Low-Noise Free-Running High-Rate Photon-Counting for Space Communication and Ranging

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ABSTRACT

We present performance data for low-noise free-running high-rate photon counting method for space optical communication and ranging. NASA GSFC is testing the performance of two types of novel photon-counting detectors 1) a 2x8 mercury cadmium telluride (HgCdTe) avalanche array made by DRS Inc., and a 2) a commercial 2880-element silicon avalanche photodiode (APD) array. We successfully measured real-time communication performance using both the 2 detected-photon threshold and logic AND-gate coincidence methods. Use of these methods allows mitigation of dark count, after-pulsing and background noise effects without using other method of Time Gating

The HgCdTe APD array routinely demonstrated very high photon detection efficiencies (>50%) at near infrared wavelength. The commercial silicon APD array exhibited a fast output with rise times of 300 ps and pulse widths of 600 ps. On-chip individually filtered signals from the entire array were multiplexed onto a single fast output. NASA GSFC has tested both detectors for their potential application for space communications and ranging. We developed and compare their performances using both the 2 detected photon threshold and coincidence methods.

Keywords: Detectors, photon-counting, avalanche photodiodes, optical communication, ranging, navigation

1. INTRODUCTION

Laser has been widely used in space instrumentation. They include laser altimeters such as the Mars Orbiter Laser Altimeter (MOLA) [1] and The Ice, Clouds, and Land Elevation Satellite (ICESat) mission [2]. For both of the missions, Siilcon avalanche photodiode (APD) were operating in linear mode as altimeter detector. Photon counting detector is also used in space laser altimeter designs. In the Ice, Cloud, and land Elevation Satellite-2 (ICESat-2)[3] laser altimeters, a 4x4 16 elements photon multiplier tube (PMT) is operating in photon counting mode as the altimeter receiver. Space optical communication and ranging is the other area high speed optical detector are required. In Lunar Laser Communication Demonstration (LLCD)[4], super conducting nanowire detector array are used as photon counting detector for space communication and optical ranging application. All of these applications need high speed, large area, and high optical detecting efficiency. Detector technology researchers and developers are constantly search detectors with these characteristics. In this paper, we are reporting two photon counting detectors and their photon counting mode performances for space optical communication and optical ranging and range rate measurements. The first detector is a Silicon Geiger-mode avalanche photodiode array or Silicon PMT[5], which has large area, single photon sensitivity, and close to 1 GHz high speed response. The high performance and low cost, and simple operating mode are the other advantages of this Silicon PMT detector. The second is Mercury Cadmium Telluride (HgCdTe) linear-mode avalanche photodiode array[6], which has wide optical spectra response window, high linear gain, single photon sensitivity and greater than 50MHz high speed responses. Its single photon sensitivity in linear operating mode and wide optical spectra response window gives this detector an unprecedented advantages in lidar optical sensing and optical communication and ranging.

2. PHOTON-COUNTING THEORY

The probability that k photon will be detected in pulses of average detectable photon rate of λ is described by the Poisson distribution

$$P(k, \lambda) = \lambda^k \frac{e^{-\lambda}}{k!} \quad (1)$$

The theoretical quantum limit for the bit error rate (BER) for on-off keying (OOK) is the error caused by non-detection because of k=0:

$$BER = \frac{1}{2} e^{-\lambda} \quad (2)$$

where λ is the average detected photon rate for the asserted signal. Some single-photon sensitive detectors can nearly achieve this quantum limit. However, dead-time, dark counts, after-pulsing and excess noise are challenges for many photon-sensitive detectors. To mitigate these effects, we compared two methods. In Method 1 we set the detection threshold at the 2-photon level. In Method 2 we use 2-arrays with a high-speed AND-gate for coincidence detection.

To begin, we are modelling our detectors as ideal detectors with no dark counts and after-pulsing. Then, we model the dark counts and after-pulsing are single-photon events (k=1). To remove dark counts and after-pulsing, in the Method 1, we use one detector and set our photon detection threshold to 2-photon level. The BER for Method 1 (Set threshold at the 2-photon level) is the sum of the probability of k=0 and k=1:

$$BER = \frac{1}{2}(1+\lambda) e^{-\lambda} \quad (3)$$

In Method 2, we use 2 identical detectors. We split the signal light evenly 50-50% onto the two detectors. The dark counts and after-pulsing are random process at individual detectors. Such process are not correlated across two detectors. The signal photons, on the other hand, are correlated in time across both detector. We set both detector detection threshold to 1-photon level. The BER for Method 2 (Use 2-arrays with AND-gate and coincidence detection) is given by:

$$BER = e^{-\lambda/2} - \frac{1}{2} e^{-\lambda} \quad (4)$$

In the next Section we compare the experimental and theoretical performance for these methods.

