Information for the

Technologies for Large Area Sub-Arcsecond X-Ray Telescopes

In response to
Request for Information (RFI)
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Prepared for:

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1. ORGANIZATIONAL INFORMATION

Northrop Grumman is pleased to provide this response to the government request for information for the Technologies for Large Area Sub-Arcsecond X-ray Telescope. In addition to our written response, we recommend and would welcome an opportunity to brief the MSFC team on our response and recommendations. Our organizational information is as follows.

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2. INTRODUCTION

Northrop Grumman brings extensive expertise and domain knowledge to mature and help implement technologies for next generation large, sub-arcsecond X-ray telescope systems.

Northrop Grumman was the prime contractor on NASA’s two flagship x-ray observatories, HEAO-B and Chandra, shown in Figure 1, and has the domain knowledge and general experience to aid the X-ray Surveyor (XRS) team with the development and integration of the various technologies that will contribute to a viable, mature concept of an x-ray optic delivering sub-arcsecond resolution and large effective area. Since the delivery of Chandra, Northrop Grumman Aerospace Systems (NGAS) and its business unit AOA Xinetics (AOX) have conducted numerous studies and, under internal and contract funds, conducted designs and analysis that bear directly on the subject of this RFI, the densely packed sub-arcsecond x-ray mirror array. This work was done for various mission concepts such a Constellation-X, Generation-X and non-space flight applications such as extreme ultraviolet (EUV) collection and synchrotron applications. We also draw on our experience from other precision optics and development programs, especially our long history in high power laser optics development.

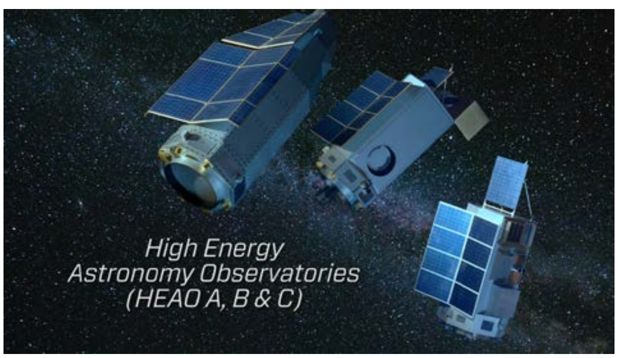

Figure 1. a) High Energy Astronomy Observatories A, B, and C; HEAO-B is the Leftmost of the Three b) Chandra X-ray Observatory

