A Proposed Multifunctional Multichannel Receiver for SGSLR

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Sigma Receiver Goals

We describe a 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 receiver optical axis which is then used to correct for 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 (see poster by Clarke et al, this Workshop.)

ORIGINAL NGSLR APPROACH TO POINTING CORRECTION*

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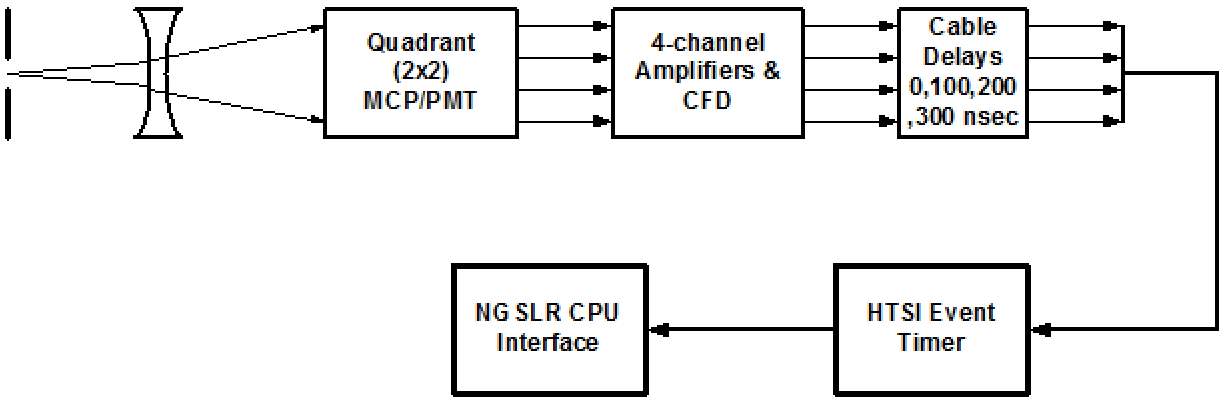


Technical Approach

1. Solar and satellite returns collected by the telescope pass through the spatial filter..

2. A negative lens diverges the light so that it fills most of the Quadrant MCP/PMT Photocathode an. Each quadrant generates an electrical pulse for each detected photon (signal or noise).

3. The electrical pulses from each quadrant are amplified independently to fall within the desired voltage range for the Constant Fraction Discrminator (CFD) for maximum range stability. This also helps compensate for any gain nonuniformity in the MCP/PMT which might result in a false pointing error.

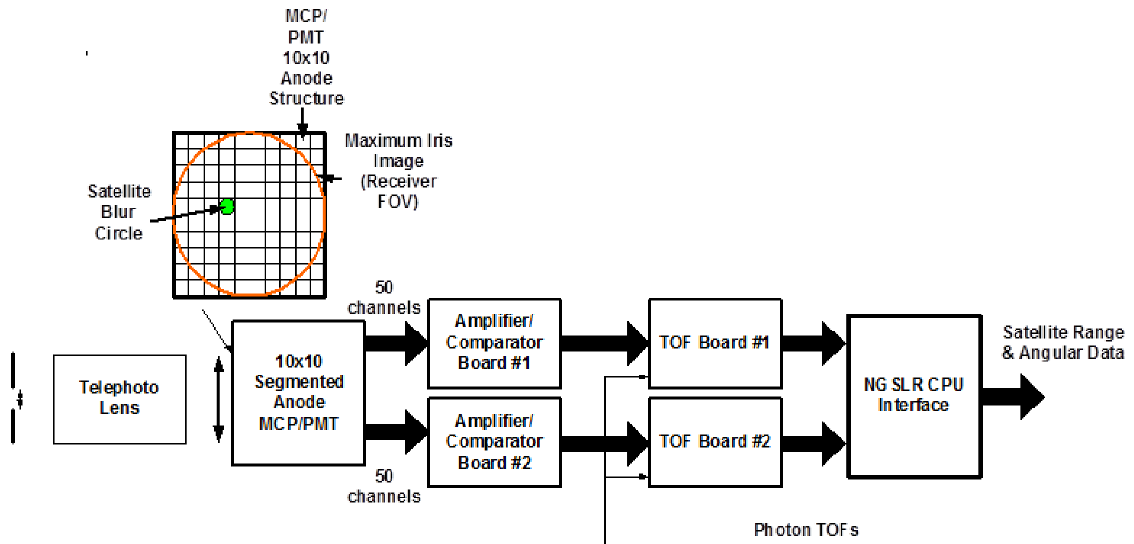
4. The outputs from each quadrant are delayed by multiples of 100 nanoseconds so that their arrival times can be recorded by the HTSI Event Timer (ET), which has a 60 nsec recovery time following a photon event.

5. On average, solar noise counts are distributed uniformly among the four quadrants. Satellite returns centered on the quadrant are also distributed uniformly among the quadrants unless the telescope is not pointed directly at the satellite. Thus, an imbalance in counts among the four quadrants , as measured over a short period of time, allows the computation of the magnitude and direction of the pointing error

6. This information is then used to drive the telescope/tracking gimbal mount and correct the pointing error.

* Degnan, J.J. and McGarry, J. F., (1997), SPIE 3218, 63-77.

