HARD X-RAY TELESCOPE FOR SPACE FLIGHT USE

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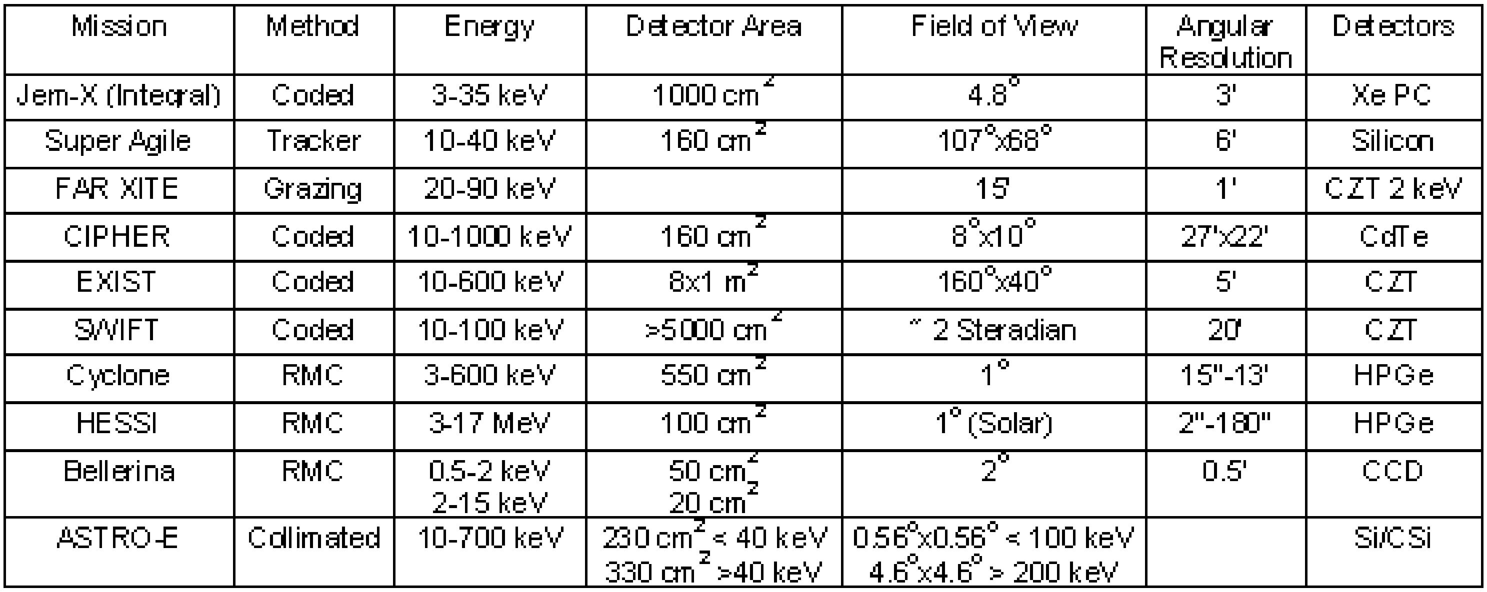
The Compton Gamma Ray Observatory (CGRO), Rossi X-Ray Timing Explorer (RXTE), and Beppo-SAX missions in recent times have clearly demonstrated the importance of hard x-ray and soft ³-ray studies to the understanding of high-energy astrophysical phenomenon. To date, hard x-ray surveys of the full sky have not yet been achieved to understand the most fundamental energetics. A high angular resolution survey of hard x-rays and soft ³-rays has been limited because of the inability of technology to fabricate coders and high spatial resolution image plane detectors. Table 1 shows instrument parameters for some of the proposed missions for hard x-ray observations in astrophysics.



Mission	Method	Energy	Detector Area	Field of View	Angular Resolution	Detectors
Jem-X (Integral)	Coded	3-35 keV	1000 cm^2	4.8°	3'	Xe PC
Super Agile	Tracker	10-40 keV	160 cm^2	107°x68°	6'	Silicon
FAR XITE	Grazing	20-90 keV		15'	1'	CZT 2 keV
CIPHER	Coded	10-1000 keV	160 cm^2	8°x10°	27'x22'	CdTe
EXIST	Coded	10-600 keV	8x1 m^2	160°x40°	5'	CZT
SWIFT	Coded	10-100 keV	>5000 cm^2	~ 2 Steradian	20'	CZT
Cyclone	RMC	3-600 keV	550 cm^2	1°	15"-13'	HPGe
HESSI	RMC	3-17 MeV	100 cm^2	1° (Solar)	2"-180"	HPGe
Bellerina	RMC	0.5-2 keV 2-15 keV	50 cm^2 20 cm^2	2°	0.5'	CCD
ASTRO-E	Collimated	10-700 keV	230 cm^2 < 40 keV 330 cm^2 >40 keV	0.56°x0.56° < 100 keV 4.6°x4.6° > 200 keV		Si/CSi