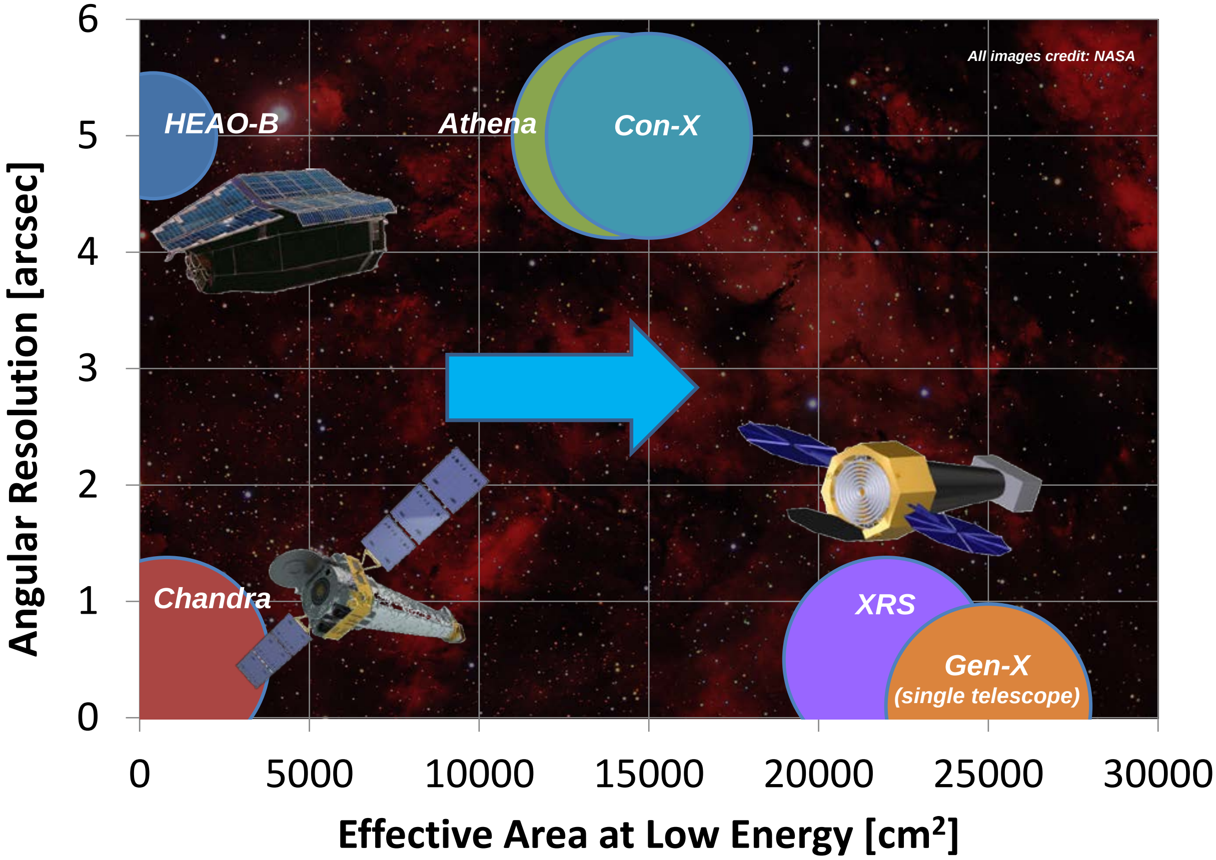

Figure 2. Trend in X-ray Observatories is Towards Greater Collecting Area

Figure 2 depicts flown and planned x-ray observatories, showing effective area versus angular resolution; energy range determines the size of the circle. This figure shows that the trend in the evolution of x-ray observatories is toward larger effective areas, with XRS reaching for Chandra-like imaging in addition to large collecting area (~50 times that of Chandra). Mirror system architectures can be broken into two classes. The first class rigidly sets the optics in place so that they remain aligned throughout the mission, as was done on HEAO-B and Chandra and is planned on Athena. The second class utilizes actuated shape and position control. The first class requires analysis and prediction of ground-to-orbit effects that must be sufficiently accurate to predict the final mirror state correctly. The second class only needs to verify that there is enough adjustability in both shape and position to cover these effects. Given the extremely large number of degrees of freedom (many times that of James Webb at ~ 70 million degrees of freedom) likely in a multi-segmented telescope such as XRS, the models of the XRS will take substantial time (money) to run and converge, maintaining the current cost paradigm. Use of an active system that can adjust shape and position as necessary requires only that the factory-to-orbit effects be bounded, a less stressing set of analyses and a potentially more convergent engineering process, potentially breaking the current cost paradigm, resulting in a lower development time and cost. The selection of active or passive mirror system will ripple through the design, manufacturing and testing of the optics and should be considered at the system or mission level to avoid local optimization around a globally sub-optimal solution.

Planning the analysis to locate the globally optimal solution should be an early set of tasks in the XRS study and one to which NGAS can make a substantial contribution.

Each of the seven topics requested in the RFI is addressed in Sections 3A through 3C. Section 3D contains additional technology areas that we feel should be considered as part of the development of a large effective area sub-arcsecond x-ray telescope. We invite follow-on discussions leading to the selection of the optimal design of the large area, high resolution mirror assembly.

3. TECHNOLOGIES

A. High-resolution light-weight mirror fabrication processes, Mounting and assembly schemes, Alignment, Metrology, and Mass production approaches

The RFI requests information regarding high-resolution light-weight mirror fabrication processes, mounting and assembly schemes, alignment, metrology and mass production approaches as separate technologies. Based on our experience in studying the Constellation-X soft x-ray telescope and other complex optical systems, we recommend that all of these factors be studied and examined together to produce a coherent and complete systems solution.

