XMM-Newton Calibration Technical Note

PN X-Ray Loading

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1 Abstract

An investigation has been made into X-Ray loading in PN exposures. X-ray loading is the inclusion of X-ray events in the PN offset map. This phenomenon occurs whenever a too large number of X-ray events per pixel is detected during the offset map calculation.

2 Introduction

The PN offset maps are calculated on board at the start of each exposure. The offset per pixel is determined from a sample of n frames from which the m_{high} highest and m_{low} lowest PHA values per pixel have been excluded. For all modes, $m_{high} = m_{low} = 3$ and $n = 100$, except for Full Frame mode, for which $n = 50$ from revolution 843 (July 2004) onwards.

X-ray loading occurs when the X-ray count rate is such that this method fails to exclude all X-ray photons in the sample, thus leading to an additional and incorrect offset shift for the pixel in question. The severity of X-ray loading depends on the sum of the energies of the contaminating X-ray events, *i.e.* those X-ray events remaining in the sample *after* the above-mentioned exclusion. Its consequences (illustrated in Fig. 1) are pattern migration from higher to lower pattern types and a shift to lower energy for all subsequent events associated with the pixel of:

$E_{Loading} = \frac{\sum E_{X-Ray}}{n - m_{high} - m_{low}}$, so, currently: $E_{Loading} \simeq 0.01 \times \sum E_{X-Ray}$

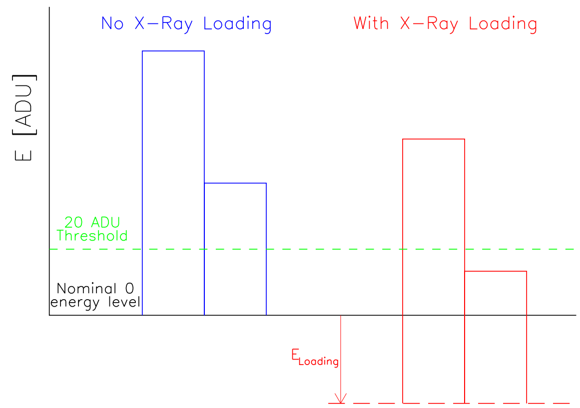

Figure 1: **Illustration of the effects of X-ray loading.** The additional offset due to the loading shifts all events of the affected pixel to a lower energy. Moreover, a double event will be recorded as a single (and likewise for higher patterns) if the secondary charge is shifted below the lower energy threshold.

X-ray loading is a consequence of excessive count rate, and is thus related to pile-up, although their effects differ: pile-up leads to apparently harder spectra, with pattern migration to higher order patterns, whereas X-ray loading results in apparently softer spectra and pattern migration tending to lower order patterns. Regarding individual event detection, an important difference between the two is that while pile-up is a stochastic effect, X-ray loading, once present in the offset map, will affect *all* subsequent events associated with the affected pixels.

The count rate thresholds above which X-ray loading will occur are mode dependent. For point sources and imaging modes the thresholds are:

Mode	Count rate (cts s^{-1})
Full Frame	7.3 (3.7 up to Rev. 842)
Extended Full Frame	1.3
Large Window	5.6
Small Window	44

3 Analysis

PN offset maps are the obvious diagnostics for X-ray loading. However, the offset data must be manipulated somewhat in order to remove the dominating common mode noise and varying column-to-column gain, which is done by subtracting the CCD column and row medians. In the resulting, so-called "residual" offset maps, local features such as optical loading and X-ray loading may readily be detected and quantified in terms of residual offset energies, *i.e.* ADUs relative to the local background. Typically, residual offset maps will have a mean offset value of $\sim 0 \pm 1$ ADU. Fig. 2 shows an example of X-ray loading in a residual offset map. In cases of exceptionally strong loading affecting a large area of the CCD and hence the local median offset, this method will tend to *underestimate* the residual offset.

