Pile-Up in CCD cameras
CCD events

Frame #1

Events which land within a single Frame and don’t touch are registered as good events.

“Good” events with different patterns

1 keV

5 keV

3 keV

9 keV
What is pile-up?

Pile-up occurs when two or more events fall within the same pixel(s) within a single frame.

Energy pile-up

- 1 keV
- 3 keV

Apparent single pixel event at 4 keV
Pattern pile-up

Pattern pile-up occurs when two or more events fall within the same pixel(s) within a single frame.

Pattern pile-up / Grade migration

- 1 keV
- 3 keV

Apparent double pixel event at 4 keV
Pattern pile-up - triple

Frame #1

Pile-up occurs when two or more events fall within the same pixel(s) within a single frame

Pattern pile-up / Grade migration

1 keV (single)

3 keV (double)

Apparent triple pixel event at 4 keV

event 1 event 2
Pattern pile-up - quadruple

Pile-up occurs when two or more events fall within the same pixel(s) within a single frame.

**Pattern pile-up / Grade migration**

- 1 keV (double)
- 3 keV (double)

Apparent quad pixel event at 4 keV
Event destruction

Event destruction

Frame #1

1 keV (double)

3 keV (double)

Apparent bad (non-valid pattern) event

event 1  event 2
At what flux is it important?

Pile-up depends on the frame time (Observing mode), the count rate (filter and spectral-model) and the Point Spread Function (PSF) but very roughly in standard mode:

- XMM EPIC-pn (0.2-12 keV) > 5x10^{-12} ergs/s/cm^2
- XMM EPIC-MOS (0.2-12 keV) > 3x10^{-12} ergs/s/cm^2
- Chandra –ACIS (0.2-12 keV) > 5x10^{-12} ergs/s/cm^2
- Swift-XRT (0.3-10 keV) > 2x10^{-11} ergs/s/cm^2
- NuSTAR – The sun or Sco X-I in flaring states 😊
- Astrosat-SXT (0.3-10 keV) > 2x10^{-9} ergs/s/cm^2
- Suzaku-XIS (0.5-10 keV) > 5x10^{-11} ergs/s/cm^2
Images – XMM-Newton EPIC-pn

2MASS 1446+68
0.5 c/s

3C273
9.4 c/s

MKN 421
54 c/s

Pile-up destroys events in the centre of the PSF
Images – Chandra ACIS-HETG

0th order image from an ACIS-HETG observation of a bright X-ray binary.

From “Chandra_ABC guide to Pile-up”
Piled-up event fractions

Solid lines = 0-60” circle
Dashed lines = 15-60” annulus
Hump is due to destroyed events

Spectral deformation

Piled-up 1 keV gaussian

An absorbed power-law appears as a power-law with a different slope

Koch-Mehrin 2016: CAL-TN-0214
Estimation Methods

• Pattern Fractions – epatplot (XMM)
• Spectral fitting - Chandra fitting in ISIS
• Diagonal event fraction
• Pre-calculated tables
An un-piled source has a ratio of single to double pixel events equal to the ground Cal.

A piled-up source has less single and more double pixel events than standard.
Estimation Methods – model fitting

Chandra: estimate pile-up level using a model in ISIS

XMM-Newton: simultaneous fit of spectra extracted at various annuli

Multiple spectra for pn sources affected by pile-up.
Estimation Methods – diagonal events

Two possibilities:

- One event with a bad pattern (unlikely)
- Two or more events landing in a single frame (pile-up)

The fraction of diagonal to single-pixel events in the PSF core gives an indication of the level of pile-up.
XMM-Newton EPIC cameras

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Mode</th>
<th>Frame time</th>
<th>Conservative [s⁻¹]</th>
<th>Tolerant limit [s⁻¹]</th>
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<tbody>
<tr>
<td>EPIC-pn</td>
<td>Extended Full Frame</td>
<td>199.1 ms</td>
<td>0.7</td>
<td>1.5</td>
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<tr>
<td></td>
<td>Full Frame</td>
<td>73.4 ms</td>
<td>2</td>
<td>4</td>
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<td></td>
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<td></td>
<td>Small Window</td>
<td>5.7 ms</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>EPIC-MOS</td>
<td>Full Frame</td>
<td>2.6 s</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Large Window</td>
<td>0.9 s</td>
<td>1.5</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Small Window</td>
<td>0.3 s</td>
<td>4.5</td>
<td>9</td>
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Conservative limit = 2–3% flux loss and <1% spectral distortion
Tolerant limit = 4–6% flux loss and 1–1.5% spectral distortion
• Observing Mode / Parameters Selection
• Place source off-axis / Use Thick Filter
• Annular extraction
• Pattern 0 only spectra – pros and cons
• Diagonal pixel correction
• Chandra pile-up model – spectral fitting
• “Add an Event” method
Observing parameters

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Downside = smaller area, less exposed area to measure background
= higher dead-time fraction, e.g. Burst mode=3% efficiency

Decrease readout time by reading out less chips – 1/8 subarray, Chandra ACIS

Filter – Thin -> Medium -> Thick = reduction in c/s for soft spectra – Lose counts

Off-axis angle = use vignetting to reduce count rate
and in some cameras the PSF is wider - Lose counts + worse cal
Annular Extraction

Excluded inner 25” where pile-up is worst
EEF=90+/-1% in 1 arcmin circle
EEF=20+/-2% between 25 and 60 arcsecs

Problem: Lose fraction of counts
Introduce a PSF (encircled energy) energy-dependent, systematic error
Annular Extraction - diagnostics

Circular extraction  Annulus, excluding inner 6”  Annulus, excluding inner 15”
SUZAKU-XIS  (from XIS_PileupDoc_20120220_ver1.1.html)

On Cyg X-1

>aepileupcheckup.py ./ 0 -f xi0check.ps -y xi0check.yaml -p region
********** aepileupcheckup.py **********
*****************************************************************************
(omit)

Pileup is likely to occur.

