Pile-up thresholds for the EPIC cameras

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13 December 2012

Abstract

New count rate thresholds for EPIC-MOS and PN cameras are presented, along with modified parameters for PHSTools pile-up fraction model.

1 Introduction

Pile-up is defined as the incidence of two or more X-ray photons in nearby CCD pixels within one frame time (i.e. read-out cycle) and leads to a suppression of the event count rate, spectral distortions, and an apparent increase in the number of multi-pixel events (pattern migration). Avoiding pile-up should be an important consideration for an XMM-Newton proposer; the thresholds are provided to signpost the count rates at which pile-up may begin to affect the quality of scientific data. The previously recommended thresholds reported in Table 3 Section 3.3.2 of the XMM-Newton Users Handbook (Piconcelli et al. 2012) were first order estimates provided early in the mission. For EPIC-MOS, an analysis of diagonal events in observations comprising the Cross-calibration database revealed that the previously predicted level of pile-up was underestimated by some 50% in Full Frame and Large Window modes (Guainazzi & Stuhlinger, XMM-SOC-CAL-TN-0084).

We perform a detailed study to derive new thresholds. The results confirm those derived from EPIC-MOS diagonal event analysis and also apply to EPIC-PN, where we again find the previously predicted level of pile-up to be an underestimate. The new thresholds are therefore more conservative than the old. This should be taken into account when choosing an observing mode, alongside other considerations (e.g. errors in background subtraction in Small Window modes). A software library to correct spectra affected by pile-up is currently being implemented in the SAS.

2 Methodology

Previous attempts at evaluating the level of pile-up in the EPIC cameras have quantified it using some observable diagnostic (e.g. diagonal events, or single to double event ratio). This approach sheds little light on how pile-up has affected our data in real terms. Useful measures for quantifying the severity of pile-up in an observation are:

$$\text{Flux Loss} = 1 - \frac{\text{measured count rate of good patterns}}{\text{expected count rate of good patterns given no pile-up}}$$

$$\text{Spectral Distortion} = 1 - \frac{\text{count rate of good patterns formed from exactly one photon}}{\text{measured count rate of good patterns}}$$

where a good pattern is single-double for PN, single-quadruple for MOS.

The only directly observable term in these expressions is the measured count rate of good patterns. To determine the other terms requires modelling of the pile-up phenomenon. We do this in two independent ways.

Table 1: Test spectral models

Model	% Singles PN/MOS	Name
phabs(log(nH) = 19.5) * bbody(E = 70eV)	97 / 94	Very Soft
phabs(log(nH) = 20) * powerlaw(Γ = 2.0)	83 / 84	Soft
phabs(log(nH) = 22) * powerlaw(Γ = 1.7)	64 / 71	Hard
phabs(log(nH) = 24) * powerlaw(Γ = 1.0)	56 / 38	Very Hard

2.1 EPIC Pile-up Simulator

We perform simulations of the EPIC cameras at the necessary level of sophistication to capture the effects of pile-up. The input parameters required by the simulator are instrument (MOS or PN), observation mode and duration, source spectral model and the rate of photons arriving at the instrument (*photon rate* as opposed to what is henceforth known as *count rate*, which is a piled-up quantity).

For each frame of the simulated observation we assign a number of photons, Poisson distributed about the mean. Each photon is assigned a random energy, position on the detector, and pattern (i.e. the shape of the pixels over which the photon's charge cloud spreads) with probabilities determined by the input spectral model and standard calibration files. Any instances of overlapping photon events are processed such the resultant event is the piled-up superposition of the two originals.

The simulator outputs event lists and spectra. We also keep track of the destination of every input photon, and hence can determine the flux loss and spectral distortion as defined above.

2.2 Analytic Pile-up Equations

We implement a set of non-linear equations described in a series of papers entitled *Pile-up on X-ray CCD Instruments* (Ballet 1998, 2000, 2001). These equations are applicable to EPIC-MOS and PN and treat pattern migration and dependence on the input spectral model. The crux of the equations is to calculate the probability that within one frame time, an event is produced in a given pixel, and not subsequently disturbed by a photon arriving in neighbouring pixels.

