PHOTON COUNTING LADAR

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Introduction

Photon counting differs from macro CW detection in that the statistics are dominated by single photon events. Photon counting receivers have been developed in two flavors; Geiger Mode and Linear Mode receiver types. Both receiver types are implemented using Avalanche Photo Diodes (APD) at relatively large gains. The main difference with the two operating modes is that in Geiger Mode the APD is overbiased into avalanche region, and once triggered will not respond to a follow on signal until it is reset. In Linear Mode, a detected photon appears as a pulse lasting about a nanosecond, depending on the bandwidth of the receiver, and multiple return photons can be detected in rapid succession. The advantage of Geiger Mode is that the signal generated from a single detected photon is large enough to trigger a counter, whereas a Linear Mode APD requires pre-amplification and thresholding circuitry before triggering a counter. Figure 1 shows a block diagram depicting both methods.

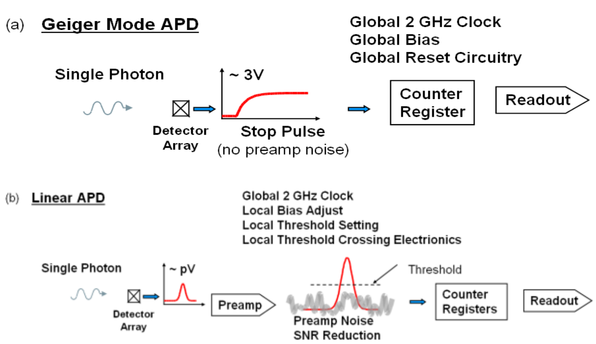

Figure 1: Simplified Block Diagram for (a) Geiger and (b) Linear Photon Counting Receiver (global items are used for the whole FPA, local items are needed one per unit cell)

In this paper, we show the statistical description of photon counting for ladar applications and compare both approaches, Linear and Geiger, to try to understand what are the advantages and disadvantages of each. Finally we will specify the quality of the Linear Mode preamp required to get performance similar to that of a Geiger Mode receiver.

Photon Counting Detection Statistics

Photon Counting detection, be it Geiger or Linear Mode, is a relatively new method for ladar systems. The detection statistics of this method of operation are distinct enough from conventional ladar detection that it requires a separate discussion. O'Brien and Fouche [1], and Osche [2] have developed and described performance statistics in the cited references.

A Geiger receiver operates by temporarily overbiasing an APD detector for a period called the range gate time, in which we expect return signal photons to arrive. A Linear receiver also has a finite range gate time, to also limit false triggers. During the receiver range gate time, there are three possible detection events that can trigger the receiver; the detection of a desired target photon, the detection of an undesired foreground clutter photon, or the undesired detection of a dark electron. Photons or dark current electrons that trigger a photon counting receiver are indistinguishable after the fact, and in the Geiger Mode case, where only one event is possible per measurement period, these three possibilities compete against each other in statistical fashion. In linear mode, the LMAPD (linear mode APD), these three possible types of events also compete, however, one will not inhibit the other, in other words, the target photons, the undesired foreground clutter photons, and dark current electrons, are all detected in an indistinguishable fashion.

Osche [2] shows that, when the received signal is subject to speckle uncertainty, the probability of detection is decreased. The modified detection probability is

$$P_{d1} = 1 - \left(\frac{\mathcal{M}}{\mathcal{M} + N_t} \right)^{\mathcal{M}} \exp(-n_n),$$

(linear) (1)

where $\mathcal{M}$ is the number of speckle lobes on the detector. This equation can be used as is for linear mode, but more is needed for Geiger mode.