3. FREE-SPACE OPTICAL COMMUNICATION BENCH EXPERIMENTS

3.1 Silicon Geiger-mode avalanche photodiode array

We present a simple method to greatly reduce dark-count and after-pulsing noise to allow high-rate free-running photon-counting receivers. The method borrows some ideas that have been used previously. Those ideas are: 1) use an array of photon-counting elements wired together as a single detector 2) use a high pass filter, ideally on each array elemen (or on the array output to only preserve the information-bearing portion of the waveform), and 3) depending on the photon-counting element excess noise, use either a "two-photon" intensity threshold level or an AND-gate with coincidence detection. We combine those idea to successfully reduce the APD dark counts, after-pulsing and excess noise.

At 850 nm, the commercial fiber data link transceivers are extremely low-cost (< $1k). 20 Gbaud rates were recently demonstrated [7] using an 850 nm Vertical Cavity Surface Emitting Laser (VCSEL) transmitter and a GaAs PIN diode 22 GHz photoreceiver. Commercial tapered amplifiers are available[8] with average powers up to 3 W and quasi-CW peak power to 56 W[9]. For free-space optical communication, atmospheric transmission is slightly lower at 850 nm. The key system component on which free-space communication depends is a high-sensitivity high-bandwidth receiver.

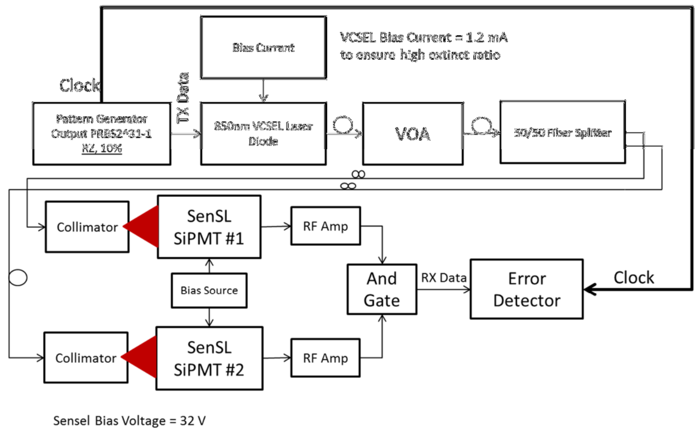

Figure 1. Free-space optical communication bench test diagram for the Sensl APD arrays using coincidence detection. VOA = Variable Optical Attenuator.

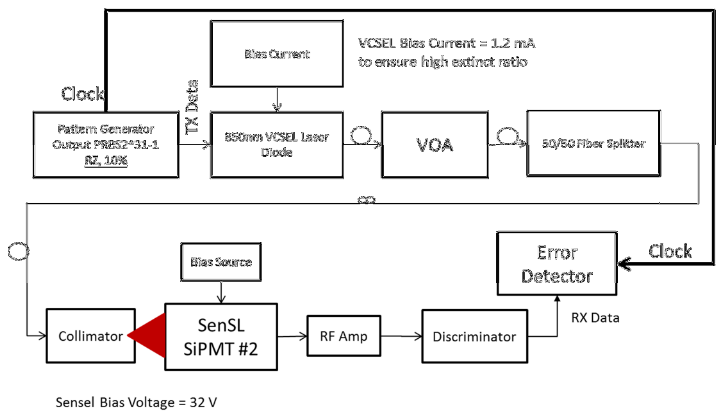

Figure 2. Free-space optical communication bench test diagram for the Sensl APD arrays using 2-photon threshold. Detector 1's RF amplifier output is left unconnected.

Figure 1 shows our free-space optical communication experimental set-up for the Sensl APD arrays using coincidence detection. Figure 2 shows our two-photon threshold experimental setup for the same Sensl APD array.

