XMM-Newton CCF Release Note

XMM-CAL-SRN-0302

Calibration of the spectral impact of X-Ray Loading (XRL) in EPIC-pn Timing Mode

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1 CCF components

Name of CCF	VALDATE	EVALDATE	Blocks changed	XSCS flag
EPN_REJECT_0007.CCF	2002-07-07		XRL2PHA	NO

This CCF component includes the first public calibration of the **X-ray Loading** correction (Smith 2004) in EPIC-pn Timing Mode. It is based on a systematic analysis of a large sample of archival exposures (cf. § 2.2), complementing (and partly superseding) the results of a specific calibration experiment performed on the Crab Nebula (cf. § 2.1).

XRL occurs when the offset map taken prior to each science exposure is contaminated by a celestial source. This is the case for almost all the exposures in EPIC-pn Timing Mode (Guainazzi et al., 2012b) taken before the 23^{rd} of May 2012. On that date an changes in operations was introduced, whereby offset maps are being calculated with the `CLOSED` optical blocking filter. This prevents XRL. However, this CCF is valid for *all* EPIC-pn Timing Mode exposure as of the 7^{th} of July 2002 (cf. §4) notwithstanding the filter being used for the calculation of the offset map. SAS does not apply the XRL correction, if the offset map is calculated with the `CLOSED` filter.

2 Changes

2.1 The original calibration experiment

Two subsequent observations of the Crab Nebula were performed in September 2011 to test the spectral impact of XRL: one with the offset map calculated with the `CLOSED` optical filter (Obs.#0611181001), the other with the offset map calculated with the same optical filter as the following science observation (`THICK`, Obs.#0611181101). XRL occurs only in the latter, because the photon sources are blocked during the integration of the offset map in the former. By comparing the spectra taken during these observations, one

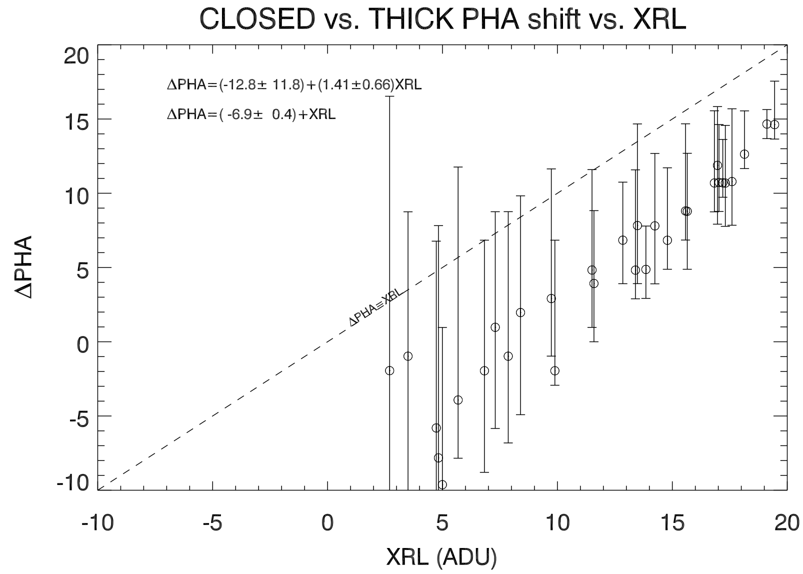

Figure 1: ΔPHA versus XRL in the [120:450] PHA range for the September 2011 experiment on the Crab Nebula. The *dashed line* indicates the identity locus. The *insets* indicate the results of a linear fit of the function $\Delta PHA = a + b \times XRL$ when b is left free to vary (*upper*), and when b is fixed to 1 (*lower*).

can directly estimate the spectral impact of XRL. The X-ray emitting area of the Crab Nebula covers several columns in the EPIC-pn Timing Mode aperture. This allowed us to estimate the spectral impact of XRL for a wide range of source count rates by analysing spectra extracted in different columns.