In Geiger mode, a noise or dark triggers before the expected arrival of target photons inhibits their detection the same as clutter in front of the target. If the target of interest is obscured by some clutter, with N_c clutter photons detected before the target, the probability of target detection would be further decreased by multiplying by the probability of NOT detecting the clutter. Eq. (1) becomes,

$$P_{d1} = \left[1 - \left(\frac{\mathcal{M}}{\mathcal{M}+N_t}\right)^{\mathcal{M}} \exp(-n_n)\right] \cdot \left(\frac{\mathcal{M}}{\mathcal{M}+N_c}\right)^{\mathcal{M}} \exp(-n_n J/2),$$

(Geiger) (2)

where J is the number of range bins in the range gate interval, and the return from the clutter is also assumed to be subjected to degradation from the speckle effect. Eq. (2) represents the probability of detection of a single pulse of a Geiger receiver, but eq. (1), which is not inhibited by noise, represents a Linear Mode receiver.

In Figure 2 we plot the probability of detecting the target when it is in the open, fully exposed, and also when it is 90% obscured. In the obscured case, the clutter return, which is at a closer range than the target, is assumed to be 9 times larger than the target (90% obscuration), inhibiting the probability of detecting the target in Geiger Mode.

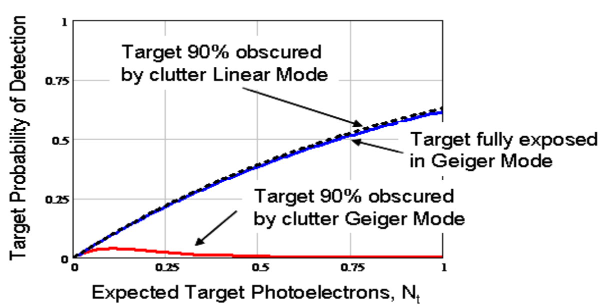

Figure 2: Probability of Target Detection as Function of Expected Photoelectrons Returns from Target.

If there are J range bins in one range gate, then the probability of a false alarm anywhere during the range gate is given by,

$$P_{fa1} = 1 - \exp(-n_n J) \qquad (3)$$

where $n_n \times J$ (expected dark counts per bin $\times$ the number of bins in the range gate) is the number of expected dark counts in the range gate interval. In the example of figure 2, the probability of dark count false alarm is 0.01.

As shown in the above example, the probability of detecting a single pulse with a Geiger Mode receiver can be fairly low, and cannot be improved by increasing the laser transmitter pulse energy as would be possible with a linear type of detection scheme. In order to make a useful image, the probability of detection must be improved, and one way to accomplish this is to divide the energy into multiple transmitter pulses, i.e. to roll the dice multiple times.

When using multiple shots to detected a target, not only does the detection probability increase, but also the probability of a false alarm, because of the additional opportunities for false detections to occur. One thresholding technique to control the level of false alarms is called coincidence detection. Coincidence detection assumes that when multiple 3-D frames or voxels are superimposed (added to each other) correctly, the target signal would tend to remain in the same voxels, while noise detections occur in random range bins. By using *m* out of *n* detections, the target returns are favored from the noise returns, thus improving the probability of detection versus the probability of false alarm ratio. The *m* out of *n* detection probability is a traditional detection method, and is given by the binomial expression,

$$P_d(m,n) = 1 - \sum_{j=0}^{m-1} \binom{n}{j} P_{d1}^{j} (1-P_{d1})^{n-j} . \qquad (4)$$

i.e., there are at least *m* out of *n* target detections, where P_{d1} is the detection probability of a single target return.

For the same example of the 90% obscured target, we evaluate eq. (4) with a threshold setting, *m* = 2 (*m* of *n* detection). We plot the probability of detection as a function of the total expected number of detected photons per train of *n* pulses, in figure 3. In this Geiger Mode example, the peak probability of detection for $n = 10$ occurs when $N_t \times n = 1$, or $N_t = 0.1$. Also, when $n = 100$, the peak is near 10, or $N_t = 0.1$, which was the peak for the single shot statistics. As *n* increases, the probability of detection approaches unity, maintaining the total expected return near 10 photo-electrons. In Geiger Mode we see that if we increase the total transmitted energy, there will almost always be a return from the obscurant, which will inhibit the target return and drive its detection probability down. The dotted line representing the Linear Mode with only 10 pulses, follows the Geiger Mode of >200 pulses very closely, without the drop due to the inhibition. In other words, in Geiger Mode, one has to break up the signal into multiple pulses (> 100) to be able to see a target behind clutter (camouflage or canopy), but in Linear Mode, just a few pulses are enough.