PROPOSED SIGMA APPROACH



<u>Technical Approach is Based on Proven Sigma 3D Imaging Lidar Technology</u>

1. Solar and satellite returns collected by the telescope pass through the spatial filter..
2. A telephoto lens images the spatial filter/iris onto the photocathode of a NxN ($N \leq 10$) Segmented Anode MCP/PMT. Each of the pixels within the iris FOV generates an electrical pulse for each detected photon (signal or noise).
3. The electrical pulses from each pixel are amplified to ensure that a single photon return will generate a voltage in excess of the required comparator threshold. Again this compensates for any gain nonuniformity in the MCP/PMT which might result in different pixel count rates in response to the same stimulus.
4. The Time-of-Flight (TOF) boards time-tag each photon event with a precision of less than 2.8 picoseconds RMS and a pixel recovery time of less than 3.4 nanoseconds between photon events.
5. On average, solar noise counts will be distributed uniformly among the N^2 pixels, while satellite returns will be concentrated on a small number of pixels determined by the image size at the MCP/PMT. Thus, the pixel with the most counts determines the magnitude and direction of the pointing correction.
6. This information is then used to drive the telescope/tracking gimbal mount and correct the pointing error.

NGSLR ISSUES AND SOLUTIONS

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NGSLR ISSUES	SOLUTION
1. Poor alignment of the off-axis telescope and tracking mount from two vendors resulted in a large (20 arcsec), amorphous (i.e. non-circular) star image quality in the focal plane making quadrant balancing difficult	1. Purchase COTS telescope and tracking mount with good image quality from a single vendor.
2. The photocathode sensitivity and microchannel plate gain can have a fair amount of variation further complicating balancing of the quadrants.	2. Signal balancing is no longer required since the angular displacement is now determined by the pixel (or small subset of pixels) containing the satellite counts.
3. All of the noise photons detected are passed on to the receiver and, since they are distributed uniformly over the range gate, can affect the measured return normal point centroid for HEO satellites with low signal count rates.	3. Only the noise counts in "signal pixels" are kept, thereby greatly reducing the number of noise counts and any noise-induced range bias in the normal point. Thus, the proposed system acts as an "electronic spatial filter".

