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Detector System Design I
<< Centroiding >>

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Detector System Design I --- Centroding

26 October 2000
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1. Introduction

Swift UVOT detector employs CCD readout coupled with a high sensitivity image intensifier (Fig. 1), which pre-amplifies a single photon to 1 million photons before entering the CCD. Because of this high pre-amplification, the CCD can be readout in high speed without loss of S/N in spite of the readout noise of ~400 electrons in our electronics. The CCD is not necessary to be cooled, therefore simple mechanical structure and large saving of power consumption are allowed. Since the detector is warmed up by the CCD, the intensifier is safe against condensation and contamination, which sometimes causes problem for a cooled bear CCD detector. The input of the intensifier is FuSi window, which is hard material, hence can be wiped at any time before the launch. Its handling is far easier than a bear CCD.

Radiation damage of CCD is one of the critical problem in space. The rear side of the CCD can be covered with a heavy metal, but it is impossible to protect photon input side for a bear CCD detector. While, the input side of our CCD is protected by the image intensifier, which is consist of FuSi window, MCPs stack and thick fibre optics. The rear side is covered with a thick Ta shield. Radiation protection of our CCD is almost perfect (except against energetic solar protons).

The disadvantage of the use of the image intensifier is the lower Q.E. in optical wavelengths, but still competitive in UV wavelengths, where the most important science information exists. Its competitiveness is maximum at the very low light level, thanking to the superb low dark current performance of our intensifiers.

Another disadvantage is loss of resolution due to the spatial spread of event splash at the phosphor screen. The size of the event splash increases with the intensifier gain. We set up the intensifier gain highest to enable photon counting. This makes the event splash large. To compensate this, our intensifier employed the shorter anode gap and smaller number of MCPs stack, but the event size is still large, typically 80um (FWHM).

This resolution loss can be recovered by the following 2 methods when the image is acquired in photon counting mode.

a) If an individual event is captured by a high speed CCD camera and the event is addressed to the peak CCD pixel position, this resolution loss can be recovered to CCD pixel size (Boksenberg 1970 [1]).

b) If centre of gravity of an individual event is calculated (Centroiding, hereafter) by a complicated image processor, superior resolution, finer than a CCD pixel size, can be achieved (Boksenberg et. al. 1985 [2]).

There are trade off between the two methods. The method (a) requires less complicated image processor, since one logical pixel corresponds to one physical pixel. It is not suffer from artificial fixed pattern associated with the logical pixelization. It does not require a very high gain intensifier either a low noise CCD camera, because only peak pixel position is used for the imaging. It, however, requires a large format CCD, hence more expensive. The frame rate is slower and dynamic range against a point source object is small.

The method (b) does not require a large format CCD, since many logical pixels are created within a CCD pixel. The smaller CCD format allows faster frame rate, keeping the pixel format large. This expands dynamic range against a point source object. It, however, should be noted that this does not expand dynamic range against a diffused object (e.g. sky background).

The frame rate jumps up by the reduction of CCD pixel number, but coverage of the sky by each CCD pixel also expand. Speed up of frame rate and increase of incoming photons cancel each other, concerning about coincidence probability. For instance, 2048x2048 CCD pxiels are required for the method-(a) to achieve 2048x2048 resolution, while only 256x256 CCD pixels for the method-(b) with 8-subpixel centroiding. Assuming 10MHz CCD clock rate, frame rate is 10/4 (FR/sec) for the method-(a) and 10/0.064 (FR/sec) for the method-(b). The frame rate of method-(b) is 64 times as fas as methods-(a). This improve dynamic range against a star. Assuming sky background of 100,000 (counts/s whole detector), photon arriving rate is 0.1/4 (counts/sec CCD_pixel) for the method-(a) and 0.1/0.064 (counts/sec CCD_pixel) for the method-(b). If divided by the frame rates, photon densities per frame are turned out to be exactly same in the both methods, i.e. 0.01 (counts/FR CCD_pixel). In terms of the coincidence for the sky background, the method-(b) does not improve the performance. It is actually far worse, because of the usage of the 3x3 CCD pixel array for centroiding. Coupled with the CCD array and actual extent of the event splash, effective coincidence territory of an event is 37 CCD pixels. Photon densities per territory is 0.37 (counts/FR territory). So, 10% coincidence will occur at the sky brightness of 30,000 counts / sec (full detector area).

