CCD Basics

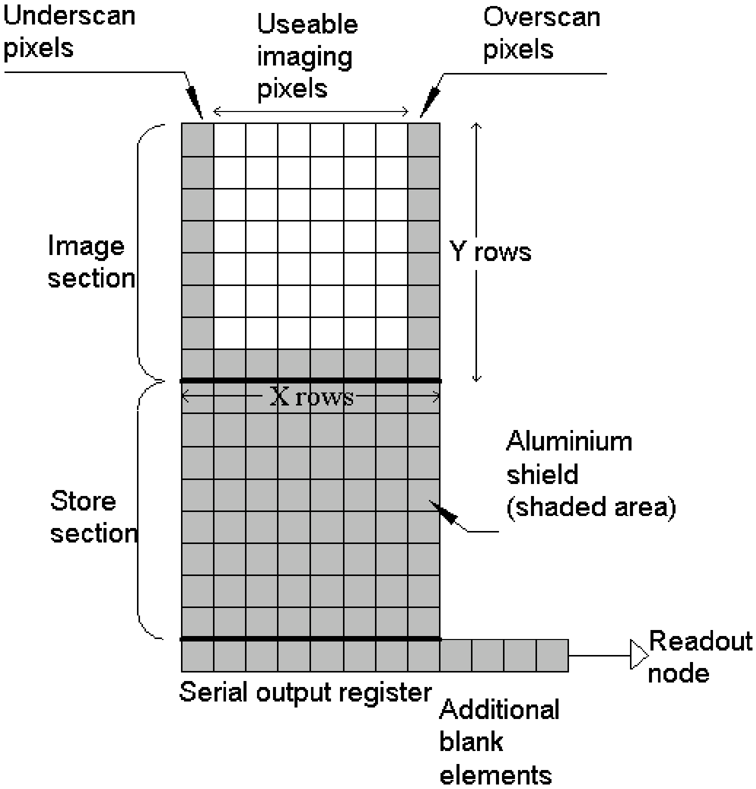
Full Frame and Frame Transfer CCDs

The CCD detectors that are supplied in ***Xcam*** camera heads are usually *full frame*, or *frame transfer* devices. Full frame CCDs use the full area of the chip for imaging, and might, therefore, need to be used in conjunction with a shutter to eliminate illumination during the readout process, depending on the application.

Frame transfer devices, such as that shown in figure 1 below, have approximately half their area covered with an Aluminium mask to prevent light from reaching the pixels below. Once an image has been acquired, the image is shifted into the masked storage region of the chip in a fraction of a millisecond, and, from that location it can be read out, whilst another image is being acquired.

In both *full frame* and *frame transfer* devices, there may be some non-imaging pixels around the side of the imaging device (usually called underscan or overscan pixels, see figure 1), and these can be used to obtain a measure of the noise of the system.

Figure 1: Frame transfer CCD with Aluminium mask over the store section.



A CCD's imaging dimensions are denoted by the number of rows and columns of active pixels that it contains, and any one pixel can be referenced using these parameters. We reference rows and columns from the bottom left edge of the CCD.

Once an image has been acquired and shifted into the store region, all of the charge that is stored in the pixels is moved down one row, then row 1, which is now in the serial output register, is moved horizontally past the readout node, whilst the contents of each pixel are measured. Then the stored image is moved down another row, and row 2 is moved horizontally out of the readout node, whilst being measured. This process continues, until the whole of the stored image has been measured, and the results are displayed as an image.

Two node Readout CCDs

Some CCD chips are *two-node readout CCDs* (see Figure 2). These chips can be read out of both nodes simultaneously so that half the chip is read out of readout node 1, whilst the other half is read out of readout node 2. This is particularly useful when the data from a large chip needs to be read out quickly.