All 831 PN offset maps of imaging mode, non (cal)closed observations from the start of the

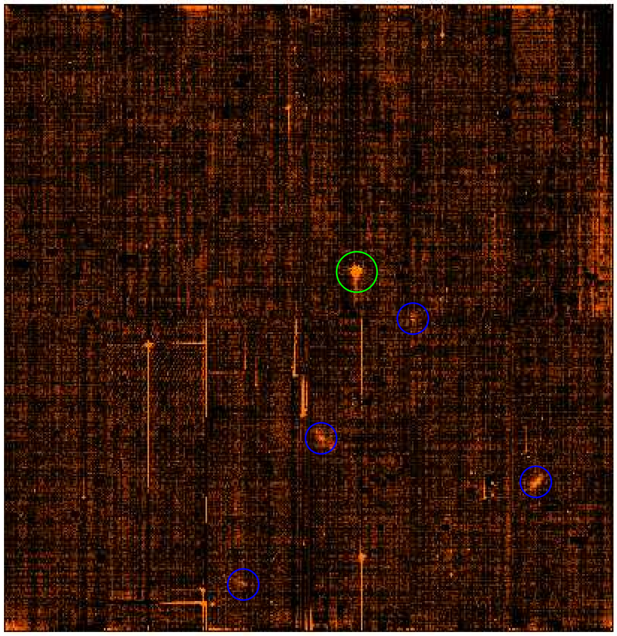

Figure 2: **Residual offset map of an exposure affected by X-Ray loading.** The X-Ray loading, indicated by the green circle, has a peak residual offset value of $\sim$ 780 ADU. Several minor cases of optical loading, indicated by the blue circles, can also be seen.

mission up to revolution 634 were thus analysed for the presence of X-ray loading within $1'.5$ of the bore sight location.

Cases of likely optical loading were excluded through optical catalogue identifications [2]; it turns out that due to filter choice there are very few such cases in the central area of interest.

4 Results

Of the 831 offset maps checked for X-ray loading within $1'.5$ of the bore sight, there were 34 cases of definite X-ray loading, of which:

- 28 cases were of science observations;
- 6 cases were of calibration observations.

Assuming $\sim 95\%$ of the offset map sample being of science observations it follows that $\sim 3-4\%$ of science observations are affected by X-ray loading at the bore sight (and presumably the target).

The case-by-case extent of X-ray loading was investigated using a somewhat larger sample of X-ray loading cases, including observations of off-axis calibration targets. The results are shown in Figs. 3, 4 and 5.

Fig. 3 demonstrates that X-ray loading occurs at lower count rates than the pile-up threshold. There are some cases of X-ray loading, albeit of low peak residual offsets, below 3 cts/100 frames/pix, where in principle the offset map algorithm should have removed all X-ray events from the sample. The occurrence of X-ray loading in these cases could however be explained by:

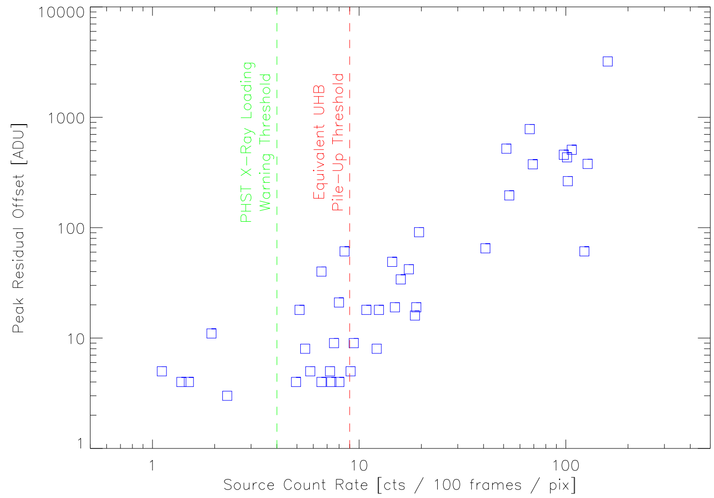

Figure 3: **Peak residual offset *versus* source count rate.** The source count rate is the mean over the exposure, and is expressed in counts per 100 frames per raw pixel. The peak residual offset is the maximum residual offset value found in the X-ray loaded region. Two count rate warning thresholds are depicted by the vertical lines: the PHS Tools X-Ray loading threshold at 4 cts/100 frames/pixel (in green) and, for comparison, the expected pile-up threshold as mentioned in the XMM-Newton Users' Handbook (in red).