The method-(b) requires complicated digital processor, since a detailed profile of single event must be investigated to create the many logical pixels. It is suffered from artificial fixed pattern (though time variable in contrary with the name) due to position inaccuracies of the centroiding. It requires very high gain intensifier and low noise CCD readout to acquire event profile in high S/N. It also requires severe blemish control. If a single position, wherever it is located at MCPs, phosphor, fibre optics or CCD, the affection extends to 3x3 CCD pixel, hence 24x24 subpixel (assuming 8-subpixel centroiding).

If increasing subpixel number per CCD pixel, for instance 16, 32, 64 subpixels/CCD pixel, the CCD pixel format can be smaller and smaller. It requires only 32x32 CCD pixels to create 2048x2048 logical pixels with the 64-subpixel centroiding. The frame rate is more than 9000 frames/sec with 10MHz CCD clocking, which allows to observe bright star of 900counts/sec with 10% coincidence. The ultimate case is 2048-subpixel centroiding with 1 physical pixel, which tends to MSSL's anode detectors (Lapington [3]), i.e. Wedege/Strip, SPAN, Vanier ..... [In contrary with CCD readout, these detectors are not suffer from 3x3 sampling array either event territory size, therefore coincidence probability is only 1% for 100,000 c/s sky background with 10MHz readout.]. The disadvantage of the large subpixel number is requirement of extremely high precision centroiding, which needs very high gain intensifier to obtain superior S/N in event profile. This causes pore paralysis against bright stars, and shorten the life time of the intensifier. There is optimum subpixel number between the technical difficulty and the dynamic range performance. A 8-subpixel/(CCD pixel) was chosen for XMM-OM project (Fordham et al (1992) [4]). Because of its success, same subpixel number will be employed for the Swift UVOT detector.

There are a lot of artifacts related with the centroiding even if only 8 subpixels/CCC pixel. The following sections will describe the mechanism of the problems and will provide practical solutions for Swift-project.

2. One dimension centroiding

Fig. 2 shows internal structure of our intensifier. A single photon enters through the concave FuSi window and hits the S-20 photocathode. The photon is converted to a single electron at the photocathode. The electron obtains kinetic energy of 400eV during travel of the 150um photocathode gap and then strikes the MCP1. The energetic electron causes cascade in the MCP1. It is amplified further by MCP2. Finally, cloud of 5E+5 electrons comes out. An individual electron in the cloud obtains kinetic energy of 5500eV during travel of the anode gap and strikes P-46 phosphor screen, which generates 80 green photons/electron. The size of splash is typically 80um (FWHM). This event splash image is directly coupled to CCD with the scale reduction of 3.37 through a tapered fibre and a fibre stub on the CCD. The brightness is attenuated to 1/30 through the both fibre optics. As the results, a single photon is amplified to 1.3 million photons with the size of 24um(FWHM) at the input of the CCD. The event splash profile is sampled by 22um CCD pixels and its centre of the gravity is calculated from the consecutive 3 CCD pixels.

Fig. 3 shows event splashes at the output of the intensifier captured by a low noise CCD camera through magnification optics. Brightness are different event by event. Fig. 4 shows pulse height distribution of XMM-FM intensifier, where the "pulse" represents the brightness at peak CCD pixel. This intensifier has remarkably narrow pulse height distribution (i.e. small variation of gain) and has very deep valley. If event splashes is recorded as it is (analog mode), a photometric error is introduced due to the gain difference among events. If individual event splash is counted as "one" by a digital processor with the threshold level of 15 ADU (= valley position), the recorded image is free from the gain variation. It also rules out dark noises generated within MCP walls, therefore the integration time can be extended largely without contamination.

