Design Concept for the International X-Ray Observatory Flight Mirror Assembly

Ryan S. McClelland
301-286-8615, ryan.s.mcclelland@nasa.gov
David W. Robinson
301-286-9926, david.w.robinson@nasa.gov
NASA Goddard Space Flight Center
Greenbelt, MD 20771

Abstract—The Flight Mirror Assembly (FMA) mechanical design for NASA's next major x-ray telescope mission, the International X-Ray Observatory (IXO), recently kicked off at NASA. [1] [2] The design presents some unique engineering challenges requiring a novel mirror design due to the high angular resolution and large effective area required to achieve the desired scientific objectives [1]. The Wolter-I x-ray telescope optical design requires about 14,000 0.4mm thick glass mirror segments to be densely packed into a 3.2m diameter FMA and supported with micron level accuracy and stability. Key challenges addressed by the FMA design concept include bonding the mirrors into the module without distortion, designing the segment support for glass survivability, keeping the structure light enough to launch, providing a large effective area, and preventing unacceptable thermal distortion. The thin mirror segments are mounted into intermediate wedge shaped structures called modules. Modules are kinematically mounted to the FMA primary structure which is being optimized for minimum mass and maximum projected area in the focal plane. The current design approach appears feasible without new technology development beyond that currently in process.

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1. INTRODUCTION

The FMA is the major focusing element of the IXO x-ray telescope, containing both primary and secondary mirrors. Development of the mirror technology needed to achieve the high angular resolution and large effective area required has been ongoing at NASA and the Smithsonian Astrophysical Observatory (SAO) in the decade since the last major x-ray mission, Chandra, was launched. This pre-Phase A project is now at a point where a preliminary design of the FMA is needed to demonstrate the feasibility of using the mirror technology developed to create a large space based telescope.

This paper presents the primary design challenges associated with creating the FMA and a preliminary design concept that addresses these challenges. The design presented in this paper represents a snapshot at the time of writing. An alternate design, not discussed herein, is being created by the European Space Agency (ESA) using silicon micro-pore mirror technology [2]. The major elements of NASA's FMA concept include the mirror segments, modules that support the segments, and the primary structure that supports the modules.

The primary increase in performance, relative to past missions, required of the IXO FMA is the effective area for x-ray photon collection in the 1 keV to 6 keV range (see Table 1). Where Chandra had 4 primary/secondary mirror pairs, IXO must have ~360. Correspondingly, the mirror must be much thinner. Supporting this large number of very thin mirrors is the central challenge of the FMA design. Past projects such as XMM-Newton have packed thin mirrors into x-ray telescopes, but never in such great number or with the 5 arc-sec resolution required by IXO.

Table 1. FMA Preliminary Requirements Summary

Effective Area	$3.0m^2$ @ 1keV $0.6m^2$ @ 6keV
Angular Resolution	5 arc-sec
Focal Length	20m
Mass	1700kg
First Mode	35Hz
Quasi-static design load	10G each axis
Operating temperature	20°C ±1

IXO Observatory Overview

The International X-ray Observatory (IXO) is a new collaboration between NASA, ESA, and JAXA which is planned to launch in 2021 [3]. It combines elements from NASA's prior Constellation X program and ESA's XEUS program. IXO will be a Great Observatory-class mission which builds upon the legacies of the Chandra and XMM-Newton X-ray observatories. IXO will have a mass of around 6600 kg and will be approximately 23 meters long

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[2] IEEEAC paper #1574, Version 3, Updated November 2, 2008.

and 4 meters in diameter. It will fly on an Atlas 5 or an Ariane V rocket into an L2 halo orbit. On orbit roll and pitch on the spacecraft are limited so that the sun always shines on one side, to ensure a very stable thermal environment. See Figure 1.

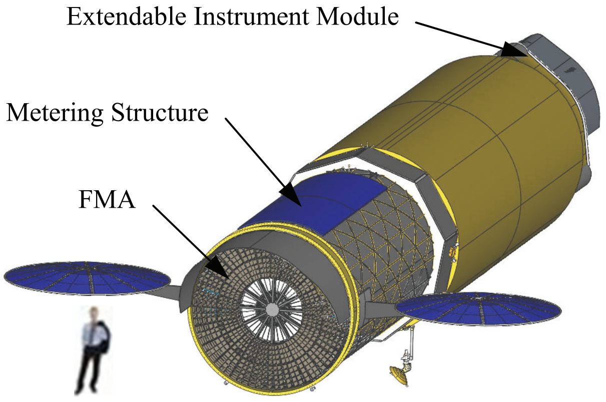

Figure 1 – IXO spacecraft, 23m long with metering structure deployed.

