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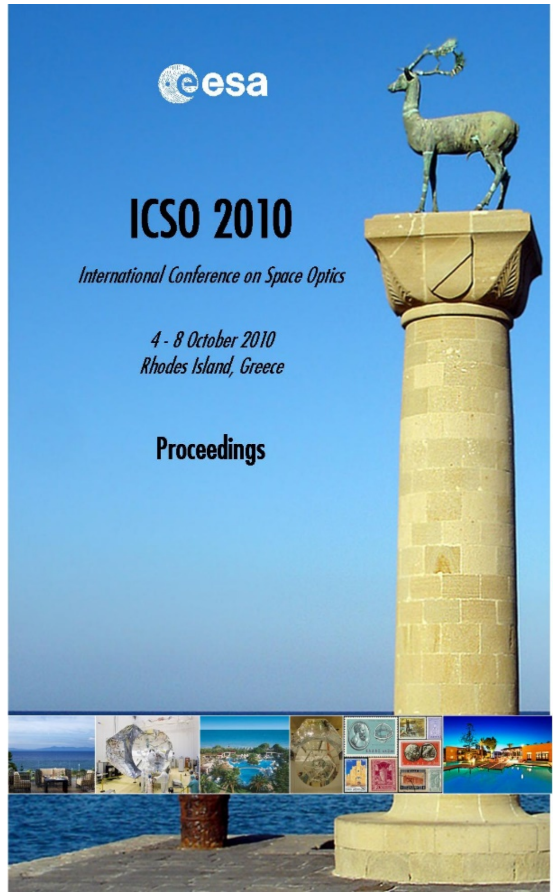

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IXO TELESCOPE MIRROR DESIGN AND ITS PERFORMANCE

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I. INTRODUCTION

The International X-ray Observatory IXO, a candidate follow-on mission for XMM/Newton and CHANDRA, has been studied in Europe in the frame of two parallel industrial assessment studies commissioned by ESA as part of the Cosmic Vision 2015-2025 programme. One of these studies was successfully carried out by EADS Astrium. The present paper is focussed on the results obtained by Astrium GmbH in this study, i.e. on the optical, mechanical and thermal design of the IXO telescope mirror and on the predicted telescope performance.

The IXO telescope mirror consists of nearly 1700 Silicon Pore Optics (SPO) mirror modules [1] accommodated on eight identical petal-shaped support structures. These *petals* are themselves supported by an optical bench. Design drivers proved to be the allowable mass, the required optical throughput as well as the axial and lateral stiffness required by the launch vehicle. To ensure light-weighting, low thermal gradients as well as robustness during AIV, the petals and the optical bench are deliberately made of a high-modulus carbon fibre material with high thermal conductivity. The telescope optical performance achievable with this design has been analysed based on rigorous finite element, thermal and optical modelling. It has been found to be fully compliant with the required optical throughput and image quality, thus enabling the scientific benefit of the IXO mission.

II. THE IXO MISSION AND ITS DRIVING TELESCOPE REQUIREMENTS

IXO is a space-borne large single-aperture x-ray telescope with a focal length of 20 m. This considerable focal length exceeds the fairing dimensions of existing launchers and is realized on a single spacecraft by means of a partly deployable telescope tube, the *Expandible Optical Bench* (EOB). The telescope's different focal plane instruments form part of the *X-ray Instrument Module* (XIM) and are moved into focus by a dedicated three-axis *Moving Instrument Platform* (MIP). The collected x-rays are focussed in the telescope mirror, i.e. in the *X-ray Mirror Assembly* (XMA). These and further essential elements of the observatory are visualized in Fig.1.

IXO will be directly injected into a huge halo orbit around the second Lagrangian point L_2 of the Sun-Earth system by either Ariane 5 or Atlas V-551. For compatibility with either launcher IXO's total mass needs to be limited to about 6500 kg. This mass constraint decisively limits the number of Silicon Pore Optics (SPO) mirror modules that can be accommodated in the telescope mirror and hence the achievable optical throughput, the effective collecting area of the telescope.