In our experiment, we used an inexpensive Finisar 850nm VCSEL transmitter and silicon avalanche photodiode array detector (Sensl Model MicroFC-SMA-10010). The binary data stream from a pattern generator was a Pseudo-Random-Bit-Sequence (PRBS) of length 2^{31} -1. We calibrated the detected-photon rate (λ) by fitting the experimental intensity histograms (detected-photon number data) in Figure 3 to the Poisson theory. We used a narrow Return-to Zero (RZ) transmitter pulse format (10% duty cycle) to reduce temporal jitter with this and other photon-counting receivers.

With the setup shown at Figure 2, we could not close the link using the real-time BER Test set (BERT) when we set the detection threshold at the one detected-photon ("1p") level. However, we successfully measured real-time communication performance with the 2 detected-photon ("2p") threshold setting (Figure 2) AND-gate coincidence methods (Figure 1). Use of these methods also improves the performance in the presence of background noise. The bit-error ratio vs. number of detected-photons is shown in Figure 3 for a 100 Mbps pseudo-random RZ data with no background noise.

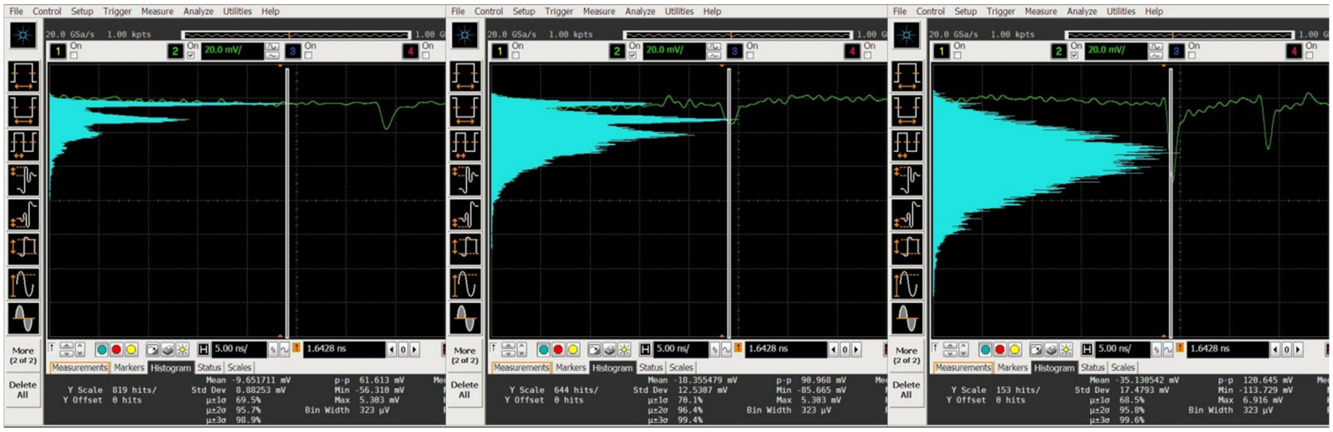

Figure 3. Sensl silicon APD photon number discrimination for a) $\lambda = 0.8$ b) $\lambda = 1.7$ and c) $\lambda = 3.2$

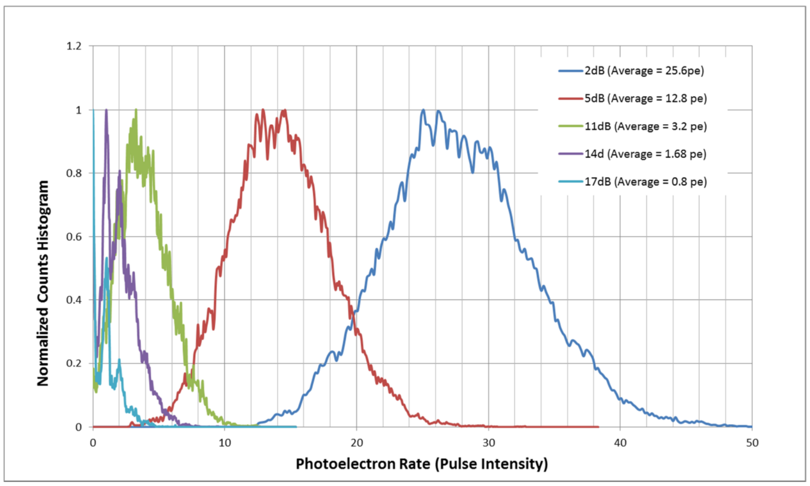

Figure 4. Sensl silicon APD pulse height distribution at various photon rate per pulse.