Using both the simulator and equations we investigate pile-up for four spectral models spanning the possible range of spectral hardness. Pile-up depends on spectral model only through distribution of event patterns: a harder spectrum will excite more multi-pixel events which, geometrically, are more likely to pile-up. In Table 1 we describe the spectral models employed, noting alongside the fraction of events which are singles for each model.

3 Results

Figure 1 shows flux loss and spectral distortion for the four spectral models at a range of photon rates. Results shown are caluclated both via analytic equations (represented by solid lines) and simulations (each data point representing a 25,000 photon run). We see excellent agreement between the two independent modelling methods. The $\sim$1% discrepency between the two methods for hard spectra in EPIC-MOS can be explained by the simulator's imperfect treatment of large ($>$ quadruple) patterns, which form a non-negligable fraction in MOS at high energies.

Table 2: New pile-up thresholds and model parameters

Instrument	Mode	Max. photon rate [s^{-1}]		PHSTools parameters		
		2.5% FL	5% FL	a	b	c
PN	FF	2	4	-1.957	1.162	-0.134
	LW	3	6	-2.179	1.212	-0.134
	SW	25	50	-3.411	1.459	-0.134
MOS	FF	0.5	1	-1.332	1.020	-0.185
	LW	1.5	3	-1.841	1.191	-0.185
	SW	4.5	9	-2.452	1.368	-0.185

Flux loss and spectral distortion increase linearly with photon rate in the ranges shown. Regarding trends with spectral shape, we see worse flux loss for hard spectra and worse spectral distortion for soft spectra. These comparisons hold true for soft and hard spectra with the same rate of photons arriving at the CCD. For two spectra with the same broadband flux, however, we expect the softer one to have a greater photon rate (due to the instrument effective area) and hence worse pile-up.

Our criteria for the new threshold photon rates are 2.5% and 5% flux losses for an average-case spectral model lying between the Soft and Hard examples. The chosen values are shown by vertical dashed lines. In the bottom panels we highlight the level of spectral distortion expected at these rates: roughly, for both PN and MOS, a 2.5% flux loss implies $< 1\%$ spectral distorion, 5% flux loss gives $> 1\%$ spectral distortion. For the Very Hard case, the threshold rate must be reduced by some 30% for the quoted levels of flux loss to remain valid.

In Figure 1 rates are given in units of photons per frame, and photons per second for Full Frame observing modes. To determine thresholds for other modes we rescale according to frame time. Aside from threshold rates, XMM-Newton proposers are alerted to potential pile-up when running the technical evaluation of their proposals, using a simple model of pile-up fraction (P_f) as a function of photons per second (R):

$$P_f = 10^{a+b\log(R)+c\log(R)^2}$$

where a, b, c are instrument and mode dependent parameters. We now define P_f as flux loss due to pile-up, which, in Figure 2, we show for a large range of photon rates. For a spectral model between the Soft and Hard cases we calculate a, b, c such that P_f best fits the flux loss function. The result is shown in black, along with residuals in the lower panels. Finally we rescale a, b, c for each instrument mode. The new threshold photon rates, at which we expect 2.5% and 5% flux loss, along with the new a, b, c parameters for the PHTools pile-up model are presented in Table 2. For very hard sources (with $> 40\%$ multi-pixel events) the quoted photon rates should be reduced by some 30%.