Table 1 on the following page summarizes essential IXO telescope requirements.

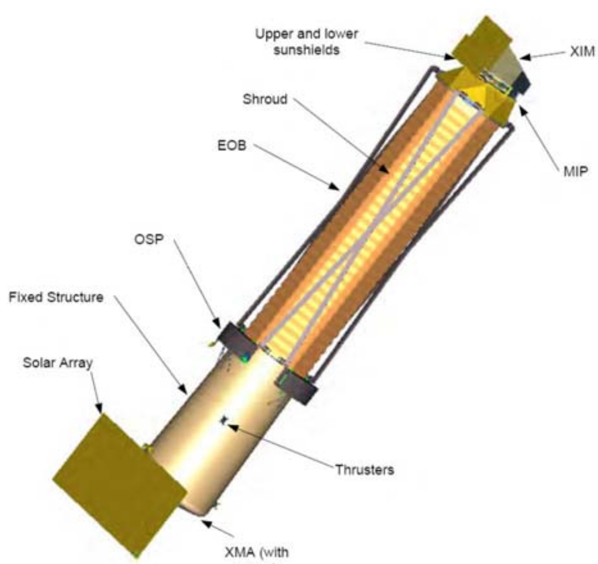

Fig. 1. The International X-ray Observatory IXO in operational configuration.
Acronyms: XMA ... X-ray Mirror Assembly, i.e. the telescope mirror, OSP ... Observatory Service Platform, EOB ... Expandible Optical Bench, XIM ... X-ray Instrument Module, MIP ... Moving Instrument Platform.

Table 1. Summary of major IXO telescope requirements.

Telescope effective area	≥ 2.5 m^2 at 1.25 keV (goal: 3.0 m^2) ≥ 0.65 m^2 at 6 keV (goal: 1.0 m^2) ≥ 150 cm^2 at 30 keV (goal: 350 cm^2)
Telescope image quality	≥ 5" half-energy width at < 7 keV ≥ 30" half-energy width from 7 to 40 keV
Stiffness of telescope mirror	≥ 35.6 Hz along optical axis (axial) ≥ 14.8 Hz normal to optical axis (lateral)
Operational temperature range for SPO mirror modules	-5 to +20 °C
Operational temperature gradients within SPO mirror modules	≤ 11 K/m along optical axis ≤ 20 K/m normal to optical axis

III. OPTICAL DESIGN

The optical design analysed for the IXO telescope is based on Silicon Pore Optics (SPO) mirror modules [1] approximating a Wolter type-I grazing incidence telescope. In this consept the primary mirror is ideally an annular segment of a paraboloid while the secondary mirror is a confocal and coaxial annular segment of a hyperboloid. Grazing incidence telescopes use incidence angles close to 90° so that their mirror pairs are nearly parallel to the telescope optical axis. Collecting area is built up by nesting many co-aligned, confocal, coaxial mirror pairs within one another. The need to maximize the telescope’s collecting area links the separation between radially adjacent mirrors to their length: small radial gaps lead to short mirrors. Short mirrors, however, allow approximating the annular segments of paraboloids and hyperboloids by coaxial annular cone segments (frusta). For IXO this *double-cone approximatio*n of the Wolter type-I concept is the baseline. Circumferential segmentation of nested annular cone segments into small *mirror stacks* is a further prerequisite for the application of SPO technology. Mirror stacks are silicon pore structures consisting of ribbed, nearly parallel mirror plates made of crystalline silicon wafers that are stacked and bonded in a cone-shaped mould on one another so that the ribbed side of one mirror plate is connected with the smooth, super-polished side of its neighboring mirror plate [2]. There are two classes of mirror stacks: *P-stacks* consisting of cone-shaped mirror plates approximating segments of nested *paraboloids* and *H-stacks* consisting of cone-shaped mirror plates approximating segments of nested *hyperboloids*. An SPO mirror module is a precisely co-aligned, compact combination of a P-stack with a corresponding H-stack held together by bracketry and equipped with a mounting interface to its support structure (cf. Fig. 2). Each individual mirror module hence represents a tiny segment of a nested Wolter type-I telescope with a typical geometrical collecting area of about 20 cm^2. In a *petal* several hundred mirror modules of different types are combined and commonly supported by a petal-shaped support structure, the *petal frame*. The *optical bench* is the structure supporting these petals.