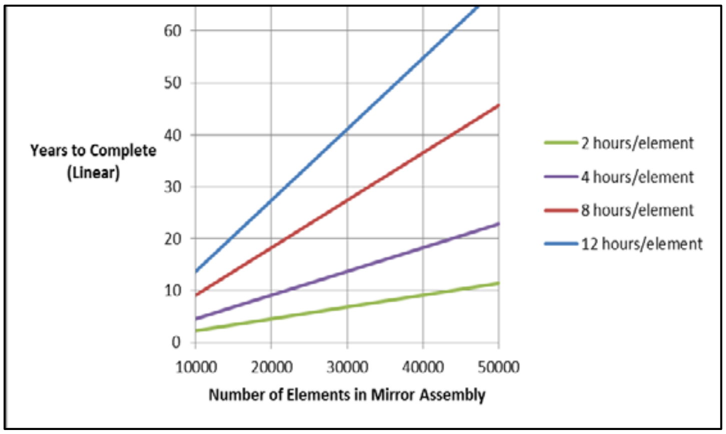

Figure 3. Time to Construct Mirror Assembly

Given that the number of individual pieces for the flight array will be in the many thousands, thought and care must be given to production concerns so as to minimize in process assessment and decision gates. For this discussion, a piece is any identifiable element of hardware needed, such as mirror elements, bonding sites, tabs and structural modules, latches, fasteners, intrinsic actuators, etc. If we consider the simplest linear model, where each of the N pieces takes time *t* to be produced, coated and installed, then the total (linear) time to make the mirror array is the product of the time per element and the number of elements, Nt. In Figure 3, N is varied from 10,000 to 50,000, and *t* is varied from 2 hours per element to 12 hours. The y-axis shows the total number of labor years needed to complete the assembly, Nt. If the work is broken down into m parallel lines, then the calendar time to complete the array is simply Nt/m. It can be appreciated given the large number of parts that *t* should be made as small as possible.

Several conclusions can be drawn from this simplified analysis. First, to achieve an executable program, the manufacturing process must be as rapid as possible with little to no analysis and decision making required. This implies that the process should be nearly completely automated, so as to be able to execute repeated tasks with great precision and speed. All of the production should be in a single location, to minimize time spent in transit. Moreover, these production lines would likely be working around the clock from the very start. Careful and deliberate thought should be given to maintenance and servicing, so as to maintain a high cadence of efficient productions. For such an "x-ray telescope factory" to be viable, all of the elements in the title of this section must be considered together as part of a system solution to realize the "x-ray telescope factory." NGAS and AOX have experience in optical production problems of this nature.[i]

B. Mirror coating processes and methods for stress mitigation

Northrop Grumman and its many partners and subcontractors have a long history of development of high performance optical coatings. This history includes the development of coatings for precise optics where coating stress plays a significant role in the determination of optical figure.[ii] A necessary element for dimensionally thin optics for x-ray applications is the management of stress. Although the RFI asks for the mitigation of stress, we have found in our work in laser and EUV that it is the variance in stress of the coatings that leads to uncertainty in the surface figure. Our work in laser and EUV optical coatings has focused not only on the reduction of stress, but on processes that also minimize the variance of that stress. This is done by careful control of the temperatures of the substrate, coating materials and environment, and results in a determinative manufacturing process.

C. Static and active post-fabrication figure correction techniques

To achieve the desired sub-arcsecond resolution, active control of the grazing incidence mirrors will likely be required.[i] The selection of the active optics approach must be chosen so that it not only improves mirror figure but can be incorporated into the mirror without adding substantial thickness or structure that would obscure the path of X-rays within the annular gap between adjacent nested mirrors and thereby reduce effective area. Northrop Grumman–AOX has been developing integrated lead manganese niobium (PMN) electrostrictive modules in which regions can be individually addressed, providing considerable displacement as well as both low and high spatial frequency figure control.

The basic concept is shown in Figure 4. Essentially, thin layers of PMN tape cast ceramics are co-fired into planar arrays to produce actuation parallel to the surface (SPA). The ground electrodes are continuous within the sheet, but the signal electrodes are discrete to a particular region and can be independently addressed. After firing, the modules are machined, bonded to a suitable substrate and electrodes are attached. The planar geometry of the arrays permits a wide variety of geometric electrode patterns which can be tailored for a particular optical application. Furthermore, because the PMN material is contiguous with the mirror face sheet and not attached to a reaction surface as in a conventional deformable mirror, considerable displacement can be achieved. What is of central importance to grazing incidence optics, the actuator arrays are on the back side of the mirror and depending on nested mirror spacing, do not add substantially to obscuration or vignetting. For development work, individual wires are attached to the individual actuation sites but these can be replaced by flex circuits or screen printed electrodes as shown in Figure 5.

