Adjustable Optics Technology Roadmap

Table of Contents

This document presents a roadmap for advancing the critical technology of the Adjustable Segmented Optics for the *Lynx* X-ray Mirror Assembly (XMA). The technology roadmap provides a description of the Adjustable Segmented Optics technology elements requiring development, identifies the maturation plan's key milestones, and provides the associated schedule, cost, and risk. Adjustable Segmented Optics is one of three optics technologies under consideration for the *Lynx* mission. The XMA is a key contributor for the *Lynx* mission, as it provides the large effective area and exquisite angular resolution over a large field of view to enable the science goals and objectives.

1 Introduction

This technology roadmap is a planning tool that lays out the steps, activities, and resources needed for maturing the Adjustable Segmented Optics from the current State of the Art (SOA) to Technology Readiness Level (TRL) 5 by project Phase A, and TRL 6 by Preliminary Design Review (PDR). This roadmap also ensures that the optics system meets the scientific performance and programmatic requirements for the *Lynx* Observatory. Additionally, this document provides the technology maturation schedule, cost, risks, and mitigation plans for technology maturation. The *Lynx Adjustable Segmented Optics Technology Roadmap* is considered a living document and will be updated as progress is made or as conditions affecting the plan become known.

The development of the Adjustable Segmented Optics is actively funded through NASA research grants.

1.1 Lynx Optics Overview

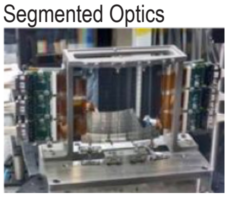
The XMA must provide a large effective area and exquisite angular resolution over a large Field of View (FOV). Anticipating future launch vehicle capabilities, the XMA and supporting structures must be designed to achieve low mass per unit collecting area, possess the structural integrity to withstand launch conditions and the environment of space, and maintain its optical precision throughout the life of the mission.

The large effective collecting areas are achieved by nesting large numbers of thin, lightweight mirror pairs that fully utilize the available aperture, resulting in a mirror assembly comprised of hundreds of full-circumference, or thousands of segmented mirror elements. The high angular resolution requires precision polishing, alignment, bonding of the mirror elements, and careful structural and thermal design to preserve optical performance throughout calibration; Observatory Assembly, Integration, and Test (AI&T); launch; and science operation.

Adjustable segmented X-ray optics is a technology designed to enable the fabrication of high-precision, lightweight X-ray optics for large aperture space-based missions. Conceptually, the approach is simple: rather than fabricate lightweight mirrors to final required performance tolerances, instead fabricate less precisely figured mirrors with a figure that can be corrected to the desired precision after assembly. The technology is currently at TRL 2–3 as assessed by the most recent Physics of the Cosmos (PCOS) Annual Technology Report. More recent than that, SOA now self-assesses at TRL 3.

The scientific requirements for the *Lynx* Adjustable Segmented Optics are shown in Table 1.

Table 1—Adjustable optics mapping to *Lynx* science goals and drivers.

Technology	Science Theme/Goal	Performance Driver	Mirror Requirements	
			Property	Value
High-resolution, large-area, lightweight X-ray grazing incidence mirror assembly with Adjustable Segmented Optics 	Observe the Dawn of Black Holes	Observe progenitors of supermassive black holes at their seed stages or soon after	Angular resolution	0.5 arcsec on-axis (assembly level)
			Grasp	600 m^2 $arcmin^2$
	Reveal the Invisible Drivers of Galaxy and Structure Formation	Observe the state of diffuse baryons in galactic halos	Effective area	2 m^2 at 1 keV
		Understand the energetics, physics, and the impacts of energy feedback	Outer diameter	3 m^2 (max)