For the segmentation of the optical bench three alternative concepts have been developed that are visualized in Fig. 3. The 8-petal concept is attractive since it uses eight identical petals that can be mounted on a robust spokewheel forming the optical bench. A drawback of this concept is its relatively low effective area for hard x-rays to which only the innermost radial rows of mirror modules contribute. At these small radii the spokes of the optical bench obstruct a significant portion of the aperture. This drawback is mitigated in the 12-petal concept where the aperture is divided into four inner petals and eight outer petals. This concept offers some additional 20% of effective area at 30 keV but is mechanically less robust. An even higher gain in effective area at 30 keV of about 30% is expected for the 9-petal concept where the aperture consists of an annular central 'petal' surrounded by eight peripheral petals. Unfortunately, a robust mechanical realization of this concept is rather challenging.

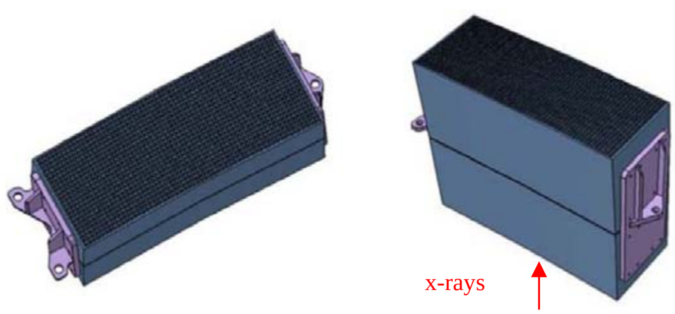

Fig. 2. Two views of a typical Silicon Pore Optics mirror module, the smallest building block of the IXO telescope mirror (courtesy of ESA). Incoming x-rays are first reflected at the P-stack.

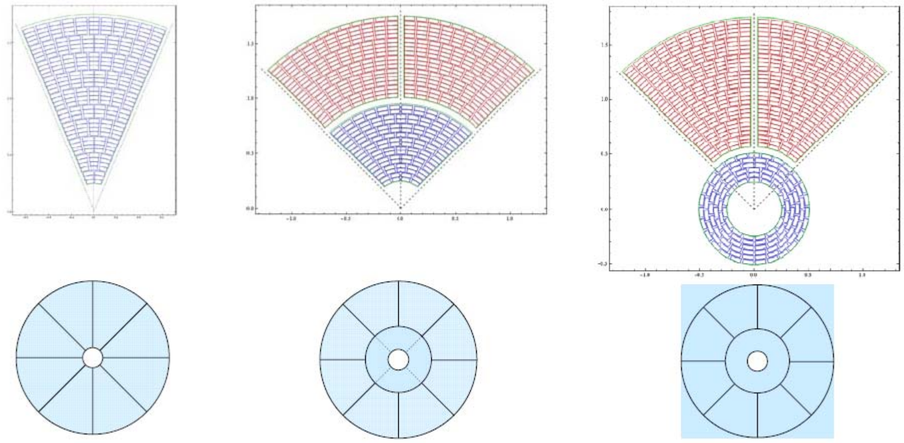

Fig. 3. Different optical bench segmentation concepts. Left: the (preferred) 8-petal concept. Middle: the 12-petal concept. Right: the 9-petal concept. The tiny blue and red rectangles represent the mirror modules.

After trading pros and cons of the three segmentation concepts the 8-petal concept was chosen as baseline. Accordingly, each of the eight identical petals is densely populated by 208 mirror modules arranged in 34 radial rows. The mirrors of the innermost five rows feature a graded-depth Pt/C multilayer coating whilst those of the outer 29 rows carry an Ir/B_4C bilayer.

