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Pile-up on X-ray CCD Instruments

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Abstract. Pile-up occurs on X-ray CCDs when several photons hit the detector at the same place between two read-outs. In that case they are counted as one (or not at all) and their energies are summed. Pile-up thus affects both flux measurements and spectral characterisation of bright sources. Here I extend a previous work on flux loss to a form directly applicable when the pixel size is comparable to the telescope's point spread function, as in *AXAF/ACIS* or *XMM/EPIC-PN*.

1. Introduction

After the *ASCA/SIS*, the current generation of X-ray astronomy satellites all incorporate CCD detectors (*AXAF/ACIS*, *XMM/EPIC*). The reason is that they are very versatile, offering good quantum efficiency, spatial resolution and reasonable energy resolution (Lumb et al. 1991).

The principle of an X-ray CCD detector is that the whole detector is read out at regular intervals. The contents of the detector as it is read out is called a frame. A local excess in the charge contents is called an event, and is usually associated with a single X-ray impact. The total charge contents of the event is directly proportional to the X-ray energy (with some dispersion of course), and is used as the energy measure.

The underlying hypothesis is that an event is due to only one X-ray. If an event is actually due to several superposed X-rays, then both the count rate and the energy measurements are wrong. This phenomenon (X-ray superposition) is known as pile-up, and is always present for bright sources.

In a previous paper (Ballet 1999), I presented a detailed statistical analysis of the pile-up phenomenon, including formulae quantifying the flux loss, applicable when the pixel size is much smaller than the telescope's point spread function, as in *ASCA/SIS* or *XMM/EPIC-MOS*. I also showed that the perturbations on the spectrum were relatively minor (not more than a few %) for single events (not even diagonally touching another one), so that at first order one could use the standard energy response function after selecting single events only.

In a later paper (Ballet 2000) I presented a second-order approximation, reaching a better precision on the spectrum, applicable both directly (using the auto-convolution of the spectrum) and iteratively in a linear formulation (for XSPEC).

Here I generalise the formulae of Ballet (1999) to the case when the pixel size is comparable to the telescope's point spread function. The formulae of

Ballet (2000) may be generalised in a similar way. Section 3 is directly relevant to *XMM/EPIC-PN*, Section 4 to *AXAF/ACIS*.

The figures are available from the author on request.

2. Framework

The way to identify an event in a frame is to look for a local maximum above some statistical threshold, and then to perform a proximity analysis around this maximum. The charge from an X-ray may either concentrate in one pixel (single events) or appear over several adjacent pixels (split events) forming a specific pattern or grade.

To generalise Ballet (1999), I call $g_{x,y}^{(m)}$ the proportion of X-rays creating the charge pattern defined by m, with $N(m)$ pixels above threshold and a certain orientation, falling at position x, y, for a fixed orientation of the telescope. This encompasses both the sky image $g_{x,y}$ (summing over m) and the pattern distribution $\alpha^{(m)}$ (summing over space). $g_{x,y}^{(m)}$ is also the PSF/pattern distribution of measured events in the ideal situation of a single point source with no pile-up. $g_{x,y}^{(m)}$ is integrated on energy, and normalised such that

$$\sum_{x,y,m} g_{x,y}^{(m)} = 1 \tag{1}$$

The reason to write it that way is that the PSF may depend on the pattern, for example if events split toward one direction occur preferentially when the X-ray interacted close to the pixel's edge in that direction. For example, in *XMM/EPIC-MOS* index 5 denotes charge patterns with 3 pixels, extending above and to the right of the central pixel (with maximum charge), as in Figure 1 of Ballet (1999), bottom center. Zero denotes strict single events (same figure, top left), 30 generalised single events, possibly touching another pixel above threshold by a corner (same figure, top right).

I call Λ the total incoming X-ray flux/frame and $M^{(n)}$ the expected (expectation value of the) count rate/frame in pattern n. I call $M^{(n)t}$ the expected count rate/frame in pattern n of clean (not piled-up) events (not something you can measure). Local quantities (per pixel) are denoted as lower case so that

$$M^{(n)} = \sum_{x,y} \mu_{x,y}^{(n)} \tag{2}$$

$1 - M^{(n)}/(\alpha^{(n)}\Lambda)$ is called the flux loss. It is the loss in detection efficiency due to pattern overlap.

$1 - M^{(n)t}/M^{(n)}$ is called the pile-up fraction. It is the fraction of measured events whose energy will be wrong.

Note that all pile-up formulae are naturally written *per pattern* (known in the data). Global quantities are obtained by summing over the patterns.

I have shown (Ballet 1999, Equations 1–3 and A5) that for strict (0) and generalised (30) single events (using the above notations), assuming a (locally) uniform X-ray flux, i.e., a pixel size small with respect to the PSF:

$$\begin{aligned}
\gamma^{(0)}_{x,y} &= 9 + 3 \sum_{N(m)=2} g^{(m)}_{x,y} + 6 \sum_{N(m)=3} g^{(m)}_{x,y} + 7 \sum_{N(m)=4} g^{(m)}_{x,y} && (3)\\
\gamma^{(30)}_{x,y} &= 5 + 3 \sum_{N(m)=2} g^{(m)}_{x,y} + 5 \sum_{N(m)=3} g^{(m)}_{x,y} + 7 \sum_{N(m)=4} g^{(m)}_{x,y} && (4)\\
\mu^{(0)t}_{x,y} &= g^{(0)}_{x,y} \exp\left[-\gamma^{(0)}_{x,y}\Lambda\right] && (5)\\
\mu^{(0)}_{x,y} &= \left(\exp\left[g^{(0)}_{x,y}\Lambda\right] - 1\right) \exp\left[-\gamma^{(0)}_{x,y}\Lambda\right] && (6)\\
\mu^{(30)t}_{x,y} &= g^{(0)}_{x,y} \exp\left[-\gamma^{(30)}_{x,y}\Lambda\right] && (7)\\
\mu^{(30)}_{x,y} &= \left(\exp\left[g^{(0)}_{x,y}\Lambda\right] - 1\right) \exp\left[-\gamma^{(30)}_{x,y}\Lambda\right] && (8)
\end{aligned}$$