Optical Design

In order to understand the challenges of the FMA design, it is necessary to have a basic understanding of grazing incidence x-ray optics as they differ significantly from the more common near-normal incidence infrared, visible, and ultraviolet optical systems.

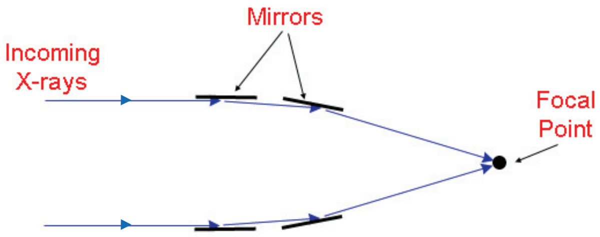

Figure 2 – Schematic of grazing incidence x-ray optics.

As shown in Figure 2, incoming x-rays must be reflected at small angles of incidence in order not to be simply absorbed. In order to be focused correctly, the x-rays must complete a double bounce, grazing off both primary and secondary mirrors. In this Wolter-I type optical design, the primary mirrors are parabolic in shape and the secondary mirrors are hyperbolic, though for mechanical design, both are well approximated by sections of cones. X-rays of various energies are reflected more efficiently at various angles of incidence. Thus the optical design is dictated by the desired effective area at the energy levels of scientific interest. Also, since the x-rays must pass through the mirror assembly, typical lightweight backing support structures used with normal incidence optics are unusable.

In order to achieve the effective area requirements, a large mirror with a 20m focal length consisting of approximately 360 concentric rings (also called shells) of primary and secondary mirrors has been studied. The diameter of the innermost shell is currently 744mm and that of the outer shell is 3200mm.

2. MIRROR SEGMENTS

Geometric Description of Mirror Segments

In order to maximize effective area, the shells must be packed together as densely as possible without one primary shadowing the next (see Figure 3). The spacing between mirrors currently ranges from 2mm to 5mm. The thinner the mirror, the more densely the shells can be packed. For this reason, the shells are currently 0.4mm thick, making holding the mirrors without distorting them at the micron level a major challenge during both integration and launch, due to their extreme flexibility.

Mirror segments are slumped from commercially available Schott AF45 glass onto polished mandrels to facilitate large scale production (see Figure 4). The current mirror fabrication technology limits the circumferential span of a mirror segment to about 360mm. Each concentric shell must be broken up into many segments based on this limitation. Currently, each shell is broken up into 12 or 24 sections, yielding an impressive ~14,000 glass segments including primary and secondary shells. The resulting segments are ~200mm long in the axial direction by ~360mm in the circumferential direction, roughly the size of a sheet of paper. The total mass of all segments is ~800kg.

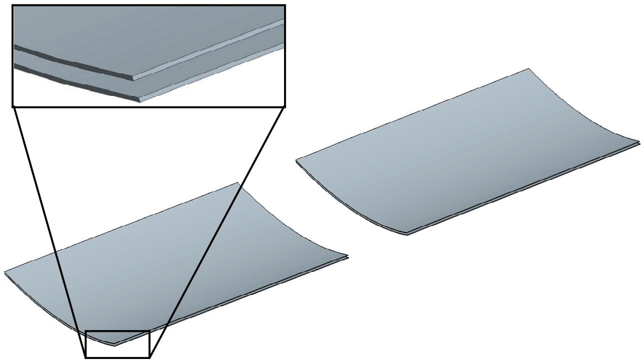

Figure 3 – Two pairs of primary and secondary mirror segments with 2mm spacing.

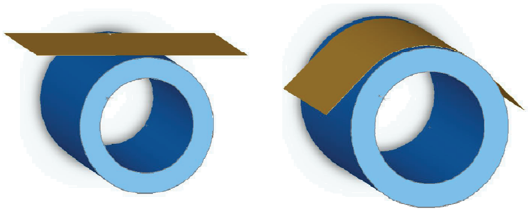

Figure 4 – Schematic of mirror slumping process.