The Sensl detector jitter was measured using a 100 ps laser pulse from Picoquant at 1030 nm wavelength. 5000 pulses were accumulated for each jitter measurement. We measured 120 ps rms jitter for the Sensl detector.

Figure 5 shows a plot comparing these theories to experimental data using the Sensl silicon APD array.

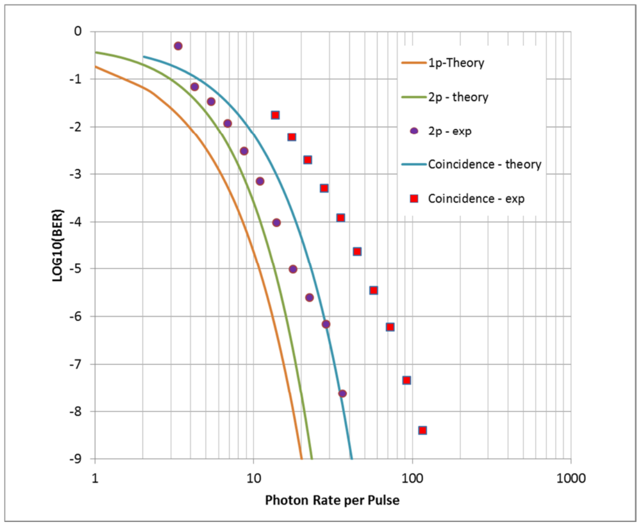

Figure 5. Bit Error Ratio (BER) vs. number of detected-photons per asserted signal for Sensl silicon APD array experimental data with AND-gate coincidence, 2 detected-photon (2p) and quantum limit (1p) threshold theories.

The experimental bit error ratio of two Sensl silicon APD arrays with AND-gate coincidence detection (and 85 kcps background noise per detector) is shown in Figure 6 for several data rates. Due to the limited bandwidth of our chosen VCSEL transmitter, our experiment stops at 400Mbps. In the future, we hope to extend our experiment to at least 1Gbps with a faster transmitter.

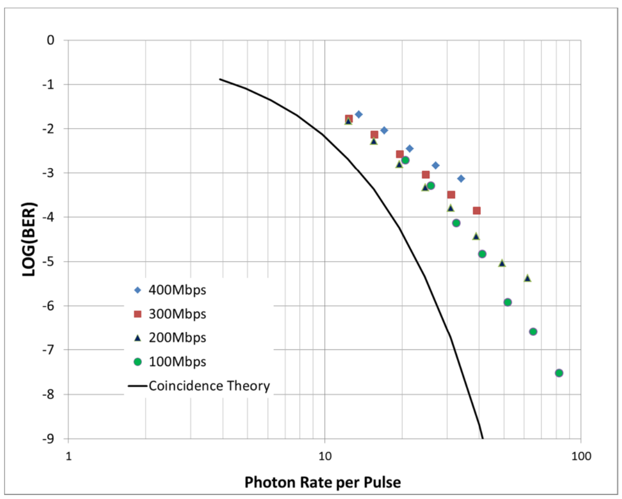

Figure 6. Experimental bit error rate using two Sensl silicon APD arrays with AND-gate coincidence detection (and 85 kcps background noise) at several data rates.

3.2 Mercury Cadmium Telluride (HgCdTe) linear-mode avalanche photodiode array

DRS Inc. has produced a set of 2x8 pixel Linear-Mode Photon-Counting (LMPC) Focal Plane Arrays[10] capable of detecting single photon events at >60% photon detection efficiency (PDE) at about 150 kcps dark count rates and producing an impulse response of about 8-ns. This HgCdTe APD array has photon detection efficiencies of greater than 50%, as was demonstrated across 5 arrays, with one array reaching a maximum PDE of 70%. High resolution pixel-surface spot scans were performed and the junction diameters of the diodes were measured. The junction diameter was decreased from 31 µm to 25 µm resulting in a 2x increase in e-APD gain from 470 (on an array produced in 2010) to 1100 on the array delivered to NASA GSFC in 2015. Mean single photon SNR's of over 12 were demonstrated at excess noise factors of 1.2-1.3. Further improvement in the timing performance and noise are expected from the next lot of the devices currently being fabricated. Two proton radiation damage tests have been performed and the results showed the devices can be used in a multi-year Earth orbiting mission. One of these detectors (which was funded by the NASA In-space Validation of Earth Science Technology - InVEST program[11]) will be integrated with a small cryocooler and will fly on a CubeSat in late 2016. All of these new LMPC HgCdTe APDs have a much superior cost*performance product vis-à-vis the currently available photodetectors in the SWIR wavelength and are expected to meet a vital need for high speed single photon detectors in MWIR wavelength region.

