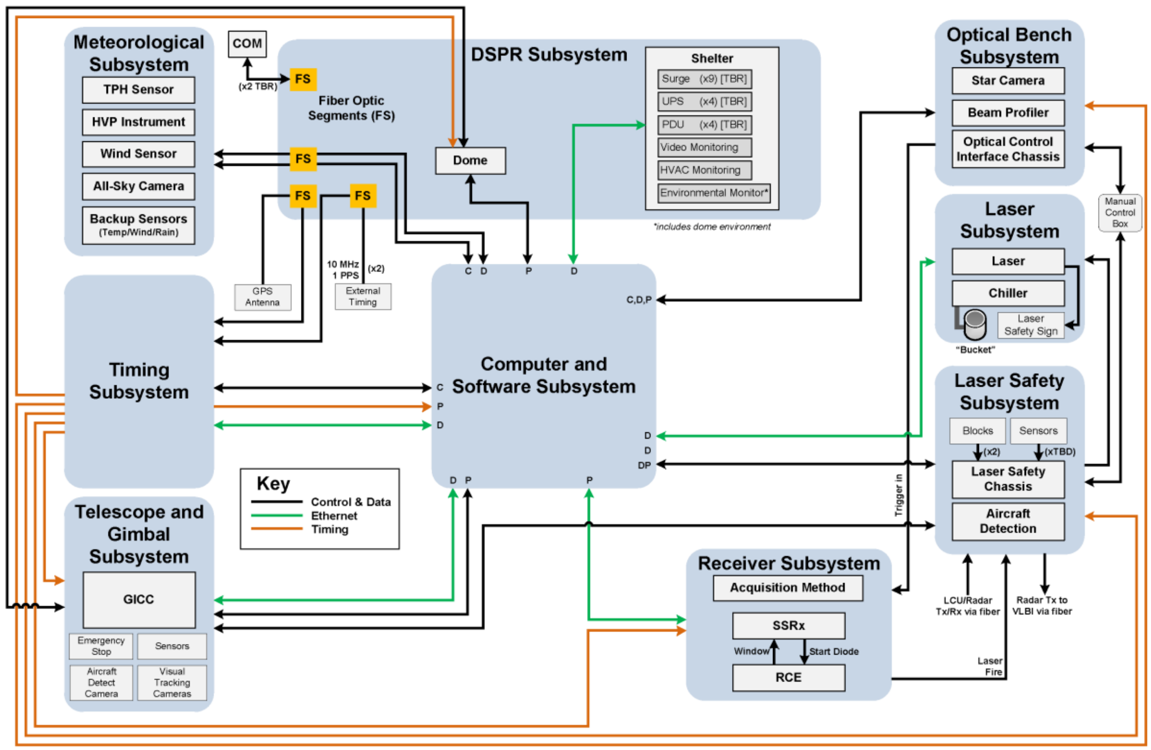

Figure 3 - Block Diagram of SGSLR Subsystem Interconnections

Figure 4 shows the system connections to the RCE itself. The station's timing subsystem provides a 10 MHz and 1 PPS reference which disciplines an internal oscillator and provide epoch time. Using this disciplined, 500 MHz oscillator, gates and fire commands can be placed with a resolution of 2 nanoseconds. These commands come as bundled data packets from the computer/software subsystem. The start diode signal is used both as a blanking verification and a command-to-laser fire measure. The window signal is delivered to the detector. The laser fire signal passes through the laser safety subsystem (LSS) on its way to the laser control electronics, which allows the LSS to act as an interlock.