Segment Mounting

In order to achieve the 5 arc-sec on-orbit angular resolution required for the IXO telescope, the primary and secondary segments must be aligned and supported relative to each other with micron or sub-micron level precision. The current technology development is focused on using low shrinkage adhesive applied in discrete areas to bridge the gap between the stiff mechanical structure that supports the mirrors, fabricated to precision machining tolerances, and the mirror segments, fabricated to optical polishing tolerances. UV cure adhesives are being investigated for this application due to their potential for low shrinkage, low CTE, and near instant UV light curing [4]. An example of a concept bonding design is shown in Figure 5.

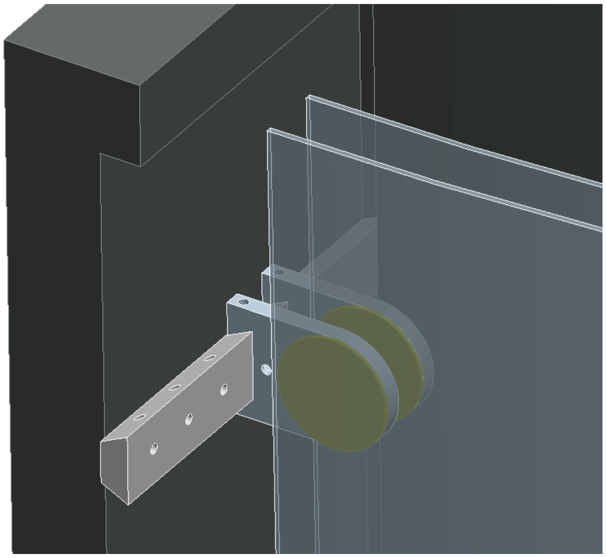

Figure 5 – Concept for one sided bond between mirror and support structure.

Due to unique properties of the Wolter-I optical design the angular resolution of the telescope is much less sensitive to the alignment between segment pairs. Pairs can be located relative to each other within tolerances achievable by precision machining practices and standard alignment tools such as theodolites and laser trackers. This has important implications for the use of a modular design as discussed in Section 3.

Segment Survivability

A major issue in the use of thin glass segments for a space telescope is survivability of the thousands of mirrors during launch. Choosing failure criteria for the glass segments is much more complex than for an analogous metal optic due to the nature of brittle glass failure. The design strength of glass is a function of the material properties, surface condition, stressed area, and desired Probability of Failure (POF) [5]. Materials testing has been performed using 30 slumped glass segments to determine the characteristic strength (σ_0) and Weibull modulus (m) as described by the two parameter Weibull strength distribution.

$$POF = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right] \tag{1}$$

The strength of the test specimens can be related to the strength of the glass segments as supported in the FMA (see Figure 6), which have different stressed areas, by the flowing equation:

$$\frac{\sigma_1}{\sigma_2} = \left(\frac{A_2}{A_1}\right)^{\frac{1}{m}} \tag{2}$$

The area used can be calculated as an effective area [6] or using the area subject to 80% or more of the maximum stress [5]. The current estimate for design strength based on materials testing, Finite Element Model (FEM) results, and a 0.0001 POF is ~2ksi.

Significant work has been done at SAO to determine the effect of number and location of bonding points between the mirror segments and support structure on the segment stress [7]. The current baseline includes three bonding points on each circumferential edge of the mirror and two on each axial edge. This arrangement will be revisited with detailed stress analysis in the near future. To minimize the mirror distortion induced during the bonding process, it is desirable to reduce the size and number of bond areas to the minimum required for survivability.

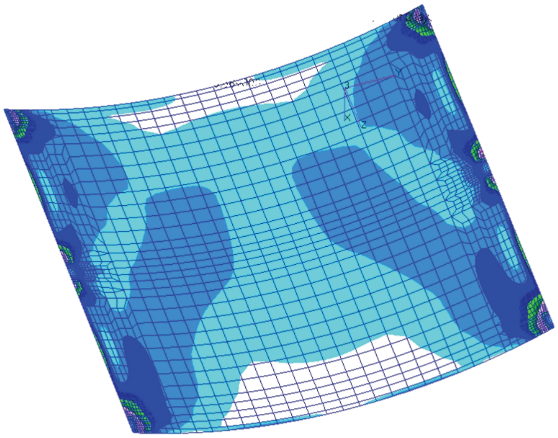

Figure 6 – FEM showing stress peaking near bond areas.

