Imaging with Coded Apertures

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Coded apertures solve the problem of making images without using refractive materials or other optical elements that focus light on a detector, by blocking parts of the aperture so that sources cast a specific shadow on the detector.

1 Pinhole Camera

Fundamentally, to make an image, we need to detect some photons (or other messengers) and know which way they came from. We need to map signals in a detector plane to sources in an image plane.

To make an image with photons at energies where refractive materials are difficult to come by, the oldest type of camera appeals: a simple pinhole aperture placed a distance in front of a screen or detector. For an infinitely small [1] aperture, photons landing on any pixel in the detector plane must have come through the aperture from one specific direction (see figure 1). What we want when we make a picture is a relation between the measurements (e.g. photon number per pixel) in the detector plane and the direction-dependent intensity from the sky. For a pinhole camera, this relation is very simple (when we don't consider detector noise), as every photon's position on the detector maps to one sky location.

The problem with pinhole cameras is that most of the photons from the source are blocked, severely limiting sensitivity to faint sources of photons. Increasing the pinhole size improves the signal-to-noise ratio, but the angular resolution deteriorates, since a wider aperture means that photons landing on one point in the detector plane could have arrived from a wider range of directions.

[1] Not actually infinitely small, because we need to stay in the ray-tracing limit here.

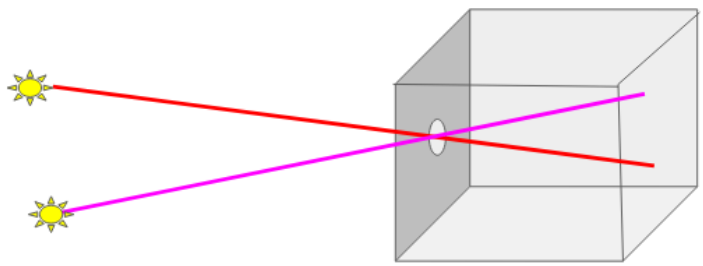

Figure 1: Diagram of a pinhole camera. Light from point sources pass through a pinhole in the aperture plane and land on unique spots on the detector plane.

2 Coded Apertures

A pinhole camera with multiple pinholes would not waste as many photons. A point source would make multiple spots on the detector and summing the pixels from the two spots improves the signal to noise. In 1968, Robert Dicke proposed making a gamma ray camera by perforating an aperture mask with randomly positioned pinholes, so that half the aperture is open[2] (Figure 2). If photons come from a point source, the detector registers a scaled and shifted copy of the aperture mask pattern. For general sources, the signal at the detector is a convolution of the sky and the mask pattern, plus background noise. The angle that one hole subtends from the position of the detector determines the image resolution.

The number of holes viewed by the detector determines the sensitivity.

The mask must be larger than detector, so that it still casts a shadow on the detector even for inclined sources. For any size mask, however, sources beyond a certain inclination won't cast a mask-shadow over the whole detector. The fully coded field of view is the maximum inclination of a source that has the whole detector within the mask's shadow. In the partially-coded field of view, at least some of the detector is within the shadow pattern, and the sensitivity decreases with inclination in this region (see e.g. [3]).

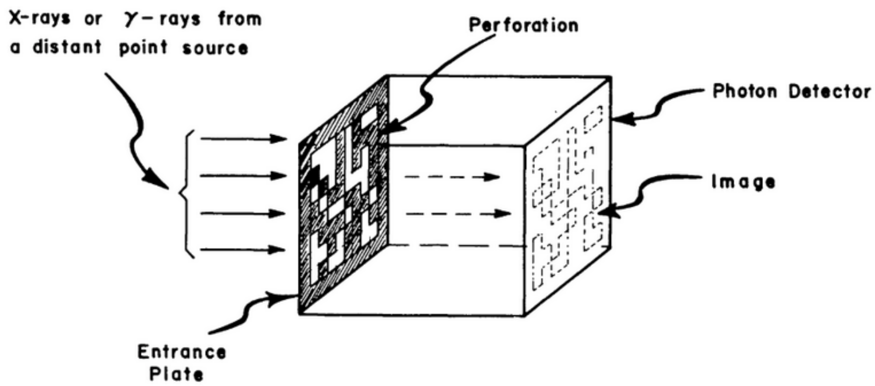

Figure 2: Diagram of a coded aperture camera of with random pinholes (Dicke 1968[2]).

3 Choice of Mask Pattern

Ideally, a point source anywhere should cast a unique shadow. This criterion clearly rules out regularly-spaced pinholes or a checkerboard-like grid. Dicke's original proposal, and some modern instruments such as Swift BAT use a fully random mask pattern[1],[2].

Mask patterns whose autocorrelation function (specifically, the cyclic autocorrelation) is a delta function satisfy the desired condition that any point source in the fully coded field of view casts a unique shadow. Trivially, a single pinhole satisfies this condition, but so do a larger set of patterns called uniformly redundant arrays (see figure 3 for an example). For these masks, the point spread function approaches a delta function and has no sidelobes. A source in the partially coded field of view will have sidelobes. Instruments that use uniformly redundant arrays include Astrosat/CZTI and Integral/IBIS.

4 Image Reconstruction

Reconstructing an image from the pattern registered at the detector is an inverse problem. Without noise and given the mask pattern this would be a straightforward deconvolution. Searching for a source in a particular direction can be done by appropriately weighting and summing the detector pixels for that direction, without deconvolving a full image. With random noise and multiple sources or extended

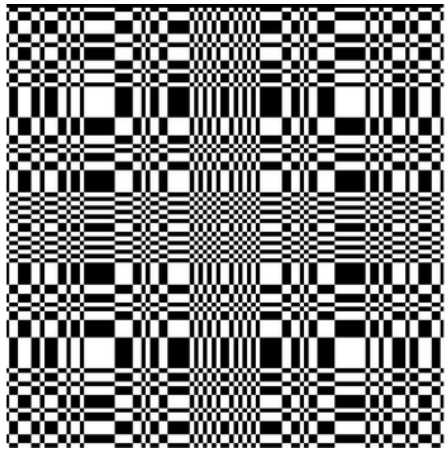

Figure 3: Mask pattern used by Integral (modified uniformly redundant array)

sources, the deconvolution problem no longer has a unique solution, and techniques such as regularized optimisation and techniques from the field of compressed sensing apply.

References

[1] Scott D. Barthelmy, Louis M. Barbier, Jay R. Cummings, Ed E. Fenimore, Neil Gehrels, Derek Hullinger, Hans A. Krimm, Craig B. Markwardt, David M. Palmer, Ann Parsons, Goro Sato, Masaya Suzuki, Tadayuki Takahashi, Makota Tashiro, and Jack Tueller. The burst alert telescope (BAT) on the SWIFT midex mission. *Space Science Reviews*, 120(3-4):143–164, 2005.

[2] R.H. Dicke. Scatter-Hole Cameras for X-Rays and Gamma Rays. *ApJ*, 153:101–105, 1968.

[3] A. Goldwurm, P Goldoni, A Gros, J Stephen, L Foschini, F Gianotti, L Natalucci, G De Cesare, and M Del Santo. Gamma-Ray Imaging with the Coded Mask Ibis Telescope. In *Exploring the Gamma-Ray Universe*.