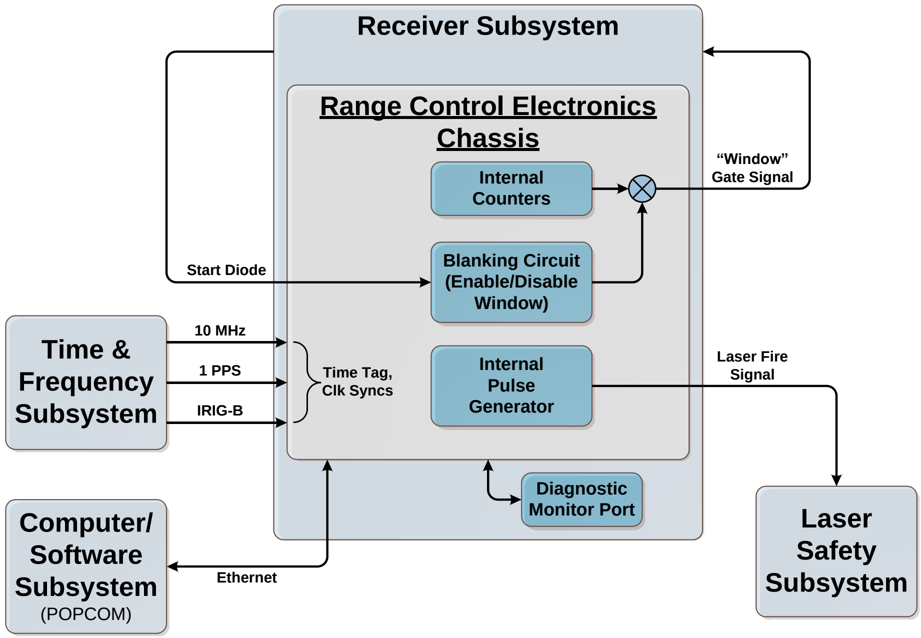

Figure 4 - Block Diagram of RCE within Receiver Subsystem

RCE Hardware/Firmware

The RCE's hardware consists of a chassis, a COTS FPGA board, a COTS Ethernet PIC controller board, and an interface board for the managing input/output. Future designs may eliminate the PIC controller for a soft-core processor in the FPGA board. All RCE logic is implemented via the FPGA using VHDL, a hardware description language. This allows bugs in logic to be corrected quickly and in the field if necessary. It also allows for added features or design changes as requirements on the system evolve over time. All external communication in its operational mode is done via an Ethernet connection. A USB connection is provided for diagnostic purposes. Figure 5 shows the front and back view of the 2U rack mountable chassis.

Figure 5 - Front and Back View of RCE Chassis

RCE Data and Timing

A single satellite pass is divided into 50 millisecond frames. The RCE receives bundled data packets from the computer/software subsystem for a given frame 25 milliseconds before the start of that frame. The RCE sends a status packet back to the computer/software subsystem 10-20 milliseconds after the end of a frame, giving information of any events (e.g., fire times, windows generated) during that frame. There is no hard real time requirement on the delivery of the data bundle, making the RCE more robust, and relaxing the processing requirements on the computer/software subsystem. Figure 6 shows a timeline of these events, as well as an example of sequential fire commands occurring within a data frame. The actual number of fire commands within a data frame will vary with PRF.

Each packet contains a header line and multiple data lines. The header contains information about the operational mode of SGSLR (ground calibration, satellite, etc) and the total number of data elements in the bundle. Each element calls out a specific laser fire command, a range prediction based on that fire, a relative PRI of the next fire, and the width of the window, to a precision of 2 nanoseconds. Table 2 and 3 show the contents of the packets.

Header of Packet
Time Tag of Bundle
Mode (Internal Cal, Ground Cal, Satellite, Transponder)
Start/Middle/End of Pass
Number of data elements in bundle
Originator ID (POPCOM Computer/RCE)

Data (per element)
Fire Number
PRI of next fire
Predicted Two-way Time of Flight
Window Width

