Arcsecond and Sub-arcsecond Imaging with Multi Image X-ray Interferometer for (Very) Small Satellites

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1. Telescopes are built with Grazing Incidence Mirrors with FL of 3-12m plus Pixel Detectors.

2. 0.5” resolution mirror is exceptional. It is very much difficult to reproduce it now.

3. Slits, Masks or Collimators are used for wide FOV surveys, in which angular resolution is limited to ~10arcminutes.

4. Interferometers have been proposed. Some function in lab, but application in orbit are even more difficult.
Multi-Pinhole (Slit) Camera is the baseline

STACK these multiple images in the analysis

http://blog.goo.ne.jp/hanahana/haru04/e/a8ef27218dee3713136a89943109a431
Multi Image X-ray Interferometer/Imager

Almost Parallel Beam

Grating

• Only employ a Grating and an X-ray Pixel Detector

• Image profile detected reflects the profile of the X-ray source.

• Stacking the image with a period of \(d\) in the analysis, accurate source profile is obtained.

• Image Width \(\theta = f d / z = 0.4'' \left( \frac{f}{0.2} \right) \left( \frac{d}{5\mu m} \right) / \left( \frac{z}{50cm} \right)\)

\[\text{Chandra Resolution with a 50cm size satellite?}\]

See Hayashida+ SPIE Proc 2016
But, in reality **Diffraction** is significant.

Simulated Image Profile with Fresnel Approximation (not stacked)

- $d=5\,\mu m$
- $f=0.2$
- $z=0.5m$
- $\lambda=0.115nm$

- $N=1$ (Single Slit)
- $N=2$ (Double Slit)
- $N=3$
- $N=10$
- $N>>1$ (Grating)

Position ($\mu m$) on the Detector
But, but, Talbot Effect can be employed

- **Talbot Effect**
  - Parallel Light through a grating makes **Self Image** of the grating at periodic distances. (H.F.Talbot, 1836)
  - Explained with **Diffraction** and **Interference** (Rayleigh, 1881)
  - Hard X-ray Talbot Effect in experiment (P. Cloetens, 1997)

- **Talbot Distance** \( z_T = m \frac{d^2}{\lambda} \)

For \( \lambda=0.1\text{nm} (12\text{keV}) \) X-rays and a \( d=5\mu\text{m} \) pitch grating, Talbot distance \( z_T \) of \( m=2 \) is 50cm
At Talbot Distance

\[ d = 5 \mu m \quad f = 0.2 \]
\[ z = 0.5 m \quad \lambda = 0.100 nm \quad (m=2) \]

Simulated Image Profile with Fresnel Approximation (not stacked)

\[ N=1 \]
(Single Slit)

\[ N=2 \]
(Double Slit)

\[ N=3 \]

\[ N=10 \]

\[ N>>1 \]
(Grating)

Position (\(\mu m\)) on the Detector
$\lambda$ dependence at a fixed setup

$\lambda_0 = 0.1$ nm

Average ($0.09954$ nm - $0.10045$ nm)

Band width ($\Delta \lambda / \lambda$) = 1%

Position (µm) on the Detector
$\lambda$ dependence at a fixed setup

$\lambda_0 = 0.1\text{nm}$

Band width ($\Delta \lambda / \lambda$) = 10%  $m=2$  Position ($\mu$m) on the Detector
Another X-ray beam incidence from 0.5arcsec offset direction

\[ \lambda_0 = 0.1 \text{nm} \]

Position (\( \mu \text{m} \)) on the Detector

\[ d = 5 \mu \text{m} \]

\[ f = 0.2 \]

\[ z = 0.5 \text{m} \]

\[ m = 2 \]

Band width \( (\Delta \lambda / \lambda) = 10\% \)  

\[ m = 2 \]
Multi Image X-ray Interferometer Module (or Mission) = MIXIM

- **X-ray Grating** with a few~10’s µm pitch and X-ray Imaging Spectrometer
- **Select** X-ray Events of which energy is within specific band around the Talbot condition.
  - Band-pass $\Delta \lambda / \lambda$ of about 10% (for $m=2$; 20% for $m=1$) can be utilized. Wider than Si-detector energy resolution of 1~2%. Good for X-ray CCD and X-ray CMOS.
- **Stacked Image** tell us the X-ray source profile

c.f. **X-ray Talbot (-Lau) Interferometer** Momose+(2003), Pfeiffer+(2006) for Phase Contrast X-ray Imaging of Light Material

Figure from [http://rsif.royalsocietypublishing.org/content/7/53/1665](http://rsif.royalsocietypublishing.org/content/7/53/1665)
Lab. Experiment with Spherical Wave

