New clocking mode for X-ray CCD detector

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X-ray CCD detector

• Pros
  • small pixel size
  • large number of pixels with a few readout nodes

• Cons
  • long exposure time (to read many pixels in sequence)
  • (requires clocking signal)

CCDs exhibit good imaging quality and moderate time resolution
pile-up problem

- two (or more) photons enter to the same pixel or neighbor

We cannot know incident X-ray energy of each photon

split event = pile-up event
Pile-up effect （Suzaku/XIS0）

〜550 mCrab in 0.3s burst 1/4window Suzaku/XIS0
〜3 mCrab for XRISM/Xtend 4s full window

(b) GX 339-4
pile-up fraction
(>7%)
0 - 25 pixel
(3-7%)
25 - 60 pixel
(2-3%)
60 - 75 pixel
(1-2%)
75 - 90 pixel
(0.5-1%)
90 - 120 pixel

*) GX339-4 in this observation had softer spectrum than typical AGNs. The effect is thus enhanced.
mitigation method

• Window mode: readout a certain region of CCD  
  → reduced field of view

• Burst mode: use a part of exposure time  
  → loose large fraction of X-ray events

• P-sum mode: continuous transfer  
  → loose coordinate information of one direction  

Loose significant information

• New mode: intermediate of normal and P-sum (or full-frame) mode:  
  → Reduce pile-up fraction without losing statistics nor information of position
New clocking mode: Panning mode

◆ A certain number of the vertical transfer is performed in the imaging area during each exposure. (We don’t move satellite attitude or CCD camera)
◆ Readout in the storage area is the same as that in the normal mode.
◆ The number of the transfer (during exposure time) is a setting parameter ($N_{\text{pan}}$)
◆ Shape of each event is unchanged. Accumulated image is elongated to vertical direction. → Reduce event rate of each pixel

LED irradiation experiment performed with a CCD

Simulation (Suzaku observation)

Simulated panning image ($N_{\text{pan}}=240$) (XIS observation of Cyg OB2 region)
Tolerance of pile-up

Count rate per one pixel in one shot image becomes small with each mode $\rightarrow$ reduce pile-up fraction
• Window/Burst
  Pixel rate of 1 shot image becomes small
  • $1/N_{\text{win}}$ window size $\rightarrow 1/N_{\text{win}}$
  • $1/N_{\text{bst}}$ snap shot time $\rightarrow 1/N_{\text{bst}}$
• P-sum mode
  point source image is extended to CCD size
  • image size $s$, CCD pixel size $X \times Y \rightarrow s/Y$
Tolerance of pile-up

Count rate per one pixel in one shot image becomes small with each mode → reduce pile-up fraction

• Panning mode

  The deformation of point source image is related to number of vertical transfer $N_{\text{pan}}$
  • image size $s \rightarrow s/N_{\text{pan}}$
$s = 10 \text{ pixel}$

The diagram shows the relationship between pixel rate (cnt/pix/shot) and incident count rate (cnt/frame). The graph includes lines for different conditions: normal, win 1/4, win 1/16, and P-sum. The criteria to avoid pile-up is indicated by a horizontal line at 0.001. The x-axis represents the incident count rate (cnt/frame), and the y-axis represents the pixel rate (cnt/pix/shot).
$s = 10 \text{ pixel}$
$s = 1 \text{ pixel}$
$s = 1 \text{ pixel}$
Decrease of pile-up fraction with realistic PSF (Xtend/XRISM)

- The peak of Point Spread Function becomes 1/16 with $n=150$ (bpix) → factor of 2 better than 1/8 window mode
Time resolution

• The shift of the image is controlled by clocking signal
  → Fine time resolution can be archived by using position of X-ray event
• Light curve is smoothed by PSF
  (If PSF is equivalent to pixel size, time resolution becomes $1/N_{\text{pan}}$)
Spectroscopic performance

• Comparison with normal mode;
  The difference is only a small number of vertical transfer
  \((0 \sim N_{\text{pan}})\)
  Little degradation of energy resolution is expected

cf. P-sum mode
  Continuous clocking (with different voltage)
  Different event extraction (split pattern is different)
  Charge injection is impossible
  \(\rightarrow\) large impact to energy resolution
Summary: Panning Mode Trade-off

• **pros**
  - Reduce pile-up fraction
  - Keep full region of imaging area
  - Exposure time is not lost in most of the imaging area
  - Possible improvement in time resolution
  - No change in hardware is needed, of course.