To simulate general characteristics and accuracies of centroiding, a CCD pixel was scanned by well known profiles, i.e. Gaussian and Lorentzian, along X-direction at Y=centre with the step of 1/120 CCD pixel. Fig. 5 shows the profiles with FWHM= 0.7 CCD pixel. In spite of the same width at core part, Lorentzian has significantly larger wing. Fig. 6 shows the sample of the event splash by CCD pixels. Pix-B is the peak CCD pixel and outputs of Pix-A and Pix-C are used for the fine position calculation (centroiding). There are 2 calculation algorithms,

$$X = \frac{C-A}{A+B+C} \quad \text{(3-pix centre of gravity)}$$

$$X = \frac{C-A}{4B-2A-2C} \quad \text{(parabola fitting)},$$

where, A,B and C denote outputs of Pix-A -B and -C. Since output of Pix-D is ignored, the calculated centre of gravity is shifted to right from the true position. If location of the event profile moves to left a little, Pix-A becomes the peak CCD pixel, hence Pix-D is involved for the calculation, while Pix-C is ignored. Then, the calculated centre of gravity is shifted to right. Therefore, discontinuity occurs at CCD pixel boundary due to the switch of sampling CCD pixels. If the event profile is sharper, the outputs of Pix-C and Pix-D become smaller, hence the discontinuity becomes smaller. Parabola profile fitting depends on the sampling CCD pixels very little, therefore the discontinuity is far smaller. Fig. 7 shows the sample by CCD pixels for 2-Pix centre of gravity algorithm. Pix-B is the peak CCD pixel and output of Pix-A is used for the fine position calculation. The equation is

$$X = \frac{C}{B+C} \quad \text{(2-pix centre of gravity)},$$

Since output of Pix-A is ignored, the calculated centre of gravity is shifted to right from the true position. If location of the event profile moves to left a little, Pix-A is involved, while Pix-C is ignored. Then, the calculated centre of gravity is shifted to right. Therefore, discontinuity occurs at CCD pixel centre due to the switch of sampling CCD pixels. The event profile must be extremely sharp to minimize the discontinuity, since the outputs of the neighbouring pixels, Pix-A and Pix-C must be minimum.

Fig. 8 shows relation (characteristic curve) of calculated position to real position, which is a priori known in this simulation. Gaussian profile was used for this calculation. None of algorithm showed linear relation to the real position. Discontinuities are seen at the boundaries of CCD pixel in 3-Pix centre of gravity algorithm for the larger event (FWHM=1.4 CCD pixel). It disappears for the smaller event, but it starts twisting. Parabola fitting algorithm does not show discontinuity but has strong twist, specially for the smaller event. The 2 pixel centre of gravity algorithm shows big discontinuity at CCD pixel centre for the larger event. But, it shrinks remarkably for the smaller event (FWHM=0.7 CCD pixel). 2-pix centre of gravity is strong against coincidence, as only 2 CCD pixels are involved, and this simulation shows better centroiding performance with the smaller event. If event profile can be really small, 2-Pix centre of gravity algorithm is ideal for high count rate imaging.

Fig. 9 shows characteristic curves with Lorentzian event profile. The discontinuities are large in 3-Pix centre of gravity and 2-Pix centre of gravity even with the smaller event. While, twist of the curve in parabola fitting becomes lighten. These are due to the extended wing of Lorentzian profile.

Fig. 10 shows the standard event profile of XMM's FM intensifier (DEP_#8). It does not only have strong wing, but also has ellipsity and asymmetry. Fig. 11 shows characteristic curves with the true event profile. Event width varies event by event up to 25%(p-p) even at a same place of our intensifier (Kawakami et. al. 1999 [5]). The standard profile was magnified and reduced by 12.5% in this calculation to see the centroiding errors at one position. The discontinuities are significant in 3-Pix centre of gravity and 2-Pix centre of gravity, which are similar to those with Lorntzian profile. The twist in parabola fitting is not so large.

Gaussian event profile has been commonly used for centroiding simulation for its convenience (Carter et. al. 1990 [6], Michel et. al. 1997 [7]), and remarkable reduction of the discontinuities have been reported with small events for centre of gravity algorithm. It would be true for such application whose event profile has no wing component. But, it is not the case with our image intensifier as shown above. At least, Lorentzian profile must be used for the simulation. Of course, a true event profile with asymmetric component is ideal.