3. MIRROR MODULES

Multiple pairs of mirror segments are mounted into wedge shaped mirror modules before being kinematically attached to the FMA primary structure (see Figure 7). This unique modular mirror approach has several important advantages vs. integrating all ~14,000 segments into one monolithic structure:

- Reduces risk. If one segment or set of segments is damaged before launch, the module can be replaced.
- Allows for easier handling. Modules are designed to be a manageable size for assembly, transportation, and test.
- Reduces FMA fabrication time. Since integrating large numbers of segments will be time consuming, the modular approach allows for parallel assembly.
- Reduces load in mirror segments. Kinematically mounted modules take segments out of primary load path.
- Reduces thermal distortion of mirror segments. Kinematically mounted modules decouple the deformation of the primary structure for the deformation of the segments.
- Approach is applicable to x-ray mirrors of arbitrary size. If the FMA size changes in future observatory design iterations, technology developed to create a module is still directly applicable.

The major disadvantage of the modular approach is that it greatly increases the mass of the FMA. The modules essentially become a payload mounted on the FMA primary structure, adding mass but minimal structural strength or stiffness. The module structure is estimated to weigh ~60% of the weight of glass supported.

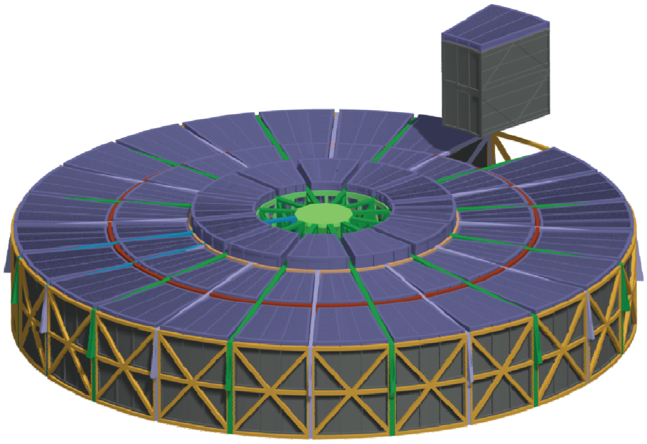

Figure 7 – Exploded view of FMA with one module removed.

Kinematic mounting between the modules and primary structure will be achieved through three flexures positioned at the axial mid-plane between the primary and secondary mirrors. In Figure 8, the flexures are shown integral to the module structural panels; however, they may also be made as separate parts. Two flexures will take radial load, one flexure will take circumferential load, and all three will take axial load since the largest quasi-static acceleration is expected in the axial direction.

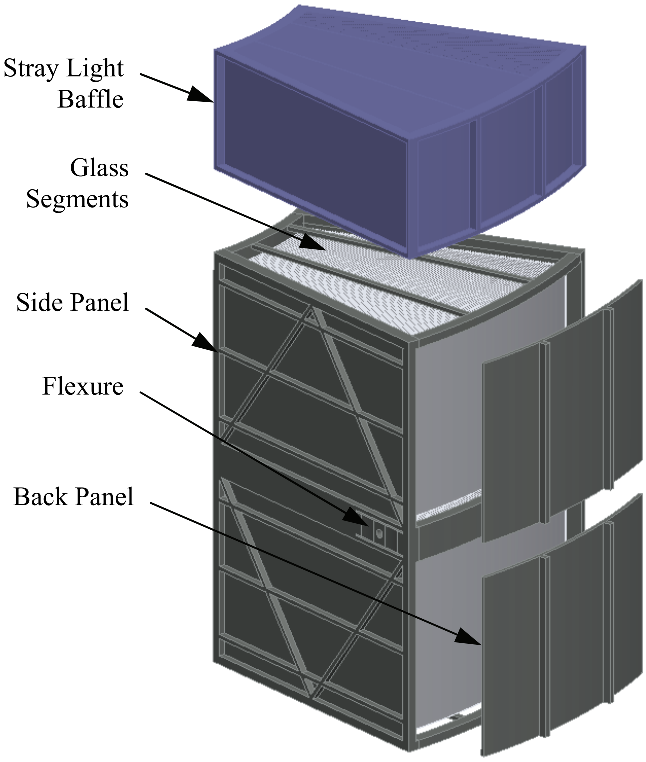

Figure 8 – Inner ring module assembly exploded view.