3. Flux loss

I will here write explicitly the formulae generalising (5–6) or (7–8) to the case when it is not true that the X-ray flux incoming to nearby pixels can be assumed to be identical. This case was already mentioned in section 4.4 of Ballet (1999).

The pattern shape is represented by $P^{(n)}_{i,j} = 1$ wherever the corresponding pixel is above threshold and 0 elsewhere, with $i, j = 0, 0$ at the center of the pattern. For example $n = 5$ (Figure 1 of Ballet 1999, bottom center) is represented by $P^{(5)}_{i,j} = 1$ in $i, j = 0, 0; 0, 1; 1, 0$.

An associated exclusion zone $E^{(n)}_{i,j}$ is then obtained by setting to 1 all pixels above 0 in the convolution with a mask $M_{i,j}$

$$E^{(n)}_{i,j} = \min\left(\sum_{k,l} M_{k,l} P^{(n)}_{i-k,j-l},\ 1\right) \tag{9}$$

where the mask is 1 where $max(|i|, |j|) \leq 1$ (strict events, for Equations 5–6) or where $|i| + |j| \leq 1$ (generalised events, possibly touching another pixel above threshold by a corner, for Equations 7–8). Note that this definition corresponds to the white + grey + black pixels in Figure 1 of Ballet (1999), and differs from that in Figure 2 of Ballet (1999), which defined exclusion zones with respect to a particular incoming pattern m and a particular target pattern n. The exclusion zones defined here relate only to the target pattern (n).

The exclusion term $\gamma^{(n)}_{x,y}$ to be injected into Equations (5–6) or (7–8) may then be obtained by summing the terms in the exponential (multiplying probabilities) for all pixels in the exclusion zone.

$$\begin{aligned}
C^{(m)}_{i,j} &= \sum_{k,l} P^{(m)}_{k,l} g^{(m)}_{i-k,j-l} && (10)\\
\gamma^{(n)}_{x,y} &= \sum_{i,j,m} E^{(n)}_{i,j} C^{(m)}_{x+i,y+j} = \sum_{i,j,k,l,m} E^{(n)}_{i,j} P^{(m)}_{k,l} g^{(m)}_{x+i-k,y+j-l} && (11)
\end{aligned}$$

where $C^{(m)}_{i,j}$ is the distribution of illuminated pixels for incoming pattern m, obtained by convolving the sky image with the pattern itself. Note that Equation (11) is the result of the correlation (not the convolution) between that distribution and the target's exclusion zone, summed over all incoming pattern types.

This equation is related to Equation (9) of Ballet (1999) by setting $u = k - i, v = l - j$ and

$$\gamma^{(n)}_{x,y} = \sum_{u,v,m} Z^{(n,m)}_{u,v} g^{(m)}_{x-u,y-v} \quad (12)$$

$$Z^{(n,m)}_{u,v} = \sum_{i,j} E^{(n)}_{i,j} P^{(m)}_{u+i,v+j} \quad (13)$$

Note that Ballet's (1999) Equation (9) was actually incompatible with the representation of $Z^{(1,m)}_{u,v}$ in its Figure 2 (the diagrams should be reversed, i.e., L in place of R and D in place of U, or the convolution replaced with a correlation).

Figures 1 and 2 illustrate the comparison of Equation (11) with Equation (3) or (4). At moderate count rate ($\sim$ 1 cts/frame) flux loss is less in the narrow PSF case (dashed curve) than in the broad PSF one (full curve) because the neighbouring pixels (at much lower level) do not act to change singles into double events. At higher count rate ($\sim$ 10 cts/frame) flux loss is larger in the narrow PSF case because the high central pixel prevents singles from being detected around it.

The large hump in the pile-up rate in the narrow PSF case (near 3 cts/frame) corresponds to pile-up in the central pixel. It depends sensitively on where the PSF is centered within a pixel, as shown by the comparison between the dashed and dotted curves. Contrary to the broad PSF case, the pile-up rate is not much larger when single events touching others by a corner are included (Figure 2).

4. Attitude Drifts

On *Chandra* the telescope's pointing direction is permanently varied (dithering) to avoid giving too much weight to local irregularities of the detector (CCD edges, bad pixels). This dithering is slow on the time scale of one CCD frame, so that within one frame the telescope's attitude is essentially constant.

As mentioned in Ballet (1999, Section 4.3), pile-up depends on what happens within a frame so the PSF to apply is the original (instantaneous) one. In the continuous case (pixel size much smaller than the PSF), dithering would have no effect at all on pile-up. In the discrete case (pixel size larger than the PSF) such as on *Chandra* it has the effect of averaging the humps in Figures 1 and 2 because at each frame the PSF will be centered differently within a pixel.

References

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