Development of
The BigMIC
Image Photon Counting Detector

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ABSTRACT

BigMIC is a large area image photon counting system that has been designed for applications in astronomy requiring the highest sensitivity and resolution such as echelle spectroscopy with very large telescopes. It consists of a 75 mm diameter image intensifier fibre-optically coupled to a fast scanning 770x576 pixel frame-transfer CCD camera. The system was built in collaboration with the Imperial College of Science, Technology & Medicine who were in charge of the intensifiers’ development.

My responsibility was to design and construct the high-speed CCD camera and processing electronics necessary to obtain high resolution. The image intensifier has, inherently, a resolution loss associated. Real time centroiding, on the photon event scintillations produced by the intensifier and captured by the CCD camera, is utilised to minimise this resolution loss.

I also had the responsibility for comparing different centroiding algorithms and their effect on system performance. Programmes that simulated the detector system were written for the algorithm comparison and were additionally used for assessing potential upgrades to the system.

In this thesis a complete description of the BigMIC system is given and a comparison with other photon counting systems, currently used for astronomical applications, is made. The electronic design of the CCD camera and processing electronics is fully explained with the inclusion of schematic diagrams. A chapter is dedicated to microchannel plate image intensifiers with the inclusion of a study of the properties of photocathode and phosphor screen materials. The computer simulations are also presented in detail with the results and their effect on the hardware design of the system. The thesis is concluded with a study of the final performance of the system and a series of recommendations for improvements in future designs are given.
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To my wife Rosalba with all my love.
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1.1 Astronomical Image Sensors

The development of image sensors has proved to be a critical and problematic branch of astronomical instrumentation. Although normally accounting for a small fraction of the total expenditure they are, in many cases, the limiting factor that determines the overall data quality and the feasibility of specific scientific projects. That is why it is important to continue research in this field, aiming at getting as close as possible to the production of an ideal detector.

An ideal astronomical sensor must, among other things:

- Be efficient, that is, being able to detect a high proportion of the incident photons in the wavelength range under consideration. A measurement of this is given by the detective quantum efficiency (DQE) which is the signal accumulation efficiency after incorporating all losses including those due to transmission efficiency of a window or the conversion efficiency of the detector, neither of which is perfect.

- Be accurate so that the input signal can be reliably and precisely calculable from the detector's output signal.

- Have high local and global dynamic ranges, with overload or saturation not occurring over a wide range of input signals.

- Be capable of long integration times by having very low noise levels and being insensitive to unwanted radiation sources such as cosmic rays.

- Have a large detection area, especially now with the development of big telescopes with large imaging fields.

- Provide good spatial and temporal resolution.

- Be compact, simple and reliable.

1.1.1 Photoelectric Sensors

Most of the modern astronomical detectors are of the photoelectric type (an electrical signal is generated in response to radiation). These have almost completely replaced the photographic emulsion that has been used since the end of the last century.

Photoelectric sensors can be classified into two groups: photoconductive and photoemissive.

Photoconductive devices are made of semiconducting materials whose electrical conductivity changes upon absorption of radiation. They can be divided into two basic groups:
• Silicon based detectors that are used primarily for the near UV, optical and near infrared regions of the spectrum. Charge coupled devices (CCDs) fit in this category and are the most commonly used detectors in astronomy due to their high DQE. Image arrays of up to 4096×4096 pixels (McLean 1997) are currently available. If developed further, charge injection devices could provide an alternative.

• Infrared (IR) detectors manufactured from compositions such as GaAs and HgCdTe which are used for the 1 μm to 10 μm wavelength range. IR arrays are currently the subject of development programmes similar to those associated with CCDs in the 1980's and arrays of up to 512×512 are now available (McLean 1997).

With these devices a photon absorbed in the semiconductor substrate releases an electron into the conduction band thus generating an electron-hole pair. In the most common photoconductive devices the energy required is of the order of 1 eV. Typically, the electron is then stored prior to readout. These devices have excellent sensitivity in the optical and near IR, CCDs having, for example, efficiencies approaching 100%. Unfortunately, these devices are also sensitive to thermally induced background requiring them to be cooled.

Recent experiments with substrates that have larger band gaps between the valence and conduction bands, like GaAlN and diamond for example, show that they have the potential to be inherently superior sensors in the UV than the current silicon based CCDs (Razeghi and Rogalski 1996).

Photoemissive detectors use photocathodes that are tailored to be sensitive to a specific wavelength range. In these devices the incident photons must have sufficient energy to eject an electron from the photocathode material into the vacuum, energies of a few eV being required. UV detectors produce negligible background at room temperature. They can also be constructed to be inherently 'solar blind', that is, practically insensitive to light at optical wavelengths. This can be important since most astronomical objects emit from 10^4 to 10^8 visible photons for each UV photon in the 1000 to 2000 Å wavelength region.

1.1.2 Photocathode Based Detectors

Photocathode based detectors have lower QE in the optical region when compared to CCDs, but, as discussed in Section 2.3, they have a number of other advantages. They are preferred for observations in the UV region because of their noiseless photon counting ability at relatively high QE, with excellent imaging capabilities in the FUV (912 to 1216 Å) spectral region.

Since a single photoelectron cannot be recorded reliably, some form of intensification is required. A gain stage, to amplify the photoelectrons to a signal level suitable for photon
counting, is normally followed by a position encoding device. If the intensification process is saturated and has sufficient gain, photon counting detectors with zero readout noise can be constructed.

Imaging photon counting systems have been under active development for a wide range of ground and space based applications, in particular in the far ultraviolet (FUV) and extreme ultraviolet (EUV). They are also used in optical applications where photon arrival rate is very low and/or high time resolution is needed (e.g. speckle interferometry and high-speed photometry).

At the present time the standard imaging detector used for astronomical applications is a cryogenically cooled charge coupled device (CCD) used in an on-chip signal integration mode due primarily to their high quantum efficiency. However, in the UK, the development of high sensitivity photon counting detectors has continued as an alternative approach for very low light level imaging and for highest resolution and time resolved applications.

1.2. Photon Counting Detectors Developed at UCL

1.2.1 The IPCS

University College London (UCL) has been involved in photon counting detector development since the early 1970s when Boksenberg and Burgess (Boksenberg 1972) proposed and developed the Image Photon Counting System (IPCS). In this design the photoelectron scintillations generated by a high gain four-stage electro-magnetically focused image intensifier are lens coupled to a fast continuously-scanning TV camera that acts as a sensor and one-frame buffer store (Fig. 1.1).

![Figure 1.1. Image intensifier, coupling lens and television camera head of the IPCS system (from Boksenberg 1972). The 40 mm diameter four stage electro-magnetically focused image intensifier, model EMI 9912 (produced by EMI Electronics Limited), consists of four intensifiers arranged in cascade providing a gain in excess of $5 \times 10^8$ photons/photoelectron at 45 kV. These intensifiers use S20 photocathodes and P11 phosphors. The television camera incorporates a Plumbicon camera and a focus, alignment and scan coils assembly. A highly stable raster, containing 2048 scan lines, is continuously produced by this camera.](image-url)
Figure 1.2a shows a block diagram of the IPCS. The output signal of the television camera is sent to a specially designed video pulse processing circuit which discriminates between scintillations generated by photon events and those generated by noise (Fig. 1.2b), then locates and digitally encodes the position of the brightest component of each event. The encoded positions are then sent to a computer (via an interface unit) which increments the contents of a corresponding address in the computer memory.

Before the development of this detector the output of the intensifier was conventionally integrated on photographic film as a pattern of overlapping variously-sized scintillations. The IPCS had the following advantages:

- Truly photoelectron noise limited data acquisition with cooling of the intensifier reducing thermal noise to negligible levels,
- Higher resolution by only recording the central position of each scintillation,
- Much longer integration times only limited by the computer memory capacity,
- Easier handling and processing of data as it was already in digital form, and
- The continuous display of the accumulating image (as it is integrated) provided immediate feedback to the observer.

![Block diagram of the IPCS](image)

**Figure 1.2.** Block diagrams of the IPCS (a), and electronic processing functions during the detection of photon and ion events (b). From Boksenberg 1972. The PDP-8 computer was later replaced by an Interdata computer and the teletype by a terminal. The camera’s amplifier noise is rejected by means of a low threshold level, and ion noise (which produce bright scintillations) by an upper threshold level. These levels are defined from the measured total brightness distribution, which includes photon and noise events

The IPCS was used extensively at most of the world’s major optical observatories and engineered systems were built for the Isaac Newton Telescope (INT) and the Anglo-Australian Telescope (AAT). The Faint Object Camera currently used in the Hubble Space Telescope is based upon this design.

The application areas for the IPCS were limited though (Fordham et al. 1991a) by detector characteristics:

- The bright limit on the dynamic range was low due to the relatively slow frame rate of the Plumbicon camera.
• The pulse height distribution was not well peaked leading to a reduction in counting efficiency (because of the difficulty to distinguish between noise and photon events).
• Small drifts in the camera scan (geometrical instability) produced mis-registration between integrations taken a few hours apart.
• Bulky and heavy focusing solenoids, with cooling required, limited its use to large telescopes.

The dynamic range and stability deficiencies were attributed to the use of the Plumbicon camera and a study (Boksenberg et al. 1985) was carried out to look into the viability of replacing this camera by a CCD.

At that time CCDs were limited to relatively small imaging formats (RCA having a CCD available with 256×256 pixels) and to achieve a resolution similar to that associated with the IPCS, sub-pixel centroiding was therefore needed. The study showed that a simple centre of gravity centroiding algorithm implemented digitally in hardware could achieve this with 8-bit digitisation of the CCD video signal being adequate. The study also showed that a frame transfer CCD was preferable to an interline CCD due to quantum efficiency variations across a pixel that are associated with the interline CCD design.

Thus it appeared that incorporating a CCD would provide a viable alternative to the Plumbicon camera, use of sub-pixel centroiding enabling faster camera frame rates (with a corresponding increase in the detector's dynamic range) and fixed CCD pixels overcoming the spatial drift problem.

1.2.2 The CCD-IPCS

A prototype second generation system, called the CCD-IPCS or IPCS2, was then developed (Fordham et al. 1986). A schematic diagram of the detector is shown in Fig. 1.3.

![Figure 1.3. Simplified block diagram of the CCD-IPCS.](image)

Particular features were:

• Incorporation of a custom built fast lens for imaging the output of the intensifier onto the CCD. The EMI intensifier has a blue (P11) output phosphor which is a poor match to the spectral response of the CCD. For this reason a fast lens was required to maximise data collection by the CCD.
Windowing on the CCD. For many applications, for example spectroscopy, the whole imaging area is not required. With the windowing facility only a selected set of rows of the CCD are read out while the unwanted rows are dumped on top of each other in the CCD’s serial register before being readout. This allowed increased frame rates.

Subsequently an engineered version of the CCD-IPCS was constructed for the William Herschel Telescope (WHT). The initial prototype used the RCA CCD but this was eventually replaced by an EEV CCD with a format of 385×288 pixels giving, with 1/8 pixel centroiding in both X and Y, a data acquisition format of 3080×2304 pixels.

Whilst the spatial stability of this second generation system was found to be high, it was also found that the dynamic range was not improved as expected.

Using the windowing facility on the CCD a spectroscopic format of 3080×32 gave a frame period of ~1.5 ms whereas, with the IPCS, the equivalent was 30 ms. As the bright limit on the dynamic range curve increases linearly with frame rate a factor 20 improvement in dynamic range was also expected. This was not the case. In fact, no real gain was achieved. It was found later that the dynamic range was not being limited by frame rate but by the accumulative effect of the four P11 phosphor screens in the EMI intensifier which caused the decay of each scintillation on the output phosphor to be ~2 ms.

Hence, performance limitations were now being governed by the image intensifier. Imperial College of Science, Technology and Medicine (ICSTM) were in collaboration with the Royal Greenwich Observatory (RGO) and Instrument Technology Ltd (ITL) on developing a Micro-Channel Plate (MCP) based intensifier specifically designed for photon counting applications. It was decided that UCL should join this collaboration, incorporating the CCD camera and centroiding electronics with the MCP intensifier in a third generation IPCS, called MIC (MCP Intensified CCD detector). The potential advantages of an MCP intensified system:

- Opened up many new application areas, such as space and small telescopes, as the intensifier was very compact and did not require electro-magnetic focusing nor cooling.
- Overcame the dynamic range limitation as only single phosphor was incorporated.
- Provided a peaked pulse height distribution allowing better discrimination against noise.
- Allowed choice of photocathode (the EMI intensifier as a commercial product had only the S20 option available) for different wavelength ranges.
1.2.3 The MIC Detector

A block diagram of the MIC detector is shown in Fig. 1.4. There are two fundamental differences between this detector and the CCD-IPCS: the image intensifier is MCP based, and the lens coupling to the CCD is replaced by a fibre optic taper. The CCD camera and the centroiding electronics were identical, initially, to those employed by the CCD-IPCS.

![Figure 1.4. Simplified block diagram of the MIC detector.](image)

1.3 Performance Comparison Between the MIC and IPCS Detectors

Telescope trials at the AAT and WHT, along with extensive laboratory trials, with the final MIC detector design allowed a direct comparison with the IPCS to be made (Fordham et al. 1991a) and this is shown in Table 1.1.

<table>
<thead>
<tr>
<th></th>
<th>IPCS</th>
<th>MIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution (µm)</td>
<td>25</td>
<td>27</td>
</tr>
<tr>
<td>Peak DQE (%)</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Dynamic Range Flat Field (counts/s)</td>
<td>not avail.</td>
<td>2x10^4</td>
</tr>
<tr>
<td>Dark Count @ 20 °C (counts/cm²/s)</td>
<td>~50</td>
<td>~50</td>
</tr>
<tr>
<td>Dynamic Range Point Source (counts/pixel/s)</td>
<td>Spectroscopic format</td>
<td>~2</td>
</tr>
<tr>
<td></td>
<td>Full format</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 1.1. Comparison of the performance characteristics of the IPCS and MIC detectors.

It can be seen that the characteristics are very similar except that the dynamic range is improved greatly with the MIC system, one of the objectives of the development. The other objectives; a compact detector with minimum power consumption and having a peaked pulse height distribution, were fundamental to the design.

1.4 Comparison Between the MIC Detector and Direct CCDs

The time of completing the MIC detector design coincided with the advent of large format CCDs which then superseded photon counting detectors in many astronomical applications. However a comparison between CCDs and the MIC detector, shown in Table 1.2, reveals that the photon counting system has a number of advantages and that direct CCDs ‘win’ primarily because of their high RQE, counting efficiency and dynamic range.
Table 1.2. General comparison between direct CCDs and a MIC photon counting system in astronomical applications. The dark noise figure for the MIC refers to that achieved with a bialkali photocathode and with the pixel size normalised to that of a CCD, taken as 20 μm square. The spatial resolution of CCDs is limited by the pixel size, the integration time by cosmic ray degradation and time resolution by the relatively long read out period (particularly true for the large format CCDs).

In addition the MIC detector has other features which are of advantage:

- On line display of the acquired image as it grows, which is not possible with a direct CCD, maximising the efficient use of telescope time.
- The pixel size can be selected to suit a particular application. For example for a particular spectroscopic application and with good seeing conditions a pixel size of perhaps 10 μm by 20 μm would be chosen; while when the seeing is bad, a pixel size of 10 μm by 80 μm might be more appropriate.
- No need for a cooling system while liquid nitrogen is usually required at the telescope for CCDs.

The image intensifier used as the primary detector for photon counting has a lower RQE over the range of the visible spectrum when compared with a thinned CCD. However, in the blue region the response is comparable and in the UV higher. Furthermore, the readout noise of the photon counting system is effectively zero. In recently developed CCDs the readout noise has been reduced to a few electrons per pixel per readout but at very low light levels (where a long exposure time is necessary) several readouts may be required with the integrated readout noise degrading the signal to noise ratio. This is why, for observations in the blue-UV region at very low signal levels, a photon counting system could be preferred.

1.5 Current MIC Detectors

The first MIC detector developed, referred to as MIC1 in this text, utilised a 40 mm diameter image intensifier (the same size as the EMI intensifier in the IPCS) to allow direct upgrading at the Observatories. Subsequently, a 25 mm diameter version was accepted for inclusion as the “Blue Detector” in the Optical Monitor (OM) experiment on the ESA X-Ray Multi-Mirror
Mission (XMM) space observatory due for launch in 1999. This observatory is an ESA Cornerstone mission and has, co-aligned, three X-Ray telescopes and an optical telescope allowing simultaneous observations in the X-Ray and Optical/UV regions. The blue detector for the OM has to operate in the 170 nm to 550 nm wavelength range and needed to have a fast frame rate to allow variability studies and an on-line telescope tracking facility. The mission lifetime is expected to be about 10 years.

1.6 The BigMIC

At the time of the MIC development, there were two areas in particular where the direct CCD had limitations that promoted the concept of a large format photon counting detector for applications such as Echelle spectroscopy and imaging with the very large telescopes under construction (Fordham et al. 1994). These limitations were format size (where arrays of very expensive CCDs would be required) and signal to noise in the blue region on very faint or very dispersed sources. Funding was provided by SERC for a collaboration between UCL and ICSTM to develop the BigMIC system. It incorporates a specially designed 75 mm active diameter image intensifier fibre-optically coupled to a fast scanning 770×576 pixel frame transfer CCD.

A block diagram of the BigMIC system is shown in Fig. 1.5 and a photograph of this system in Fig. 1.6.

A schematic of the detector head in Fig. 1.7. Incident photons are initially detected by the bialkali (NaKSB) photocathode. The resultant primary photoelectrons are proximity focused to a z-stack of MCPs which provide a saturated pulse height distribution. The charge pulse at the output of the channel plate stack is proximity focused onto a P20 phosphor screen deposited on a fibre optic window. Each scintillation on the output screen contains ~10^7 photons. These scintillations are coupled to a fast scanning CCD (EEV05-20, format 770×576 pixels) by means of a 3.46:1 fibre optic taper.
Figure 1.6. Photograph of the BigMIC system. From left to right: The CCD camera, its power supply, the Processing Electronics, and the IBM Compatible PC.
Photon events are centroided in both the X and Y directions by the system's electronics to yield, at the highest centroiding resolution of 1/8 of a CCD pixel, an array of 6160×4608 data acquisition pixels. With each pixel being ~10 µm square when subtended to the plane of the photocathode, this leads to an active detector area of 61×46 mm² (75 mm diagonal).

The following facilities are available with the BigMIC system:

- **Resolution.** The centroiding resolution can be set (independently in X and Y) to 1/8, 1/4, 1/2 or 1 CCD pixel. Thus, for example, a resolution of 1/8 of a CCD pixel in X and 1/2 of a CCD pixel in Y can be selected (giving a pixel size of 10 by 40 µm in the image plane) which could be ideal for high resolution spectroscopy in medium seeing conditions.

- **Windowing.** In many applications (spectroscopy for example) the full format of the detector is not required. It is possible to read (and process) data in only selected rows of the CCD. The use of this facility modifies the frame rate of the detector. On full format the frame time is 47 ms while when only 32 rows are read out the frame time is reduced to 3.5 ms. This has a profound effect on the dynamic range and time resolution of the system.

- **On-line display.** The data is accumulated in a large memory contained within the computer. On-line display facilities enable the observer to view the data as it is being integrated. This is very beneficial to maximise the efficient use of telescope time as it allows the observer to terminate an exposure when a required signal to noise ratio has been achieved.

- **Frame Store.** A memory is contained within the Processing Electronics of the detector system. This is used as a frame grabber where a single CCD frame of analogue data is stored. This facility is essential in analysing individual photon...
events and thus characterising the image intensifier, via pulse height and pulse width distributions.

Some potential scientific applications for the BigMIC detector identified so far are:

- **Observations with Large Telescopes.** A number of large optical telescopes have now been constructed or are under construction. These include the Gemini 8 m, the Keck 10 m, and the ESO VLT. For such telescopes the required detector area must be very large to match the image scale associated with the large telescopes, typically 300 μm-arcsec⁻¹ to 500 μm-arcsec⁻¹. Hence, in good seeing conditions a pixel size in the range 30 μm to 50 μm might be required and in poorer conditions a 50 μm to 100 μm option might be more appropriate. The BigMIC detector is ideal for these applications since the pixel size is within the above requirement and the active area is much greater than any available single CCD. It is envisaged that the principal application of the BigMIC system would be high resolution spectroscopy in the blue spectral region using a low noise bialkali photocathode.

- **Echelle Spectrographs.** The use of Echelle spectrographs is under consideration for all of the major new telescopes to provide high spectral resolution. Furthermore, a number of these spectrographs have been constructed for telescopes which are currently in operation. For example, within the UK community, the UCL Echelle Spectrograph (Walker et al. 1986) at the AAT and the Utrecht Echelle Spectrograph on the WHT. A large detector is required for this application to make maximum use of the folded wavelength array. These instruments have very high dispersion and hence a low background is required.

- **Space Borne Applications.** The MIC detector systems are ideal for use in space applications that demand the highest performance from the detector. A version of the original MIC is being built for the European Space Agency XMM Observatory (Fordham et al. 1991b). The detector is to operate in the 170 nm to 550 nm wavelength range. The principles adopted can be applied to a version of the BigMIC when a large active area is required. Additionally, similar detectors for the far UV using either a CsTe semitransparent photocathode or, alternatively, a CsI opaque photocathode in a windowless device could be developed.

This thesis describes the development of the 75 mm system and its performance, concentrating on the electronic design for which I was responsible. In addition, studies have been carried out on the centroiding procedure and its effects on both resolution and image quality. The results associated have applications in all of the MIC systems.
CHAPTER 2
The Image Intensifier

2.1 Image Intensifiers

Image intensifiers are electro-optical devices used to intensify and detect images from the gamma-ray to the infrared regions of the electromagnetic spectrum. Apart from astronomy they are used in night vision, radiology, medical research, gamma and x-ray imaging, electron microscopy etc. An intensifier makes use of the photoelectric effect whereby the energy of incident photons is converted into the energy of moving electrons (because electrons, unlike photons, are electrically charged particles their energy can be increased by acceleration in an electric field).

Image intensifiers are classified into three categories:

The first generation technology (introduced in the 1960's) where photons incident on a semi-transparent photocathode eject electrons into the vacuum inside a tube. Electric fields, or electric and magnetic fields in combination, then accelerate and direct the electrons through the device to hit a phosphor-coated output window that converts them into a visible image (Fig. 2.1). Optical gain is provided by the phosphor, which may release thousands of photons for each accelerated electron that impacts into it. Higher gains can be obtained by cascading two or more of these devices. This kind of intensifier have been used in space and ground based astronomy for the last 20 years. Their main drawbacks are limited dynamic range, complexity of the assemblies, high power consumption, size, and weight.

Second generation intensifiers (Fig. 2.2a) are compact distortion-free tubes that use one or more microchannel plates for internal current multiplication to provide greater intensification. They have a flat photocathode whose photoelectrons are proximity focused to the input of the MCP. The output of the MCP is proximity focused onto a phosphor screen or an electron readout device. Compared to first generation intensifiers they provide greater mechanical and electrical stability, are more compact and their associated power supply has lower mass, volume, and power dissipation.

Third generation intensifiers (Fig. 2.2b) are similar to second generation tubes, the main difference being their photocathodes. In the previous generation tubes the photocathodes are typically of the bialkali or multialkali type. Third generation tubes use the more recently developed gallium arsenide (GaAs) photocathodes that give, in particular, higher sensitivity the red and near IR. GaAs photocathodes have the disadvantage of been more susceptible to deterioration by contamination and to prevent ions and gas emanating from the MCP from hitting the photocathode a very thin aluminium oxide barrier is normally deposited on the surface of the MCP.
Figure 2.1. First generation image intensifiers (from Csorba 1985).
a) Biplanar or proximity focused tube. This is the most simple of the intensifiers. It consists of a photocathode and a phosphor screen in close proximity to it. By the application of high voltage between the phosphor screen and the photocathode a homogeneous axial electric field is produced which proximity focuses the photoelectron image onto the phosphor screen. This is a distortion free device.
b) Electrostatically focused tube. This low weight tube is mostly used when an inverted and magnified image is required. This tube has a spherical cathode, a spherical screen, and a conical anode with its aperture placed near the centre of curvature of the photocathode. Sharp focusing is produced by the cathode aperture diameter and magnification by the separation between the anode aperture and the screen. Because the photocathode and the screen need to be in curved surfaces the input and output windows are often made of fibre optics, thus making this tubes insensitive to the UV.
c) Electromagnetically focused tube. Used in the areas where superior image quality is required. Consists of a plane photocathode and a plane phosphor screen separated by the accelerator rings structure. The tube is enclosed by a magnet which, together with the accelerator rings, focus an erect image of the photocathode onto phosphor screen.

Figure 2.2. Second and third generation image intensifiers (from Csorba 1985). a) Second generation tube. The photocathode and the output of the MCP are proximity focused to the input of the MCP and the phosphor screen respectively. If required, image inversion can be provided by a fibre-optic twist as shown. b) Third generation tube. These devices use more sensitive GaAs instead of bialkali and multialkali photocathodes.
It is the generation 2 intensifier used in the BigMIC and MIC detectors and a more detailed description of the basic components of this intensifier's technology follows.

2.2 The Input Window

An input window serves two purposes: as support (substrate) for the photocathode and to form, with the intensifier's body, a vacuum seal.

The window and the photocathode determine the spectral response of the intensifier. Fig. 2.3 shows the transmittance curves of some frequently used window materials. For sensitivities in the visible and infrared regions Corning 7066 glass and fibre optics are normally used. For the UV a choice of materials is available. These include Sapphire, Lithium Fluoride and fused silica.

![Figure 2.3. Typical transmission characteristics of input window materials (from Csorba 1985).](image)

Sapphire windows have the undesired characteristic of fluorescing when bombarded with radiation. Oldfield (1991) showed that cosmic rays and radioisotopes within the window produce frequent flashes which are seen at the intensifiers output.

There are some difficulties in photocathode deposition on lithium fluoride due to its granular structure. This leads to spatially non-uniform responsive quantum efficiencies. For these reasons fused silica windows, which do not present these problems, have been used in the MIC intensifiers.

2.3 The Photocathode

Photocathodes are semitransparent photoemissive materials deposited on the vacuum side of the input window of the image tubes and convert input photons into photo-electrons.

Their operation is based on the photoelectric emission effect which, for semiconductors, may be considered as a three-step process:
• Photoelectrons are excited from the valence band to the conduction band by the absorption of light in a thin semiconductor film.

• The excited electrons are transported through the semiconductor film to the semiconductor-vacuum interface, and

• The electrons escape over the surface barrier into the vacuum.

Fig. 2.4 shows an energy band model to explain the principle of photoemission. The responsive quantum efficiency (RQE) is determined by the losses in all three of the above steps.

![Energy Band Model](image)

**Figure 2.4.** Semiconductor energy band model to explain photoemission (from Csorba 1985). The horizontal axis represents the spatial co-ordinate perpendicular to the surface, and the vertical axis represents energy. The valence band is completely filled with electrons and the conduction band is empty. The conduction band and the valence band are separated by the forbidden band $E_g$. An incident photon with an energy $E_p=h\nu$ just slightly greater than $E_g$, on absorption, can excite an electron from the valence band to the conduction band. The electron produced is free to migrate through the solid, but because of the electron affinity $E_a$ it cannot escape from the solid. Photoemission may occur only if $E_p>E_a+E_g$. Any excess in energy will be transferred to the escaping electron in the form of kinetic energy. The maximum electron energy is given by $E_m=E_p-(E_a+E_g)$. Because of energy loss processes (collisions) the emission energy corresponding to monochromatic radiation ranges from zero to $E_m$.

Photocathode materials are selected on the basis of quantities such as the band gap, extent of hygroscopic behaviour, mass absorption coefficient and photon yield data. Fig. 2.5 shows the response of some of the most commonly used photocathodes.

The photocathode used in the 40 mm and 25 mm MIC intensifiers has been the S20. It is a semi-transparent polycrystalline semiconductor film that is deposited in high vacuum on the input window of the image intensifier. The approximate composition of this multialkali photocathode is Na$_2$KSb(Cs). The bulk material of the cathode film is a sodium, potassium and antimony semiconducting compound alloyed by a small quantity of caesium. This film is coated with caesium in order to reduce the electron affinity, hence improving its red response. This photocathode is most sensitive in the UV-blue region of the spectrum. For extended sensitivity in the UV, a bialkali (Na$_2$KSb) photocathode was used in the BigMIC 75 mm intensifiers. A comparison of the quantum efficiencies of these two materials can be seen in Fig. 2.6. An added
advantage of the bialkali photocathode is its lower thermal background emission due to its lower red response.

Figure 2.5. Absolute sensitivity of some photocathode material. From Csorba (1985).

Figure 2.6. Quantum efficiency characteristics of bialkali and S20 photocathodes.
2.4 The Microchannel Plates

MCPs (Siegmund et al. 1992, Sams 1991, Corbett 1990, and Lampton 1977) are used in many low level signal and imaging applications where the detection of extremely brief, faint or low contrast features is necessary. These include night vision, x-ray diagnostic systems, electron microscopy, and x-ray and ultraviolet astronomy.

An MCP consists of millions of independent microscopic electron multiplying tubes (channels) fused in a solid wafer which provide a convenient means of achieving high gains (>10^6 e⁻/e⁻) with high spatial resolution (<20 μm), fast time response (< 1ns) and large format sizes (>100x100 mm²).

When an electron, an ultraviolet photon, an x-ray photon or a positive ion strikes the surface of a channel, secondary electrons are emitted. These electrons are accelerated down the channel by an applied electric field (~2×10⁶ V·m⁻¹) and with each additional impact with the wall, more electrons are released. The growing electron avalanche propagates to the output of the channel where it can be detected. The level of gain realised is an exponential function of the form

\[ G = \delta_1 \delta^n, \]

where \( \delta_1 \) is the yield of the initial collision, \( \delta \) is the average yield on each subsequent collision, and \( n \) is the number of times the secondaries strike the wall. These values are dependent upon the channel's length to diameter ratio \( (L/D) \), surface composition and the applied voltage.

The material for making a channel multiplier must satisfy two requirements. First, the wall of the channel must be able to emit more electrons than it absorbs. A variety of materials, including many glasses, emit an average of 1.4 electrons for each incident electron. Second, the electrical conductivity of the material must be predictable and controllable, so that charge removed from the channel wall can be replenished and a uniform electric field can be re-established.

2.4.1 MCP Manufacture

MCPs are made of glasses composed of a mixture of ~50% lead oxide, ~40% silicon dioxide and smaller quantities of several alkali oxides. The technique used to fabricate MCPs is known as the two-draw process based on the methods for drawing or stretching glass into microscopically fine fibres. Certain glass compositions that can be worked over a wide range of temperatures have the property of preserving their cross section when heated and drawn. An explanation of this technique can be seen in Fig. 2.7.
Figure 2.7. The two-draw process (from Lampton 1981). Channel-multiplier glass is cast to form a cylindrical ingot, then cooled and ground into a uniform rod several centimetres in diameter. The rod is bored along its axis and another rod, made of glass with a different composition, is fitted into the bore. At the end of the process this core is removed by etching it away in a bath of hot dilute acid, but during the intervening stages of manufacture it acts as support for the outer cylinder so that the finished microchannels are nearly uniform in size and shape. During the first draw (a) the glass cylinder is suspended vertically in a zone furnace where the temperature can be controlled from point to point. The bottom of the cylinder is heated to about 500 °C and a droplet of soft glass descends from the furnace, suspended by a drawn-glass fibre whose diameter is about a millimetre. By the time the fibre has descended several metres below the furnace it is cool enough to be handled by a traction machine that regulates the speed of draw and hence the fibre diameter. Below the traction machine the fibre is cut into segments about 15 centimetres long. Several thousand segments are assembled into an hexagonal bundle. The second draw (b) is similar to the first. The hexagonal bundle is suspended and heated in a zone furnace and drawn into a hexagonal compound fibre about a millimetre across. The spacing between the centres of the individual cylinders is thereby reduced to the final separation of some micrometers. Again the drawn glass is cut into segments which are later packed together and fused in a vacuum to form a boule of hexagonal solids. Boules can be as large as 125 millimetres in diameter and incorporate millions of microchannels. Plates are made by slicing the boule into wafers about a millimetre thick (c), polishing the faces of each wafer and then dissolving the core glass in acid (d). The slice is usually made at an oblique angle to the axis of the microchannels so that in the finished plate electrons will collide with the channel wall near its input rather than flying straight through to the anode. This angle also has the important function of reducing ion and light feedback. Finally metal is evaporated onto both surfaces of the wafers so that electrical connections can be made (e).

In the absence of treatment MCP glasses have high electrical resistivity. Conductivity is improved by removing the oxygen from the lead oxide at the surface of the channels by heating the plates in an atmosphere of hydrogen. After several hours at 400 °C the reduction of the lead oxide penetrates to a depth of several tenths of a micrometer. Most of the reduced lead has
evaporated from the surface creating a silica-rich semiconducting layer and the lead underneath the surface has coalesced into metallic clusters forming a conducting layer.

The wafer is finished by evaporating a metal film onto both faces so that electrical connections can be made to all the channels.

2.4.2 MCP Operation

The performance and gain behaviour of MCPs are basically determined by the channel geometry and the composition of the various layers that result from the surface treatment process. Fig. 2.8 shows a schematic diagram of these different layers in the MCP channel walls.

![MCP channel wall and secondary emission process](image)

Figure 2.8. MCP channel wall and secondary emission process (from Corbett 1991). When an electron strikes the semiconducting emitting layer, electron-hole pairs are produced. As the secondary electrons travel to the surface energy is lost due to collisions (with free electrons and defect states) but some have sufficient energy to escape into the channel. These are accelerated until they strike the pore wall further up the channel where the process is repeated and more secondary electrons are generated.

When in operation an incoming photoelectron striking the input of a channel will start a cascade process that will generate a cloud of electrons at the output of the channel. These emitted electrons are replenished by electrons from the strip current that runs through the conducting layer. The gain that is obtained is dependent upon the band-gap in the pore material. Impurities, notably OH, H$_2$O and CO$_3^-$, absorbed in the pore walls lower the work function of the secondary electrons thus increasing the gain. However, detrimentally, gas desorption during electron amplification leads to (a) lowering of the gain and (b) generation of ions that can damage the photocathode. Because of this MCP pores are electron scrubbed, during the manufacture process, to remove most of the impurities (Norton et al. 1988) and provide a stable gain with low ion generation.
When the channels are operating at high gain after scrubbing, gas atoms in the pore can be ionised by collisions with the cascading electrons. A positively charged ion formed in this way is accelerated by the electric field towards the input end of the tube, where it can hit the channel wall and induce pulses that will be superimposed on the originating pulses at the output introducing noise. Moreover, ions that strike the photocathode can shorten its life. There are two ways to reduce ion feedback. One consists of depositing a thin film of aluminium oxide, permeable to electrons but not ions. Unfortunately this causes a reduction in DQE. The second is to use curved or multiple MCPs (Fig.2.9) to inhibit ions reaching the photocathode by collisions with the walls. For intensified CCD photon counting detectors such as the MIC system, a phosphor screen is used to convert the electron cloud emitted from the MCP stack back to photons. However, the photocathode is sensitive to any light fed back from the phosphor. Curved and multiple MCPs have the added advantage of being opaque enough to prevent optical feedback between the phosphor and the photocathode.

When operated at highest gain, charge saturation occurs due to space charge effects within the MCP pores that limit secondary electron emission. When the electron cascade reaches a density of $\sim 10^6 \, e^{-}\text{mm}^{-1}$ mutual electrostatic repulsion tends to return additional secondary electrons to the surface of the channel before the field can significantly accelerate them. The result is to limit further growth of the cascade. In many applications, such as photon counting applications like the MIC detector, this effect is actually beneficial because it makes the output pulses of the multiplier more nearly identical suppressing random fluctuations in the total charge carried by each cascade, thus allowing discrimination against noise.

After the amplification process for each event, the associated pores are depleted of electrons and need to be re-charged. Typical pores in an MCP have a length to diameter ratio of 40:1, a diameter of 10 $\mu$m, a centre to centre spacing of 12 $\mu$m, and a very high electrical resistance ($\sim 10^{14} \, \Omega$). Each channel typically holds a charge $q_c$ of about $10^4 \, e^-$ when operated in or near the saturation voltage, each incoming electron causes the channel to release most of its stored charge instantaneously. The capacitor then recharges by drawing current through the channel resistance. The lower this resistance then the higher the current drawn and the shorter the recharging time. However, the lower resistance leads to heating of the MCP and hence are called ‘hot MCPs’.

If a given channel is never stimulated more than once in a recharge time its PHD is independent of count rate. More frequent stimulation does not allow a full recharge, and hence the pulses are not as large as under quiescent conditions. This decreases the number of photons detected in each pore.