All of our test data for the HgCdTe APD is taken at an operating temperature of 77K. A surface scan of a single pixel (made of 4 mesas) is shown in Figure 7.

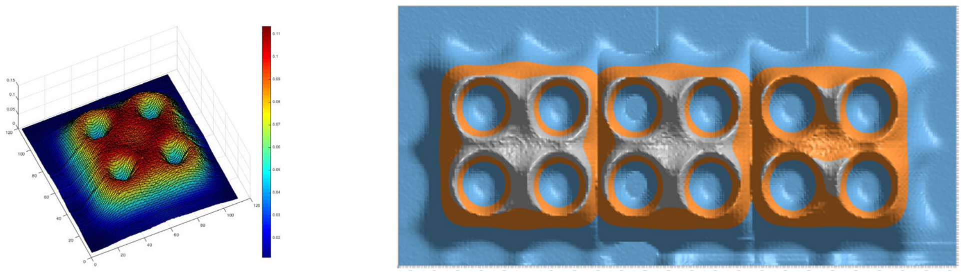

Figure 7. DRS HgCdTe APD surface scan of illuminated a) single pixel consisting of 4 mesas with 11 V applied b) 3 pixels.

The pulse height distribution for several fixed intensity levels is shown in Figure 8. We calibrated the detected-photon rate by fitting the experimental intensity histograms (detected-photon number data) in Figure 8 to Poisson theory.

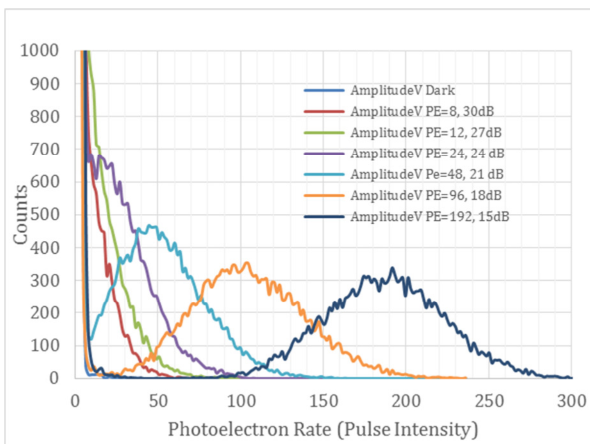

Figure 8. DRS HgCdTe APD pulse height distribution at several intensities.

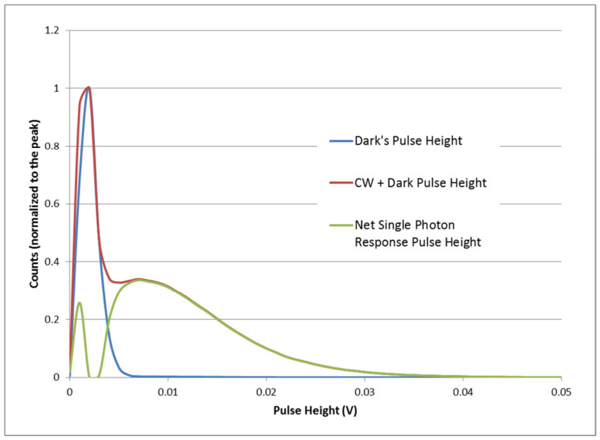

Figure 9. DRS HgCdTe APD pulse height distribution comparison between dark counts and signal pulse response to CW light (1-pe). The detector output pulse waveforms are captured by an oscilloscope and each waveform is smoothed by a σ =10ns Gaussian Filter. The net single photon response shows high excess noise.