Module Structure

It is desirable to close out the module with structural panels on all but the axial ends, where x-rays must pass through. There are several advantages to closing out the module with panels:

- Panels protect the mirror segments from Foreign Object Damage (FOD).
- Panels can be thermally controlled to reduce thermal distortion of the segments.
- Panels provide lightweight structural stiffness needed to keep the segments aligned during integration, testing, and launch.
- Panels protect the mirror surfaces from direct impingement of acoustic energy, reducing launch stresses.

The assembled panels form the module structure which carries the mirror segments. Rails rigidly fastened to the interior of the modules are used to mount the bonding tabs to which the mirrors are bonded. Ribs are machined into the panels to stiffen them from acoustic distortion and efficiently transfer load to the flexures. A custom low Coefficient of Thermal Expansion (CTE) Titanium/Molybdenum alloy was selected for the module structure to closely match the CTE of the AF45 glass being used for the segments (6.0 ppm/C vs. 4.5 ppm/C). Other materials being considered include Carbon Fiber Reinforced Plastic (CFRP), Nickel/Iron alloys such as Kovar and Alloy 42, and various metal matrix composites.

Module Size and Layout

Modules were sized to adhere to the maximum circumferential mirror size and maintain a size and mass amenable to handling and testing while minimizing the total number of modules. It is desirable to minimize the module count in order to reduce the testing time, since each module will go through an extensive acceptance program.

The module layout was chosen based on allowing for an efficient design of the FMA primary structure. Since the degree of symmetry between the module rings determines where primary structure can exist, the design of the primary structure is constrained by the module layout. This issue will be discussed in more detail in the following section.

The current module layout is shown in Figure 9 (12/24/24). There are three rings of modules with 12 modules in the inner ring, 24 modules in the middle ring, and 24 modules in the outer ring. Using this layout, the average module has ~120 shells (240 segments), a mass of ~20kg, and overall dimensions of 360mm x 360mm x 500mm (about the size of a small two drawer file cabinet). The total mass of all modules including mirrors is ~1300kg.

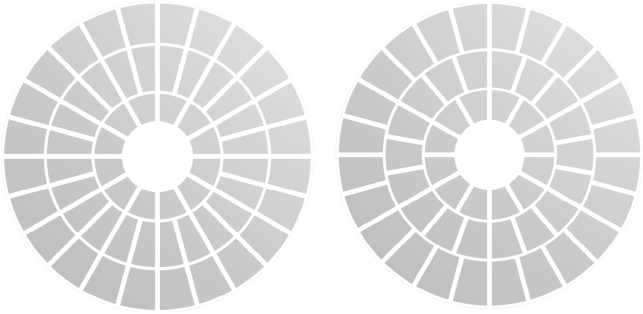

Figure 9 – Schematic of modular approach using 12/24/24 and 12/18/24 module layouts.

Stray Light Baffles (SLBs)

In order to prevent single bounce x-rays from falling on the focal plane, each mirror shell must have a baffle blocking incoming x-rays at certain critical angles (see Figure 10). The height of baffle needed is dependent on the cone angle of the shell. A SLB consisting of many thin aluminum foils in an aluminum frame will be kinematically mounted to each module to provide baffling for the mirror pairs. The SLB must be aligned such that the baffles obscure only the segment edges and do not detract from the effective area. The necessary foil thickness to effectively absorb the blocked x-ray is only 0.03mm. The foils may be individually formed from sheet stock or machined from a solid block using wire Electrical Discharge Machining (EDM).

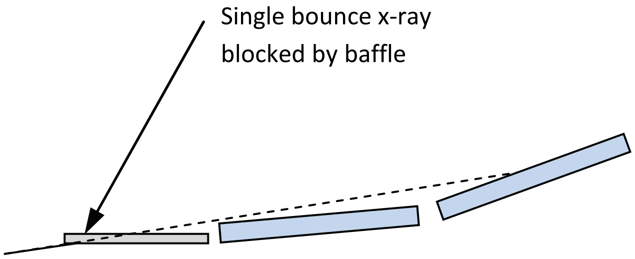

Figure 10 – Schematic of SLB.