From an electronic point of view the channel plate behaves as millions of tiny resistances $R_c$ and capacitances $C_c$ connected in parallel (Sams 1990). The total parallel DC resistance ranges from $\sim 10^5 \, \Omega$ for ‘hot’ plates to $\sim 10^9 \, \Omega$ for normal plates. If $n$ is the effective number of dynodes
in each channel (about 20 in the commonly used 40:1 plates) then each channel has an effective recharge resistance $R_r$ of

$$R_r \approx \frac{R_e}{n} \approx \frac{10^{14} \Omega}{20} = 5 \times 10^{13} \Omega,$$

so that recharge time is just the time it takes to charge a capacitance $C_c$ with $q_c$ electrons through a resistance $R_r$. With a potential of $V = 1000V/n = 50$ V, the current flowing in each channel should then be $50V/5 \times 10^{13} \Omega = 2 \times 10^{11}$ A. Only about 10% of the available current can be used for recharging the depleted channel. At higher currents the channel cannot maintain a uniform electric field. A non uniform electric field alters electron trajectories, changes the effective number of dynodes (and thus the gain), and produces a non-linear response. Hence the maximum current density which recharges the channel is $I_{\text{max}} = 2 \times 10^{12}$ A, the recharge time is then

$$\tau_r = \frac{q_c}{I_{\text{max}}} = \frac{10^4 \, \text{e}^-}{10^6 \, \text{e}^- \, \text{s}^{-1}} = 0.01 \, \text{s}.$$  \hspace{1cm} (2.3)

This suggests that a given channel cannot be stimulated more than 100 times per second without changing the shape of its pulse height distribution.

### 2.4.3 Operating Limitations of MCPs

There are a few operational limitations in MCPs, the most common being:

- **Current saturation.** This occurs when the event rate in MCPs is too high and results from the electric charge removed from the glass not being immediately replenished. The number of electrons extracted from the MCP channel wall results in significant positive charging of the walls. At these high positive wall charge densities the effective potential drop that accelerates the electrons is reduced. This in effect reduces the secondary electron emission coefficient, hence reducing the amplifying efficiency almost to unity. Experimental data has indicated that MCPs will operate in a linear fashion until the output current reaches 10 to 15% of the strip current. Assuming that saturation does not result from other mechanisms gain is thus limited by the speed at which charge can be re-supplied to channel walls after the passage of a pulse.

- **Open area ratio.** This is the ratio of the open area to the total area of the MCP. Because of the geometry and thickness of the channel the surface area of the entrances to the channels is less that the surface area of the entire plate. The open area ratio ($OAR$) for cylindrical channels is given by:

$$OAR = \frac{2\pi \left( \frac{r}{D} \right)^2}{\sqrt{3}}.$$
where \( r \) is the channel radius and \( D \) is the channels centre to centre spacing. For a typical MCP (10 \( \mu \text{m} \) pores on 12 \( \mu \text{m} \) centres) this is \(-63\%\).

- **Cosmetic defects.** The output intensity of an MCP stack, having a uniform intensity input is not perfectly uniform. In most plates there are defects such as dark spots due to fabrication problems. There is also an hexagonal pattern (chicken wire) across the entire MCP that corresponds to the edges of the hexagonal multi-fibre bundles. This hexagonal pattern reflects in changes in the local gain and the direction of the output charge cloud causing \(-10\%\) modulation in the image.

- **Background noise.** It has been found (Fraser et al. 1987, Lees and Pearson 1996) that the main source of background noise (\(-0.2 \text{ events cm}^{-2} \text{ s}^{-1}\)) in MCP plates comes from the \( \beta \) emission by \(^{40}\text{K}\) in the glass. Low noise MCPs are now manufactured from material containing no radioactive isotopes allowing the noise levels to be reduced to \(-0.03 \text{ events cm}^{-2} \text{ s}^{-1}\). This noise is very low and about twice the level expected from the natural cosmic ray background.

### 2.4.4 MCP Configurations

The optimum MCP configuration for any given detector application depends upon a number of operating characteristics. Among these the gain, Pulse Height Distribution (PHD), plate resistance, recovery time, size of emergent cloud of electrons, freedom from ion feedback effects, background event rate, quantum efficiency, MCP size, and required electrical potential are some of the most important parameters.

Single MCPs operate at low gain and have the disadvantage of having an exponential PHD by virtue of the large statistical variation in the number and energy of electron-wall collisions. For this reason they are used in applications where the image quality requirements are not very high, like in night vision systems.

High resolution analogue imaging systems require high gain with tight PHDs and small emergent cloud sizes. In these cases a single curved channel plate (Fig. 2.9c) which gives narrow PHDs and gain \( >10^6 \text{ e'/e'} \) combined with small cloud spread and relative immunity to ion feedback effects has been found to be ideal.

Most photon counting detectors that employ MCPs require high gain, tight PHDs, and broad cloud sizes to allow centroiding. Some possible configurations are tandem and z-stacks (Figs. 2.9a and b). These provide gains as high as \( 10^8 \text{ e'/e'} \) with low ion feedback and very tight PHDs. At large modal (most probable) gains the PHD of a z-stack becomes tight due to saturation. Table 2.1 shows the typical characteristics of the most common MCP configurations.
Figure 2.9. Schematics of high-gain MCP structures (from Timothy 1991). a) Chevron stack and b) z-stack fabricated with conventional straight channels where ion-feedback is inhibited at the boundary between the plates. c) curved plate in which the mean free path of ions is minimised, lowering their kinetic energy and hence reducing the probability of secondary emission.

<table>
<thead>
<tr>
<th>Maximum Gain $(e'/e')$</th>
<th>Voltage (kV)</th>
<th>Energy Resolution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single straight</td>
<td>$10^{-10}^{10}$</td>
<td>$-1$</td>
</tr>
<tr>
<td>Single curved</td>
<td>$10^{-10}^{10}$</td>
<td>$-2$</td>
</tr>
<tr>
<td>Chevron assembly</td>
<td>$10^{-10}^{10}$</td>
<td>$-3$</td>
</tr>
<tr>
<td>Curved and straight</td>
<td>$\sim 10^{7}$</td>
<td>$-3$</td>
</tr>
<tr>
<td>Z-stack</td>
<td>$10^{-10}^{10}$</td>
<td>$-4$</td>
</tr>
</tbody>
</table>

Table 2.1. Characteristics of MCP configurations. The energy resolution is defined as the full width at half maximum divided by the modal gain of the energy distribution histogram obtained from a large number of pulses at the output of the intensifier.

2.5 The Phosphor Screen

Phosphor screens are relatively smooth layers of luminescent material deposited on an optical quality glass or a fibre optic plate. The basic function of the phosphor screen is to convert the electron beam energy to light. The exact details of energy conversion to light may be different for different phosphors but, in general, part of the electron beam energy is used to produce excited states within the material and light emission occurs when the excited states return to the normal state.

After being deposited on the substrate, the luminescent material is coated with a thin opaque film of aluminium (Fig. 2.10) whose functions are 1) to provide a conductive layer so that a uniform potential can be applied to accelerate the electron beam. 2) to prevent light feedback from the phosphor screen to the photocathode, and 3) to serve as a light reflector for the phosphor screen, thus improving its efficiency.
The most common families of phosphors are based on zinc sulphide (ZnS) and zinc cadmium sulphide (ZnS-CdS) with silver and chlorine as activators. Silver acts as a p-type impurity and chlorine as an n-type one (Fig. 2.11).

In equilibrium, chlorine donates its electron to the silver, so both impurities are charged. Luminescence occurs when an energetic electron creates free electrons and holes in the sulphide. These charge carriers lose their energy to the lattice by phonon production while drifting through the crystal until captured by the charged impurity atoms. De-excitation, and light emission, occurs when the electrons transfer from the chlorine to the silver re-establishing the equilibrium condition (Fig. 2.12).

The efficiency of the phosphor (conversion of the electron beam energy to radiant energy) depends on the competition between the radiative and radiationless transitions. The largest energy losses occur in the process of electron-hole pair production followed by phonon generation. Typically, a well designed phosphor has an efficiency of about 25%, with the remaining energy of the electron being lost as heat.
Other factors affecting efficiency are thickness of the phosphor screen, particle size of the phosphor, electron beam energy, and losses in the aluminium film.

A phosphor screen thicker than the penetration depth of the electrons absorbs some light as it passes through the material. On the contrary, if the phosphor screen is too thin the electron beam is not stopped by the fluorescent material but passes through giving its energy to the substrate without participating in the production of light. In general, the larger the particle size of the phosphor, the greater the screen efficiency. Unfortunately this will also result in the loss of resolution. An optimum balance of conversion efficiency and resolution requires a trade-off between particle size and screen thickness. Ideally the particle size should be equal to the screen thickness (a monolayer screen). In such screens, however, the microscopic irregularities reduce the performance of the screen. Therefore smaller particles are also included to provide a smooth screen layer. The losses in the aluminium film may be minimised by keeping it as thin as the opacity requirements allows.

For photon counters phosphor screen resolution is not of importance (since it is governed by the centroiding process) and to provide greater consistency in event shape, small grain sizes are desirable. As the phosphor is hit by \( \sim 2 \times 10^5 \) e\(^{-}\) the small irregularities over an area of \( \sim 80 \mu m \) diameter, due to grain size variation, are then smoothed through.

Fig. 2.13 shows the spectral energy emission characteristics of some phosphor screens.
There are two factors to take into consideration when choosing a phosphor for an intensified CCD camera:

- **Spectral efficiency.** A phosphor that best matches the transmission characteristics of the fibre taper and the sensitivity of the CCD is preferred. Also, the more efficient the phosphor is the less gain is required of the intensifier and the longer its lifetime.

- **Decay time.** If the phosphor's decay time is much longer than the frame period of the CCD camera then photon events will be counted two or more times. This could be avoided by using a facility to continuously subtract a number of the preceding frames from the current frame before it is analysed.

It has been found that the P20 phosphor (ZnS-CdS:Ag,Cl), with radiation centred at 560 nm and a decay time of ~2 μs to 10%, is the best option.

### 2.6 The MIC Image Intensifiers

#### 2.6.1 First Intensifier Design

Initially a consortium between ICSTM, RGO and ITL developed a 40 mm diameter intensifier based upon two 80:1 MCPs (double the standard 40:1 length to provide additional gain) in a chevron configuration that provided a gain of $1.5 \times 10^7$ photons/photelectron (Norton et al. 1988). An S20 photocathode was incorporated and the output charge cloud was imaged onto an aluminium backed P20 phosphor screen. This screen, which was deposited on a fibre optic
output window, replaced the P11 phosphor used in the EMI intensifier as it provided better matching to the CCD's spectral response (being green and not blue in colour).

The first MCP had a very thin (5 nm) SiO$_2$ film deposited on its input face to prevent negative ions generated in the high gain MCP stages from being accelerated back to the photocathode. The MCPs had 12 $\mu$m diameter pores with a 15 $\mu$m centre to centre spacing and a bias angle of 8°.

Field trials with the detector at the AAT where a direct performance comparison with the IPCS was carried out (Fordham et al. 1988), showed that the dynamic range was effectively improved but two problems existed: the quantum efficiency was 50% lower, and halation was present which created wings on emission line profiles and in-filling of absorption line profiles.

Both of these artefacts were attributed to the ion-barrier film. It was found that 50% of photoelectrons did not penetrate this film, thus reducing the QE, and it was surmised that scattering of photoelectrons from the film was primarily responsible for the halation.

### 2.6.2 Final MCP Design

To overcome these intensifier artefacts it was important to remove the ion barrier film while, somehow, preventing ions from reaching the photocathode. Two designs were compared (Airey et al. 1990) against the initial chevron configuration (Fig 2.14).

![Figure 2.14](image)

*Figure 2.14. Types of MCP intensifiers used for photon counting. Chevron configuration with ion barrier (a). Z-stack (b). Curved-straight combination (c).*

With the z-stack, the ion barrier is replaced by a 40:1, highly scrubbed, MCP. The scrubbing lowers the gain of the MCP to such an extent that ions are not produced within that plate whereas ions produced in the higher gain following stages are absorbed by this MCP. The alternative curved-straight combination, which has been used in some MAMA detectors (Timothy 1991b) relied upon the curvature of the first MCP to absorb ions produced further along the pore walls.

Both designs worked effectively with minimum ion feedback being associated. It was decided, though, to opt for the z-stack design as the curved MCP was difficult to manufacture, showed considerable variations in gain from place to place, and had a higher number of cosmetic defects.
Table 2.2 shows the measured characteristics of the EMI-9912 intensifier and some MCP based detectors produced for photon counting.

<table>
<thead>
<tr>
<th></th>
<th>Chevron</th>
<th>Z-stack</th>
<th>Curved-Straight</th>
<th>EMI-9912</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain (photons/event)</td>
<td>$2\times10^3$</td>
<td>$4\times10^3$</td>
<td>$5\times10^7$</td>
<td>$5\times10^6$</td>
</tr>
<tr>
<td>Resolution, FWHM (μm)</td>
<td>27</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Dark Counts @ 0 °C (counts cm$^{-2}$ s$^{-1}$)</td>
<td>3.2</td>
<td>7.5</td>
<td>3.5</td>
<td>53</td>
</tr>
<tr>
<td>Phosphor Decay to 10% (μs)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2000</td>
</tr>
<tr>
<td>Photoelectron Counting Efficiency (%)</td>
<td>30</td>
<td>62</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>Peak DQE (%)</td>
<td>4.5</td>
<td>18.5</td>
<td>10</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 2.2. Characteristics of some 40 mm detectors produced for photon counting compared to the EMI-9912 intensifier. All the detectors use S20 photocathodes. The EMI-9912 has four P11 phosphor screens while the other intensifiers have a single much faster decay P20. From Airey et al. 1990 except curved-straight data taken from Read et al. 1990.

2.7 The 75 mm Intensifiers

Using the expertise acquired by ICSTM in the development of the 40 mm MCP intensifiers (Norton et al. 1988, Airey et al. 1990, and Norton et al. 1991), three 75 mm diameter MCP intensifiers were built for astronomical applications.

These intensifiers incorporated a bialkali semi-transparent photocathode, three MCPs in a z-stack configuration, and a P20 phosphor screen in a dual proximity focused arrangement. The input MCP is a 40:1 channel plate conditioned to run at low gain and to act as an ion barrier for the succeeding 80:1 chevron pair allowing the intensifier to operate at very high gain with a saturated (peaked) pulse height distribution while ensuring good noise rejection and high DQE.

The intensifiers were manufactured in a de-mountable stainless steel ultra high vacuum (UHV) chamber by Photek Ltd., England. The first two intensifiers used 25 μm diameter pore on 32 μm centres in all MCPs of the stack. It was decided to use these more robust plates while manufacturing techniques for large diameter intensifiers were under investigation. The final version of the detector had a 10 μm diameter pores on 12 μm centres MCP at the input of the stack in order to provide the higher resolution required for astronomical applications.

Some changes were made to the original production procedure:

- The 40 mm intensifiers were found to lose some photocathode sensitivity during the seal off in the vacuum chamber (Norton et al. 1991). This reduction was attributed to over-heating of the photocathode during the seal off process. To minimise this problem in the 75 mm intensifiers a low melting point indium-bismuth solder was used. This solder melts at 70 °C compared to 130 °C for the indium-tin solder previously used (Airey et al. 1991).
- MCPs are liable to bow when exposed to humid air or to high temperatures (Fordham et al. 1991a). This phenomenon becomes increasingly important in large
area MCP detectors, as the same degree of bowing in a 75 mm intensifier will produce a larger variation in gain and event size across the field than the 40 mm intensifier. In the worst case the MCPs may touch. To minimise this problem the plates chosen for MCP2 and MCP3 of the 75 mm intensifiers were of a type manufactured without a solid glass rim surrounding the channels (called 'soft edged plates'). These plates had 25 µm diameter pores, and hence are twice as thick as the 12 µm pore diameter MCPs used in the 40 mm intensifiers making them less susceptible to bowing during intensifier processing.

- A problem was associated with the supply of a uniform, large area, excitation source that was required for the scrub procedure. The electron flood gun used for scrubbing the 40 mm plates was simply a heated filament, coiled inside a cup, with a field applied between it and the front MCP. This emission source was found to produce a very non-uniform electron beam. A novel design of electron gun was produced to scrub the 75 mm MCPs. This electron gun used a stack of three 18 mm diameter MCPs to supply the flood beam. The input MCP of this stack was excited by an ultraviolet (UV) lamp shone through a glass window into the UHV chamber (the glass window absorbs most of the light but enough is transmitted to excite the input channel plate). By running the rear plate into hard saturation a uniform current was supplied, washing out any non-uniformities in the exciting UV source. A diverging electrostatic lens was then used to expand the cloud and cover the whole 75 mm diameter with the electron beam (Butler at al. 1994).

2.7.1 Processing of the Intensifiers

The scrubbing of these tubes was carried out with no problems encountered with the electron flood gun which was found to produce an adequate current to run the 75 mm stack at high enough levels to desorb unwanted gas from the plates. The scrub was stopped, following procedures defined for the 40 mm intensifiers, when a pressure rise of less that $0.5 \times 10^{-10}$ torr was observed with a 10 µA scrub current. The process took about 8 days for each tube with a total charge of $\sim 0.7$ C-cm$^{-2}$ extracted from each.

All the intensifiers had a bialkali (NaKSB) photocathode deposited onto a quartz window which was then sealed onto the intensifier using the hot seal indium bismuth alloy.
2.7.2 Performance of the 25/25/25 μm Intensifiers

The performances of the first two 75 mm intensifiers, labelled here as A and B, were measured in a series of tests using a pulse height analyser at ICSTM and the BigMIC system at UCL. The results are summarised in Table 2.3.

<table>
<thead>
<tr>
<th></th>
<th>Intensifier A</th>
<th>Intensifier B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FWMH (μm)</strong></td>
<td>52</td>
<td>36</td>
</tr>
<tr>
<td><strong>RQE at 350 nm (%)</strong></td>
<td>19.5</td>
<td>29</td>
</tr>
<tr>
<td><strong>Gain (photons/photoelectron)</strong></td>
<td>10⁷</td>
<td>10⁷</td>
</tr>
<tr>
<td><strong>DQE at 350 nm (%)</strong></td>
<td>11.5</td>
<td>18.0</td>
</tr>
<tr>
<td><strong>PHD=ΔG/G (%)</strong></td>
<td>129</td>
<td>125</td>
</tr>
<tr>
<td><strong>Dark Current (counts-cm⁻²-s⁻¹)</strong></td>
<td>15.7</td>
<td>10.4</td>
</tr>
</tbody>
</table>

Table 2.3. Performance of the 25/25/25 μm intensifiers (Butler et al. 1994).

The counting efficiency (DQE/RQE) of intensifier B was slightly higher than that of intensifier A as the latter had to be run at reduced cathode voltage due to an arcing problem between the photocathode and the front MCP. This problem was a source of edge emission from the cathode, resulting from the vacuum sealing process, which caused intensifier A to have high background noise.

The dark noise of intensifier B was seen to decrease to ~4 counts-cm⁻²-s⁻¹ after an extended period of darkness suggesting that an element of the dark noise was due to photon-stimulated luminescence in the cathode optics.

Another noise source was observed in these intensifiers: when the photocathode was gated off and the intensifier run up to operating voltages a large area of the intensifier was seen to be producing faint low level events. These could be associated with electron emission from the MCPs maybe triggered by the radio-active decay of contaminants in the MCPs. To determine the contribution to the total noise by these events, the dark noise was measured with the cathode gated off. This source of noise produced dark currents of ~0.9 counts-cm⁻²-s⁻¹, hence this being of little importance.

When the intensifiers were operated with the BigMIC electronics a number of problems became apparent.

- Using 10 μm data acquisition pixels, the 25 μm pores of the first MCP could be totally resolved showing the MCP1 sampling of the input image. If it is assumed that two pixel sampling of the input is required for scientific analysis of acquired images then a limiting resolution of 64 μm is associated rendering it unusable for high resolution astronomical applications.

- There were two very noticeable features in the images: (1) a 'chicken wire' pattern was clearly visible and (2) a large number of dead spots were present. Tests
showed that the dead spots were not cathode related nor gain dependent. The fact that there were no counts detected at all in these regions suggested that they were not an artefact of the plates due to gain variations or to variability in the secondary emission yield of the first collision with a channel, but were either dislocations or blocked channels.

2.7.3 Performance of the 10/25/25

To overcome the resolution limit imposed by using 25 µm pores in MCP1, allowing imaging of the pores with 10 µm detector pixels, a third intensifier using 10 µm pores in 12 µm was then manufactured. On incorporation in the BigMIC system it was found that the intensifier had a light emitting defect on the edge of the active area which provided a very high, non-uniform, background that made the intensifier unsuitable for astronomical trials. Later an electrical breakdown at the intensifier started to occur rendering it unusable. ICSTM were of the opinion that the only way this defect could be removed was via re-processing of the intensifier at Photek.

The intensifier was taken back to ICSTM where the problem was found to be an extraneous particle within the intensifier. The breakdown problem was fixed so that the intensifier could be used, though the bright edge emission was still present.

The performance of this 75 mm intensifier when incorporated in the BigMIC detector is discussed in detail in Section 8.1.
CHAPTER 3
The Fibre Taper

A fibre optic taper is used in ICCD systems to couple the MCP intensifier to the CCD. The main advantage over a lens coupled system is that the light transmission is higher, allowing operation of the image intensifier at a lower gain with a corresponding increase in lifetime. Because of the approximately lambertian angular distribution of the light emitted by a phosphor screen, even a very fast lens cannot transmit more than a small fraction of the light (1 to 3% compared with ~6% for a 3.47:1 fibre taper).

A second disadvantage of lenses is optical aberrations which cause variable profiles of events. Fibre tapers are also shorter, lighter, and mechanically and optically more stable than lenses. The only disadvantage is that the flexibility of lenses, with regard to magnification, is not shared by fibre optics so that a fixed magnification must be specified and this must lie within a very restricted range.

A fibre optic taper (Siegmund 1991, Coleman 1984) is a bundle of millions of tapered optical fibres fused together that acts as a magnifier. Each of the fibres is clad so that light is contained by total internal reflection. The magnification is given by the ratio of the diameters of the large and the small end of the taper \( \frac{D_1}{D_2} \). Since light can pass through in either direction it can also act as a minifier as in the MIC systems.

The fibres are made with enough cladding to prevent cross-talk at the smallest end of the taper where fibres are the smallest. To control stray light (light which is not properly confined within the fibres by total internal reflection and basically produced by scattering at imperfections in the fibres) which enters through the cladding or escapes from the fibres, a stray light absorber is normally included. This consist of placing small black fibres interstitially among the clear fibres and is referred as extra-mural absorption. This minimises cross talk between fibres enhancing contrast at the expense of light transmission.

One of the most important parameters of an optical fibre is its numerical aperture. In parallel fibres, the maximum cone angle at which rays can be transmitted by total reflection is a function of the refractive indices of the core \( n_1 \) and cladding \( n_2 \) glasses. In a taper this maximum angle occurs at the smallest cross section \( d_2 \) of the taper and is given by

\[
a_2 = \sqrt{n_1 - n_2}.
\] (3.1)

The numerical aperture varies along the taper and decreases as the diameter increases in such a way that the effective numerical aperture (at the large end) of the taper is:
\[ a_i = a_2 \frac{d_2}{d_1} = a_2 \frac{D_2}{D_1}. \]  

(3.2)

Current tapers are made with glasses chosen to provide a relative high value of \( a_2 \) (~1.0). Because of this light leaving this end spreads ~180 degrees and very close coupling to another components is important to minimise the loss of resolution. Thus, the flatness of the surface to be coupled must be held within a few wavelengths and immersion oil could be used to avoid losses by Fresnel reflections in the interface. Fig. 3.1 shows the fibre tapers used in the systems developed at UCL and Table 3.1 presents their characteristics.

**Figure 3.1.** Fibre tapers used in our systems. From left to right: XMM, MIC, and BigMIC.

<table>
<thead>
<tr>
<th>FIBRE TAPER</th>
<th>( D_1 ) (cm)</th>
<th>( D_2 ) (cm)</th>
<th>Minification</th>
<th>( L ) (cm)</th>
<th>( d_1 ) (( \mu )m)</th>
<th>( d_2 ) (( \mu )m)</th>
<th>( a_2 )</th>
<th>( a_1 )</th>
<th>( C_A )</th>
</tr>
</thead>
<tbody>
<tr>
<td>BigMIC</td>
<td>7.67</td>
<td>2.21</td>
<td>3.46:1</td>
<td>5.59</td>
<td>25</td>
<td>7.2</td>
<td>1</td>
<td>0.29</td>
<td>0.75</td>
</tr>
<tr>
<td>MIC</td>
<td>4.16</td>
<td>1.21</td>
<td>3.44:1</td>
<td>3.97</td>
<td>10</td>
<td>2.9</td>
<td>1</td>
<td>0.29</td>
<td>0.75</td>
</tr>
<tr>
<td>XMM</td>
<td>2.80</td>
<td>0.96</td>
<td>2.92:1</td>
<td>2.77</td>
<td>8</td>
<td>2.7</td>
<td>1</td>
<td>0.34</td>
<td>0.75</td>
</tr>
</tbody>
</table>

**Table 3.1.** Characteristics of some fibre tapers used.

Fibre tapers do suffer from geometrical distortions like barrel, pin-cushion and image dislocations. For this reason the highest quality tapers must be procured.

Proper electrical grounding of the taper’s body, to avoid surface tracking and capacitive coupling of high voltage, is also recommended.

According to Siegmund (1991) the transmission of diffuse light by a fibre taper is given by

\[ T_{\text{diff}} = T_{\text{core}} \cdot C_A \cdot (1 - R)^2 \cdot a_1^2, \]  

(3.3)

were \( T_{\text{core}} \) is the internal transmittance of the core glass which varies with wavelength and length of the taper, \( C_A \) is the relative area of the core to the area of the overall fibre (~0.75), \( R \) represents the Fresnel reflection losses from the end faces (~0.08 when no optical oil is used), and \( a_1 \) is the effective numerical aperture of the taper.

From this equation, the typical transmittance curve for core glass in fibre tapers (Siegmund 1991), and the information in Table 3.1 expected transmission curves were calculated and the results shown in Fig. 3.2.
Fig. 3.3 shows the effect of using optical oil in the interfaces between the image intensifier and the fibre taper and the fibre taper and the CCD. It can be seen that the transmission efficiency is increased by about 20% when optical oil is used.

Figure 3.3. Effect of optical oil on transmission efficiency. The empty squares represent the intensified event's energy distribution without optical oil while the solid squares correspond to the same set-up but with optical oil used in the intensifier/fibre taper and fibre taper/CCD interfaces. The event energy is given by the addition of the values of the 9 pixels forming the DAA (See Section 5.4).
CHAPTER 4
The CCD Camera

4.1 Charge Coupled Devices

Cryogenically cooled charge coupled devices (CCDs) have become the imaging detectors of choice for nearly all scientific investigations from the near-infrared (≈1000 nm) to the near-ultraviolet (≈300 nm). Apart from their excellent quantum efficiency and broad spectral response these detectors are also characterised by high linearity and photometric accuracy, not to mention good spatial resolution, geometric stability, low noise, reliability, and durability among other factors. Their main disadvantages over some other detectors are their relatively small imaging areas, strong sensitivity to cosmic rays, electroluminescence in some devices, and the unavoidable cosmetic defects generated during their manufacture.

Buried, or bulk, channel CCDs (Mackay 1986, Beynon 1977, Lamb 1977, Séquin and Tompsett 1975, and Amelio 1974) are integrated circuits that generally consist of a p-type silicon substrate on which an n-type layer is formed by epitaxial growth or by ion-implantation. The n-type layer is covered by a thin insulating silicon oxide layer, upon which an array of closely spaced transparent polysilicon electrodes are formed (Fig. 4.1). The n-type layer and the associated reverse biased diodes in contact with it cause potential wells to form some distance into the bulk semiconductor, thus avoiding the surface states in the semiconductor-oxide interface.

Surface states are generated by lattice defects in which charge becomes easily trapped. The slow release of charge by these traps affects adversely the charge transfer efficiency and reduces the maximum frequency of operation of these devices. Spurious charges are also injected by these defects producing increases in dark current. Using the buried channel technique overcomes these problems.

![Figure 4.1. Cross section through a buried channel CCD. In this example there is no voltage applied to the electrodes. The dotted lines represent some typical equipotentials lines generated by the reverse biased diodes which are in contact with the n-type silicon layer.](image-url)
The electrodes are connected in a periodic manner into phase systems. Each phase set comprises a picture element or pixel. The application of voltages to each of these phases generate potential wells that merge or ‘couple’ as shown in Figure 4.2.

During the integration time, photons imaged into the CCD’s surface penetrate the electrode structure into the n-layer and substrate where, by the photoelectric effect, they generate electron-hole pairs in numbers precisely proportional to the number of incident photons. The holes diffuse away into the bulk of the silicon, and are effectively lost, while the electrons migrate rapidly towards the nearest, and highest biased, electrode to be collected in its potential well (located inside the n-layer). After the charge generation and collection the voltages on the electrodes are manipulated in a systematic way so that the accumulated charge packets are transferred to one of the extremes by shifting from one pixel to the next.

Fig. 4.2. Charge transfer mechanism on a 3-phase CCD with a representation of the potential wells under the electrodes (after Amelio 1974).

Fig. 4.3 shows the quantum efficiency versus wavelength characteristics for a typical front-side illuminated (through the electrodes) CCD and for a thinned backside-illuminated CCD.

In the case of frontside-illuminated CCDs, short wavelength photons are reflected and absorbed by the electrodes before they can penetrate to the substrate thus the dramatic loss of efficiency at the blue end of the spectrum. Longer wavelength photons do not have this problem but, since penetration into the substrate increases strongly with wavelength, the electrons generated by the reddest photons have more chances of recombining (and become lost) while they are diffusing back to the potential wells under the electrodes. At the longest wavelengths photons are not detected because they do not have enough energy to generate electron-hole pairs.

To enhance the quantum efficiency and the spectral coverage of this type of device, thinned backside-illuminated CCDs have been developed. In this approach the substrate faces the incoming light so that the blue photons do not have to confront the impenetrable electrodes.
Despite the impressive response of these devices, there still are some problems that have to be solved. In order to maximise the collection of photoelectrons the substrate must be thinned (by mechanical and chemical abrasion) to a thickness of less than 20 \( \mu \text{m} \). There still are technological difficulties with uniformly thinning and then mounting these fragile devices flat in their final packages.

After a CCD is thinned, a silicon oxide (SiO\(_2\)) film grows naturally (on the backside) due to contact with air. The dangling molecular bonds at the Si-SiO\(_2\) interface, due to abrupt termination of the silicon crystal lattice, creates a positive potential well which prevents electrons from migrating to the collecting sites. This produces a lowering of the quantum efficiency of these untreated devices even below that of frontside-illuminated CCDs. Different ways of eliminating this potential well are currently employed or under investigation like: UV-flooding (exposure to UV light in the presence of oxygen), chemical treatment of the CCD surface, doping of the backside layer to create a negative potential, flash gate deposition (a very thin electrically conductive coating allowing for the application of an adjustable voltage at the surface), surface etching with an acid and then oxidation with de-ionised water, etc. (McLean 1997).

![Figure 4.3 Typical quantum efficiency characteristics of a thinned backside-illuminated CCD and a frontside-illuminated CCD (after Hughes 1995).](image)

4.2 Frame Transfer CCDs

Frame transfer imagers, as are used in the BigMIC detector, consist of two distinct arrays of storage pixels on the same chip. One array is light sensitive and constitutes the imaging zone while the other, identical in structure but covered by an aluminium mask, is the storage zone.

Fig. 4.4 shows a simplified representation of a frame transfer CCD. As can be seen in this figure the boundaries of each pixel in the vertical direction are defined by the electrodes themselves while for the horizontal direction channel stops are used. Channel stops are diffusions of highly doped p-type material that keep the potential of the oxide-silicon interface near zero.
After integration in the imaging zone charge is transferred, as fast as possible, into the storage zone. This limits any image smearing (as no mechanical shutter is employed) during the frame shift time, which is considerably shorter than the readout time. Whilst the image is readout from the storage zone a new image is integrated in the image zone. Thus the imaging time equals the readout time. During the passage of the charges from the imaging zone to the storage zone, the clocks applied to order the transfer in these two sections (A and B) are identical. On each cycle of the clock phases the contents of each row are simultaneously transferred into its neighbour.

The information contained in the storage zone is then transferred row by row towards the horizontal register where the charge packets are transposed in a serial fashion (shifted) to an on-chip amplifier that converts them to voltage levels proportional to their charge.

![Diagram of a frame transfer CCD](image)

**Figure 4.4.** An ideal, simplified 3x3 frame transfer CCD to illustrate the typical architecture with a 3-phase clock structure.

The design almost universally adopted for the CCD charge detection (Fig. 4.5) comprises an n+ contact diffusion at the end of the register, a reset transistor and a source follower stage consisting of an output transistor and its load. The contact diffusion is actually a strongly reverse biased diode acting as a very small capacitor. Prior to charge output the potential on the node capacitance $C_n$ (mainly associated with the output diffusion capacitance and the gate-source capacitance of the output transistor) is reset to a reference voltage $V_{RD}$ using a control pulse (RESET) applied to the gate of the reset transistor. Then, by normal clocking operation, the signal charge $Q$ in the last CCD element is deposited onto the node capacitor causing the latter’s potential to change linearly with the quantity of charge received, i.e. $\Delta V = Q/C_n$. A low value of $C_n$ (~0.1 pF typically) is advantageous for achieving high output responsivity (in term of volts per electron) and low noise.
The output gate, whose function is to act as a partial barrier to charge so that charge can only flow to the output diode, is normally held at a constant and fairly low voltage ($V_{OG}$).

The source follower transistor serves as a buffer between the high impedance of the diode and the much lower impedance of the following circuitry and typically has a gain of $-0.7 \mu V/e'$. 

![Figure 4.5](image) On chip floating diffusion amplifier and 'dummy' output amplifier.

Some CCD amplifier designs, including EEV, incorporate a 'dummy' amplifier into the output structure which is clocked simultaneously with the imaging output. Assuming that the amplifiers are in close proximity on the device and that their geometries are the same, it is expected that the output video signals will be similar, but for the fact that one is carrying the information of the charge from the CCD pixels (Fig. 4.6). As the two amplifiers will share similar quantities and types of distortion, such as reset feedthrough and serial clock ringing, the subtraction of these two signals (in the early stages of the analogue processing chain) will eliminate those noise components.

![Figure 4.6](image) Timing diagram of the output stage of the CCD. The 'clean' signal is obtained by subtracting DOS from OS.
4.3 Requirements on the CCD Camera

The effective operation of an intensified CCD photon counting system needs the CCD camera to meet certain basic requirements. The most evident of these is frame rate. If the phosphor screen of the image intensifier is not sampled fast enough then photon events arriving at approximately the same position, but maybe at different times, will start to overlap making the identification of each single event difficult. So, in order to maximise the system’s dynamic range a very fast camera is necessary.

In many applications, like spectroscopy, there is no need to read the full active area of the CCD. A windowing facility that reads only a selected region of the CCD will have the added advantage of providing faster frame rates, which will reflect in an added improvement in dynamic range.

The image format of the CCD employed in the BigMIC camera is governed by the practical limitations on the fibre optic taper demagnification from the image intensifier, which for image quality and transfer efficiency reasons, needs to be kept below 4:1. Assuming a CCD with a 4:3 aspect ratio on the image area is employed, then the equivalent area on the intensifier is 60×46 mm² (75 mm diagonal). Thus with a maximum of 4:1 demagnification a CCD image area of >15×11.25 mm² was required. EEV’s CCD05-20 (with an active area of 17.3×12.96 mm²) was found to best match this requirement. This device is of the front-side illuminated type, thinning not being required because of the bright scintillations received from the intensifier.

At the time of the BigMIC development there were no commercially available cameras that met the desired requirements, hence it was decided that I should be responsible for designing and constructing the camera at UCL.

Later it was decided to use the same electronics with small modifications to operate and test a very similar architecture, but smaller format, CCD fabricated EEV (CCD02-06). This was done in order to compare its performance to the Thomson’s TH7863 CCD currently used in the MIC system (Bellis 1992) and on the XMM Blue Camera project. It was thought that CCD02-06 was better suited for the latter application because of its higher radiation hardness.

The basic characteristics of these CCDs, together with the frequencies at which they are operated (see Section 4.5), are shown in Table 4.1.