Non-linear response of the algorithms is revealed as fixed pattern when acquiring F-F image. If a CCD pixel is divided into 8 subpixel trusting in the calculated value (hereafter "equal boundaries"), subpixel-1 is faint because of its small pixel size in the real geometry as shown in Fig. 12 with parabola fitting algorithm. While, subpixel-4 is bright because of its large pixel size in the real geometry. This problem, however, can be solved if the characteristic curve is introduced for correction.

The characteristic curve can be determined so that response of each subpixel becomes flat for F-F input. A CCD pixel was uniformly bombarded by 57600 events in the step of 1/240 x 1/240 CCD pixel. The true event profile without magnification nor reduction was used for this bombardment test. Number distribution of the calculated value (M/N) is shown in Fig. 13. Where, "M" denotes numerator of equations in each algorithm and "N" denominator. The bin size along abscissa is M/N=1/240. The number distribution was integrated from the smaller M/N to the larger M/N. The integrated count at M/N=1.0 must be total number of the bombardments, i.e. 240x240 =57600 counts.
We assume,
1) M/N increases monotonously from left to right in the real position,
2) M/N=-0.5 corresponds left edge of the CCD pixel (i.e. X=-0.5) and M/N=+0.5 right edge (X=+0.5),
3) Events are uniformly bombarded, and uniformly detected.

The central position of the CCD pixel is easily determined from this diagram, because events fell in the left hand side and in the right hand of the central position should be balanced. "X2" at the ordinate is such position, i.e. number of event above "X2" is 28800 counts and below 28800 counts. The corresponding position "M/N=B2" at the abscissa is determined via the integrated distribution curve. Now, the boundary between subpixel-4 and subpixel-5 is obtained.
Next, we should concentrate on the left half of a CCD pixel in order to determine the quarter position. Events fell in the left hand side and in the right hand of the quarter position should be same if the world is restricted within the left half of the CCD pixel. "X4" at the ordinate is such position, i.e. number of event above "X4" is 14400 counts

and below 14400 counts. The corresponding position "M/N=B4" at the abscissa is determined via the integrated distribution curve. Now, the boundary between subpixel-2 and subpixel-3 is obtained.
Next, we should concentrate on the left quarter of a CCD pixel in order to determine the octavo position. Events fell in the left hand side and in the right hand of the quarter position should be same if the world is restricted within the left quarter of the CCD pixel. "X8" at the ordinate is such position, i.e. number of event above "X8" is 7200 counts and below 7200 counts. The corresponding position "M/N=B8" at the abscissa is determined via the integrated distribution curve. Now, the boundary between subpixel-1 and subpixel-2 is obtained.

Repeating this procedure, all 7 boundaries of the 8-subpixel centroiding are obtained. If the procedure is repeated further, we can determine any fine boundary for 16, 32-, 64-, 128-subpixel centroidings. Actually, the ordinate for the integrated (M/N)-distribution corresponds to real position. By swapping the ordinate and the abscissa, we can obtain characteristic curve as shown in Fig. 14. To test this characteristic curve, a CCD pixel was uniformly bombarded by events in the step of 1/120 x 1/120 CCD pixel, and fixed pattern was calculated. The lower panel of Fig. 15 shows the fixed pattern with equal boundaries, while the upper panel with new boundaries. This simulation proven the successful flattening of the fixed pattern. Tiny undulation seen in the fixed pattern is due to calculation inaccuracies of the computer and a small imperfection of this (M:N)-distribution approach, which will be discussed in the next section.

Discontinuity in the characteristic curve is another cause of the fixed pattern. It is far more difficult to treat. Fig. 16 shows the discontinuity with 2-Pix centre of gravity algorithm. The width of events varies place by place globally in an actual intensifier. We assume that the width FWHM=1.4 CCD in the right hand side of the intensifier and the width FWHM=0.7 CCD in the left half, and the characteristic curve was determined in the right half. If an event arrived at sub-CCD position of X=X0 at the left half of the intensifier, it is interpreted as X=Z0 by the characteristic curve. If an event arrived at sub-CCD position of X=X2 at the left half of the intensifier, it is interpreted as X=Z1. Exactly same mechanism works at the right hand side of the CCD pixel in the manner of mirror symmetry. Therefore, a black hole will appear around CCD pixel centre in the centroiding image. There is discontinuity in 3-Pix centre of gravity algorithm at the edge of a CCD pixel. The same mechanism works and black square stripe will appear at the edge of CCD pixel. There is no discontinuity in parabola fitting algorithm. This is significant advantage.