• **cons**
  - PSF is elongated
    • degradation of imaging capability
    • S/BD ratio is reduced
  - The exposure time at the CCD boundary of the far side from the FOV center is reduced
  - Need additional calibration time (there would be little difference in spectroscopy)
  - Impact to processing software
- pixel count rate is reduced
- relative position indicates photon arriving time
  (not 1 to 1 relation smeared with PSF tail)

If a source has a variability within exposure time, the image should be different from the constant flux case. In principle, variability information can be extracted.

← A part of exposure is lost at the pixel boundary (far side of the FOV center)
supplemental slides
TABLE I: Characteristics of various modes, for the observation of point-like objects.

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>Window</th>
<th>Burst</th>
<th>P-sum</th>
<th>Panning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile-up Tolerance</td>
<td>1</td>
<td>$N_{\text{window}}$</td>
<td>$N_{\text{burst}}$</td>
<td>$N_{\text{line}}/N_{\text{image}}$</td>
<td>$1 \sim N_{\text{line}}/N_{\text{image}}$</td>
</tr>
<tr>
<td>Field of View</td>
<td>1</td>
<td>$N^{-1}_{\text{window}}$</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Photon Statistics</td>
<td>1</td>
<td>1</td>
<td>$N^{-1}_{\text{burst}}$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Time Resolution</td>
<td>1</td>
<td>$N^{-1}_{\text{window}}$</td>
<td>1</td>
<td>$1/N_{\text{line}}$</td>
<td>$1 \sim N_{\text{image}}/N_{\text{line}}$</td>
</tr>
<tr>
<td>Pattern Selection</td>
<td>$\bigcirc$</td>
<td>$\bigcirc$</td>
<td>$\bigcirc$</td>
<td>$\triangle$</td>
<td>$\bigcirc$</td>
</tr>
<tr>
<td>Image Resolution</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>$N_{\text{line}}/N_{\text{image}}$</td>
<td>$1 \sim N_{\text{line}}/N_{\text{image}}$</td>
</tr>
</tbody>
</table>
Pile-up limit of XRISM/Xtend scaled from Suzaku/XIS

<table>
<thead>
<tr>
<th></th>
<th>Suzaku/XIS</th>
<th>XRISM/Xtend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame integration time</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>(sec)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pixsel scale (arcsec)</td>
<td>1.04</td>
<td>1.74</td>
</tr>
<tr>
<td>Effective area (cm²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5 keV</td>
<td>390 (BI)</td>
<td>400</td>
</tr>
<tr>
<td>8 keV</td>
<td>100 (BI)</td>
<td>300</td>
</tr>
<tr>
<td>HPD (arcmin)</td>
<td>2.0</td>
<td>1.26</td>
</tr>
</tbody>
</table>

Pixel count rate $\propto$ (frame time) $\times$ (pixel scale)$^2$ $\times$ (HPD)$^{-2}$ $\times$ (Effective area) → 3.6 ~ 10.6 times larger than XIS

(1 keV: $(4/8)\times(1.74/1.04)^2\times(2.0/1.26)^2\times(400/390)\sim3.6$
8 keV: $(4/8)\times(1.74/1.04)^2\times(2.0/1.26)^2\times(300/100)\sim10.6)$

We use factor 7.7 in the following discussion to be consistent with Astro-H SWG discussion

Xtend will suffer a severer pile-up problem
Pile-up (3%) limit of XIS : 12 cts/sec $\sim$ 10 mCrab
→ 1.3 mCrab in Hitomi/SXI and XRISM/Xtend

https://heasarc.gsfc.nasa.gov/docs/suzaku/prop_tools/suzaku_td/node10.html#SECTION01022100000000000000
Flux 14-195keV (10^{-12} erg/s/cm^2)

Data from https://swift.gsfc.nasa.gov/results/bs105mon/

AGN in Swift BAT 105months Catalog

- CenA
- NGC4151
- 3C273

XIS pile-up limit (3%)
<table>
<thead>
<tr>
<th>Flux 14-195keV (10^{-12} erg/s/cm^2)</th>
<th>10000</th>
<th>1000</th>
<th>100</th>
<th>10</th>
<th>1</th>
<th>0.1</th>
<th>0.01</th>
<th>0.001</th>
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<tbody>
<tr>
<td>CenA</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>NGC4151</td>
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<td></td>
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<td></td>
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<td></td>
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<tr>
<td>3C273</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10mCrab</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1mCrab</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100mCrab</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pile-up is a problem not only for bright binary sources but also for a significant fraction of XRISM target AGNs.