- the finite probability that there will be more than the expected number of X-ray events included in the sample; especially if these few events happen to be of high energy this will lead to a detectable level of loading;
- uncertainty in the source count rate, which is determined as the mean over the exposure; variability could result in a higher than mean count rate during offset calculation.

Apart from these considerations, it must be noted that there are a few observations (GD 153, a very soft source (WD) and excluded from the data sample presented here) with count rates $\ll 3$ cts/100 frames/pix, which show consistent loading which cannot be accounted for optically. These presumed (and peculiar) cases of X-ray loading require further investigation.

5 Impact on Science Quality

Fig. 3 shows that observations with source count rate $\leq$ pile-up limit may still be affected by a peak energy shift ranging from several to several tens of ADU ($\sim 15-\sim 400$ eV). Fig. 5 shows that typically $\sim 50\%$ of the encircled energy is affected to some extent.

An example of an exposure affected by X-ray loading is shown in Figs. 6 and 7, which illustrate the change in pattern distribution and energy shift as described in Section 2.

Possible corrective measures for X-ray loading are under investigation. These include adding the residual offsets to the raw energies of all events associated with the respective pixels so as to compensate somewhat for the systematic shift to lower energies. An example of a resulting spectrum is shown in Fig. 8. However, this alone is insufficient as it would not correct the changed pattern distribution or restore the secondary charges in lost doubles.

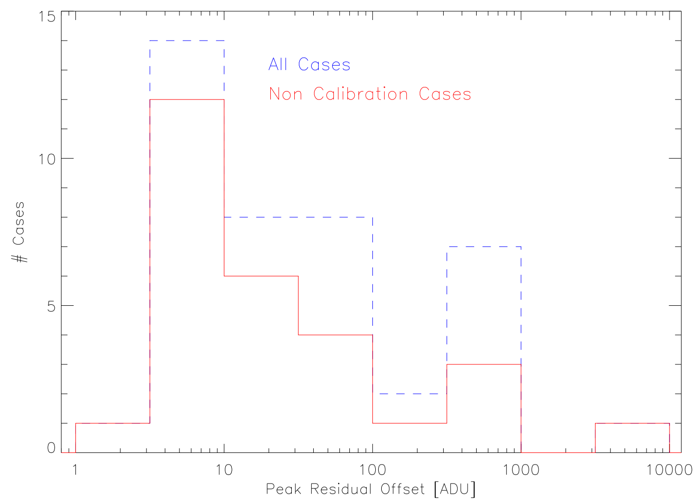

Figure 4: **Distribution of the peak residual offset of X-ray loading cases.** The red line represents science observations.

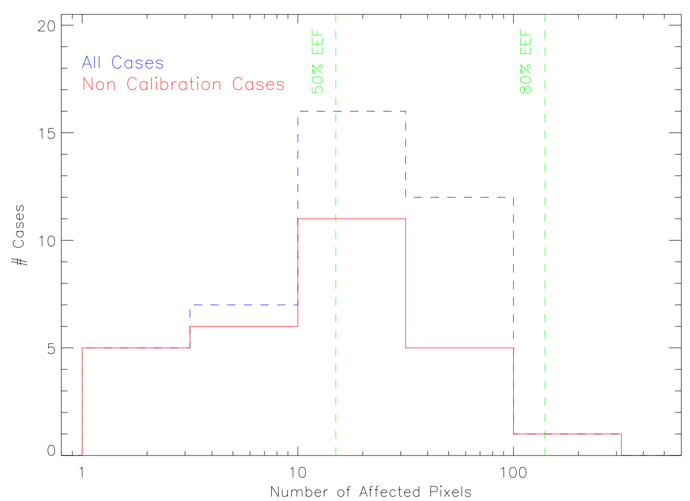

Figure 5: **Distribution of the number of affected pixels per loading case.** The red line represents science observations. The equivalent 50% and 80% encircled energy fractions (assuming a circular distribution of affected pixels) are indicated by the green dashed lines.