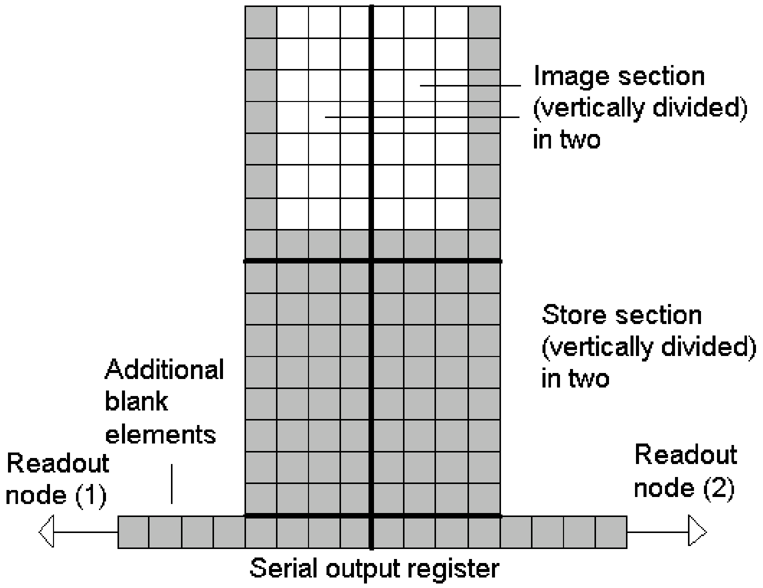


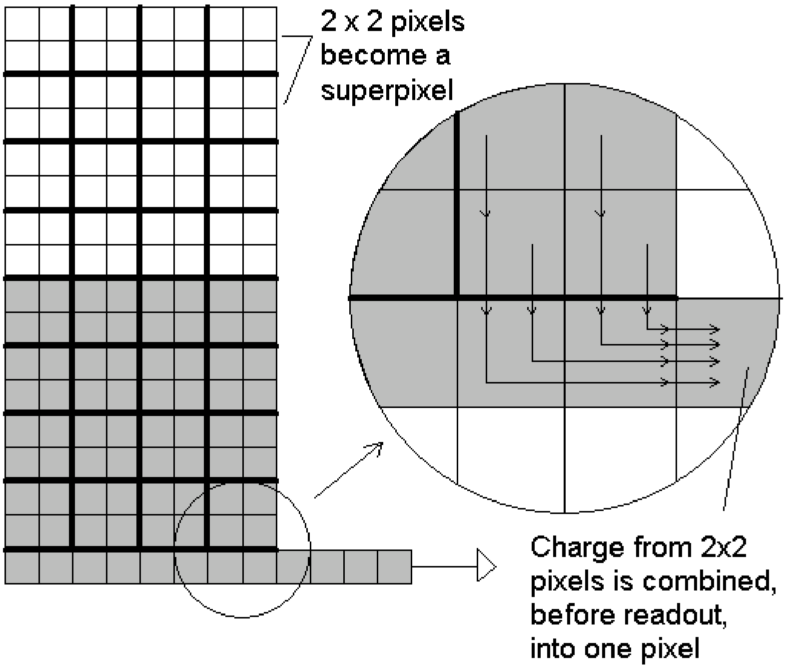
Figure 2: Example of a two-node readout CCD e.g. e2v Technologies 47-20

Pixel Binning

For some applications, it can be desirable to *bin* pixels (see Figure 3). This means that, for the purpose of image readout, more than one pixel is combined to create a *superpixel*. Pixels may be treated as if they are 2x2 or 3x3 pixels in size, for example. This has the effect of increasing the pixel size, which increases the dynamic range of the system, and it also makes frame read out much faster. In the case of 2x2 binning, for example, the maximum charge that can be stored in the four combined pixels is the same as it would be in four individually read out pixels, but there is only one contribution from the readout noise in the binned case, compared to four times the readout noise from the individually readout pixels. This increases the dynamic range available in critical applications.

Pixels may be binned *on-chip*, when the charge from the individual pixels is combined into one pixel before it reaches the readout node, or *off-chip*, in which case the pixels continue to be treated as in the un-binned case, until they reach the readout node, where they are electronically summed before the readout node is reset.

Figure 3: Example of on-chip binning.