The results of the corresponding data analysis summarised in Fig. 1, which shows the "spectral shift" (ΔPHA) as a function of XRL for spectra extracted in individual `RAWX` columns. (ΔPHA) is defined as the shift to be applied to the spectrum extracted with the offset map in `THICK` filter to minimise the following quantity:

$$\chi^2(\Delta PHA) = \frac{1}{N} \times \sum_i (C_{i,\mathtt{CLOSED}} - C_{i,\mathtt{THICK}}(\Delta PHA))^2 / \sigma^2_{i,\mathtt{CLOSED}}$$

where C_i are the exposure-corrected counts, N is the number of spectral channels, and σ_i are the Poissonian errors on each channel according to the Gehrels (1986) prescription. The ΔPHA derived from the above equation were further divided by column-dependent gain factors extracted from `EPN_ADUCONV_0140.CCF`. A linear fit of the function: $\Delta PHA = a + b \times XRL$ yields numbers marginally consistent with a simple linear relation, with large error bars: $a = -12 \pm 11$ ADU; $b = 1.4 \pm 0.7$ (1σ errors). If one *assumes* $b \equiv 1$, a systematic "offset" $a = -6.9 \pm 0.4$ ADU is required by the data.

The discovery of a non-zero offset is puzzling. In principle, one might expect that the spectral impact of XRL is "purely" linear, *i.e.* $a = 0$. The origin of the behaviour observed in the Crab Nebula exposure is unknown (as well as the reason for the ubiquitous XRL in EPIC-pn Timing Mode, by the way). Putting these results in a wider context, the data points corresponding to the Crab Nebula deviate from the tight correlation between

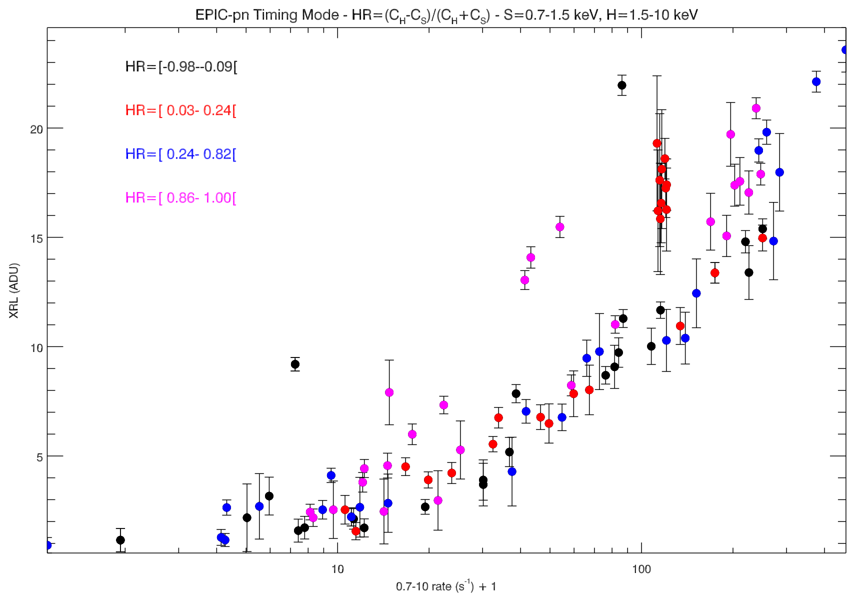

Figure 2: XRL (in ADU units; 1 ADU = 5 eV) as a function of the 0.7–10 keV count rate in the boresight column for a sample of 100 exposures taken in EPIC-pn Timing Mode. *Colours* identify the quartiles of the hardness ratio distribution: HR=$(C_H$-$C_S)/(C_H$+$C_S)$, where C_H and C_S are the counts in the 1.5–10 keV and 0.7–1.5 keV energy ranges, respectively. The cluster of *red points* for $CR \simeq 100$ s $^{-1}$, and XRL = 15–19 are the Crab Nebula results.

the net 0.7–10 keV Count Rate (CR) and the XRL (cf. the cluster of red points for $CR{\simeq}100$ s^{-1} in Fig. 2). The determination of the count rate in EPIC-pn Timing Mode exposures of the Crab Nebula could be affected by multiple FIFO resets (M.Freyberg, private communication). It should be born in mind that the standard EPIC-pn Timing Mode instrumental set-up is not optimised for sources as bright as the Crab Nebula, that would be heavily piled-up if point-like. There are reasons to seek for an independent confirmation of the results obtained with the experiment performed on it. We have therefore verified the calibration of the XRL spectral impact using a larger, and more diverse source sample.