<table>
<thead>
<tr>
<th>CCD</th>
<th>Pixel Pitch (μm)</th>
<th>Imaging Format (pixels)</th>
<th>Imaging Area (mm²)</th>
<th>Number of Clock Phases</th>
<th>Horizontal Clock Frequency (MHz)</th>
<th>Vertical Clock Frequency (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCD05-20</td>
<td>22.5</td>
<td>770H,576V</td>
<td>17.30×12.96</td>
<td>3H,3V</td>
<td>10.66</td>
<td>0.59</td>
</tr>
<tr>
<td>CCD02-06</td>
<td>22.0</td>
<td>38SH,288V</td>
<td>8.50×6.30</td>
<td>3H,3V</td>
<td>10.66</td>
<td>0.59</td>
</tr>
<tr>
<td>TH7863</td>
<td>23.0</td>
<td>384H,288V</td>
<td>8.83×6.62</td>
<td>2H,4V</td>
<td>10.00</td>
<td>1.25</td>
</tr>
</tbody>
</table>

Table 4.1. Characteristics of the CCDs used in the MIC projects and frequencies of operation.
The quantum efficiency curves of these chips are shown in Fig. 4.7. It can be seen that the quantum efficiencies of CCD05-20 and TH7863 are very similar while for CCD02-06 is much lower. This is due to a loss in sensitive area because of the anti-bloom drains implemented in its design.

![Figure 4.7. Quantum efficiency curves for the three CCDs.](image)

The cameras' frame rate is defined by the speed of the vertical and horizontal clocks.

For the vertical clocks, the maximum frequency is limited by the associated inter-electrode capacitance. It was experimentally found that the vertical clock could be operated at $\tau_v=0.59$ MHz without any noticeable degradation in transfer efficiency.

The maximum horizontal clock frequency is governed by the frequency of operation of the processing electronics, the inter-electrode capacitance or the bandwidth of the output amplifier. According to EEV’s data sheet the CCD could be operated at up to 15 MHz. In this case the processing electronics provided the limitation and for this reason the horizontal clock frequency had to be set at $\tau_h=10.66$ MHz.
4.4 CCD Camera Electronics

As mentioned in Section 4.3 two EEV cameras with very similar designs were produced, one including the large format CCD05-20 which will be referred to as the BigMIC camera and a second one with a small format CCD02-06 referred to as the MIC2 camera.

The electronics for these cameras are divided into three parts, each one implemented on its own printed circuit board. Fig. 4.8 shows a block diagram of the CCD Camera and how it is connected to the Processing Electronics.

CMOS logic circuits of the 74HC family were used extensively in the design of the electronics. These circuits are fast enough to generate the required clock pulses and have the advantage of being less power consumptive and more immune to noise pickup when compared to other options like the TTL family of logic circuits.

![CCD Camera Block Diagram](image)

**Figure 4.8.** Block diagram of the EEV CCD Cameras electronics and its connection to the Processing Electronics.

Fig. 4.9 is a more detailed version of Fig. 4.8. The CCD Board receives a series of clock signals from the Controller Board and generates an analogue video signal that is sent, in differential mode, to the ADC Board. The ADC Board conditions this video signal and then digitises it with 8-bit resolution. The digitised video data along with synchronisation signals are then sent, continuously, to the processing electronics stage.

The OrCAD for PC program was used to draw the schematic diagrams and to generate the artwork for the production of the printed circuit boards. A little explanation on the notations used here and in the description of the Processing Electronics is required: 1) If a signal’s name ends with back slash or star characters it means that this signal is active while in the low state. 2) A data bus is represented as, for example, NAME/[0..7] this being equivalent to the eight wires from NAME0 to NAME7.
Figure 4.9. Block diagram of the BigMic and the Mic2 CCD cameras.
4.4.1 The CCD Board

A block diagram of the BigMIC and MIC2 CCD boards is shown in Fig. 4.10. The board design consists of the CCD itself, voltage regulators to provide some constant level voltages (bias), drivers to level convert the digital clock signals arriving from the Controller Board which control the different clock phases of the CCD, and an amplification stage at the output of the CCD.

![Figure 4.10. Block diagram of the CCD board.](image)

BigMIC’s CCD (CCD05-20) is an integrated circuit that operates on the principles of buried channel charge transfer and three phase clocking as discussed in Section 4.1. The architecture of this device is shown in Fig. 4.11a. It can be seen that it has two light sensitive areas (sections A and B) which can be independently driven. Due to the number of pixels associated, the phase electrodes of these sections represent a large capacitive load to the driving circuits. For this reason each electrode has connections on both sides of the chip for the driving clock signals to effectively reduce the capacitance effect.

Each section has its own readout register (D and C) with two amplifiers at their extremes. For slow scan mode (like in long integration time astronomical applications) the charge packets are transferred to a high performance low noise amplifier (A4 and A2) and for operation at fast pixel rates, as in the BigMIC detector, the charge packets are shifted in the opposite direction where they are sensed by high speed amplifiers (A3 and A1).

Fig. 4.11b is a representation of the line output format of this device. Each row of the CCD is composed of 770 light sensitive pixels with five shielded pixels at each end. Only four of the shielded pixels are guaranteed to be totally shielded and can be used as dark references allowing, in the following processing stages, removal of any bias produced basically by thermal effects.

For BigMIC this device is used in the frame transfer mode with section A coupled to a fibre block and acting as the imaging area and section B covered with an opaque material and acting as the storage area.

Clock signals quickly transfer the image in section A into section B. Once in section B this image is sent line by line to section C where each pixel is readout serially by amplifier A1. During the readout process a new image is being integrated in section A.
A photograph of the BigMIC CCD board is shown in Fig. 4.12 and its detailed schematic diagram in Fig. 4.13.

The 44-pin CCD chip with its connections is shown in the top right corner of the schematic diagram. There are two sets of drivers, the high speed horizontal and reset drivers and the slower speed vertical drivers. These drivers receive from the Controller standard digital signals (0-5V) and convert them to the required MOS levels (0-15V) with enough current capability to drive the large capacitive loads of the CCD electrodes.

Three different types of power MOSFET integrated circuits (ICs) are used:

1) For the relatively low frequency vertical clocks the low power (200 mA peak) ICL7667 driver is employed,
2) The DS0026, with current capability of 1.5 A peak and rise and fall times of ~25 ns for the horizontal clocks, while
3) EL7212 (2A peak) with faster rise and fall times (~10 ns) was found to be better for the reset signal.

Since the combination of high speed, large voltage swings and large capacitive loads can easily induce ringing noise onto other signals it was very important to use decoupling capacitors on all of the chip’s power lines and to reduce to a minimum the length of the output wires.

A resistor in series with each clock output was also used to reduce any ringing (by dumping the output signal) while at the same time allowing optimisation of rise and fall times.

Figure 4.11. Architecture of the CCD05-20 (a), and its line output format (b). After EEV (1990a).
Figure 4.12. BigMIC's CCD board.
Figure 4.13: The BigMIC's CCD board schematic diagram.
The amplitudes of the clock signals produced by these drivers was adjusted with the help of LM317 adjustable regulators. The output voltage of this device can be set with two resistors; one connecting pins 1 and 2 (\(R_{12}\)) and the other between pin 1 and the ground plane (\(R_{\text{GND}}\)). The output voltage is given by \(V_{\text{out}}=1.25(1+R_{12}/R_{\text{GND}})\). The same circuit was also used for generating the different bias levels. High power LM317T (1.5 A) were used for the clock drivers and LM317LZ (100 mA) for the less demanding bias supplies.

The outputs of both the data and dummy on-chip amplifiers of the CCD were AC coupled to the inputs of a Maxim MAX435 preamplifier circuit. The data sheet of this wideband high-speed differential instrumentation amplifier guarantees a bandwidth of 275 MHz, a slew rate of 800 V/\(\mu\)s, a settling time of 18 ns (to 1% of a 0.5V step), and a common mode rejection ratio (CMRR) of 53 dB at 10 MHz. The function of the MAX435 was to act both as a pre-amplifier and as a driver. The gain, with the configuration shown in Fig. 4.13, is defined by the external resistor connected between pins 3 and 4.

The MIC2 system can be considered as a simplified version of BigMIC. The architectures and line output format of MIC2's CCD (CCD02-06) is shown in Fig. 4.14. A photograph of its CCD board is shown in Fig. 4.15 and the schematic diagram in Fig. 4.16.

It can be seen that the main differences of this design and the BigMIC's is that the number of vertical drivers is reduced in half and that there are no voltage regulators to set the amplitude of the clock signals, a 10 V power supply being used instead.

![Figure 4.14. Architecture of the CCD02-06 (a), and its line output format (b). After EEV (1990b).](image)
Figure 4.15. MIC2's CCD board.
Figure 4.16. The MIC2 CCD board schematic diagram.
4.4.2 The ADC Board

The same ADC board is used for both the BigMIC and MIC2 cameras. A block diagram of this board is shown in Fig. 4.17.

The CCD video signal, arriving from the CCD Board, is received by an amplifier and sent to one of the inputs of a subtractor and to a circuit that, in each line, samples and holds the level of one of the dark reference pixels. This dark reference level is maintained for the rest of the line so that it can be subtracted from each of the signal pixels of the line. The output of the subtractor is fed to an analogue to digital (A/D) converter whose digital output is buffered and sent, together with some synchronisation signals, to the processing electronics.

![Block diagram of the ADC board.](image)

A photograph of this board is shown in Fig. 4.18 and its schematic diagram in Fig. 4.19. The design revolves around an AD773 A/D converter. This low-cost device is capable of producing up to 18 million samples per second with 10-bit resolution and has a full-power bandwidth of 100 MHz. Its design is based on the novel ‘multistage differential pipelined architecture with error correcting logic’ which reduces the number of comparators from 1023 (in an equivalent 10-bit flash A/D converter) to 48 and power dissipation to ~1.2 W (Analogue Devices 1992).

The operation of the AD773 requires ±5 V power, a 2.5 V reference, a clock signal to trigger the conversions (CONVERT), and the input signal to be between 0 and 1 V. Because of the design of this device the digitised output of each sample is delayed by 4 clock cycles.

The voltage reference is provided by an AD580. This high precision, temperature compensated, voltage reference produces a fixed 2.500 V ±0.4% output from an input between 4.5 and 30 V.

The differential video signal from the CCD board needs to be conditioned before being fed to the A/D converter. This signal is received by a MAX436 which provides amplification in the range of 2.7 to 8 depending upon the position of potentiometer R3. This amplified signal, VIDEO, is then fed to one of the differential inputs of the dark level subtractor and to the input of the dark level clamp circuit.
The clamp circuit consists of an AD783 sample and hold amplifier. This circuit is capable of producing an stable sampled signal in less than 250 ns (to 0.01%) and to hold it at a droop rate of ~0.02 \(\mu\)V/\(\mu\)s while dissipating only 95 mW. The circuit is triggered by the S/H signal (coming from the Controller Board) when the signal of the second dark reference pixel of each CCD line is present. The output of this circuit, DARK, is connected to the other differential input of the dark level subtractor.

A variable voltage reference which produces a voltage between -1.25 and 0 V is used to shift the output signal of the A/D converter. This circuit is based on an AD708 operational amplifier and its output voltage, OFFSET, is adjusted with potentiometer R11.

The dark level subtraction is carried out by an AD830. This high-speed video difference amplifier is a very versatile device that can accurately amplify differential input signals and produce an output voltage referred to a chosen level. According to its data sheet it has a bandwidth of 60 MHz, 35 ns to 0.1% settling time, and slew rate of 530 V/\(\mu\)s. With the configuration shown in the schematic diagram the circuit produces an output equal to \(2(\text{VIDEO-DARK}+\text{OFFSET})\) which is fed directly to the A/D converter.

Of the 10 bits generated by the A/D converter only the 8 most significant ones are latched, buffered and sent to connector J2 (and then the processing electronics).

Connector J1 brings, from the Controller Board, the S/H signal for the dark level clamp, the ADC signal to trigger the conversions in the A/D converter, and the synchronisation signals which are just passed to connector J2.
Figure 4.18. The ADC board.
4.4.3 The Controller Board

The Controller Board is responsible for the generation of all the necessary signals to operate the CCD and the A/D converter. The same circuit is employed for both the BigMIC and the MIC2 cameras with only slight wiring modifications. A block diagram of this circuit is shown in Fig. 4.20.

![Block diagram of the Controller Board.](image)

All the signals are based on a 32 MHz oscillator. The HORIZONTAL CLOCKS and VERTICAL CLOCKS are state machines that generate the clock sequences to activate the charge transfers in the CCD. The clock cycles of these state machines are continuously monitored by their respective CONTROLLERS which generate status signals when a pre-set number of pulses are counted. In the case of the HORIZONTAL CONTROLLER the desired number of pulses is hardwired while for the VERTICAL CONTROLLER the window definition parameters are received from the system's computer, via the Processing Electronics, and stored in the WINDOW SET-UP circuit.

A general description of the CCD readout cycle will help to better understand the controller's electronics. On switching on, the CCD camera enters into a continuous repetition of a CCD readout cycle but before the camera can operate properly the information defining the size and location of the window of interest has to be loaded. The readout cycle has, referring to Figures 4.21 and 4.22, the following components:

1) The frame in the imaging zone is quickly transferred to the storage zone. This is done by simultaneously sending FrameSize clock pulses to both vertical phases of the CCD (A and B), this number of pulses being equal to the number of rows in the CCD frame.

2) The phases of the imaging zone (A) are left constant and a new frame starts being integrated while:
3) The stored frame is shifted down $SkippedRows$ times so that all the rows before the window are dumped into the serial register. This is done by activating phases B only.

4) The window is read-out by $WindowSize$ times: (a) shifting one row to the serial register (one cycle on phases B), and (b) activating phases C, for a number of cycles (814 for BigMIC and 408 for MIC2), in such a way that each pixel of the row is passed through the output amplifier.

By the time the last pixel of the window has been read a new frame has already been integrated in the imaging zone and the cycle repeats by going to step 1).

The first five rows of the window are used to clean out the charge of the previous unwanted lines (which were simply dumped onto the serial register). Since the information they contain is of no use, they do not appear at the output of the camera system. This must be taken into account by the data acquisition program on the PC.

**Figure 4.21.** Frame readout cycle: (a) CCD showing the window, defined by the parameters shown on the left, to be read. (b) The full frame is quickly transferred to the storage zone, phases A are left fixed (and a new frame begins integration). (c) The stored frame is shifted down until the start of the window is reached. (d) The window is read-out by repeatedly shifting one row to the serial register where it is shifted to the output amplifier one pixel at a time.
Figure 4.22. Timing diagram of some of the signals of the Controller Board. At time $a$ the frame in the imaging zone of the CCD starts being transferred to the storage zone. After $FrameSize$ cycles of both vertical phases (time $b$) the full frame has been shifted to the storage zone, the phases of the imaging zone are stopped (and a new frame begins integration). By clocking the phases of the storage zone $SkippedRows$ times the window is moved to the serial register and the WINDOW flag is activated (time $c$). The rows on the window are read as indicated by the activity of the horizontal clocks (C1\). The first five rows are ignored by not activating the LINE flag. The process then repeats at time $a'$. 
Fig 4.23 shows a timing diagram of the vertical clock signals required for the shifting of the frame in the direction of the serial register. The packets of charge will keep moving to the highest biased electrode as indicated by the arrows. During the 'rest state' (image integration time for section A and while waiting for a row to be read for section B) charge is gathered under electrodes number 2 as indicated. To maximise transfer efficiency, it is recommended by EEV that the clock signals overlap at a point above their 50% peak value.

![Timing diagram of vertical clock signals](image)

Figure 4.23. Timing diagram of the vertical clock signals at the CCD. In this representation the rows in the image and store sections are shifted two positions in the direction of the serial register.

The timing requirements for the serial register's clocks and reset signals with a representation of the amplifier's output are shown in Fig. 4.24. Before a row is shifted into the serial register the electrodes are biased in such a way that the charge packets are collected under electrodes C1 and C2 as seen in the region labelled ‘rest state’. Again, charge flow is indicated by the arrows. A complete cycle finishes on the high to low transition of C3 which is when a charge packet is transferred to the output amplifier. The reset of the output capacitor must take place before this transfer, the associated clock being short enough to allow the previous output signal to stabilise and be measured.

![Timing diagram of horizontal clocks, reset signal, and output](image)

Figure 4.24. Timing diagram of the horizontal clocks, reset signal, and output of the amplifier.
4.4.3.1 Clock Phases Generators

It can be seen that the clock sequences for both the horizontal and vertical clocks are very similar, the only difference being their frequencies. Similar circuit designs can then be employed to produce the desired repetitive sequence shown in Fig. 4.25 where the fact that the MOS drivers (on the CCD board) act as inverters has been taken into account.

![CLK diagram](image)

Figure 4.25. Required sequences and the clock to trigger them.

There are two ways in which this electronic circuit could be implemented: 1) using a bit-map method in which a random access memory (RAM) is loaded with the correct sequence and is then continuously read at the clock frequency, or 2) with a simple state machine (sequential logic circuit made of flip-flops and logic gates).

Option 2 was chosen as it provided a simpler design. The truth table associated with the sequencing is shown in Table 4.2.

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>c</th>
<th>a+</th>
<th>b+</th>
<th>c+</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4.2. Desired states of the sequential circuit. The current state is shown to the left and the following state to the right.

For the design of the state machine two factors were taken into account: 1) The use of JK flip-flops in order to reduce the number of gates, and 2) The restriction that if, for any reason, an invalid state is reached the circuit goes back to the cycle.

Figure 4.26 shows the state diagram of this simplified sequential circuit.

![State diagram](image)

Figure 4.26. Block diagram of the state machine. The circuit should continuously cycle between the three shadowed states. If for any reason the circuit gets in any of the other states then the state machine will automatically evolve until entering the cycle again.
The implementation of this circuit (made of three interconnected JK flip-flops) is shown in Fig. 4.27. For the horizontal clocks fast 74AC112 integrated circuits are employed (U2A, U2B, and U3A) while for the vertical clocks the normal 74HC112 are used (U10A, U10B, and U11A).

The output of these circuits are sent to a bank of D-type flip-flops (U4A, U5A, U5B horizontal U12A, U13A, U13B vertical) which provide reshaping (by shortening their high state duration) so that the desired overlaps are obtained. These conditioned signals go to a data selector (U6 horizontal, U14 vertical) which selects between the sequential signals (for charge transfer) or constant levels (for the rest states) before sending them to line drivers (U7 horizontal, U15 vertical) to buffer the outputs before being sent to the CCD board via connector J1 and J2.

The reset signal was derived from pin 5 of U3A in the horizontal state machine.

For the vertical phases a couple of additions were needed:

1) A circuit to generate the state machine's clock signal (VCLOCK). One of the 10.66 MHz horizontal signals was fed to a divide by six circuit implemented with a decade counter (U9) to produce this signal. This same circuit was also found to be useful for the generation of the overlap trigger signal (VOVERLAP).

2) A circuit to force the state machine into the 'rest state' (so that no charge is dumped onto the serial register while it is being read). This simple circuit comprises an AND gate (U8B) and a flip-flop (U12B).
Figure 4.27. The horizontal and vertical clock generators.
4.4.3.2 The Vertical Controller and Window Set-up

As has just been shown, the transfer of an image from the image zone to the storage zone and then to the readout register is a three stage process.

1. The whole image is shifted into the storage zone
2. Rows in advance of the active window area are dumped on top of each other in the readout register and then read out
3. Rows within the active window area are transferred to the readout register and read out one at a time.

Control of these functions is provided by the vertical controller and window set-up circuit, a schematic of which is shown in Fig 4.28, the window size and position being set by the control computer.

The window information is received as a serial data stream (DATUM) with a synchronisation clock (STROBE) from the computer via the Processing Electronics. This data which is 32 bits in length is converted into a parallel output by a serial to parallel converter made up of four 8-bit shift registers (U24-U27).

The 12 LSBs (Q0-Q11) define the total number of vertical shifts to be made during each frame period (Total) and hence are equal to the sum of the number of rows in the image zone (FrameSize), the number of rows to be dumped in the readout register in advance of the active window (SkippedRows), and the number of rows in the active window (WindowSize).

This value is loaded at the end of each frame period, equivalent to the end of the active window period by signal ENDWINDOW\ into a 12-bit down counter comprising three 74HC191 4-bit up/down counter ICs (U28,U29,U30). For each vertical shift in the CCD the number in the counter is decremented by 1 by VCOUNT until the counter value reaches zero, when ENDWINDOW\ is generated and the counter reloaded.

The output of the counter is compared against two values:

1. The first, set by the computer on outputs Q12-Q21 of the serial to parallel converter, defines the end of the image to storage zone transfer. The value stored equals (Total - FrameSize). When this comparison, implemented by two 8-bit comparator ICs (U32,U33), comes true, signal FREEZA is generated preventing any further shifts from the image to storage zone.

2. The second, set by the computer on outputs Q22-Q31 of the serial to parallel converter, defines the end of the dump period. The value stored thus equals (Total - FrameSize - SkippedRows). The comparison is carried out by the 8-bit comparators U34 and U35 and when true the signal WINDOW, defining the start of the window period, is activated. At the end of the active window period WINDOW is reset by the ENDWINDOW\ signal when the counter reaches 0.
Thus output from this circuit are two signals: \texttt{FREEZA} which controls transfer from the image to storage zones, and \texttt{WINDOW} which control transfer from the storage zone to the readout register.

\textbf{4.4.3.3 Horizontal Controller}

For each row that is transferred to the readout register during the active window period, the following actions must be taken: 1) Every pixel, including the underscan and overscan pixels, must be readout, and 2) A trigger signal for the black level clamping must be generated.

These actions are controlled by the horizontal controller. A schematic for the two configurations (BigMIC and MIC2) is shown in Fig. 4.29.

The heart of the circuit is a 12 bit counter (U18), of which only the 10 LSBs, B0-B9, are used. This counter is reset at the end of each row read out by signal \texttt{FREEZEB} received from the horizontal clock generator and is incremented by the 10.66 MHz pixel clock, HCOUNT.

The output of the counter is compared against four values associated with the CCD row format as defined, for the BigMIC camera, in Fig. 4.11:

- A value of 19, at which the second dark reference signal is available. Signal \texttt{S/H} being generated to allow sampling of the dark level in the video amplifier.
- A value of 27, defining the start of active data within each row. Signal \texttt{LINE} is activated.
- A value of 792, defining the end of the active data pixels within each row. When this comparison is made, \texttt{LINE} is de-activated.
- A value of 814, defining the end of the row including overscan pixels.

The comparisons are made by NAND gates contained within U19A, U20, U21 and U22.

The signal \texttt{LINE} is not generated for the first 5 rows of the active window. This is because these lines are defined as holding the charge dumped from inactive rows that precede valid data. The inhibiting function is performed by a shift register (U17) that is cleared at the start of the window period by \texttt{WINDOW} from the vertical controller and incremented by the vertical clock, VCOUNT. On each vertical clock, a '1' is shifted into the register and when the 5th output reaches a '1' the start of active data comparison is enabled.

In summary, output from the horizontal controller are three signals \texttt{S/H}, which controls the black level sampling, \texttt{LINE}, defining the active pixels in each row, and \texttt{LASTPIXEL} defining the end of each row.

A photograph of the Controller board is shown in Fig. 4.30.
Figure 4.28. Vertical controller and window set-up.
Figure 4.29. The BigMIC and the MIC2 horizontal controller.
Figure 4.30. The Controller board.
5.1 General Description

The Processing Electronics (PE) are a set of digital electronics cards whose purpose is to continuously process, in real time, image frames received from the intensified CCD camera. It basically scans the arriving frames looking for valid photon events, computes their centroids to 1/8 of a CCD pixel in both the X and Y directions and dispatches their centroid co-ordinates to an IBM compatible personal computer (PC) to be accumulated into an image.

In order to reduce power consumption and to increase the noise immunity of the system, most of the integrated circuits used in the PE’s design belong to the high speed CMOS (HC) family of logic circuits. Some HCTs were used when there was a need to interface to the components (TTL compatible) which were not available in CMOS. To ease modifications and expansions in the design most of the electronic cards were made using the wire-wrap technique. The actual design of the electronics was carried out with the help of OrCAD, a schematics drawing package running under a PC, the protocols associated being described in Section 4.1.

A block diagram of the PE and its relation to the CCD camera and the PC can be seen in Fig. 5.1.

In the normal mode of operation of the system (data acquisition) each CCD frame of data (received one pixel at a time and row by row) is arranged by the Delay Lines and the Data Analysis Array (DAA) in such a way that each pixel and its eight neighbours in the frame are, as shown in Fig. 5.2, temporarily presented to the Event Validate, Thresholds Table, and Centroid circuits. This is equivalent to stepping a 3×3 array sequentially through each frame of CCD data.
Event Validate compares the central pixel with the neighbours and activates a flag (ECD*) if an event condition is detected. In parallel, the centroid circuits compute the centroid from the data within the DAA. The centroids, the central pixel of the array, and ECD* are then sent to the Thresholds Table which discriminates against noise and finally determines if a valid event has been found.

![Event Capture by CCD](image)

**Figure 5.2** Event capture, digitisation and rearrangement by the processing electronics.

Again, in parallel, the Address Generator produces the X/Y CCD pixel co-ordinates of the event within the frame and will send them, together with the computed sub-pixel centroid, to the PC via the memory interface if an active VALID* signal is received from the Thresholds Table. The PC then increments by one the contents of the memory location corresponding to the pixel co-ordinates.

To manage all the activities in the PE, a Control Interface receives data and commands from the PC and then sends the appropriate signals to associated elements of the PE and CCD camera. For example it is used for controlling data flow, defining the window format of the CCD camera, and reading or writing to any of the memories in the PE.

A Real Time Display circuit continuously displays the digitised video input to the PE on an oscilloscope. This is useful for monitoring the well-being of the CCD camera and for verifying that the intensifier is not over illuminated.

Finally a Frame Store acts as a frame grabber for the digitised images coming from the CCD camera so that the system can be operated in an 'analogue' mode. In this mode of operation a series of unprocessed frames are sent to the PC where they can be individually analysed or accumulated into an image. By having access to these frames it is also possible to monitor the performance of the CCD camera. Testing and troubleshooting of the system (test mode) is also possible by loading a test pattern in the Frame Store memory and then sending this pattern repeatedly to the digitised video input from the PE instead of that of the CCD camera. The PE will see these test frames in identical fashion to real data in the acquisition mode and the generated output can then be compared with that expected, thus allowing a check that the electronics are operating correctly.
For the hardware implementation of the design the PE was divided into seven boards. All the cards are of the wire wrap kind except for the real time display that is on a printed circuit board. Together with a power supply, they are contained in a chassis and are backplane interconnected. Three spare slots in the chassis are left available for possible upgrades.

Fig. 5.3 shows the interconnections between these cards, the PC and the CCD camera. Two cables go to the CCD camera. One connects to the control interface card and is used for setting up the CCD, basically to define its readout format (window size). The other cable brings the digitised frames of the CCD, along with associated timing signals, to the Delay Lines / Timing Circuit card.

There is a 50 pin cable that connects the PE to a commercial plug-in PC interface card (Brain Boxes’ PC DIO48) that has six 8-bit bi-directional ports. The transfer of information is controlled by a computer programme developed by Quantum Vision Limited (QVL) and adapted for BigMIC by Martin Clayton of UCL. Ports PA2 and PB2 are used to receive the events’ addresses coming from the address generator and memory interface card. Port PA1 is used for the bi-directional transmission of data between the Control Interface and the PC while three lines of port PB1 are used for sending control signals to the PC.
Figure 5.3. Interconnection of the Processing Electronics cards.
5.2 The Control Interface

A schematic diagram of the Control Interface can be seen in Fig. 5.4 while a photograph of this card is shown in Fig. 5.5 and its circuit diagram in Fig. 5.6. This circuit takes care of all the operational aspects of the system. It controls the flow of 8-bit data between the data bus of the PE and the PC. It generates under the control of software in the PC various strobe signals, or operational commands (OC), necessary for the set-up and control of the PE. As mentioned before it also acts as an intermediary between the PC and the CCD camera.

![Figure 5.4. Block diagram of the Control Interface circuit.](image)

Crucial to the design is the PC Handshake circuit (Fig. 5.4). It was designed by QVL and its function is to control the transmission of data on PA1/PB1 in conformance with the communications' protocol of the interface card in the PC. It generates;

- The R/W* signal which defines the flow direction of data (when high the PC can read the DATA bus and when low it can write to it),
- The ACK* signal to tell the PC interface card that data has been properly received by the PE,
- The STB1* signal to inform the PC interface card that data is available on the DATA bus and ready to be read, and
- The PWIDTH signal to control the duration of the OC signals.

Fundamentally, the PA1 bus is used for transmitting and receiving 8-bit data from the PC and the PB1 bus is used for defining the address within the PE of the storage element to be accessed. The PA1 bus is connected to a transceiver (U3) and then goes to different parts of the system as the internal bus DATA. The three least significant bits (LSBs) of PB1 are buffered (U4) and then sent to a 3 to 8 line decoder (U5) that generates eight mutually exclusive (only one can go low at a time) operational command signals whose negative going pulse duration is defined by PWIDTH. The destination of these signals and their function is shown in Table 5.1.
There is also the need for a set of signals to define the mode of operation of the detector system. For this OC3 is used to latch the four LSBs of DATA into U1. A 3 to 8 line decoder (U2) then generates the, active low, operation mode signals from the three LSBs as defined in Table 5.2. The fourth output of U1 (PEAKCENT) is used to define a special mode of data acquisition that is explained in Section 5.5.

Another feature of this circuit is the CCD Camera Control section. It consists of an 8 bit write only data bus (U10), three address bits and an enable signal (E*) supplied by U11. These are required to load the bit-map memory that defines the readout format on the first generation MIC camera designed by Dr. David Bone and based on a Thomson CCD. For the simpler BigMIC and MIC2 cameras (see Section 4.3.3) only one of the data bits and the enable signal are needed.
Figure 5.5. The Control Interface card.
Figure 5.6. Schematic diagram of the Control Interface.
5.3 The Delay Lines and Timing Circuit

The frames of data generated by the CCD are input to the PE in serial form (one pixel at a time, line by line). In order for the events to be processed it is necessary to have simultaneous access to the data in each pixel (of each frame) and its eight neighbours. This is accomplished by the Data Analysis Array (DAA) whose block diagram is shown in Fig. 5.7. It consists of two delay lines whose length is equal to the number of pixels in a CCD row, three sets of three serially connected latches and a timing circuit to control the data flow. In this design the Delay Lines and the Timing circuit are on one circuit card (Figures 5.9 and 5.10) while the actual array is on a separate card.

![Figure 5.7. Delay lines and data analysis array.](image)

The CCD signals are input through a 34 pin connector (JP1) along with timing signals (see chapter 4). The 8 bit CCD data (CCD) goes to the Delay Lines circuit while the synchronisation signals go to the Timing circuit which controls the operation of the delay lines.

The input data of the delay lines can come from one of two sources; from the CCD camera during normal operation or from the Frame Store for system testing. The outputs of the circuit are the values of three contiguous column pixels of the frame (A1, A2, A3).

Fig. 5.11 shows the Delay Lines circuit. Two configurations are available on the input to meet the demands of different centroiding algorithms as described in Section 5.5. The configuration for the gaussian algorithm is presented in this diagram. In this case there is a read only memory (ROM) that receives the VIDEO data and outputs its logarithm normalised to the maximum value available with 8 bits (255). For the centre of gravity and parabola algorithms this ROM is replaced links that connect each input to its corresponding output, thus presenting the input data directly to the delay lines.

There are four sections to the circuit:

1. A set of three latches (U54, U52, U53) that delay the input data to maintain synchronisation with the delay line outputs, generating A1.

2. Delay Line 1 (U48) that accepts the input data via U51 and transmits the delayed data as A2 via U50.
3. Delay Line 2 (U33) that accepts data from delay line 1 via U41 and transmits the delayed data as A3 via U49.

4. A Counter (U46, U53) that generates the address for the delay lines.

The delay lines are designed around 2K×8 bit static RAMs whose address is incremented on each CCD line from 0 to the line length of the CCD in synchronism with the incoming data, this task being performed by the Counter. At each address setting, two operations are carried out:

1. The data in that location is read out and latched. This data was stored at the same position in the previous CCD row and is hence delayed by exactly one line with respect to the input.

2. The new incoming data is written in.

Thus the output of the Delay Line 1 memory is delayed by 1 row with respect to the incoming data and the output of Delay Line 2 is delayed by two rows meeting the requirements shown schematically in Fig. 5.7.

The detailed operation of the circuit can be better explained with the help of the timing diagram shown in Fig. 5.8.

![Figure 5.8. Basic timing diagram for the delay lines.](image)

When the CCLK, derived directly from the 10.66 MHz system clock, goes from low to high (time a) the counter is incremented presenting a new address to the two memories U48 and U33. As MWRITE* is high, the memories are in read mode and the data in the location specified is output and then latched in U50 and U49 by DCLKB (time b).

Simultaneously with the latching of the memory outputs, the data to be written into the memories is being set up. The data for Delay Line 1 is latched into U51 by CCLK and the data for Delay Line 2 is latched into U41 by DCLKC. Note that during the read cycle the outputs of these two latches are placed in high impedance (DIEN* being high) to prevent a contention with
the data being read. The start of the write cycle (time \( c \)) is then initiated on MWRITE* and DIEN* going low, the latched input data being presented to the memories. When MWRITE* goes high (time \( d \)) the settled data is then written into the defined address.

As only 94 ns is available for the read followed by the write operations, the timing associated is critical, the circuit associated being shown in Fig. 5.12. It is a simple combination of flip-flops (FFs) and delay lines to obtain the appropriate timing signals (as shown in Fig. 5.8). Buffer U0 is used to compensate for the delays introduced by the logarithm lookup table when in the gaussian centroiding configuration and is replaced by links for the other configurations.
Figure 5.9. The Delay Lines and Timing card.
Figure 5.10. Schematic diagram of the Delay Lines and Timing circuit.
Figure 5.11. Schematic diagram of the Delay Lines circuit.
Figure 5.12. Schematic diagram of the Timing circuit.
5.4 The Data Analysis Array and Event Validate

The DAA and the Event Validate circuits reside on a single card (Figures 5.13 and 5.14). As described in Section 5.3 the DAA is a 3x3 array of contiguous CCD pixels through which all incoming data from the camera passes. Input to the DAA are the three 8-bit outputs of the Delay Line circuit (A1, A2, A3). These are fed into three pairs of 8-bit latches, each acting as a single pixel delay, as shown in the circuit diagram (Fig. 5.15) providing to the rest of the electronics an array with the value of a pixel and its eight neighbours (Fig. 5.7). The latches are clocked by a buffered version of the 10.66 MHz system clock, PCLKD.

The Event Validate circuit (Fig. 5.16) determines whether a potential event is present in the DAA by comparing the central pixel of the DAA with its neighbours and activating a flag (ECD*) if an event condition is detected. For an event to be valid, the central pixel \( a_{22} \) must be greater or equal to the pixels that are not going to have another opportunity to be central to the DAA \( (a_{23}, a_{31}, a_{32}, \text{ and } a_{33}) \) and at the same time greater than the other pixels \( (a_{21}, a_{11}, a_{12}, \text{ and } a_{13}) \). This is done in a simple way by using 8 bit magnitude comparators and some logic gates. The output of the OR gate formed by U10A, U10B and U12A is latched by U13A which will give an active ECD* (low) only when all the inputs of the OR gate are low. U0 is used to buffer \( a_{22} \) before being used by the next processing stages.
Figure 5.13. The Data Analysis Array and Event Validate card.
Figure 5.14. Schematic diagram of the Data Analysis Array and Event Validate circuits.
Figure 5.15. Schematic diagram of the Data Analysis Array circuit.
Figure 5.16. Schematic diagram the Event Validate circuit.

A22 > A11, A12, A13, A21
A22 >= A23, A31, A32, A33
5.5 The Event Centroid

The Event Centroid circuit receives the cross hair pixels of data from the DAA ($a_{21}$, $a_{22}$, $a_{23}$, $a_{31}$ and $a_{32}$) and calculates the centroid, both in X and Y, to one eighth of a CCD pixel (Figures 5.17 and 5.18). This is used to recovering, as far as possible, the loss of resolution in the image intensifier. It is carried out independently in X and Y and hence two circuits, which are identical in design, are associated.

![Data Analysis Array](image)

Figure 5.17. Centroid calculation for one of the directions.

