Calibration of an intensified CCD camera at low light levels

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Much work undertaken in imaging and spectroscopy relies on charge coupled device (CCD) detectors. Charge-coupled semiconductor devices were conceived in 1969 by Boyle and Smith [1] who described an array of conductor-insulator-semiconductor capacitors for storing minority carriers. In the same journal issue as the paper by Boyle and Smith, transfer efficiencies of 98% along CCD arrays were verified [2]. The read-out of a CCD relies on transferring charge through the array. Scientific grade CCDs have since become the instrument of choice for imaging applications with transfer efficiencies of 99.999% [3]. The use of CCDs now extends beyond physics with many medical and commercial applications, including photography. CCDs have largely replaced film in imaging applications. Particular advantages over film include their linearity of response, high sensitivity and instant image production. Film requires careful calibration for use in quantitative imaging [4].

The calibration of an Andor™ iXon EMCCD, consisting of an Impactron™ 1004 × 1002 pixel frame transfer imager is described in this report. This intensified CCD has variable gain from nominally 1-1000 with pixels of size 13 × 13 μm^2. After the creation of an electron-hole pair due to photon impact, electrons are accelerated on the chip. The accelerated electrons cause further excitation of electrons from valence to conduction band and hence a higher level of signal.

The CCD camera was exposed to white light radiation scattered from a white ceiling with varying sheets of tissue paper used to attenuate and further diffuse impinging light in order to ensure a low level of uniform illumination. Plotting the average signal level (in counts) as a function of the variance (standard deviation squared) of the pixel-to-pixel variation from the exposure gives a linear fit. The inverse slope G of this fit can be shown to be equal to the electrons/count of the CCD digitising process [5]. We found a value of G = 1.462 electrons/count.

The intensified CCD was also calibrated by directing helium-neon laser light at 633 nm onto the active chip area. The beam was expanded to fill approximately 5% of the chip area and filtered with neutral density filters. By adjusting the neutral density filters, it was verified that the CCD response is linear up to saturation at 46813 electrons/pixel which is equivalent to 32020 counts/pixel. The manufacturer of the CCD has produced a plot of the 'actual gain' g_a under intensified operation compared to the gain setting [5]. This calibration was checked by measuring the slope of the line of the CCD response (in counts) as a function of the incident photon energy per pixel (in eV). The energy of exposure of the helium neon laser was determined by measuring the laser power using a calibrated laser power meter (Leader LPM-8000). The incident energy per pixel was then deduced using the time of CCD exposure and by integrating the CCD response over the area of exposure on the chip after subtracting the background counts. A summary of the CCD response for different 'actual gain' settings g_a is shown in figure 1. A linear fit of the CCD response R in terms of the 'actual gain' on figure 1 gives $R = 0.175\, g_a + 0.259$ (counts/eV),

or

$$R = 0.343\, g_a + 0.508 \text{ (counts/photon)}. \qquad (1)$$

The counts x per pixel are related to the flux F of exposing radiation in photons/pixel or eV/pixel by simply $x = RF$. The exposure required to produce a response equal to the background counts as a function of gain is shown in figure 2.

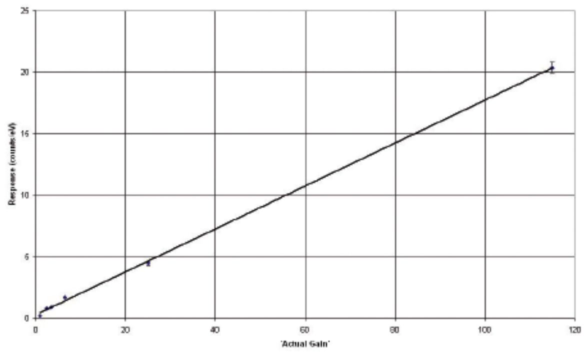

Figure 1. CCD response in counts per eV of photon energy at 632 nm (1.964 eV) as a function of 'actual gain' (as defined by the CCD manufacturer). A linear fit to the data is shown.

The accuracy of making a radiation flux measurement depends on the area of the CCD chip illuminated. An indication of the error in making a flux measurement can be gauged by considering the errors arising due to the number of counts and the standard deviation from pixel-to-pixel after charge transfer and digitisation. The standard deviation arising due to the number of counts is $\sqrt{Nx}$, where N is the number of pixels illuminated and x is the number of counts per pixel. The standard deviation σ from pixel to pixel associated with the read-out process plus background is given by [5]

$$\sigma^2 = \frac{x}{G} + \sigma_b^2 \qquad (2)$$

where σ_b is the background standard deviation from pixel to pixel without exposure. Equating Nx to σ_b enables us to deduce the minimum number N of illuminated pixels where the error in a flux measurement is dominated by the statistics of the number of counts, rather than the statistics of the variation of pixels (figure 3). It is clear that provided the exposure produces a count per pixel above some minimum (e.g. 20 for $g_a = 1$), then it is possible to measure a radiation flux accuracy determined by the count statistics (e.g. an error $\leq \frac{\sqrt{20}}{20} \cong 20\%$ for $g_a = 1$) rather than the pixel to pixel variation associated with the read-out process and inherent pixel to pixel variation.

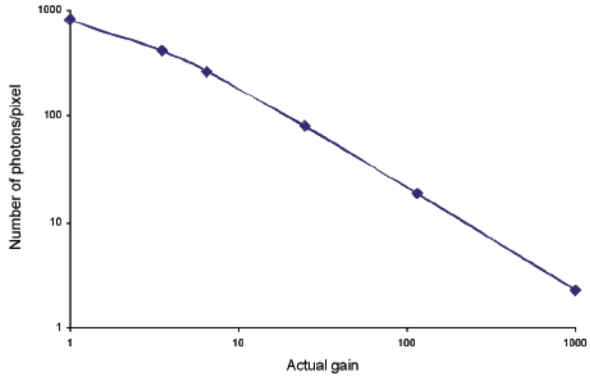

Figure 2. The exposure of the CCD in photons/pixel required to produce a CCD count equal to the background count as a function of the actual gain setting. The chip temperature was set at – 50°C.

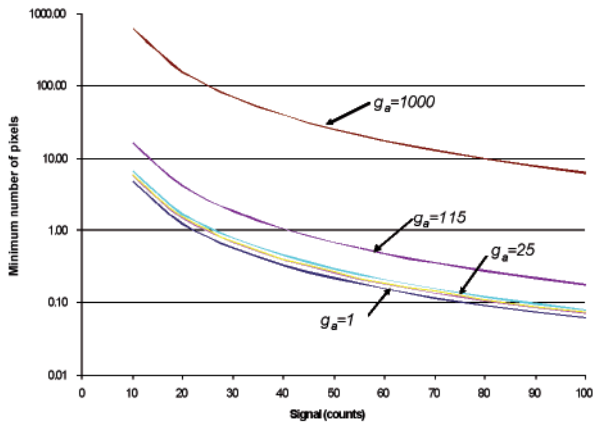

Figure 3. The minimum number of pixel *N* required to be illuminated in order to ensure that the error due to pixel to pixel variations after read-out is small compared to the error of the count statistics as a function of signal *x* for different actual gain settings 1, 3.5 6.5, 25 115 and 1000.

In conclusion, the on-chip intensified Andor™ iXon EMCCD has been calibrated using uniform illumination over the chip surface and using attenuated light from a helium neon laser. The absolute sensitivity of the CCD has been obtained for different gain settings. An indication of the area of the chip that needs to be irradiated in order to obtain accurate radiation flux measurements has been deduced.

References

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