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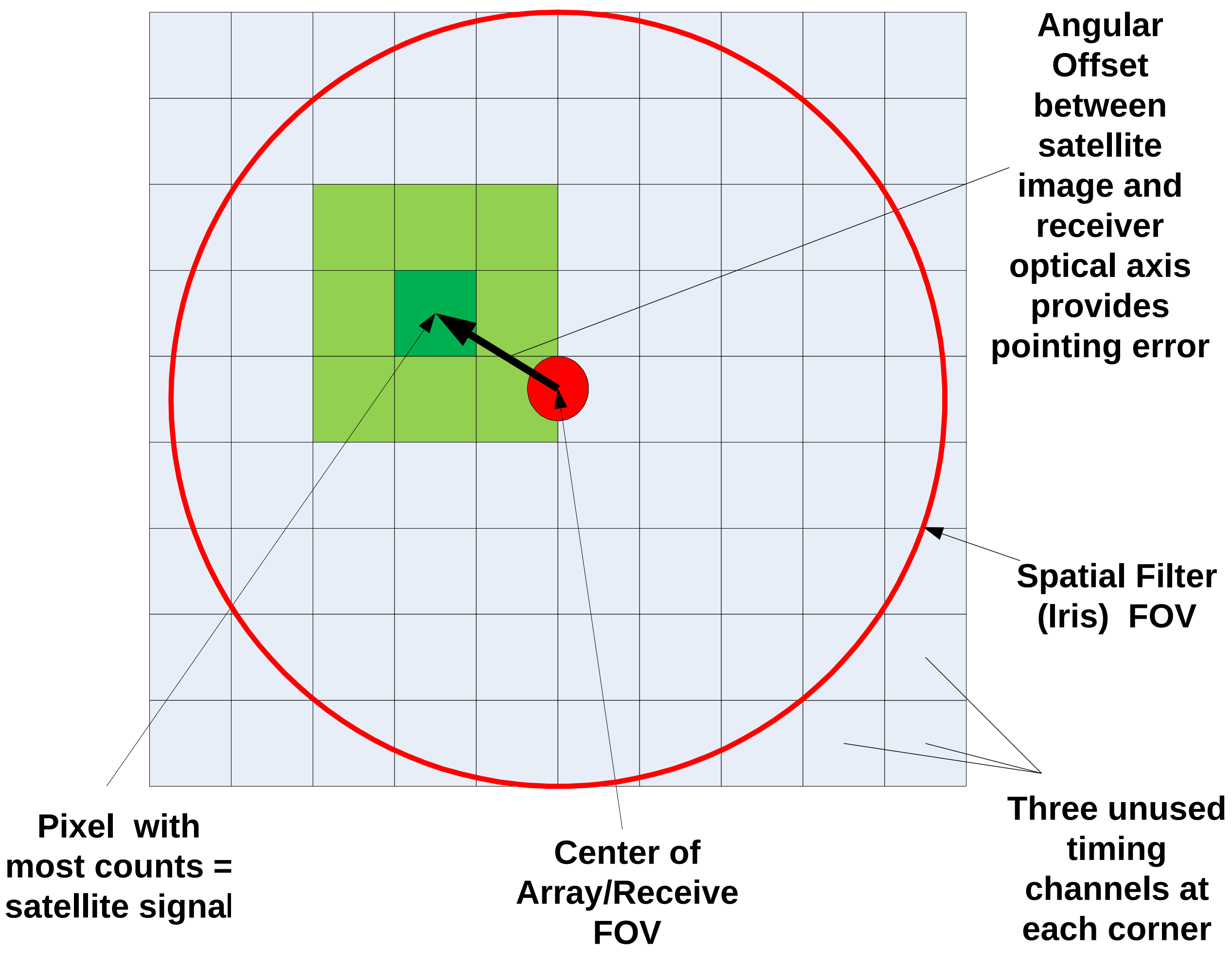
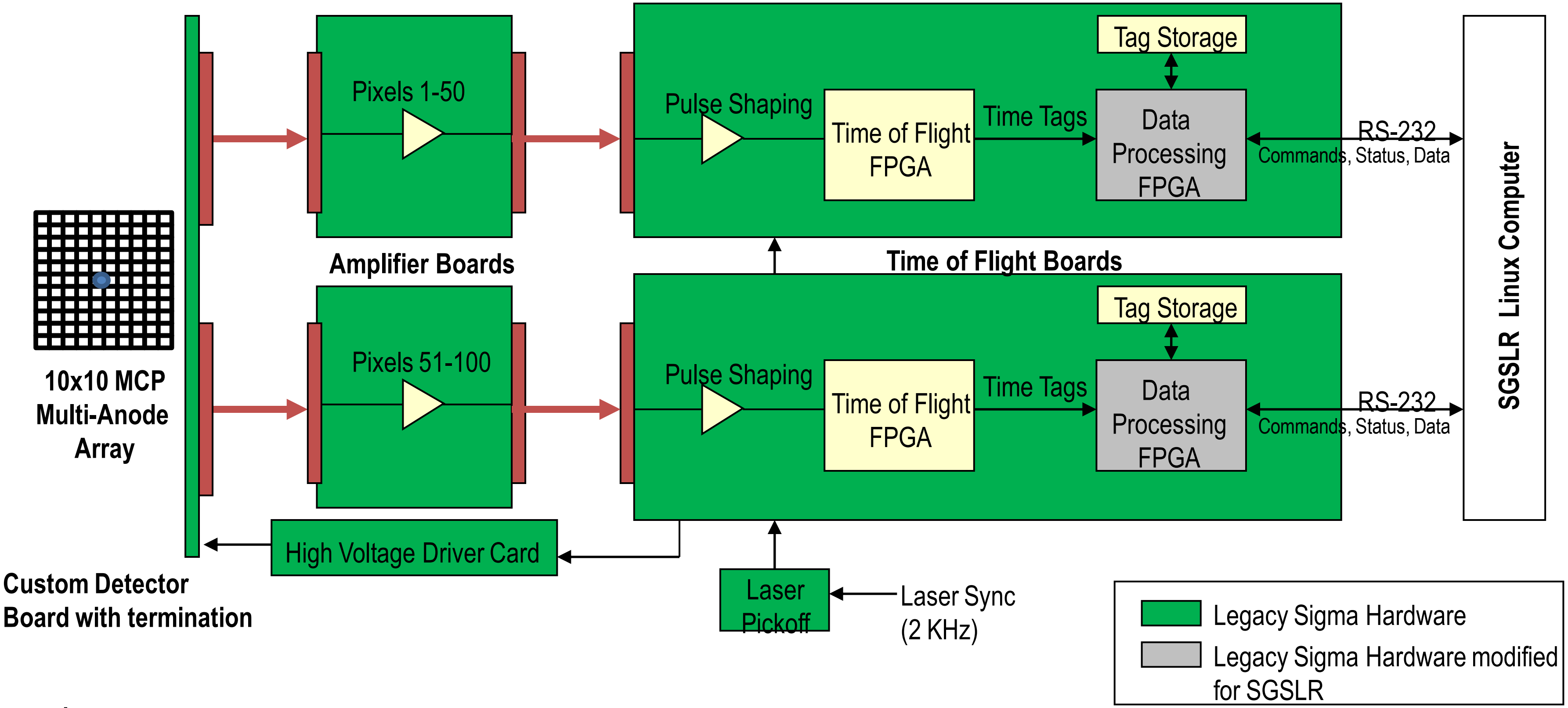
10x10 Array Example



- Improved estimate of angular offset may be obtained by computing centroid of counts within a 9 pixel area (dark and light green pixels).
- Since noise is distributed uniformly over the entire pixel array, this implies that at least 91% of the noise counts can be discarded, thereby greatly reducing the potential for noise induced range bias errors in weak links.
- Unused timing channels can record other events (e.g. GPS 1pps, MOBLAS synch, etc.)

