TEMPORAL APERTURE MODULATION

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ABSTRACT

The two types of aperture modulation techniques useful to X-ray imaging are reviewed. The use of optimum coded temporal aperture modulation is shown, in certain cases, to offer an advantage over a spatial aperture modulator. Example applications of a diffuse anisotropic X-ray background experiment and a wide field of view hard X-ray imager are discussed.

1. INTRODUCTION

In all fields of astronomy imaging satisfies the prime need for source locations and structure. In X-ray astronomy imaging also provides a freedom from source confusion and an answer to the question of "which part of the detected flux is source and which part is detector background?". The latter requirement is particularly relevant at photon energies greater than 10 Kev, the regime of "hard X-ray" astronomy. Unfortunately at energies above 10 KeV it is not efficient to use reflecting optics for imaging and some other method is necessary. The means to produce images at energies greater than 10 KeV appear to be limited to aperture modulation or scanning methods. Aperture modulation is the encoding of the photons incident on a detector such that their angular dependence can be recovered. This method has a multiplex advantage over more classical scanning methods (Fellget 1958) and is thus to be preferred.

2. TYPES OF APERTURE MODULATION

There are two basic types of aperture modulation, spatial and temporal aperture modulation. Spatial aperture modulation is a static method providing time independent imaging and is epitomized by Dicke's random pinhole camera (Dicke 1968), whilst temporal aperture modulation is a dynamic method and is epitomized by Mertz's mock interferometer (Mertz 1965) which is more generally known as the rotation modulation collimator of X-ray astronomy (Oda,1965; Schnopper,1968). The basic principles of the two methods are illustrated in Fig 1. The spatial aperture modulator casts an X-ray shadowgram onto the position sensitive detector and hence requires N detector elements to detect N mask elements whilst each element of the temporal aperture modulator detects the full N elements of the modulator, albeit in a finite time. This basic time to produce an image is the image cycle time defined as the time it takes the *complete* N aperture elements to traverse the detector element. For both methods the reconstruction of the source direction can be achieved by back-projection of the count rate modulation through the mask onto the sky. Both methods have been improved by the use of optimum coded apertures based on Cyclic Difference Sets (Gunson and Polychronopulos,1976) or one of their less generalized subsets such as PN codes, Hadamard codes or Uniform redundant arrays (Harwit & Sloane,1979; Fenimore & Cannon,1978). The optimum encoding allows the *unique* decoding of complicated point and extended source fields. Optimum coded spatial aperture modulation has been used in X-ray astronomy to image the galactic center between 2 and 10 KeV (Proctor,Skinner and Willmore,1978) whilst optimum temporal aperture modulation has been used in numerous Infra-red spectroscopy and imaging applications (Harwit and Sloane,1979)

The future of spatial aperture modulation with its time independent imaging has been recognized by many people. An optimum coded telescope to image clusters of galaxies to 3' in the energy range 2 to 25 KeV has been built by the University of Birmingham and is scheduled to fly on Spacelab 2 (Skinner,1980). Wide field of view spatial aperture modulation cameras have been proposed for the European X80 and Japanese ASTRO B missions to monitor large fractions of the sky for transient sources. At extreme separations between the coded aperture and the detector, the spatial aperture modulation technique allows the possibility of very good angular

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resolution (Hudson and Lin,1978) The Pinhole/Occulter Facility Science Working group has incorporated this feature into a strawman model for a spatially coded aperture modulation telescope for providing 20 arc second images of the sun combined with a Fourier Transform telescope to provide ≈arc second images over a smaller field of view (Hudson et al.,1980). The concept is shown in Fig 2.

3. TEMPORAL APERTURE MODULATORS

When constant or slowly varying X-ray sources are of interest then the technique of temporal aperture modulation can be used. It offers the unique feature that one detector element can produce an image of many elements of sky Thus a high resolution, wide field of view camera can be built. A spatial aperture modulation system cannot provide this option because it is constrained to have N detector elements to image N sky elements, thus it only provides options of high resolution,narrow field of view or poor resolution, wide field of view A high resolution camera normally involves the difficult problem of attitude solution but a high resolution wide field of view camera can see the brighter X-ray sources and generate its own internally consistent attitude solutions. One potential disadvantage appears to be that variable background and source components create image background fluctuations. Provided the time to complete one image cycle of the dynamic mask is less than one minute a temporal modulator will experience no difficulty from normal cosmic ray background variations in near earth orbit. A variable source in the field of view adds a component to the image only of amplitude $\delta I/\sqrt{2/N}$ where δI is the amplitude change and N is the number of mask elements. Additionally variable sources will have a period uncorrelated with the image cycle period hence over M image cycle periods the residual image fluctuations will be uncorrelated and introduce a further $1/\sqrt{M}$ reduction in their relative amplitude. Two example instruments, DAXBE and FOXI, will be discussed to illustrate that the features of temporal aperture modulation can be applied to X-ray astronomy.

