Improving the Performance of Coded Mask Instruments

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Problems with current instrument designs

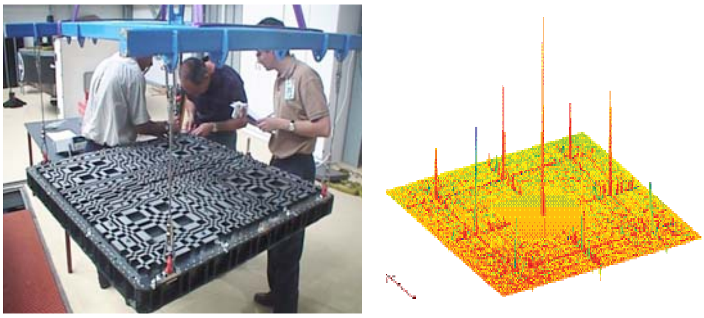
All coded mask cameras flying today have analysis problems related to one or several of the following effects:

A) Coding noise,arizing from an incomplete sampling of the coding pattern.

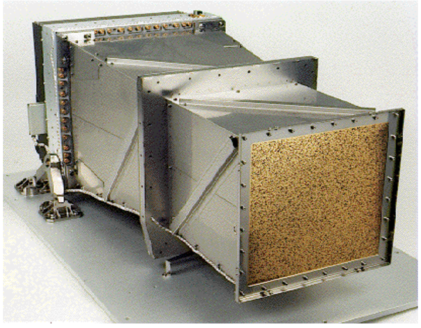
B) Ghost images arising from the use of repeated copies of the coding pattern in the physical masks.

C) Background photons from outside the fully coded field of view.

Ideally we only want sky photons from within the fully coded field to arrive at the detector. But without collimation more than half of the photons may arrive from the partially coded field. Of course these are not only background photons - but sources in this sky region are more difficult to analyze because of the incomplete coding. A classical collimator in front of the detector can limit the background, but also interferes badly with the image coding.



1) IBIS mask and raw image with ‘ghost’-sources. Code pattern is repeated four times in the mask.



2) SAX WFC. Code pattern and detector of the same size. Vignetting for all off-axis sources

The coding problem is the following: In order to realize the ideal constant value for the correlation between any two source shadowgrams it is mandatory that each shadowgram covers the full mask pattern.

In practice this has been achieved in many instrument designs by repeating the the basic pattern several times in the physical mask. (INTEGRAL IBIS, Figure 1.) The detector is sized to cover the full mask pattern only once. This configuration allows the detector to collect shadowgrams corresponding to complete mask patterns across a finite field of view. However the fact that the basic pattern is repeated in the physical mask implies that several strong 'ghost' sources appear in the reconstructed image for every real source observed. Thus the image reconstruction is still far from ideal - and most of the photons anyway arrive from the partially coded sky regions.

Other designs have avoided the ghost image problem by using only a single instance of the basic pattern in the mask. (SAX Wide Field Cameras, Figure 2). But with this design it is only possible to sample the full pattern for an on-axis source. So apart from the on-axis singularity the coding is incomplete for the full field of view. Serious vignetting of the image is inherent in this design. SPI on INTEGRAL is limited by incomplete sampling everywhere in the image and JEM-X both by incomplete sampling and collimator vignetting.

Despite these limitations these nonideal coded mask instruments have in fact yielded excellent results, but it is my hope that the developments described below will lead to significantly improved peformance in future instruments.

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Solving the Coding Problem

The new ‘Quarterback’ Configuration

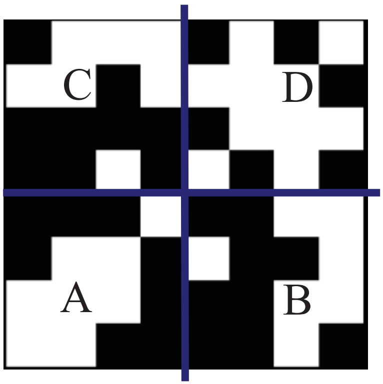
1. Divide an ideal cyclic residue*) mask pattern into four quarters.

2. Through cyclic permutations of rows and columns make four new patterns each of which is centered on a different quarter of the original pattern.