IV. MECHANICAL DESIGN

The mechanical configuration and design of the X-ray Mirror Assembly (XMA) is driven by requirements derived from the IXO spacecraft (S/C) launch and performance requirements. In particular the launch mass constraint of 6500 kg requires putting the design focus on consequent structure light-weighting whilst meeting the stringent stiffness and launch load requirements imposed by Ariane 5 ECA (exceeding those of the alternative Atlas V-551 launcher). The required optical throughput (cf. Table 1) calls for maximum collecting mirror area. Correspondingly, any obstruction of the telescope's clear aperture owing to structures supporting the mirror modules needs to be minimized. Furthermore, the mechanical and thermo-elastic stability of these structures is affecting the achievable image quality.

The elaborated overall XMA mechanical configuration (cf. Fig. 4) is based on the 8-petal concept of Fig. 3 and comprises eight identical petals each equipped with 208 mirror modules and with one thermal baffle. The petals are supported by the optical bench and can be individually assembled and tested. The optical bench in the form of a spoke-wheel with its height of only 0.41 m forms the backbone of the XMA and interfaces with the spacecraft at its outer diameter of 3.3 m. The centre of the optical bench provides the space and interface to accommodate a metrology package. The overall XMA mass amounts to 1612 kg including maturity margin. Nearly half of this mass (48%) is due to the Silicon Pore Optics mirror modules. The XMA contributes 38% to IXO's dry mass. The need for a stiff and light-weight XMA design with high robustness in view of the involved assembly and integration activities (mounting and precision alignment of 8×208 mirror modules) necessitates a sound material trade-off for petals and optical bench.

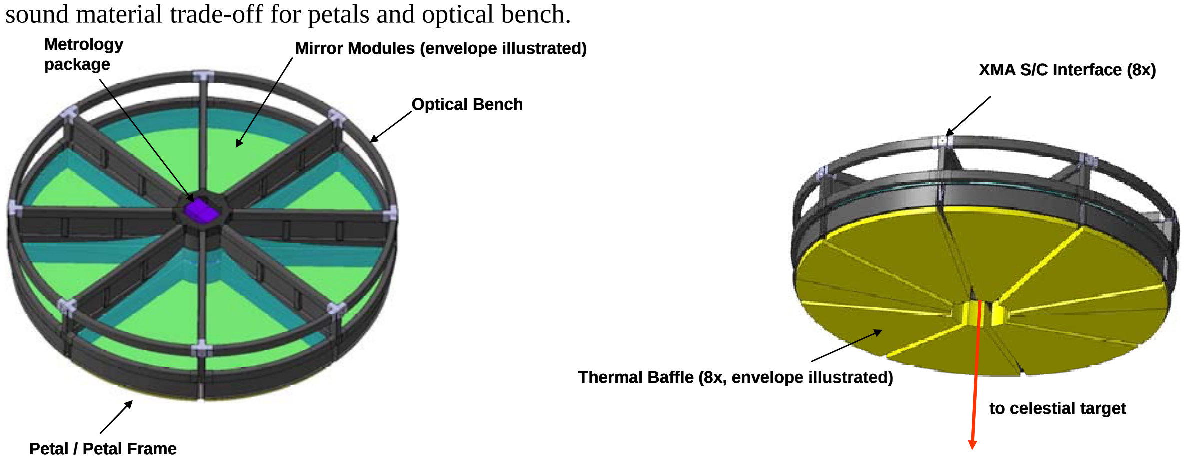

Fig. 4. Two views of the mechanical configuration of the IXO telescope mirror assembly (XMA).