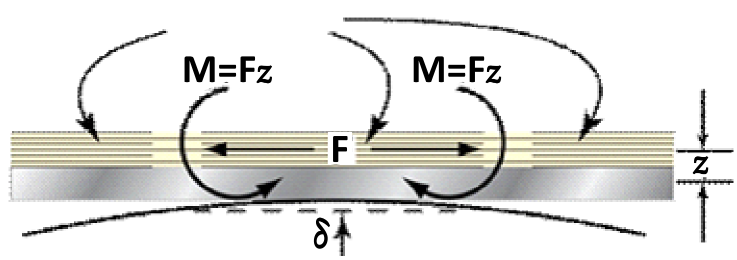

Figure 4. Surface Parallel Actuation Deformable Mirrors

We selected as an initial design a simple SPA geometry with an actuation spacing of about 15 mm providing an areal density of slightly less than 6000 actuation sites per m^2. The model was based on an existing prototype mirror that could serve as a subscale test object to verify actuator influence functions and mirror figure control.

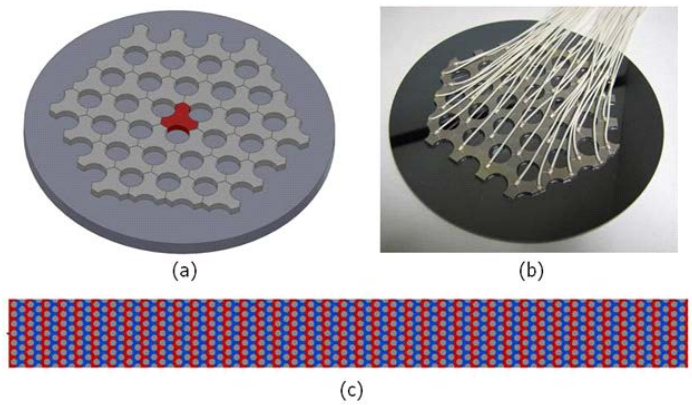

Figure 5. Finite element analysis model (c) and test optic component (b). Diagram (a) shows region (red) that constitutes one actuator within lamellar structure.

The model and prototype mirror are shown in Figure 5. The mirror membrane was made of optical grade single crystal silicon a few mm thick and the actuator array bonded to the back was Northrop Grumman–AOX PMN-PT electrostriction ceramic of order 1 mm thick. The actuator array was bonded to the silicon under a bias voltage to provide both negative and positive bending with control voltages above and below bias. We anticipate needing to make this stack thinner for a flight mission and believe that this represents a viable proposition. This density provides adequate figure control at low spatial frequencies without risking an increase in uncorrectable error at the actuation spacing which correlates to the mid spatial frequencies. A finite element model 1 m long by 0.1 m wide was built. The width of the model was selected to economize computer resources and run times. The model had 623 actuators with approximately 8 actuators across the width, giving good figure control along the center of the panel in the axial direction, the primary figure of merit we were trying to achieve relative to Gen-X.

Figure 6 shows residual error plots generated from our finite element modeling. We first analyzed for bending of the plane to match the outermost primary reflector prescription in the axial direction. We used a 2nd order Legendre polynomial (parabola) having the same axial sag as the Gen-X prescription to simplify analysis rather than the exact prescription. This polynomial captures the main low spatial frequency shape of interest. This is the most important criterion for obtaining the 0.1 arc-second resolution goal of Gen-X. The residual error of the entire surface was 40 Å rms. This is below the 65 Å rms error requirements over the spatial frequency bandwidth of 0.001 to 0.01 mm^{-1} suggested by Reid *et al*[iii] and demonstrates that active control is a viable candidate for XRS.