Proposed Missions

Presently available natural or synthetic materials do not efficiently reflect or refract photons above 10 keV, and thus no analog to optical imaging systems exists for ³-ray photons. Non-imaging systems, passively collimated and constrained in length by satellite size and weight restrictions, provide only crude angular resolution, of the order of degrees. A new technique to fabricate very fine collimators using high 'z' material like tungsten has recently been developed by Tecomet.[1] It is this new technology which has enabled our present pursuit of higher angular resolution hard x-ray imaging.

In 1961 Mertz and Young[2] first proposed shadow-casting (total absorption) as a viable option for high-energy photon imaging, particularly for x-ray astronomy. A Fresnel Zone Plate (FZP) with alternating zones of total absorption and total transmission was used as a reticle to cast geometrical shadows. A resurgent interest in coded aperture imaging in hard x-rays and ³-rays began in the late 1970s and has led to extensive development of instruments for use in astrophysics, nuclear medicine, and fusion research. An extensive survey of the subject is given by Caroli,[3] et al. The bi-grid modulator of Oda[4] and the rotation modulation collimators (RMC) of Mertz[5] measure, by lateral or rotational scanning respectively, the amplitudes and phases of the spatial Fourier components of an object, as shown by Schnopper.[6] These techniques are analogous to the aperture synthesis method of imaging employed in radio-astronomy. Modulation collimation techniques have been reviewed by Bradt[7] et al., and Makashima[8] et al.

Satellite instruments using single plane coders for hard X-rays and soft ³-rays have been flown by Russian-French collaborations on the GRANAT (ART-P and SIGMA experiments) and Mir-KVANT (TTM/COMIS experiment) missions. To image the source field, these coders employ uniformly redundant array (URA) patterns, which afford good sensitivity, good angular resolution, and sufficient field of view.

Coded aperture telescopes require position-sensitive detectors. The detector plane is tiled with contiguous elements, with sizes as diverse as CCD pixels or centimeter-sized scintillators. A system's point spread function depends upon the angular size of the single smallest mask element as seen from the detector plane. The theoretical angular resolution is therefore dependent upon the ratio of the mask smallest element size to the separation between coder and detector planes. With separations of a few meters and centimeter-sized elements, angular resolutions of order 10 arc minutes are realized.

The other alternatives for hard X-ray/soft ³-ray imaging - RMCs or multi-pitch modulation collimators - do not require position-sensitive image plane detectors, but use either temporal modulation, or perform a spatial Fourier transform on the object field, or both. For Fourier transform designs, sub-collimators with fine pitch must be introduced to record the high spatial frequency components of the image. The individual detectors of the sub-collimators must be identical, and each sub-collimator must be maintained in precise alignment over long periods, or else flexion and torsion must be monitored by an auxiliary optical system.

We have used two separated Fresnel zone plates as a coder (Mertz 1965).[9] Such paired Fresnel zone plates provide two-dimensional spatial coding in the form of parallel Moiré fringes whose spatial frequency and orientation are dependant on the off-axis location of the source. In such a scheme, spatial Fourier components can be measured for all azimuth angles and over a broad range of source size scales using a matrix of detectors with only **modest** spatial resolution. The complete instrument, capable of providing imaging information that can be unambiguously deconvolved, would consist of at least four telescopes with appropriate phasing. Such an X-ray imaging scheme using Fresnel zone plates differs from schemes using rotating modulation collimators (Mertz 1962) in that far less stringent alignment of hardware elements would be required and the time resolution would be determined by the X-ray flux rather than by the grid rotation rate. The Fresnel zone plate scheme also offers a zooming capability for higher angular resolution.

Approach

In our preliminary experiments for proof of concept we have used zone plates made from tungsten 1 mm thick. The total thickness of 2 mm of both FZPs enables shadow casting of x-rays up to ~250 keV. The plates have an overall diameter of 2.4 cm and are comprised of 144 zones, with the finest zone having a width of 41 ¼m. Figure 1a shows a picture of one of the zone plates taken with 100 keV photons. The high contrast clearly indicates the stopping power of the 1 mm thick tungsten zone plates. An enlarged section of one of the zone plates, highlighting the finest zone features, is shown in Figure 1b. The separation between the two zone plates for the telescope was 30 cm. The best angular resolution provided by this configuration is ~30 arcseconds.