3. Two dimension centroiding

One dimension centroiding with fine position correction by centroiding LUT (characteristic curve) looks good as described in the previous section. If the same approach is applied to the other axis, Y-axis, the centroiding can be extended to 2-dimension imaging.

The lower panel of Fig. 17 shows contour map of X-characteristic curve slicing at many Y-positions, where event profile was sampled by 3X- and 3Y-CCD pixels around peak pixel (cross-hair sampling). There is tilt shifting from right to left along +Y axis. This is caused by mis-orientation of the elliptic feature (see Fig. 10). The orientation of MCPs against CCD chip is specified in order to minimize this effect but accuracy is 5 degrees. There is curvature in the contour map, which is due to the asymmetric component of the event profile. Two X-characteristic curves sliced at Y positions, Y=-0.46875 and +0.46875 are shown in Fig. 18. There is shows systematic difference between the 2 curves. If single X-LUT is applied to the both Y positions, centroiding error will occur systematically. Fig. 19 shows extraordinary behaviour of X-characteristic curves for the 3 algorithms at Y-CCD edge (Y=-0.5 and +0.5). The jump of the curves were caused by the transition of peak CCD pixel in Y-direction, hence transition of sampling region of the event profile.

We can force to create 2-dimension image with 1-dimension X-LUT and 1-dimension Y-LUT. The M:N distribution for the 2 LUTs were generated by bombarding a CCD pixel in the step of 1/240 x 1/240 CCD pixel. Fig. 20 shows position errors at subpixel boundaries with parabola fitting algorithm. Fig. 21, 22 and 23 show true subpixel geometries for 3-pix centre of gravity, parabola fitting and 2-pix centre of gravity algorithms. Parabola algorithm shows the most modest distortion. Some subpixels occupy the larger area and some the smaller. These are seen as the fixed pattern in centroiding image. The displacement of the subpixel position causes distortion in the image, though the amounts are small, <1/4 subpixels (~2 um). It should be noted that CCD pixel boundary is not hard boundary of the subpixels.

The distortion and size variation of subpixels are not so large if the two 1-dimenision LUTs are tuned to the event profile. But, the event size changes across detector filed. For instance, if the LUTs are tuned using detector central region, they may be out of tune at detector edge. Fig. 24 shows subpixel distortion when event size is smaller by 12.5% than tuned, and Fig. 25 when event size is larger by 12.5%. The distortion of subpixels are significantly larger. Fig. 26 shows fixed patterns for smaller, right size and larger events. The variation of fixed pattern reaches 20%.

If a pure 2-dimension LUT is introduced, the centroiding error should be zero for the right event size. But, this 2-dimension LUT can not cope with the variation of event size across the detector field as shown in Fig. 27 for the smaller event and in Fig. 28 for the larger event. Another practical problem is deriving the LUT. Since we knew the event position a priori in this simulation, we could make X-LUT at Y=-0.46875 (Fig. 18). We had to carry out M:N distribution approach to get X-LUT in a real detector. The M:N distribution approach assumed;

1) M/N=-0.5 corresponds left edge of the CCD pixel (i.e. X=-0.5)
and
2) M/N=+0.5 corresponds left edge of the CCD pixel (i.e. X=+0.5)

It is obvious this assumption breaks down in Fig. 18, where M/N=-0.5 corresponds to real position X=-0.588 and M/N=+0.5 to X=+0.412. If M:N approach is applied, the result shifts the characteristic curve left wards by 0.088 CCD pixels. The M:N approach shifts the characteristic curve right wards. The characteristic curve at Y=+0.46875 is in the opposite sense, and shifts the characteristic curve left wards. The pure 2-dim LUT sounds good but can not be obtained in the real detector. It should be noted, the 1-dimension LUTs are also suffer from un-appropriate data from Y=+0.46875 and Y=-0.46875 when applying the (M:N)-distribution approach. But, the both effect cancel each other hopefully and lighten the impact.