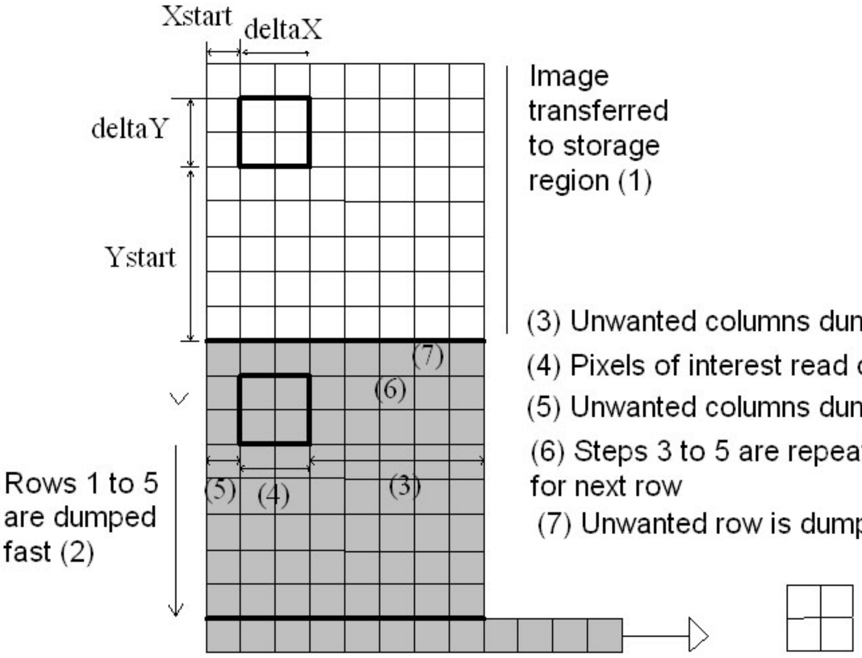


In some applications, it may be desirable to combine pixels to obtain the optimum pixel scale for the system of interest. Sometimes binning is used for setting up an experiment, taking advantage of (in the case of 2x2 binning) image readout that is four times faster, and then data collection takes place using unbinned mode with maximum resolution.

Windowing Mode

For some applications, it may be advantageous to read out a small part of the chip's imaging area, benefiting from the reduction in readout time that this provides. In this case, unwanted rows and columns are dumped at a very fast rate, and the pixels of interest, only, are read out, see Figure 4 below.

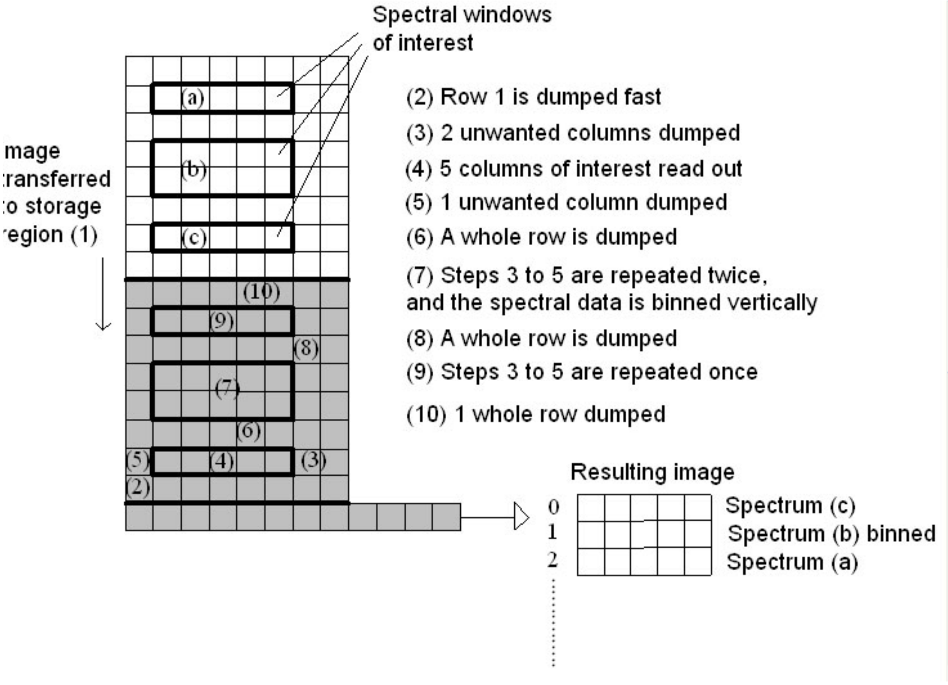
Figure 4:
Windowing Mode



Spectral Zone Mode

For applications in which many spectra are dispersed over the chip, the spectral zone mode of operation allows extremely fast readout of just the spectra of interest. Typically between 8-32 spectra can be imaged in this mode (but the number is only limited by the chip), and these can be read out at a rate of up to 200 frames per second (depending on chip size and the number of spectra), allowing up to 3200 spectra per second to be obtained. In this mode, *spectral windows* are specified, which identify which pixels need to be read out. The regions of interest are read out carefully, whilst unwanted pixels are dumped. Figure 5 shows how this is achieved.