4. THE DIFFUSE ANISOTROPIC X-RAY BACKGROUND EXPERIMENT (DAXBE).

Most cosmic radiations are thought to have "diffuse" background components. The microwave $2.7^{o}K$ background and neutrino background are believed to be truly diffuse and date from the "Big Bang" of current cosmology whilst the X-ray background is believed to originate from discrete sources since the epoch of galaxy formation i.e. at redshifts of $z \lesssim 3$. Very little is as yet known about a gravitational radiation background. There may be a difference in the anisotropies of the microwave and neutrino backgrounds which are effectively at redshifts of $z \approx 1000$ as compared to the locally produced X-ray background at $z \lesssim 3$ (Wolfe,1970; Fabian & Warwick,1979; Rees,1980). Unfortunately the neutrino background has not as yet been observed but microwave observations from balloons have determined a 24 hour anisotropy in the approximate direction of our local supercluster (Conklin,1969; Smoot et al.,1977; Cheng et al.,1979) Assuming the dipole effect is totally due to the motion of the sun and not intrinsic to the $2.7^{o}K$ background then the effect is equivalent to an infall of our galaxy towards the local supercluster at a velocity of 401±19 kms/sec (Cheng et al.,1980). Recent studies on the redshifts of 300 spiral galaxies give a net solar motion with respect to nearby galaxies ($\lesssim 30$ Mpc) of comparable velocity but of widely different direction from the motion with respect to the $2.7^{o}K$ background (Rubin et al.,1976; de Vaucouleurs et al ,1981). The 24 hour diffuse anisotropy has been measured in the range 2-10 KeV by the HEAO-1 A2 experiment to be 0.005±0.0009 of the diffuse flux (Boldt,1981). The pole of the distribution lies at the same position as the microwave, at approximately the position of the local supercluster. However Boldt also shows that this anisotropy may not be inconsistent with a reasonable luminosity of X-ray sources in the local supercluster. It may be possible to test this hypothesis if the anisotropy can be detected without using the data from the local supercluster. The situation is made more interesting by the discovery of an inhomogeneity in the universe which is larger than the local supercluster. An apparent deficit in the number of optical galaxies exists in the constellation of Bootes. It is interpreted as a void of size 10^{6} Mpc^{3} at a distance of ≈200 Mpc with $\delta M/M \approx 1$ (Kirshner,Oemler,Schecter and Shectman,1981). It is calculated by Kirshner et al. that such an inhomogeneity will give an approximately 150 Km/sec perturbation to our galaxy's velocity relative to distant galaxies ($z \approx 1$).

In the near future the Cosmic Background Explorer will make very detailed microwave & far infrared observations of the cosmological background radiation to provide the large scale picture of our galaxy's peculiar velocity whilst surveys of the redshifts of nearby galaxies will provide the local picture of our galaxy's peculiar velocity. Better X-ray data are needed to complement and complete these studies by providing the intermediate picture and allow the local and cosmological effects to be separated.

HOW WELL CAN WE MEASURE THE X-RAY ANISOTROPY?

The basic $2.7^{o}K$ 24 hour effect has an amplitude of 0.0013 of the diffuse background. In X-rays the Compton-Getting effect (Compton & Getting,1935), magnifies the amplitude to 0.005 of the diffuse background. Hence our detection sensitivity must be at least 0.001 in order to obtain a 5 sigma detection. The measurement of the anisotropy to an accuracy of at least 0.001 requires an approach free of systematic problems. The requirement is effectively to map the sky with sufficient accuracy to exclude known X-ray sources. The conventional method involves the scanning of an asymmetric detector in the local anisotropic radiation field which especially at energies > 20 KeV produces a variable background problem. The use of wide field, optimum coded temporal aperture modulation allows the use of a symmetrical detector *and* gives a much greater signal to noise ratio such that the local background becomes negligible The problem of experimental systematic effects should be greatly reduced and because only a single detector element is needed for imaging the experiment is very simple to build and operate.