Multifunctional Range Receiver



- **3rd generation, flight proven Sigma design with excellent performance**
- **Automated calibration provides real-time updates of timer delays as affected by voltage and temperature**
- **Very low risk approach based on heritage electronics**
- **Linux computer selects operating parameters, receives time tags and pixel number/count values**
- **High Speed, High Bandwidth Interconnects**

Sigma 32 kHz PMT Gating Board

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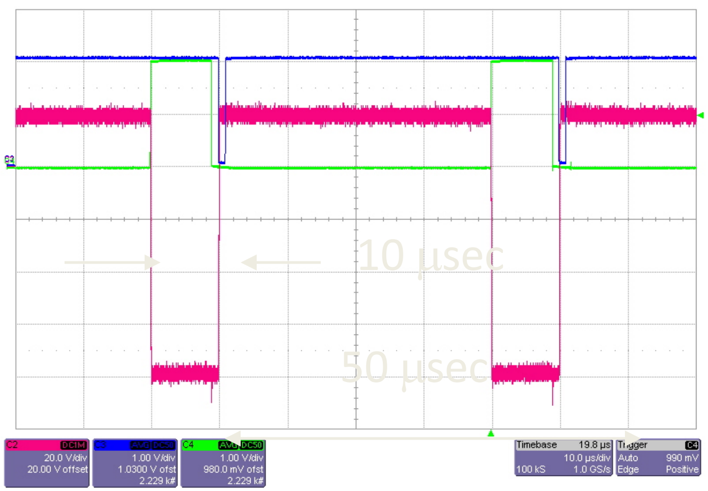
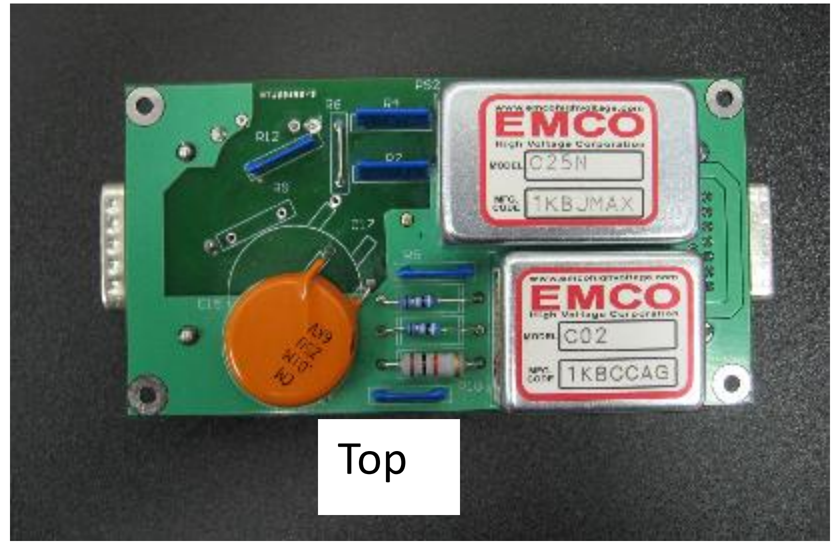
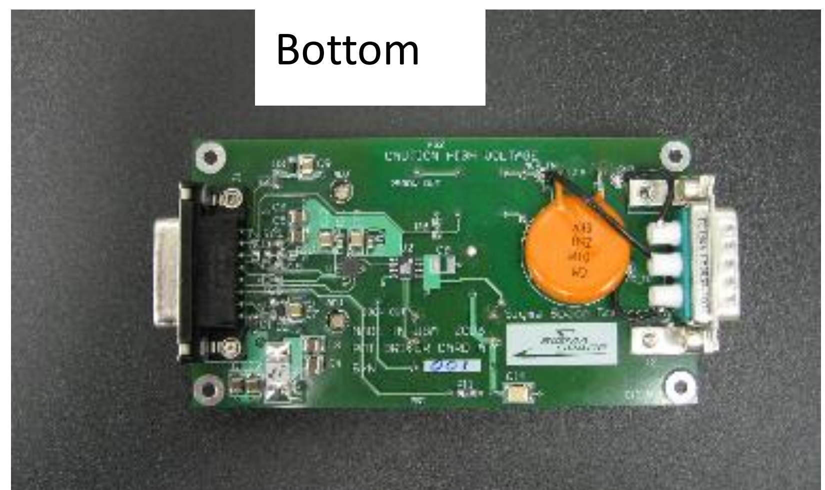
- Provides 200 V gating pulse to turn MCP/PMT on or off
- Tested at rates up to 32 kHz
- Rise/Fall Time: 250 nsec
- Min Gate Width: ~1 μsec