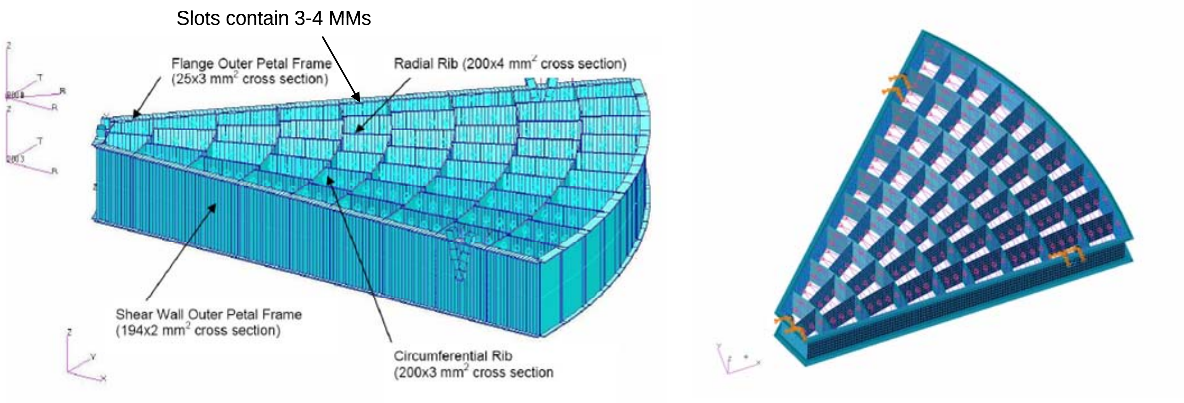

Fig. 5. CFRP petal frame supported by three kinematic mounts

As a result of this trade-off a particular type of high-modulus carbon fibre plastics (CFRP) material with high thermal conductivity was selected. The CFRP shrinkage effect under vacuum due to the release of the on-ground absorbed moisture is very well known and precisely predictable. The mechanical design of the petal frame made of this selected type of CFRP is depicted in Fig. 5. Clustering of 3-4 mirror modules within one petal slot helps to minimize the obstructing area and mass. The petal frame design features an outer CFRP C-beam frame connected by a grid of eight circumferential and 45 radial CFRP ribs.

The XMA primary structure is the optical bench. It has the shape of a spoke-wheel and consists of CFRP filament-wound beams, of monolithic radial CFRP shear walls and of a central CFRP tube. CFRP and Invar corner joints are foreseen to connect the beams. The optical bench mass amounts to 166 kg including a maturity margin of 20%.

The suspension of the optical bench within the spacecraft is foreseen at the upper side of the XMA in order to enable maximum shock attenuation just by maximizing the structural path length between the mirror modules and the shock source.

The XMA design has been analysed based on rigorous finite element modelling comprising a very detailed FEM of the petal to justify the compliance with the requirements and in order to reliably quantify the mirror module loads in terms of accelerations and imposed interface distortions. Analyses on XMA level as well as on spacecraft level have been performed to precisely cover the launch and the in-orbit environment.

As a result, the first axial frequency of the XMA at 38.6 Hz is above the required 35.6 Hz. Similarly, the computed first lateral frequency at 21.2 Hz lies well above the required 14.8 Hz. These results indicate sufficient XMA stiffness to avoid dynamic coupling with the spacecraft. The stress analysis shows sufficient margin of safety for the optical bench and the petal frame. The corresponding global stress levels are all smaller than 76 MPa and are well within the materials' strength capability.

V. THERMAL DESIGN

On XMA level as well as on mirror module level temperature gradients have to be minimized, in order to limit thermo-elastic distortion effects on the optical performance. A further design driving requirement is the operation of the deep-space oriented mirror modules at temperatures close to room temperature, because on one hand the mirror modules (made of silicon) have a high emissivity of about 0.9 which implies a strong radiation interaction with the 4 K space background, and on the other hand applying heaters directly on them is not allowed. Furthermore the mission scenario and the spacecraft configuration impose a quite complex thermal environment on the XMA as depicted in Fig. 7.