Figure 5: Description of spectral zone mode readout



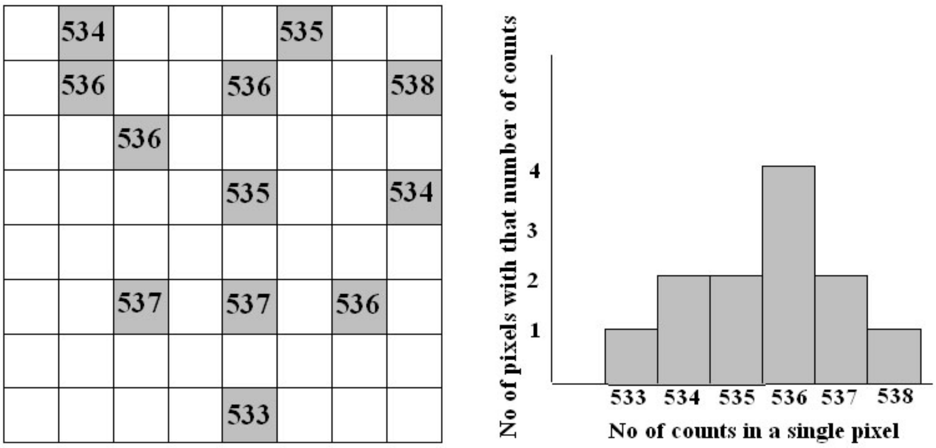
X-Ray Photon or Particle Counting with CCDs

When CCDs operate in the optical region of the electromagnetic spectrum, they exhibit a quantum efficiency of less than one. For example, 10 photons of light of wavelength 650 nm, may generate around 6 to 7 charges to be counted, in a pixel. At X-ray wavelengths, however, the energy carried by a single photon is sufficient to generate many charges in a single pixel. In fact, the number of charges generated in a pixel is directly related to the energy of the photon that hit that pixel. In this way, the CCD can be used as an X-ray spectroscope. Of course, care needs to be taken to ensure that the X-ray flux is low enough, and the images are refreshed frequently enough to ensure that *double hits* do not occur too often, as it is not possible to unambiguously determine the X-ray energy of two photons that have been detected in a single pixel. Additionally, the CCD drive system must be very low noise, in order to do spectroscopy.

Figure 6 shows a hypothetical CCD chip of 8 x 8 pixels. The white pixels have not been hit by X-ray photons and will therefore contain only background noise. The grey pixels have been hit by x-rays of a specific energy, and therefore contain roughly the same number of counts, representing that x-ray energy.

The ***Xcam*** X-ray spectroscopic system is operated in such a way that the individual events can be counted, and used to generate a spectrum, as shown in the figure. In practice, spectra will contain many more peaks due to X-rays of various energies incident on the CCD.

Figure 6: Use of CCD as an X-ray spectroscope



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Multi-Spectral Imaging

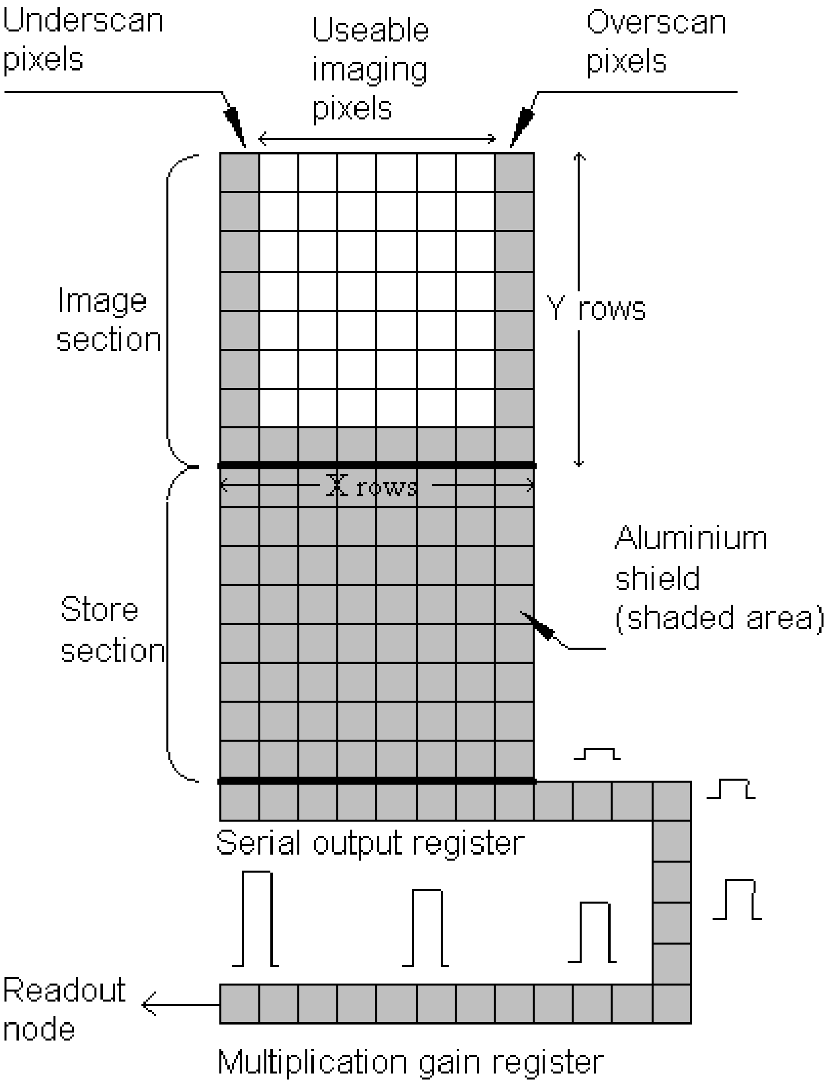
The linear nature of the size of the charge signal generated in the depletion layer of a CCD, and its relationship to the incident X-ray photon energy can be used to measure the energy of incident photons to within ~200 eV, dependent upon the X-ray energy. This allows relatively monochromatic images formed by X-rays of different energies to be accumulated. If a sufficiently low X-ray flux is used to generate only isolated pixel events in the CCD, and if all split events are rejected by image analysis software, then the histogram of recorded events corresponds to the incident X-ray spectrum, and is used to calibrate the X-ray energy from the known X-ray source spectrum. Once calibrated, images formed at different energies can be reconstructed, and obtained simultaneously. This technique of multi-spectral imaging avoids any alignment problems that would occur if such images were acquired separately. Phase retrieval algorithms can then be used to extract the density distribution of the sample from the multi-spectral image.