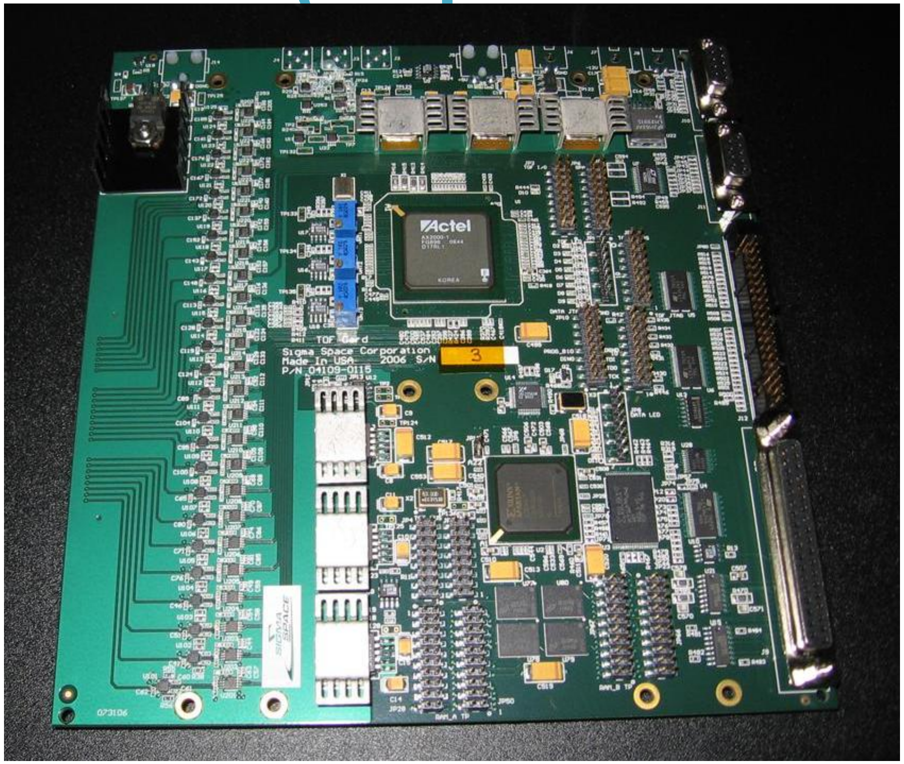


20 kHz

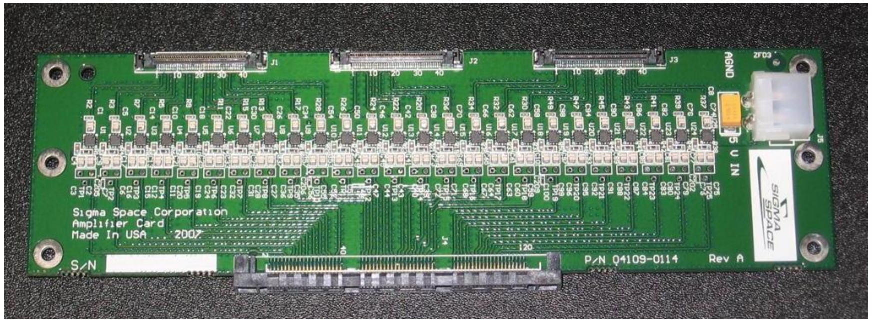




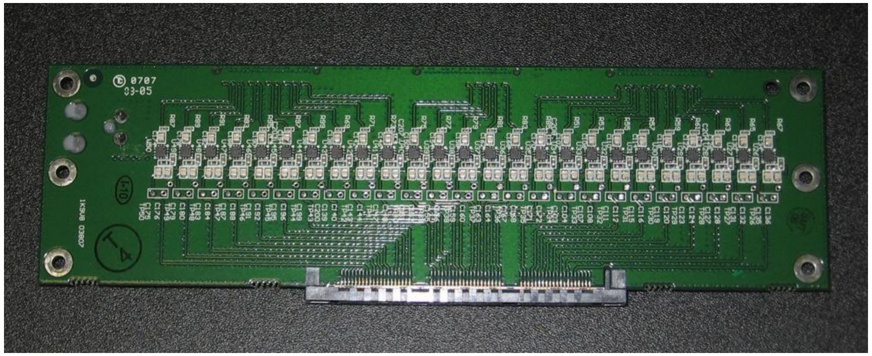
Existing TOF Electronics (Amplifier Card & TOF Card)