An example of how such an instrument could be operated is shown in Fig 3 The figure shows no superstructure but only the spinning detectors and coded mask. The detectors are simple detectors of either gas counter or scintillating type optimised for a symmetric response. No position sensitivity is required. The detectors are constrained by the superstructure to see the diffuse background only through the coded aperture. Low level leakage through the superstructure is not critical as only photons coded by the mask are "imaged". The spinning subsatellite receives an optimally modulated count rate from which an image of the fluctuations in a strip of the sky is made Taking the dimensions of Table 1, the statistical sensitivity of DAXBE in one month is given in Fig 4 in terms of a one sigma sensitivity as a fraction of the diffuse background flux. The sensitivity is per image element If the sensitivity to a 24 hour component of the background is required then this may be considered as the comparison between two hemispheres of sky. Thus the sensitivity is obtained by dividing by $\sqrt{Q/4}$ where Q is the number of source free image elements used in the analysis. The fundamental limitation on the precision that can be obtained for the anisotropy is from the fluctuation in the individual image element intensities due to sources just below the detection threshold. For the example instrument outlined here (e.g with 43 elements) the limit is $\delta I/I \approx 0.004$ per image element (Warwick,Pye & Fabian,1980). This translates into a 24 hour anisotropy detection of 0.005 ± 0.0006 of the diffuse background. This is much worse than the 5-80 KeV statistical limits from one month of observation, e.g. for 5-15 KeV its ± 0.00015 (± 12 kms/sec) The statistical limit can be reached if external information on the number of bright extragalactic sources per image element is known because it is mainly the sources just below the detection threshold (≈ 1 UFU for DAXBE) which cause the fluctuations. This information should be forthcoming from optical surveys and ROSAT (the German X-ray sky survey satellite) The presence of high latitude galactic components (≥ 10 times the 2-10 KeV anisotropy) complicates the analysis still further but these components fall more rapidly with energy than the diffuse X-ray flux (Iwan et al.,1981) Hence more reliable measurements will be obtained if energies greater than 20 KeV are used where the galactic components are smaller. It is noted that any incomplete galactic component subtraction leaves a 12 hour component and hence the minimisation of the galactic component gives more confidence in any detected 12 hour component. Such components are expected from the shear on the X-ray background produced by large mass inhomogeneities (Fabian & Warwick,1979).

5. FERRIS-WHEEL ORBITING X-RAY IMAGER (FOXI)

The study of the energy generation mechanisms in active galactic nuclei (AGN's) is complicated by the need to monitor the variability of their total energy output with time (Lightman, these proceedings). Previous observations have shown that the majority of the power emitted by many Seyfert galaxies, some QSO's and Centaurus A lies in the high energy X-ray range The typical variability observed for AGN's is of order 1 day with the record for the fastest time of variation of $\tau \approx 100$ seconds held by NGC 6814 (Tennant et al.,1981). The problem then is to monitor as many AGN's as possible for variability on time scales of minutes to years over as wide a photon energy range as possible. A possible method uses a Ferris-wheel Orbiting X-ray Imager (FOXI) imaging a strip of the sky every 3-4 secs (an eighth of the rotation period). The concept is shown in Fig 5. FOXI is similar to DAXBE in principle but the dimensions are enormously inflated to 50 meters diameter. The use of a flexible jointed mask which unfurls in orbit, after a Space Shuttle launch, allows such a rotating configuration to be attained. The rotating mask modulates a large solid angle of sky in its rotation thus providing the large field of view neccessary for a survey instrument. To obtain good angular resolution the central detector must be one dimensionally position sensitive in its azimuthal direction and be fixed with respect to the stars i.e. non co-rotating. The parameters of a system composed of 100 cm long, 1cm wide strip detectors imaging 4% of the sky to 3' x 140' over a photon energy range of 3-500 KeV are given in Table 2. The instrument would be constrained to image perpendicular to the ecliptic in order to limit differential heating of the mask. This constraint means a complete sky survey would occur every 6 months. The time spent on any one source in this time would be 4 days. The minimum detectable source fluxes are given in Table 3. These minimum fluxes combined with the linear relationship between X-ray and M_B optical luminosity (Zamorani et al.,1981) suggest that the sensitivity is such that QSO's of the mean or greater L_x/L_{opt} ratio will be detected down to M_B=+15 at 80-120 KeV and down to M_B=+17 between 3 and 20 KeV. It is noted that the large scatter in the ratio of L_x/L_{opt} means that some QSO's of M_B > +15 or > +17 will be detected. The Log N versus M_B curve of Bracessi et al.(1980) shows that we would expect ≥ 50 QSO's to be detected in the 80-120 KeV energy band and ≥1000 to be detected 3-20 KeV. All Seyferts within 100 Mpc (≈500) would be detected if brighter than 10^{42} ergs.sec^{-1} and those above $2x10^{43}$ ergs.sec^{-1} would be detected at 80-120 KeV.