4. PRIMARY STRUCTURE

The primary structure supports all the modules during integration, launch, and on-orbit operation. It is constrained to the spacecraft at as many as 24 points around the perimeter. A circumferentially thin but axially thick structure is desired to minimize the projected area of the structure in the focal plane in order to maximize the effective area of the FMA while supplying a high area moment of inertia to reduce bending. Figure 11 demonstrates the effect of structural thickness on effective area.

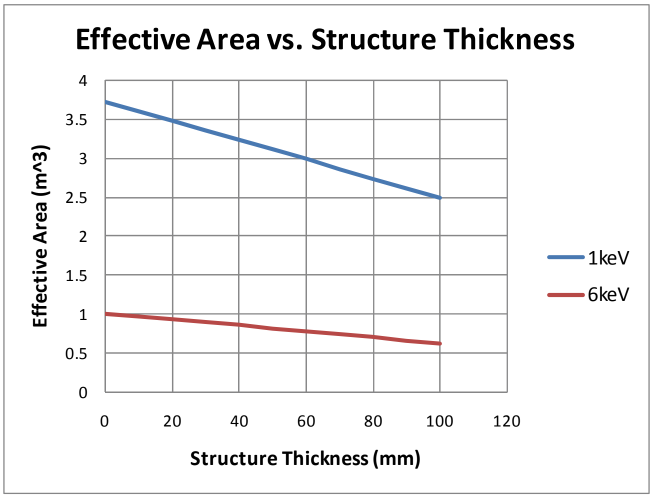

Figure 11 – Effective area at 1keV and 6keV as a function of circumferential structure thickness.

The 12/24/24 module layout described in Section 3 allows for 6 beams to fully span the FMA diameter and also allows for each module to have at least one attachment to the fully spanning beams. A 12/18/24 module layout was also investigated. This layout results in modules of more uniform size and mass as well as six fewer modules. However, the load path for some modules is very indirect, leading to a heavier FMA structure. Based on FEA of the two designs, the 12/24/24 layout yields a 25% lighter structure for the same 35Hz target first mode due to the more efficient load path. See Figure 12.

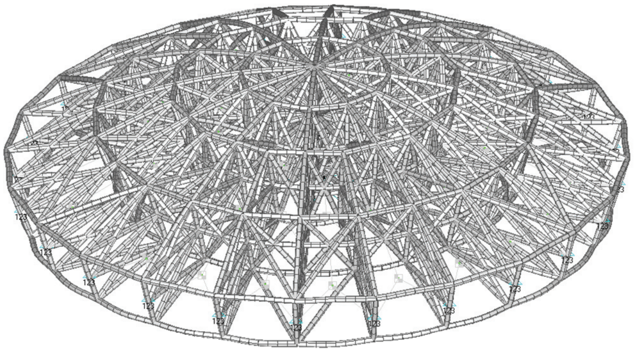

Figure 12 – Beam element FEM of FMA deformed at 35Hz first mode.

The current concept consists of main beams, secondary beams, and rings all machined into truss elements connecting in a central hub as shown in Figure 13. Due to the desire for a lightweight and high stiffness structure bridging a large opening, a truss structure is highly desirable. The design has the advantage of only having seven unique parts. All parts may be fabricated from 6061-T651. However, a stiffer and lower CTE material may be desirable in the future such as Titanium or CFRP to reduce the structure thickness and thermal deformation. The mass of the aluminum truss concept is ~400kg, bringing the total mass of the FMA to ~1700kg, the heaviest subsystem on the 6600kg spacecraft.

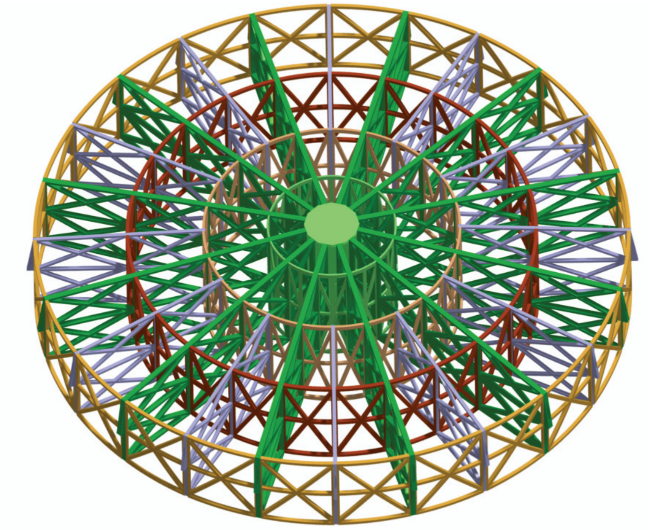

Figure 13 – FMA truss assembly.

