Imaging reconstruction method on X-ray data of CMOS polarimeter combined with coded aperture

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1. Introduction

- Polarization from a celestial object contains rich information about its anisotropic configuration, including details about emission geometry and magnetic field structure.
- While IXPE [1] achieves imaging polarimetry below 10 keV, and several other missions cover energies above 30 keV (PoGO+ [2], Hitomi-SGD [3]), the 10–30 keV range remains unexplored. This band holds significant importance, as non-thermal emissions from astrophysical systems dominate over thermal unpolarized radiation with sufficient photon flux.
- We are developing a CubeSat mission, called ***cipher*** (coded imaging polarimeter of high energy radiation) [4,5], which achieves imaging polarimetry in the 10–30 keV band. Through a series of proof-of-concept experiments at SPring-8, we demonstrated that the combination of a CMOS sensor and coded apertures realizes imaging polarimetry in this band.
- The imaging reconstruction with coded apertures so far has utilized conventional "cross-correlation" method, which is associated with notable artifacts and background noise levels.
- A new imaging reconstruction technique with less artifacts and noise levels is necessary to reconstruct a polarization map from photons collected by the limited effective area of the CubeSat.

2. New imaging reconstruction method of polarized X-rays

- We applied the EM algorithm [6] for imaging reconstruction of the polarization map. It is a statistical method that iteratively performs the E-step (expectation) and M-step (maximization) to find the most likely solution from observation data.

E-step: $\tilde{D}_v^{(l)} = \sum_u M_{vu} \tilde{S}_u^{(l)}$

M-step: $\tilde{S}_u^{(l+1)} = \frac{1}{\sum_{v'} D_{v'}} \sum_v D_v \frac{M_{vu} \tilde{S}_u^{(l)}}{\tilde{D}_v^{(l)}}$

D_v: Actual number of detected events on v-th pixel

$\tilde{S}_u^{(l)}$: Expected intensity on u-th sky region at l-th step

$\tilde{D}_v^{(l)}$: Expected number of events on v-th pixel at l-th step

M_{vu}: Mapping from the sky (S_u) to the detector (D_v)

- For imaging polarimetry, we extended the above formulation as follows:

$\tilde{S}_u$: Angular distributions of Stokes parameters (I, Q, U). We focus solely on I and Q in this paper because of the limited sensitivity of the CMOS sensor to U.

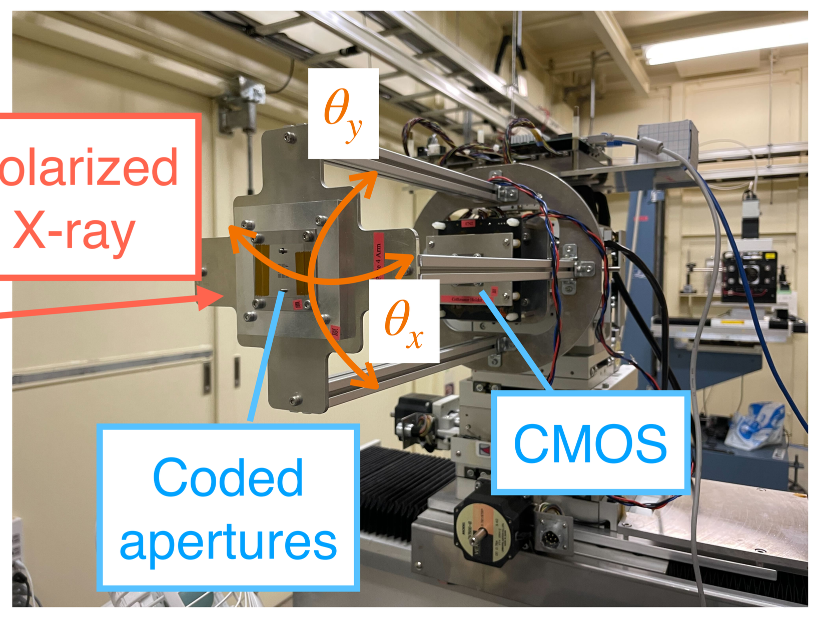
D_v (or $\tilde{D}_v$): Spacial distribution of double-pixel events associated with their types. These events are categorized into H-type (horizontal) and V-type (vertical) events, linked to the polarization angle of incident photons through the modulation factor m.

For the details of polarimetry, see Poster 155 (T. Iwata)

M_{vu}: Constructed by calculating the geometrical configuration between the detector and coded apertures. The effect of the modulation factor is also taken into account.

$$\underbrace{\begin{pmatrix} \mathrm{H-type} \\ \mathrm{V-type} \end{pmatrix}}_{\tilde{D}_v} = \underbrace{\begin{pmatrix} \mathrm{Aperture} \\ \mathrm{pattern} \end{pmatrix} \begin{pmatrix} 1/2 & m/2 \\ 1/2 & -m/2 \end{pmatrix}}_{M_{vu}} \underbrace{\begin{pmatrix} I(\theta_x, \theta_y) \\ Q(\theta_x, \theta_y) \end{pmatrix}}_{\tilde{S}_u}$$

3. Results



- We evaluated imaging performance using a concept demonstration model (left image).