TOF Card – Top Side



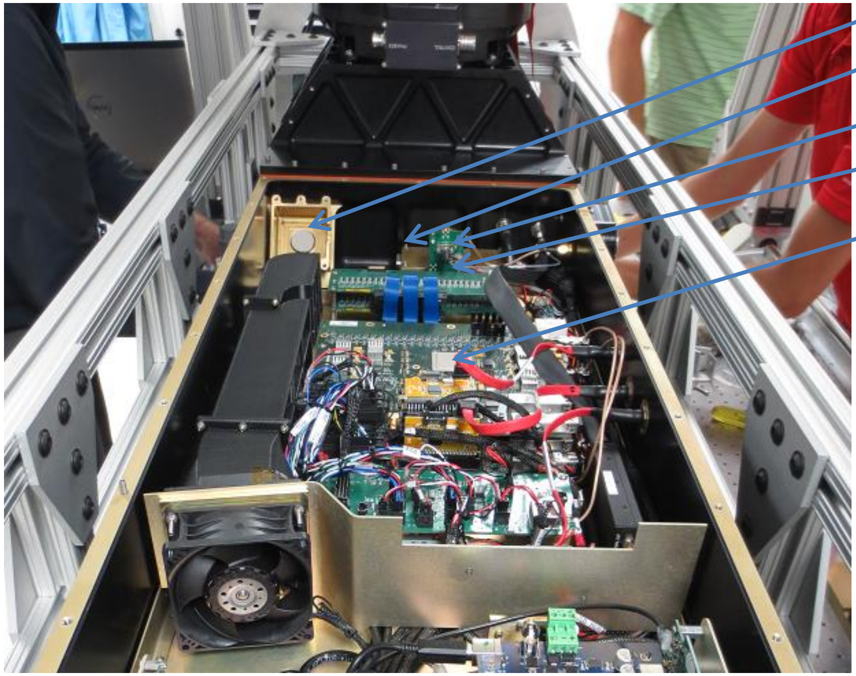
Amplifier Card – Top Side



Amplifier Card – Bottom Side

Current 100-channel lidar system incorporates 2 Amplifier & 2 TOF Cards. Using just 50 channels halves the recurring cost of systems.

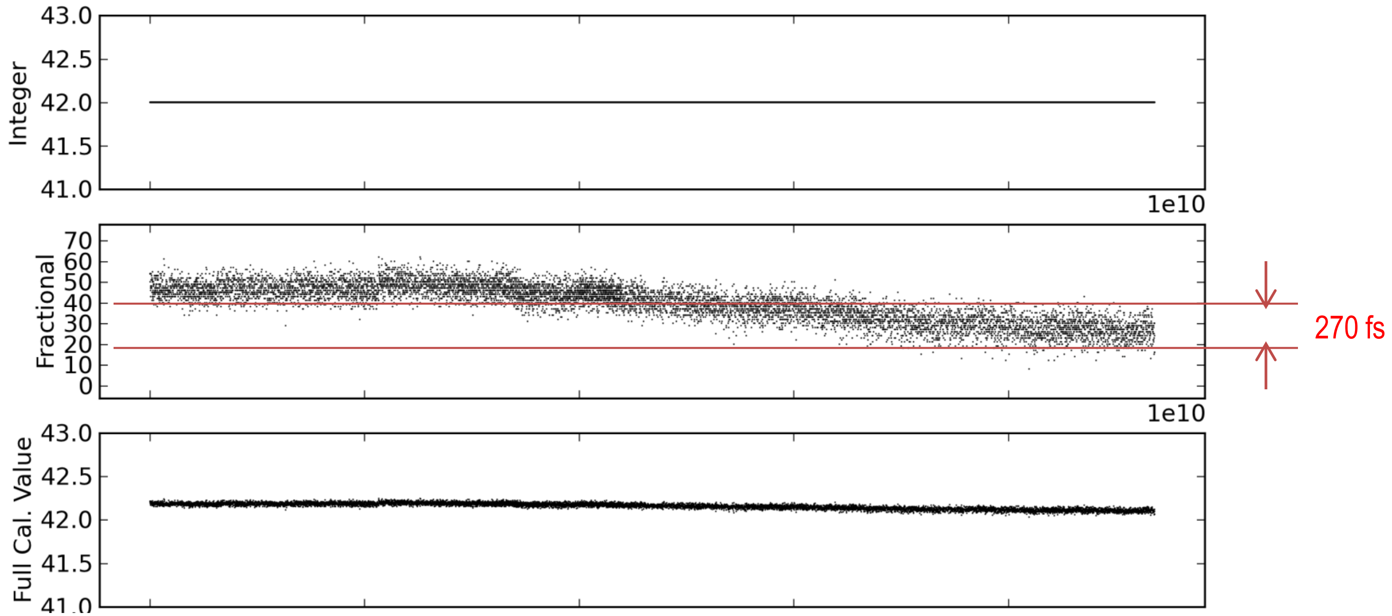
Hardware is Flight-Tested



- Detector Board
- High Voltage Driver Board
- Laser Pickoff
- Amplifier Boards
- Time of Flight Boards

- Sigma develops and flies complete instruments based on our photon counting lidar hardware. All mechanical, electrical, optical, flight and test software, assembly, integration and test is done in-house.
- Sigma has flown and successfully demonstrated the timing hardware in a variety of 100 beam ,airborne 3D imaging lidars to altitudes o f 65,000 including an external pod-mounted version .

Timer Stability during Aircraft Flight



- Data taken over a 1.5 hour flight in a Twin Commander aircraft at 25,000 feet using proposed hardware.
- Timer is extremely stable for long durations at a given temperature and voltage, changing only about 270 fs peak to peak.
- Changes due to temperature and voltage variations can be removed by using the reported calibration value when calculating time of flight.