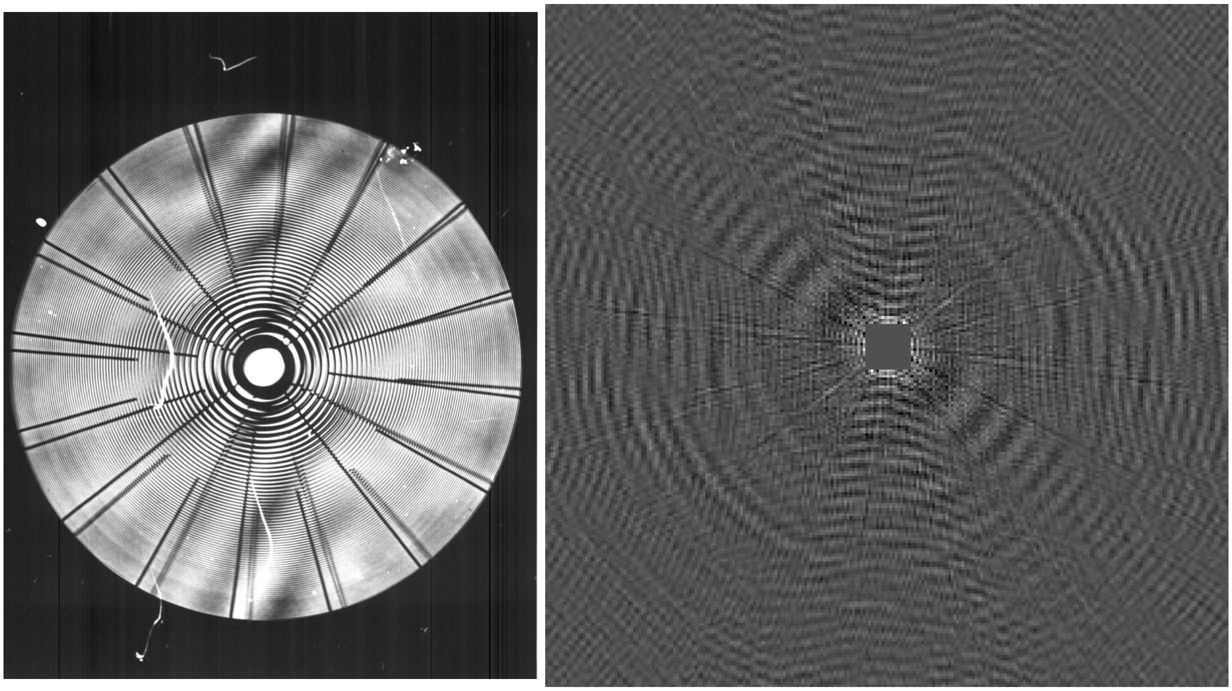
Figure 1. Picture of a 1-mm thick tungsten zone plate taken with 100 keV photons. Figure 1a shows the center of the zone plate, while Figure 1b shows a section in which the finest feature of theb plate is indicated.

We have tested this telescope using the x-ray beam facility at the NASA Marshall Space Flight Center. We used photographic film to record the images obtained with this prototype unit. Long exposures (several hours) were needed to record the images due to the low x-ray flux. Exposures were taken at three different angular separations between the beam direction and the telescope axis, nominally ~0Ú, ~0.1Ú, and ~0.2Ú. The results of these exposures are shown in Figures 2 through 4.

The image for Figure 2a was obtained by aligning the telescope axis with the beam direction. The alignment was not perfect as indicated by the very coarse fringe pattern seen in the image. The images of Figures 3a and 4a were obtained with the telescope axis tilted ~0.1Ú, and ~0.2Ú respectively to the beam direction. In Figure 3a one sees a definite phase shift in the fringe pattern, as expected from the Fresnel transformation. Figure 4a clearly shows the fringe pattern with a well-defined regular spacing.

To obtain deconvolved source profiles from the measured images, we have carried out the 2D inverse Fourier transformation of the digitized x-ray images (using 256 x 256 pixels). The results of this deconvolution process are shown in Figures 2b, 3b, and 4b where we display the raw image data compared to the deconvolved source profiles. The deconvolution results clearly show two **point sources** for the image with the very regular fringe pattern (Figure 4b) and the two **extended sources** for the phase-shifted fringe pattern of Figure 3b. The fact that we see two sources in our deconvolution results for this preliminary experiment is due to the fact that we have only used the "cosine" (symmetrical) part of the transformation using identical zone plates. Therefore, we have a two-source ambiguity in the results. The use of both "SINE" and "COS" Fresnel pairs would remove this ambiguity.