Incident photon: 16 keV
Incident polarization: 100%
Modulation factor: $m = 10.3$ %
Angular resolution: 29″

- We blended 0˚ and 90˚ polarization data to create a reference dataset, on which we applied imaging reconstruction using the EM algorithm.
- The reference data have uniform intensity over $420'' \times 420''$, but four separate regions with different polarization degrees represented by Stokes parameter Q ($= I_{0\mathrm{deg}} - I_{90\mathrm{deg}}$).

✦Reference data (420″ × 420″)

$I(\theta_x, \theta_y)$

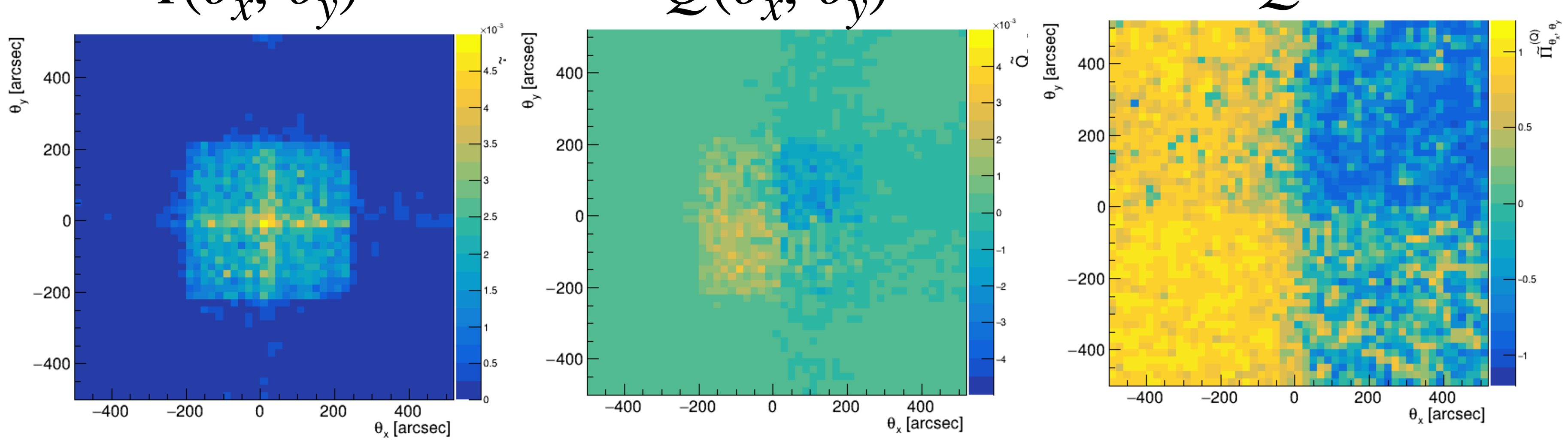
1.0	1.0
1.0	1.0

$Q(\theta_x, \theta_y)$

0.4	-1.0
1.0	0.0

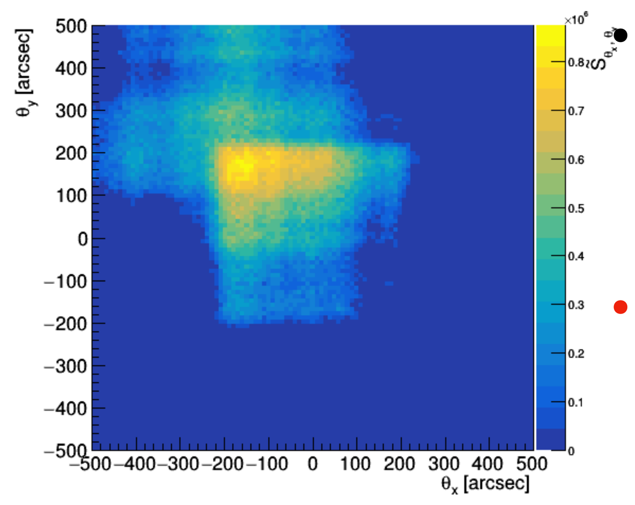
✦Imaging reconstruction results

$I(\theta_x, \theta_y)$ $Q(\theta_x, \theta_y)$ Q/I



- **We succeeded in performing imaging reconstruction for both $I(\theta_x, \theta_y)$ and $Q(\theta_x, \theta_y)$ by running $l = 1500$ steps.**

4. Comparison with conventional method



- The left image shows the imaging reconstruction results for $I(\theta_x, \theta_y)$ generated by the cross-correlation method.
- The large artifacts and high noise levels prevent us from generating a polarization map, i.e., the image of $Q(\theta_x, \theta_y)$.

Noise evaluation: $\nu = \frac{\text{(standard deviation of background region)}}{\text{(Average intensity of source region)}}$

We obtain $\nu = 0.11$ for EM algorithm and $\nu = 0.70$ for cross-correlation method. The noise level is reduced to 17%.

5. Conclusions

- We developed a new imaging reconstruction method for polarized X-rays collected by a CMOS sensor and coded apertures, applying the EM algorithm to the observation data.
- Compared to the conventional method, our imaging reconstruction method exhibits fewer artifacts and significantly reduced background noise levels, enabling the generation of a precise polarization map.

References

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