Coded Mask Imagers

when to use them – and when not

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Abstract

Coded mask imagers are among a class of high energy astronomical instruments in which spatial or temporal coding, or a combination of the two, allows 'multiplexing' of the detection process. In this way many 'pixels' of an image can be observed and measured simultaneously. In certain circumstances this gives an advantage in signal to noise ratio, compared with an alternative approach in which each pixel is examined sequentially. The signal-to-noise ratio will, however, never be as good as that possible with focussing optics.

The possible types of multiplexed instrument are discussed in the context of gamma-ray line astrophysics and compared with instruments in which optics are used to concentrate the flux.

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1 Introduction

A coded mask imager (Figure 1b) records the shadow of a mask containing a transparent/opaque pattern, cast by a the combination of sources in a large region of sky. Thus in contrast to a classical imaging system (Figure 1a) the 'Point Source Response Function' (PSF) is in a sense spread over the whole of the detector. Of course it is well known that image processing techniques can improve the PSF of an instrument, and the objective in selecting a coded mask pattern is that an appropriate reconstruction algorithm should be able to recover a response as close to the ideal as possible. Thus habitually for

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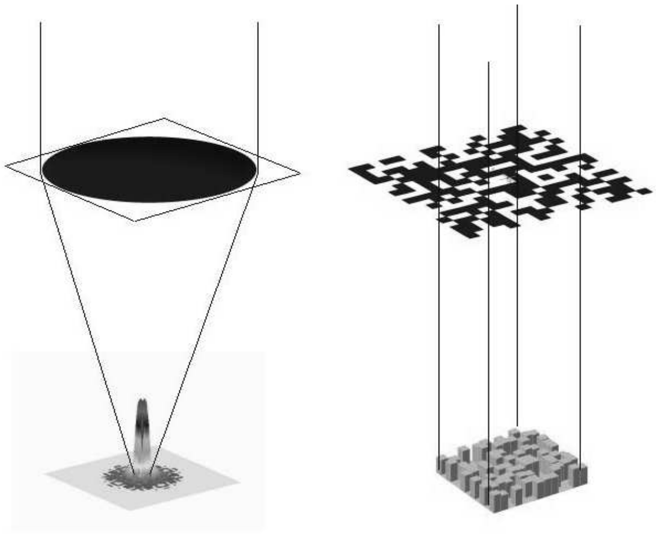

Fig. 1. Comparison of (a) An idealised imaging system with its point source response function (PSF) and (b) A coded mask telescope and its PSF

a coded mask system one talks of the PSF of the instrument *plus* an image reconstruction algorithm.

The disadvantage of the multiplexed approach is that reconstruction of the intensity at a particular point in the field of view involves harvesting photons from all over a detector. The detector has to be large – it will always be larger than the effective area required for the telescope because no concentration takes place. Thus a large number of background events (weeds) are harvested at the same time. The mean level due to the background can be suppressed in the reconstruction, but the associated random noise remains, and noise from every background event contaminates every image pixel.

Thus coded mask imaging is an indirect and inefficient way of obtaining an image. Nevertheless, coded mask imagers provided the first hard X-ray images of cosmic sources 25 years ago and are in wide use today (4 such instruments on INTEGRAL). Furthermore they currently planned for missions which will not be launched for perhaps another 10-15 years or more (e.g. Exist).

2 Spatial and temporal multiplexing

The classic coded mask telescope illustrated in Figure 1 uses multiplexing in the spatial domain. It is just one member of a family of types of instrument which use different combinations of spatial and temporal coding and multiplexing, shown in Figure 2. A simple static coded mask instrument (Figure 2(d)) bears the same relationship to a pinhole camera (a) as do certain 'modulation collimators' (f) to a simple scanning collimator (c). In the former case, part of the sky are mapped onto spatially distinct pixels, or bins, in the detector, either in a one-to-one basis (a), or in a one-to-many mapping (d). In (c,f) the mapping is onto time bins.

In both the spatial and temporal domains, the coding may be simple or cyclic (d) versus (g); (f) versus (i).

Of particular interest here is the central column in the figure, where a combination of spatial and temporal coding is used. the SPI spectrometer of INTEGRAL, for example, corresponds to Figure 1(e) and uses a modest number of spatial elements, together with 'dithering' of the pointing direction to resolve the ambiguities associated with mapping onto the detector plane more sky pixels than the number of detector pixels.

3 Alternatives - focussing in the gamma-ray domain

Because of the effects discussed above, coded-mask or other non-focussing instruments, either non-multiplexed (Figure 2a–c) or multiplexed (2d–i), will never have a sensitivity as good as an instrument which concentrates radiation from a large collecting surface onto a small detector. Methods of focussing gamma-rays are starting to be developed in the form of crystal diffraction lenses (1) and Fresnel lenses (2; 3). At lower energies grazing incidence reflection, in particular from graded multilayers, can be used.

These techniques all rely on changing the direction of the radiation by relatively small angles. This means that the radiation from a point on the sky arrives in the detector plane as beam with a small cone angle. For point sources this is acceptable because one can use a long focal length optic and have a large collecting area despite the low solid angle of the beam.

Consider, though, what happens in the study of the large scale structure of diffuse sources. A simple 'light bucket' instrument used for such low resolution studies already has radiation from many square degrees falling in the detector. If in addition one has the multiplex advantage of a coded-mask telescope, enabling imaging and observing many directions at the same time, it is not surprising that focussing optics offer no advantage.

Even for point sources, there is a related reason why coded-mask instruments will continue to play a part in the high energy astronomy of the foreseeable future. No known gamma-ray focussing techniques can accept radiation from a wide range of angles – that is to say, none has wide field capability. Perhaps the most important use of coded-mask instruments is in wide-field surveys and for detection and localisation of bursts or other events which can happen in any direction at any time.