Another design option, currently in its infancy, trades mass efficiency for increased effective area (see Figure 14). In order to minimize circumferential width and maximize stiffness and strength, all the area must be packed into a solid rectangular cross section. For a beam of fixed width, a solid rectangular cross section maximizes the area moment of inertia. Initial FEA results show this design results in a 60% reduction in projected area of the structure and a 40% increase in structure mass vs. the truss design for the target first mode. This design lends itself well to CFRP fabrication, which would help offset the mass increase.

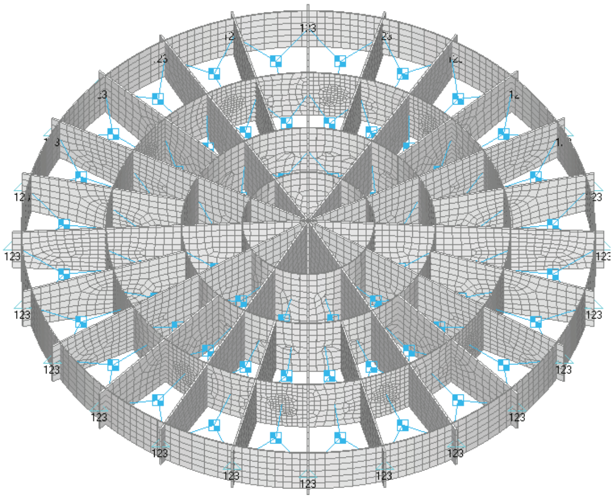

Figure 14 – Plate element FEM of FMA blade structure concept.

The FMA structure will be optimized to achieve the target frequency without yielding or buckling under the quasi-static design load, currently 10G in each axis. Much work remains to be done optimizing the structural members of the FMA and trading materials options.

5. THERMAL CONTROL

In order to keep the thermal distortion of the segments within acceptable limits (~1 arc-sec) during integration and on-orbit operation, the temperature of the FMA will be tightly controlled at room temperature. The maximum thermal gradients and bulk temperature change allowable are strongly dependent on the materials used for the module and FMA structure. Current estimates range from ±1°C to ±0.1°C. The allowable gradient will likely be different in the axial and radial directions since different mirror distortions are induced. Structural Thermal Optical Performance (STOP) analysis for the system is currently in process for the baseline design. Design and analysis is somewhat simplified by the L2 orbit and unchanging orientation of the spacecraft relative to the sun. Thermal control strategies under consideration, in part based on heritage X-ray missions such as Suzaku and XMM-Newton, include:

- Active control of module temperature with heaters to control temperature of segments through radiation and conduction.
- Active control of SLBs with heaters to control temperature of segments through radiation.
- Choice of thermally conductive materials for module structure and SLBs.
- Choice of CTE matched material for module structure.

- Use of thin aluminized plastic thermal shields on the inner ring of modules to buffer the module from the thermal environment of space.
- Use of thermal pre-collimators on the middle and outer rings of modules as a thermal buffer. Thermal shields cannot be used on these modules since the lower energy x-rays would be absorbed. See Figure 15.

Thermal distortion control of the FMA primary structure is less critical due to the kinematic attachment of the modules. The effect of thermal distortion of the primary structure will mainly be rigid body motion of the modules, to which the optical design is relatively insensitive. Even using an aluminum structure, a 1°C bulk temperature change results in a maximum thermal distortion of an acceptable .04mm.

6. INTEGRATION AND TEST

Integration and Test (I&T) of the FMA has been considered in design from inception since there will be significant challenges, especially in applying performance results in 1G to on-orbit performance. The I&T test flow is envisioned as follows:

Segments

(1) Slump segment.
(2) Cut to shape.
(3) Coat with x-ray reflective coating.
(4) Inspect segment for correct optical shape, mechanical size, and unacceptable surface or edge flaws.
(5) Repeat all steps for ~14,000 segments.