1.2 Adjustable Optics Description

1.2.1 Overview of Technology

Adjustable segmented X-ray optics is a technology designed to enable the fabrication of high-precision, lightweight X-ray optics for large aperture space-based missions. Conceptually, the approach is simple: rather than fabricate lightweight mirrors to final required performance tolerances, instead fabricate less precisely figured mirrors whose figure can be corrected to the desired precision after assembly. This approach is attractive for several reasons. First, initial fabrication tolerances are eased. Admittedly, this easing comes at the expense of the implementation of correction technology. But, for a large-area mission such as *Lynx* with many thousands of mirror segments, reduced segment fabrication requirements may result in significant reduction in development cost and schedule. Second, due of *Lynx*'s large area requirements, the mirrors are of necessity much lighter than previous high-accuracy imaging missions such as *Chandra*. The *Chandra* High-Resolution Mirror Assembly (HRMA) produced 1,200 cm^2 effective area at 1 keV for a HRMA mass of ~1,600 kg, or 0.75 cm^2/kg. *Lynx* requires >20,000 cm^2 at 1 keV area at less than 2,000 kg, or >10 cm^2/kg. In fact, the problem is more difficult, because the envelope for the XMA cannot exceed ~2.5 times that of the HRMA, so the mirrors must be much thinner than *Chandra*'s to meet the area to mass ratio required. Thinner mirrors are less stiff, and less stiff mirrors deform more readily when mounted into an assembly, degrading imaging performance. The demonstrated best imaging thin mirrors successfully flown to date include the ~1-arcminute-resolution, 0.2-mm-thick *NuStar* optics and the 1-mm-thick, 15-arcsecond *XMM-Newton* optics. In either case, the resolution achieved is the equivalent of being legally blind in comparison to *Lynx* requirements (and existing *Chandra* performance). The adjustable, post-fabrication figure correctable approach breaks this paradigm of performance being mirror stiffness-dependent. Third, related to the significantly reduced *Lynx* mirror stiffness relative to *Chandra*, adjustable optics technology can enable on-orbit figure correction of X-ray mirrors. In-situ figure correction is a standard technique in active (Optical Infrared (OIR)) applications, operating at relatively high bandwidths (>10 Hz) to remove the blurring effects of atmospheric turbulence and motion. Adjustable X-ray optics borrow from this concept in terms of an extremely low bandwidth (~micro-Hz) correction to adjust for a potentially changing thermal environment on-orbit and the resulting imaging degradation due to thermally induced distortions of thin, flexible mirrors.

Motivations for developing adjustable X-ray optics are simple:

- Potentially ease segment fabrication requirements, reducing segment cost and schedule.
- Correct thin segment mounting-induced distortions that degrade imaging performance.
- Correct thin segment distortions resulting from X-ray reflective coating stresses and any potential time evolution of those stresses.
- Correct thin segment distortions over time resulting from (mounting) epoxy creep.
- Provide the on-orbit capability to correct for post-launch environmental (temperature) changes and potential long-term effects of epoxy creep and coating stress evolution.

To date, the developmental implementation of our technology was to sputter deposit a thin (1.5 µm) continuous film of piezoelectric material—lead zirconate titanate, or PZT—on the back (convex) surface of a 0.4-mm-thick slumped glass (Corning Eagle XG^{TM}) X-ray mirror segment. Between the PZT layer and the mirror is a deposited continuous film (~100 nm) of conducting metal such as platinum, which serves as a ground electrode. On top of the PZT layer is lithographically printed pattern of individually addressable top electrodes. Applying a low (≤10 V) DC voltage to the top electrode (i.e., across the thickness of the PZT) produces a stress in the piezoelectric material in the plane of the material. The stress is spatially confined to the lateral extent of the top electrode. The resulting stress introduces a localized bending of the mirror analogous to the "bimetallic effect," which is called an "influence function," or I/F (in the tradition of the active optics field). The application of "in-plane" (of the mirror surface) stress enables a change in mirror shape without the need for a heavy, stiff reaction structure, allowing dense nesting of the mirror shells. The process of correcting the mirror figure starts with calibrating the I/Fs for each piezoelectric "cell," defined by its top electrode, and then optimizing the set of voltages that needs to be applied to the set of cells to minimize figure error. Nominally (based upon simulations and experiments), the expectation is that for starting a mirror figure of ~5- to 10-arcseconds Half Power Diameter (HPD), each individual segment (depending upon figure error power spectrum) can be corrected to better than 0.5 arcseconds HPD for a segment pair. The starting figure requirement is within the range achieved in the past by the NASA Goddard Space Flight Center (GSFC) group using Schott D-263 glass for the *International X-ray Observatory* (IXO) and has been achieved at the Smithsonian Astrophysical Observatory (SAO) using Corning Eagle.