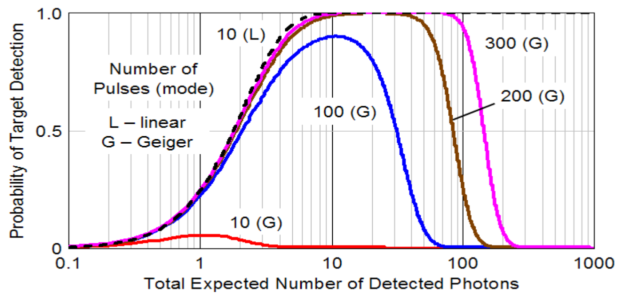

Figure 3. Probability of Target Detection in Linear (L) and Geiger (G) Modes for Various Number of Shots, n = 10 (L & G), 100 (G), 200 (G), 300 (G), and Threshold, m, set at 2 (of n).

If we were to create a histogram of the 100 returns for Geiger Mode detection, we would see with high probability at least two counts from the target at the target range bin, and over 90 counts at the range where the obscuration clutter resides. By creating a histogram of multiple trials (pulses) one can recreate the amplitude measurement that would be obtained from a single higher energy pulse detected with a linear (non-Geiger) type receiver, i.e. a high return from the clutter and a faint second return from the target.

The probability of *m* detections out of *n* trials for false alarm is calculated in a similar fashion as the probability of detection expression. The *m* out of *n* detection means that at least *m* false returns must coincide in the same range bin. Similarly as eq. (4), we write the expression for the false alarm as the binomial series,

$$p_{fa}(m,n) = 1 - \sum_{j=0}^{m-1} \binom{n}{j} p_{fa1}^{j} (1 - p_{fa1})^{n-j} \text{ . (5)}$$

where p_{fa1} is the probability of a false count at a specific range bin. Equation 5, is the probability of false alarm for a single range bin using *m* of *n* detections. If we assume that the target returns are few, such that they don't appreciably inhibit the false returns in the *n* frames from the *n* pulse train, then the probability of a false alarm anywhere in the range gate is,

$$P_{fa}(m,n) = 1 - (1 - p_{fa})^{J} \text{ . } \qquad (11)$$

Part of optimizing a GMAPD ladar is to decide the number of pulses and energy per pulse required to maximize the probability of detection. Fig. 4 shows contour plots of the total probability of detection of the target, for Linear and Geiger cases. We assumed that clutter (canopy or net) is obscuring the target by 90%, the range gate is 1 μs, the range bin is 1 ns, threshold is 2 coinciding returns, and the total expected noise is 0.01 and 0.5 respectively.

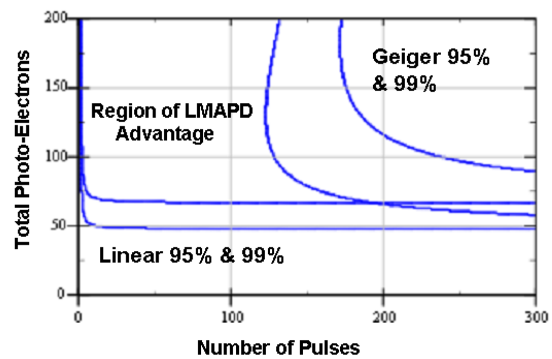

Figure 4. 95% and 99% Probability of Detection Contours for a 90% Obscured Target, for both LMAPD and GMAPD Detection (photo-electrons are from both target and clutter)

Notice that when P_d is the same for both methods, the curves meet when the energy is distributed over a large enough number of transmitted pulses. Clearly, when targets are obscured, and if there are timing constrains that requires the image to be generated faster with fewer transmitted pulses, then the Linear Mode detection will have a great advantage.

