L3CCD'S: FAST PHOTON COUNTING FOR OPTICAL INTERFEROMETRY

Statistics of Photon Counting

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Abstract: Low light level charge coupled devices (L3CCD) have a large on-chip gain which can allow a signal to be detected above the noisy readout. A technique allowing photon counting at any light level is investigated, and found to add noise to the signal at higher light levels due to the statistical nature of the gain. Accurate signal estimation can be achieved with very faint signals, up to about one photon per pixel per read. Optical interferometry requires detection of very faint signals, and the use of an L3CCD is found to allow reproduction of interferometric visibilities to high precision. Custom instrumentation used for control is also detailed.

Key words: L3CCD, Controller, Interferometer, Photon counting, Statistical gain

1. INTRODUCTION

Low light level charge coupled devices (L3CCD's) are newly developed CCD's, which can give high internal gain. However, the gain process is statistical, achieved by avalanche multiplication. Therefore the CCD output cannot be used to calculate the exact photon input, rather, it can only infer the most likely photon input. The accuracy of this prediction determines how useful the L3CCD is as a photon-counting device.

Optical interferometry involves the detection of interference fringes from two or more light beams. The temporal variation of these fringes must be measured as the relative delay between the light paths is altered, requiring sampling up to 10kHz. High speed detection can result in a very low signal, which can be lower than one photon per pixel. For interferometric spectroscopy, frame sizes of at least 100 pixels in one dimension are required needing detection with sub-electron read noise. The use of L3CCD's as spectroscopic detectors is investigated, with particular regard for how accurately the interferometric visibilities can be reproduced.

Section 2 discusses the statistics of photon counting, section 3 discusses interferometric requirements, and section 4 discusses the custom controller.

2. PHOTON COUNTING STATISTICS

An L3CCD is able to provide a large internal gain by passing electrons through a multiplication register, an extension of the serial register. As electrons pass through this register, a high voltage on one of the pins can cause avalanche multiplication to occur. The probability of creating an extra electron at each stage is small (1-2%), but many such stages can lead to a large overall gain, which can be adjusted between 1-10000. The probability distribution for the electron output (x) is given by:

$$P(x) = g^{-n}\, x^{n-1}\, e^{-x/g} / (n-1)! \qquad (1)$$

where the mean gain, $g = (1+m/100)^r$ (for large r), m is the multiplication factor, r is the multiplication register length and n is the number of electrons entering the multiplication register. This distribution is shown in figure 1(a).

The probability distribution can be used to estimate the number of received photons from a given output. The L3CCD can generate an output event with a high signal-to-noise ratio (SNR) from a single electron detected by the CCD imaging array. This allows processing of the output signal in a variety of ways. There is no spatial or temporal dispersion due to the amplification, giving advantages over some intensifier methods, allowing much higher mean photon arrival rates to be handled properly.

2.1 Readout Modes

There are several different ways in which we can interpret the output from the L3CCD, each of which has advantages in different situations.

2.1.1 Analogue Mode

The output is treated as with normal CCD's, the input times the mean gain. Due to the Poisson nature of the multiplication, the output noise scales as $\sqrt{(2n)}$, n being the number of photons. This is $\sqrt{2}$ greater than we would expect from photon shot noise and effectively halves the quantum efficiency of the device. This mode is best used at higher light levels.

2.1.2 Single Threshold Mode

If the input signal is low, with an average of less than one photon per pixel per frame, then we can assume that any detected event above a threshold level corresponds to one photon. This eliminates the dispersion caused by the multiplication process, and adding many frames gives a noise of $\sqrt{n}$. However, at higher light levels, there will be significant coincident losses, and we will underestimate the true input.

Where the losses are modest, they are easily estimated statistically and corrections can be introduced to improve linearity. This method only works up to a mean of about one event per pixel per frame.

2.1.3 Multiple Threshold Mode

For a given output signal and known gain, we can estimate the most likely value of the input number of photons. There will be errors made but at low signal levels these are small, minimising the additional noise factor.

At higher signal levels we lose accuracy progressively. This leads to noise scaling as $\sqrt{n}$ at low light levels (standard Poisson photon shot noise statistics) where a single threshold is effectively used, and tends towards $\sqrt{(2n)}$ as the light level increases. In choosing the thresholds for selecting the input, a noise level (typically 6σ, where σ is the mean readout noise) is first subtracted from the signal. Then the remaining signal is placed into equal sized bins (the threshold step size), representing the predicted number of photons.

This gives the benefits of both the single threshold mode and the analogue mode, allowing photon counting at low and higher light levels.

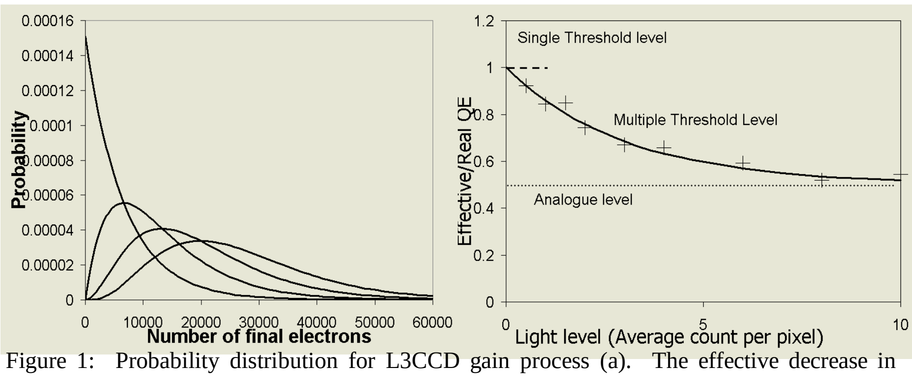

Figure 1: Probability distribution for L3CCD gain process (a). The effective decrease in quantum efficiency (QE) is also shown (b), due to statistical noise being added during the multiplication process.

The threshold step size that gives the best estimate for the photon input is dependent on the gain and light level. There is more allowance for errors in the step size at lower light levels where larger steps are optimum, tending to infinity as light tends to zero (single threshold mode).

At high light levels, the ideal step size tends to the expected gain and gives noise similar to the analogue case, as shown in figure 1(b).

We have investigated the ideal step size, and found that it is possible to predict from the average light level using the following relation:

$$\text{Threshold Step Size} = \text{gain}(1+0.5\times(\text{mean photons per pixel})^{-3/4}) \qquad (2)$$

This gives a good fit to the data over a wide range of gain and light levels.

3. L3CCD CONTROLLER DESIGN

We are currently constructing a controller in our lab, capable of operating in any of the readout modes. A Digital Signal Processor (DSP, Analog Devices SHARC-21160) is used to generate L3CCD control waveforms (clock and signal process) at up to 15MHz (with capability for higher pixel rates). The DSP is controlled by an embedded web server, allowing machine independent operation. Custom circuit boards with a field programmable gate array will convert the DSP output into CCD waveforms, and the CCD output will be digitised to 14 bits. A host PC and frame grabber (Matrox Meteor II/dig) will then be used to capture the data and provide real time analysis of the visibilities and processing of the data for telescope control feedback.

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