The recent selection of single crystal silicon as the baseline design for *Lynx* has changed the focus of development. Current work to develop the technology attempts to sputter deposit a thin (1.5 µm), continuous film of piezoelectric material on the back (convex) surface of a 0.5-mm-thick, single-crystal silicon X-ray mirror segment. The switch from slumped glass substrates to single-crystal silicon substrates is recent, but advantageous. Between the PZT layer and the mirror is a deposited continuous film (~100 nm) of conducting metal, such as platinum, which serves as a ground electrode. On top of the PZT layer is a lithographically printed pattern of individually addressable top electrodes. Applying a low (≤10 V) DC voltage to the top electrode (i.e., across the thickness of the PZT) produces a stress in the piezoelectric material in the plane of the material. The stress is spatially confined to the lateral extent of the top electrode. The result of the stress introduces a localized bending of the mirror analogous to the "bimetallic effect," which is called an "influence function, or I/F" (in the tradition of the active optics field). The application of "in-plane" (of the mirror surface) stress enables a change in mirror shape without the need for a heavy, stiff reaction structure, allowing nest mirror shells to be deeply nested. The process of correcting the mirror figure starts with calibrating the I/Fs for each piezoelectric "cell," defined by its top electrode, and then optimizing the set of voltages that need to be applied to the set of cells to minimize figure error. Nominally (based upon simulations and experiments), the expectation is that for a starting mirror figure of ~2- to 5-arcseconds HPD for each individual segment (depending upon figure error power spectrum), this can be corrected to better than 0.4-arcsecond HPD for a segment pair. The starting figure requirement is well within the range achieved by the GSFC group in producing silicon segments for *Lynx* development.

Advantages of changing mirror substrates from slumped glass to single crystal silicon:

- Silicon is the industry-standard substrate for PZT deposition—commercial "foundries" produce trillions of PZT in silicon devices every year.
- Silicon enables higher PZT annealing temperatures than glass. This results in (1) approximate doubling of piezo coefficient, which "cancels" out loss in correction range due to higher stiffness of silicon with respect to glass; and (2) reduced annealing stress non-uniformity and reduced impact of annealing stress due to higher stiffness.
- Eliminates the contamination control issues impacting thermal forming of glass.

Of course, implementing this technology is more complex than this. Electrical pathways to each piezo cell must be printed on each mirror's back surface so that voltage can be applied to the top electrodes. Simulations have demonstrated improved correction performance with smaller cells with little space between them, so is there room to route these electrical traces? And if the piezo cells get smaller, how many are there on any single mirror? How many wires must be attached to each mirror? Fortunately, all these problems have been solved at various levels in the microelectronics industry. To place the piezo cells as close together as possible, an insulating layer will be deposited above the top electrodes with conductive paths—vias—through the insulating layer. This allows all the electrical traces to be routed on top of the insulating layer without requiring the traces to conform to only the spaces between the electrodes. And while the expectation is that between 400 and 1,600 piezo cells will be needed per mirror segment, the same principles of active pixels and row-column addressing will be employed on LC displays (which have in excess of 4 million separately addressable elements on them), limiting the number of connections to between 41 and 81 (including the ground connection). This is realized by lithographically printing a set of ZnO-thin film transistors on each piezo cell, acting as the command gates to open or close the switch to apply voltage to a particular cell. Of course, the plan is not to attach 40 to 80 individual wires to each mirror. Ultimately, the plan is to directly print an Application-Specific Integrated Circuit (ASIC) on each mirror segment that would receive a (n ~50 bit) digital word from a central command bus containing the address of a particular piezo cell (which mirror segment, which cell on that segment) and the desired voltage for it, which the ASIC would suitably distribute by controlling row-column addressing gates—in principle identical to digital TVs, laptops, and smartphone screens. Due to the long RC decay time of each cell (50–100 seconds), voltage updates need only be done for each cell at ~10 Hz. Such an approach is already utilized in the LCD industry, including for smartphone (and before that, "flip" phone) displays, employing a microelectronics technology called "chip-on-glass," or COG.