3 % at 59.9 pixel, 1 % at 97.7 pixel ( 1 pixel ~ 1 arcsec)

Creating region files ..... 

Problem: Lose fraction of counts
Introduces a PSF (encircled energy) systematic error

Horizontal lines are 3% and 1% pileup fraction.
Annular Extraction – PSF fitting

Extract radial profile
Fit radial profile with the known Point Spread Function
Extract events from annulus of 8-40"

https://www.swift.ac.uk/analysis/xrt/pileup.php
Use Pattern 0 events

Ballet 1999 – Using a spectrum with single-pixel events experience minimises spectral pile-up

Frame #1

1 in 9 chance of energy pile-up

Corner: No good event – 2 events lost = 4
Adjacent: Double event – 2 events lost = 4
On Top: One wrong energy event = 1

event 1  event 2
Pattern 0 – Spectral distortion

Ballet 1999 – Single pixel events experience minimum spectral pile-up

Spectral distortion = $1 - \frac{\text{non-piled Events}}{\text{Piled events}}$

Solid = single+dub
Dashed = singles

Jethwa et al. 2015

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IACHEC 2020

24 Nov 2020

R. Saxton
Scaling by number of diagonal events

\[ \tilde{S}(E) = \tilde{S}_{obs}(E) + \frac{\gamma_1}{4\alpha_1} \tilde{S}_{dia-p0}(E) - \frac{1}{4} \tilde{S}_{dia}(E). \]

Molendi & Sembay 2003

\( S = \) emitted pattern 0 counts(E)
\( S_{obs} = \) Observed pattern 0 counts(E)
\( S_{dia-p0} = \) Counts(E) obtained by splitting diagonals into two singles
\( S_{dia} = \) Counts(E) observed in diagonal events
\( \alpha_1 = \) fraction of single-pixel events
\( y_1 = \) probability factor for encountering a diagonal (fn of pattern fractions)

Possible if software allows diagonal events to be split into 2 charges. More useful for cameras where the pixel size is small compared to the PSF. e.g. XMM-MOS.
From Chandra ABC pile-up guide

Simulated piled-up $\Gamma = 2$
absorbed power-law

Spectral fitting returns a
$\Gamma = 1.26$ power-law

Fitted with pile-up model,
Returns $\Gamma = 1.82$

Models: \texttt{pileup} (xspec, isis, Sherpa) - fast pile-up algorithm from Davis 2001.
\texttt{jdpileup} (Sherpa) – Gratings, Novak et al. 2008

With variable parameter, $\alpha$, the grade migration survival probability
Add event model – XMM-Newton

- Start from an event file
- Add one new event into each frame
  - in psf-weighted pixel
  - with a trial PI channel
  - with pattern chosen from p.f. ratio
- Calculate what happens to the event
- Produce a distribution of the output event PIs for each input PI

Frame #1

= event from ODF  = trial event
Add event at a given energy

- Add one event into each frame
  - in psf-weighted pixel
  - with a trial PI channel
  - with pattern chosen from p.f. ratio

- Calculate what happens to the event

- Produce a distribution of the output event PIs for each input PI

Double event

= event from ODF  = trial event
Output: Piled-up spectrum for 1.1 keV

Initial power-law spectrum from observation. Add a 1.1 keV event many times.

Initial (black) and output (brown) RMFs
Write the piled-up distribution for each energy into the RMF. Produce an RMF which is not normalised to one, hence model the events which produce bad patterns and are lost.
Results – simulation

Koch-Mehrin (2016)  - CAL-TN-0214

Black-body 40 eV

Works well for sources observed with EPIC-pn in imaging modes with low or moderate pile-up.

Koch-Mehrin (2016)  - CAL-TN-0214
Results – MKN 421

Koch-Mehrin and Constantino (2016) - CAL-TN-0213-1
Relevant Papers

- Ballet 1999 – Stats of pile-up on CCDs, single-pixel events ok.
- Ballet 2001 – Effects when pixel size is large compared to PSF
- Davis 2001a – Spectral analysis of non-piled up sources
- Davis 2001b – Description of Chandra pile-up model
- Molendi & Sembay 2003 – triangular events as a diagnostic
- Jethwa et al. 2015 – count rate limits for XMM-Newton cameras
- Swift-XRT pile-up – https://www.swift.ac.uk/analysis/xrt/pileup.php
- Tomsick et al. 2004 – effect on timing analysis (reduction of noise)
- Yamada et al. 2012 – Pile-up effects on Suzaku-XIS
- CAL-TN-0213 and CAL-TN-0214 XMM-Newton technical notes – testing of “Added event” model
- Nowak et al. (2008) – Chandra gratings pile-up model