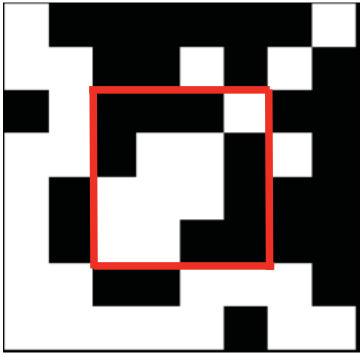
3. Let 4 independent detectors, each of the size of one quarter pattern observe the sky through these four masks. Detector size is indicated by the red squares in the figures.

4. Then for every direction in the fully coded field the combined image from the four detectors will cover fully the original pattern, → we have perfect coding!

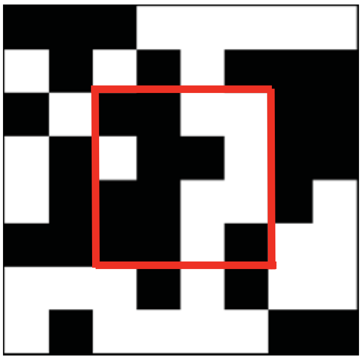
5. There will be no ghosts in the image because each detector is only seeing one full code pattern.



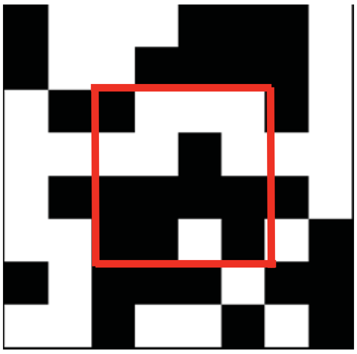
Original complete mask pattern divided into four quarters A,B,C and D



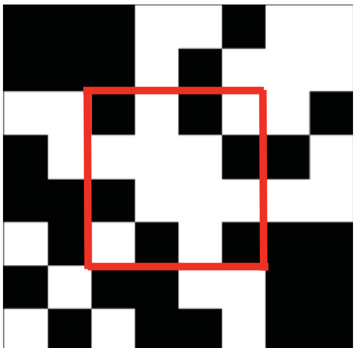
Mask pattern cyclically shifted to bring corner A into center



Mask pattern cyclically shifted to bring corner B into center



Mask pattern cyclically shifted to bring corner C into center



Mask pattern cyclically shifted to bring corner D into center

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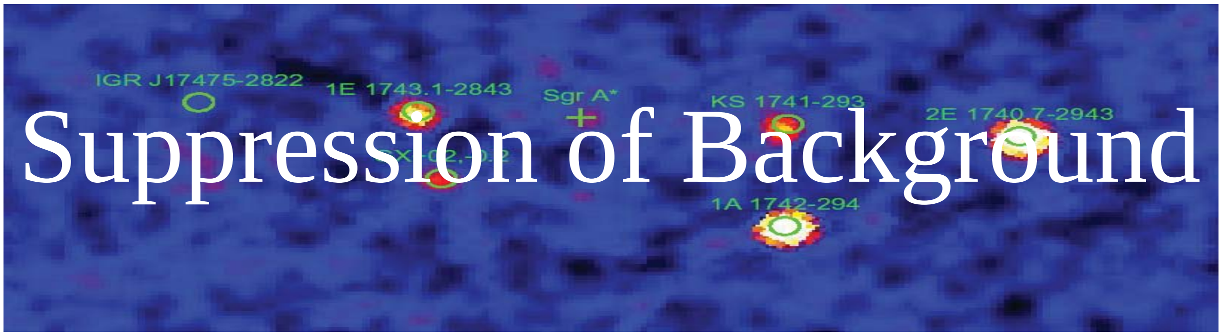
*) see for instance:
in’t Zand et al. A&A **288**, p 665 (1994)

Suppression of Background



Collimating Masks

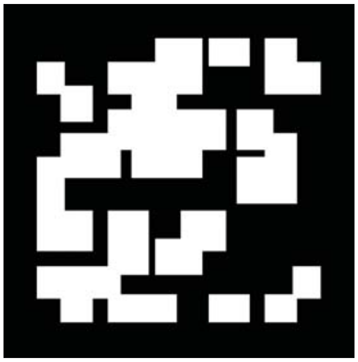
The most straightforward way to limit the field of view without interfering with the mask coding is to place a long shield cone in front of the masks. Unfortunately, this solution is very bulky. Effective shielding requires shield cones several times longer than the detector-mask separation, and in order to avoid interference between the four shield cones the footprint of the quarterback configuration grows to unmanageable dimensions.