On-orbit monitoring will be accomplished via semiconductor strain gauges deposited directly on the piezoelectric cells. Strain gauges undergo a change in resistance in response to being strained—measuring that change in resistance yields the strain. With suitable calibration, the strain can be correlated with local mirror bending. Strain gauges also undergo a change in resistance due to temperature changes. Semiconductor strain gauges are much more sensitive to both strains and temperature changes than other types of strain gauges. The use of on-orbit figure monitoring for thin X-ray optics is new and potentially groundbreaking. But because of its newness, it represents unproven technology (even if semiconductor strain gauges are a commercially available product). We envision essentially three potential different applications to on-orbit correction, depending upon the level of success of the technology. Simplest and most mature, a small number of strain gauges mounted on the mirror at discrete locations near mirror attachment points can periodically assess impacts of (mirror mount) epoxy shrinkage. A middle-of-the-road approach is to use many strain gauges oriented to measure strain in the direction normal to the surface of the mirror—out-of-plane strains. Because there are no out-of-plane strains produced, that leaves these sensors sensitive only to temperature changes of the mirror. Thus, it is possible to map mirror temperature (on many or all mirror elements) to an accuracy of ~0.01 °C. These temperature changes can be input to a thermal-mechanical finite element model of the mirror assembly, informing us of figure changes on the basis of changes in the thermal environment. A revised set of piezo cell voltages can account for both the initial mounted mirror figure errors, plus the thermally-induced changes, and the mirror figure corrected on-orbit. The ideal approach is to have both the temperature-only sensing strain gauges along with in-plane strain gauges (basically one/piezo cell). The thermal map temperature corrects the in-plane sensors, providing the change in in-plane strain. This can help determine the shape of the mirror relative to the shape and temperature at the time of calibration, and a revised set of piezo voltages can be supplied to correct mirror figure as necessary. Estimates indicate that it will be necessary to measure strains at the 1 to 10 nano-strain level in order to correct the figure to 0.5 arcseconds. While that level of precision has not demonstrated yet, semiconductor strain gauge suppliers do claim routine measurement of 10–20 nano-strains. Similar to piezoelectric cell voltage control, an additional bus, ASIC, and set of row-column addressing can monitor strain gauges (done at a lower update rate than piezo voltage because temperature changes would be expected to have relatively long time constants).

The implementation of adjustable optics marries recent and mature technologies:

- Established microelectronics LCD technologies of row-column addressing, including the use of integrated ASICs directly on the adjustable segment (chip-on-glass), which dates to “flip” phones.
- New technology of zinc oxide-thin film transistors to control the adjustable mirror “pixels” or cells.
- Selection of sputtered lead zirconate titanate—used for trillions of microelectronic capacitors—as the piezoelectric adjuster material.
- Incorporation of single crystal silicon segment substrates with sub-arcsecond imaging capability, developed by GSFC.

Finally, several comments about the technology are in order:

1. Temperature sensitivity of piezoelectric materials. One of the reasons for choosing PZT is its relative insensitivity to temperature in the regime around 20 °C (Wolf & Trolier-McKinstry 2004), where the telescope mirror will be controlled and operated (*Chandra* is held to and operated at 21.1 °C, the metric equivalent of 70 °F). In fact, the impact of piezo-coefficient temperature sensitivity in this regime is about 1 to 2 orders of magnitude less than the impact of temperature change and temperature gradients on the mirror assembly structure and the various (different) coefficients of thermal expansion for the materials of the mirror substrates, coatings, structure, etc.

2. The piezoelectric material PZT is a microelectronics standard for capacitors. It is extremely well characterized in terms of performance, rad hardness, and lifetime testing. It is not an unknown or new material, only the application to grazing incidence X-ray optics is new.

3. Like all capacitors, the piezo cells do not possess infinite resistance to ground, and so slowly leak charge—the leakage current. For our size piezoelectric cells and operating voltages, the adjustable optics team has measured leakage currents of typically 10–100 pico-amps at 10 V, per cell. Thus, even for an expected 107 piezo cells, cumulative required piezo power is tiny relative to the ~1,500 W required by the mirror assembly thermal control system to keep the mirror assembly at ~20 °C while viewing cold dark space.

4. The original design process uses slumped glass as a mirror substrate. Other substrate materials will work, as long as the substrate back surface is sufficiently smooth (~≤10 nm rms roughness). In fact, due to the temperature limitations of glass, it is easier to deposit PZT on other materials such as single crystal silicon (in fact, mono-Si is the standard substrate material for PZT deposition for nearly all other applications). Adjustable optics technology is adaptable to a wide range of mirror substrate materials and technologies. In light of recent developments regarding the Si segments, the plan is to incorporate the piezoelectric adjustability onto the back side of Si segments.

5. Piezoelectric materials typically used in an AC application (with positive and negative applied voltages) sometimes need to be "re-poled"—have their dipole moment domains realigned in the same direction. This is sometimes raised as a concern about or weakness of piezoelectric materials. This is not an issue for this application. Only a positive DC voltage is supplied to each piezo cell. Once poled, there should be no de-poling due to routine operation. That said, the control electronics are now/will be designed to supply the ±15 V DC for both on-demand de-poling and re-poling, if necessary. Poling is actually only a ~1-hour operation by itself, and so is not very intrusive.