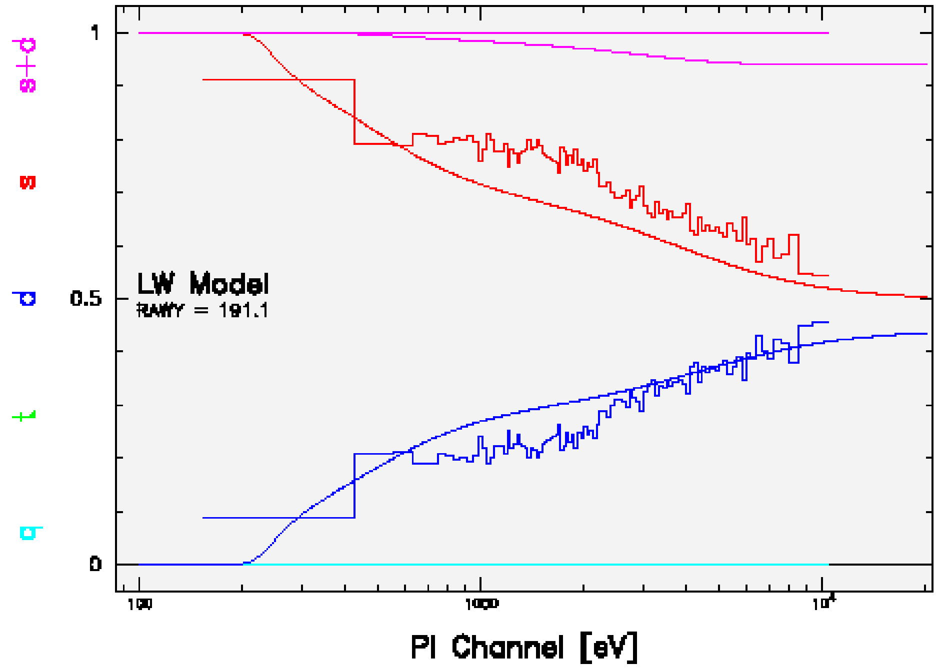

Figure 6: **Pattern distribution resulting from X-ray loading.** This *epatplot* output of an exposure affected by X-ray loading shows an excess of singles and a deficit of doubles with respect to the model. This is the opposite to what one sees in pile-up cases.

6 Conclusion

Observers should be aware that observations which may be acceptable from pile-up considerations (based on source count rate) may nevertheless be affected to varying degree by X-ray loading. Up to now X-ray loading has been seen in $\sim 3-4\%$ of science observations. The effects are a systematic energy shift to lower energies and a pattern migration from doubles to singles. Possible corrective measures are under investigation.