FOXI was concieved as a free flying satellite but with the advent of long duration manned space stations the working environment should include spin induced "gravity". Such large spinning structures could easily include a coded mask and central detector to perform FOXI type X-ray imaging. Similarly in a future which included O'Neill space colonies a FOXI type imager could be added to the very large ≈1km diameter structures !

TABLE 1

Parameters for DAXBE

ITEM	*VALUE*	*COMMENTS*
General System		
Mode	2-4 weeks free flyer	-Recoverable ?
Spin period	≈5 seconds	
Image cycle time	Same as spin period.	
Sky coverage	40% per rotation	-Precession quickly results in 100%
Data rate	300-2000 bits/s	-Function of mask & spin period.
Attitude Solutions	Internal from bright sources.	
Mask		
Dimensions	0.2cmx50cmx300cm diameter	
Material	Graded Z Tungsten	
Pattern	15-43 element optimum coding	-Tradeoff
Angular-Resolution	$24^{o}-8^{o}x18^{o}$	
Detectors:		
Dimensions	50cmx20cm diameter	-3 detectors
Material	Xenon and/or Phoswich	
Energy range	5-10 KeV to 200 KeV.	
Solid angle	1x2.0 Steradians 2x1.5 Steradians	
Area to a point source	$3x500cm^2$	-Allows a factor 0.5 for the mask
Options:		
Non-rotating segmented detector	Allows detection of the whole diffuse BG and not just the fluctuations in it.	-Tradeoff Study.

TABLE 2

Parameters for FOXI

ITEM	VALUE	COMMENTS
General System		
Spin period	20-30 seconds	
Image cycle time	[spin period]/8= 3-4 secs.	
Sky coverage	4% per rotation	-100% every 6 months
Data rate	≤30 Kbits/s	
Attitude Solutions	Sun pointed and X-ray sources.	-Sources ≥5 UFU seen in one spin.
Mask		
Dimensions	0.3cmx100cmx5000cm diameter	
Material	Graded Z Tungsten	
Pattern	8 times a 1023 element code	
Mask element dimensions	0.3cm x 2cm x100 cm	
Angular-Resolution	3' x 140'	
Detectors		
Dimensions	100cm x 100cm diameter	-3 cylindrical detector blocks.
Material	Xenon gas counter plus Phoswich	-Xenon on the outside Phoswich inside
Element size of a detector "strip"	1cm wide x 5 cm x 100cm	-Xenon and Phoswich systems are independent.
# of detector elements/block	≠300	-On the circumference of a cylinder.
Energy range	Xenon 3-20 KeV Phoswich 20-500 KeV	
Solid angle	3 x 0.25 steradians	
Area to a point source	$3x3500cm^2$	-Allows a factor 0.5 for the mask

TABLE 3

FOXI MINIMUM DETECTABLE SOURCE FLUXES (5 SIGMA)

In units of photons.$cm^{-2}sec^{-1}KeV^{-1}$

	1 minute	1 hour	4 days
5 - 15 KeV	$7x10^{-4}$ (2 UFU)	$1.5x10^{-4}$ (0.4 UFU)	$1.5x10^{-5}$ (0.04 UFU)
80 - 120 KeV	$7x10^{-5}$	$1.5x10^{-5}$	$1.5x10^{-6}$
200 - 300 KeV	$4x10^{-5}$	$8x10^{-6}$	$8x10^{-7}$

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FIGURE CAPTIONS

FIGURE 1

The basic principles of the two methods are shown. The spatial aperture modulator casts an X-ray shadowgram onto the position sensitive detector and hence requires N detector elements to detect N mask elements whilst each element of the temporal aperture modulator detects the full N elements of the modulator. Both methods provide an N element image of the sky.

