The Saphira array's charge packet size distribution

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ABSTRACT

The Saphira electron avalanche photodiode (eAPD) array provides unprecedented low noise performance at near-infrared wavelengths, providing new opportunities for high-performance AO wavefront sensors. Recent investigations have examined the pulse-height distribution at low flux rates to search for a peak corresponding to single photon events, but no such peak has been clearly identified. In this paper we show that the pulse height distribution is in fact quantized at a value of approximately gain/3.

Keywords: infrared arrays, avalanche photodiodes, photon counting detectors

1. INTRODUCTION

The Saphira electron avalanche photodiode array was developed and characterized by the European Southern Observatory and the Leonardo company. Its intended use was in the Gravity instrument at the VLT observatory.[1] This detector is constructed of two HgCdTe layers, one responsible for converting photons into electrons (the "detector layer"), and a second layer responsible for the avalanche process which features charge multiplication that exceeds the read-noise allowing sub-electron readnoise measurements. Since its successful rollout, this detector has been highly sought after due to it's exceptional low-noise performance and has now been characterized by several other groups.[2,3]

A perfect detector with operating with avalanche gain G would produce exactly G electrons for each photon collected. In this case, the measured noise would be equal to the shot noise distribution from the incoming photons. In reality there is likely a distrubution in the number of electrons produced resulting in a higher noise level. The ratio of the measured noise to the theoretical shot noise is known as the noise factor. In electron-multiplication CCDs the multiplication process is well understood and is known to be approximately 1.4. The packet size distribtion is not quantized in the EMCCD case. In the Saphira array there was an expectation that the noise factor would be lower and initial measurements seemed to bear this out,[1] but more recent measurements indicate that it is more like 1.4.[3]

In this investigation we wish to understand whether the underlying distribution of produced packets is quantized or broad. We carried out our experiment using a CRED-ONE camera built by First Light Imaging.[4] This camera was purchased as part of a prototype phasing sensor for the Giant Magellan Telescope.[5]

The data are comprised of many sequences of 200 images taken with non-destructive readout, each 1.4msec long. We compute the differences between adjacent frames. We took frames first with no light and then with a low flux level of less than 1 photon per pixel per frame. The avalanche gain was set to 150. (Note that subsequent to taking these data we have been advised not to operate the detector with gain > 100 to avoid damage to the detector). The histogram of pixel values is shown in Fig. 1.

If the avalanche process produced exactly 150 electrons per photon we would expect to see peaks in the histogram at 0, 150, 300, etc. The observed histogram shows no obvious single peak at $150\,e^-$. This is consistent with previously published results.[2,3]

In this paper we investigate further whether the underlying distribution of charge packet sizes produced in the avalanche process can be inferred from these two histograms.

2. METHOD

We begin with a simple thought experiment. If every pixel contained exactly $150\,e^-$ in addition to the dark current and noise, then the resulting histogram would be equal to the dark histogram, but shifted to the right by $150\,e^-$. This is illustrated in in Fig. 2.

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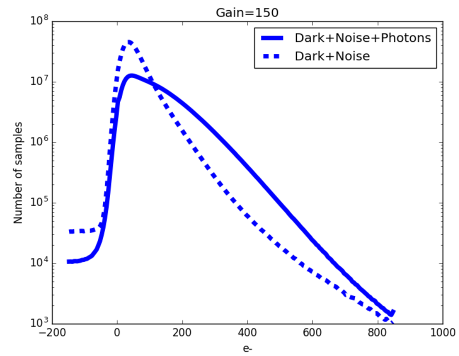

Figure 1. Observed histograms of pixel value, with and without photons

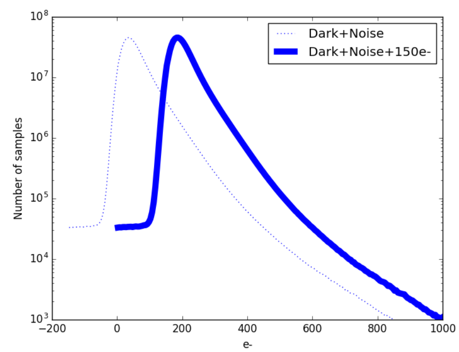

Figure 2. Resulting histogram if every pixel had exactly 150 e^- in addition to dark current and noise

If there is a distribution of charge packet sizes $P(n)$, then the resulting observed histogram will be a superposition of shifted histograms, as illustrated in Fig. 3.