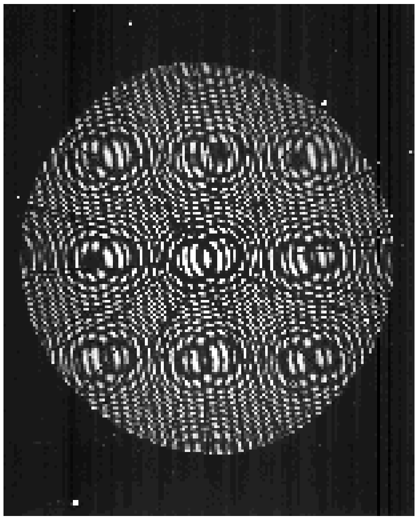
Fig 2a, 2b. Fresnel Zone Plate Telescope Exposure 1



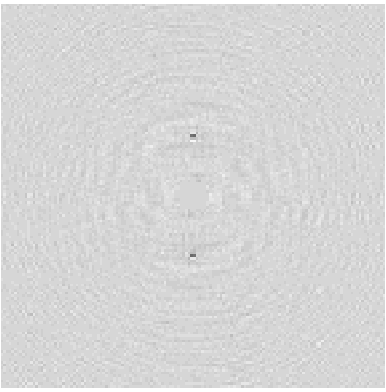
Fringe Pattern due to Nearly On-Axis Source

Deconvolved Image of Exposure 1

Fig 3a, 3b. Fresnel Zone Plate Telescope Exposure 2

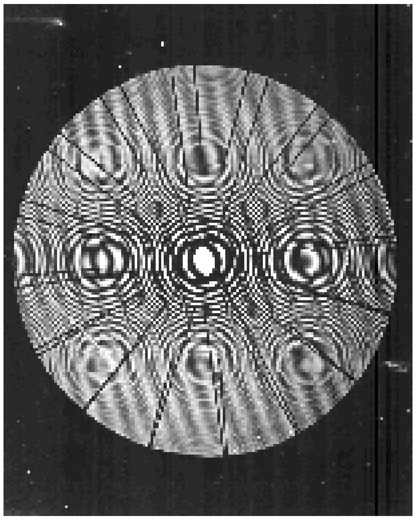


Fringe Pattern due to Source ~ 0.3 Off Axis

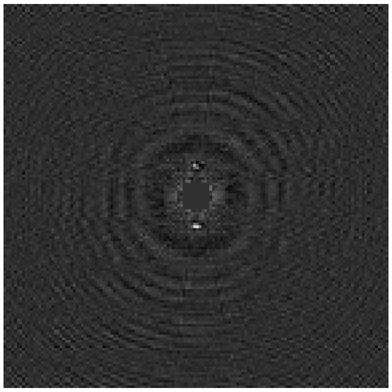


Deconvolved Image of Exposure 2

Fig 4a, 4b. Fresnel Zone Plate Telescope Exposure 3



Fringe Pattern due to Source ~ 0.15 º Off Axis



Deconvolved Image of Exposure 3

This concept of imaging offers a number of advantages over other methods. It works over a wide energy band. The upper energy depends on the thickness of the coder. The concept is a cheap, scaleable technology to increase the aperture of the telescope. It also provides high throughput (25% worst case). It has the ability to take snap-shots. The very high time resolution can be achieved in very intense transient events like solar flares, and ³-ray bursts. The centro-symetric geometry offers zooming capability too. The ability to get higher angular resolution with a coarse spatial resolution detector is unique to this concept.

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Fresnel Zone Plate Telescope Exposure 1