**microFocusX-ray**
- 60kV, 100µA, Target=W
- Source Size=3~5µm

**X-ray Grating**
- Pitch $d=4.8µm$
- Open frac. $f=0.5$
- 17µm thick Au on Si

**X-ray CMOS**
(XRPIX2b)
- inside Vacuum Chamber
- Cooled -40degC
- Window=0.2mm Thick Al

XRPIX2b (Tsuru+2014)
- pixel size 30µm
- 152x152 pix
Lab. Experiment Result 1/2

**XRPIX Image**  R=42mm, 25X

- **Focus**
- **Grating**
- **XRPIX**
- **L=1040.5mm (fixed)**

- **Projection to CA-axis**

- **Stacked Profile**

- **WLβ 9.8keV**
- **WLα 8.4keV**
- **WLγ 11.3keV**
- **MoKα 17.5keV**

- **Single Pixel Event**
- **Double Pixel Event**

※Only Double Events (split along CA direction) are employed

**Projected Profile**

**Stacked Profile**

**Normalized Counts**
• micro-Focus source size of 3-5μm is not small enough to be regarded as a point source as illustrated in the Stacked profile.
Near Field $z \ll z_T$

- $d=25\mu m$, $f=0.2$, $\lambda_0=0.1nm$
- $z=0.5m \ll z_T (m = 1) = 6.25m$

Band width ($\Delta \lambda / \lambda$) = 60%

Position ($\mu m$) on the Detector
Very Preliminary Design

\[ z = \frac{md^2}{\lambda} = 50\text{cm} \left( \frac{m}{2} \right) \left( \frac{d}{5\mu m} \right)^2 / \left( \frac{\lambda}{0.1\text{nm}} \right) \]

\[ \theta = \frac{fd}{z} = f\lambda/dm = 0.4'' \left( \frac{f}{0.2} \right) \left( \frac{\lambda}{0.1\text{nm}} \right) / \left( \frac{d}{5\mu m} \right) \left( \frac{m}{2} \right) \]

- Positional Resolution of Pixel Detector is essential.

- Energy Range 5-20keV
  - Grating transmission \( \eta_{\text{gra}} \) at open (Si filled) part, and Detector efficiency \( \eta_{\text{det}} \) limits the range.

- Effective Area \( A_{\text{eff}} = A_{\text{geo}} \cdot \eta_{\text{gra}} \cdot \eta_{\text{det}} \cdot f \cdot \Delta\lambda/\lambda \)

- FOV must be limited by collimators to \(~1\text{deg.}\)

- Background
  - Imaging capability reduce the CXB and NXB factor of \( f \).
  - Rough estimate CXB=0.2 mCrab, NXB=4mCrab  Very preliminary

\[ \theta : \text{Image Width} \]
\[ d : \text{Pitch} \]
\[ f : \text{Open. Frac} \]
\[ z : \text{Distance} \]
\[ m : \text{Talbot Order} \]
## MIXIM options

<table>
<thead>
<tr>
<th>Mission Size</th>
<th>Sampler</th>
<th>Short</th>
<th>Tall</th>
<th>Grande</th>
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</thead>
<tbody>
<tr>
<td>Distance (z)</td>
<td>0.5m</td>
<td>0.5m</td>
<td>2m</td>
<td>10m</td>
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<tr>
<td>Pitch (d)</td>
<td>25(\mu m)</td>
<td>5(\mu m)</td>
<td>10(\mu m)</td>
<td>10(\mu m)</td>
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<tr>
<td>Open. Frac. (f)</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
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<tr>
<td>Talbot Order (m)</td>
<td>(0.1)</td>
<td>2</td>
<td>2</td>
<td>10</td>
</tr>
</tbody>
</table>

for 0.1nm X-ray

| \(\theta\) | 2\(^''\) | 0.4\(^''\) | 0.2\(^''\) | 0.02\(^''\) |
| \(\Delta\lambda/\lambda\) | 1 | 0.2 | 0.2 | 0.2 |

| No. of X+Y unit | 1+1 | 4+4 | 25+25 | 100+100 |

\((A_{geo}=10cm^2/unit \text{ assumed})\)

| \(\eta_{det}\) at 10keV | 0.78 | 0.78 | 0.78 | 0.78 |

\((200\mu m \text{ Si assumed})\)

| Effective Area \((@10keV)\) | 3\(cm^2\) | 2.5\(cm^2\) | 16\(cm^2\) | 31\(cm^2\) |
Targets: e.g. Structure of Relatively Bright Point-like Sources, i.e., (SM)BH and NS

Recoiled SMBH candidates

CXO J101527.2+625911

(X-ray: NASA/CXC/NRAO/D.-C.Kim; Optical: NASA/STScI)

Binary SMBHs

NGC6240

Torus Type2 and 1 AGNs

NGC1068

ALMA image

Garcia-Burillo+2016
-Instruments for X-ray Astronomy- Agree?

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No, in future, with MIXIM or any other methods.