References

[1] XMM-Newton Users' Handbook, v2.1

[2] PN Optical Loading, XMM-SOC-CAL-TN-0051, M.J.S. Smith

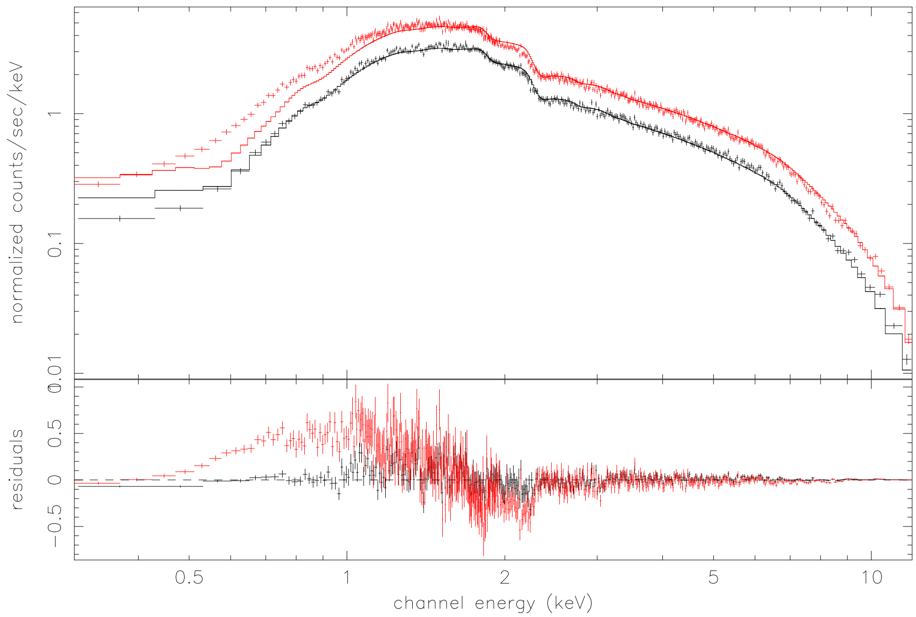

Figure 7: **X-ray loading spectral effect.** The red data represent the source spectrum of the same observation as that of Fig. 6. For comparison, in black, the spectrum of the source from which the PSF core (where the X-ray loading is at its most severe) has been excised, thus severely reducing the effects of X-ray loading. The same model is used to fit both data sets; the shift to lower energies due to X-ray loading can be seen, especially where the spectrum is steep. The peak residual offset in this particular case is ~ 61 ADU (~ 300 eV), and the source count rate is below the pile-up limit.

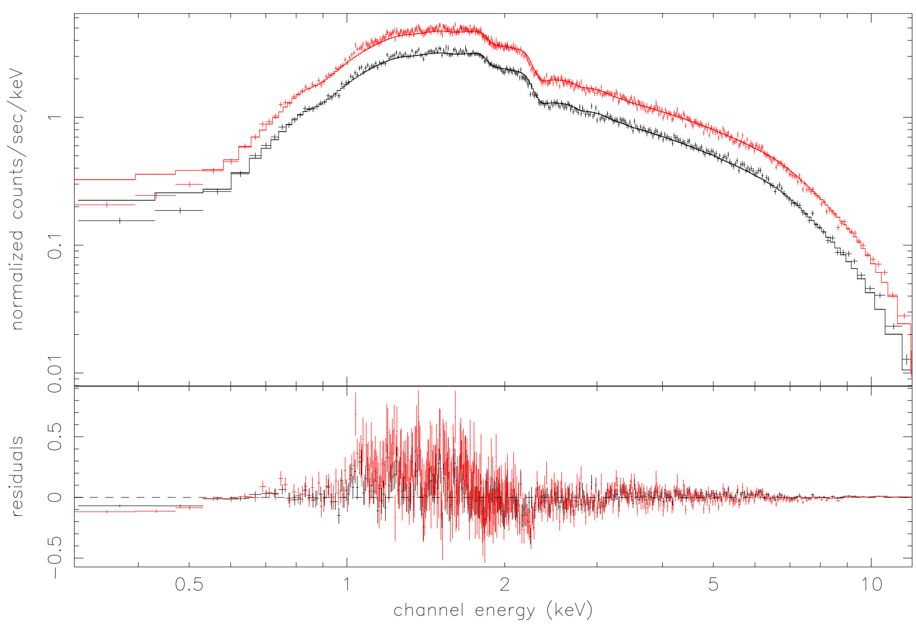

Figure 8: **First order correction of X-ray loading.** This is the same observation as that of Fig. 7 with, again, in black the spectrum of the source from which the core has been excised. The red data show the source spectrum of the corrected data, with drastically reduced residuals compared to the original in Fig. 7.