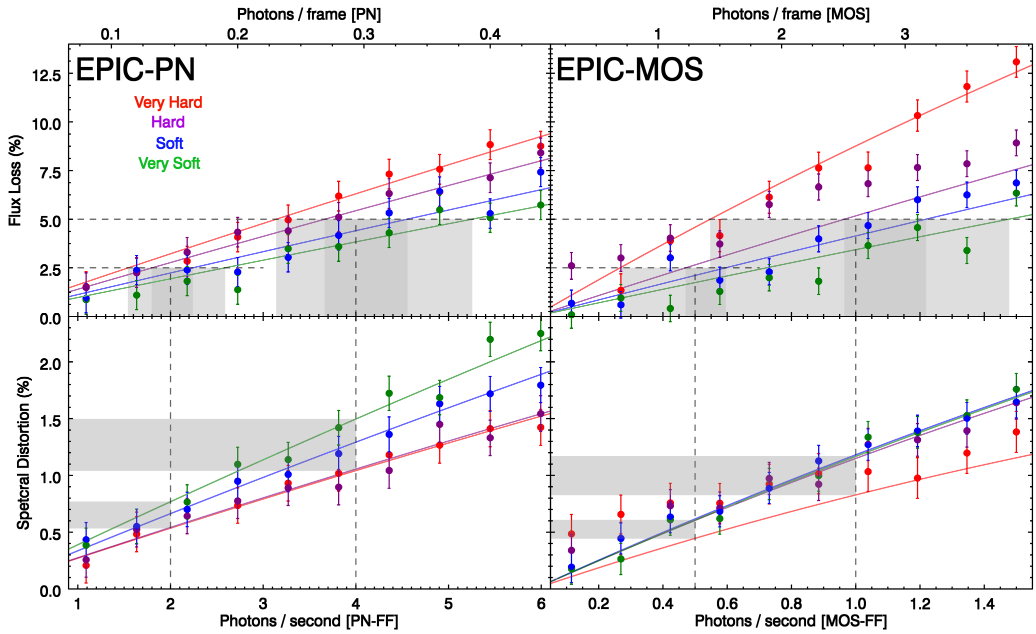

Figure 1: Flux Loss and Spectral Distortion in EPIC-PN and MOS, for four spectral models (colour-coded) at increasing photon rates. The data points are simulation results, the solid lines are equation predictions. The grey regions highlight rates at which see 2.5% and 5% flux loss and the associated level of spectral distortion. The dashed lines show the new thresholds.

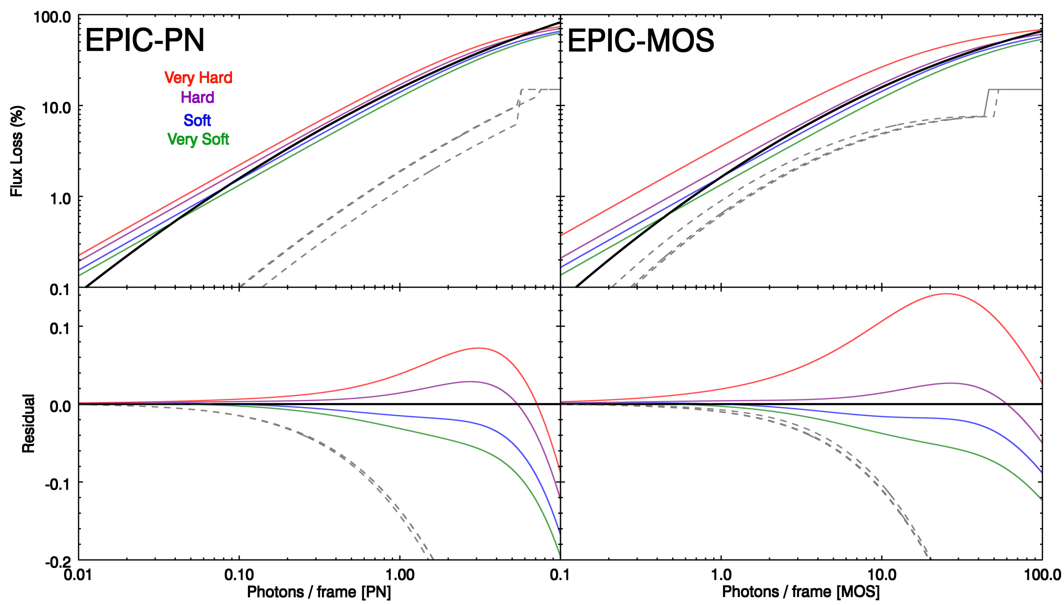

Figure 2: The top panels show predicted flux loss for four spectral models (colour-coded) over a large range of photon rates. The best fitting model is shown in black. The previous PHSTools pile-up fraction predictions are represented by dashed lines for comparison. Below we show the residuals between the new predictions and the flux loss calculations.