Centroiding is achieved by applying a simple algorithm to the data within the DAA. Three different algorithms have been evaluated and these have been the subject of a study, comparing the errors associated and their sources, which is described in Chapter 6. To enable a comparison between the theoretical modelling and actual hardware implementation, the facility to select between all three algorithms exists in the hardware design. The three algorithms are:

- **Centre of Gravity**
  \[
  \frac{M}{N} = \frac{a - c}{a + b + c},
  \]

- **Parabola**
  \[
  \frac{M}{N} = \frac{a - c}{2b - a - c},
  \]

- **Gaussian**
  \[
  \frac{M}{N} = \frac{\ln a - \ln c}{2\ln b - \ln a - \ln c},
  \]

where $a=a_{21}$, $b=a_{22}$, and $c=a_{23}$ for the X direction and $a=a_{12}$, $b=a_{22}$, and $c=a_{32}$ for the Y direction.

It can be seen that the Parabola and Gaussian algorithms have the same form except for the Gaussian using the logarithm of the input pixel data. When utilising the Gaussian algorithm, the natural logarithm function is applied to the data at the input to the DAA as described in Section 5.3. Thus two different centroid circuit designs, one for the Parabola and Gaussian algorithms and a separate one for the Centre of Gravity algorithm, must be accommodated. All three algorithms are of the form $M/N$ and the centroiding takes place as a two stage process:

1. The numerator $(M)$ and denominator $(N)$ are calculated in hardware by the Formulate circuit, these being simple mathematical operations.
2. The division $M/N$, which would be difficult to implement in hardware, is carried out using a Look-Up Table (LUT). Included in the LUT are corrections for minimising systematic centroiding errors (see Section 6.3).
The circuit for carrying out the centroiding has two parts. Fig. 5.19 shows how these two circuits are interconnected and their interfacing to the PE backplane.

5.5.1 Formulate Circuit

Figures 5.20 and 5.21 show the circuit diagrams for the X and Y formulate operations that produce the values of \( M \) and \( N \). As can readily be seen, these circuits are identical just having different input data sets. To provide an understanding of the circuit operation, the circuit for the Y formulate is described here. The operation for X is identical.

\[
M = (a-c) = (\overline{\overline{332} - \overline{12}}) \text{ is obtained by inverting } c \text{ with } U33 \text{ (to find its 1's complement) and then adding 1 to it (to produce the 2's complement) and } a \text{ using an 8-bit full adder (U34, U35). The result of this operation is 9 bits in length, -255 to +255, the sign bit being the carry out signal on U35. A problem existed though, in that at the time of designing the circuit, a 64K RAM had to be used for the following centroid LUT which meant confining the result of } M \text{ to 8 bits, thus providing a limit to the range of } -127 \text{ to } +128. \text{ To overcome this, results outside of this range are sensed by comparing the sign bit (YMSB_M) with the MSB of the 8 bit adder result (U15E, U31C) and if they are the same dividing the magnitude of } M \text{ by 2. By shifting the adder output using the multiplexers U36, U37 the required result is obtained. In order to compensate for this, } N \text{ is also divided by two when this condition occurs.}
\]

To calculate \( N=2b-a-c, a+c \) is generated first using adders U39 and U40 and then the 1's complement of the result obtained with inverters U41 and U15D. This it then added to \( 2b \) using the full adders U42, U43, and U44. \( 2b \) is easily obtained by shifting all the bits one position higher and placing a zero in least significant bit position, this is done using wire links on U0. Since, for valid events, \( b \) will always be greater or equal to \( -a-c \) the result will always be positive and lower than 512. \( N \), as with \( M \), must be limited to 8 bits due to the following LUT and if the result is \( \geq 255 \) (8 bits) the output and that for \( M \) are divided by 2.

For the centre of gravity \( (N=a+b+c) \) U41 is replaced by a simple buffer and pins 2 and 3 of jumper J2 are connected so that \( a+c \) is not inverted. Another set of connections are made in U0 so that B is input to the adder instead of 2B.

The final values of \( M \) and \( N \) are latched (U38, U47) by ECD* only if an event present condition has been detected by the Validate circuit (see Section 5.4) so that they stay available to the rest of the electronics for as long as possible (until a new event is found). This also reduces electrical interference to the other circuits and power consumption.
Figure 5.18. The Event Centroid card.
Figure 5.19. Schematic diagram the Event Centroid circuit.
Figure 5.20. Schematic diagram of the Formulate in Y circuit.
Figure 5.21. Schematic diagram of the Formulate in X circuit.
5.5.2 Look-Up Tables

The final centroids are given by two look-up tables (Fig. 5.22), one for X and one for Y. These lookup tables consist of two pre-loaded 64Kx4 bit RAMs (U10 and U11) that receive the previously calculated $M$ and $N$ values as their addresses and output the centroid position within the central pixel to a resolution of 1/8 of a pixel. This centroid is latched by U13 and X1, X2, and X3 correspond to the centroid in X and Y1, Y2, Y3 to the centroid in Y.

The LUTs have to be pre-loaded by the computer during detector set-up, LOOKUP mode being activated on the Control Interface. During this period the latches that hold the $M$ and $N$ values are put in a high impedance state effectively liberating the address inputs of the lookup memories so that the PC can access them.

After providing the centroiding positions, a final stage of event validation takes place. The photon counting threshold to discriminate against noise is dependent upon the position of the centroid of the event within a CCD pixel as defined by the X, Y centroid LUT outputs (see Section 6.6). This array of 64 thresholds is held in a separate LUT (U12) that is programmed during instrument set-up by the computer. The thresholds table takes the central pixel value (PEAK), the calculated centroids and the ECD* signal (from the event validate circuit) and activate a flag (VALID*) if the PEAK is greater than the threshold value pre-defined for the sub-pixel position and if ECD* is active (low).

When the PE is in lookup mode (LOOKUP* low) the PC can simultaneous access all of these memories. To simplify the design the address is generated by a 16 bit counter (U1 and U2) that is incremented by the OC4 strobe signal. This address is fed to the three memories with pairs of tri-state buffers (U4-U9) enabled with the LOOKUP* signal. Data is written or read from these memories with the help of an octal bus transceiver (U3) that is also enabled with the LOOKUP* signal and with transmission direction defined by R/W*. The memories are normally in the read mode and go to the write mode only when an OC5 pulse is received.
Figure 5.22. Schematic diagram of the Look-Up and Thresholds Tables circuit.
5.6 The Address Generator and Memory Interface

Having found the sub-pixel centroid position of each event, this must then be combined with
the CCD row/column position to defined the event address which is then transmitted to the PC for
data accumulation. These tasks are performed by the Address Generator and Memory Interface
circuit. The component parts of this circuit are:

- A counter that defines the position within the CCD from which data is currently
  available.
- A data acquisition control circuit that controls writing of each valid event address
to a First In First Out memory (FIFO).
- A 512 word FIFO that stores each valid event address.
- A control circuit that controls transmission of the event addresses stored in the
  FIFO to the PC computer.

A block diagram of the circuit is shown in Fig. 5.23.

The FIFO is required to overcome timing problems between the random arrival rates of event
addresses and the overheads associated with incrementing the PC memory location corresponding
to each address. A single commercial interface card in the PC, described in Section 5.1, accepts
the event data along with providing control of the BIGMIC system. The data acquisition port on
this card is operated in an interrupt mode, breaking in on the PC software routine that is active
during data acquisition (this being responsible for displaying the accumulating image on the PC
monitor). The interrupt service routine associated has significant overheads and to minimise these
event addresses are not transferred singly but as blocks of 256 when the FIFO becomes half full.

A photograph of this card is shown in Fig. 5.24 and a schematic diagram of the
interconnections between the component parts of this circuit and their interfaces to both the PE
backplane and the PC in Fig. 5.25.
Figure 5.24. The Address Generator and Memory Interface card.
Figure 5.25. Root diagram of the Address Generator and Memory Interface.
5.6.1 Address Generator

This consists of two Counters, the first defining the pixel within the row of the CCD being processed (the X position) and the second defining the row number (the Y position). A circuit diagram of the address generator circuit is shown in Fig. 5.26.

The Pixel Counter (U19, U20) is cleared at the start of each new CCD row by XCLR*, derived from the Line Sync signal from the CCD camera. It is then enabled by XCLKEN*, derived from the Window Active signal from the CCD camera. A windowing facility is available with the camera and the event address is relative to the start of this window, not the first pixel in the CCD. The Counter is then incremented by the 10.66 MHz pixel clock until the Window Active signal is negated. Thus, for example, if a window of width 700 pixels is set up in the CCD camera, the Pixel Counter increments from 0 to 699 for each active CCD row.

The Row Counter (U23, U18) is cleared at the start of each new CCD frame by YCLR* and then enabled by YCLKEN*, both derived from the Frame Sync signal received from the CCD camera. The Row Counter is then incremented by XCLR* which is equivalent to Line Sync.

The derivation of the clocks for the Counters is shown within the circuit diagram Fig. 5.27. The XCLR* signal is output from a shift register (U31) that delays the Line Sync signal (LS_1*) by 5 pixel clock periods, this being required to maintain synchronism with the processing electronics - it taking 5 clock period to produce the centroid address for each event. The XCLKEN* is also output from a shift register (U28) that delays the window active signal (WA_1) by 5 clock periods. The Frame Sync (FS_1*) is delayed by the same amount using a D-type FF (U3A) whose outputs are YCLR* and YCLKEN*.

The output of the Pixel Counter is combined with the incoming X centroid position (X1, X2, X3) and the output of the Row Counter is combined with the incoming Y centroid position (Y1, Y2, Y3) to then form the event address XADDR/0— >XADDR/13 and YADDR/0— >YADDR/13 that is presented to the inputs of the FIFO. This address is of the form:

<table>
<thead>
<tr>
<th>Row Address</th>
<th>Pixel Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Row Position</td>
<td>Y-Centroid</td>
</tr>
<tr>
<td>9 bits</td>
<td>3 bits</td>
</tr>
</tbody>
</table>

A mode is available whereby part of the event address is replaced by the data in the central pixel in the DAA (PEAK0— >PEAK7). This allows a fast method of obtaining 64 separate pulse height distributions for the different sub-pixel centroid positions as is required for defining the multiple thresholds used in the Centroid circuit. In this mode, data is not accumulated into an image but is stored as pulse height histograms in separate arrays defined by the sub-pixel centroid addresses, X0— >X2 and Y0— >Y2, the remaining event address bits being ignored by the computer.
software. When this mode is activated by the computer, signal PEAKCENT on the Control Interface card becomes active that allows (U40) the PEAK signals to replace bits YADDR/3→YADDR10 of the event. The data transmitted is of the form:

<table>
<thead>
<tr>
<th>Don't Care</th>
<th>Peak Value</th>
<th>Y Centroid</th>
<th>Don't Care</th>
<th>X Centroid</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 bit</td>
<td>8 bits</td>
<td>3 bits</td>
<td>9 bits</td>
<td>3 bits</td>
</tr>
</tbody>
</table>

5.6.2 FIFO

Four 512×9 bit word FIFOs are used for storing each event address during data acquisition. These are shown in the circuit diagram Fig. 5.25 (U14, U15, U16, U17). Input to the FIFO is each event address on XADDR/0→XADDR/13 and YADDR/0→YADDR/13 and these are written into the FIFO by the signal WFIFO* from the Data Acquisition control circuit. When the FIFO is half full, a flag within the FIFO chips, HF, is set that initiates a read sequence to the PC computer memory. Continuous reads then take place until the FIFO is empty signified by the FIFO flag EF becoming active.

5.6.3 Data Acquisition Control

Control of data acquisition is perform by the PC computer. It outputs a command, OC0, to start an integration and a separate command, OC1, at the end of the required integration time to stop the exposure. The associated circuit diagram is shown in Fig. 5.27.

Prior to the start of each exposure, the FIFO is reset by signal FIFORE* generated from the computer command OC2 clearing the FIFO of any extraneous data. At the start of the exposure, OC0 then sets a D-type FF (U6A) whose output feeds into a second FF (U6B) clocked by Frame Sync. It is the output of this second FF that defines whether an exposure is in progress and hence the start of all exposures are synchronised to the beginning of a CCD frame period. When a valid event is detected the signal ECD A*, derived from VALID* output from the Threshold circuit, is generated and ANDed with the output of U6B and the system clock (U7A, U7B) to generate the WFIFO* signal that then stores the event address in the FIFO. If the data rate is too high and the PC interface cannot cope with the level of data then, eventually, the FIFO overflows and sets a flag, FIFOF*. This signal is then used to inhibit further data acquisition (U7C) until space in the FIFO is available. At the end of an exposure, governed by the computer setting OC1, further writing to the FIFO is inhibited at the end of the current CCD frame period by the resetting of U6B.
5.6.4 Data Transmission

The start of data transmission to the PC is initiated by the FIFOs reaching the half full condition. Continuous transfers then take place until the FIFO is empty. The circuit diagram of the control circuit is shown in Fig. 5.27 and was developed by Quantum Vision Ltd. It is basically a sequencer that allows handshaking in accordance with the protocols of the PC interface card. Input to the Sequencer (formed by U32, U33, U34) are the half full, FIFOHF*, and empty, FIFOE*, flags from the FIFO and the handshake signal IBF from the PC card. Output from the Sequencer are a Read FIFO signal, RFIFO*, that places the next event address on the FIFO output lines and a handshake signal to the PC, STB*. The sequence then followed is:

\[
\text{FIFOHF*} \rightarrow \text{FIFOR*} \rightarrow \text{STB*} \rightarrow \text{IBF} \]

until the FIFO is empty.

For each event address there is a computer memory location defined within an image array and this is incremented by one on receipt of that address. Thus data is accumulated into an image in this manner.
Figure 5.26. Schematic diagram of the Address Generator circuit.
Figure 5.27. Schematic diagram of the Transfer Control circuit.
5.7 The Frame Store

The Frame Store (Fig. 5.28) is a critical circuit, being used in the testing of the whole detector system. It can act as a source of test frames with computer generated dummy events of which the correct centroid positions are known so that possible design or wiring errors in any part of the PE can be traced. It can also function as a frame grabber for the CCD camera allowing:

1) evaluation of the camera performance, and
2) image integration in a pseudo analogue mode in which a number of unprocessed frames are added together.

![Block diagram of the Frame Store circuit.](image)

A photograph of this card can be seen in Fig. 5.30 while the schematic diagram of this circuit can be seen in Fig. 5.31. The circuit basically consists of a memory block (U10-U13), an address generator formed by two asynchronous binary counters in series (U1 and U2), a transceiver (U4) to connect to the VIDEO bus, and another transceiver (U5) to connect to the DATA bus.

There are three modes of operation of this circuit:

- The NORMAL mode in which frames of CCD data are continuously stored allowing the frame grabbing facility.
- The TEST mode in which the contents of the frame memory (normally a test pattern) are repeatedly transmitted in synchronism with each CCD frame to the input of the PE.
- The FRAME mode in which the PC can read or write to the frame memory.

When the circuit is in NORMAL mode transceiver U4 is enabled and the flow of data is from the VIDEO bus to the memory’s IO bus, U5 is dis-enabled, and the memory control signals come from section A of the multiplexers (U8).

Fig. 5.29 shows a simplified timing diagram for this mode of operation. Before the start of each frame the address generator is cleared by the PFS* signal. When the first pixel of data in each frame has stabilised on the IO bus a write enable (WE*) pulse is sent to the memory block and the data stored in memory location 0. The high to low transition of the INCREMENT signal
then increments the address by one so that when the second pixel data has stabilised on the IO bus it can be stored in location 1. This process continues until all the pixels of the frame have been stored in the memory. At the end of the frame the address generator will again be cleared by PFS* and a new frame will be stored overwriting the previous one, and so on.

A FF (U7A) is used so that when changing to frame mode the acquisition is not stopped and continues until the end of the last frame.

![Timing diagram for the NORMAL mode of operation.](image)

The TEST mode is very similar to the NORMAL mode except that WE* is continuously high preventing write to the memory and the data read out is sent to the VIDEO bus.

When the circuit is in the FRAME mode the control signals are generated by the computer and come from the control interface (section B of U8), U4 is disconnected (high impedance mode) and the connection to the DATA bus enabled. The general procedure for writing into the frame memory is the following:

An OC7 strobe signal is sent to clear the address generator, a series of OC4s are given until the desired memory location has been reached, data is placed on the DATA bus, and finally an OC5 is given to write the data onto memory.

Clearly if a contiguous block of data has to be written this can be accomplished with single increments and writes. The reading of the memory is the same except that no OC5s (WE*) are given.
Figure 5.30. The Frame Store card.
Figure 5.31. Schematic diagram of the Frame Store circuit.
5.8 The Real Time Display

The Real Time Display provides visual feedback of the data captured by the CCD allowing, for example, checking that an input source is not too bright. The circuit (Figures 5.32, 5.33 and 5.34) was designed by Dr. David Bone. It consist of two ramp generators (one for X and one for Y) with controllable offset and amplitude, and a digital to analogue converter (DAC) with a two stage amplification. The outputs X, Y, and Z connect directly to the corresponding inputs of a 'xyz' oscilloscope.

An octal FF (U1) latches every pixel on the VIDEO bus and then sends it to the input of a DAC (U3). The outputs of U1 are cleared after the last pixel of a line has been received (PLSDD*), so the signal at Z will be minimum during the return of the cathodic ray tube’s beam.

![Block diagram of the Real Time Display circuit.](image-url)
Figure 5.33. The Real Time Display board.
Figure 5.34. Schematic diagram of the Real Time Display circuit.
6.1 Centroiding in the MIC Photon Counting Detectors

Three main resolution loss mechanisms have been identified in the image intensifier incorporated in the BigMIC and MIC detectors.

- The proximity focused gap between the cathode and first MCP (MCPl). Each primary photo-electron released from the cathode has a wavelength dependent transverse emission energy component $V_{or}$ associated which causes a spread $s$ in the photo-electrons' trajectories governed by the equation

$$s = 3.5L \left( \frac{V_{or}}{V} \right)^{1/2},$$

where $L$ is the length of the gap and $V$ is the voltage applied across it (Eberhard 1977). Typically, with a 0.2 mm gap and 300 V applied, the spread at 500 nm ($V_{or} = 0.1$ eV) is $\sim 13 \mu m$. *This resolution loss CANNOT be recovered by centroiding.*

- Sampling of each primary photo-electron by the pores of MCPl. Typically, MCPl utilises hexagonally packed 10 $\mu m$ pores on 12 $\mu m$ centres. *This resolution loss CANNOT be recovered by centroiding.*

- Charge cloud spread primarily associated with MCP2 sampling of the charge cloud from MCPl and MCP3 sampling of the charge cloud from MCP2 but also associated with the spread in the gaps between the three MCPs and the gap to the phosphor screen. The charge cloud spread is typically 80 $\mu m$ FWHM at the phosphor. *This resolution loss CAN be recovered by centroiding.*

To recover the loss associated with charge spread, centroiding is employed. This is normally limited to 1/8 of a CCD pixel in both X and Y, equivalent to $\sim 10 \mu m$ at the input, as the irrecoverable losses provide a limit above this level.

Centroiding is carried out on the data present in the DAA (Fig. 6.1), the electronic design of the circuit associated having been described in Chapter 5. In principle, there are two stages to the centroiding process:

1. **Event Validation.** An event must be central in the DAA. Here, two conditions must be met:
   - The central pixel must have the highest data value
   - This value must be greater than the valley in the pulse height distribution to discriminate against noise. As is shown in Section 6.6 this value is a variable that is dependent upon the event position within the central pixel.
2. Event Centroid. For this data set, the event centroid is then found.

![Data Analysis Array and Elements Used for Centroiding](image)

*Figure 6.1. The data analysis array and the elements used for centroiding.*

### 6.2 Centroiding Algorithms

To minimise the time overheads associated with processing of each event, the centroiding algorithm should be simple in form allowing fast computation of the event centre. Ideally, the algorithm employed would match the profile of each event. However, events have an asymmetrical profile due to the bias angle on the MCPs leading to a complex equation. In addition, there is some variation in profile between events. Thus, no simple algorithm can be directly employed to produce an accurate centroid position and special procedures have been developed to compensate for errors. Three algorithms have been analysed to determine their effectiveness:

The Centre of Gravity, which was employed in the original MIC systems, with the centroid position given by

$$x_0 = \frac{c - a}{a + b + c}, \quad (6.2)$$

and the newer Parabola Fitting

$$x_0 = \frac{c - a}{2(2b - c - a)}, \quad (6.3)$$

and Gaussian Fitting

$$x_0 = \frac{\ln c - \ln a}{2(2\ln b - \ln c - \ln a)}. \quad (6.4)$$

The determination of these Equations can be found in Appendix A. As these do not exactly match the event profiles, errors will result which will then affect two areas of detector performance:

- Resolution as is discussed here, and
- Image quality as is discussed in Chapter 7.
Other equations have been considered like fitting a Lorentzian or a Hyperbolic Secant Squared to the three points. In these two cases the centroids are given by (Lau and Pyrlik 1995):

\[ x_0 = \frac{1}{2} \frac{b(a - c)}{b(a + c) - 2ac} \]  

(6.5)

for the Lorentzian and,

\[ x_0 = \frac{\beta}{\pi} \tanh^{-1} \left[ \frac{\sqrt{b/c - \sqrt{b^2/a}}}{2 \sinh(\pi/\beta)} \right], \quad \beta = \pi \left[ \cosh^{-1} \left( \frac{\sqrt{b/c} + \sqrt{b^2/a}}{2} \right) \right]^{-1} \]  

(6.6)

for the Hyperbolic Secant squared. These have been rejected due to the complexity associated with their hardware implementation.

In the BigMIC system centroiding is carried out independently in the X and Y directions. The input parameters are given by the data in the cross-hair elements of the Data Analysis Array, as described in Section 5.4 and shown in Fig. 6.1, with \( a = a_{31}, b = a_{22}, c = a_{23} \) for the X direction and \( a = a_{12}, b = a_{22}, c = a_{32} \) for the Y direction.

### 6.3 Systematic Centroiding Errors

For each of the centroid algorithms there will be a characteristic function \( g \) that connects the computed centroids \( x_0 \) and the true centroid position \( x \)

\[ x = g(x_0). \]  

(6.7)

This curve can be obtained experimentally. Using a flat field input, the frame grabber within the detector Processing Electronics can be used to capture individual events and transfer them to the computer. The computer can then, using each of the algorithms, centroid the captured events to high precision and build up histograms of calculated positions (Fig. 6.2).

The characteristic curve can then be obtained by integrating the experimental centroid histograms using Equation 6.8 to produce the curves shown in Fig. 6.3.

\[ g(x_0) = -\sqrt{2} + \frac{\int_{x_0}^{x_S} \rho \, dx_0}{\int_{-x_S}^{x_S} \rho \, dx_0} \]  

(6.8)

The true answer lies in the range -0.5 to +0.5, this being referenced to the centre of the CCD pixel. The difference between the true (straight line) and computer curves is the error associated with that particular algorithm. An allowance for this systematic error must then be made when carrying out the centroid with the detectors hardware.
Figure 6.2. Histograms of the distribution of centroid positions for the three algorithms studied.
Figure 6.3. The characteristic functions for the three algorithms.
6.4 Hardware Implementation of Centroiding

There are two different ways in which the centroiding procedure can be implemented:

1) A number of groups (Carter et al. 1990, Fidouh 1993) have used sophisticated devices, like digital signal processors and transputers, to calculate the centroids. The advantage of these systems is that the centroiding is done in software and any algorithm can be easily, and quickly, implemented. The main disadvantage is that the processing speed provides a limit to the maximum data rate.

2) Using look-up tables in which the centroids for any combination of parameters have been pre-calculated and loaded onto memories.

The LUT technique has been adopted for the MIC systems as the applications are in both ground-based and space astronomy and it was desired to maximise data rates and minimise electronic complexity.

There are two ways that the LUT approach can be implemented:

1. To directly feed the data from the DAA to each LUT (Figure 6.4a). Three 8 bit data sets \((a_{21}, a_{22}, a_{32})\) for X, \((a_{12}, a_{22}, a_{32})\) for Y) are input which requires a \(2^{24} = 8M\) location memory.

2. To carry out a partial calculation prior to presenting the data to each LUT. All three algorithms are of the form \(M/N\) from which, as detailed in Chapter 5, 8 bit results for \(M\) and \(N\) can easily be calculated in hardware. The results of \(M\) and \(N\) are then fed into a \(2^{16} = 64K\) location memory (Figure 6.4b).

The first option is the most simple and powerful method since the results for any algorithm can be programmed into each LUT. The problem is the large memory size required, this being the reason that the second option was selected for the BigMIC and MIC detectors.

The inputs to the LUTs are \(M\) and \(N\) and the output is a 3 bit number that defines the centroid position to 1/8 CCD pixel accuracy.

---

Figure 6.4. Two different ways of implementing a centroiding algorithm with the use of look-up tables. (a) Feeding the three centroiding parameters directly to a look-up table memory, and (b) partially calculating the result beforehand allowing a 256 fold reduction in memory requirements.
6.5 Programming of the LUTs

The LUTs are loaded by the computer prior to operation of the detector system. The objective when calculating the result of $M/N$ to be programmed into the LUTs is to define boundary positions between the division range of 8 associated with the CCD pixel. If the algorithm employed exactly matched the profile of events, as given by the straight line fit in Fig. 6.3, then these boundaries would be simple to calculate. The first sub-pixel would be associated with results between -0.5 and -0.375, the second sub-pixel between -0.375 and -0.25 etc. However, the boundary positions must be derived from the characteristic curve shown in Fig. 6.3. What then defines the boundaries? With a flat field illumination of the detector the data accumulated in each sub-pixel should, with statistical variations, be equal. From this it can be readily deduced that the boundaries should be set so that equal number of events are integrated into each answer range. Table 6.1 shows typical settings for the Parabola algorithm, these being transposed onto the characteristic curve in Fig. 6.5. Of importance to note is that the boundary values are not symmetrical about the centre of the CCD pixel. This is because of the asymmetrical profile of events. Using these boundary values the LUTs are then loaded for all combinations of $M/N$.

The values for the X and Y LUTs are calculated separately and, for the three algorithms, the two dimensional representation of the sub-pixel boundaries is shown in Fig. 6.6.
Table 6.1. The centroid values assigned by the LUT after including the corrections from the characteristic curve shown in Fig. 6.5.

<table>
<thead>
<tr>
<th>Answer Range of $x_0 = M/N$</th>
<th>Assigned Centroid Value Decimal</th>
<th>Assigned Centroid Value Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.500 → -0.182</td>
<td>0</td>
<td>000</td>
</tr>
<tr>
<td>-0.182 → -0.072</td>
<td>1</td>
<td>001</td>
</tr>
<tr>
<td>-0.072 → -0.017</td>
<td>2</td>
<td>010</td>
</tr>
<tr>
<td>-0.017 → 0.018</td>
<td>3</td>
<td>011</td>
</tr>
<tr>
<td>0.018 → 0.052</td>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>0.052 → 0.101</td>
<td>5</td>
<td>101</td>
</tr>
<tr>
<td>0.101 → 0.194</td>
<td>6</td>
<td>110</td>
</tr>
<tr>
<td>0.194 → 0.500</td>
<td>7</td>
<td>111</td>
</tr>
</tbody>
</table>

**Figure 6.5.** Boundaries for the Parabola algorithm.
Figure 6.6. X and Y boundaries for the three algorithms.
6.6 Event Validation

As noted in Section 6.1, the centroiding process has two stages to it; event centroiding and event validation where the event validation determines whether an event is central in the DAA and whether that event is above a discrimination level that rejects background noise.

The conditions that control the decision on whether an event is central are described in Section 5.4.

In early MIC designs a single threshold was employed to discriminate against noise, this being placed in the valley of the intensifier pulse height distribution (PHD) as captured by the CCD camera. A typical PHD is shown as TOTAL in Fig. 6.7. An analysis of the detectors operation, though, shows that the use of a single threshold is only an approximation. Events centred close to the boundary of 4 CCD pixels will inherently have a different PHD to those centred in the middle of a pixel. This is because the charge associated with each scintillation will be more uniformly spread between those four pixels. In fact, for each of the 64 centroid positions associated with a pixel, a different PHD applies and hence a different threshold position. Eight typical PHDs on a diagonal across the CCD pixel are shown in Fig. 6.7.

To derive the 64 separate PHDs event height data is transferred along with the centroid position to the computer (Section 5.6.1). The thresholds can then be visualised (Fig. 6.8) and defined from the plotted histograms. The thresholds are then held in a separate LUT in the Processing Electronics as described in Section 5.5.2, the centroid position being required to define whether the event is above the threshold and hence valid.
Figure 6.7. Peak Height distributions for the Centre of Gravity algorithm. The one labelled as Total corresponds to the values of the central (peak) value of events while the other correspond to the diagonal sub-pixels. The dotted lines represent the typical thresholds obtained from these graphs.

Figure 6.8. The Peak Height distributions as generated by the processing electronics. Each of the 64 lines corresponds to each of the possible centroid positions.
6.7 Resolution Loss

The accuracy of centroiding is very dependent upon a number of parameters including the profile, energy and width of the intensified event.

From Equation 6.7 it can be seen that the resolution loss is dependent upon both the random errors, $\Delta x_0$, and any errors in the curve programmed into the LUTs. As a first order approximation the total error in centroiding can be calculated as:

$$\Delta x \approx \frac{d g}{dx_0} \Delta x_0.$$

(6.9)

To do this a data base of 10,000 events was captured with the MIC detector and used in a software simulation of the detector to derive typical errors in centroiding. This data base is the same as the one used to produce Figures 6.2 and 6.3.

Since graphs for function $g$ (Fig. 6.3) were already available, it was a matter of simply calculating its derivative using a numerical method provided by a software package called Origin. The results are shown in Fig. 6.9.

Approximate expressions for the errors in centroiding for the three algorithms can be derived as is explained in Appendix B. These expression are:

Centre of Gravity:

$$\Delta x_0 \approx \sigma \frac{\sqrt{3x_0^2 + 2}}{a + b + c}$$

(6.10)

Parabola Fitting:

$$\Delta x_0 \approx \sigma \frac{\sqrt{6x_0^2 + 2}}{2b - c - a}.$$  

(6.11)

Gaussian Fitting:

$$\Delta x_0 \approx \sigma \sqrt{\frac{(x_0 - 1)^2}{a^2} + \frac{4x_0^2}{b^2} + \frac{(x_0 + 1)^2}{c^2}} \frac{2 \ln b - \ln a - \ln c}{2 \ln b - \ln a - \ln c}.$$  

(6.12)

For the deduction of these expressions it was assumed that the system had only two components that governed the level of the errors, these being the CCD’s readout noise and noise on each scintillation on the output phosphor of the intensifier. If the CCD readout noise is assumed to be 1 ADU (normally about 0.6 ADUs) and the scintillation noise equalled 1% of the events' energy, $E$, given by the addition of the data in the nine pixels of the DAA then the noise factor is given by:

$$\sigma = \sqrt{1^2 + (E/100)^2}$$

(6.13)
Using this and Equations 6.10, 6.11, and 6.12 the graphs shown in Fig. 6.10 are obtained. By
multiplying these by their corresponding derivatives (Fig. 6.9) the graphs shown in Fig. 6.11 are
finally obtained where for each event $x$ and $\Delta x$ are calculated.

It can be seen that the Centre of Gravity and Gaussian algorithms provide relatively uniform
errors whilst for the Parabola algorithm the error is very dependent upon centroid position. The
important point to note, though, is that for all three algorithms the maximum error is only ±0.05
of a CCD pixel. If it is assumed that the CCD has a 23 μm square pixel size and that the fibre
taper that couples the CCD to the intensifier output has a de-magnification of 3.4:1 then ±0.05 of
a CCD pixel is equivalent to 7.82 μm spread at the intensifier. When this value is compared
against the irrecoverable resolution losses detailed in Section 6.2, it can be seen that the effect of
centroiding errors on resolution is negligible whichever algorithm is used.
Figure 6.9. Derivative of characteristic function. These derivatives were obtained numerically.
Figure 6.10. Centroiding error $\Delta x_0$ as a function of the calculated centroid position $x_0$ for the three algorithms compiled from 10,000 events acquired with the MIC system.
Figure 6.11. Total centroiding error $\Delta x$ as a function of the corrected centroid position $x$ for the three algorithms compiled from 10,000 events acquired with the MIC system.
CHAPTER 7
Fixed Pattern Noise

7.1 The Fixed Pattern Noise Mechanism

In Chapter 6 it was shown that there is a characteristic curve that relates the true centroid position to the computed centroid position. The systematic errors associated, which are dependent on the centroiding algorithm that is employed, can be compensated for by defining boundary positions that give equal weight to the sub-pixel results programmed into the centroid LUTs. This technique, though, only provides the greatest accuracy if there are no changes in the characteristic curve over the imaged field. As will be shown here, if there are changes in the event profile as captured by the CCD over the field this then leads to localised residual characteristic curves. Although, from the error analysis carried out in Section 6.7, the residual minimally affects detector resolution it does lead to a degradation in image quality.

If a residual curve is present then the results as programmed into the centroid LUTs will not give equal weight to each sub-pixel. This then results in a Fixed Pattern Noise (FPN) in accumulated images that repeats every CCD pixel. The problem is then exacerbated if the residual is a variable over the imaged field as this will lead to different levels of FPN over that field. Simplistically, the error on any event centroid will depend upon:

- The size of the residual
- The position of the centre of that event with respect to the CCD pixels it subtends.

Typical examples of FPN for the three algorithms defined in Section 6.2 are shown in Fig 7.1. When centroiding to 1/8 of a CCD pixel in both X and Y and being limited to a relatively low data rate by the dynamic range limitation of the detector (Section 8.3) it can take a very long exposure (typically 12 hours) to accumulate sufficient data per sub-pixel to adequately measure the level of FPN. To overcome this, it is assumed that over localised areas the FPN is a constant which permits, via modulo 8 addition in both X and Y of the data in each CCD pixel, generation of a high signal to noise ‘standard pixel’ that is also shown in Fig 7.1. This can then be used for accurate measurements.

In order to quantify this modulation a parameter called \( f_{pn} \) has been defined as:

\[
 f_{pn} = \frac{\text{max} - \text{min}}{\text{mean}} 
\]  

(7.1)

where \( \text{max} \) is the maximum value, \( \text{min} \) the minimum and \( \text{mean} \) is the mean value in the 8×8 standard pixel. An example is shown in Table 7.1.
Figure 7.1. Flat field images (128x128 sub-pixels) acquired by the MIC system. An identical contrast level on the three images is used. A fixed pattern noise with a period of 8 sub-pixels (1 CCD pixel) is clearly visible in the images generated by the Centre of Gravity and Parabola algorithms. The images on the right represent the modulo 8 addition of the data in each flat field image and are used to calculate the FPN parameter being, in this case, 27% for the Gaussian, 66% for the parabola, and 75% for the centre of gravity.

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<td>0.752</td>
<td>0.751</td>
<td>0.778</td>
<td>0.736</td>
<td>0.402</td>
</tr>
</tbody>
</table>

Table 7.1. Array formed by the addition of the values of the corresponding sub-pixels on an image (the one labelled as Centre of Gravity in Fig. 7.1). The results are presented in the normalised form (each cell is divided by the value of the biggest element on the array). In this case max = 1.000, min = 0.397 and mean = 0.806 so $fpn = 74.8\%$. 
If it is assumed that there are no variations in event profile across the detector field then the residual characteristic curve will just be governed by the CCD pixel sampling of the event profile. As an event typically covers 1 CCD pixel at FWHM it is undersampled by the CCD leading to a position dependent variation in captured profile and hence residual curve. It is important to note here that this affect alone inherently defines the curve and resultant FPN as being two dimensional in nature whereas centroiding in X and Y are carried out independently. This is discussed further in Section 7.2.4.

Any variations in event profile then add an additional FPN in accumulated images. These could result from a number of potential sources including:

- Tilt between, or non-uniformities in the surfaces of, the fibre optic components that optically couple the intensifier to the CCD.
- Non-parallelism between the MCPs and the output phosphor of the intensifier.
- Shear and pin-cushion distortions in the fibre optic components, in particular the fibre optic taper.
- Defects in the pore structure of the MCPs.
- Signal induced background (SIB) in the image intensifier contaminating the real event scintillations on the output phosphor.
- Charge transfer inefficiency in the CCD.
- Spatial coincidence between events in a CCD frame period.

