THE JEM-X MASKS

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ABSTRACT

The two JEM-X (Joint European X-Ray Monitor) instruments on-board INTEGRAL (International Gamma-Ray Astrophysics Laboratory) will each carry a coded mask in the form of a Hexagonal Uniformly Redundant Array (HURA). The masks will contain around 24247 hexagonal cells, approximately 50% opaque (tungsten) and 50% open, within a circular area of diameter 535 mm. The scientific and engineering considerations which led to this choice of mask design are described.

Tungsten was selected for the mask material due to its opacity and strength, but the complexity of the mask pattern combined with the scientific and mechanical requirements has led to a difficult engineering task. The most feasible approach is to cut the mask pattern from a thin tungsten sheet, of total thickness only 0.5 mm. Then to reach the required stiffness and strength characteristics, a novel solution is proposed: namely, the tungsten sheet will be pre-stressed to act as a membrane, and it will be supported by a thin but deep "exoskeleton" on either face.

Finally, the image reconstruction algorithm to be used is described along with the expected imaging performance under nominal noise conditions, and some imaging simulations are presented.

Keywords: Coded Masks, Image Reconstruction

1. INTRODUCTION

The two JEM-X instruments on-board INTEGRAL are identical X-ray telescopes operating in the energy range 3 - 60 keV, which are designed to complement the two main payload instruments – the Spectrometer (SPI) and the Imager (IBIS) – which will operate from roughly 20 keV to 10 MeV. Likewise, the Optical Monitoring Camera (OMC) will supply simultaneous photometry.

Each JEM-X instrument will carry an identical coded mask in the form of a Hexagonal Uniformly Redundant Array (HURA). The masks will contain around 24247 hexagonal cells, approximately 50% opaque (tungsten) and 50% open, within a circular area of diameter 535 mm. See ref. EID-B for a pictorial representation of the mask pattern.

The JEM-X masks will be fixed side-by-side, bolted to a PLM (Payload Module) structural panel that will hold them at a height of 3,385 mm above the detector plane window. The position of the masks within the overall payload configuration is illustrated in ref. EID-A.

2. MASK DESIGN DRIVERS

2.1 Scientific Requirements

Table 1 summarises the scientific performance requirements for each JEM-X mask:

Operational energy range	3 - 60 keV
Angular resolution	3 arcmin
Fields of View (FOV) (Circular Aperture)	FC (Fully Coded) 4.8° PC (Partially Coded) 9.1° ZC (Zero Coded) 13.2°
Opacity of solid mask cells	>99.9% @ 35 keV >95% @ 60 keV
Transparency of open cells	100% All energies

Table 1

The mask is circular, to match the circular detector, and the coding pattern is a HURA with 120° rotational symmetry, based on the work of Finger & Prince (1985).

2.2 Mechanical Requirements

The above FOV and angular resolution requirements dictate the mask dimensions (diameter, cell-size, mask – detector distance) as given below. In addition, there are a number of mechanical requirements to ensure the proper functioning of the mask in the storage, launch and operating environments it will encounter. The key parameters are summarised in table 2:

Mask coded diameter	535 mm	
Coded cell size	3.3 mm (short axis)	
Mask—detector distance	3,385 mm	
Mass Budget	5.45 kg	
Stiffness: first global freqs above…	Axial: Lateral:	60Hz 120Hz
Strength: applied simultaneously…	Axial: Lateral:	12g 12g

Table 2

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3. CURRENT MASK DESIGN

3.1 Mask Material

The opacity requirements combined with the mechanical properties (stiffness, loading) led to the selection of tungsten foil of thickness 0.5mm as the preferred mask material. It has a high density (~19g/cc) and strength, and the thinness of the foil will ensure that the vignetting of off-axis photons will be minimised.

3.2 Manufacturing Considerations

The complexity of the mask pattern combined with the stiffness and strength requirements has led to a difficult engineering challenge.

3.2.1 Coded pattern

First, the mask pattern must be manufactured to a high degree of accuracy to produce sharp, well defined X-ray shadowgrams: photo-chemical milling was selected as the best process for this.