FIGURE 2

The layout of a "Pinhole/Occulter Facility" to be deployed from the Space Shuttle. The 50 meter boom supports a spatially encoded aperture mask to give $\leqslant 1$ arc second spatial resolution for hard X-rays. For solar observations an occulter will also be used to provide a shadow for coronagraphic observations.

FIGURE 3

A conceptual Diffuse Anisotropy X-ray Background Experiment (DAXBE) is shown. The concept is for a free-flying internally powered experiment The spinning sub-satellite causes the individual detectors to see an optimum modulated count rate from separate strips of sky. The total active field of view is $\approx$40% of the sky per rotation. With precession a 100 % coverage can be obtained in a short time. The energy range is detector dependent but 5-200 KeV seems easily achievable.

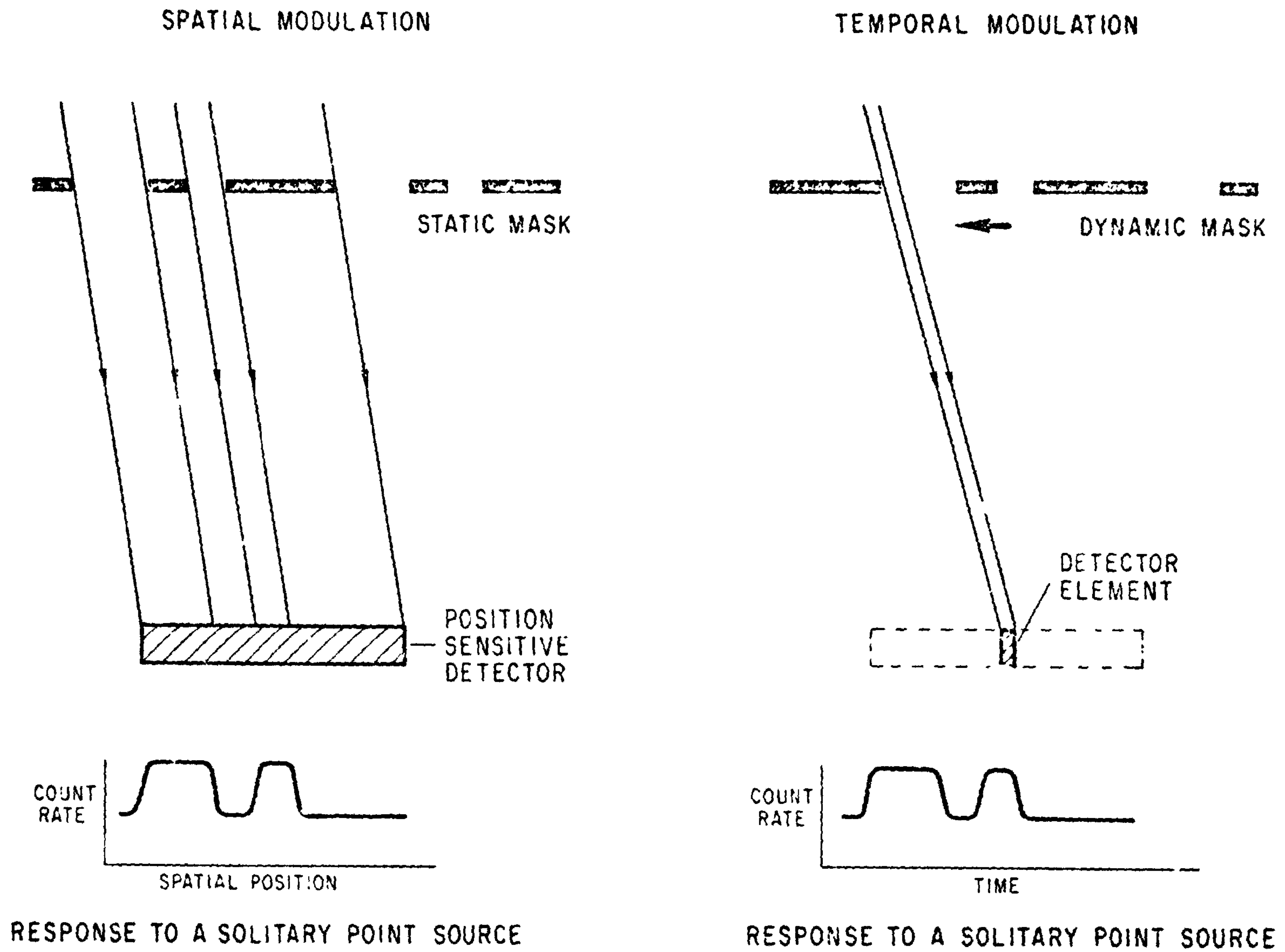
FIGURE 4

The one sigma statistical sensitivity *per sky bin* of DAXBE in one month (2×10^6 seconds) is shown. It is thought that the effect of source fluctuations and the galactic diffuse component will not significantly degrade the sensitivity (see Text).