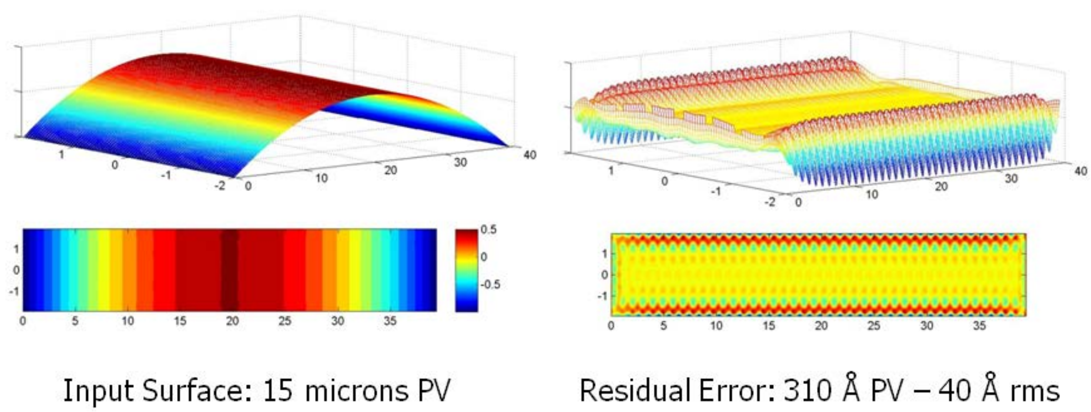

Figure 6. Residual error from actuating a plane surface to the axial figure required of one of the primary mirror reflectors of the Gen-X concept

D. Other relevant technologies

In addition to the technologies requested in the RFI, there are additional technologies and expertise that are required for a proper and complete development and implementation of the desired x-ray optic.

1) Vibration Suppression Technology

During the Chandra development, dynamics analysis revealed that the disturbance from the reaction wheels was exciting the mirrors and causing a large degradation in imaging performance. To rectify this problem, isolation was added to the reaction wheels. The dynamic response of the Chandra high-resolution mirror assembly (HRMA) was relatively simple, so a simple passive, damped spring system was sufficient to avoid deleterious effects on performance. For the much more numerous and vastly thinner shells under consideration for XRS, it can be intuited that the dynamic response will be far more complex in terms of number of nodes. Based on this increase in complexity (and perhaps nonlinearity) it is expected that a more aggressive tiered approach to vibration control will be required.

NGAS has experience in these damping and isolation technologies, including viscoelastic constrained layer damping and magnetic tuned-mass damping of a mirror segment and passive isolation of spacecraft disturbances. All of these techniques are within the NGAS experience base.

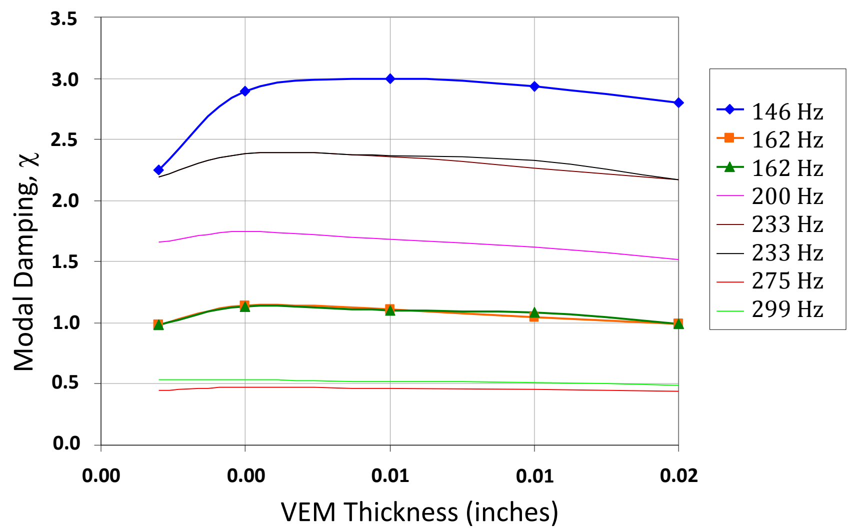

Figure 7. Damping performance vs. VEM thickness. Legend shows original un-damped natural frequency.