Data from https://swift.gsfc.nasa.gov/results/bs105mon/
Perseus cluster observed with Hitomi SXI (Nakajima+2018)

Overlaid 1/8 window area (2.35’ width)
1/8 Window mode
- Mitigates pileup by factor of 8
- Lose Information of the Sky around the target (Some fraction of Resolve FOV is outside the window)
  - One of the role of Xtend is to estimate contamination into Resolve FOV.
- Periodic (every 0.5s) deadtime up to 10%

cf
Annular Extraction or Burst Mode can also mitigates pileup, but lead to loss of photons (dead area at the PSF core or deadtime)

1/16 window mode is not adequate, as its width is only 1.2’
pile up rateの計算

・仮定する条件
  • 天体の明るさ: f (cnts/sec)
  • 露出 1sec (normal mode)
  • 天体の広がり (PSF): a × a (pixel²), 一様
  • CCDの縦方向のpixel数: y = 1024 (pixel)

→ 1 pixel内に入れる平均 photon数を計算し、
  pile upの指標とした

normal modeの場合:
(pile up rate) = f /a²
mode ごとの pile up rate

- normal mode
  \[ f / a^2 \]
- window (1/n size)
  \[ f / a^2 / n \]
- P-sum
  \[ f / a / y = (f / a^2) \times a / y \]
changes in software

<table>
<thead>
<tr>
<th>item</th>
<th>change</th>
<th>impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>position</td>
<td>+1/2n</td>
<td>small</td>
</tr>
<tr>
<td>timing</td>
<td>---</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>rawy - rawy$_0$ -&gt; $\Delta t$</td>
<td>large</td>
</tr>
<tr>
<td>energy</td>
<td>$1/((1 - c_{vs})^{n/2}$</td>
<td>small</td>
</tr>
<tr>
<td></td>
<td>rawy - rawy$_0$ correction</td>
<td>large</td>
</tr>
<tr>
<td>QE</td>
<td>$x(0 \sim 1)?$</td>
<td>small or 0</td>
</tr>
<tr>
<td></td>
<td>---</td>
<td>0</td>
</tr>
</tbody>
</table>

If the process depends on the source position, impact becomes large.
Changes in software (spectrum)

1. CTI correction: Additional 0 – n (very) slow transfer
   A) Modified CTI correction (1): $\Delta E \triangle$
      1. Add CTI correction for (very) slow transfer of $n/2$ lines
         $$PH = PH_0 (1 - c_f)^{Y_0} (1 - c_{f0})^{Y_1} (1 - c_a)^{Y_2} (1 - c_{a0})^{Y_3} (1 - c_s)^{Y_4}. (1 - c_{vs})^{n/2}$$
   B) Modified CTI correction (2): $\Delta E \bigcirc$
      1. Reduce uncertainty of the number of very slow transfer by using "rawy-rawy$_0"$
   C) No additional correction: $\Delta E \triangle$
      1. No change in software (sxipi)
      2. Calibrate energy gain (similar to window mode of Suzaku)
         + Prepare CTI parameters, response function for panning mode in all cases

*Sawtooth correction is identical to that of normal mode; relative position is preserved

**Unified correction may be possible by referring the number of transfer for all mode
prediction of energy resolution

• CTI effect with additional 0-n bpix transfer
  \[(1 - c_{vs})^{0~n}\]
  
  ex. \(C_{vs} = 5 \times 10^{-5}\), \(n=150\)
  
  \[\rightarrow \quad 1 \sim 0.9925\]

\[\Delta E = 45 \text{ eV}@6\text{keV} \text{ (maximum shift)}\]

Degradation of energy resolution (overestimate)

\[\sqrt{(130^2 + 45^2)} = 137.6\]

※energy resolution of normal mode is assumed to be 130eV

Consider only photon statistics \(\frac{1}{\sqrt{0.9925}} = 1.004 \text{ times larger} \text{ (under estimate)}\)