CCD sample along 3X+3Y (2X+2Y for 2-pix centre of gravity) around a peak pixel (cross hair sample) was assumed until now. This is because of minimizing coincidence distance of an event. Ignoring the high count rate performance, 5x5 CCD array sample gives superior centroiding accuracies. The upper panel of Fig. 17 shows contour map of 2-dimension characteristic curve. There is neither tilt nor curvature in spite of the asymmetric profile of the true event. The M:N distribution approach can be applied precisely, as M/N=-0.5 and +0.5 exactly corresponds to X=-0.5 and X=+ 0.5. Fig. 29 shows negligible position error and superior geometry of subpixel boundary. Figs. 30 and 31 are for the smaller events and the larger events. Unfortunately, the 5x5 sample also failed perfection against the variation of event size.

To conclude this section;
There is no solution to overcome the variation of event size across detector field. The correction must be carried out on centroiding image (science image). The pure 2 dimension LUT, if obtained, gives the true geometry of subpixels for correction of the image. It needs support of the 5x5 CCD sample centroiding to know the true position of events, when making the pure 2-dimension LUT.

4. Detection probability along CCD pixel.

The M:N distribution with F-F illumination plays essential role to obtain the LUTs. This approach assumes events are bombarded and detected uniformly within a CCD pixel. The uniform detection is, however, suspicions assumption, because the brightness of peak CCD pixel depends on the location of the event within the CCD pixel. For instance, almost all energy falls into the peak CCD pixel when the location is centre of the CCD pixel, while the energy shared by 4 CCD pixels when the location is at the corner of the CCD pixel. The left hand panel of Fig. 32 shows change of brightness of the peak CCD pixel against the location of the true event. The brightness changes by the factor of 2 from the CCD centre to the corner.

The variation can be suppressed in photon counting image with excellent pulse height distributions (Fig. 33). There was non-negligible noise component in the lower energy end of the distribution in the QM-intensifier. The threshold level for event detection had to be set to 37 ADU. This relatively large threshold level and the shallow valley left the brightness variation in the photon counting image along a CCD pixel. The FM-intensifer showed very low noise and deep valley in its pulse height distribution. The threshold level was set to 15 ADU. The residual variation in the photon counting image was very little. These suggest the M:N distribution approach was not really accurate for the QM-intensifer, while pretty goof for the FM-intenisfeir.

5. Effect of CCD camera

Time variability of the fixed pattern has been recognized in contrary with its name. It has been believed to be partly due to event profile change of an intensifier and partly to readout electronics.

A large time variation was seen with a XMM-engineering intensifier (manufactured by Photek). The intensifier itself was doubted in the beginning and power on/off of the intensifier was repeated many times. But, there was no correlation with the change of the fixed pattern. Eventually, the algorithm was changed from 3-Pix centre of gravity to parabola fitting, then the time variation stopped completely. It was turned out that the intensifier slowly charged up the CCD camera electronics and D.C. bias of the 10MHz electronics was shifted a very little. Since the change of D.C. bias was smaller than 1 ADU, it was not obviously recognized in CCD snap frames. If D.C. bias was 0.1 in the beginning and increased to 0.4 in the end, the D.C. levels were seen as 0 ADU in the CCD snap frames at all time. This small change, however, could affect building up centroiding image systematically by acquiring many events. An event with a brightness of 80.8 was converted to be 80ADU in the beginning, while to 81 in the end. Of course, most of events were converted to the same value but 30% of events were converted to higher values. We must be cautious about D.C. bias change even invisible.

The following equations describe the sensitivity of the algorithms to the D.C. bias (denoted by "e").