Table 2 and 3 - Contents of RCE Data Packets

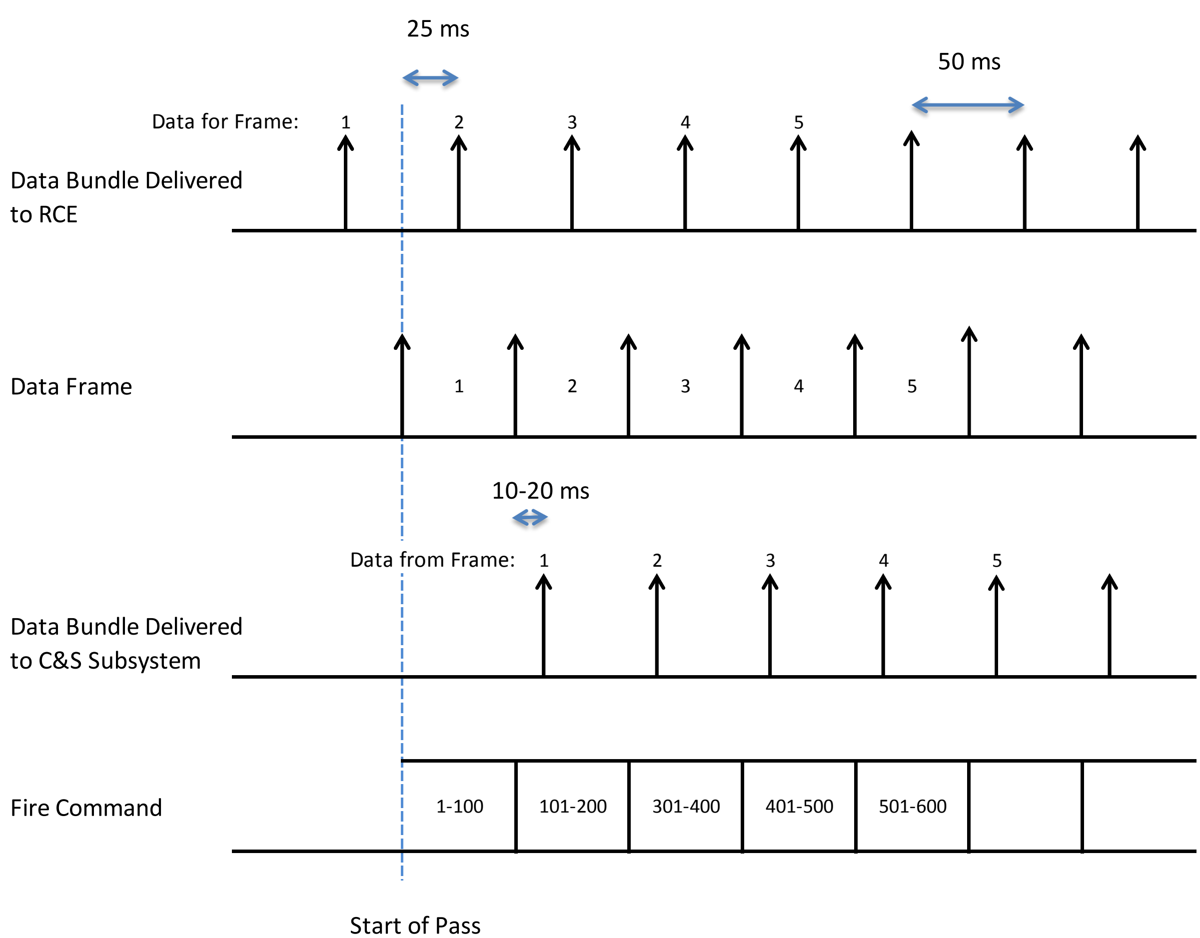

Figure 6 - RCE Data Timing Diagram, showing the timing of the delivery of packets/bundles between the RCE and computer/software subsystem. Data bundles are delivered for the next frame halfway into the current frame. The RCE delivers information relevant from the previous frame 10-20 ms after the end of that frame. The fire commands shown are for a nominal 2 kHz PRF, but in practice the actual number of fires occurring during a frame will vary with PRF.

Figure 7 shows a timing diagram of the primary events and signals related to the RCE. The fire commands and window times are placed via a rolling continuous master counter disciplined by the timing subsystem. The start diode inputs are also measured via this counter, and the delay between the command and actual fire is applied to the range window.