Proposed Processing Loop

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• SGSLR Linux computer sends commands to define key parameters such as # of laser shots in an integration frame, mode (diagnostic, functional), gate width/position, start/stop collecting, etc.

• Data Processing FPGA maintains an event counter for every pixel, and transmits all event count values at the end of the integration period and clears counters. This information is used to update tracking, and maintain satellite blur circle within array field of view.

• SGSLR Linux computer decides which pixels are of interest based on event counts from both boards, and requests time tags from that integration interval for specific pixels. Up to N^2 pixels can be requested.

• Data Processing FPGA transfers all requested time tags, along with real-time calibration data that is used for minor corrections in the time-of-flight calculation. The calibration data can be requested at a higher rate than the integration period if desired.

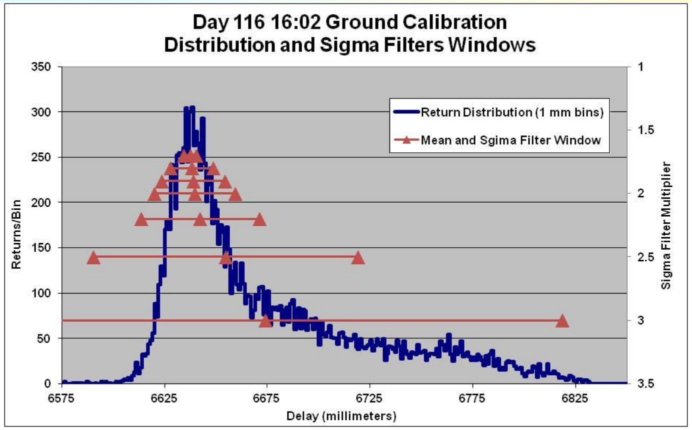
Note 1: Time tag storage and event counts are arranged in a ping-pong scheme, such that there is **no pause in data collection** from one laser shot to the next. Data from prior integration period is transferred during collection of current period.

Note 2: In this scheme, the **software maintains control and flexibility** to change the electronic gate, integration times, number of pixels used to identify the signal, and exactly which time tag channels it wants to read.

Requirements for 1mm Normal Point RMS

1 mm normal point RMS = 6 psec normal point RMS
Implies single shot RMS must satisfy

$$6\,p\sec \geq \frac{\sigma_{SS}}{\sqrt{N}} = \sqrt{\frac{\sigma_L^2 + \sigma_S^2 + \sigma_D^2 + \sigma_{ET}^2}{N}}$$



NGSLR ranging to calibration target with MCP/PMT, 50 psec laser, and HTSI ET (Clarke et al, 18th SLR Workshop, Japan)

50 psec FWHM laser: σ_L = 42 psec
LAGEOS Impulse response: σ_S = 460 psec/6 = 77 psec
Hamamatsu MCP/PMT: σ_D = 1600psec/6 =267psec*
Sigma ET quantization: σ_{ET} = 80 psec/$\sqrt{12}$ = 23 psec (current configuration)

Enhanced Timing Channel= 2.8ps single shot RMS

Enhanced Timing Channel with post processing = 1.8 psec single shot RMS

Current unmodified ET configuration implies a single shot RMS of σ_{SS} = 282 psec (dominated by MCP/PMT response). Thus, the minimum number of ranges per 1mm normal point is N> 2209 which further implies, for a two minute normal point, a minimum LAGEOS return rate of
2209/2kHz*120 sec $\geq$ 0.92%
which is routinely achieved by NGSLR and will be enhanced significantly in SGSLR.

***MCP/PMT risetime of 170 psec is comparable to fastest 0.1 mm x 0.1 mm SPADs**

Receiver Recovery Time Effects

From Poisson statistics, the solar photon count rate will cause the mean signal count to be reduced by a “Reduction Factor” given by*

$$RF = \exp\left(-\dot{n}\,\tau_d\right)$$

where

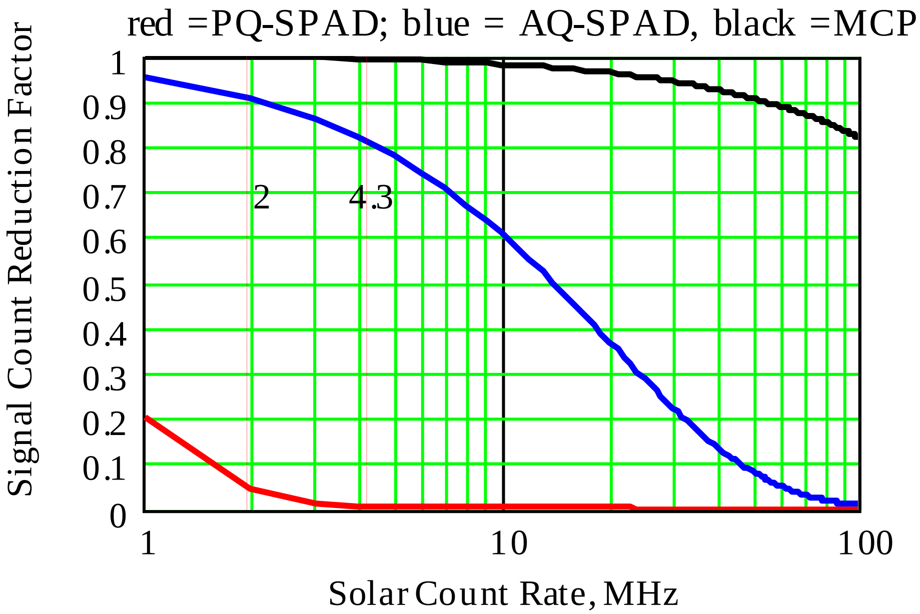
$\dot{\eta}$ is the solar count rate and