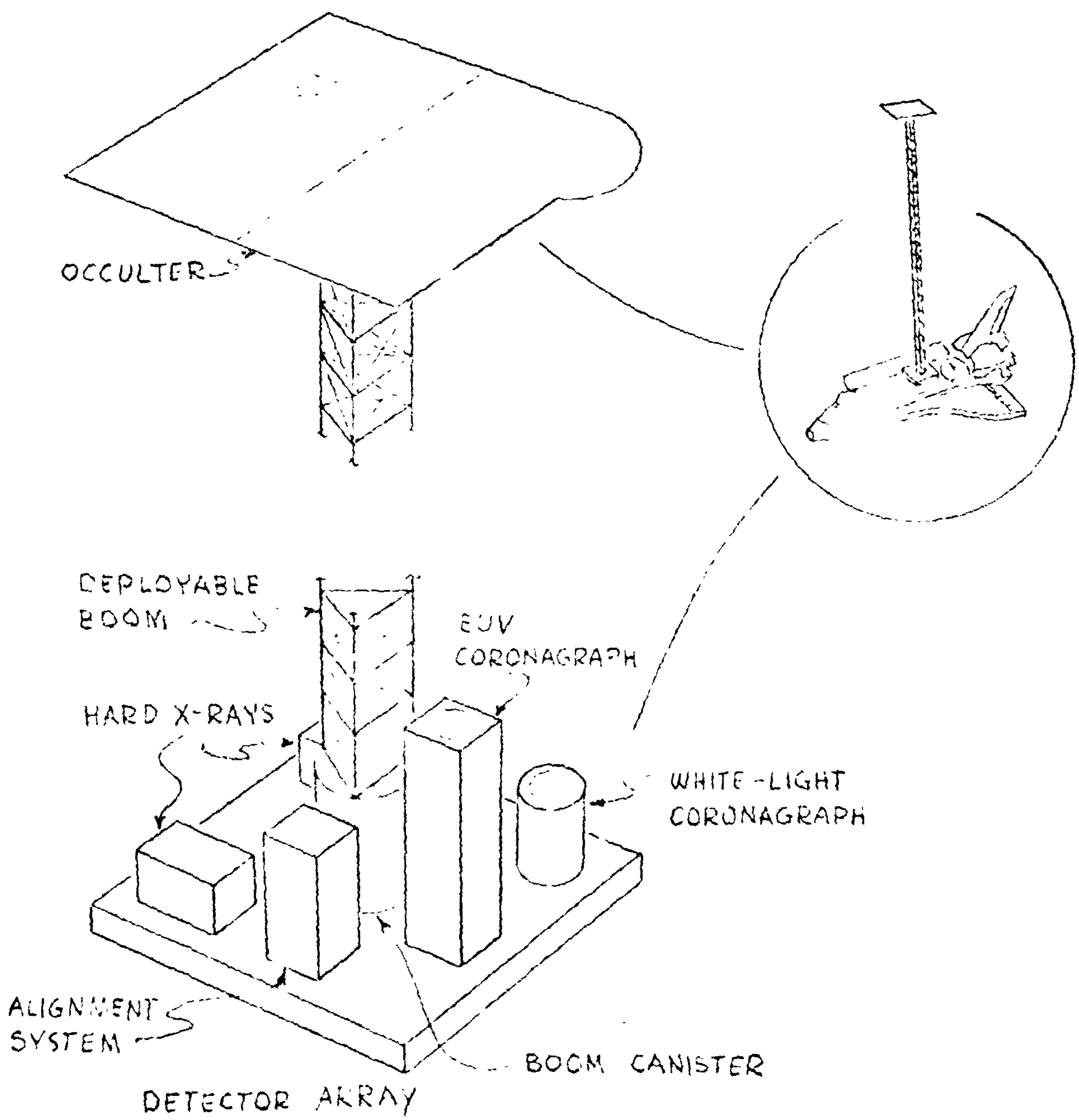
FIGURE 5

A conceptual Ferris-wheel Orbiting X-ray Imager (FOXI) is shown. The concept is of a free-flying satellite which unfurls in orbit after a Shuttle launch. It is envisaged that the mask would rotate every 20-30 seconds whilst the detector remained fixed relative to the stars The mask would consist of a basic 1023 element optimum code repeated 8 times to give an image cycle time of one eighth of the spin period. The detector consists of 3 units of 1 meter diameter made up of 1 cm wide gas counter and scintillator strip elements FOXI will image 4% of the sky every 3-4 seconds with a resolution of 3' x 140' over the photon energy range 3-500 KeV 100% sky coverage is obtained every 6 months. Over 2000 Active Galactic nuclei should be detected (see Text).