2.2 The XRL calibration embedded in this CCF

We have analysed a sample of 26 EPIC-pn Timing Mode exposures, where the number of shifted electrons, N_e in the 0.7–10 keV energy band is lower then 50. N_e is defined as

$$N_e = \frac{\Sigma_{i=1}^{N_p} E_i}{N_{pixels} \times T_{exp} \times 3.6}$$

where E_i is the energy of the i-th photon, N_{pixels} is the number of pixels of the column whence each spectrum was extracted, N_p is the number of detected photons, T_{exp} is the exposure time and the factor 3.6 (in eV) represents the energy required to produce an electron-hole pair. It has been shown (Guainazzi 2013) that the energy scale is not affected by rate-dependent effects below this threshold. This sample can be therefore used

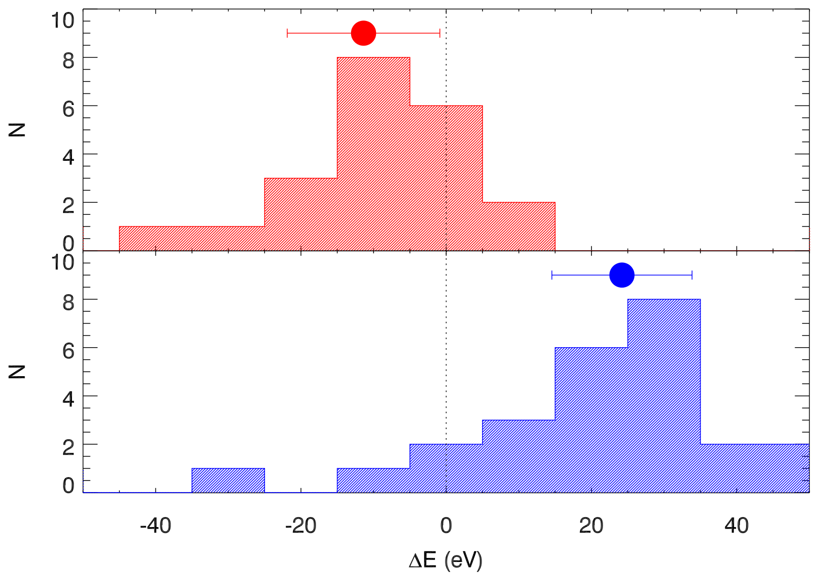

Figure 3: Histograms of the energy scale deviations at the Au edge ($\simeq$2.3 keV) for a sample of weak (N_e<50) sources observed in EPIC-pn Timing Mode. *Red histogram*: $a = 0$; *blue histogram*: $a = -6.9$. The *large points* represent the median of the histogram values, and of their 1σ errors: -11 ± 11 eV, and 24 ± 10 eV, respectively.

to estimate the accuracy of the XRL correction *alone*[1]. Sources with strong emission lines in the soft X-ray band were excluded from the sample, to ensure that the spectra were featureless in the 1.5–3 keV energy band. Spectra were extracted from a box in `RAWX` coordinates 9 pixels wide around the boresight column. We used standard data reduction and screening criteria as recommended, for instance, in Guainazzi et al. (2012a)

In order to estimate the accuracy of the energy scale, we made use of the steep effective area gradient at the Si ($\simeq$1.8 keV) and Au ($\simeq$ 2.3 keV) edges. We fit the spectra with a simple phenomenological model: the combination of a power-law and an accretion disk blackbody[2], seen through a screen of photoelectrically absorbing neutral gas. A shift to the energy scale was applied during the fitting procedure (through the command `gain fit` in XSPEC) to estimate the average deviation between the energy scale in the data and in the response. We tested on real data that such a procedure, while not entirely rigorous, yields comparable results (within the statistical accuracy of the data) as the direct shift of the `PI` energy scale in the event lists.