I propose to use instead ‘multilayer masks’, with one central layer defining the real mask code, and additional collimating layers perforated to avoid (or minimize) interference with the coding of the sky photons. The collimating masks can be effective even with smalle separations because the relevant dimension here is the cell size in the code mask rather than the detector size.

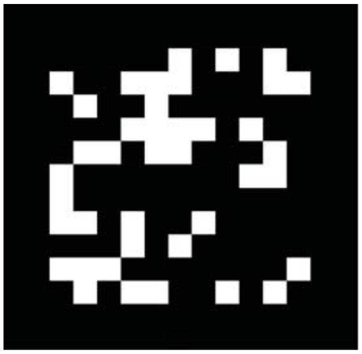
I have developed analytical and Monte Carlo tools to evaluate the efficiency of this approach, and the technique appears promising. The table below summarizes the results so far.

Ratio of photon flux from fully coded directions
to flux from partially coded directions
(for selected mask transparencies)
(in red: relative photon count inside fully coded field)

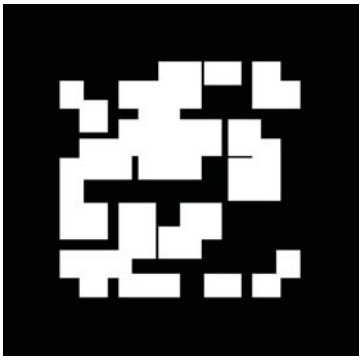
Mask transparency:	*25 %*	*33 %*	*50 %*
Without collimation:	*45 %*	*45 %*	*45 %*
	50	*65*	*100*
With 2 collimating masks	*52 %*	*50 %*	*48 %*
	50	*65*	*100*
With 2 collimating masks with increased separation	*68 %*	*62 %*	*55 %*
	38	*52*	*86*



Outer collimating mask



11x11
Code mask
33 % open



Inner collimating mask

The above patterns are for illustration only. the adjacent table was calculated for 150x150 patterns which are closer to realistic sizes for practical use.

Further work and conclusions

Choice of code pattern

One may have expected that the construction of the quarterback masks demanded that the cyclic residue set underlying the basc mask could be factorized such that the set would exactly fit into a rectangle without surplus or missing elements. Fortunately this is not the case. If the set has fewer elements than required to fill the mask rectangle one should just fill the remaing places with the first elements repeated, i.e. one should just keep counting modulo the set length.
(Such a fill has been done in the 8x8 mask used to illustrate the qurterback construction. The underlying set has 63 elements, so the last element in each of the five masks shown is just a repetition of the first element in the same mask).

Another issue is the choice of mask transparency. Cyclic residue sets can be constructed with transparencies 1/M, where M is an integer. Transparencies of 50%, 33% and 25% have been used in the past. Coded mask instruments for which the background is dominated by photons entering through the mask will achieve the highest sensitivity for weak sources with mask transparencies between 25 and 33%. If detector internal background is dominating a 50 % mask will be preferable. The higher mask transparency is also an advantage if the primary scientific objective is the study of short duration, intense bursts.

When mask collimation is now introduced this works in favor of small transparencies.So maybe a 33% transparency is a good compromise.

Further work

The mask collimation technique is only beginning to be investigated and the theoretical results reported here are preliminary. Further work is needed to find the optimal number and configuration of the collimating masks. Fabrication techniques must also be investigated

Conclusions

A novel mask and detector configuration, 'quarterback', for coded mask instruments have been presented. This configuration will eliminate two of the three systematic noise sources which have been present in past instruments, of this type, namely coding noise and ghost images (within the fully coded field).
A new collimation technique, 'mask collimation' is proposed to counteract the third noise source: the photon background and the imperfectly coded source signals coming from the partially coded field. The initial analysis shows that mask collimation can reduce the fraction of background photons from 55 to 33 % of the photons collected from the fully coded field.
These developments may lead to significant improved sensitivities of future coded mask instruments.

Acknowledgements

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