3-pix centre of gravity is most sensitive.

$$\frac{(C+e) - (A+e)}{(A+e)+(B+e)+(C+e)} = \frac{C-A}{A+B+C+3e}\ .$$

2-pix is next sensitive.

$$\frac{C+e}{(B+e)+(C+e)} = \frac{C\quad +e}{B+C+2e}\ .$$

Parabola fitting is independent of the D.C. bias at all.

$$\frac{(C+e) - (A+e)}{4(B+e)-2(A+e)-2(C+e)} = \frac{C-A}{4B-2A-2C}\ .$$

D.C. stability is the most difficult item for a high speed analog electronics, hence the most possible cause of the time variation. The perfect independence of parabola fitting on the D.C. bias must not be thrown out.

Quality control in a modern CCD is pretty good, but it is still difficult to control hot pixels. Figs. 34, 35 and 36 show centroiding error caused by a hot pixel, whose intensity is 1/80th of an average brightness of peak CCD pixel. The impact of the hot pixel reaches up to 24x24 subpixels. Fig. 37 shows fixed pattern at 3x3 CCD pixel array around the hot pixel. Only the effect of hot pixel was extracted in these figures, i.e. the intrinsic centroiding inaccuracies due to the 1-dimension LUTs were removed beforehand. 3-pixel centre of gravity algorithm is most suffered from the effect in terms of displacement, but not much in fixed pattern. While, 2-pixel centre of gravity algorithm is least suffered in terms of displacement, but is most suffered in fixed pattern. These are due to sudden change of displacement vector with 2-Pix centre of gravity algorithm and continuous change with 3-Pix centre of gravity algorithm. Parabola fitting is most moderately affected by the hot pixel, in other word medium level of displacement and continuous change.

6. towards Swift-Project

Centroiding accuracy is the most essential factor to chose algorithm. The parabola fitting algorithm is the best in all round cases.
Its advantages are;
1) Continuity in characteristic curve,
2) Independence of D.C. bias of a CCD camera,
3) Modestly affected by a hot pixel.
Disadvantage is;
1) Non-linearity in characteristic curve,
but this can be overcome by LUT.

The 3X+3Y cross-hair CCD sampling will be employed for Swift-project. The 5x5 CCD array sampling is most accurate for the centroiding, but is not suitable for high count rate imaging. It also requires complicated electronics, which is not suitable for TTL digital electronics.

Two 1-dimenstion LUTs approach will be employed for Swift project because of its simplicity. The 2-dimension LUT is accurate in centroiding, but parameters cannot be determined by the M:N-distribution. It also requires complicated hardware and calibration procedures in the orbit.

Event width changes across detector field, which causes systematic centroiding error. Non of algorithms nor sampling methods overcome this problem. This must be corrected on the centroiding images (science images). The true geometry of subpixel boundaries provides sufficient information for the correction. It, however, cannot be determined from the centroiding image without a controversial assumption. The geometries at various place of the detector field will be determined with the help CCD snap frames before the launch for Swift project. This was not carried out in XMM-OM project, therefore ambiguity was left on the science image.

The event detection probability varies along a CCD pixel, i.e. highest at CCD pixel centre and lowest at the corner. This would not be problem, if the pulse height distribution of FM-intensifers are superb. The detection probability, however, should be measured with the FM-system before the launch.

6.1. M:N distribution

plays the key role to update the centroiding LUTs in the orbit. Swift centroiding process electronic (hereafter, BPE) has a special function to transfer pre-processed event data (combination of M:N values) to 2 memory banks, corresponding to X-axis M:N map and Y-axis M:N map. Where,

M=(C - A),
N=(2B-A-C) [parabola fitting] .

Fig. 38 is 2 dimension display of the X-memory bank obtained by XMM-QM's BPE. 8 MSB bits of address were given by "M" and 8 LSB bits by "N", which occupies 16bit memory space. The memory value at the address of (M:N) was incremented by "1" when a (M:N) value arriving from the BPE. The calculated position, M/N, corresponds to the gradient in the figure. The (M/N) number distribution was built up by histograming the counts within tiny sectors in the size of 2/8192 (see Fig. 39). Then, the (M/N)-distribution was integrated along M/N values from the left to the right. The integrated (M/N)-distribution was reversed and converted to the characteristic curve (see Fig. 14). Fig. 40 shows photon counting image acquired with equal boundaries, and Fig. 41 with the new boundaries. The improvement of the image quality is outstanding.