The results are summarised in Fig. 3 The reconstruction of the energy scale is more accurate, and consistent at the 1σ level with the nominal, when no offset term ($a = 0$) is included in the XRL correction. As this parameter choice reflects the expected behaviour of the camera, we implemented in this CCF the following XRL correction parameters: $\mathbf{a = 0.0}$, $\mathbf{b = 1.0}$. As we do not have an explanation for the residual $\sim$-10 eV systematic error in the energy scale, and this level of uncertainties is consistent with the systematics

[1] This assumes that the special gain correction in EPIC-pn Timing Mode (default option `withgaintiming=yes` in `epchain`) is correct. Guainazzi (2013) shows that this option indeed yields the most accurate energy scale in this mode.

[2] The choice of this component is driven by the fact that most of the sources are X-ray binaries in soft state.

associated to the energy scale in Full Frame (the reference mode for the gain correction), we have not attempted at further correcting it.

3 Scientific Impact of this Update

The XRL correction embedded in this CCF constituent goes together with an updated calibration of the Rate-Dependent CTI, presented in an accompanying CCF Release Note (Guainazzi 2013). Their goal is achieving an accurate calibration of the energy scale, once the ubiquitous XRL in this mode is properly subtracted.

This CCF does not affect the energy scale of any other EPIC-pn instrument modes.

4 Estimated Scientific Quality

With this calibration, we expect that the average accuracy of the energy reconstruction in EPIC-pn Timing Mode is better than 25 eV on the whole calibrated energy bandpass (0.7–10 keV), and for all level of count rates up to the threshold level ($\simeq$800 s^{-1}). The following caveats, however, apply:

- before Rev.$472 (started on the 7^{th} of July 2002) no offset maps were taken prior to the science exposure. In this case SAS cannot correct for the (unknown) level of XRL, and does not attempt at it. For these cases, the accuracy of the energy scale quoted in this document does not hold. Applying the RDCTI correction as in `EPN_CTI_0028.CCF` and earlier may still allow users to recover an accuracy of the energy scale better than 30 eV for energies lower than 4 keV, and better than 50 eV for energies higher than 4 keV. `epevents` issues a warning during the reduction of ODFs lacking an offset map. We plan to implement a statistical XRL correction for these ODFs (based on the correlation shown in Fig. 3) in a future SAS version
- the accuracy of the energy reconstruction in EPIC-pn Timing Mode exposures of the Crab Nebula could be affected by a systematic error of $\simeq$30-40 eV. Users are recommended not to use EPIC-pn Timing Mode for spectroscopic measurements on this (or a comparably bright!) source. Two specific exposures in Burst Mode were designed for this purpose: Obs.#0160960401, and Obs.#0160960601. Readers are referred to Kirsch et al. (2006) and Weisskopf et al. (2010) for a more extensive discussion on EPIC spectroscopy on the Crab Nebula
- The XRL correction is not the default in the SASv13.0.1. It has to be explicitly activated in, *e.g.*, `epchain` by setting the following parameters: `runepreject=yes`, `withxrlcorrection=yes`. The SAS task performing the XRL correction is `epreject`.

5 Test procedures and results

The results of the tests performed with a combination of this CCF and of the updated calibration of the RDCTI are discussed in an accompanying RN (Guainazzi 2013).

6 Expected updates

None.

7 References

Gehrels, 1986, ApJ, 303, 386

Guainazzi M., 2013, XMM-SOC-CAL-SRN-0304
(available at: `http://xmm2.esac.esa.int/docs/documents/CAL-SRN-0304-1-0.ps.gz`)

Guainazzi M., et al., 2012a, XMM-SOC-CAL-TN-0018
(available at: `http://xmm2.esac.esa.int/docs/documents/CAL-TN-0018.pdf`)

Guainazzi M., et al., 2012b, XMM-SOC-CAL-TN-0083
(available at: `http://xmm2.esac.esa.int/docs/documents/CAL-TN-0083.pdf`)

Kirsch M., et al., 2006, A&A, 453, 173

Smith M., 2004, XMM-SOC-CAL-TN-0050
(available at: `http://xmm2.esac.esa.int/docs/documents/CAL-TN-0050-1-0.ps.gz`)

Weisskopf M., et al., 2010, ApJ, 713, 912