Figure 7: Example of a Multi-Spectral Image

Electron Multiplying CCDs

Electron multiplying CCDs have an output amplifier circuit that enables these devices to operate at an equivalent output noise of much less than one electron at high pixel rates. The output amplifier stage has an additional gain register, in which the charge is multiplied, before it is read-out. The multiplication gain can be varied by a factor of up to at least a thousand, by control of the gain stage voltage.

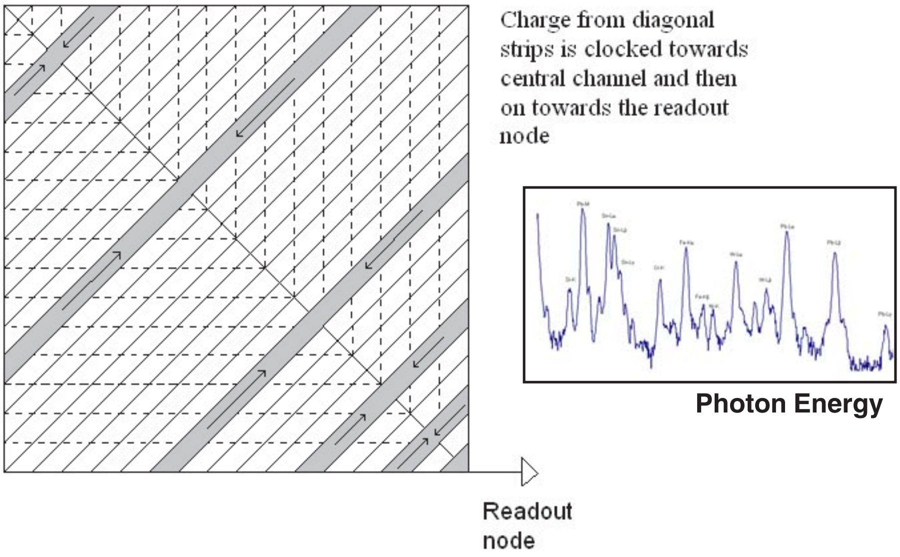
Figure 8: Electron-Multiplying CCD Schematic



Swept Charge Devices (SCDs)

Swept Charge Devices are specifically designed to be used as X-ray spectrometer detectors. These devices are non-imaging, and the charge packets that are generated from X-rays absorbed, are transferred by the voltages applied to diagonal electrodes to a charge detection circuit in one corner of the device (see Figure 7 below). This type of devices may replace a Si Pin diode in spectroscopy applications, and is designed to be operated at a relatively high temperature, and so can be cooled using a peltier cooler.

Figure 7: Schematic of a Swept Charge Device



Charge from diagonal strips is clocked towards central channel and then on towards the readout node

The Xcam readout and processing electronics provides a spectrum, or event file for later processing.

Further Reading

There are many good books and papers that describe CCD technology, and the characteristics and properties of CCDs in some detail. A few suggestions are listed below:

- *Scientific Charge-Coupled Devices, Janesick*
- *CCD Astronomy, Christian Buil*
- *The Handbook of Astronomical Image Processing, Richard Berry and James Burnell*