3.2.2 Inter-cell ribs & pretensioning

Next, the mask pattern has many groups of opaque cells which are mechanically very poorly connected to neighbouring cells, including several which are completely isolated. Given the need to support the pattern, it was decided to link every free corner of every cell with its nearest neighbour by using inter-cell "ribs": bridges of width 0.25mm and full thickness (0.5mm). In addition, this uniform distribution of ribs enables the mask foil to be radially pre-tensioned to act as a membrane, augmenting its otherwise low natural frequency to around 40 Hz.

The cost of the ribs, in scientific terms, is a loss of around 15% of the mask open area.

3.2.3 Exoskeleton

Finally, to increase the frequency even more to the 60Hz requirement, the last component is added: a titanium "exoskeleton" of width 2mm and X-axis thickness of 40mm, which will be attached to both faces, as illustrated in Figure 1. The loss of open area is negligible: around 1.5% for on-axis photons, rising to around 5% for off-axis photons.

3.3 Final Configuration

The main components of the mask are illustrated in Figure 1. These are:

- Mask pattern including inter-cell ribs
- Pretensioning devices
- Exoskeleton (x 2)
- Interface ring plus bolts

The above components are all to be made of titanium, with the exception of the mask foil itself in tungsten.

The current design has been modelled using a detailed Nastran FEM (Finite Element Model) analysis which confirms the design goals are met for the key parameters.

3.4 Stop-Press

At the time of writing (August), we faced a difficult procurement problem with the mask foil due to the large diameter required (557mm, including the overlap for attachment to the pretensioning devices). Our preference was to use an alloy of tungsten, e.g. Densimet 17 which has a slightly lower density but is more machinable and less brittle, but only pure tungsten foils are currently available.

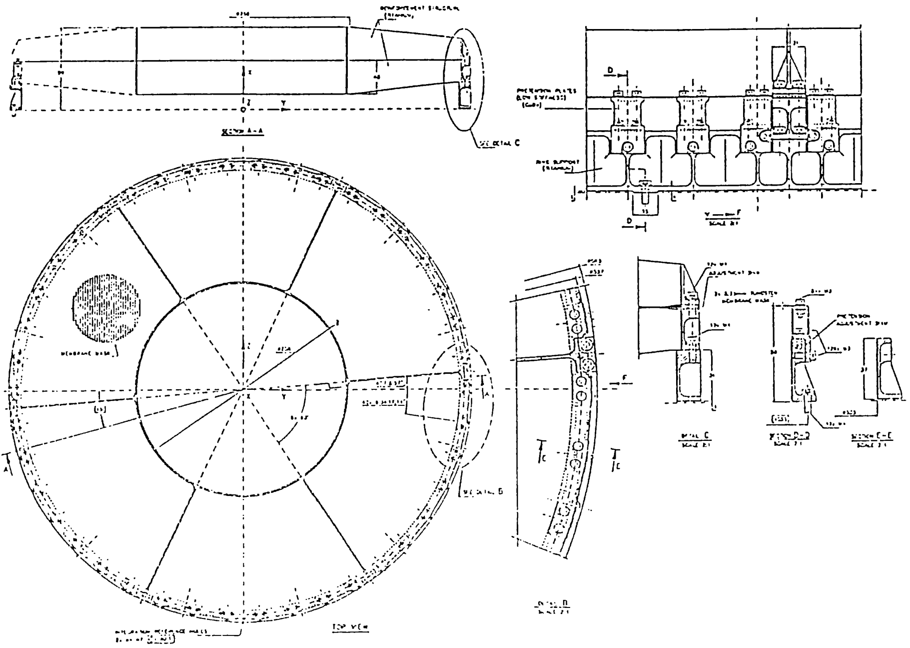

Fig. 1: JEM-X Mask Mechanical Assembly

Another problem is the width of the inter-cell ribs (0.25mm). With this width, the uniformity of the ribs can not be guaranteed if the foil thickness is 0.5mm. It was therefore planned that the photochemical milling would be carried out using two separate foils of thickness 0.25mm, which would then be combined to make a single mask. However, the pure tungsten foils are only available in thickness 0.5mm.

We are planning to manufacture some foils to test the feasibility of the process.