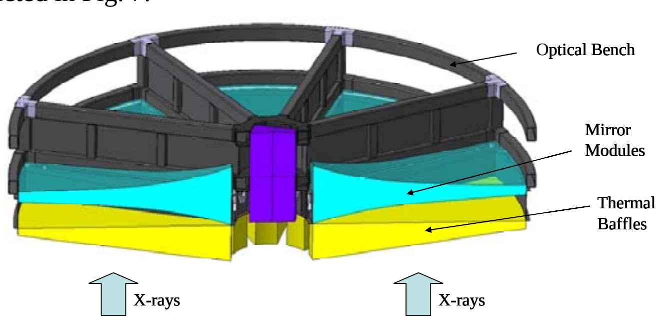

Fig. 6. XMA bench design features

Because of the poor conductance across all internal and external mechanical XMA interfaces, this inhomogeneous radiation environment might introduce strong temperature gradients in all directions of the XMA if no specific thermal control means would be applied.

The proposed design solution comprises the following features: (1) thermal baffles at the deep-space oriented side of the XMA which are mounted to the petal frames and have a linearly varying height which increases towards the center of the XMA (cf. Fig. 6), (2) heaters which are located on the radial ribs of the petals close to the mechanical interface to the mirror modules (MMs) and indirectly heat up the MMs via radiation (cf. Fig. 5), and (3) petals and optical bench made of carbon fibre material with high thermal conductivity to support heat transfer inside these structures.

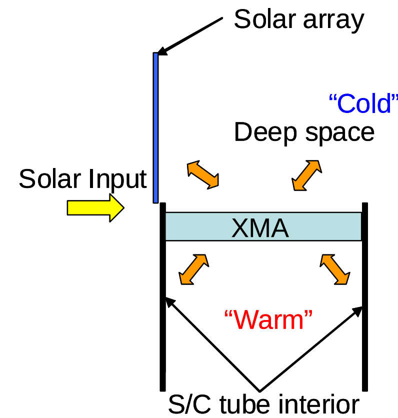

Fig. 7. Schematic view of the XMA thermal environment.

In order to justify the thermal design, thermal models had to be established under the time and budget constraints of a study. These should be capable to provide reliable results even on MM level. Note that a simplified thermal model of a single MM already consists of about 20 thermal nodes, and that modelling only a portion of the about 1700 MMs would end up with a thermal model completely unaffordable within this study. Therefore a quite tricky approach has been selected, as outlined below.

Different types of geometrical mathematical models (GMMs) and thermal mathematical models (TMMs) with different levels of detail have been developed, one consisting of only either one or twelve MMs and their neighboring petal and baffle structure (*Single-MM* or *MM-Cluster GMM/TMM*), the other one describing the complete XMA including its environment, but without MM details (*XMA GMM/TMM*). With these models a three-step approach has been applied:

1) First the XMA external radiation couplings with deep space and solar array as well as the XMA internal couplings between P-stack, H-stack, petal and thermal baffle have been calculated. For this purpose the Single-MM GMM has been embedded in the XMA GMM at 64 positions, and the radiation data have been condensed to 64 areas for 4 XMA layers (P-stack, H-stack, petal and thermal baffle).
2) In the second step the XMA TMM has been used to calculate temperatures, applying both, radiation data from the XMA GMM (standard method) and the condensed radiation data from the previous step.
3) Finally a combined XMA / MM-Cluster TMM with approx. 1000 thermal nodes has been set up which used radiation data from a combined GMM where the MM-Cluster GMM has been embedded in the XMA GMM, as shown in Fig. 8. This third step allowed a detailed assessment of temperature gradients on MM level.

The thermal analysis results indicate that all temperature and temperature gradient requirements are met. About 1330 W of heater power are needed to keep all MMs within a range of about 10 to 25 °C assuming a non-optimized, equally distributed heater power per MM, independent from the location of the MM inside the XMA. The most critical axial temperature gradients between P-stack entrance plane and H-stack exit plane are calculated to be < 0.4 °C, equivalent to 6-7 K/m even for the shortest, outermost located MMs. This meets the axial requirement of 11 K/m with sufficient margin.