There is in the spectral domain a situation analogous to that in the spatial domain. The focussing techniques tend to be narrow band; the wider the band, the lower the efficiency. As more and more layers are added to multilayer optics, they become closer to interference filters and are effective only over a narrow band-pass. For a given crystal plane spacing and incidence angle, Bragg diffraction occurs for a specific energy. And Fresnel lenses are intrinsically chromatic. Coded mask instruments are limited in bandpass only by detector technology. In fact higher energy detectors can be placed behind low energy ones, sharing the same mask (e.g. INTEGRAL Ibis).

Finally it is interesting to note that the angular resolution improves in direct proportion to the mask to detector separation, which in principle can be very large. It will eventually be limited by diffraction at the holes in the mask, but only at the milli arc-second level. However it will never be competitive with the ultra high resolution possible with a Fresnel lens, for which it is the size of the entire aperture which dictates the limit. Also, lacking the focussing capability of a lens, a coded mask instrument may lack the sensitivity to benefit from such resolution.

4 Other possibilities

Space here does not permit a comparison of coded mask instruments with Compton telescopes. Such a comparison is more difficult than that with focussing instruments because Compton telescopes rely for getting high sensitivity on a background reduction, which enables them to perform well despite a very low effective area.

We note the interesting possibility of combinations of the two techniques, in which a Compton camera can be used to record the mask shadow in a coded mask telescope, selecting only those events which are consistent with having passed through the mask.

5 Conclusions

Coded mask telescopes are indirect and inefficient. They should not be used where viable alternatives exist, in particular where there is the possibility of concentrating (focussing) the incoming flux. But nevertheless there are important regions of parameter space in which they are the preferred technique and

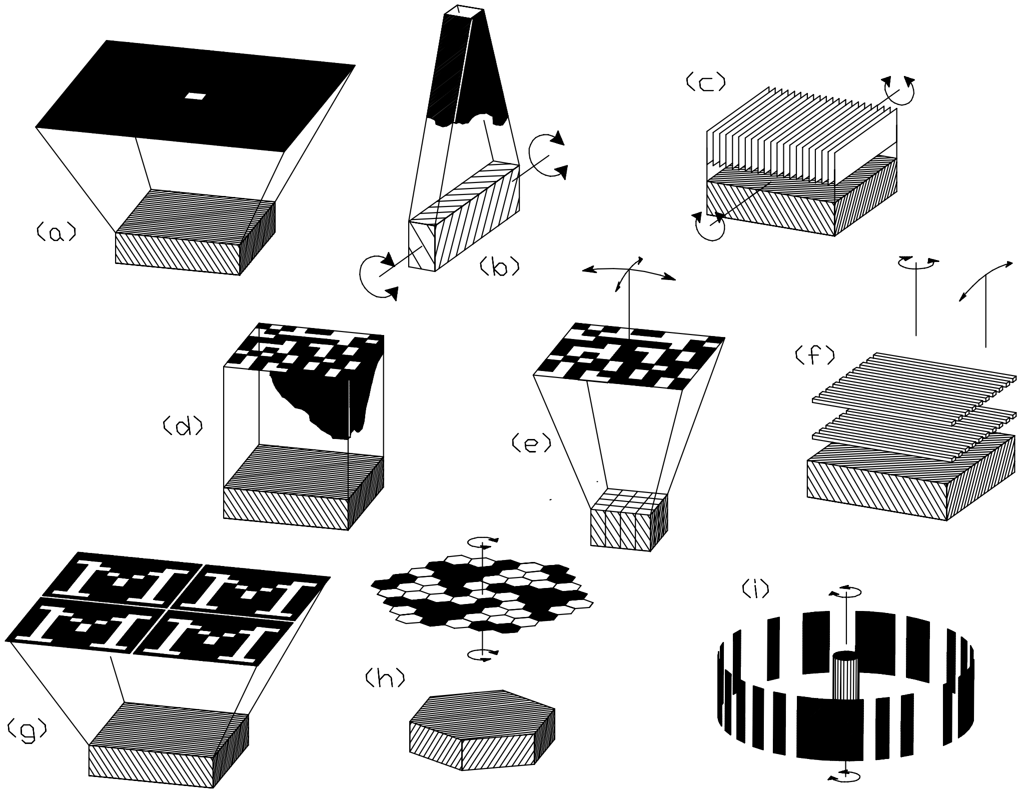

Fig. 2. Instruments with various degrees and types of multiplexing (coding). The extent of multiplexing increases in each row compared with the preceding one. Instruments in the left-hand column use only spatial coding and require a position sensitive detector. Those in the right-hand column use pure temporal coding and can operate with a single spatially unresolved detector element. Instruments in the central column utilise a mixture of the two. The types illustrated and one or more examples of each which have flown are : (a) Pinhole camera (used in early solar experiments), (b) 1-dimensional scanning pinhole camera (Ariel 5 ASM), (c) Scanned collimated detector (Uhuru, Ariel 5 SSI, OSSE), (d) coded mask camera (TTM, Sigma), (e) Coded mask with dithering (SPI; the RXTE ASM is also related to this class), (f) (Rotation-) Modulation Collimator (RHESSI), (g) Cyclic coded mask (SL2 XRT), (h) Cyclic Rotating Coded Mask (GRIP), (i) Cyclic temporal coding (TGRS has flown with a very simple coding; GGAP has been proposed).

(like certain members of the scientific community) they are likely to continue to be employed despite their idiosyncracies.

References

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