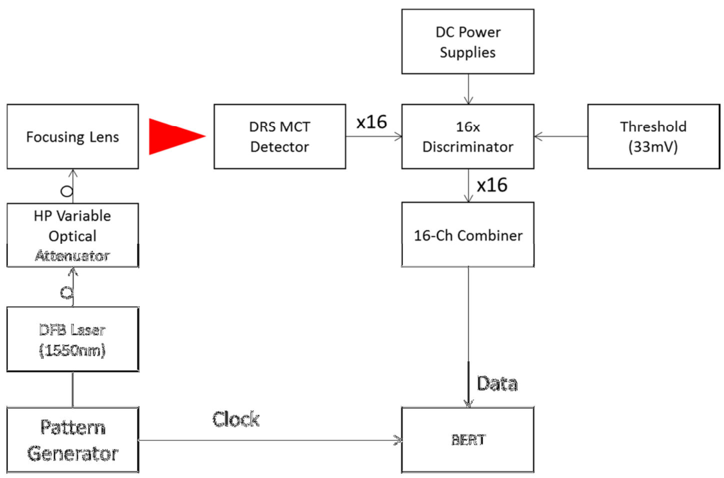

Figure 10. Free-space optical communication bench test diagram for the DRS Mercury Cadmium Telluride (MCT – a.k.a. HgCdTe) APD array.

Our bit error ratio tests of the DRS APD array were conducted at 1550 nm wavelength using an RZ pulse waveform with 10% duty cycle OOK, i.e. RZ-OOK, at a data rate of 50 Mbps. The test set-up block diagram is shown in Figure 10. Figure 11 shows the experimental and theoretical communication performance of a single pixel of the DRS HgCdTe APD array.

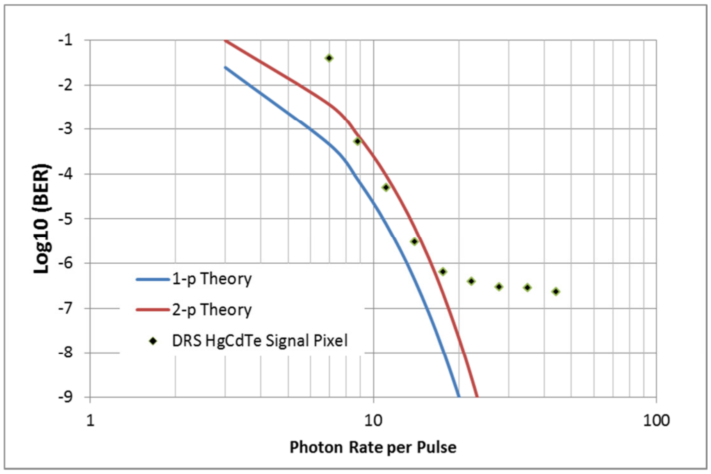

Figure 11. DRS HgCdTe APD experimental BER data with RZ-OOK 50 Mbps data rate with PRBS=2^31-1 from a single pixel compared to 1 and 2 detected-photon threshold theories.

Using a 2x4 subsection of the DRS HgCdTe 2x8 APD array, we added a high-pass filter to each pixel's external output and combined the 8 pixel filtered outputs with an impedance-controlled electrical combiner to demonstrate a real-time communication through the Bit-Error-Ratio Tester at 110 Mbps (RZ-OOK 10% duty cycle) at 8×10^{-8} BER. With this duty cycle (10%), the maximum data rate is limited by the detector timing jitter (measured as ~900 ps). Further improvements are needed in the electrical combiner circuitry to optimize the system.

4. FREE-SPACE OPTICAL RANGING BENCH EXPERIMENTS

4.1 Silicon Geiger-mode avalanche photodiode array

We reconfigured the communication bench test setup to test the photon counting accuracy with a ranging clock code (Figure 12). Our test utilizes our dual-mixer time different (DMTD) ranging setup. The work has been reported in IEEE Aerospace Conference 2016[12]. The DMTD setup has a noise floor of 10^{-16} which is limited by the timing resolution of the Agilent Time Interval Counter. Our original DMTD experiment is performed in a benchtop setup with 622Mbps data communications link. In the single frequency amplitude modulation mode, it achieved a two-way ranging accuracy of 0.8 um/s with 10 second averaging time.