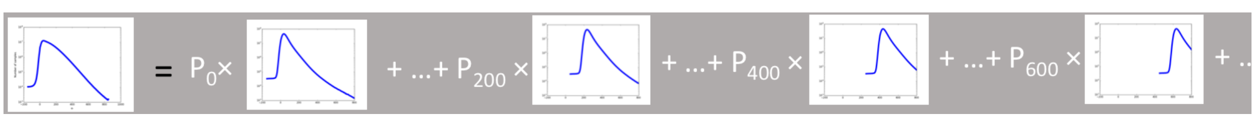

Figure 3. The observed histogram is a superposition of shifted histograms.

Formally this can be expressed as follows: Let $P(j)$ be the fractional number of pixels with actual charge j when the detector is illuminated with photons. This is the quantity we wish to determine. We observe the two histograms $D(j)$, and $L(j)$ the fraction of pixels with measured charge j under dark and light illumination conditions. We must solve for P in the matrix equation $A \cdot P = L$. The i-th row of A is the shifted dark histogram: $A_i(j) = D(j-i)$. We solve for $P(j)$ using non-linear least squares, thus enforcing the constraint that $P(j)$ is everywhere positive or zero.

3. RESULTS

Fig. 4 shows the result of the least squares solution for gain $G = 150$. Somewhat unexpectedly, the derived charge distribution P does show discrete peaks with size approximately $G/3$. The amplitude of each peak scales as $(2/3)^n$.

At lower gain values we also observe a quantized set of charge distributions with peaks at multiples of G/3, though the distribution is noisier.

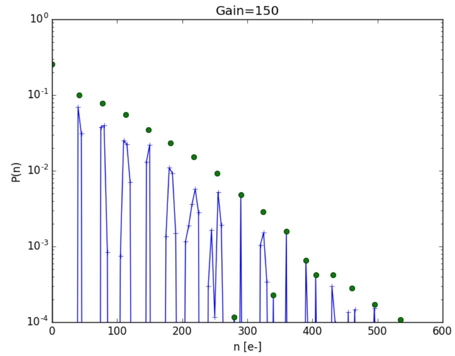

Figure 4. Inferred underlying charge distribution for G=150.

The mechanism for producing this distribution is not yet clear and further investigations are underway.

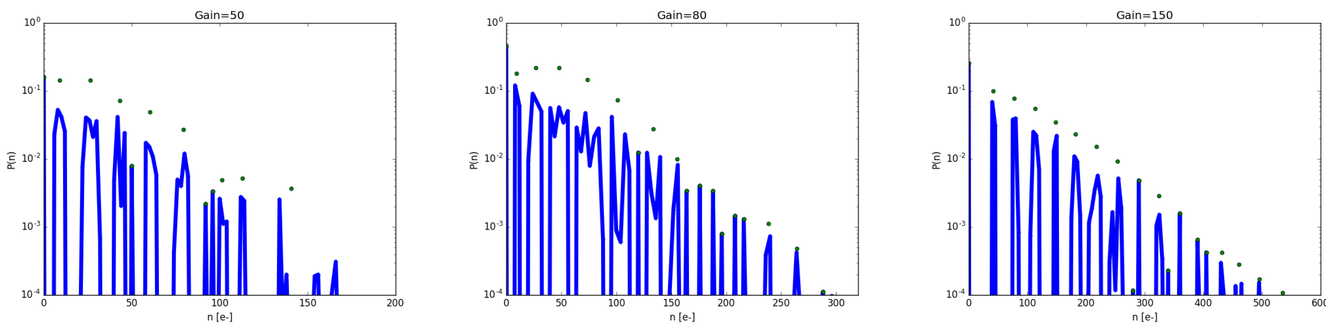

Figure 5. Inferred underlying charge distribution for several gain values, shown in log scale.

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