Of importance to note is that all of these except SIB and event coincidence are fixed providing that the detector is mechanically stable and can thus be compensated for during data reduction. With high quality photon counting image intensifiers SIB should be minimal and can be discounted. *The errors associated with event coincidence are data rate dependent and cannot be removed by, for example, dividing by a flat field.*

Thus it can be expected that a level of FPN will be present in all images. How will this affect the quality of scientific data? This can best be envisaged by using an example in spectroscopy. A single row slice (or cross section) through the Parabola flat field in Fig. 7.1 can be seen in Fig. 7.2. Now imagine that the detector is being used for analysis of faint absorption lines in a continuum spectra where the continuum will inherently contain this FPN. The absorption lines cannot be seen directly. As will be shown, flat field division during data reduction does not work accurately - it will bring out the features but their level will be wrong - for this type of detector artefact. To minimise the affect it is then necessary to fully understand the mechanisms associated and define observing constraints to meet scientific objectives. This analysis has been carried out by computer simulations and then a comparison against acquired data.
7.2 Computer Simulations

Five possible sources that could affect the level of FPN have been identified. These are:

1) The centroiding algorithm being used,

2) Change in width of the event which will result from artefacts such as CCD pixel sampling or tilt between the fibre optic components,

3) Random change in event shape resulting from coincidence between events,

4) Variations in CCD bias levels due to instability of the camera, and

5) The sub-pixel boundaries being defined independently in X and Y.

To study the effects of these factors a computer programme was written to simulate the generation of flat field images with the MIC system. The Flat Field Simulation (FFS) programme is listed in Appendix D. In the FFS programme a predetermined number of events are randomly placed in a pseudo CCD frame. This frame is scanned for valid events and, for each algorithm, their centroid positions computed to a resolution of 1/8 of a CCD pixel in both X and Y. The centroids are then accumulated into images and the process repeated until adequate data to allow analysis is collected.

The events are taken, also at random, from a database of about 40,000 events that can either be obtained from the MIC systems (real events) or generated by another computer programme called Synthetic Events Generator (SEG) which is listed in Appendix E.

In addition to the 3-pixel algorithms (Section 6.2) which uses the cross-hair pixels of the DAA, the programme allows to investigate the possible advantages of centroiding using all of the 9 pixels of the DAA. In this case \( a = a_{11} + a_{21} + a_{31}, \ b = a_{12} + a_{22} + a_{32}, \ c = a_{13} + a_{23} + a_{33} \) for the X direction and \( a = a_{11} + a_{12} + a_{13}, \ b = a_{21} + a_{22} + a_{23}, \ c = a_{31} + a_{32} + a_{33} \) for the Y direction.
7.2.1 Change in Event Width

In order to obtain data on how the characteristic curve (systematic error) produced by the centroiding algorithms changes as a function of event width a simple one dimensional simulation was made. A simulated ‘event’ with gaussian shape (symmetrical) was shifted by small increments to different positions with respect to the fixed CCD pixels. For each position the area of the gaussian was integrated under the three pixels used for centroiding with the 3-pixel algorithms. Fig. 7.3 shows some examples of this.

\[ x_0 = 0.05 \]
\[ a = 49 \]
\[ b = 238 \]
\[ c = 66 \]

\[ x_0 = 0.15 \]
\[ a = 35 \]
\[ b = 226 \]
\[ c = 84 \]

\[ x_0 = 0.25 \]
\[ a = 23 \]
\[ b = 202 \]
\[ c = 100 \]

\[ x_0 = 0.35 \]
\[ a = 14 \]
\[ b = 171 \]
\[ c = 112 \]

\[ x_0 = 0.45 \]
\[ a = 8 \]
\[ b = 137 \]
\[ c = 119 \]

**Figure 7.3.** Simulated event generation by integration of a gaussian by three ‘CCD pixels’. The FWHM of the gaussian is 1.2 CCD pixels in this example. The position of the gaussian with respect to the CCD pixel structure \( x_0 \) and the accumulated signal under the left (a), centre (b) and right (c) pixels are also shown.

The process was repeated for gaussians with different widths and the known centroid positions were then plotted against those produced by the algorithms. Simulated events were used due to the difficulty in generating real events with different widths. The results for full width at half maximum (FWHM) from -0.8 to 3.2 CCD pixels are shown in Fig. 7.4. It can immediately be seen that the Gaussian algorithm presents the least sensitivity to variations in event width.
The Parabola characteristic curves are not linear. This should not be a problem since this can be compensated by the LUTs. The real problem is the marked variation of these curves which get worse as the events get smaller.

The Centre of Gravity is the most sensitive algorithm to event width. Although it shows good linearity the fact that the computed centroids cover different ranges for different event widths (unlike the other algorithms which always give computed centroids from -0.5 to 0.5) will introduce strong discontinuities in the boundaries between pixels.

The FFS and the SEG programmes were then used to determine how the optimum boundaries varied with respect to event width. The results are shown in Figures 7.5 and 7.6. In general the best algorithm for reducing FPN will be that whose boundary positions (implemented in the look-up tables) are least sensitive to variations. As expected from the previous results both the 3 and 9 pixel Gaussian algorithms are best in this respect. The boundaries are seen to stabilise at a FWHM of about 0.8 CCD pixels. After that, little change in the boundary positions occur. The Centre of Gravity and Parabola are never seen to reach a stable level.

The boundary positions as loaded in the LUTs are inherently fixed, being determined by the global characteristic curve. To show the effect of localised variations in event profile, and hence residual characteristic curve, on image quality a further simulation was carried out. Here, the boundaries were set based upon an event width of 1 CCD pixel. Then 'flat field' images were generated whilst changing the event width between 0.6 and 2 CCD pixels. Fig. 7.7 shows that the Gaussian algorithms are the most accurate. When going below 1 CCD pixel the events are too under-sampled and hence the errors for all the algorithms become large.
Figure 7.4. Characteristic curves for the three pixel centroiding algorithms analysed showing the position dependent systematic error between the true and computed centroid positions. A value of 0 corresponds to the centre of a CCD pixel. The solid line depicts perfect correspondence between the true and computed positions. It can be seen clearly that the Gaussian algorithm is the least affected by variations in this parameter.
Simulation with synthetic events. Boundaries optimised at each FWHM.

**Figure 7.5.** The optimum boundaries as a function of event width for the 3-pixel centroiding algorithms. The Parabola and Centre of Gravity are greatly affected by this parameter.
Simulation with synthetic events. Boundaries optimised at each FWHM.

Figure 7.6. Variations of optimum boundaries as the events width changes for the 9-pixel centroiding algorithms. These show basically the same pattern as the 3-pixel algorithms.
Simulation with Synthetic Events

Boundaries optimised at FWHM = 1.0 pixels. Events Rate = 0.0024 events/ccd pixel/frame.

Figure 7.7. Effect of change in event width on fixed pattern noise. At the top, the 8x8 arrays from which the FPN parameter was calculated. It can be seen in the graphs below that FPN deteriorates quickly for all the algorithms except the Gaussian ones. Going to lower FWHMs deterioration is faster because the events are extremely undersampled.
7.2.2 Coincidence Between Events

Another important parameter affecting centroiding (and FPN) is the distortion of event shape produced by event coincidence. The FFS programme was used again to determine how coincidences affected the boundary positions. In this case a data base of real events (acquired from the MIC system) was used. Figures 7.8 and 7.9 show the results with the different algorithms. The Gaussian and Parabola are least affected because the centre pixel has more weight in the centroid calculation and coincidences are primarily expected to affect the wings of captured events.

Fig. 7.10 shows the data rate dependent FPN for the different algorithms up to 0.035 events/CCD pixel/frame equivalent to $2 \times 10^5$ events per second on a 256x256 CCD pixel frame. The 3-pixel Gaussian and Parabola algorithms give the least change with count rate. Event rate produces a smaller change in the boundary positions than event width variations. It is believed that this is due to the random nature of coincidences.
Simulation with real events. Boundaries optimised at each event rate.

**Figure 7.8.** Computer modelling of change in optimised boundary positions with data rate for the 3-pixel algorithms.
Figure 7.9. The change of the boundary positions to compensate for event rate effects for the nine pixel algorithms.
Figure 7.10. Effect of coincidence between events on fixed pattern noise.
7.2.3 Bias Level

By looking at the centroiding algorithms it is evident that if a bias level (constant) is added to each of the pixel values this constant will cancel out when employing the Parabola algorithms and hence the system will be immune to variations in, for example, bias level of the CCD camera. This will not be the case for the other algorithms. If these are employed then special precautions must be taken to insure that the bias does not change. Fig. 7.11 shows how changes in bias affect FPN. After the Parabola algorithms it is found that the 3-pixel Gaussian gives the next best results.

![Graph showing Fixed pattern noise dependence on bias changes.](image)

**Figure 7.11.** The Fixed pattern noise dependence on bias changes.

7.2.4 Boundaries Being Independent

The fact that the sub-pixel size is controlled by the boundaries and that the latter are completely independent in X and Y in the current systems will introduce a high level of FPN because events are not symmetrical. If a facility existed that allowed the boundaries in the two directions to be inter-dependent then the sub-pixel sizes could be given the flexibility to better adapt to the shape and orientation of events (Figures 7.12 and 7.13).

To investigate the way in which this will affect FPN a simulation with dependent boundaries and real events was carried out (Fig. 7.14). When these results are compared against those with independent boundaries (Fig. 7.10) it can be seen that the FPN is reduced by about 20%. Because of this, the implementation of this in hardware is highly recommended, the only disadvantage is that it will require 8 times more memory in the LUTs.
Figure 7.12. The independent and dependent boundaries for the 3-pixel algorithms.
Figure 7.13. The independent and dependent boundaries for the 9-pixel algorithms.
Dependent Boundaries. Real Events

Algorithm: 3Gau 3Par 3CoG 9Gau 9Par 9CoG

Event Rate (events/ccd pixel/frame)

Figure 7.14. FPN with dependent boundaries.
7.3 Data Acquired with the MIC Detector

A series of experiments were carried out to compare the actual image quality with the simulations when using the 3-pixel algorithms. A CCD with a non uniform surface on its fibre block was used in order to exaggerate the event profile variation across the camera. An image area of 256×256 CCD pixels was used and images were acquired with 1/8 CCD pixel centroiding accuracy in both X and Y, providing a 2048×2048 sub-pixel data acquisition format.

7.3.1 Flat Field Response

The FPN was analysed using cells of 128×128 sub-pixels (16×16 CCD pixels) within an area of 1920×1920 sub-pixels, giving an array of 15×15 samples. One of these images is shown in Fig. 7.15. The results of these measurements are presented in Appendix F and represented in graphical form in Fig. 7.16. The illumination level varied by about 30% across the field due to optical aberrations. This had to be separately considered from event width. The Parabola algorithm is the least uniform because of its greater sensitivity to variations in event width. As predicted by the simulations the Gaussian fitting provides the best results as it is least affected by the combination of coincidences and change in event width.

![Figure 7.15. Flat field response of the Centre of Gravity Algorithm showing the 128×128 sub-pixel cells used for the calculation of FPN and illumination level.](image-url)
7.3.2 Event Rate Response

A mask with different layers of neutral density filter was then projected onto the detector, to provide a variable input event rate across the field (Fig. 7.17), enabling the measurement of FPN with both coincidences and the inherent event width variations of the low quality camera. The FPN was then analysed with 64x64 sub-pixel cells and the results are shown in tabular form in Appendix G and in graphical form in Fig. 7.18. The Centre of Gravity is most affected by coincidences and the Parabola fitting by event width. As expected from the simulations the Gaussian fitting provides the lowest errors.

Figure 7.16. Response to a 'flat field' illumination of the three centroiding algorithms implemented in the hardware of the BigMIC system.
Figure 7.17. One of the images acquired with different layers of filter. There are seven stripes corresponding, from left to right, to 8 to 2 layers of filter. The image size is 2048x2048 sub-pixels.
7.3.3 Division by Flat Field

In order to measure the image quality after data reduction a set of brightly illuminated flat fields was divided by their normalised dimly illuminated flat fields. Fig. 7.19 (data in Appendix H) shows that both the Parabola and Gaussian fittings give similarly good results. This means that, for these two algorithms, the modulation pattern remains more constant in the different cells of the image regardless of coincidence level. Again the Centre of Gravity gives poor results.
7.4 Conclusions

The analysis of errors related to change in profile of an event has shown that there is a fixed pattern noise inherently associated with the technique of sub-pixel centroiding and is two dimensional in nature.

For scientific evaluation of acquired images it is not possible to remove the FPN during data reduction by flat fielding as the mechanism is associated with re-positioning of, as opposed to loss of, data. The FPN is, essentially, caused by the sub-pixel sizes being unequal. Dividing by a flat field will enhance the photon count acquired in the smaller sub-pixels. As an example in direct imaging, if two identical magnitude stars are imaged into a small and large sub-pixel then, after flat fielding, the magnitude of the star in the smaller sub-pixel will be artificially enhanced.

In spectroscopy the FPN will adversely affect the profiles of emission and absorption line features leading to, for example, mis-identification of lines.

It has been shown here that to minimise the FPN, and hence provide the highest accuracy scientific data, a Gaussian fitting algorithm should be employed. However, a remnant will always be present using the current system design. This level can be improved by the use of dependent boundaries allowing better matching to the event shape. Its implementation in hardware is thus strongly recommended. However, for the highest quality scientific images, the detector operation should be confined to low input flux levels to minimise the effect of coincidences.

Currently, only one potential method for overcoming FPN without affecting resolution can be suggested and that is to utilise a dithering technique (Jorden and Fordham 1986). Here the image to be acquired is moved in an 8x8 raster scan with incremental steps equal in size to a sub-pixel across the input of the detector. The movement is then corrected for at the stage of defining the centroid address for each event. This procedure then smoothes through the FPN and any other detector artefact without affecting the quality of the acquired image.

Ideally, the movement of the input image would be carried out by applying a variable electromagnetic field influence to the primary electron released by the photocathode of the intensifier. This is not possible with an MCP intensifier as the gap between the photocathode and the first MCP is too small (typically 0.2 mm). Therefore, it can only be carried out optically on the input interface.
CHAPTER 8
Detector Performance

The ultimate test of a new detector is its performance when compared against the ideal characteristics of a perfect detector (Section 1.1). Each detector is normally developed with specific applications in mind for which some characteristics are more relevant than others. For the BigMIC detector, developed for large-format high-resolution imaging applications, the important areas are:

- Image Quality
- Resolution
- Dynamic Range
- Quantum Efficiency

In all of these areas, as will be shown, ultimately the performance is governed by the image intensifier.

8.1 Image Quality of the final design of 75 mm image intensifier

To test the 75 mm intensifier it was decided that a direct comparison against a 40 mm diameter intensifier be carried out. In both cases the BigMIC CCD camera was used for acquiring data as it was essential that the performance of the camera be taken out of the equation when analysing the data. A 40 mm intensifier from ICSTM was used for the comparison.

Unfortunately, in the middle of testing, whilst the BigMIC camera was connected to the 40 mm intensifier, the CCD was destroyed along with some of its associated electronics. It was apparent from the components that failed that a high voltage somehow got into the camera electronics, this being corroborated by an arcing heard from the vicinity of the intensifier at the time of failure. It was believed that an electrostatic build-up of charge may have occurred in the body of the intensifier.

By then, though, enough data on both flat fields and pin-holes had been acquired to allow a comparison between the two intensifier designs to take place. This data was then added to with further data acquired using the MIC2 CCD camera.
8.1.1. Operating Voltages

Figure 8.1 shows the different electrical connections inside the intensifiers and the bias voltages that are applied. Table 8.1 shows the values of these voltages for both the 75 and the 40 mm intensifiers. Because of photocathode emission defects in both intensifiers, the photocathode voltage could not be raised to the normal operating value of 300 V, being limited to 50 V, but this only affects resolution and not image quality.

<table>
<thead>
<tr>
<th>Vc-1 (V)</th>
<th>V1 (V)</th>
<th>V23 (kV)</th>
<th>V3-P (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>750</td>
<td>2.4</td>
<td>4.6</td>
</tr>
<tr>
<td>50</td>
<td>800</td>
<td>2.6</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Table 8.1. Intensifiers' bias voltages.

8.1.2. Pulse Height Distribution

The pulse height distributions obtained with these intensifiers are shown in Fig. 8.2.
The pulse height distribution of the 40 mm tube looks normal, with a clearly visible peak and valley that can allow definition of a threshold to discriminate noise from photon events. In contrast, the 75 mm intensifier shows basically a negative exponential distribution (similar to the old EMI intensifiers) without the saturated pulse height distribution ideal for photon-counting applications. ICSTM believed that this was due to the emission defect which caused various energy particles to be input to MCP1. It is probable though that other mechanisms contribute as is discussed in Section 8.1.5.

8.1.3. Flat Field Data

Flat field data at a low count rate was acquired with both the 75 mm and 40 mm intensifiers incorporated in the BigMIC system. Subsets of typical images are shown in Fig. 8.3 and Fig. 8.4 respectively. Centroiding to 1/8 of a CCD pixel was used giving a data acquisition pixel size of 10x10 µm². The counts acquired in both images are approximately equal.

**Figure 8.3.** Flat field image obtained with the 75 mm intensifier. The size of this image is 512x256 sub-pixels which corresponds to 5.12x2.56 mm² at the photocathode plane.

**Figure 8.4.** Flat field image obtained with the 40 mm intensifier. The size of this image is 512x256 sub-pixels which corresponds to 5.12x2.56 mm² at the photocathode plane.
The 75 mm images show a number of artefacts:

A very large number of defects

From the number of defects seen in Fig. 8.3 it is estimated that ~50,000 defects will be present over the whole detector area. All of these defects have approximately the same size. Their measured width in the accumulated data is ~50 μm. Because of the width consistency it is believed that they originate from defects in the MCP pores as opposed to the photocathode.

The only other possibility visualised was that they originated in the fibre taper that couples the intensifier to the CCD. This, however, was discounted by very high resolution analysis of the fibre taper. Whilst there are some defects in the fibre taper's structure, these are at a far lower frequency than those present in the 75 mm image and confined to single broken fibres. Since each scintillation on the output phosphor of the intensifier is ~120 μm FWHM and is thus imaged onto ~40 fibres, one bad fibre will make very little difference to the event profile as captured by the CCD.

In which MCPs are the defects present? If the defects are in MCP1 then they would cause a loss of data from just the associated pores and the maximum size of the defect in the acquired image would be equivalent to the distance between surrounding pores - i.e. ~24 μm. Due to electron collimation effects (Fig. 8.5) MCP2 undersamples the charge cloud from MCP1 and hence dead pores in this MCP will then, in acquired images, have a greater effect due to the larger pore spacing leading to a maximum defect size of 64 μm.

Thus it is believed that the defects originate in MCP2. It is not known whether these were present in the MCP as received from Galileo, or were introduced in the processing or reprocessing at Photek. To overcome this problem in future intensifiers, it will be very important to analyse the MCPs individually before processing.

Hexagonally packed MCP sections with differing sensitivity

It was seen (Fig. 8.3) that the counts accumulated in one of the hexagons are noticeably higher than in the surrounding hexagons. Analysis of the data shows that ~20% more counts are obtained in this area. This artefact has not been noticed with any previous intensifier and it is believed that the resistivity of this hexagon is slightly different leading to the gain difference.

There is one other big difference between this intensifier and previous generations which leads us to this conclusion; it does not have a saturated pulse height distribution. With a saturated pulse height distribution all events above a threshold (placed in the valley of the distribution curve) are counted with equal weight and any variations in gain across the MCP area excluded. With no valley in the distribution curve small variations in gain do become noticed due to the arbitrary position of the threshold.
Imaging of the structure of the 25 μm pores of MCP2

This is noticeable as a high frequency modulation in Fig. 8.3. It was found that the modulation level introduced into a flat field is ~50% and that the period is ~32 μm (the pore to pore spacing on MCPs 2 and 3) implying that imaging of the MCP2 pores is occurring.

This conclusion is backed up by the data from the 40 mm intensifier, where the only difference between the two intensifiers is the pore spacing on MCP2 and MCP3. Here a basically smooth flat field is obtained (Fig. 8.4). A low frequency modulation which could be attributed to a non-uniformity in cathode response or uneven light illumination is the only artefact present.

Why does imaging of the MCP2 pores occur? It is believed that this is due to an electron lensing affect created by the end-spoiling (the distance the electroding on the MCP face penetrates into pores) of MCP1. This is supported by data from Galileo Electro-Optics Corporation (1995) which states that: “End-spoiling on the output face of the MCP acts as an array of microlenses which provide a strong collimating effect on the electrons exiting each pore”.

The effect of this electron lensing is shown schematically in Fig. 8.5, where it can be seen that the electron cloud from MCP1 which is confined to a single pore is undersampled by MCP2 and thus a modulation will inherently be introduced.

\[
\text{(a) 10/12 μm pores on MCP1 and 20/30 μm pores on MCP2, (b) 10/12 μm pores on both MCPs.}
\]

8.1.4. Point Spread Function

Data was acquired with the MIC2 CCD camera to give a feel for the data quality that could be obtained on a star image or a narrow spectral emission line. A carefully focused 5 μm pin-hole image was projected onto the photocathode of both intensifiers. The position of the pin-hole image was moved in increments of ~10 μm on the photocathode between each exposure. The exposure time for each integration was kept the same. Fig. 8.6 shows thirty contiguous pin-hole images acquired with the 75 mm intensifier while Fig. 8.8 shown their associated profiles. A similar procedure was followed with the 40 mm intensifier, Fig. 8.7 showing the images and Fig. 8.9 the profiles.
Figure 8.6. Five micron pin-hole images at different positions on the photocathode of the 75 mm intensifier. The equipotential curves go from 0.1 to 0.9 of the maximum brightness. Very apparent is the distortion to the image profile produced by pore sampling.

Figure 8.7. Five micron pin-hole images at different positions on the photocathode of the 40 mm intensifier. The equipotential curves go from 0.1 to 0.9 of the maximum brightness. All of the pinhole images have very similar shape.
Figure 8.8. Histograms of the point spread function of the 75 mm intensifier. The FWHM of these histograms is 4.48 ±0.62 sub-pixels which corresponds to ~44.8 ±6.2 μm at the photocathode. There is a very high variation in the intensities, the normalised energies having a standard deviation of 0.26.

Figure 8.9. Histograms of the point spread function of the 40 mm intensifier. The FWHM of these histograms is 2.64 ±0.12 sub-pixels which corresponds to ~26.4 ±1.2 μm at the photocathode. The intensities of the pin-hole images are quite uniform, the standard deviation of the normalised energy was measured to be 0.06.
The data for the 75 mm intensifier shows a number of features:

- From Fig. 8.6 it can be seen that a variety of image shapes are acquired. In the case where the pin-hole is centred on a pore relatively sharp images are obtained (co-ordinate position [60,60] for example). In other cases the pin-hole subtends a number of pores and a very distorted image results (co-ordinate position [80,20] for example). For the distorted images, these will comprise the summation of the separate pore images.

- From Fig. 8.8 it can be seen that there is a variation in both the width and intensity of the acquired images as the pin-hole traverses the pore structure. In some cases the width is narrow and the intensity high, where it can be assumed that the pin-hole subtends the centre of co-aligned 10/25μm pores, and in other cases the width is broad and counts are lost, where the assumption is that the pin-hole subtends the webbing between pores. There is no correlation between width and strength (sensitivity) as may be expected. It is believed that this results from the complex structure produced by the imaging of the 10 μm pores of MCP1 on to the 25 μm pores of MCP2.

8.1.5. Conclusions on 75 mm Intensifier

A number of problems with the 75 mm diameter 10/25/25 μm pore intensifier led to the conclusion that this particular device was not suitable for observing trials with the BigMIC system. The problems were:

- The bright emission at the edge of the intensifier which provides a very high background.
- A large number of defects which probably originated in either MCP2 and/or MCP3.
- A non-saturated pulse height distribution. In addition to the bright emission being responsible it is believed that two other mechanisms could be associated:
  a) Obtaining a saturated pulse height distribution is dependent upon the gain of MCP1 (the charge cloud from MCP1 detected by MCP2 must be above a particular level before saturation occurs). As can be seen in Fig. 8.5, the level of charge detected by MCP2 for this intensifier design will be variable and totally dependent upon the pore in MCP1 in which the primary photoelectron is detected. For many spatial positions the cloud accepted by MCP2 could be below the required level for saturation and thus cause in-filling on the pulse height distribution curve.
b) There are variations in sensitivity across the field as highlighted by the high sensitivity hexagon in Fig. 2. This variation will produce a broadening of the pulse height distribution curve.

- Imaging of the pores of MCP2, resulting from electron lensing due to the end spoiling of MCP1. This affects resolution, as shown by the point spread measurements. As the MCP pores provide the initial sampling of the input image, under-sampling occurs when the input subtends less than two pores. The standard definition of limiting resolution used in astronomy is two pixel sampling at FWHM of the input image. Under this definition, with the resolving of the pores of MCP2, a limiting resolution of \( \sim 64 \, \mu m \) results.

- Spatial variations in sensitivity across the field which are, again, due to the under-sampling of the MCP1 cloud by MCP2.

The primary problems are those associated with the non-saturated pulse height distribution and the imaging of the pores of MCP2. These could be overcome by increasing the gap between MCP1 and MCP2 allowing adequate sampling of the cloud from MCP1 but the problem visualised is the size of gap required. The cloud at MCP2 must be \( >64 \, \mu m \) FWHM and with the electron lensing this could lead to a very large gap. Alternatively, the end spoiling on MCP1 could be minimised which would reduce the gap size requirements. A final alternative is to use 10 \( \mu m \) pore plates throughout.

Although none of these problems are believed to be fundamental they did prevent detailed performance characterisation and observing trials taking place. It will require further development of the intensifier before these can be achieved.

In the context of providing data on performance of the final version, this had to be put in terms of the measured performance of the MIC detector and a theoretical extrapolation to BigMIC until further funding is available.

### 8.2 Resolution

In has been shown (Section 6.1) that the main unrecoverable resolution loss mechanisms in the MIC systems have their source in the image intensifier and are:

- **The gap between the photocathode and MCP1.** This resolution loss arises from the transverse emission energy component of the photo-electrons (emitted by the photocathode) which depends on the energy of the incident photons. For this reason the resolution is wavelength dependent and inherently better in the red region of the spectrum. The photocathode to MCP1 voltage acts as a focusing mechanisms and by increasing it improvements on resolution are obtained.
• *The sampling of each primary photo-electron by MCP1.* As explained before, MCP1 typically consists of hexagonally packed 10 μm diameter pores with centre to centre separations of 12 μm.

An experiment was carried out at MSSL to measure the resolution of their XMM detector as a function of wavelength and photocathode to MCP1 voltage. A mask of 5x5 30 μm diameter pin-holes was projected onto the photocathode by means of a high-quality reducing lens in such a way that each pin-hole had a diameter of ~6 μm at the photocathode. Images in three colours were integrated for different values of the photocathode to MCP1 voltage. For each voltage set-up three images were acquired by illuminating the pin-hole mask with red, green and blue light. In the case of the red and blue the illumination was provided by light emitting diodes while for the green a fluorescent panel was used.

For each image the FWHM of all the 25 pin-holes was measured and the average values are reported in Fig. 8.10. The wavelength and voltage dependence of resolution is clearly seen and, as expected (Equation 6.1), the resolution gets better for shorter wavelengths and is inversely proportional to the square root of the applied voltage. At the normal operation voltage (300 V) the PSF is found to be less that 30 μm for all the colours.

![Figure 8.10. The Points Spread Function of a typical MCP intensifier as function of the photocathode to MCP1 voltage and energy of incident photons. Data provided by MSSL (H. Kawakami, private communication).](image)

An alternative method of measuring resolution of an imaging system is using the Modulation Transfer Function (MTF) technique in which a test pattern with alternating black and clear bars of different thickness, such as the USAF Resolution Mask, is projected onto the sensor and the
response then measured. One of these test patterns, illuminated with a green fluorescent panel, was used and the image in Fig. 8.11 was obtained. One eighth pixel centroiding with parabola fitting was employed. Some defects in the intensifier and the test pattern slide are apparent in the image. The integration time for this image was 9.5 hours which shows the stability of the detector.

The MTF is a function that defines the ability of an optical (or electronic) device to transfer signals faithfully as a function of the spatial (or temporal) frequency of the input signal and can be expressed as the ratio of percentage modulation of a square wave signal leaving to that entering the device over the range of frequencies of interest. It is given by:

$$\text{MTF} = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}$$

(8.1)

where $I_{\text{max}}$ and $I_{\text{min}}$ are the measured intensities of the output signal.

To measure this parameter two cross sections through the image in Fig. 8.11 were taken. For the low frequency pattern sets, lines 1020-1070 of the image were added together. The result is shown in the top graph of Fig. 8.12. Similarly for the higher frequency sets, lines 300 to 350 were added producing the bottom graph of Fig. 8.12. The original acquired image had to be rotated by 2° in software before summation took place, to provide correct alignment.

Figure 8.11. Image of a test pattern mask acquired with the MIC2 system. One eight centroiding with the parabola algorithm was used. The image covers an area of 1850x1155 sub-pixels² which corresponds to 18.14x11.32 cm² at the photocathode (1 sub-pixel = 9.8 μm).
By measuring the average values of the maximum and minimum values of the sets of bars and taking into account that one sub-pixel is equal to 9.8 \( \mu m \) at the photocathode the graph in Fig. 8.13 was obtained. The limiting resolution is normally defined as the point at which a 30\% modulation occurs (Csorba 1985). It can be seen from the extrapolation in the graph that this is expected to occur at \(~14.2\) lp/mm which is equivalent to one line in \(~35\) \( \mu m \) which matches well the measurements of PSF which gave a resolution of \(~30\) \( \mu m \).

**Figure 8.12.** Horizontal profiles of the sets of bar in Fig. 8.11.

**Figure 8.13.** The modulation transfer function of the MIC2 detector. The solid squares correspond, from left to right, to the line pattern groups labels from 100 to 800 in the image. The dotted curve is the best gaussian fit through the points.
8.3 Dynamic Range

The dynamic range of any detector can be defined as the range of input light intensities over which, within the constraints of any particular programme, scientifically analysable data can be obtained.

8.3.1 Faint Limit

With the BigMIC and MIC systems the faint, or low, limit is governed by the noise contribution from the detector. This could come from two sources; the image intensifier and the CCD camera.

The CCD camera electronics contributes a very low level of noise (<1 ADU) which is well below the threshold level provided by the Processing Electronics.

The image intensifier has a number of noise emission sources:

- **Thermal emission** from the photocathode. Thermally generated electrons will look identical to photo-electrons and cannot be recognised as a separate component in an integrated image.

- **Fluorescence** within the input window. With quartz windows this has not been measurable. However, alternative windows such as fibre optic or sapphire do show appreciable fluorescence due to radioactive decay of impurities.

- **Cosmic Rays.** These can impact with either the window, creating a track of photons that are detected by the photocathode, or MCPs, creating a track of electrons. For the MCPs, only MCP1 is of concern as noise produced within MCPs 2 and 3 will not have sufficient gain to be recognised as events. Additionally, cosmic rays can impact directly on the CCD but the accumulated charge is too low for events to be recognised.

- **Radioactive decay** of impurities in the lead-glass MCP substrate (Fraser et al. 1987, Lees and Pearson 1996). This leads to a very low noise contribution (~0.2 events-cm^{-2}·s^{-1}) from MCP1 that can be measured with the photocathode switched off. Noise generated in MCPs 2 and 3, again, will not have sufficient gain to be recognised as events.

The most dominant of these mechanisms is the thermal noise from the photocathode which is dependent upon red sensitivity (a higher red response being associated with a lower band gap and hence higher probability of thermal release).

For an S20 photocathode the typical dark count at room temperature is ~50 counts/cm^{2}/s (5x10^{-5} counts/sub-pixel/s with 1/8 centroiding). For the bialkali photocathode used in the BigMIC intensifiers this background is ~10 counts/cm^{2}/s (due to the lower red response).
In both cases the background can, if required, be reduced by cooling. Following the classical cooling curve for semiconductors, a factor of 2 reduction for each ~7 °C drop in temperature will be expected.

8.3.2 Bright Limit

The upper limit on dynamic range is governed by spatial coincidence losses where a number of factors are associated:

- Frame rate of the CCD camera
- Size of events as detected by the CCD
- Pore paralysis in the MCPs
- Phosphor decay time

The dominant loss mechanism is associated with the frame rate of the CCD camera but, inherently, includes the effects of event size and phosphor decay.

Looking at a single CCD frame, coincidences losses occur at a CCD pixel level and are independent of centroiding accuracy which only affects resolution, i.e. are independent of whether centroiding occurs to 1, 1/2, 1/4 or 1/8 of a CCD pixel.

8.3.2.1 The Coincidence Loss Mechanism

To understand the mechanisms that lead to coincidence loss, four fundamental characteristics of the detector need firstly to be described:

C1. The electron gain of the image intensifier for each event detected is \(-2 \times 10^5\) e'/e' and this electron cloud from the MCP output produces a scintillation, on the S20 phosphor, containing \(~10^7\) photons. At this intensity the MCP pores are operating in a non-linear regime, the central pores being more highly saturated. The output scintillation has a diameter of typically 80 μm FWHM.

C2. A CCD pixel, when subtended to the image intensifier, approximately equals 80 μm square. Thus a CCD pixel size approximately equals the FWHM of an event.

C3. Although the MCPs are described as operating in a saturated mode, this is something of a misnomer - it is a non-linear region associated with the onset of saturation. For true saturation, the energy of each event would be identical.

C4. There is a decay curve on the phosphor after excitation by the arrival of an event.

Spatial coincidences can then be categorised into three types:
A. Direct Coincidence

When two or more events are spatially coincident (within a few microns) of each other on the detector within a frame period of the CCD then this is defined here as a direct coincidence.

Two cases exist:

1. The events are simultaneous in time as well as in space. Here charge depletion (C1) will limit the energy of the combined output signal. Hence when two events are present coincidence cannot be recognised.

2. The two events are not coincident in time. Here the second event will arrive whilst the phosphor is decaying from the first event (C4). The CCD will then integrate, within the period of a single CCD frame, the flux emitted by both events. However there are two variables associated: (a) the arrival time of the first event within a CCD frame (the later the arrival time the less light is integrated), and (b) the time between the two events (the later the second event arrives the lower the flux that is integrated on it). The effect of this is to cause a broadening of the pulse energy distribution (C3) but no defined threshold being available for discriminating between two events.

B. Unresolved Coincidence

As referred to in C2, the size of a CCD pixel is approximately equal to the FWHM of the scintillation. If two events occur within two adjacent pixels then this causes a broadening of the profile output from the CCD as shown in Fig. 8.15

![Figure 8.15. Unresolved coincidence between two events.](image)

Here, because the second event only overlaps the first event in the tail of the event profile (C1) where the MCPs can be considered as operating in a non-saturated regime, it can be considered that significant increase in the combined pulse energy is obtained. In the ideal situation this produces a new event energy curve as shown in Fig. 8.16.
By defining a suitable threshold a discrimination between single and coincident events can be made based upon event energy. Obviously a certain number of single events will be counted as double and vice versa, but by choosing the correct threshold these statistical effects can be overcome. This facility is not currently implemented in the BigMIC and MIC systems and hence this type of coincidence results in a loss.

C. Resolved Coincidence

If the two events overlap but are more than a FWHM apart then the output of the CCD will be similar to that shown in Fig. 8.17.

In this case, when comparing against the conditions for event validation (Section 5.4), no problem exists and the two events will be detected.

To understand the effect of the different types of coincidence on coincidence loss, three different size features within an image are considered. These are tabulated in Table 8.2.

<table>
<thead>
<tr>
<th>Feature size (CCD Pixels)</th>
<th>&lt;1</th>
<th>1 to 2</th>
<th>&gt;2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of coincidences</td>
<td>A</td>
<td>A and B</td>
<td>A, B and C</td>
</tr>
</tbody>
</table>

Table 8.2. Coincidence type as a function of feature size.
The important point to note is that point sources will have a different coincidence loss curve when compared against extended sources. The level of coincidence per CCD frame will be lower leading to a higher bright limit per pixel.

8.3.2.2 Dynamic Range curve

From probability theory, the loss per frame which arises from type A and B coincidences with a flat field illumination is approximately governed by the equation:

\[
\frac{D}{I} \approx 1 - \frac{1}{2} \left[ 1 - \left( \frac{N - t}{N} \right)^{I-1} \right]
\] (8.1)

where \( N \) is the number of pixels in the detector. The event territory, \( t \), is the coincidence loss area in pixels associated with each event. \( I \) is the number of captured events per frame within the active area of the CCD and \( D \) is the number of accumulated events per frame.

For point sources where all coincidences are of type A, \( N \) in Equation 8.1 becomes the frame rate, \( t \) approximates to 1, and \( I \) and \( D \) are the number of incident and detected events per second respectively.

Many experiments have been carried out at UCL on the dynamic range of the MIC detectors for both XMM and ground-based applications. The result of a sample experiment using a flat field illumination is shown in Fig. 8.19 where a detector format of 384x288 CCD pixels (no windowing) was employed. The event size was ~1 CCD pixel FWHM. The data was acquired by using a constant illumination \( \beta \) light source, varying calibrated neutral density filters, and recording the number of events accumulated through the MIC system.