Viscoelastic materials (VEM) have properties which are temperature and frequency dependent. Material selection and overall damping results depend on the expected temperature range and modal frequencies of interest. The viscoelastic layer design should maximize modal strain energy in the VEM layer for optimal damping. A stiff constraint layer can help increase strain in the relatively soft viscoelastic material by increasing shear forces in the VEM layer, and stiffening the constraint layer further enhances the shear strain. Of course, damping performance must be balanced against resulting weight increase and higher natural frequencies. NGAS has investigated the effects of several damping treatment configurations on the overall damping performance of a simple tube, including constraint layer stiffness, segmentation of VEM and constraint layer, number of segments and overlap, number of layers in VEM layup, and the use of two VEM to improve damping performance over a broad temperature range. It is possible to achieve modal damping values better than 5% of critical in a certain temperature range by carefully designing the viscoelastic and constraint layers, as previously demonstrated by analysis and tests, and the results are shown in Figure 7.

A magnetic damper uses the electrical phenomenon known as eddy current damping, where a conductor is exposed to a changing magnetic field due to relative motion between the magnet and the conductor, causing the flow of electrons within the conductor, see Figure 8.

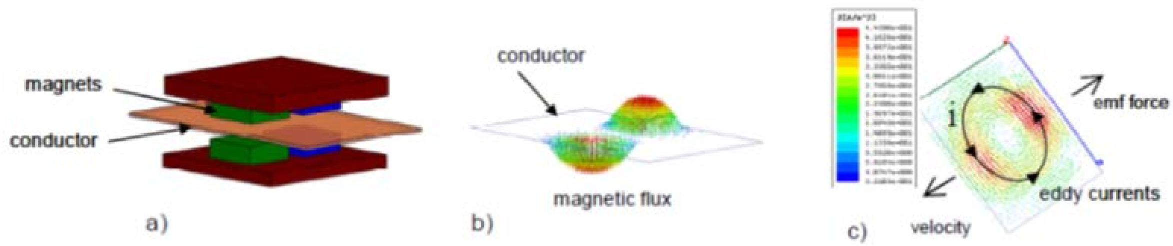

Figure 8. a) Maxwell 3D fine element model of magnetic damper. b) Magnetic flux distribution at the conductor center plane (from magneto-static analysis). c) Eddy currents generated on conductor as it moves at a constant velocity (from transient analysis).

These eddies of current create effective poles in the conductor, resulting in a net force which opposes the motion. The stronger the magnetic field, or the lower the electrical resistivity of the conductor, the greater the eddy currents and resulting viscous damping force. Several material characterization tests have been performed since both magnet and conductor properties are temperature dependent, and test results show damping performance remains linear at cryogenic temperatures down to 15K and over a large range of amplitudes. For this application, the magnetic tuned-mass dampers were designed to address both acoustic vibrations and jitter with minimal additional mass. The dampers were placed at mirror locations showing significant modal kinetic energy (near the mirror edges). Results show that properly optimized tuned-mass dampers can provide better than order of magnitude reduction of resonant responses while adding negligible mass (less than 3% of total mirror mass).

The reaction wheel assembly (RWA) isolator (RWAI) developed for Chandra, shown in Figure 9, is a flight proven technology and design that drastically reduces the level of RWA-generated dynamic disturbances transmitted to the X-ray optical train. The key component of the RWAI design is the set of six machined spring elements that utilize a bonded viscoelastic material (VEM) to provide damping. These spring elements serve as the interface between two larger brackets. The upper bracket, or cradle, attaches to the reaction wheel, while the lower bracket interfaces with the spacecraft. Aligned in a geometry commonly known as a Stewart platform arrangement, the six springs essentially function as a truss system, with the RWA disturbance loads being transmitted to the spacecraft as axial tension/compression spring forces. The attachment points of the springs to the brackets are designed so that each spring acts as a two force member. Transverse bending effects in the springs are small and are alleviated via internal flexures coaxially aligned with the two attachment ends.