The randomizing technique was involved when making the (M/N)-distribution in the above. The details are described here. Fig. 41 shows Y-axis (M/N)-distribution with DEP's straight intensifier (pre-engineering model for XMM-OM) highlighted in the range of M/N= -2/32 and +2/32. There is a big spike at M/N=0.0 and are psudo-periodic small spikes in the both sides. These spikes are caused by eclipses of lattice points in the M:N map viewed from the origin (M,N)=(0,0). There are the largest number of eclipse points in the direction of M/N=0, i.e. along N-axis. The next biggest eclipse occurs in the direction of M/N=+/-1.0 (45 degrees), then followed by M/N=+/-0.5 (22.5 degrees). In order to resolve this eclipse, the lattice address was artificially shifted in the following rules when making the (M/M)-distribution and LUT,

M/N ==> (M -0.250)/N	If Mod(M,4)=0 and M >= 0
M/N ==> (M+0.250)/N	If Mod(M,4)=1 and M >= 0
M/N ==> (M -0.125)/N	If Mod(M,4)=2 and M >= 0
M/N ==> (M+0.125)/N	If Mod(M,4)=3 and M >= 0
M/N ==> (M+0.250)/N	If Mod(M,4)=0 and M < 0
M/N ==> (M -0.250)/N	If Mod(M,4)=1 and M < 0
M/N ==> (M+0.125)/N	If Mod(M,4)=2 and M < 0
M/N ==> (M -0.125)/N	If Mod(M,4)=3 and M < 0 .

The new (M/N)-distribution successfully suppressed the spikes as shown in Fig 42. The big spike at M/N=0.0 actually caused problem with the DEP straight tube, whose Y-boundary between subpixel-4 and -5 coincided with M/N=0.0. If the boundary is set at M/N=-0.00001, subpixel-5 was bright, and if M/N=+0.0001, sibpixel-4 bright. Its fixed pattern along Y-axis is shown at the upper panel of Fig. 43. The undulation at subpixel-4 and -5 had never been settled. Introducing randomizing in the Y-LUT, the fixed pattern was levelled off as shown in the lower panel.

Swift project will employs this randomizing technique when updating the 2 LUTs in the orbit.

6.2. Variation of event profile

The LUTs will be regularly updated in the orbit using F-F image at detector central region. These LUT values are suitable only for the detector centre. A significant centroiding error, which will be revealed as 10-20% fixed pattern, will occur at detector boundary region. It may be possible to determine true geometry of subpixels on the ground before the launch. It is sufficient to restore full science information if the true subpixel geometry is given. The calibration procedures are as follows,

a) The detector field is divided into 4x4 sectors and the subpixel geometries are derived for the individual sectors.
b) Two 1-dimension LUTs are derived for 5x5 sampling, parabola centroiding from (M:N)-distribution approach with the help of CCD snap frames.

c) Many events are centroided with the 5x5 sampling LUTs. Simultaneously, 3X+3Y sampling parabola centroiding is carried out, and the pure 2-dimension characteristic curve is built up using the position information.

d) Boundaries for FM-BPE are determined by the routine calibration procedure. Then, the true subpixel geometry is drawn referring to the pure 2-dimension characteristic curve.

6.3. Detection probability along a CCD pixel

The (M/N)-distribution approach for updating LUTs assumes uniform illumination and detection of photons along a CCD pixel. This assumption is not necessarily true, since the brightness of Peak CCD-pixel changes by twice. Fig. 44 shows the pulse height distributions with the DEP-straight tube for events falling at the pixel centre and at the pixel corner. The detection probabilities can be estimated from the distributions with given threshold level.

8x8 pulse height distributions will be measured separately according to 8x8 sectors within a CCD pixel. Then, the detection probability along X-axis and Y-axis will be estimated. The response is hopefully flat, expecting superior FM-intensifers. But, if the response will show variation (see Fig. 32 for XMM-QM intensifier), it will require small modification for updating centroiding boundaries. For instance, X4-point at the ordinate in Fig. 13 should be lowered, though X2-point may remain the same position.

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