![Figure 8.19](image_url)

**Figure 8.19.** Measurement of dynamic range for the MIC2 detector. The solid line corresponds to Equation 8.1 with \( N=256 \times 256 \) pixels and \( t=12 \). The dotted line represents perfect linearity. Raw data from C. Moorhead, private communication.
The best fit to Equation 8.1 is overlaid on Fig. 8.19. This is related to the coincidence area $t$ being equal to a value of 12. By inspection of the criteria that control validation of an event (Section 5.4) within the DAA, it can readily be seen that if any two events occur within the DAA then a type A or B coincidence will occur giving, also, a value of 9 for $t$. Thus theoretical application of Equation 1 matches the expected loss from the practical implementation of the event validate circuit.

Of importance to note is that the dynamic range curve for the MIC detector is not linear at any input flux rate. On faint sources, where the probability of coincidence is very low, the statistics on acquired data will be dominated by shot noise and hence a very close approximation to linearity occurs. To define a bright limit with all photon counting detectors a value of 10% coincidence loss is standardly used.

### 8.3.2.3 Factors governing the Bright Limit

From Equation 8.1 it can be seen that the bright limit to the detector is primarily governed by:

- the size of an event which then affects $t$
- the CCD camera’s frame rate. The faster the frame rate the lower the value of $I$ for any given illumination level.
- the size of features within an image which affects the form of Equation 8.1.

**The event size as captured by the CCD**

The event size is set in the intensifier design to project to ~1 CCD pixel FWHM at the CCD. This then allows accurate centroiding.

Obviously, the larger the event width the greater the probability of coincidence. To evaluate the effect of event width on dynamic range of the MIC detectors a computer simulation, using the FFS programme and data bases of real and synthetic events, was carried out. Different event rates were simulated and the number of events that went undetected because of coincidence was then registered. The results are shown in Fig. 8.14.
Frame rate for the MIC Detectors

The frame rate should be as fast as possible to minimise the probability of coincidences. From the description of the CCD camera operation (Section 4.4.3) it can be found that the frame period of the CCD cameras is governed by the formula:

$$\tau_F = V\tau_V + (s - C)\tau_V + (C + r)(\tau_V + H\tau_H)$$  \hspace{1cm} (8.2)

where $V$ is the number of rows in the storage area, $H$ is the number of pixels in each CCD line (including blank and dark reference pixels), $C$ is the number of rows that are read before the window in order to extract the charge of the pre-window rows, $s$ is the starting row of the window, and $r$ is the number of rows in the window.

The first term of the equation is the time it takes to transfer the image to the storage area, the second term is the time to shift image $C$ rows before the starting row of the window and the third term is the time to read out the $C$ rows and the window.

Fig. 8.18 shows the relationship between frame rate and window size.
Figure 8.18. Frame period versus window size curves for the BigMIC, MIC2 and MIC1 systems. The window was assumed to be in the centre of the frame. There will be slight variations when the window is placed in different regions of the frame.

Type of image

If spectroscopy is taken as an example application area, just about all combinations of image type can be present. Narrow emission lines, giving rise to type A coincidences, broad emission lines, where type B coincidences will dominate, and narrow emission lines on a high continuum background, where types A and B could have equal importance, are examples.

Thus for scientific quantification of data, due allowance must be made for variations in coincidence loss across an image. Ideally, to minimise this effect, the maximum count rate should be limited so that shot noise dominates.

8.3.3 Limiting Dynamic Range mechanisms

If it is assumed that the frame rate does not provide a limitation to the bright limit of the dynamic range, then two underlying factors will dominate:

Pore Paralysis in the MCPs

Charge is extracted from the MCP pores during amplification of an event. It then takes time for the associated pores to recover, this being dependent upon the resistivity of the plates. If a second event occurs spatially coincident with the event causing charge depletion within the recovery time then it will produce a lower gain output, which could be below the detection threshold. From tests carried out by ICSTM (T. Norton, private communication), with the MIC intensifiers it takes ~0.3 ms for pores to recover to 90% of full charge. If, as an example, the threshold in the pulse height distribution (Section 6.6) is placed at 30 ADUs, a 10% reduction in gain associated with a coincident event will lead to a 3 ADU drop in height. As the threshold is placed in the valley of the PHD, this loss will lead to a relatively small change in acquired counts
when operating with frame rates of >1 ms. However, at very fast frame rates or when using anode readout detectors (Section 9.3) this will provide an ultimate limit.

**Phosphor Decay**

The current MIC intensifiers use a P20 phosphor on the output. When operated in a pulsed mode, Bellis (1992) has found that there are 3 long term decay components associated with this phosphor. These could lead to enough charge being accumulated in the CCD frame following event arrival to cause the 'decay' event to be above the defined photon counting threshold leading to double counting and a false compensation for loss due to coincidences. From experiments carried out at UCL, it has been found that the dead period of the detector when transferring from the Image to Storage zones of the CCD, is long enough to prevent this mechanism occurring. However, if this dead period was shortened significantly, associated with higher CCD frame rates, then a problem could then exist. In this situation a faster phosphor such as P46 or P47 would need to be employed.

**8.3.4 Current Bright Limit**

Using Equation 8.1, and assuming maximum window sizes, it is expected that a 10% coincidence loss on a flat field will be reached at ~0.54 events/CCD pixels/s for the BigMIC and ~2.06 events/CCD pixel/s for MIC1 and MIC2.

For point source images a 10% loss is expected at 5.7 events/object/s for the BigMIC and 19.5 events/object/s for MIC1 and 2.

**8.4 Detective Quantum Efficiency**

The Detective Quantum Efficiency (DQE) of the MIC detectors is determined by three main components:

1) The responsive quantum efficiency of the photocathode ($RQE_p$) which includes the transmission characteristics of the window on which it is deposited.
2) The open area ratio of MCP1 ($OAR_1$) as explained in Section 2.4.
3) The counting efficiency ($CE$) of the CCD camera and processing electronics.

When these factor are taken into account the DQE can be expressed as:

$$DQE = RQE_p \times OAR_1 \times CE$$

(8.3)

The CE is defined as the fraction of time in which the CCD camera can detect events. From the terms defined in Equation 8.2 the counting efficiency can be calculated as:

$$CE = (\tau_f - V \tau_v) / \tau_v$$

(8.4)

In this case the CE is going to be very dependent on the window size used for integration. Fig. 8.20 shows how the CE depends on window size.
An experiment to measure the DQE of the XMM MIC was carried out by MSSL. The set-up for this experiment consisted of an illumination source provided by a Deuterium lamp and a monochromator. These were placed in vacuum together with the MIC detector, a calibrated photomultiplier tube used as a reference, and a mirror that switched the light beam between the detectors. The intensifier (DEP serial number E218303) had a S20 photocathode and MCPs with 10 \( \mu \text{m} \) pore diameter and 12 \( \mu \text{m} \) centre to centre spacing (OAR = 0.63). The MIC1 camera was used with a window size of 200 CCD lines.

From Fig. 8.20 it can be seen that the counting efficiency of the MIC1 system for this window size is -0.96.

From Equation 8.3 the DQE and RQE are expected to have the following relationship:

\[
\text{DQE} = \text{RQE} \times 0.63 \times 0.96 = 0.6048 \text{RQE}. \tag{8.5}
\]

Figure 8.21 shows the RQE of the photocathode and the DQE of the intensifier-MIC1 combination. It can be seen that both curves have a similar shape. By analysing the data it is found that: \( \text{DQE} = (0.59 \pm 0.1)\text{RQE} \), which matches well with the prediction.
CHAPTER 9
Alternative Photon Counting Detectors

In this chapter a description of alternative photon counting detector technologies is given and a performance comparison made.

There are basically three types of photon counting detector; ones that employ cameras for capture of the intensifier output and then use centroiding (MIC type), those that provide a 'DIRECT' sensing of the intensifier output, such as the MAMA, SPAN and Delay Line, and the EBCCD. A general comparison between these technology types follows.

9.1 Analogue Photon Counting Systems

With analogue readout systems the division of charge cloud by a resistive sheet or pattern of conductors provides analogue information from which the centroid of the cloud can be located. These systems require relatively simple processing electronics.

9.1.1 Quadrant Anode

This was one of the first imaging photon counting systems to be developed (Lampton and Malina 1976). It consists of four electron-collecting electrodes located behind the output face of an MCP intensifier. The electrodes are insulated from each other and connected to the input of their respective low-noise charge-sensitive amplifiers. The electron cloud from each detected event is partly intercepted by each of the quadrants and the position of the charge pulse is determined by the relative amounts of charge collected by each. The opposing amplifiers drive analogue-input circuits which provide output voltages proportional to the centroid. In the X direction the centroid position is given by:

\[ x = \frac{V_2}{V_2 + V_4} \]

(9.1)

while in the Y direction is given by:

\[ y = \frac{V_1}{V_1 + V_3} \]

(9.2)

where \( V_1 \) to \( V_4 \) are the amplifiers' output signals (Fig. 9.1). The centroid positions may be displayed on an oscilloscope or stored digitally by encoding the \( x \) and \( y \) signals and accumulating the image in random access computer memory. This extremely simple system has the disadvantage of a very limited active area (determined by the diameter of the charge pulse arriving at the electrode structure) and image distortions which increase rapidly off-axis. Its resolution is limited by the channel spacing of the MCP and to a lesser degree by the partition...
shot noise in the dissection of the electron cloud, the amplifier charge noise, and amplitude dependent division errors in the ratio circuitry.

\[ V, \quad Y = \frac{V_1}{V_1 + V_3} \]

\[ X = \frac{V_2}{V_2 + V_4} \]

**Figure 9.1.** Schematic of the quadrant anode readout system (from Timothy 1985).

### 9.1.2 Resistive Anode

The charge from an MCP intensifier is collected on a resistive sheet with four electrodes at its corners. This continuous anode acts as an RC transmission line and the location of an impinging charge cloud can be determined either from the difference in arrival times to opposing collection electrodes or from analysing the fraction of charge arriving at each electrode (Crocker et al 1986).

The time difference technique imposes conflicting requirements for high-count rate applications. Choosing the characteristics of the anode to yield relatively long delay times minimises the requirements of the electronic timing resolution required to achieve a specified spatial resolution, but necessarily increases the dead time and upper count-rate limit of the system. Because of the high electronic timing resolution required to achieve good spatial resolution the charge division technique is used for high count-rate applications.

A good description of the charge division technique can be found in Downie et al. 1993. The signals from the four corner electrodes are fed to pulse-shaping pre-amplifiers which provide signals whose peak values are proportional to the charge collected. These peak values are digitised by fast (flash) analogue-to-digital (A/D) converters so that, eventually, four numbers \((Q_a, Q_b, Q_c, Q_d)\) proportional to the charge collected by each of the four electrodes are sent to a computer (Fig. 9.2).

The computer calculates the centroid of each event as:

\[ x = \frac{Q_a + Q_b - Q_c - Q_d}{Q_a + Q_b + Q_c + Q_d} \]

(9.3)
\[
y = \frac{Q - Q_a - Q_b + Q_c}{Q_a + Q_b + Q_c + Q_d}.
\] (9.4)

Eventually each event is accumulated in a memory by incrementing an address which corresponds to each \(x\) and \(y\) position.

![Schematic diagram showing the resistive anode detector and pulse-sampling position encoding system (from Downie et al. 1993).](image)

**Figure 9.2.** Schematic diagram showing the resistive anode detector and pulse-sampling position encoding system (from Downie et al. 1993).

The resolution of this kind of system is limited by shot noise in the anode. In order to compensate for this, intense signals are required and it is not uncommon to use intensifiers that provide gains of \(\sim 10^6\) e/e'.

The maximum detected count rate is limited by the recovery time of the pores in the MCPs and by the electronic processing time. Analogue methods have been used to perform the necessary arithmetic to compute the co-ordinates of the event location. Although these methods are less accurate they do not suffer the drawback of lower speed (and thus increased dead time) if carried out with a microprocessor, or inflexibility if the arithmetic is implemented in digital hardware.

Apart from the centroiding electronics it is also possible to define a lower threshold to reject small noise pulses and an upper threshold to reject coincident events detected as a single large event. There must also be a certain degree of spatial oversampling to preserve information on the statistical distribution of the event on the resistive anode and allow the detection of lines and features in the image which would be lost if the image were not well oversampled.

**9.1.3 Wedge and Strip Anode Array**
The wedge and strip anode array (Siegmund et al. 1988, Siegmund et al. 1986, Lampton et al. 1986, Schwarz and Lapington 1985) operates by the division of incident charge between several electrodes. It consists of three electrodes (wedge, strip and zigzag conductors) that share the anode plane. The wedge pattern provides a charge capture that varies linearly with position in the Y direction while the interleaved strips have widths that increase linearly with X (Fig. 9.3).

Since three electrodes share the total charge from each photoevent, x and y may be simultaneously determined for each photon by the ratios of the pulse heights. Each of the three electrodes is connected to a low noise charge sensitive amplifier whose output is passed though a bipolar shaping circuit. The amplitude of the signals is then sampled by performing a peak and hold operation, and the resultant dc levels are converted to digital signals ($Q_w$, $Q_s$ and $Q_z$) which are then used to calculate the events’ positions in software. Provided that the incident charge cloud is larger than the repetition period of the anode the centroid position is given by:

$$x = \frac{Q_w}{Q_w + Q_s + Q_z}, \quad (9.5)$$

$$y = \frac{Q_s}{Q_w + Q_s + Q_z}. \quad (9.6)$$

The spatial resolution of this detector is limited by the charge partition noise and the charge amplifier’s noise. Since the charge amplifier’s noise contribution is sensitive to the anode’s capacitance, spatial resolution is determined by the size of the anode array, unless the MCP gain is increased or a mosaic of anodes are used to compensate. A relatively large gap between the rear MCP and the anode is required (~15 mm) so that the charge cloud can spread out enough to cover several elements at the anode. This large gap can make the detector susceptible to electromagnetic fields affecting geometric and spatial linearity.
9.1.4 Spiral Anode

The spiral anode (SPAN) is an enhanced derivative of the wedge and strip anode array. It consists of a planar structure of six electrically isolated electrodes. The ratio of the charges collected by the electrodes determines a two-dimensional position. Although this design has double the number of electrodes (three electrodes per axis) of the wedge and strip anode array, it has a marked spatial resolution advantage since the spatial resolution is an order of magnitude higher than the charge measurement accuracy (Lapington et al. 1991). For each direction, the three electrodes have a form whereby their amplitudes and wavelengths decrease in a sinusoidal fashion so that each position on that axis has a unique electrode fractional area ratio (Fig. 9.4a). The locus of the co-ordinate representing the variation in the electrode fractional areas along the axis describes a curve in space which lies on a plane (Fig. 9.4b), because the sum of the electrode fractional areas is equal to the width or pitch which is constant. This curve is an Archimedean spiral \( r = k \theta \) which gradually spirals in towards the centre with decreasing amplitude and wavelength. The form of the spiral is further constrained by keeping the rate of change of arclength with respect to position \( (\delta s/\delta x) \) constant along the length of the spiral so that the resolution will not vary along the axis. For two-dimensional implementation the pitches are interleaved and angled at 45° to each other. In deciding the parameters governing the pattern (pitchwidth, amplitude, wavelength and its rate of change) the size and shape of the charge cloud must be taken into consideration. The wavelength must be long enough and the pitch small enough that the circular charge cloud will encode its position with the correct fractional areas defined by the measured charge values.

Figure 9.4. The SPAN detector. a) Schematic of the implementation of a two-dimensional spiral anode. The shaded pitches encode the y-axis and the others the x-axis. The box beneath represents one pitch of the spiral anode demonstrating the unique fractional area ratio of the electrodes (A, B and C) at each position along the axis. b) Variation of the electrodes along the pattern axis plotted in the 3-D volume defined by the fractional electrode areas. The arc length, along the spiral, gives the position along the axis. From Lapington et al. 1991.
These anodes are made from 60 mm diameter, 2 mm thick quartz blanks which are coated with a very thin layer of chrome (for adhesion) followed by 2-3 μm layer of aluminium. A laser and an X-Y co-ordinate table (with accuracy of 1 μm) are used to remove narrow (10-20 μm) lines of aluminium to form the insulating gaps between the electrodes, the final pitch (6 electrodes) being about 680 μm. Each electrode has its own electronics consisting of a charge sensitive preamplifier, a shaping amplifier and an analogue to digital converter. The charge collected on each electrode is measured and then read into a computer for image decoding and processing.

9.1.5 Delay Line Anode

This is based on the use of a distributed RC delay line. In one dimension the event position centroid is encoded through the determination of the difference in arrival times of the event signal at the two ends of the delay line, without the need of any special algorithms.

For two-dimensional implementation it is composed of an orthogonal pair of flattened helical delay lines, wound one inside the other on a square frame. Each delay line consists of two windings of very thin (200 μm diameter) bare copper wire with 1 mm pitch. One winding is wound midway between the turns of the other to form a two-wire transmission line. The dc levels of the windings are adjusted so that only one winding of each delay line collects charge (Williams and Sobottka 1989).

A more recent approach is described by Friedman et al. (1996). The multi-layer serpentine delay line (SDL) consists of two crossed (one stacked above the other) independent SDLs as depicted in Fig. 9.5. Each SDL being a microstrip transmission line consisting of a printed circuit board of bare copper on a dielectric substrate with a copper ground plane on the reverse side. This microscopic three-dimensional architecture, with a pitch of ~400 μm, is possible thanks to new developments in laser ablation machining. The use of a solid substrate provides much greater mechanical robustness, necessary for space applications where position accuracy must be maintained after the launch vibrations and the routine thermal cycling over the lifetime of an instrument.

The main advantage of this position encoding technique is that in contrast to charge partition methods, as in the resistive anode, increasing the format size does not degrade spatial resolution and may even improve it.
9.2 Digital Encoding Photon Counting Systems

These systems rely on the incidence of the electron charge cloud on two or many orthogonal conductors. Large numbers of charge amplifiers are needed to detect the incident charge event with the use of encoding schemes. As formats become larger and larger this requires hundreds of amplifiers (128 for 1000×1000). This leads to increasingly complex electronics with associated reliability, power consumption and weight problems, particularly for space applications. Apart from this anode fabrication has proved to be difficult and expensive.

9.2.1 Multi-Anode Microchannel Plate Array

In the multi-anode microchannel plate array (MAMA), two sets of interleaved anodes coupled in groups to each amplifier are used to uniquely identify the position of the charge cloud in one dimension, two orthogonal arrays are used for two dimensions as shown in Fig. 9.6b.

A single high gain curved-channel MCP with the photocathode material deposited on, or mounted in proximity focus with, the front surface is used (Fig. 9.6a). The electrodes are mounted in proximity focus with the output surface of the MCP to detect and measure the position of the electron cloud generated by single photon events. The charge collected by the anode electrodes is amplified and shaped by high-speed amplifier and discriminator circuits. Digital circuits respond to the simultaneous arrival of the shaped signals from several of these
electrodes in each axis, the electrodes being arranged in groups to uniquely identify a×b pixels in one dimension with only a+b amplifiers. A square two-dimensional array of (a×b)² pixels being implemented with 2(a+b) amplifier and discriminator circuits.

![Diagram](image)

**Figure 9.6.** The MAMA detector. a) Schematic diagram showing details of curved-channel MCP and the imaging multi-layer anode array b) Simplified layout of one level (for one of the two directions) of the anode array. The spots represent the size of charge clouds from the MCP. From Morgan et al. 1989.

The MAMA is capable of detecting simultaneous events and of operating at high count rates which are normally limited only by the recovery time of the MCPs. For this reason it is usual to use high conductivity MCPs in order to increase the maximum count rate limit. These are also less sensitive to MCP gain reduction at high count rates.

The spatial and geometric linearity are determined by the individual pixels and, therefore, excellent. The large number of components places a limit in the number of detector elements that can conveniently be used and there are some problems with cross-talk due to inter-channel capacitance.

The MAMA is used in a number of different applications, e.g. direct imaging, speckle imaging, spectroscopy, and photon time-tagging. (Horch et al. 1992, Timothy 1992, Morgan et al. 1989, Timothy 1986, and Timothy 1985).

### 9.2.2 Coded Anode Converter

The coded anode converter (CODACON) is described by McClintock et al. (1982). The output of a curved MCP is proximity focused onto a coded array anode. Charge collected on a pixel electrode is capacitively coupled onto output electrodes arranged in a gray code pattern. Simultaneous detection of coincident pulses on the coded anodes defines a bit pattern which identifies the spatial location of the detected charge cloud in one dimension (Fig. 9.7). Two orthogonal arrays are utilised for a two dimensional imaging CODACON.
The coded plate has three layers: the top layer consists of 1024 charge spreaders (13 mm long and 15 μm wide) with a centre-to-centre spacing of 25.4 μm, the middle layer is a dielectric material 10 μm thick, and the bottom layer consists of ten pairs of binary coded tracks and a discriminator track used to determine which of the 1024 charge spreaders was struck by any pulse leaving the MCP. The spreaders run perpendicular to the code tracks, and pass above all the pairs of tracks. Each code track consists of alternate wide and narrow metal strips. These strips form capacitors with the charge spreaders and the total charge induced is proportional to the width of the metalisation directly below the charge spreader.

Figure 9.7. The CODACON. a) Schematic of the detector. UV photons incident on the front surface of the MCP result in a burst of $10^6$ e$^-$ exiting from the back surface. The position in one dimension of the pulse is determined by a coded anode array. A 10-bit address is produced for each electron pulse corresponding to which one of 1024 charge spreader wires was struck by the pulse. b) Example of an 8-channel CODACON. A charge pulse on a charge spreader causes charge to be induced in the code tracks. Differential amplifiers connected to each bit track pair determine which side of a pair has the most charge based on how wide the code track is directly below the charge spreader. From McClintock et al. 1982.

A differential amplifier is used to determine which side of a code track pair has the larger induced charge (the thicker one). To keep the charge spreaders from accumulating charge as they are struck by successive pulses of electrons it is necessary to provide a leakage path to ground, this is done by using a dielectric material with a resistance sufficiently low to allow charge to leak away between pulses.

9.3 Hybrid Electronic readout Detector System

9.3.1 The Photicon

The Photicon (also known as the high-resolution imager- HRI) is a hybrid system that uses two orthogonal arrays of discrete wires linked by resistors with every eighth wire connected to an amplifier (Fig. 9.8). It employs interpolation algorithms to determine the exact location of the detected charge cloud to a precision of a fraction of the wire spacing (Kellogg et al. 1977, and Kellogg et al. 1976).
9.4 Silicon Detector Photon Counting Systems

9.4.1 Intensified CCD Detectors

Apart from the MIC and BigMIC detectors developed at UCL other intensified CCD detectors have been described by Nakajima et al. (1993), Read et al. (1992), Carter et al. (1991), and Roberts et al. 1986.

9.4.2 Electron-Bombarded CCD

In the case of the electron-bombarded CCD (EBCCD) photoelectrons generated in a photocathode are accelerated, with a potential of the order of 15 kV, to impact on a thinned back-side illuminated CCD. A diode array detector was used in the previous designs but it has been replaced by a CCD because the second offers the advantages of self-scanning and lower readout noise allowing operation at lower accelerating voltages.

When one electron of several keV impinges on silicon, it creates electron-hole pairs through a semiconductor cascading process which has two major characteristics: firstly the average gain $G$ in this process is related to the energy $E$ (in eV) of the incident electron by the relationship $G = E/3.66$. This provides a gain of several thousands compared to the detection of a single photon by the CCD. Secondly, the multiplication process exhibits low fluctuations, the variance being $\sigma^2 = 0.12G$.

However, this ideal performance can only be obtained if: i) the incident energy is actually dissipated in the active material, ii) no incident electrons are lost, iii) the signals produced in the CCD substrate are properly collected, and iv) the electron bombardment does not disturb the CCD behaviour (Richard and Vittot 1992). This is why thinned back-side illuminated CCDs are required, their use has the added advantage that 100% of the surface is sensitive to incident electrons.

These detectors have excellent performance characteristics, especially in the open-structure EBCCD (Fig. 9.9), utilised in space applications where an opaque oblique-focus photo-cathode is

---

**Figure 9.8.** The Photicon’s processing electronics (from Kellogg et al. 1976).
used with quantum efficiencies of ~70% being reported (Delamere et al. 1992). The only drawback is that the magnetic focusing system is bulky and complex which can be an inconvenience, especially for space applications.

There are other designs for the EBCCD in which electrostatic, rather than magnetic focusing is used (Opal 1986). The resulting tube is lighter, more compact and the CCD is easier to shield from direct illumination (which must reach the CCD via a tiny aperture in the anode) as shown in Fig. 9.10. The disadvantage of these tubes (electrostatic focusing) is that they suffer from greater geometric distortions than the magnetically focused ones.

![Figure 9.9](image1)

**Figure 9.9.** The Interstellar Medium Absorption Spectrograph’s intensified CCD (from Delamere et al. 1992).

![Figure 9.10](image2)

**Figure 9.10.** Internal structure of the C81020E electron-bombardeed CCD image tube (from Opal 1986).

The fact that thousands of electrons produced diffuse into a few neighbouring pixels can be used as an advantage by centroiding the charge pulse, thus increasing the resolution of the system (Hier et al. 1984).

In general these systems are stable in geometry and sensitivity, have good electronic linearity and dynamic range, and are immune to signal induced effects such as ‘lag’ and ‘afterglow’. Their lifetime is at least that of MCPs (~4000 hours at 10^7 lux on photocathode).
There are still some problems associated with the survival of the CCD because of the high temperatures required to condition the detector tube prior to photocathode deposition. Other factors that must be considered are the amount of damage to the device caused by the energetic primaries, the potential degradation due to charge build-up in the back surface, and damage to the front side electrodes by brehmsstrahlung X-rays.

9.4.3. Imaging Silicon Pixel Array

The imaging silicon pixel array (ISPA) consists of a photocathode evaporated onto an optical fibre window, viewed at a 30 mm distance by a hybrid circuit that consists of a silicon pixel diode array bonded with solder bumps to a chip with matching readout elements (D’Ambrosio et al. 1995, Gys et al. 1995, and Anghinolfi et al. 1992). The diode array contains 64×16 pixels with 75μm × 500 μm edges. The signal processing functions are contained in each cell of the readout chip and consist of a charge amplifier and comparator (threshold) followed by an adjustable digital delay element, a strobe multiplexer and a flip flop (memory element), thus providing a binary response to the photoelectrons (Fig. 9.11).

![Figure 9.11. The ISPA detector.](image)

The event information in a pixel can be strobed into a local memory by trigger signals and subsequently read out. 16 pixels are read in a parallel mode at a frequency of 10 MHz resulting in readout times of 6.4 μs. The binary data from the rows is sequentially clocked out, as 16-bit words, via parallel shift registers into an external FIFO memory.
9.5 Photomultiplier Base Photon Counting System

9.5.1 Precision Analogue Photon Address Camera

The precision analogue photon address (PAPA) camera consists of a series of lenses, masks and photomultiplier tubes which create multiple copies of the output phosphor of an MCP intensifier (Fig. 9.12). The electrical signals created by the photomultipliers are interpreted to yield a detected photon position. A total of \(m+n+1\) masks and photomultipliers are needed to define a field of \(2^n \times 2^n\) pixels (Lawson 1994a, Lawson 1994b, and Sams 1991).

![Figure 9.12. The PAPA detector. a) Layout of the optical components. Incident photons generate bright spots at the output of the image intensifier, which are re-imaged onto an array of masks that optically encode their co-ordinates. The output beam of the large collimating lens is subdivided into many smaller beams by an array of small lenses, each of which reforms an image of the spot onto a mask. Each mask is followed by a small field lens and a photomultiplier tube. There is a strobe channel that has no mask which is used to detect the presence and amplitude of an event. The output of this strobe channel is compared to a constant threshold in order to decide if the event is a photon detection or noise. b) Representation of the first four gray code encoding masks used for defining the events’ position. From Lawson 1994.

The masks are striped by equal width bands of clear and opaque material having 2,4,8,...,256 bands arranged in Gray code. In practice, a set of 9+9+1 photomultiplier tubes are mounted behind coded masks to provide the spatial information for a format of 512x512 pixels. The event’s co-ordinates are found by observing all masks simultaneously. The detector’s output is a time ordered stream of digital binary codes indicating each detected photon’s position in the image field.

This detector is primarily used in astronomical speckle imaging (an interferometric technique which compensates for the image degradation caused by astronomical turbulence).

Artefacts unique to this kind of detector are caused by optical misalignment, incorrect thresholding in the electronics and light level problems with the image intensifier. Particularly
serious is vignetting of the lenses which causes a field dependent error that makes it impossible to
flat field the images.

9.6 Detector Comparison

9.6.1 Performance

Of the detectors described the MIC, MAMA and Delay Line technologies are mature and the
EBCCD and Span detectors under development. The remaining detectors have largely been
superseded and are included for completeness. Table 9.1 provides a comparison between the
different technologies. There may be large inaccuracies in the figures quoted in this table as the
data, in some cases, was obtained from papers associated with development programmes for
which anticipated performance figures are given. This makes a direct performance comparison
difficult and, hence, is put in terms of generalities.

Quantum Efficiency

The DQE of the DIRECT and MIC detector types should, in principle, be identical being
limited by the photocathode and OAR of the first MCP. The EBCCD, which does not employ
MCPs and hence overcomes the OAR limitation, potentially has a ~37% higher DQE.

Spatial Resolution

Different approaches with all detectors are taken for maximising resolution. For the MIC
detectors a centroiding algorithm is employed and the accuracy is primarily limited by artefacts of
the intensifier. The EBCCD, where the CCD senses single electrons, the resolution is limited by
the CCD format, no centroiding being employed. Although the EBCCD has the potential for
highest resolution, not needing to overcome the sampling limitation of MCPs, to achieve this
small pixel size and large CCD formats are required. The DIRECT detectors have an additional
noise associated which is governed by the partitioning of the charge cloud that is being sensed.
This is why, in general, the spatial resolution of DIRECT detectors is lower.

Dynamic Range - Point sources

For the MIC detector, localised coincidence losses provide a limitation. The EBCCD, which
can sense coincident events through the flux in each CCD pixel, and DIRECT camera do not
have this limitation. For the DIRECT camera, it is pore paralysis in the MCPs that is the
governing factor. Thus, if it is assumed that it takes 0.3 ms to recover to a 90% level, it could be
expected that DIRECT cameras have a factor ~10 higher bright limit. The limit with the EBCCD
will in principle be still higher, this being governed by the number of secondary electrons
produced by each event, the saturation level of a CCD pixel and the CCD frame rate.

Dynamic Range - Global illumination

The global dynamic range on the MIC detector is again limited by coincidence losses that are
frame rate dependent. However, the coincidence losses are localised. With DIRECT cameras, if
<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>Format (pixels)</th>
<th>Pixel Dimensions (μm²)</th>
<th>Active Area (mm²)</th>
<th>Number of Amplifiers</th>
<th>Point Spread Function (μm)</th>
<th>Temporal Resolution (μs)</th>
<th>Active Pixels / Temporal Resolution (x10⁶ s⁻¹)</th>
<th>Local Dynamic Range (c/p/s)</th>
<th>Global Dynamic Range (x10⁶ c/s)</th>
<th>MCP Gain (x10⁶ c/e⁻)</th>
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<tr>
<td>Analogue</td>
<td>Quadrant Anode</td>
<td>100x100</td>
<td>15x15</td>
<td>1.5x1.5</td>
<td>4</td>
<td>~30</td>
<td>1</td>
<td>1</td>
<td>~40</td>
<td>~0.5</td>
<td>2</td>
</tr>
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<td>Resistive Anode</td>
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<td>21.5x21.5</td>
<td>22x22</td>
<td>4</td>
<td>62</td>
<td>2</td>
<td>0.5</td>
<td>~10</td>
<td>0.5</td>
<td>100</td>
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<td>28x28</td>
<td>3</td>
<td>70</td>
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<td>0.1</td>
<td>~20</td>
<td>0.05</td>
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<td>16x16</td>
<td>32x32</td>
<td>6</td>
<td>24</td>
<td>33</td>
<td>0.03</td>
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<td>35</td>
<td>10</td>
<td>0.1</td>
<td>~20</td>
<td>0.1</td>
<td>20</td>
</tr>
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<td>MAMA</td>
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<td>25x25</td>
<td>51.2x51.2</td>
<td>529</td>
<td>~50</td>
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<td>~100</td>
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<td></td>
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<td>14x14</td>
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<td>91</td>
<td>~28</td>
<td>0.4</td>
<td>2.5</td>
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<td>38x38</td>
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<td>17</td>
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<td>13x26</td>
<td>11</td>
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<td>10x10</td>
<td>26x26</td>
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<td>~20</td>
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<td>0.01</td>
<td>~40</td>
<td>0.1</td>
<td>10</td>
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<td>10x10</td>
<td>61x46</td>
<td>~5</td>
<td>21</td>
<td>46000</td>
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<td>5.7</td>
<td>0.24</td>
<td>10</td>
</tr>
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<td></td>
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<td>31x0.32</td>
<td>~5</td>
<td>21</td>
<td>40000</td>
<td>630.8</td>
<td>56.3</td>
<td>19.5</td>
<td>0.23</td>
</tr>
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<td></td>
<td>EBCCD</td>
<td>288x604</td>
<td>15.6x10</td>
<td>4.5x6</td>
<td>~5</td>
<td>~30x20</td>
<td>20000</td>
<td>8.7</td>
<td>45</td>
<td>1.5</td>
<td>no MCPs</td>
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<td></td>
<td>ISPA</td>
<td>16x64</td>
<td>8x4.8</td>
<td>~2</td>
<td>~1000x150</td>
<td>6.4</td>
<td>160</td>
<td>45</td>
<td>~0.16</td>
<td>no MCPs</td>
<td>1</td>
</tr>
<tr>
<td>PMT</td>
<td>PAPA</td>
<td>256x256</td>
<td>78x78</td>
<td>20x20</td>
<td>64</td>
<td>~156</td>
<td>0.9</td>
<td>1.1</td>
<td>~40</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 9.1. Characteristics of photon counting systems.
two or more events occur over the whole detector field during the time period associated with processing a single event (typically 1 to 2 μs), then either a coincidence loss occurs (if a coincidence energy threshold is employed) or the combined data is centroided to a position between the events - i.e. completely misplaced. If, for example, two bright features are present in an image then a ghost image between the two features occurs in acquired data. The processing time in the DIRECT detectors is hence equivalent to the frame time with the MIC detectors but is limited by global coincidences. This results in the maximum global illumination level being, typically, lower with the DIRECT detectors. The EBCCD does not suffer from a global coincidence problem and each CCD pixel will be governed by the point source dynamic range limitation.

**Detector Size**

The maximum detector size with the MIC detectors is limited by the diameter of MCPs that are commercially available (currently around 100 mm diameter). However, as the fibre taper that connects the intensifier to the CCD needs to be limited to ~4:1 maximum reduction ratio due to manufacturing constraints, the CCD size needs to increase with intensifier diameter. This then imposes greater limitations on dynamic range. Although, in principle, the DIRECT detectors, are also limited by MCP size an additional constraint is associated. As anodes are employed as the capture medium in this type of detector, the capacitance and resistivity of the anode increases with increased detector diameter limiting centroiding accuracy. Although development programmes have been carried out on a number of 40 mm diameter DIRECT detectors high resolution has not yet been obtained. The EBCCD is limited in detector size by the size of the CCD and the de-magnification of the Gen. 1 intensifier used. Currently the de-magnification is about a factor of 3.

**Lifetime**

For MCP based detectors the lifetime is dependent upon the electron gain employed. The amplification of events is equivalent to a low level electron scrubbing of the pores, removing impurities and, as is discussed in Chapter 2, lowering gain and generating ions. For the DIRECT detectors, typically an electron gain ~100 times higher than the MIC detector is employed, that then provides a lower lifetime limit. The EBCCD incorporates the CCD in a Gen. 1 intensifier. The CCD itself is a source of outgassing that can then affect the photocathode. However, lifetimes similar to those of MCP intensifiers have been reported.

**9.6.2 Discussion**

Whilst it appears that the EBCCD provides the highest performance in DQE, resolution and dynamic range, key attributes of a detector, there are format size problems associated. In addition, the EBCCD when incorporating a large format CCD is very expensive and component
failure in either the intensifier or CCD will result in the complete detector having to be replaced. These problems are overcome with the MIC detectors using commercially available separate components and has longer lifetime, higher resolution and larger available detector formats when compared against DIRECT detectors. The DIRECT readout detectors have, like the EBCCD, to be specially manufactured. They do have a high local dynamic range but this is counterbalanced by the problems associated with global coincidences. The area to which these are most suited, it is suggested, is where the highest time resolution is required this being limited with both the EBCCD and MIC by the CCD frame rate.
CHAPTER 10
Future Developments

As with all detector systems, the MIC and BigMIC can make use of technological advances for improving their performance. With the BigMIC, the most obvious improvements can be obtained by the development of higher quality image intensifiers, thus allowing the initial objectives of the programme to be achieved. Here, of greatest importance, is the introduction of small pore channel plates in MCPs 2 and 3 as described in Section 8.1.5.