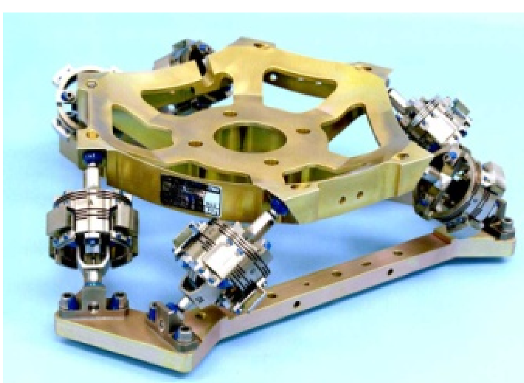

Figure 9. TRL 9 Reaction Wheel Assembly Isolator (RWAI) for reduction of jitter

Consequently, the assembly behaves approximately as a statically determinate kinematic mount. The line of action for each pair of springs intersects at the plane that contains the isolated mass center and, therefore, results in a decoupling of all fundamental modes of the combined assembly except the torsional bending mode. The angular orientation of the springs with respect to the cradle and bottom bracket is selected such that the three translational and two rocking mode frequencies are equalized. The effective axial stiffness of the springs determines the fundamental frequency of the isolator assembly. The Chandra RWAI axial stiffness was designed to meet an analytical 9 Hz cutoff frequency followed by a -12 dB/octave roll-off, and was chosen to correspond with the relevant reaction wheel speeds and excitations above the 8.3 Hz (500 rpm) minimum operating speed. Each RWAI spring/assembly consists of three primary flexile elements. The parallel flexure/VEM load path allows shared strain energy, while the series flexure load path reduces the cutoff frequency and desensitizes the design to potentially large changes in shear stiffness of the VEM due to temperature fluctuations. Damping action in the isolator elements is obtained by shearing four small VEM pads. Material properties and dimensions were selected to yield a 5% modal damping ratio for the aforementioned isolator/reaction wheel system resonant frequencies at nominal operating temperature.

In addition to the passive systems described above, NGAS has also a number of active technologies for damping control should that become required.

2) Systems Engineering

Another critical expertise that NGAS can contribute to the X-ray surveyor team is a disciplined systems engineering approach, backed by program experience on Chandra and other relevant domain knowledge. Achieving the right design for the mirror array desired will be a balancing act among many factors, and finding the global optimum is the central question of systems design. This process will make sure that the choice of mirror technology can operate and survive in all of the environments to which is will be subjected, especially shipping and launch, not just the benign flight environment.

3) Coating Design and Optimization

During the TRW Extreme Ultra-Violet collector program, from the early 2000s, a graded thickness Si/Mo coating designed for 13.2 nm wavelength was developed with approximately 1% coating thickness error and was demonstrated on an optic ~90 cm in diameter with a very large sag. This process was developed by TRW and partners, demonstrating the ability to repeatedly apply coating in complex situations and achieve acceptable results. This is proof of concept for a tailored thickness coating that can be used

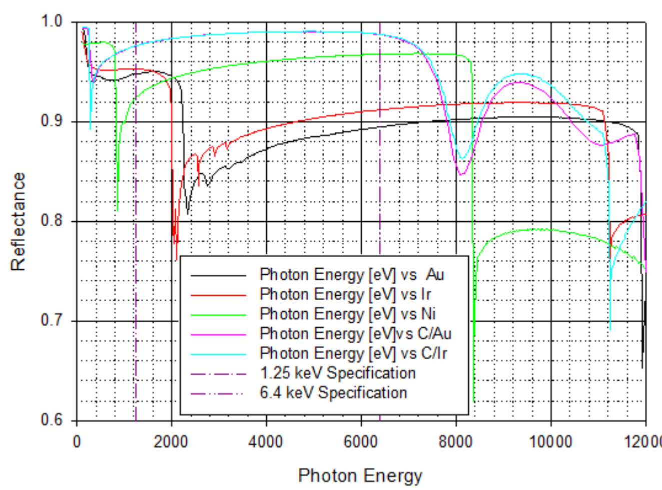

Figure 10. Reflectance vs. Photon Energy for Different Surface Coatings

to vary stress in the coating should it be required. Figure 10 shows a plot of reflectance as a function of photon energy for several different surface coatings.

During the Constellation-X studies, methods of optimizing coating design for each shell (or small families of shells) showed the ability to increase the effective area significantly, from 10-25%. This increase in effective area can deliver greater effective area for a fixed number of elements or a means to reduce part count in any flight design.

4) Modal Image Optimization (MIO)

Actively controlled mirror segments require a method for sensing and maintaining the optimal figure of each segment as well as the mirror as a whole. Conventional adaptive optics systems have used many different wavefront control techniques including Shack-Hartmann sensors, Dispersed Fringe and Dispersed Hartmann sensors and Phase Diversity. Each of these methods has limitations in dynamic range or resolution and typically requires dedicated components that add to system complexity. Additionally, since the wavefront sensor measures quantities which are only indirectly related to the image quality at the science camera, calibration between the two is necessary and critical to system performance.