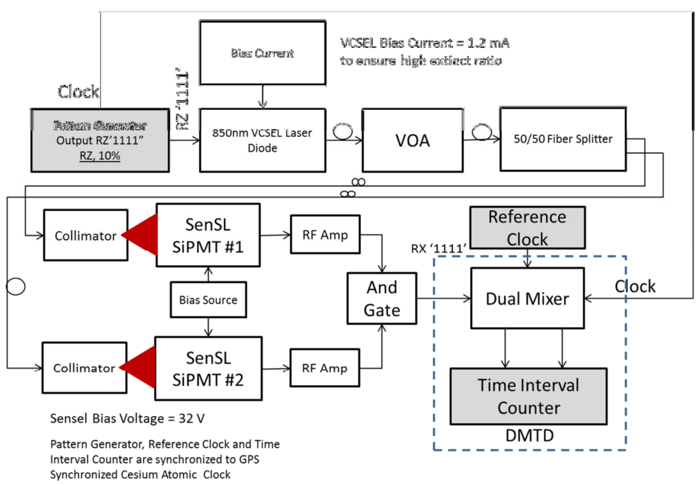

Figure 12. Free-space optical ranging bench test diagram for the Sensl APD arrays using co-incident detection.

The input ranging code is RZ '1111' pattern with 10% duty cycle at 100MHz clock rate. The reference clock is set at 1kHz offset from 100MHz. Pattern generator, reference clock generator and Time Interval Counter are all synchronized to the 10MHz reference from a GPS Synchronized Cesium atomic clock.

We measured the ranging accuracy with various detected photon rate. Figure 13 shown time interval results Modified Allen Deviation at various averaging times. The slopes of the Modified Allen Deviation suggest the existence of random phase walk noise which is from photon counting detector's temporal jitter.

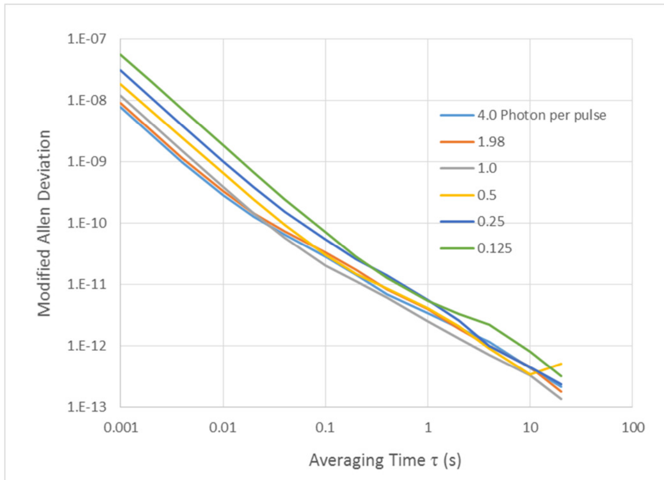

Figure 13. Modified Allen Deviation of the Sensl APD using co-incident detector for photon counting free-space optical ranging over 100MHz optical link.

At this current stage, we calculated that the Sensl APD arrange using co-incident detection, we can achieve millimeter ranging accuracy at 1s averaging time (See Table 1)

Table 1. The one-way ranging accuracy for 1 second averaging time of the Sensl APD using co-incident detection.

# ph per pulse	4	2	1	0.50	0.25	0.125
Modified Allan Deviation	3.48E-12	3.97E-12	2.49E-12	4.06E-12	5.54E-12	5.49E-12
Ranging Error (mm/s)	1.0	1.2	0.7	1.2	1.7	1.6

4.2 Mercury Cadmium Telluride (HgCdTe) linear-mode avalanche photodiode array

We repeat the photon counting ranging test with DRS HgCdTe detector. The accuracy is dominated by each pixel's temporal jitter, we decide to only use one pixel for the ranging test. The pattern generator outputs 10MHz RZ '1111' ranging clock code to trigger a PicoQuant Pulse Laser. The pulse laser generates 100ps FWHM (Full Width Half Maximum) laser pulses at rising edges of the ranging clock and minimizes the detector's output temporal jitter to about 800 ps. The DMTD reference clock is set to 1kHz offset from 10MHz.

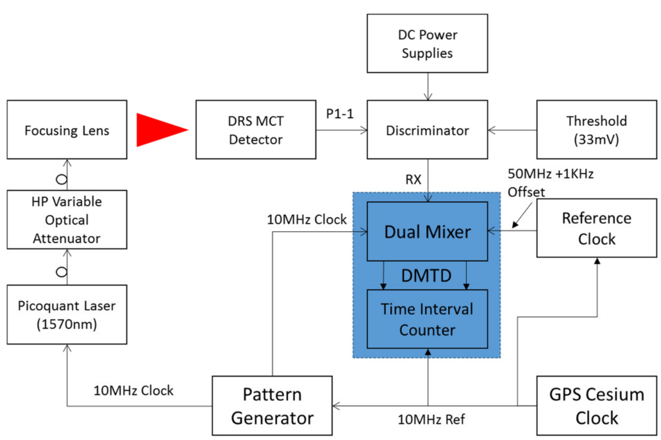

Figure 14. DRS HgCdTe APD Ranging Experiment with Short Pulse RZ-OOK 10MHz from a single pixel.