4. IMAGE RECONSTRUCTION

The usual reconstruction methods work by correlation methods: an inverse response function array G is correlated with the detector array D in order to obtain a reconstructed sky map O. The best results are obtained with URA (Uniformly Redundant Array) mask patterns, or their modifications (HURA - Hexagonal-, MURA - Modified -). The problem with JEM-X is the existence of the inter-cell ribs and the exoskeleton, which spoil the reconstructed image obtained by these methods. Better results are obtained using maximisation methods such as Maximum Entropy (MEM) or Maximum Likelihood (MLM). However, with MEM, there is no analytical solution, so the reconstruction must be solved numerically (for example by iterative methods). The existence of some free parameters (the Lagrange multipliers) slows down the process significantly.

The maximisation method we are going to consider is the E-M algorithm (Dempster et al. 1977). It is an algorithm for computing maximum likelihood estimators iteratively (by construction). A description of it can be found in Ballesteros et al. (1996). The E-M algorithm is designed to increment the likelihood in each iteration.

Figure 2 represents the shadowgram formed by a point source of intensity 100 ph/cm^2, located at (2.23,0) in the Y-Z plane. The noise was modelled as contributing 30±5 counts/cm^2 with a flat distribution. The shadow of part of the ring and two spokes of the exoskeleton can clearly be seen. Figure 3 is the reconstruction, with the geometry of the exoskeleton explicitly included in the restoration process. The reconstructed source strength is 101.78 ph/cm^2/s.

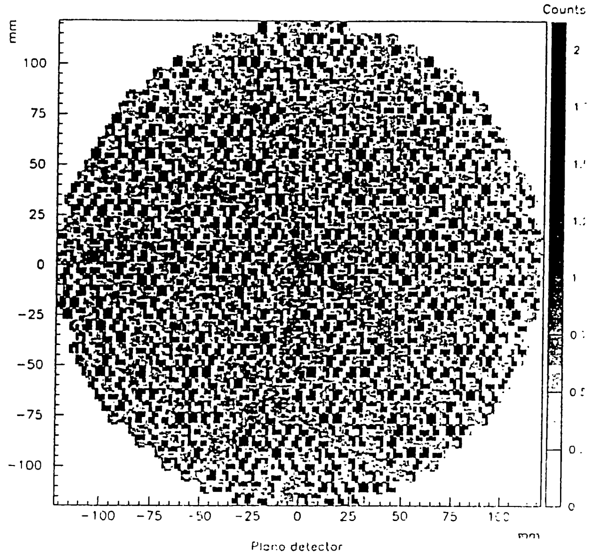

Fig. 2: JEM-X Shadowgram

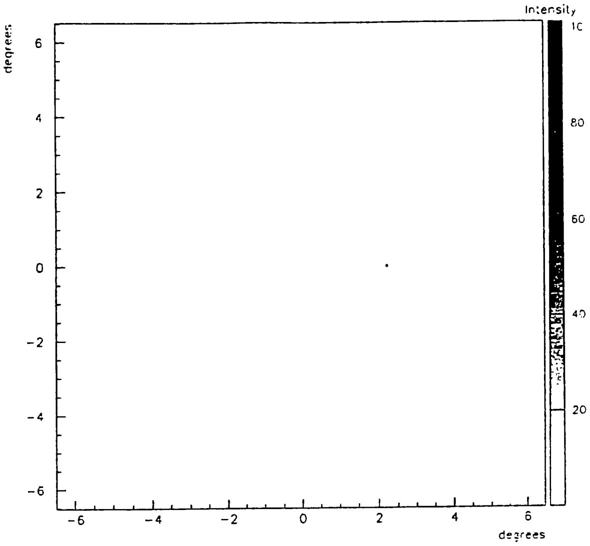

Fig. 3: Reconstruction of a point source located at (2.23,0)

5. CONCLUSIONS

The current mask design successfully fulfils the scientific and technical design goals. The slight reduction in the received flux caused by the need for inter-cell ribs and the exoskeleton structure is an inevitable compromise given the conflicting scientific and engineering requirements. However, knowing the geometry of these components, the effect on the received shadowgram can be removed during the reconstruction process.

6. REFERENCES

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