τ_d is the receiver recovery time:

MCP/PMT: <2 nsec

AQ-SPAD: several tens of nsec

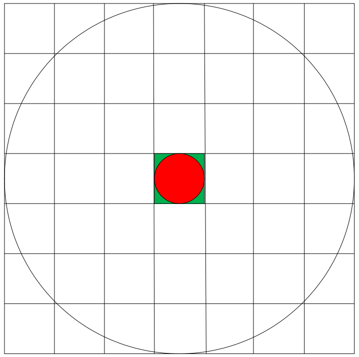
PQ-SPAD: ~1600 nsec



Only MCP/PMTs and Actively-Quenched SPADs (AQ-SPADs) have adequate recovery times for single photon ranging systems. New “silicon photomultipliers” can provide comparable pixellated arrays with 100s to 1000s of small aperture, actively quenched APDs per pixel and **may** have cost, flexibility, and availability advantages as well.

*** J. Degnan, Proc. 16th International Workshop on Laser Ranging, 2008.**

Array Design Trades



7x7 Array

- **Single photon sensitive array detectors to be tested**
  - Segmented Anode Microchannel Plate Photomultiplier
  - Silicon Photomultiplier
- **Number of Pixels (NxN) in the Array**
  - Each set of 50 timing channels requires 1 amplifier and 1 TOF card
    - One set implies $N \leq 7$
    - Two sets implies $N \leq 10$
    - Fewer pixels imply lower cost per array and timing receiver
  - Odd N has the advantage that the receive optical axis falls on one pixel whereas for even N the receive optical axis falls between 4 pixels
  - Using fewer pixels for precise timing of the satellite signal allows the hardware resources to provide significantly better timing resolution by splitting the pixel output into multiple timing channels (typically 4) while also freeing up more channels for the timing of ancillary signals.
- **Per pixel angular coverage**
  - Sets the minimum resolution of the pointing error measurement
  - Should be significantly smaller than the full $1/e^2$ transmit beam divergence to center the Gaussian beam on the satellite
  - Should be large enough to contain the nominal telescope tracking jitter to minimize spillover into adjacent pixels during the integration time between pointing corrections.
- **Total Array FOV**
  - Should not exceed the expected maximum full transmit beam divergence since larger pointing errors will result in zero satellite signal

Other Trades

Detector Board: A modified Detector Board would need to be produced if the physical connector is different from the baseline 10x10 MCP detector used in our 3D imaging lidars, or if a smaller than 10x10 array is selected.

Minimizing Impact to Existing Electronic Architecture: Determine minimum impact to existing architecture for time tagging additional low rate ancillary functions such as a 2 KHz on-time signal, two 1pps signals, and two events from MOBLAS-7 used to tie systems together. Note that separate channels exist for the start pulse as well as an additional 51'st channel for each card. The idea would be to utilize timing channels corresponding to corner pixels of the array for these ancillary functions.

Summary

- The proposed system provides an accurate measure of the magnitude and direction of the angular error between the satellite and the receiver optical axis while simultaneously serving as a Multichannel Event Timer, providing up to 100 channels of multistop ranging data having deadtimes less than 2 nsec. Current unmodified range receiver has an RMS timing accuracy of 23 psec (3.4 mm range). Enhanced timer resolutions down to 1.8 psec (0.3 mm) can be achieved with deadtimes less than 3.4 ns but such enhancements may not be warranted in the presence of larger sources of range error, such as laser pulsewidth, detector impulse response, and satellite signature effects. This will be investigated in our trade study.

- Unlike the NGSLR quadrant approach, the proposed receiver is insensitive to nonuniformities in detector sensitivity or gain and can also eliminate noise counts within the receiver FOV that do not originate in the angular vicinity of the satellite being tracked. For the 10x10 example shown, this eliminates at least 91% of the noise that can bias the satellite centroid range measurement in sufficiently weak HEO passes. Currently, the noise counts are reduced by HTSI in post-processing (see poster at this Workshop by Clarke et al).

- With the exception of the alternate silicon photomultiplier and new SGSLR interface, all of the required components have been successfully demonstrated in Sigma's single photon sensitive 3D imaging lidars at laser repetition rates up to 32 kHz.