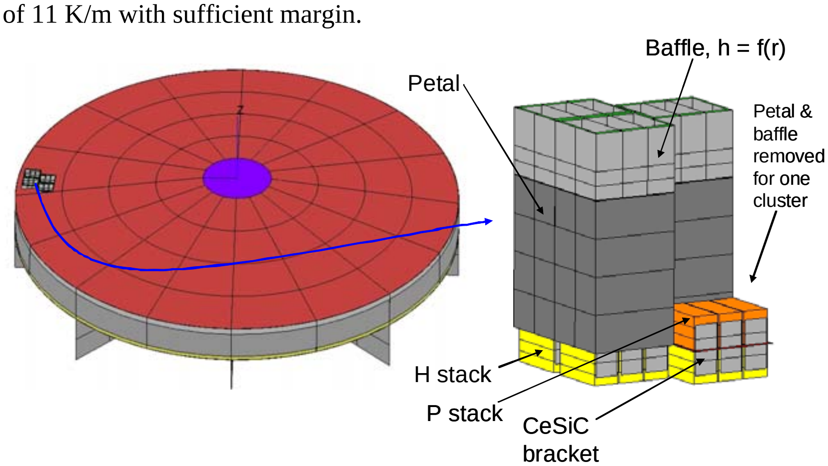

Fig. 8. Modelling approach, MM-Cluster GMM (right side) embedded in XMA GMM (left side).

VI. TELESCOPE PERFORMANCE

Customarily, the performance of x-ray telescopes is quantified by two parameters: by their effective collecting area and by their optical resolution expressed as half-energy width (HEW).

The effective area of the XMA concept presented above has been calculated for photon energies ranging from 0.1 to 100 keV. To account for mirror contamination, mirror module internal obscurations and coating imperfections this *gross* effective area has been reduced by 10%. The resulting *net* effective area is visualized in Fig. 9 together with the required levels of Table 1. It can be seen that the optical throughput at 1.25 keV and at 6 keV is well above the specification. At 30 keV the required level is just met. By applying the multilayer coating to mirror modules not only in the five innermost rows but e.g. to those in the six or seven innermost rows the high-energy throughput can be easily increased by 20% or more which ensures sufficient margin also at 30 keV.

The HEW budget of the XMA is dominated by the contribution of the individual mirror module specified to 4.3". The combined effect of moisture release, gravity release and thermo-elastic distortions contributes 1.4" (based on finite element analysis) when added in quadrature. Further contributions to be added in quadrature are limitations in line-of sight knowledge due to metrology errors (0.8") and micro-vibrations (0.6"). Summing up all these contributions yields a HEW of 4.6" which is well below the required 5.0".

VII. CONCLUSIONS

A robust, light-weight and simple design concept for the IXO telescope mirror assembly has been established that – based on extensive analyses – fully meets all imposed mechanical, thermal and performance requirements. It has been demonstrated to be fully compatible with a launch on Ariane 5 ECA and on Atlas V-551.

ACKNOWLEDGMENTS

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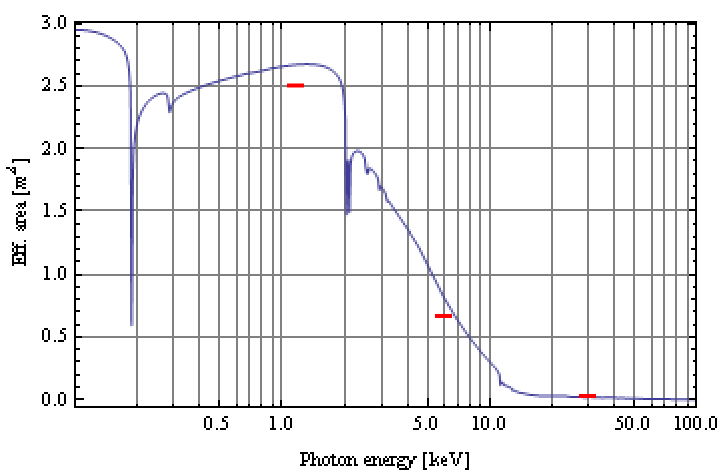

Fig. 9. Telescope effective collecting area in units of [m^2] versus photon energy. Required levels (cf. Table 1) marked in red.