Also of concern is the large number of defects found in the 75 mm MCPs. It is very important to find their source so that it can be avoided.

Looking further into the future, and addressing performance areas separately, there are a number of ways that improvements can be made.

10.1 Resolution

The resolution is basically being limited by the spatial sampling provided by the pore structure of MCP1. The obvious way in which the resolution could be improved will be to use MCPs with smaller centre to centre spacing between their pores. MCP plates with 5 μm pore diameter and 6 μm centre to centre spacing which provide a limiting resolution of ~70 lp/mm have been available for some time (Galileo Electro-Optics 1995). The use of this generation of plates in future intensifiers is strongly recommended, provided their defect levels are low.

A method of overcoming the limiting resolution of MCPs which would need evaluating has been suggested (J. Fordham, private communication). The resolution limitation associated with MCP1 comes from sampling a single photo-electron emitted from the photocathode. This could be overcome by MCP1 adequately sampling a charge cloud from the photocathode. This implies that an initial gain stage must be placed in front of the z-stack (Generation 2) intensifier. By using a Generation 1 intensifier (Section 2.1) that is fibre-optically coupled to the z-stack intensifier as shown in Fig. 10.1 this can be achieved. If, for example, the input stage is operated with a gain of 200 then, allowing for the OAR of the fibre optics and RQE of the Gen. 2 cathode, ~30 photo-electrons will be emitted per event. These will spread (according to Equation 6.1) in the cathode gap and provide adequate sampling by MCP1.

Potential problems that could be encountered with the inclusion of a Gen. 1 intensifier are believed to be primarily associated with relatively high dark noise. This would need to be investigated and, if necessary, cooling with a peltier cooler be employed.
10.2 Quantum Efficiency

There are a number of ways in which the quantum efficiency characteristics of the MIC detectors could be improved:

Photocathode Response Enhancement. The peak RQE of the bialkali photocathode used in the intensifier is, at present, ~30%. Recent work on photocathode formation by molecular beam epitaxy (Dubovoi et al. 1991) shows that it should be possible to produce fully optimised bialkali photocathodes with ~45% RQE. Since the intensifier processing is carried out in an ultra high vacuum chamber it would not be difficult to incorporate this technique. In addition, it may be possible to further increase the sensitivity of the photocathode by field enhanced photoemission.

A programme to obtain high QE photocathodes is currently under way at UCL in collaboration with industry.

Minimising Loss Due to OAR. As explained in Section 8.4 the quantum efficiency of a microchannel plate is closely related to its open area ratio. Several manufacturers now offer funnelled plates in which the channels at the input face of the microchannel plate are selectively etched to provide a large effective open area. This measure has raised the OAR from ~60% to ~80%. Alternatively, the inclusion of a Gen. 1 intensifier as shown in Fig. 9.1 will inherently overcome this problem.

Frame rate. As shown in Figure 8.20 the frame rate of the CCD camera can have a strong influence on counting efficiency especially when the system is used with a small window format. What directly affects this parameter is the time it takes to transfer an image from the imaging to the storage zones of the CCD. This can only be reduced by increasing the speed of the vertical clocks without decreasing the charge transfer efficiency.
Interline Transfer CCD devices are much better in this respect but have the inconvenience of
their sensitive area not being 100% and the QE being much lower because of the area used by the
interline masks. Their application, though, could be explored.

Another alternative could be the use of Charge Modulation Devices (CMDs) which are very
similar to CCDs but with the capability of providing direct access (and clearing) of each of its
pixels. The CMDs currently available are not suitable for intensified photon counting
applications because of the small pixel sizes (<15 μm) but it is expected that advances in this
technology will take place in the near future.

10.3 Dynamic Range

As explained in Section 8.3.1 the lower limit on dynamic range is essentially set by the
thermal noise from the photocathode and the only ways to reduce this are by cooling or utilising
less red sensitive photocathodes.

The bright or upper limit (Section 8.3.2) is set by spatial coincidences which could be
reduced by basically: (a) increasing the frame rate of the CCD camera and processing electronics
and (b) using faster decay phosphors.

There are faster phosphors available, like the P43, P46 and P47, that could be utilised in
place of the P20 used until now. The disadvantage of first ones is that their conversion efficiency
is not as good as the P20’s and higher gains in the intensifier are then needed to compensate for
that. Hopefully higher efficiency phosphors with better matching to the transmission
characteristics of fibre optics and sensitivity of CCD (redder phosphors) will be developed in the
near future.
APPENDIX A
Centroiding Algorithms

Centre of Gravity
The centre of gravity of a set of particles aligned on a straight line (one dimensional case) is given by:

\[ x_0 = \frac{\sum m_i x_i}{\sum m_i}. \] (A1)

where \( m_i \) is the mass of the \( i \)'th particle, \( x_i \) its position and \( x_0 \) the centre of gravity's position.

Applying this concept to the signals accumulated in pixels \( a, b, \) and \( c \) of an event (as represented in Fig. A.1), we find that:

\[ x_0 = \frac{a(-1) + b(0) + c(1)}{a + b + c} = \frac{c - a}{a + b + c}. \] (A2)

![Figure A.1. Fitting a parabola and a gaussian to three points.](image)

Parabola Fitting
General equation of a parabola with its axis parallel to the y-axis:

\[ y = \alpha + \beta (x - x_0)^2 \] (A3)

Fitting this equation through points \((-1,a),(0,b), \) and \((1,c)\) as shown in Fig. A.1:

\[ a = \alpha + \beta (-1 - x_0)^2, \] (A4)

\[ b = \alpha + \beta x_0^2, \] (A5)

\[ c = \alpha + \beta (1 - x_0)^2. \] (A6)
The objective now is to find \( x_0, \alpha, \) and \( \beta. \) Expanding (A4) and using (A5):

\[
a = \alpha + \beta(1 + 2x_0 + x_0^2) = (\alpha + \beta x_0^2) + \beta(1 + 2x_0) = b + \beta(1 + 2x_0). \tag{A7}
\]

Similarly for (A6):

\[
c = \alpha + \beta(1 - 2x_0 + x_0^2) = (\alpha + \beta x_0^2) + \beta(1 - 2x_0) = b + \beta(1 - 2x_0). \tag{A8}
\]

From (A7) and (A8):

\[
\frac{a - b}{c - b} = \frac{1 + 2x_0}{1 - 2x_0}. \tag{A9a}
\]

Rearranging:

\[
x_0 = \frac{c - a}{2(2b - c - a)}. \tag{A9b}
\]

Adding (A7) and (A8):

\[
a + c = 2b + 2\beta \tag{A10}
\]

Making \( \beta \) the subject:

\[
\beta = \frac{(2b - c - a)}{2} = \frac{a - c}{4x_0}. \tag{A11}
\]

From (A5) and (A11):

\[
\alpha = b - \beta x_0^2 = b - \frac{a - c}{4x_0} = b + \frac{c - a}{4} x_0. \tag{A12}
\]

**Gaussian Fitting**

General equation of a gaussian with axis parallel to the \( y \)-axis (Fig. A.2):

\[
y = \delta e^{-\gamma(x-x_o)^2}. \tag{A13a}
\]

Taking natural logarithms in both sides:

\[
\ln y = \ln \delta - \gamma(x - x_0)^2. \tag{A13b}
\]

It can be seen that this equation is the same as (A3) if the following changes of variable are made: \( y \equiv \ln y; \quad a \equiv \ln a; \quad b \equiv \ln b; \quad c \equiv \ln c; \quad \alpha \equiv \ln \delta; \quad \beta \equiv -\gamma. \)

So, from (A9b) and the changes of variable:

\[
x_0 = \frac{\ln c - \ln a}{2(2 \ln b - \ln c - \ln a)} = \frac{\ln \left( \frac{c}{a} \right)}{2 \ln \left( \frac{b^2}{ca} \right)}. \tag{A14}
\]

From (A11) and the changes of variable:

\[
\gamma = \frac{\ln c - \ln a}{4x_0}. \tag{A15a}
\]
using (A14):

\[ \gamma = \frac{1}{2} \ln \frac{b^2}{ca} \quad (A15b) \]

From (A12) and with the changes of variable:

\[ \ln \delta = \ln b + \frac{\ln c - \ln a}{4} x_0, \quad (A16a) \]

exponentiating both sides:

\[ \delta = b \exp \left( \frac{\ln c - \ln a}{4} x_0 \right). \quad (A16b) \]

Another important parameter is the full width at half maximum (w), from its definition:

\[ \delta e^{-\gamma [(x_0 + y) - x_0]} = \frac{\delta}{2}. \quad (A17a) \]

Taking natural logarithms and making w the subject:

\[ w = \left( \frac{-4 \ln \frac{\gamma}{2}}{\gamma} \right) \Rightarrow \quad (A17a) \]

using (A15b):

\[ w = \left[ \frac{-8 \ln \frac{\gamma}{2}}{\ln \left( \frac{b^2}{ca} \right)} \right]^{\frac{1}{2}} = 2.35 \left( \frac{b^2}{ca} \right)^{\frac{1}{2}}. \quad (A17b) \]
APPENDIX B

Estimation of Errors

Centre of Gravity
The centroid for the Centre of Gravity algorithm is given by:

\[ x_0 = \frac{c-a}{a+b+c}. \]  \hspace{1cm} (B1)

The error in \( x_0 \) will be given by:

\[ \Delta x_0 = \frac{(c + \Delta c) - (a + \Delta a)}{(a + \Delta a) + (b + \Delta b) + (c + \Delta c)} - x_0, \]  \hspace{1cm} (B2a)

this can be rewritten as:

\[ \Delta x_0 = \frac{(c - a) + (\Delta c - \Delta a)}{a + b + c} \left(1 - \frac{\Delta a + \Delta b + \Delta c}{a + b + c}\right) - x_0. \]  \hspace{1cm} (B2b)

Using the approximation:

\[ \frac{1}{1+z} \approx 1 - z \]  \hspace{1cm} for \( z \ll 1, \]  \hspace{1cm} (B3)

the following expression is obtained:

\[ \Delta x_0 \approx \left(x_0 + \frac{\Delta c - \Delta a}{a + b + c}\right) \left(1 - \frac{\Delta a + \Delta b + \Delta c}{a + b + c}\right) - x_0. \]  \hspace{1cm} (B4a)

Expanding (B4a):

\[ \Delta x_0 = \frac{\Delta c - \Delta a}{a + b + c} - x_0 \left(\frac{\Delta a + \Delta b + \Delta c}{a + b + c}\right) - \frac{(\Delta c - \Delta a)(\Delta a + \Delta b + \Delta c)}{(a + b + c)^2}. \]  \hspace{1cm} (B4b)

Ignoring the last term of this equation which is very small and rearranging,

\[ \Delta x_0 = \frac{-\Delta a(1 + x_0) + \Delta bx_0 + \Delta c(1 - x_0)}{a + b + c} \]  \hspace{1cm} (B5)

If it is assumed that the system only suffers from read-out and dark current noise and that they vary randomly it can be assumed that \( \Delta a = \Delta b = \Delta c = \sigma \). The error can then be calculated as the square root of the quadratic addition of the noise terms:

\[ \Delta x_0 = \sqrt{\frac{\sigma^2(1 + x_0)^2 + \sigma^2x_0^2 + \sigma^2(1 - x_0)^2}{(a + b + c)^2}}, \]  \hspace{1cm} (B6a)

simplifying:

\[ \Delta x_0 = \frac{\sigma \sqrt{3x_0^2 + 2}}{a + b + c}. \]  \hspace{1cm} (B6b)
Parabola

The centroid for the Parabola algorithm is given by:

\[ x_0 = \frac{c - a}{2b - c - a} \]  \hspace{1cm} (B7)

The calculated centroid, which will include the uncertainties in each pixel, is given by:

\[
\Delta x_0 = \frac{(c + \Delta c) - (a + \Delta a)}{2(b + \Delta b) - (c + \Delta c) - (a + \Delta a)} - x_0 = \frac{(c - a) + (\Delta c - \Delta a)}{(2b - c - a) + (2\Delta b - \Delta c - \Delta a)} - x_0. \]  \hspace{1cm} (B8a)

This can be expressed as:

\[
\Delta x_0 = \frac{(c - a) + (\Delta c - \Delta a)}{2b - c - a} \left(1 + \frac{2\Delta b - \Delta c - \Delta a}{2b - c - a}\right) - x_0. \]  \hspace{1cm} (B8b)

Again, using approximation (B3) and (B7):

\[
\Delta x_0 = \left(x_0 + \frac{\Delta c - \Delta a}{2b - c - a}\right) \left(1 - \frac{2\Delta b - \Delta c - \Delta a}{2b - c - a}\right) - x_0. \]  \hspace{1cm} (B9a)

Expanding:

\[
\Delta x_0 = \frac{x_0(2\Delta b - \Delta c - \Delta a)}{2b - c - a} + \frac{\Delta c - \Delta a}{2b - c - a} - \frac{(\Delta c - \Delta a)(2\Delta b - \Delta c - \Delta a)}{(2b - c - a)^2}, \]  \hspace{1cm} (B9b)

ignoring the last term and rearranging:

\[
\Delta x_0 = \frac{1}{2b - c - a} \left[\Delta a(x_0 - 1) - 2\Delta b x_0 + \Delta c(x_0 + 1)\right] \]  \hspace{1cm} (B10)

assuming the same noise in \( a, b \) and \( c \) and that it is equal to \( \sigma \):

\[
\Delta x_0 = \frac{\sigma \sqrt{6 x_0^2 + 2}}{2b - c - a}. \]  \hspace{1cm} (B11)
**Gaussian**

The centroid for the Gaussian algorithm is given by:

\[
x_0 = \frac{\ln c - \ln a}{2 \ln b - \ln a - \ln c}.
\]  

(B13)

The centroid error then being

\[
\Delta x_0 = \frac{\ln(c + \Delta c) - \ln(a + \Delta a)}{2 \ln(b + \Delta b) - \ln(a + \Delta a) - \ln(c + c c)} - x_0,
\]  

(B14a)

this can be rewritten as:

\[
\Delta x_0 = \frac{\ln \left[ \frac{c(1 + \Delta c)}{b} \right] - \ln \left[ \frac{a(1 + \Delta a)}{a} \right]}{2 \ln \left[ \frac{b(1 + \Delta b)}{b} \right] - \ln \left[ \frac{a(1 + \Delta a)}{a} \right] - \ln \left[ \frac{c(1 + \Delta c)}{c} \right]} - x_0,
\]  

(B14b)

or

\[
\Delta x_0 = \frac{\ln c + \ln \left( 1 + \frac{\Delta c}{c} \right) - \ln a - \ln \left( 1 + \frac{\Delta a}{a} \right)}{2 \ln b + \ln \left( 1 + \frac{\Delta b}{b} \right) - \ln a - \ln \left( 1 + \frac{\Delta a}{a} \right) - \ln c - \ln \left( 1 + \frac{\Delta c}{c} \right)} - x_0.
\]  

(B14c)

Using the series expansion

\[
\ln(1 + z) = z - \frac{z^2}{2} + \frac{z^3}{3} - \frac{z^4}{4} + \ldots \quad \text{for} \quad -1 < z \leq 1
\]  

(B15)

to make a first order approximation of the noise terms:

\[
\Delta x_0 = \frac{(\ln c - \ln a) + \left( \frac{\Delta c}{c} - \frac{\Delta a}{a} \right)}{(2 \ln b - \ln a - \ln c) + \left( \frac{\Delta b}{b} - \frac{\Delta a}{a} - \frac{\Delta c}{c} \right)} - x_0.
\]  

(B16)

This resembles the parabola case (Equation B8a), making the necessary changes of variable:

\[
\Delta x_0 = \frac{1}{2 \ln b - \ln a - \ln c} \left( \Delta a \frac{x_0 - 1}{a} - \Delta b \frac{2 x_0}{b} + \Delta c \frac{x_0 + 1}{c} \right).
\]  

(B17)

So

\[
\Delta x_0 = \frac{\sqrt{(x_0 - 1)^2 + \frac{4 x_0^2}{a^2} + \frac{(x_0 + 1)^2}{c^2}}}{2 \ln b - \ln a - \ln c}.
\]  

(B18)
APPENDIX C

Noise sources on CCD cameras

In almost every area of measurement, especially for weak signals, the ultimate limit of detectability is set by noise. Noise can be defined as any unwanted signals that will obscure the desired signal and degrade the accuracy of its measurement. Noise appears as random variations, either in time or space, of the registered signal about an average value. It is important to understand the sources of noise so that their effect can be reduced as much as possible. For a CCD camera the main noises are (Buil 1991):

**Reset noise**

The major sources of noise in a CCD are to be found in the output circuit. The predominant one being reset noise. It has its origin in the Johnson noise in the reset transistor which gives rise to fluctuations in the potential to which the output node is reset before the detection of each charge signal. Its value is given by the relation

\[ \sigma_r = \frac{1}{q} \sqrt{kTC_n} \]  

where \( q \) is the charge of electron (1.6\times10^{-19} \text{ C}), \( k \) is Boltzmann’s constant (1.38\times10^{-23} \text{ JK}^{-1}), \( T \) is the CCD’s temperature in degrees Kelvin, and \( C_n \) is the output node capacitance in farads.

**Thermal noise**

This noise depends on the mean level of dark current and is given by the square root of the average number of thermally generated electrons, that is

\[ \sigma_t = \sqrt{N_t} \]  

According EEV’s data sheet (EEV 1990a) the dark current of these devices is given by

\[ N_t = 2.44 \times 10^6 \tau T^3 e^{-6400/T} \]  

where \( T \) is the CCD’s temperature in degrees Kelvin and \( \tau \) is the frame integration time in seconds.

**Transfer noise**

When a charge packet moves along the CCD, a certain fraction of this packet stays behind at each transfer. This noise varies in a random way as a function of the quantity of charges carried \((N_s + N_i)\), of the number of transfers carried out \((n)\), and of the transfer inefficiency \((\epsilon)\) of the device. Assuming that each transfer is independent, this noise is

\[ \sigma_e = \sqrt{2\epsilon n(N_s + N_i)} \]  

**Quantification noise**

The CCD is used with additional electronics whose role is to amplify the video signal and then to digitise it for further processing. These circuits introduce a noise given by
where $N_{\text{max}}$ is the maximum signal, detected by the A/D converter, in electrons and $m$ is number of bits in the A/D converter.

**Signal noise**

Also called photon or shot noise. This noise is extrinsic to the CCD and originates in the corpuscular nature of light. Since, in this case, the arrival of photons follows a Poisson distribution the value of this noise is equal to the square root of the average number of signal electrons collected during integration time, in other words

$$\sigma_i = \sqrt{N_i} .$$  \(\text{(C.6)}\)

**BigMIC's CCD camera noise budget**

According to the CCD data sheet the guaranteed maximum signal before the resolution starts to degrade is $\sim 3 \times 10^5$ electrons per CCD pixel. The image intensifier's gain is normally set in such a way that it generates about half that number of electrons in the brightest pixel of the events, this implies that in the worse case condition $N_i = 1.5 \times 10^5$ e$^-$. 

The measured temperature of the BigMIC CCD during normal operation is $T = 310$ K.

If the whole CCD is read then the maximum frame integration time is $\tau = 45$ ms.

The node capacitance has a value of $C_n = 0.2$ pF.

The transfer inefficiency is quoted as $\varepsilon = 5 \times 10^{-6}$, and the maximum number of transfers is two times 576 vertically plus 770 horizontally so $n = 1922$.

Using these values it can be found that for the BigMIC CCD camera:

$\sigma_s = 387$ e$^-$, $\sigma_t = 59$ e$^-$, $\sigma_r = 183$ e$^-$, $\sigma_e = 54$ e$^-$, and $\sigma_q = 173$ e$^-$. 

The expected maximum noise will then be given by the quadratic addition of all the previously listed noises, that is

$$\sigma_{\text{max}} = \sqrt{\sigma_s^2 + \sigma_t^2 + \sigma_r^2 + \sigma_e^2 + \sigma_q^2} = 470\text{ e}^- .$$  \(\text{(C.7)}\)

The readout noise is calculated in a similar way but without the signal term:

$$\sigma_{\text{readout}} = \sqrt{\sigma_r^2 + \sigma_e^2 + \sigma_q^2} \approx 264\text{ e}^- .$$  \(\text{(C.8)}\)

The readout noise of the MIC2 camera was measured to be $291 \pm 20$ which is slightly higher than the expected value.
APPENDIX D

Flat Field Simulation Programme

PROGRAM Flat_Field_Simulation

c This program simulates a Microchannel Plate Image Intensified Photon Counting System by generating flat field images so that pattern noise and different centroiding algorithms can be studied.

c A predetermined number of 7x7 ccd pixel events are randomly placed in a 70x70 pixel frame. Centroids generated by different algorithms are computed and then added to arrays containing condensed images and global statistics. Only the inner 64x64 pixels are used in order to avoid edge effects. The process is repeated until a number of events per image is reached. It is also possible to repeat the cycle as many times as desired. This is specially useful to find the optimum subpixel boundaries for a new setup.

c Before starting the program, there must be three files:
c 1. 'ff.com' with the program's input parameters.
c 2. 'IniCondFile' with:
c - Desired resolution (from 1 to 8 ccd subpixels),
c - Initial Boundaries and Multiple Thresholds for each of the 8 algorithms.
c 3. 'FileName' containing a data base of real or synthetic 7x7 ccd pixel events. Notice that, to save disk space, this file must be in binary form.

c The program will generate the following files:
c energy.out  - Energy histogram of all valid events
c peak.out  - Histograms with peak value of events (in x and y)
c width.out  - FWHM in x and y of all valid events
c centroids.out  - Centroid histograms of all valid events during program run.
c heights#out  - Peak value histograms for all subpixels. #=algorithm number.
c patterns.out  - Sums of events in each subpixel.
c lastcond.out  - Last conditions file, similar to 'IniCondFile'
c boundaries.out  - Subpixel boundaries used in each cycle.

c Raul Michel

c May 1996

C Common blocks:
REAL*8  StanDev, Mean
INTEGER*4  Eve(7,7,40000), NumEveInDataBase, cols, rows, & NLevels, Maximum
COMMON /EVENTS/  StanDev, Mean, Eve,
&  NumEveInDataBase, cols, rows, NLevels, Maximum

INTEGER*4  Frame(70,70),PeakHist(255),EnergyHist(2295), & WidthHist(2,1000),Seed,Bias,EvePerFra,EvePerImp,Counter,Display
COMMON /FRAME1/  Frame,PeakHist,EnergyHist,WidthHist,
&  Seed,Bias,EvePerFra,EvePerImp,Counter,Display

REAL*8  Mask(70,70), RFrame(70,70)
COMMON /MASK1/  Mask, RFrame

REAL*8  Boundary(2,8,8),Centroid(2,8)
INTEGER*4  DigitalCent(2,8), NumSubPixels
COMMON /BOUNDS/  Boundary, Centroid, DigitalCent, NumSubPixels

INTEGER*4  ImagePattern(8,8,8), Threshold(8,8,8),
&  CentHist(2,-10000:10000,8), HeightHist(8,8,255,8)
COMMON /IMTHRES/  ImagePattern,Threshold,CentHist,HeightHist
c Local variables:

    INTEGER*4 NumberOfCycles,Cycle
    CHARACTER EventsFile*60, IniCondFile*60, ChangeBoundaries*1,
        & DisplayEvents*1, EventsType*1, Comment*78

cols = 7       ! Size of Events (in CCD pixels)
rows = 7
NLevels = 256  ! 8 bit A/D Converter

c Read Input Parameters:

OPEN (8,FILE='ff.com',STATUS='OLD')
READ(8,*)  EventsFile, IniCondFile, EvePerFra,
        &    Bias, Mean, StanDev, EvePerIma, NumberOfCycles,
        &    Seed, ChangeBoundaries, DisplayEvents,EventsType
CLOSE(8)

PRINT *, ''  Flat Field Simulation Program. '
PRINT *, ''
WRITE(*,'(a38,$)') Events File: '
WRITE(*,'(a60,$)') EventsFile
WRITE(*,'(a38,$)') Initial Conditions File: '
WRITE(*,'(a60,$)') IniCondFile
WRITE(*,'(a38,$)') Number of Events per Frame: '
WRITE(*,'(a38,$)') EvePerFra
WRITE(*,'(a38,$)') Frame Bias: '
WRITE(*,'(a38,$)') Mean of Events'' Peak: '
WRITE(*,'(a38,$)') Mean
WRITE(*,'(a38,$)') Standard Deviation of Events'' Peak: '
WRITE(*,'(a38,$)') StanDev
WRITE(*,'(a38,$)') Number of Events per Image: '
WRITE(*,'(a38,$)') EvePerIma
WRITE(*,'(a38,$)') Number of Cycles: '
WRITE(*,'(a38,$)') NumberOfCycles
WRITE(*,'(a38,$)') Random Number Generator''s Seed: '
WRITE(*,'(a38,$)') Seed
WRITE(*,'(a38,$)') Change Boundaries After Each Cycle: '
WRITE(*,'(a1)') ChangeBoundaries
WRITE(*,'(a38,$)') Display Events: '
WRITE(*,'(a1)') DisplayEvents
WRITE(*,'(a38,$)') Events Type: '
WRITE(*,'(a1)') EventsType
PRINT *, ''

IF(DisplayEvents.EQ.'y'.OR.DisplayEvents.EQ.'Y') Display=1
IF(ChangeBoundaries .EQ. 'y') ChangeBoundaries = 'Y'
IF(EventsType .EQ. 'r') EventsType = 'R'

CALL Load_Initial_Conditions(IniCondFile)
CALL Read_Events_Data_Base(EventsFile)
CALL Make_Mask(Seed)
CALL Open_Output_Files(NumberOfCycles)

CALL Clear_Histograms
CALL Write_Current_Boundaries(0)

DO Cycle = 1,NumberOfCycles

    CALL Clear_Arrays
    Counter = 0

    DO WHILE ( Counter .LT. EvePerIma )
        IF (EventsType .EQ. 'r') THEN
            CALL Generate_Frame_Real_Data
        ELSE
            CALL Generate_Frame
        END IF
    END DO

    CALL Write_Image_Patterns(Cycle)
    CALL Write_Fixed_Pattern_Noise(Cycle)

    CALL Write_Hoefft_Histgrams(Cycle)
IF (ChangeBoundaries .EQ. 'Y') THEN
   CALL Define_New_Boundaries
   CALL Write_Current_Boundaries(Cycle)
END IF
END DO ! Cycle

CALL Close_Output_Files
CALL Write_Centroid_Histograms
CALL Write_Peak_Energy_Statistics
CALL Save_Last_Conditions
PRINT *, '  
PRINT *, '  End of program.'
END

SUBROUTINE Load_Initial_Conditions(FileName)
   c Read Resolution, Boundaries, and Thresholds for current run.
   REAL*8 Boundary(2,8,8), Centroid(2,8)
   INTEGER*4 DigitalCent(2,8), NumSubPixels
   COMMON /BOUNDS/ Boundary, Centroid, DigitalCent, NumSubPixels

   INTEGER*4 ImagePattern(8,8,8), Threshold(8,8,8),
               CentHist(2,-10000:10000,8), HeightHist(8,8,255,8)
   COMMON /IMTHRES/ ImagePattern, Threshold, CentHist, HeightHist

   INTEGER*4 i, j, Axis, Alg
   CHARACTER FileName*60, Comment*78
   OPEN(5, FILE=FileName, STATUS='OLD')
   READ(5, ' (a78) ') Comment
   READ(5, ' (a78) ') Comment
   READ(5, ' (a78) ') Comment
   c Read Resolution (number of subpixels):
   READ(5,*) NumSubPixels
   DO Alg = 1, 8
      c Read Boundaries, starting by the most negative:
      DO Axis = 1, 2 ! 1=x 2=y
         c Read Thresholds, row by row.
         c Read (Boundary(Axis,j,Alg), j = 1,NumSubPixels-1)
         END DO
         c Read (Threshold(i,j,Alg), i = 1,NumSubPixels)
         END DO
      END DO
   CLOSE(5)
   RETURN
END

SUBROUTINE Save_Last_Conditions
   c Save Corrected Boundaries. Also Thresholds and Resolution.
   REAL*8 Boundary(2,8,8), Centroid(2,8)
   INTEGER*4 DigitalCent(2,8), NumSubPixels
   COMMON /BOUNDS/ Boundary, Centroid, DigitalCent, NumSubPixels

   INTEGER*4 ImagePattern(8,8,8), Threshold(8,8,8),
               CentHist(2,-10000:10000,8), HeightHist(8,8,255,8)
   COMMON /IMTHRES/ ImagePattern, Threshold, CentHist, HeightHist

   INTEGER*4 i, j, Axis, Alg
   CHARACTER fdate*24
   CHARACTER*45 Algorithm(8)

   Algorithm(1) = ' 1.- 3 Pixel Gaussian Fitting  
   Algorithm(2) = ' 2.- 3 Pixel Parabola Fitting  
   Algorithm(3) = ' 3.- 3 Pixel Centre of Gravity  
   Algorithm(4) = ' 4.- 3x3 (Added Pixels) Gaussian Fitting  
   Algorithm(5) = ' 5.- 3x3 (Added Pixels) Parabola Fitting  
   Algorithm(6) = ' 6.- 3x3 (Added Pixels) Centre of Gravity  
   Algorithm(7) = ' 7.- 5x5 Pixels Centre of Gravity  
   Algorithm(8) = ' 8.- 3 Pixel Gaussian Fitting with LUTs  

OPEN(5,FILE='lastcond.out',STATUS='UNKNOWN')
WRITE(5,'#')
WRITE(5,'(a4,a24)') '# ',fdate()
WRITE(5,'(a36)') '# Resolution (number of subpixels): ' NumSubPixels
WRITE(5,'(i6)') NumSubPixels
DO Alg = 1,8
WRITE(5,'(a2,a45)') '# ',Algorithm(Alg)
& WRITE(5,'<NumSubPixels-1>f12.6')
& (Boundary(Alg, j, Axis), j = 1,NumSubPixels-1)
END DO
DO j = 1,NumSubPixels
WRITE(5,'(15x,<NumSubPixels>i6)') (Threshold(Alg, j), i = 1,NumSubPixels)
END DO
END DO
CALL flush(5)
CLOSE(5)
RETURN
END

SUBROUTINE Read_Events_Data_Base(FileName)

REAL*8  StanDev, Mean
INTEGER*4  E ve(7,7,40000), NumEveInDataBase, cols, rows,
& NLevels, Maximum
COMMON / EVENTS/ StanDev, Mean, E ve,
& NumEveInDataBase, cols, rows, NLevels, Maximum
CHARACTER FileName*60
INTEGER*4  i,j,k

OPEN (5,FILE=FileName,FORM='UNFORMATTED',STATUS='OLD')
WRITE(*,' ') Reading Events' Data Base ...'
WRITE(*,' ') Events in data base = ',NumEveInDataBase
WRITE(*,' ') 

DO k= 1,3
READ(5, '( (E ve(i,j,k),i=1,cols ),j=1,rows )
DO j = 1,rows
WRITE(*,'(cols-i11)') (E ve(i,j,k),i=1,cols)
END DO
WRITE(*,' )
END DO

C Read rest of events:
DO k= 4,NumEveInDataBase
READ(5) ((E ve(i,j,k),i=1,cols),j=1,rows)
END DO
CLOSE(5)
PRINT *, ' Done with Reading Events' Data Base'

C Find maximum pixel value of all the events:
Maximum = 0
DO k= 1,NumEveInDataBase
DO j = 1,rows
DO i = 1,cols
IF( E ve(i,j,k).GT.Maximum) THEN
Maximum=E ve(i,j,k)
END IF
END DO
END DO
WRITE(*,' )' Maximum = ',Maximum
RETURN
END
SUBROUTINE Make_Mask(Seed)
  c Generate random mask representing non-linearity of CCD (+/- 2%), and
  c clear first frame.
  REAL*8     Mask(70,70), RFrame(70,70)
  COMMON /MASK1/ Mask, RFrame
  INTEGER*4 Seed, i, j
  DO j=1,70
    DO i=1,70
      Mask(i,j) = 0.98d0 + RAN(Seed)*0.04d0
      RFrame(i,j) = 0.0d0
    END DO
  END DO
END

SUBROUTINE Generate_Frame
  c Generate a 70x70 pixel frame with 'EvePerFra' events placed at random.
  REAL*8     StanDev, Mean
  INTEGER*4 Eve(7,7,40000), NumEveInDataBase, cols, rows,
               NLevels, Maximum
  COMMON /EVENTS/ StanDev, Mean, Eve,
               NumEveInDataBase, cols, rows, NLevels, Maximum
  INTEGER*4 Frame(70,70), PeakHist(255), EnergyHist(2295),
               WidthHist(2,1000), Seed,Bias,EvePerFra,EvePerIma,Counter,Display
  COMMON /FRAME1/ Frame, PeakHist, EnergyHist, WidthHist,
               Seed,Bias,EvePerFra,EvePerIma,Counter,Display
  REAL*8     Mask(70,70), RFrame(70,70)
  COMMON /MASK1/ Mask, RFrame
  INTEGER*4 i,j,k,m,n,times,XOffset,YOffset
  REAL*8     PeakOfEvent, factor
  c New frame. Include ghost image of previous frame.
  k = INT(1.20d0*RAN(Seed)) ! one of every 6 frames
  DO j=1,70
    DO i=1,70
      RFrame(i,j) = 0.125d0*RFrame(i,j)*k ! 1/8th of previous frame
    END DO
  END DO
END

c Generate Frame:
  DO times = 1, EvePerFra
  c Take one event from data base at random:
  k = INT(RAN(Seed) * (NumEveInDataBase-1)) + 1
  c Define top left coordinates on frame, also at random:
  XOffset = INT(RAN(Seed) * 63.0)
  YOffset = INT(RAN(Seed) * 63.0)
  c Define Peak (and energy) of event at random with normal distribution:
  PeakOfEvent = StanDev * Random_Gauss(Seed) + Mean
  IF(PeakOfEvent .LT. 2.0) GOTO 35
  factor = PeakOfEvent / DFLOAT(Maximum) ! scaling factor
  c Put event on frame.
  DO n=1,rows
    DO m=1,cols
      i = XOffset+m
      j = YOffset+n
      RFrame(i,j) = RFrame(i,j) + factor*Eve(m,n,k)
    END DO
  END DO
END DO ! times

  c add shot noise [between +/- SQRT(Signal)], multiply by non-linearity
  c mask and add bias:
DO j=1,70
  DO i=1,70
    RFrame(i,j) = RFrame(i,j) +
    & DSQRT(RFrame(i,j))*(-1.0d0+2.0d0*RN(Seed)) ! Shot Noise
    RFrame(i,j) = RFrame(i,j) * Mask(i,j) + Bias
  END DO
END DO
    
c Check for saturation:
    IF (RFrame(i,j) .GT. DFLOAT(NLevels))
    & RFrame(i,j) = DFLOAT(NLevels) - 1.0d0
    IF (RFrame(i,j) .LT. 0.0d0) RFrame(i,j) = 0.0d0
    Frame(i,j) = NINT(RFrame(i,j)) ! Digitise
    