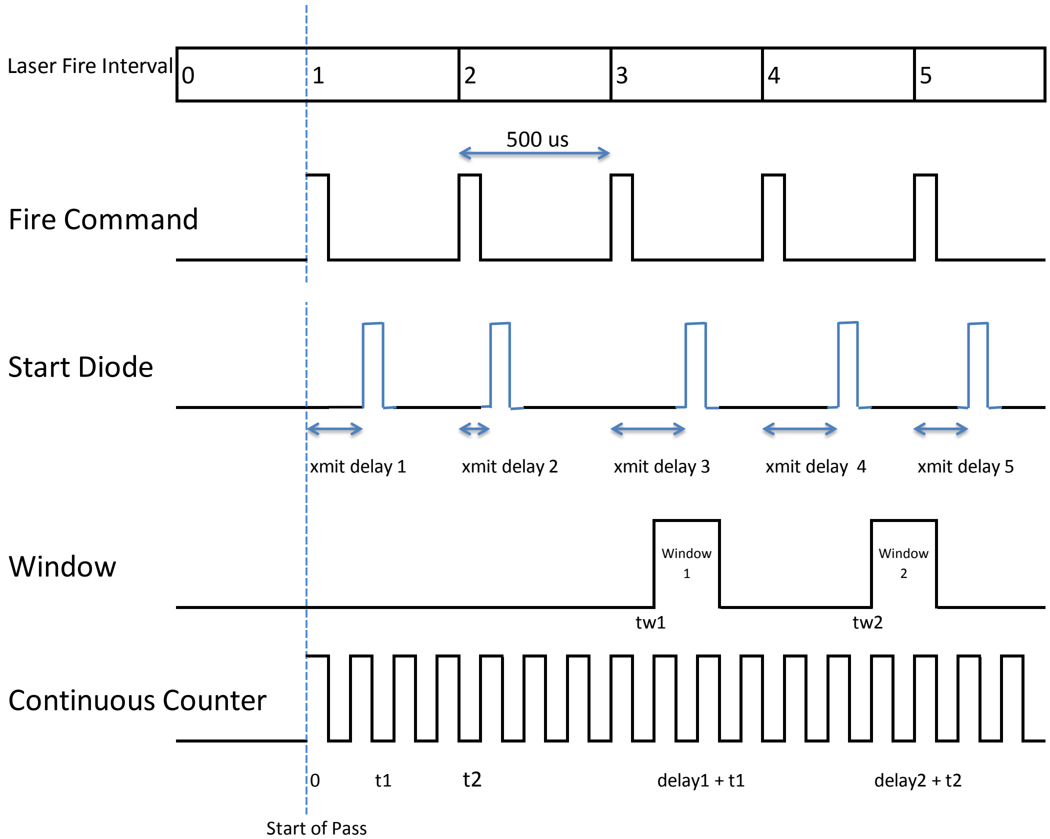

Figure 7- RCE Signal Timing Diagram, showing synchronization between important signals. The fire command interval will vary as shown in Table 1.

Conclusion

The range control electronics provide a snapshot into the design philosophy of SGSLR and show many improvements on the NGSLR prototype. The bundled data packets allow a relaxation of the real time requirement of the computer/software subsystem, increasing the robustness of the subsystem. The natural evolution of electronics technology has permitted the implementation of RCE functions into a reprogrammable FPGA package, allowing for logic fixes and added features in the field. The entire package fits into a 2U chassis with room to spare, and future designs could see this shrinking further.

Using COTS pieces when available and a design that lends itself to future improvements, SGSLR's RCE will be inexpensive, and maintainable far into the future.

References

[1] J. J. Degnan, "Millimeter accuracy satellite laser ranging: A review," in *Geodynamics Series*, vol. 25, D. E. Smith and D. L. Turcotte, Eds. Washington, D. C.: American Geophysical Union, 1993, pp. 133–162.

[2] J. J. Degnan, "Impact of Receiver Deadtime on Photon-Counting SLR and Altimetry during Daylight Operations," in *Proceedings of the 16th International Workshop on Laser Ranging*.

[3] Paul Titterton and Harold Sweeney, "System/Usage Impact of Operating the SLR2000 at 2 kHz," presented at the 11th International Workshop on Laser Ranging Instrumentation, Deggendorf, Germany.