In general, for the Geiger Mode detection to meet high P_d, especially in the presence of noise, the transmitted energy will have to be broken up into multiple pulses. This complexity and added operational requirement is offset by the high power efficiency and readout simplicity of this approach. Geiger Mode APD based receivers are gaining much ground were large detector arrays are desired, especially in high area mapping missions.

Linear Mode Photon Counting Detection

So far, we have compared the Linear Mode, LM, to the Geiger Mode, GM receiver, assuming they both have the same intrinsic performance, meaning the same dark counts and the same probability of detection (trigger) for a photon event. Typical operational performance of GMAPD operating at $\lambda \sim 1$ μm is to have a single photon probability of avalanche trigger of ~ 35%, and a dark count rate of ~ 3 kHz [3]. In this section we will look at some the key requirements to have a LMAPD operate at similar performance. Specifically, the LMAPD signal must be amplified by a Trans-Impedance Amplifier, TIA, to generate a signal that can be used by digital logic circuitry as depicted in Figure 1. The GMAPD creates signals due to the avalanche, already in the 3 V region that can directly trigger a digital counter. The inherent need of the TIA to the LMAPD imposes a noise requirement on the TIA that may me hard to meet.

The Threshold is adjusted such that the probability of detecting a single photon reaches ~ 35% that is observed in the GMAPD detectors. We assume that all the significant false counts are due to the TIA (i.e., the detector has negligible dark current), and the APD as a perfect gain, yielding a unity excess noise factor, $F = 1$. For the numerical models, we will relax that assumption of perfect gain. Based on these assumptions, the expected results for the noise requirement of the TIA will be somewhat optimistic. Figure 5 shows the plots of expected dark or false counts as function of the TIA noise, given in terms of Amps/root-Hz, for APD gains of 100, 500, 1,000, and 2,000.

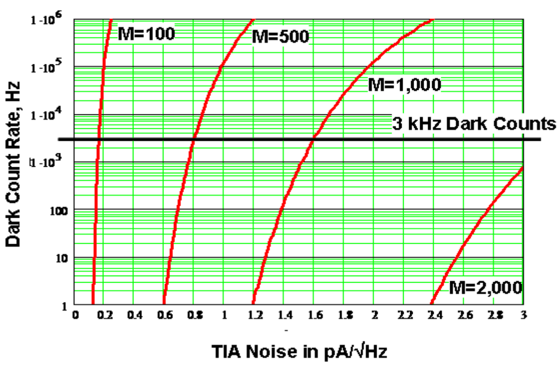

Figure 5. Dark or False Counts as Function of the TIA Current Noise in pA/root-Hz, for APD gains of 100, 500, 1,000, and 2,000

The NEP that yields the dark counts of ~ 3 kHz are read from the graph and listed in Table 1.

Table 1: Preamp Input Referred Noise for 3 kHz Dark Count Rate for Various APD Gains

M	$pA/\sqrt{Hz}$
100	0.18
500	0.8
1,000	1.6
2,000	3.2

TIA's consist typically of a high gain amplifier with feedback impedance. If the impedance is resistive, just the Johnson (thermal) noise of the resistor will create noise levels comparable or greater than the maximum tolerated. A survey of commercial discrete low noise devices, shows that for a bandwidth of ~ 1 GHz, it is challenge to find devices with noise floors below 5 pA/root-Hz. Even more challenging would be packaging the circuitry into the small unit cell of a receiver FPA of 50-100 μm pitch. In addition to the TIA preamp, threshold setting and logic must be implemented per detector element. All this circuitry creates an additional challenge when a large FPA desired (64x64, 128x128, or larger). If all the circuitry does not fit in a single unit cell, the rest must be fanned out to the periphery of the array, requiring signal wires crossing over the entire array. This will limit the size of the FPA that would be achievable, especially when very low noise must be maintained.