END DO
END DO
    
c Increment counter:
    Counter = Counter + EvePerFra
    RETURN
END

SUBROUTINE Generate_Frame_Real_Data

c Generate a 70x70 pixel frame with 'EvePerFra' events placed at random.
REAL*8 Standev, Mean
INTEGER*4 Eve(7,7,40000), NumEveInDataBase, cols, rows,
& NLevels, Maximum
COMMON /EVENTS/ Standev, Mean, Eve,
& NumEveInDataBase, cols, rows, NLevels, Maximum
INTEGER*4 Frame(70,70),PeakHist(255),EnergyHist(2295),
& WidthHist(2,1000),Seed,Bias,EvePerFra,EvePerima,Counter,Display
COMMON /FRAME1/ Frame,PeakHist,EnergyHist,WidthHist,
& Seed,Bias,EvePerFra,EvePerima,Counter,Display
REAL*8 Mask(70,70), RFrame(70,70)
COMMON /MASK1/ Mask, RFrame

    
c Internal variables:
    INTEGER*4 i,j,k,m,n,times,XOffset,YOffset
REAL*8 PeakOfEvent, factor

    
c New frame.
    DO j=1,70
      DO i=1,70
        RFrame(i,j) = 0.0d0
      END DO
    END DO

    
c Generate Frame:
    DO times = 1, EvePerFra
      k = NINT(RN(Seed) * (NumEveInDataBase-1)) + 1
      
c Define top left coordinates on frame, also at random:
      XOffset = NINT(RN(Seed) * 63.0)
      YOffset = NINT(RN(Seed) * 63.0)

      
c Put event on frame.
      DO n=1,rows
        DO m=1,cols
          i = XOffset+m
          j = YOffset+n
          RFrame(i,j) = RFrame(i,j) + Eve(m,n,k)
        END DO
      END DO
      END DO
    END DO

    
c Add bias, Check for saturation, and digitise:
    DO j=1,70
      DO i=1,70
        RFrame(i,j) = RFrame(i,j) + Bias
        IF (RFrame(i,j) .GT. DFLOAT(NLevels))
          RFrame(i,j) = DFLOAT(NLevels) - 1.0d0
& RFrame(i,j) = DFLOAT(NLevels) - 1.0d0
IF (RFrame(i,j) .LT. 0.0d0) RFrame(i,j) = 0.0d0
Frame(i,j) = NINT(RFrame(i,j)) ! Digitise
END DO
END DO

c Increment counter:
Counter = Counter + EvePerFra
RETURN
END

C SUBROUTINE Process_Frame

C Validate event, centroid and addition to statistics.
INTEGER*4 Frame(70,70), PeakHist(255), EnergyHist(2295), & WidthHist(2,1000), Seed,Bias,EvePerFra,EvePerima,Counter,Display
COMMON /FRAME1/ Frame,PeakHist,EnergyHist,WidthHist, & Seed,Bias,EvePerFra,EvePerima,Counter,Display
REAL*8 Boundary(2,8,8), Centroid(2,8)
INTEGER*4 DigitalCent(2,8), NumSubPixels
COMMON /BOUNDS/ Boundary, Centroid, DigitalCent, NumSubPixels

INTEGER*4 i,j

C Scan frame for events.
DO j=5,66
  DO i=5,66
    IF (Frame(i,j) .GE. 8 .AND. & Frame(i,j) .GE. Frame(i-1,j-1) .AND. & Frame(i,j) .GE. Frame(i+1,j-1) .AND. & Frame(i,j) .GE. & Frame(i,j) .GT. Frame(i, j+1) .AND. & Frame(i,j) .GT. Frame(i+1, j+1) ) THEN
      CALL Find_Centroids(i,j)
      CALL Digital_Centroids
      IF (Display .EQ. 1) CALL Display_Event(i,j)
      CALL Add_To_Statistics(Frame(i,j))
    END IF
  END DO
END DO
RETURN
END

C SUBROUTINE Find_Centroids(i,j)

C Compute centroids around element i,j of Frame.
C 1 3 Pixel Gaussian Fitting
C 2 3 Pixel Parabola Fitting
C 3 3 Pixel Centre of Gravity
C 4 3x3 (Added Pixels) Gaussian Fitting
C 5 3x3 (Added Pixels) Parabola Fitting
C 6 3x3 (Added Pixels) Centre of Gravity
C 7 5x5 Pixels Centre of Gravity
C 8 3 Pixel Gaussian Fitting with LUTs

INTEGER*4 Frame(70,70), PeakHist(255), EnergyHist(2295), & WidthHist(2,1000), Seed,Bias,EvePerFra,EvePerima,Counter,Display
COMMON /FRAME1/ Frame,PeakHist,EnergyHist,WidthHist, & Seed,Bias,EvePerFra,EvePerima,Counter,Display
REAL*8 Boundary(2,8,8), Centroid(2,8)
INTEGER*4 DigitalCent(2,8), NumSubPixels
COMMON /BOUNDS/ Boundary, Centroid, DigitalCent, NumSubPixels

INTEGER*4 i,j,a,b,c,d,e
three pixel algorithms:

\[
\begin{align*}
    b &= \text{Frame}(i, j) \\
    a &= \text{Frame}(i-1, j) \\
    c &= \text{Frame}(i+1, j)
\end{align*}
\]

Centroid(1,1) = Gaussian LUT\((a, b, c)\)
Centroid(1,2) = Parabola Fitting\((a, b, c)\)
Centroid(1,3) = Centre of Gravity\((a, b, c)\)

Add event to X width histogram:

\[
e = \text{INT}\left(\text{FWHM}(a, b, c) \times 100.0d0\right)
\]

IF\((e < 1000 \, \text{ AND } \, e > 0)\) THEN

\[
\text{WidthHist}(1, e) = \text{WidthHist}(1, e) + 1
\]
ELSE

\[
\text{WidthHist}(1, 1000) = \text{WidthHist}(1, 1000) + 1
\]
END IF

\[
a = \text{Frame}(i, j-1) \\
\]

Centroid(2,1) = Gaussian LUT\((a, b, c)\)
Centroid(2,2) = Parabola Fitting\((a, b, c)\)
Centroid(2,3) = Centre of Gravity\((a, b, c)\)

Add event to Y width histogram:

\[
e = \text{INT}\left(\text{FWHM}(a, b, c) \times 100.0d0\right)
\]

IF\((e < 1000 \, \text{ AND } \, e > 0)\) THEN

\[
\text{WidthHist}(2, e) = \text{WidthHist}(2, e) + 1
\]
ELSE

\[
\text{WidthHist}(2, 1000) = \text{WidthHist}(2, 1000) + 1
\]
END IF

9 pixel algorithms, sum of rows and columns:

\[
a = \text{Frame}(i-1, j-1) + \text{Frame}(i-1, j) + \text{Frame}(i-1, j+1) \\
\]

\[
b = \text{Frame}(i, j-1) + \text{Frame}(i, j) + \text{Frame}(i, j+1) \\
\]

\[
c = \text{Frame}(i+1, j-1) + \text{Frame}(i+1, j) + \text{Frame}(i+1, j+1)
\]

Centroid(1,4) = Gaussian LUT\((a, b, c)\)
Centroid(1,5) = Parabola Fitting\((a, b, c)\)
Centroid(1,6) = Centre of Gravity\((a, b, c)\)

Add event to peak and energy histograms:

\[
\text{PeakHist}(\text{Frame}(i, j)) = \text{PeakHist}(\text{Frame}(i, j)) + 1
\]

\[
a = a + b + c
\]

EnergyHist\((a) = \text{EnergyHist}(a) + 1
\]

5x5 pixel centre of gravity:

\[
a = \text{Frame}(i-2, j-2) + \text{Frame}(i-2, j-1) + \text{Frame}(i-2, j) + \text{Frame}(i-2, j+1) + \text{Frame}(i-2, j+2)
\]

\[
b = \text{Frame}(i-1, j-2) + \text{Frame}(i-1, j-1) + \text{Frame}(i-1, j) + \text{Frame}(i-1, j+1) + \text{Frame}(i-1, j+2)
\]

\[
c = \text{Frame}(i, j-2) + \text{Frame}(i, j-1) + \text{Frame}(i, j) + \text{Frame}(i, j+1) + \text{Frame}(i, j+2)
\]

\[
d = \text{Frame}(i+1, j-2) + \text{Frame}(i+1, j-1) + \text{Frame}(i+1, j) + \text{Frame}(i+1, j+1) + \text{Frame}(i+1, j+2)
\]

\[
e = \text{Frame}(i+2, j-2) + \text{Frame}(i+2, j-1) + \text{Frame}(i+2, j) + \text{Frame}(i+2, j+1) + \text{Frame}(i+2, j+2)
\]

Centroid(1,7) = Centre of Gravity_5\((a, b, c, d, e)\)

Add event to X width histogram:

\[
\text{WidthHist}(1, e) = \text{WidthHist}(1, e) + 1
\]

\[
a = \text{Frame}(i-2, j-2) + \text{Frame}(i-1, j-2) + \text{Frame}(i, j-2) + \text{Frame}(i+1, j-2) + \text{Frame}(i+2, j-2)
\]

\[
b = \text{Frame}(i-2, j-1) + \text{Frame}(i-1, j-1) + \text{Frame}(i, j-1) + \text{Frame}(i+1, j-1) + \text{Frame}(i+2, j-1)
\]
c = Frame(i-2, j) + Frame(i-1, j) + Frame(i, j) + Frame(i+1, j) + Frame(i+2, j)
&
d = Frame(i-2, j+1) + Frame(i-1, j+1) + Frame(i, j+1) + Frame(i+1, j+1) + Frame(i+2, j+1)
&
e = Frame(i-2, j+2) + Frame(i-1, j+2) + Frame(i, j+2) + Frame(i+1, j+2) + Frame(i+2, j+2)
&
Centroid(2,7) = Centre_of_Gravity_5(a,b,c,d,e) ! y

RETURN
END

SUBROUTINE Digital_Centroids

REAL*8 Boundary(2,8,8),Centroid(2,8)
INTEGER*4 DigitalCent(2,8), NumSubPixels
COMMON /BOUNDS/ Boundary, Centroid, DigitalCent, NumSubPixels

INTEGER*4 Axis, Alg, j

DO Alg = 1, 8
  DO Axis = 1, 2
    DigitalCent(Axis,Alg) = NumSubPixels
    DO j = 1, NumSubPixels-1
      IF(Centroid(Axis,Alg) .LT. Boundary(Axis,j,Alg)) THEN
        DigitalCent(Axis,Alg) = j
        GOTO 44
      END IF
    END DO
  END DO
  CONTINUE
END DO
RETURN
END

SUBROUTINE Display_Event(i,j)

INTEGER*4 Frame(70,70), PeakHist(255), EnergyHist(2295),
& WidthHist(2,1000), Seed, Bias, EvePerFra, EvePerima, Counter, Display
COMMON /FRAME1/ Frame, PeakHist, EnergyHist, WidthHist,
& Seed, Bias, EvePerFra, EvePerima, Counter, Display

REAL*8 Boundary(2,8,8), Centroid(2,8)
INTEGER*4 DigitalCent(2,8), NumSubPixels
COMMON /BOUNDS/ Boundary, Centroid, DigitalCent, NumSubPixels

INTEGER*4 i, j, n, m, Alg

DO n = -2, 2
  WRITE(*,'(5i8)') (Frame(i+m,j+n), m=-2,2)
END DO
WRITE(*,'(8f10.4)') (Centroid(1,Alg), Alg=1,8)
WRITE(*,'(8i10)') (DigitalCent(1,Alg), Alg=1,8)
RETURN
END

SUBROUTINE Add_To_Statistics(Peak)

REAL*8 Boundary(2,8,8), Centroid(2,8)
INTEGER*4 DigitalCent(2,8), NumSubPixels
COMMON /BOUNDS/ Boundary, Centroid, DigitalCent, NumSubPixels

INTEGER*4 ImagePattern(8,8,8), Threshold(8,8,8),
& CentHist(2,-10000:10000,8), HeightHist(8,255,8)
COMMON /IMTHRES/ ImagePattern, Threshold, CentHist, HeightHist

INTEGER*4 i, j, Alg, Peak, x, y

DO Alg = 1, 8
  x = DigitalCent(1,Alg)
y = DigitalCent(2,Alg)
  HeightHist(x,y,Peak,Alg) = HeightHist(x,y,Peak,Alg) + 1
IF (Peak .GE. Threshold(x,y,Alg)) THEN
    ImagePattern(x,y,Alg) = ImagePattern(x,y,Alg) + 1
    i = NINT(Centroid(1,Alg)*10000.0d0)
    IF (i .LT. -10000) i = -10000
    IF (i .GT. 10000) i = 10000
    CentHist(1,i,Alg) = CentHist(1,i,Alg) + 1 ! x
    j = NINT(Centroid(2,Alg)*10000.0d0)
    IF (j .LT. -10000) j = -10000
    IF (j .GT. 10000) j = 10000
    CentHist(2,j,Alg) = CentHist(2,j,Alg) + 1 ! y
END IF
END DO
RETURN
END

SUBROUTINE Define_New_Boundaries
    ! Find new boundaries in function of m/n histograms.
    REAL*8 Boundary(2,8,8), Centroid(2,8)
    INTEGER*4 DigitalCent(2,8), NumSubPixels
    COMMON /BOUNDS/ Boundary, Centroid, DigitalCent, NumSubPixels
    INTEGER*4 ImagePattern(8,8,8), Threshold(8,8,8),
               & CentHist(2,-10000:10000,8), HeightHist(8,8,255,8)
    COMMON /IMTHRES/ ImagePattern, Threshold, CentHist, HeightHist
    INTEGER*4 i, j, Axis, Alg
    DO Alg = 1,8  ! Algorithm
        Total = 0.0d0
        DO i = -10000,10000
            Total = Total + CentHist(1,i,Alg)
        END DO
        Fraction = Total / DFLOAT(NumSubPixels)
        DO Axis = 1,2
            i = -10001
            j = 1
            Sum = 0.0d0
            DO WHILE (j .LT. NumSubPixels)
                DO WHILE (Sum .LT. Fraction)
                    i = i + 1
                    Sum = Sum + CentHist(Axis,i,Alg)
                END DO
                Excess = Sum - Fraction
                Boundary(Axis,j,Alg) = ( DFLOAT(i) + 0.5d0 -
                                         & Excess / DFLOAT(CentHist(Axis,i,Alg)) ) / 10000.0d0
                Sum = Excess
                j = j + 1
            END DO
        END DO ! Axis
    END DO ! Alg
RETURN
END

SUBROUTINE Clear_Arrays
    ! Clear ImagePattern and HeightHist arrays
    INTEGER*4 ImagePattern(8,8,8), Threshold(8,8,8),
               & CentHist(2,-10000:10000,8), HeightHist(8,8,255,8)
    COMMON /IMTHRES/ ImagePattern, Threshold, CentHist, HeightHist
    INTEGER*4 i, j, k, Alg
    DO Alg = 1,8
        DO i = 1,8
            DO j = 1,8
                ImagePattern(i,j,Alg) = 0
                DO k = 1,255
                    HeightHist(i,j,k,Alg) = 0
                END DO
            END DO
        END DO
SUBROUTINE Clear_Histograms

c Clear PeakHist, EnergyHist, and CentHist arrays

INTEGER*4 Frame(70,70), PeakHist(255), EnergyHist(2295),
& WidthHist(2,1000), Seed,Bias,EvePerFra,EvePerIma,Counter,Display

COMMON /FRAME1/ Frame, PeakHist, EnergyHist, WidthHist,
& Seed,Bias,EvePerFra,EvePerIma,Counter,Display

INTEGER*4 ImagePattern(8,8,8), Threshold(8,8,8),
& CentHist(2,-10000:10000,8), HeightHist(8,8,255,8)

COMMON /IMTHRES/ ImagePattern, Threshold, CentHist, HeightHist

INTEGER*4 i,j,Alg

DO i = 1,255
   PeakHist(i) = 0
END DO

DO i = 1,1000
   WidthHist(1,i) = 0
   WidthHist(2,i) = 0
END DO

DO i = 1,2295
   EnergyHist(i) = 0
END DO

DO Alg = 1,8
   DO i = 1,2
      DO j = -10000,10000
         CentHist(i,j,Alg) = 0
      END DO
   END DO
END DO

RETURN
END

C -------------------------------------------------------------
SUBROUTINE Open_Output_Files(NumCycles)

c Open files to store the changes of heights, centroids and boundaries

CHARACTER Name(8)*12,fdate*24
INTEGER*4 NumCycles
CHARACTER*45 Algorithm(8)

Algorithm(1) = ' 1. - 3 Pixel Gaussian Fitting'
Algorithm(2) = ' 2. - 3 Pixel Parabola Fitting'
Algorithm(3) = ' 3. - 3 Pixel Centre of Gravity'
Algorithm(4) = ' 4. - 3x3 (Added Pixels) Gaussian Fitting'
Algorithm(5) = ' 5. - 3x3 (Added Pixels) Parabola Fitting'
Algorithm(6) = ' 6. - 3x3 (Added Pixels) Centre of Gravity'
Algorithm(7) = ' 7. - 5x5 Pixels Centre of Gravity'
Algorithm(8) = ' 8. - 3 Pixel Gaussian Fitting with LUTs'

OPEN( 7,FILE='fpn.out',STATUS='UNKNOWN')
WRITE( 7, '(a4)' ) '# '
WRITE( 7, '(a4,a21)' ) '# ', Fixed Pattern Noise '
WRITE( 7, '(a4,a24)' ) '# ',fdate()
WRITE( 7, '(i10)' ) NumCycles

OPEN( 8,FILE='patterns.out',STATUS='UNKNOWN')
WRITE( 8, '(a4)' ) '# '
WRITE( 8, '(a4,a21)' ) '# ', Image Patterns '
WRITE( 8, '(a4,a24)' ) '# ',fdate()
WRITE( 8, '(i10)' ) NumCycles

OPEN( 9,FILE='boundaries.out',STATUS='UNKNOWN')
WRITE( 9, '(a4)' ) '# '
WRITE( 9, '(a4,a21)' ) '# ', Boundaries '

WRITE( 9 , '(a4,a24)', '# ', fdate() 
WRITE( 9 , '(i10)', ' NumCycles 

Name(1) = 'heights1.out'
Name(2) = 'heights2.out'
Name(3) = 'heights3.out'
Name(4) = 'heights4.out'
Name(5) = 'heights5.out'
Name(6) = 'heights6.out'
Name(7) = 'heights7.out'
Name(8) = 'heights8.out'
DO Alg = 1, 8
  fn = 20 + Alg
  OPEN( fn, FILE=Name(Alg), STATUS='UNKNOWN')
  WRITE(fn, '(a4,a18),'#','Heights Histogram'
  WRITE(fn, '(a4),'#'
  WRITE(fn, '(a4,a45),'#',Algorithm(Alg)
  WRITE(fn, '(a4,a24)','#',fdate()
  WRITE(fn, '(i10)') NumCycles
END DO
RETURN
END

SUBROUTINE Close_Output_Files
INTEGER*4 i
CLOSE(7)
CLOSE(8)
CLOSE(9)
DO i = 21, 28
  CLOSE(i)
END DO
RETURN
END

SUBROUTINE Write_Image_Pattern3(Cycle)
INTEGER*4 ImagePattern(8, 8, 8), Threshold(8, 8, 8),
& CentHist(2,-10000:10000,8), HeightHist(8, 8, 255, 8)
COMMON /IMTHRES/ ImagePattern, Threshold, CentHist, HeightHist
REAL*8 Boundary(2,8),Centroid(2,8)
INTEGER*4 DigitalCent(2,8), NumSubPixels
COMMON /BOUNDS/ Boundary, Centroid, DigitalCent, NumSubPixels

INTEGER*4 x,y,Alg,Cycle
DO y = 1, NumSubPixels
  WRITE(8 , '( i5,8<(NumSubPixels)i6,3x) ')
  Cycle, ((ImagePattern(x,y,Alg),x=1,NumSubPixels),Alg=1,8)
END DO
CALL flush(8)
RETURN
END

SUBROUTINE Write_Fixed_Pattern_Noise(Cycle)
INTEGER*4 ImagePattern(8, 8, 8), Threshold(8, 8, 8),
& CentHist(2,-10000:10000,8), HeightHist(8, 8, 255, 8)
COMMON /IMTHRES/ ImagePattern, Threshold, CentHist, HeightHist
REAL*8 Boundary(2,8),Centroid(2,8)
INTEGER*4 DigitalCent(2,8), NumSubPixels
COMMON /BOUNDS/ Boundary, Centroid, DigitalCent, NumSubPixels

REAL*8 fpn(2,8,8),Total(8)
INTEGER*4 i,j,Alg,Axix

C Find total number of counts in image patterns:
DO Alg = 1, 8
  Total(Alg) = 0.0d0
  DO i = 1, NumSubPixels
    DO j = 1, NumSubPixels
      Total(Alg) = Total(Alg) + ImagePattern(i,j,Alg)
DO Alg = 1, 8
  c Add columns and divide by mean:
  DO i = 1, NumSubPixels
    fpn(1,i,Alg) = 0.0d0
    DO j = 1, NumSubPixels
      fpn(1,i,Alg) = fpn(1,i,Alg) + ImagePattern(i,j,Alg)
    END DO
    fpn(1,i,Alg) = NumSubPixels * fpn(1,i,Alg) / Total(Alg)
  END DO
  END DO

  c Add rows and divide by mean:
  DO j = 1, NumSubPixels
    fpn(2,j,Alg) = 0.0d0
    DO i = 1, NumSubPixels
      fpn(2,j,Alg) = fpn(2,j,Alg) + ImagePattern(i,j,Alg)
    END DO
    fpn(2,j,Alg) = NumSubPixels * fpn(2,j,Alg) / Total(Alg)
  END DO
  END DO

  c Write results:
  DO i = 1, NumSubPixels
    WRITE(7,'(i5,8f8.4,5x,8f8.4)') Cycle, ((fpn(Axis,i,Alg), Alg=1,8), Axis = 1,2)
  END DO
  CALL flush(7)
  RETURN
END

SUBROUTINE Write_Current_Boundaries(Cycle)
  REAL*8 Boundary(2,8,8), Centroid(2,8)
  INTEGER*4 DigitalCent(2,8), NumSubPixels
  COMMON /BOUNDS/ Boundary, Centroid, DigitalCent, NumSubPixels

  INTEGER*4 Axis, Bou, Alg, Cycle
  DO Bou=1, NumSubPixels-1
    WRITE(9,'(i5,8f9.4,5x,8f9.4)') Cycle, ((Boundary(Axis,Bou,Alg), Alg = 1,8), Axis=1,2)
  END DO
  CALL flush(9)
  RETURN
END

SUBROUTINE Write_Centroid_Histograms
  c In order to save disk space the histogram is binned

  INTEGER*4 ImagePattern(8,8,8), Threshold(8,8,8),
  & CentHist(2,-10000:10000,8), HeightHist(8,8,255,8)
  COMMON /IMTHRES/ ImagePattern, Threshold, CentHist, HeightHist

  REAL*8 Boundary(2,8,8), Centroid(2,8)
  INTEGER*4 DigitalCent(2,8), NumSubPixels
  COMMON /BOUNDS/ Boundary, Centroid, DigitalCent, NumSubPixels

  INTEGER*4 Axis, Ele, Alg, i, binned(2,8)
  CHARACTER fdate*24

  OPEN(10,FILE='centroids.out',STATUS='UNKNOWN')

  WRITE(10,'(a4)') '#
  WRITE(10,'(a4,a21)') '# Centroid Histograms'
  WRITE(10,'(a4,a24)') '#',fdate()

  DO Ele = -1000,999
    DO Alg = 1, 8
      DO Axis = 1,2
        binned(Axis,Alg) = 0
      END DO
      DO i = 0,9
        DO Alg = 1, 8
          DO Axis = 1,2
            binned(Axis,Alg) = 0
          END DO
          DO i = 0,9
& binned(Axis,Alg) = binned(Axis,Alg) +
    CentHist(Axis,Ele*10+i,Alg)
END DO
END DO
WRITE(10,'(f8.3,2(I17,5x))')
& Ele/1000.0,((binned(Axis,Alg),Alg=1,8),Axis=1,2)
END DO
CLOSE(10)
RETURN
END

SUBROUTINE Write_Heights_Histograms(Cycle)

INTEGER*4 ImagePattern(8,8,8), Threshold(8,8,8),
    CentHist(2,-10000:10000,8), HeightHist(8,8,255,8)
COMMON /IMTHRES/ ImagePattern, Threshold, CentHist, HeightHist
REAL*8 Boundary(2,8), Centroid(2,8)
INTEGER*4 DigitalCent(2,8), NumSubPixels
COMMON /BOUNDS/ Boundary, Centroid, DigitalCent, NumSubPixels

INTEGER*4 x,y,Ele,Alg,Cycle,fn

DO Alg = 1,8
   fn = 20 + Alg
   DO Ele = 1,255
      WRITE(fn,'(i3,i4,<NumSubPixels**2>i5)')
      Cycle,Ele,((HeightHist(x,y,Ele,Alg),
                      x=1,NumSubPixels),y=1,NumSubPixels)
   END DO
   CALL flush(fn)
END DO

RETURN
END

SUBROUTINE Write_Peak_Energy_Statistics

INTEGER*4 Frame(70,70), PeakHist(255), EnergyHist(2295),
    WidthHist(2,1000), Seed,Bias,EvePerFra,EvePerIma,Counter,Display
COMMON /FRAME1/ Frame,PeakHist,EnergyHist,WidthHist,
    Seed,Bias,EvePerFra,EvePerIma,Counter,Display

INTEGER*4 i
CHARACTER fdate*24

OPEN( 5,FILE='peak.out',STATUS='UNKNOWN')
WRITE( 5,'(a4)' ) '#'
WRITE( 5,'(a4,a21)' ) '#', 'Peak Statistics'
WRITE( 5,'(a4,a24)' ) '#', fdate()
WRITE( 5,'(a4)' ) '#

DO i = 1,255
   WRITE(5,'(2i10)') i,PeakHist(i)
END DO
CLOSE(5)

OPEN( 5,FILE='width.out',STATUS='UNKNOWN')
WRITE( 5,'(a4)' ) '#
WRITE( 5,'(a4,a21)' ) '#', 'Width Statistics'
WRITE( 5,'(a4,a24)' ) '#', fdate()
WRITE( 5,'(a4)' ) '#

DO i = 1,1000
   WRITE(5,'(f8.2,2i10)') i/100.0,WidthHist(1,i),WidthHist(2,i)
END DO
CLOSE(5)

OPEN( 5,FILE='energy.out',STATUS='UNKNOWN')
WRITE( 5,'(a4)' ) '#
WRITE( 5,'(a4,a21)' ) '#', 'Energy Statistics'
WRITE( 5,'(a4,a24)' ) '#', fdate()
WRITE( 5,'(a4)' ) '#
DO i = 2, 2295
  IF(EnergyHist(i).GT.0) WRITE(5,'(2i10)') i, EnergyHist(i)
END DO
CLOSE(5)
RETURN
END

FUNCTION Random_Gauss(i)
INTEGER*4 i, iset
REAL*8 v1, v2, r, fac, gset
DATA iset/0/
IF(set .EQ. 0) THEN
  v1 = 2.0d0 * RAN(i) - 1.0d0
  v2 = 2.0d0 * RAN(i) - 1.0d0
  r = v1*v1 + v2*v2
  IF(r .GE. 1.0d0 .OR. r .EQ. 0.0d0) GOTO 11
  fac = DSQRT(-2.0d0*DLOG(r)/r)
  gset = v1*fac
  Random_Gauss = v2*fac
  iset = 1
ELSE
  Random_Gauss = gset
  iset = 0
END IF
RETURN
END

FUNCTION Gaussian_LUT(a, b, c)
c Gaussian algorithm using a logarithms lookup table before data
analysis array. One is added in order to avoid error when a or c
have a value of zero.
INTEGER*4 a, b, c, al, bl, cl, n, k
REAL*8 m
IF(a .LE. 0) a = 1
IF(b .LE. 0) b = 1
IF(c .LE. 0) c = 1
al = NINT(DLOG(a+1.0d0)*255.0d0/DLOG(256.0d0))
b1 = NINT(DLOG(b+1.0d0)*255.0d0/DLOG(256.0d0))
c1 = NINT(DLOG(c+1.0d0)*255.0d0/DLOG(256.0d0))
al = NINT(DLOG(a+1.0d0)*255.0d0/DLOG(255.0d0))
b1 = NINT(DLOG(b+1.0d0)*255.0d0/DLOG(255.0d0))
c1 = NINT(DLOG(c+1.0d0)*255.0d0/DLOG(255.0d0))
m = DFLOAT(cl-al)
n = 2*bl-al-cl
k = 2*MOD(n, 2) - 1
IF(n .EQ. 0) THEN
  Gaussian_LUT = 0.0d0
  ELSE
    Gaussian_LUT = (m+0.25d0*k)/DFLOAT(n)
END IF
RETURN
END

FUNCTION Gaussian_Fitting(a, b, c)
c Gaussian algorithm:
c One is added in order to avoid error when a or c have a value of zero.
INTEGER*4 a, b, c
REAL*8 al, bl, cl, n
al = DLOG(a+1.0d0)
b1 = DLOG(b+1.0d0)
c1 = DLOG(c+1.0d0)
n = 2.0d0*(2.0d0*bl-al-cl)
IF(n .EQ. 0.0d0) THEN
  Gaussian_Fitting = 0.0d0
ELSE
  Gaussian_Fitting = (cl-al) / n
END IF
RETURN
END
FUNCTION FWHM(a,b,c)

One is added in order to avoid error when a or c have a value of zero.

c 2.77258787 = -4*ln(0.5)

INTEGER*4 a,b,c
REAL*8 al,bl,cl,Gamma

al = DLOG(a+1.0d0)
b1 = DLOG(b+1.0d0)
c1 = DLOG(c+1.0d0)

Gamma = (2.0d0*bl-al-cl)/2.0d0

IF (Gamma .EQ. 0.0d0) THEN
FWHM = 0.0d0
ELSE
FWHM = DSQRT(2.7725887d0/Gamma)
FWHM = 1.73d0 * FWHM**0.75 - 1.04d0 ! Correction
END IF
RETURN
END

C

FUNCTION Parabola_Fitting(a,b,c)

INTEGER*4 a,b,c,n,k
REAL*8 m

m = DFLOAT(c-a)
k = 2*MOD(n,2)-1 ! -1,1

IF (n .EQ. 0) THEN
Parabola_Fitting = 0.0d0
ELSE
Parabola_Fitting = (m+0.25d0*k)/DFLOAT(n)
END IF
RETURN
END

FUNCTION Centre_of_Gravity(a,b,c)

INTEGER*4 a,b,c,n,k
REAL*8 m

m = DFLOAT(c-a)

k = 2*MOD(n,2)-1 ! -1,1
Centre_of_Gravity = (m+0.25d0*k)/DFLOAT(n)
RETURN
END

C

FUNCTION Centre_of_Gravity_5(a,b,c,d,e)

INTEGER*4 a,b,c,d,e,n,k
REAL*8 m

m = DFLOAT(2*e+d-b-2*a)

k = 2*MOD(n,2)-1 ! -1,1
Centre_of_Gravity_5 = (m+0.25d0*k)/DFLOAT(n)
RETURN
END

C

FUNCTION SECHS(a,b,c)

REAL*8 al,bl,cl,alpha,k1,k2,pi

al = a+1.0d0
bl = b+1.0d0
cl = c+1.0d0

k1 = DSQRT(bl/al)
k2 = DSQRT(bl/cl)
pi = 3.141592654d0
alpha = 0.5d0 * ( k1 + k2)
c pi / arccosh(alpha)
alpha = pi / DLOG( alpha + DSQRT(alpha*alpha-1) )
SECHS = 0.5d0*(k1-k2)/DSINH(pi/alpha)
c arctanh(SECHS)
SECHS = 0.5d0 * DLOG( (1.0d0+SECHS) / (1.0d0-SECHS) )
SECHS = SECHS * alpha / pi
RETURN
END
APPENDIX E

Synthetic Events Generator Programme

This programme produces a data base of synthetic events that emulate the events produced by the MIC intensifiers. Four gaussians are combined to generate a surface whose axis is randomly shifted within (+0.5 and -0.5 CCD pixels in both the X and Y directions) before being integrated in cells of an array representing the pixels of the CCD camera.

The surface is given by the function:

\[
z(x, y) = f(x) \cdot g(y) = \exp(-\gamma_x x^2) \cdot \exp(-\gamma_y y^2)
\]

\[
\gamma_x = \gamma_{x_n} \text{ for } x \leq 0, \quad \gamma_x = \gamma_{x_p} \text{ for } x > 0
\]

\[
\gamma_y = \gamma_{y_n} \text{ for } y \leq 0, \quad \gamma_y = \gamma_{y_p} \text{ for } y > 0.
\]

The \(\gamma\) parameters defines the width of the gaussians as shown in Appendix A it is given by:

\[
\gamma = \frac{-4 \ln \frac{\gamma}{w^2}}
\]

where \(w\) is the FWHM of the gaussian.

An example of functions \(f\) and \(g\) is shown in Fig. E.1 and a contour diagram of two different cases on Fig. E2 followed by the listing of the programme.

![Figure E.1](image)

**Figure E.1** Functions \(f\) and \(g\) whose multiplication generates the 'egg shaped' event used to produce simulated intensifier events. The solid line represents a function whose components are a gaussian with a FWHM of 1.2 CCD pixels on the negative side and another gaussian with a FWHM of 1.5 CCD pixels in the positive side. The dashed line is made of two gaussians whose FWHM is 1.2 CCD pixels.
PROGRAM GenerateEggEventsRandomly

C This program generates a data base of NEPP*NEPP 'egg shaped' events.
C Four gaussians are combined to generate a surface which is shifted
C in x and y by steps of size delta (1/NEPP).
C The surface is integrated in each pixel which are subdivided in
C NDiv*NDiv squares.

C Variables:

INTEGER*4  NEPP, NDiv, i, j, k, l, m, n, ReadError, IEvent(-3:3,-3:3), Seed
REAL*8       fwhmXn, fwhmXp, gammaXn, gammaXp, x, f, offsetx, originx,
             fwhmYn, fwhmYp, gammaYn, gammaYp, y, g, offsety, originy,
             increment, delta, factor, Event(-3:3,-3:3)
CHARACTER OutFile*60

NDiv = 20
increment = 1.0d0/NDiv       ! increment of integrations

OPEN (2, FILE='genegggrnd.com', STATUS='OLD')

C Read first set of parameters:
C NEPP   = Number of events per pixel in x and y (even is better)
C fwhmXn = Full width at half maximum x left (pixels).
C fwhmXp = Full width at half maximum x right (pixels).
C fwhmYn = Full width at half maximum y left (pixels).
C fwhmYp = Full width at half maximum y right (pixels).
C OutFile = File to contain results.

READ(2,*,IOSTAT = ReadError) NEPP, fwhmXn, fwhmXp, 
      fwhmYn, fwhmYp, OutFile, Seed

WRITE(*,*)
WRITE(*,*)
WRITE(*,*) ' Full width at half maximum x left = ', fwhmXn
WRITE(*,*) ' Full width at half maximum x right = ', fwhmXp
WRITE(*,*) ' Full width at half maximum y left = ', fwhmYn
WRITE(*,*) ' Full width at half maximum y right = ', fwhmYp
WRITE(*,*)
WRITE(*,*) NEPP*NEPP, ' events being written to ', OutFile
WRITE(*,*)

DO WHILE (ReadError .NE. -1)  ! -1 = end of file

  gammaXn = -4.0d0*DLOG(0.5d0)/((fwhmXn*fwhmXn))
  gammaXp = -4.0d0*DLOG(0.5d0)/((fwhmXp*fwhmXp))
  gammaYn = -4.0d0*DLOG(0.5d0)/((fwhmYn*fwhmYn))
  gammaYp = -4.0d0*DLOG(0.5d0)/((fwhmYp*fwhmYp))
OPEN (8, FILE=OutFile, FORM='UNFORMATTED', STATUS='UNKNOWN')
WRITE(8) NEPP*NEPP ! total number of events

c Define scaling factor, all pixels smaller than maximum INTEGER*4
factor = 2147000000.0d0 / DFLGAT(NDiv*NDiv)

c Integrate events:
c shift:
DO n = -NEPP/2,(NEPP-1)/2
  offsety = RAN(Seed) - 0.5d0
  DO m = -NEPP/2,(NEPP-1)/2
    offsetx = RAN(Seed) - 0.5d0
    c scan pixels:
    DO i = -3,3
      Event(i,j) = 0.0d0 ! Clear row i
    END DO
    originy = j + offsety
    DO i = -3,3
      originx = i + offsetx
      c integrate pixel:
      DO l = 1,NDiv
        y = originy + l*increment
        IF( y .LT. 0.0d0) g = DEXP(-gammaYn*y*y)
        IF( y .GE. 0.0d0) g = DEXP(-gammaYp*y*y)
        DO k = 1,NDiv
          x = originx + k*increment
          IF( x .LT. 0.0d0) f = DEXP(-gammaXn*x*x)
          IF( x .GE. 0.0d0) f = DEXP(-gammaXp*x*x)
          Event(i,j) = Event(i,j) + f*g
        END DO
      END DO
      IEvent(i,j) = NINT(factor*Event(i,j)) ! Scale pixels
    END DO
  END DO
END DO
WRITE(8) ((IEvent(i,j), i=-3,3), j=-3,3)
END DO
END DO
CLOSE(8)
READ(2,*,IOSTAT=ReadError) NEPP,fwhmXn,fwhmXp,
fwhmYn,fwhmYp,OutFile
END DO ! while
# APPENDIX F

## Data for Graphs in Figure 7.16

### Illumination

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# APPENDIX G

Data for Graphs in Figure 7.18

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## APPENDIX H

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Fordham J. and Michel R. "Analysis of the 75mm 10µm/25µm Pore Intensifier when Incorporated in the BigMIC Detector". Internal Report to Imperial College. 1994.