Figure 2a

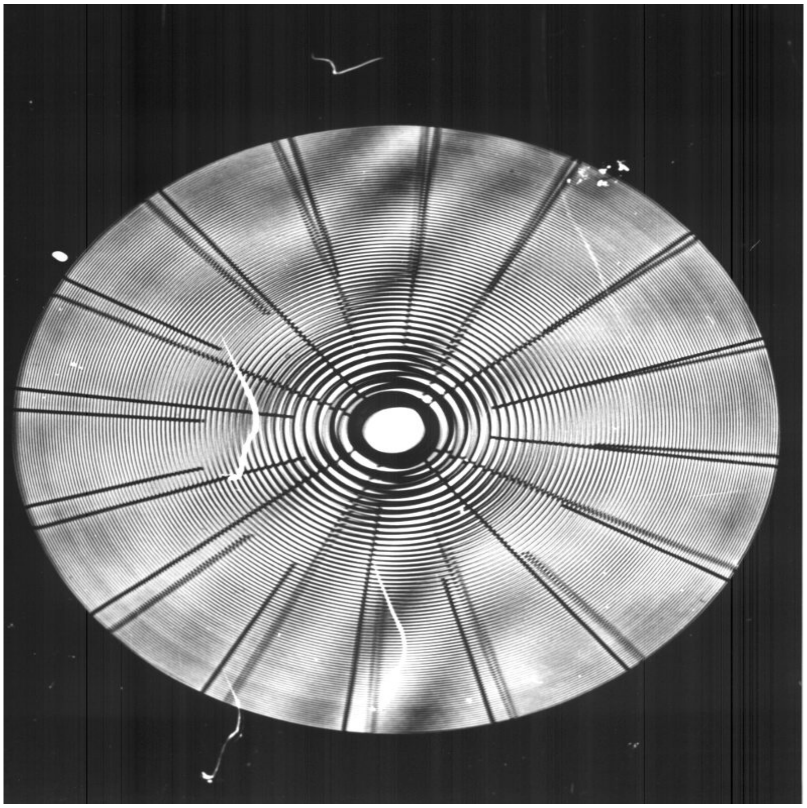
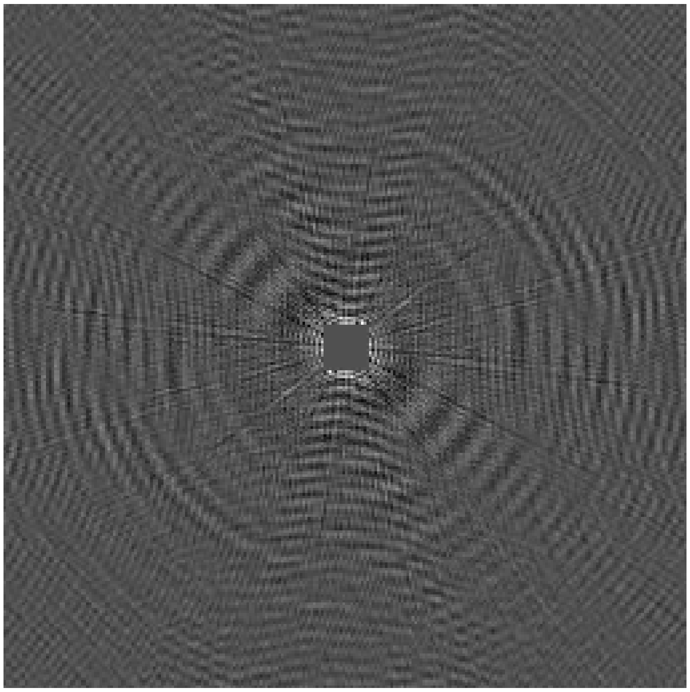
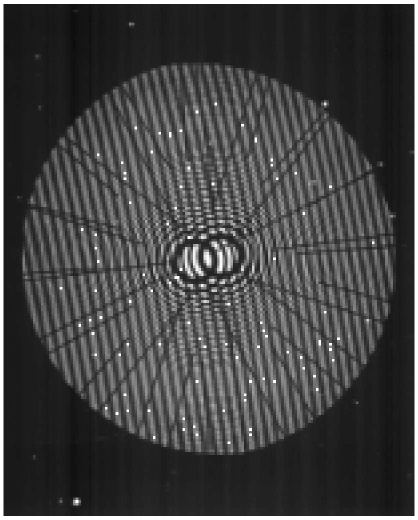


Figure 2b



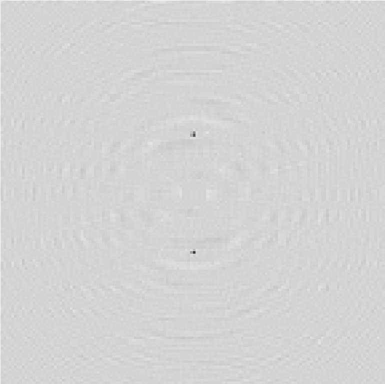
Fresnel Zone Plate Telescope Exposure 3

Figure 3a



Fringe Pattern due to
Source ~ 0.3 Off Axis

Figure 3b



Deconvolved
Image of Exposure 2

Fresnel Zone Plate
Telescope Exposure 3