As mentioned earlier, as difficult as it is to meet the TIA requirements in Table 1, those requirements are expected to be optimistic, because among other things, we assumed that the APD gain would be perfect (not distributed around an average). This has recently been discovered to be possible with HgCdTe material, when operating in electron only carrier [4], [5], [6]. Other materials will have a gain distribution following the McIntyre model [7]. This will reduce the ability to sense a single photon event, because now it would not always appear as a fixed current step but distributed according to the APD gain distribution

Conclusions

We described a model of photon counting for both Linear and Geiger Mode receivers. With this model, the design parameters of a ladar can be adjusted by determining laser average power, pulse rate and number of pulses per measurement, to meet specified detection and false detection probabilities. We showed that Geiger Mode detection improves detection under obscuration by increasing the number of pulses in which the total energy is divided. We also showed that when the number of pulses is high enough, the Geiger Mode approaches the Linear Mode in detection performance.

Model results indicate that a challenging low noise level will be required to make the LMAPD comparable to the GMAPD noise performance. A comparable level of performance has not been achieved for LMAPD, yet it may be possible in the future.

We showed, however, that when targets are moving fast and the measuring time or measuring number of pulses is limited, that LMAPD may have a clear advantage, since GMAPD may not have a solution [10]. In addition, when trying to determine target reflectivity by measuring intensity (photon returns bunched into greater than unity) the LMAPD can make the measurement with much fewer pulses. The total energy per measurement would still remain the same as when multiple pulses are used. Of course, in order to perform intensity measurements with LMAPD, additional circuitry must be added to the already crowded detector unit cell, or be fanned out to the periphery. Complexity of hardware will have to be weighed against complexity of post processing and time of measurement.

For efficient Linear Mode Photon Counting, we showed that material that is not bounded by McIntyre statistics has a clear advantage as far as how low the TIA noise must be. So far only HgCdTe, operating with electron only ionization, seems to give unity excess noise factor, independent of gain.

The achieved dark counts for the GMAPD are in the neighborhood of 3 kHz. For the same P_d and P_{fa} (per pulse) the LMAPD is in the order of 300 kHz. An improvement of about 100 is needed. Finally, the ROIC Circuitry needed for the LMAPD mode receiver is considerably larger then for GMAPD mode, which may limit the size achievable in future arrays.

REFERENCES

[1] M. E. O'Brien and D. G. Fouche, "Simulation of 3D Laser Radar Systems," Lincoln Laboratory Journal, vol. 15, no. 1, p. 37 (2005)

[2] G. R. Osche, "Optical Detection Theory for Laser Applications", Wiley-Interscience (2002)

[3] J. C. Boisvert et al., "Large Area InAlAs/InGaAs single-photon-counting avalanche photodiodes," Proc. SPIE, vol. 5412, p. 126 (2004)

[4] J. Beck et al., "Performance and Modeling of the HgCdTe e-APD for Active Systems Applications," Meeting of the Military Sensing Symposia (MSS) Specialty Group on Active EO Systems, vol. 1 (2008)

[5] J. Asbrock et al., "Ultra-High sensitivity APD based 3D LADAR sensors: linear mode photon counting LADAR camera for the Ultra-Sensitive Detector program," Proc. SPIE, vol. 6940, 69402O (2008)

[6] G. M. Williams, "GHz-rate single-photon-sensitive linear-mode APD receivers," Proc. SPIE, vol. 7222, 72221L (2009)

[7] R. J. McIntyre, "The Distribution of Gains in Uniformly Multiplying Avalanche Photodiodes: Theory", IEEE Transactions on Electron Devices, vol. ED-19, no. 6, p 703 (1972)

[8] J. Conradi, "The Distribution of Gains in Uniformly Multiplying Avalanche Photodiodes: Experimental," IEEE Trans. Electron Devices, vol. ED-19, no. 6, p. 713 (1972)

[9] P. P. Webb, R. J. McIntyre, and J. Conradi, "Properties of Avalanche Photodiodes", RCA Review, vol. 35, p. 234 (1974)

[10] G. M. Williams and A.S. Huntington, "Probabilistic analysis of Linear Mode vs. Geiger Mode APD FPAs for advanced LADAR enabled interceptors," Proc. SPIE, vol. 6220, 622008 (2006)