Modules

(1) Assemble module structure.
(2) Install, locate, and bond tabs onto module rail.
(3) Align segment using optical metrology.
(4) Bond segmenting to bonding tab.
(5) Repeat steps 2-4 for ~200 segments per module.
(6) Install SLB.
(7) Verify performance with optical testing.
(8) Perform random vibration testing and verify optical performance.
(9) Perform acoustic testing and verify optical performance.
(10) Perform thermal vacuum testing.
(11) Verify performance with x-ray testing.
(12) Repeat all steps for 60 modules.

FMA

(1) Assemble FMA structure.
(2) Install mass dummies and G-negate structure.
(3) Install modules one at a time and align using laser tracker and theodolite.
(4) Check common focus of modules with scanning pencil beam.
(5) Repeat steps 3 and 4 for 60 modules.
(6) Install thermal pre-collimators (see Figure 15).
(7) Perform random vibration testing and verify optical performance.
(8) Perform acoustic testing and verify optical performance.
(9) Perform thermal vacuum testing.
(10) Verify performance with x-ray testing.

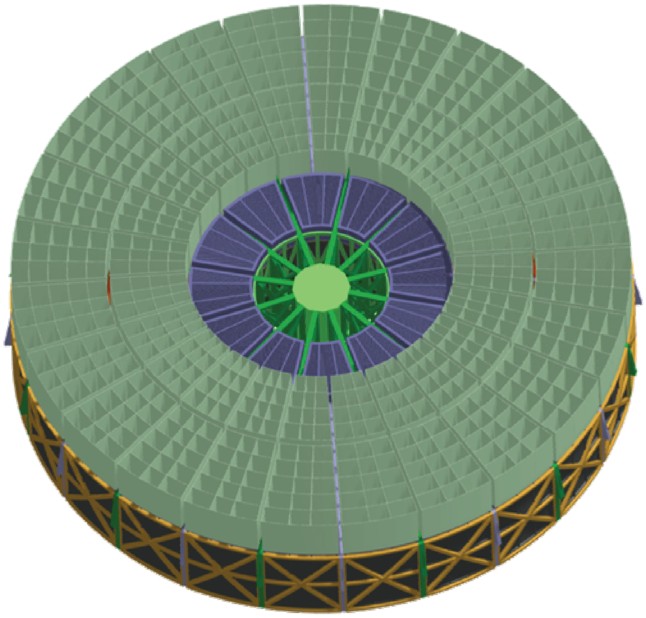

Figure 15 – Fully integrated FMA including thermal pre-collimators on the outer two module rings.

Qualification modules which are tested to greater environmental extremes are planned. Additional performance verification is also likely to be performed at the spacecraft level. Optical and x-ray performance testing will likely require new environmentally controlled facilities, especially at the FMA level due to the large diameter of the mirror.

7. CONCLUSIONS

The design of the IXO FMA requires new approaches to x-ray mirror design due to its high angular resolution and large effective area requirements. Some of the key challenges include bonding the mirrors into the module without distortion, designing the segment support for glass survivability, keeping the structure light enough to launch, and providing a large effective area. Standard mechanical design techniques such as FEM modeling and optimization, integrated optomechanical analysis, and materials test are being applied to this unique problem. Based on the concept presented in this paper, the design appears feasible without new technology development. The FMA design will continue to be matured through ongoing design and analysis iteration cycles. Much work remains ahead on this interesting and challenging x-ray mirror design.

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BIOGRAPHY

Ryan McClelland *is a Senior Mechanical Systems Engineer at SGT Inc. currently leading the design of the IXO Flight Mirror Assembly. His previous technology development experience includes work on aluminum foam core optical systems and non-linear effects of clearances in kinematic mechanisms. Ryan has also worked on flight missions with designs currently on orbit aboard the Hubble Space Telescope and Space Technology 5 spacecraft. He received a B.S in Mechanical Engineering, summa cum laude, from the University of Maryland.*

David Robinson *is the Lead Mechanical Systems Engineer of the IXO Project at the NASA Goddard Space Flight Center. He has worked on several scientific satellites including the Solar Dynamic Observatory, Swift, and the James Webb Space Telescope. He started his career with NASA Glenn Research Center in 1990 working on the International Space Station and microgravity space experiments for shuttle and the Russian Mir space station. He received a B.S in Aerospace Engineering from the University of Virginia, a M.S. in Mechanical engineering at Cleveland State University, and a M.S. in Space Studies at the International Space University in Strasbourg, France.*