For the XRS observatory, a wavefront control technique which was recently developed and demonstrated by Northrop Grumman–AOX could provide a means for controlling active mirror segments without the need for additional hardware. The technique would use the x-ray imager itself to sense and optimize the mirror figure. Results obtained from simulations and laboratory demonstrations indicate that the method has a wide dynamic range with low residual wavefront errors. NG-AOX refers to this technique as Modal Image Optimization (MIO).

The MIO process is comprised of several steps. First, a Karhunen–Loève decomposition is used to generate the “natural” modes of the mirror system. Small perturbations of each mode are then applied to the mirror segments in turn and the resulting effect on an image metric (e.g., contrast) is measured using images from the science imager. Multiple sub-images across the field are used to define a metric which optimizes the image over the entire field. The mirror shape is then updated and this is repeated in an iterative “hill climbing” process.

Given that the MIO method is iterative, it is not applicable to all adaptive optics scenarios; however, it is highly applicable to compensation of slowly varying thermal, mechanical, and gravitational disturbances in a space-based optical system. The MIO method works equally well with point sources and extended objects and has even been extended to the problem of segment phasing in multi-segment telescopes.

4. SUMMARY

Northrop Grumman, its business units and partners are eager to engage to make the large area sub-arcsecond x-ray telescope a reality and to enable the exciting science program plan. Our team has the experience in the technology areas requested by the RFI. Moreover, while the technologies for high-resolution light-weight mirror fabrication processes, mounting and assembly schemes, alignment, metrology, and mass production approaches are important, we believe that those technologies need to be considered and matured as a system (i.e., as a whole) to ensure critical performance and science objectives are satisfied. For instance, a desire to fabricate light-weight mirror segments may lead to extremely thin mirror segments that cannot be mass produced or would be extremely difficult to mount and align. Furthermore, such a light-weight mirror segment may not be capable of surviving transportation or launch environmental conditions.

In addition to the requested technologies, we have discussed several key areas of concern in developing a viable large area sub-arcsecond x-ray mission concept, including highly matured (TRL 8+) vibration suppression techniques that are currently being implemented on JWST, a disciplined systems engineering approach based on 50+ years of space systems development including Chandra and other relevant program experience, and modal image optimization utilizing NG-AOX's adaptive optics expertise. The Table below summarizes our TRL assessment for the technologies needed to develop a large area sub-arcsecond x-ray system.

Technology	Current TRL	TRL in ~2020	Comments
High-resolution light-weight mirror fabrication processes	4	6	Individual mirrors have been made to near spec level using lab processes; needs investment
Mounting & assembly scheme	3	6	Laboratory demonstration; needs investment
Alignment	2/3	6	Module to module alignment needs investment
Metrology	3	6	Automated metrology needs investment
Mass production	1/2	6	Investment needed for viable concept development
Mirror coating processes and methods for stress mitigation	4	6	One-off coating demonstrated but requires coating as part of an integrated manufacturing process
Static and active post-fabrication figure correction	4	6	Northrop Grumman-AOX demonstrated technology
Viscoelastic materials (VEM) damping	9	9	Flown on Chandra; implemented on JWST
Magnetic tuned mass damping (MTMD)	8	9	Implemented on JWST; TRL 9 after 2018
High frequency disturbance isolation (e.g., RWAI)	9	9	Flown on Chandra and implemented on JWST
Modal image optimization (MIO)	3	6	Investment needed to demonstrate applicability for XRS

As presented in this RFI response, our team has the right balance of experience and expertise to support the definition of an executable X-ray Surveyor mission concept, and we look forward to our continued partnership with MSFC and the high energy astrophysics community.

References:

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[ii] J.W. Arenberg, et al, "Uncooled Optics Technology", Presented at IEEE/Laser and Electro Optical Society Topical Meeting on Electro-Optics in Space, 2000, Miami, Florida (Invited talk)

[iii] P. Reid, *et al.*, "Constellation-X to Generation-X: Evolution of large collecting area, moderate resolution grazing incidence x-ray telescopes to larger area, high resolution, adjustable optics" SPIE Proc., vol. **5488**, 325 (2004).