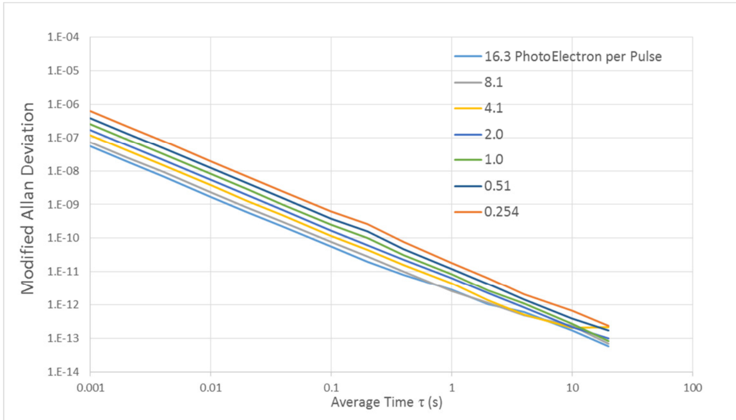

Figure 15. Modified Allen Deviation of the DRS HgCdTe APD detector single pixel for photon counting free-space optical ranging over 10MHz optical link.

We calculated that the ranging accuracy of the DRS HgCdTe APD single pixel has ranging accuracy just about 1 mm with 1 second average time.

Table 2. The one-way ranging accuracy for 1 second averaging time of the DRS HgCdTe APD with single pixel simple detection thresholding.

# of Photoelectron per pulse	**16.3**	**8.1**	**4.1**	**2.0**	**1.0**	**0.5**	**0.25**
Modified Allen Deviation	2.78E-12	2.63E-12	4.40E-12	6.49E-12	8.35E-12	1.19E-11	1.83E-11
Ranging Error (mm/s)	0.84	0.79	1.32	1.95	2.50	3.58	5.50

5. SUMMARY

We demonstrated high-data-rate (up to 400 Mbps) free-space optical communication with a photon-counting receiver using three ideas: 1) use an array of photon-counting elements wired together as a single detector 2) use a high pass filter, ideally on each array element (or on the array output to only preserve the information-bearing portion of the waveform) and 3) depending on the photon-counting element excess noise, use either a “two-photon” intensity threshold level or an AND-gate with coincidence detection. Use of these methods allows mitigation of dark count, after-pulsing and background noise effects without using time gating. Commercial 850 nm VCSEL transmitters and silicon APD Geiger-mode arrays provide a viable path to low-cost high-rate (500 Mbps) free-space optical communication links. We achieved excellent communication performance at 50 Mbps @1550 nm with single-pixel HgCdTe APD and demonstrated external filtering and multi-pixel array combining to achieve 110 Mbps data rate.

We also demonstrated photon counting ranging with both APD detectors at very low (<1) photon rate per pulse. We achieved millimeter level of accuracy. This accuracy would generally satisfy the navigation needs for space exploration. The performance will be improved if we can further reduce detector temporal jitter and operate the detector at higher data rate. We look forward to see if the photon counting ranging performance can be improved to meet strict science mission requirements. The encouraging overall performance on both data communication and ranging accuracy opens many possibility for future space application on data communication and ranging.

6. FUTURE WORK

Under a lidar receiver program, we are developing a resonant-cavity silicon APD array[13] optimized for use at 1030 nm wavelength. For optical communications, a similar device optimized for use at 850 nm wavelength is promising. At 1550 nm wavelength, we hope to pursue an array of InGaAs Negative-Feedback-Avalanche-Diodes[14] (NFAD). We believe that >1 Gbps with a single array (in InGaAs) and multi-Gbps with WDM should be viable. We plan to improve the electrical combiner circuitry for the HgCdTe APD. Including this circuitry as part of a Read-Out-Integrated Circuit (ROIC) would be ideal. The HgCdTe APD temporal jitter can be improved by incorporating an external electric field into the device design.

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