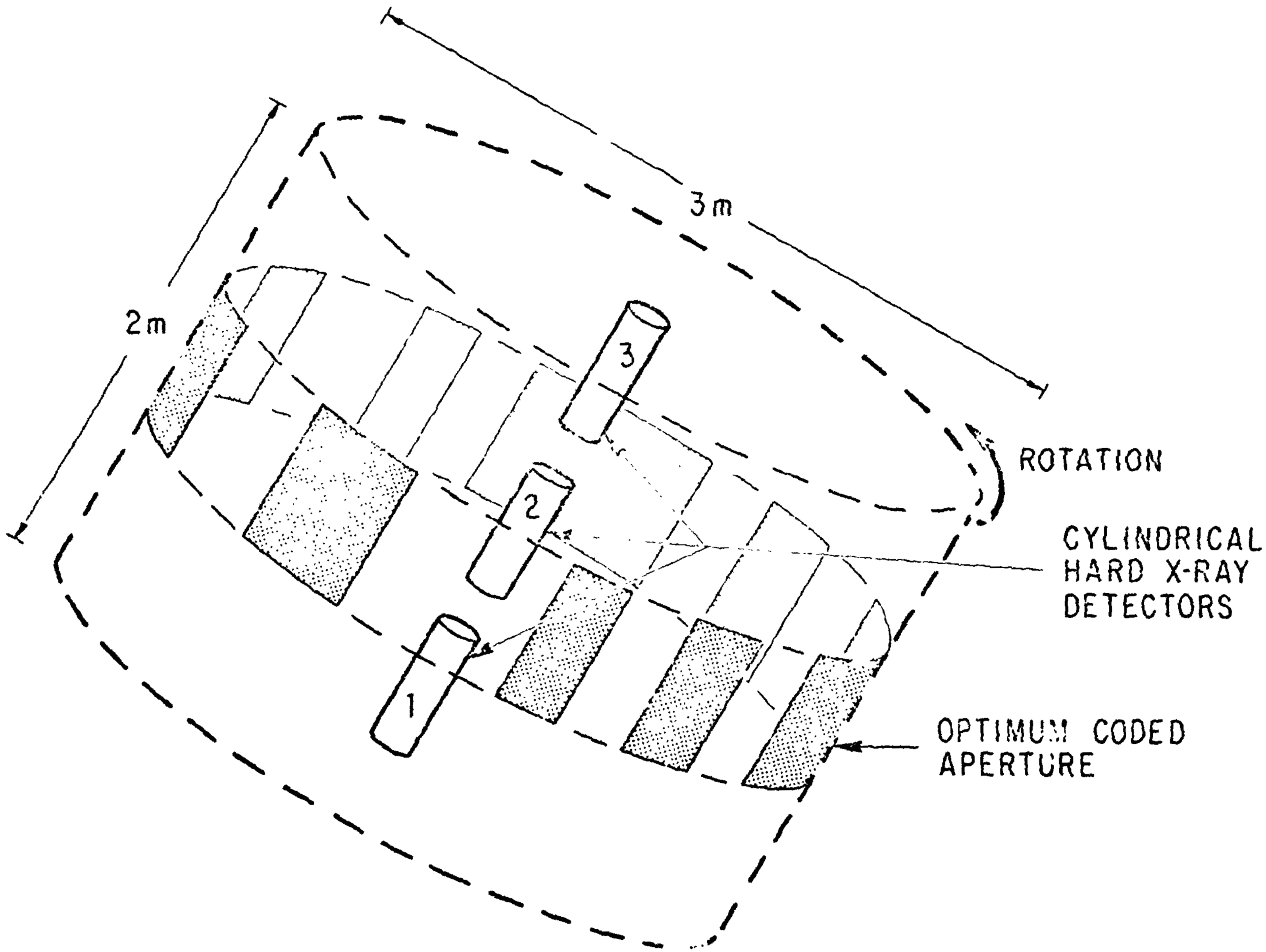
ONE DIMENSIONAL REPRESENTATION OF APERTURE MODULATION



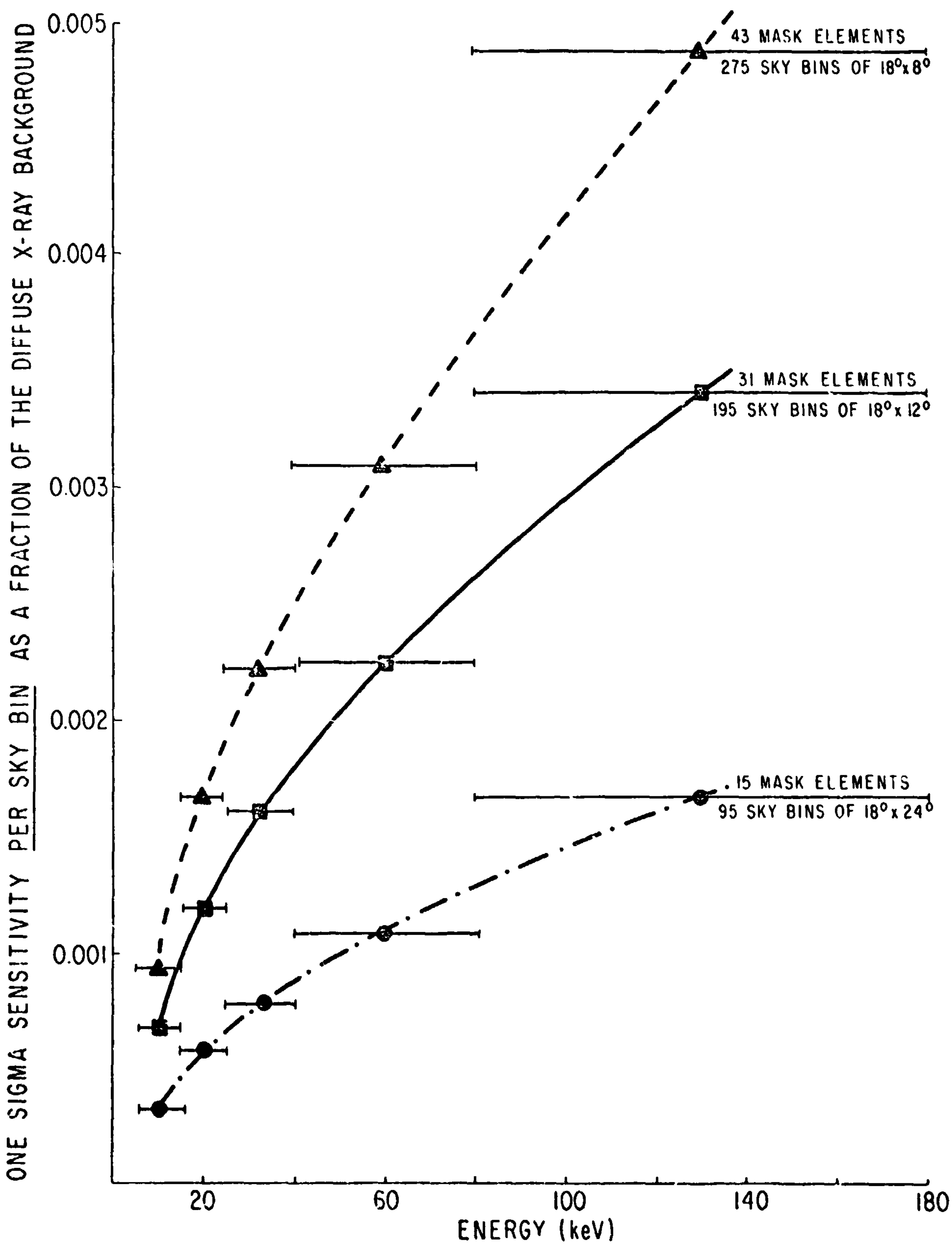
SPACELAB
PINHOLE / OCCULTER
FACILITY



DIFFUSE ANISOTROPIC X-RAY BACKGROUND EXPERIMENT



SENSITIVITY OF DAXBE FOR A ONE MONTH MISSION



FERRIS-WHEEL ORBITING X-RAY IMAGER