6. Lastly, there may be concerns about the apparent complexity of millions or 10s of millions of adjusters (piezo cells) as part of the mirror assembly. First, each mirror itself only will possess ~103 adjusters, not 107. Second, using row-column addressing and digital electronics on or near each mirror segment reduces complexity to near zero; an integrated on-segment ASIC will require only connections for logic power (2), piezo cell power (2, including ground), and the 50 bit ± command word data bus operating at several GHz (all this excluding redundancy). An example of an integrated driving circuit placed directly on the LCD is shown in Fig. 1 with the driver electronics mounted directly to the flip phone display. These five connections to each mirror segment (strain gauges do not need to be monitored at nearly

the same temporal frequency since changes due to temperature or aging will occur slowly (hours to years)) would all be sequentially "tee'd" off a central (to the mirror assembly) set of cables with command bus, logic power, piezo power, etc. A branch from each would flow to each module, and then eventually branch off to each mirror.

Current Technology Status — Current mirror technology is assessed as TRL 3. Some key development points follow. Of greatest significance, a deterministic figure change has been successfully applied to a mounted cylindrical test mirror, producing exactly the predicted change (DeRoo 2017). The test configuration is shown in Fig. 2. A 220-mm radius of curvature cylindrical adjustable test mirror is shown mounted in the mirror housing, along with cabling connecting all 112 piezo cells to the control electronics (mirror does not have the ZnO transistors and row-column addressing, so each cell is individually connected). Initial mirror figure to be corrected was 6.8 arcseconds HPD, and the predicted residual based upon cell voltage optimization was 1.4 arcseconds HPD. Upon making the actual figure change, the measured residual equivalent X-ray performance at 1 keV was 1.2 arcseconds HPD (single surface). The predicted optimized residual measured calibrated influence functions, which suffered from metrology noise. It was hypothesized that noise on the wings of the influence functions were limiting the ultimate achievable figure (DeRoo 2017). Using noise free (FEA-modeled influence functions) gave a simulated residual of 0.3 arcseconds HPD, which includes 0.29 arcseconds HPD of aperture diffraction—used the measured influence functions because at present the model is mis-registered to the physical mirror, mount and cell locations, and data by ~1 to 1.5 mm. Expectations are this error source will decrease significantly as both (a) the real mirror and model are precisely registered, and (b) metrology noise is significantly reduced through an interferometer for I/F calibration rather than the significantly coarser wavefront sensor. This hypothesis was tested upon moving test labs to a seismically quieter location and incorporating specialized low-pass filtering of the influence functions (the central peak of the I/F is essentially unfiltered, whereas the wings are highly filtered). This resulted in a reduction of the predicted and actual residuals to 0.54 arcseconds HPD-equivalent (single surface, 1 keV), again including 0.29 arcseconds HPD of aperture diffraction. Results are shown in Fig. 3. (Note: About half the improvement was due to change in the lab environment, and the other half due to I/F filtering.) Thus, the ability to deterministically correct mirror figure has been demonstrated. A significant reduction in the predicted and actual residuals is expected as metrology noise is reduced and/or registration corrected between models and as-built hardware.

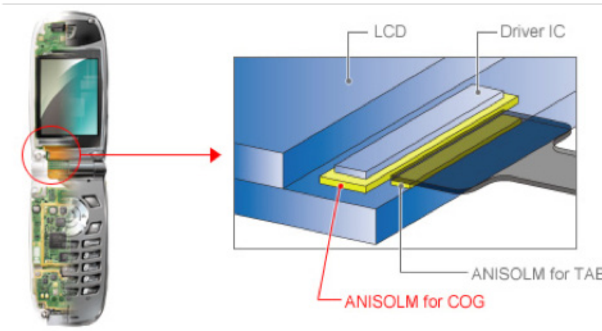


Fig. 1—Image copyright Hitachi Chemical, Ltd.

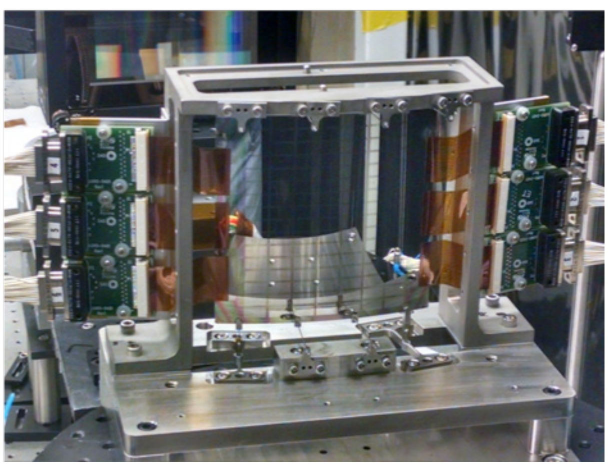


Fig. 2—Deterministic mirror figure control test configuration, viewed from the back (convex) surface of the mirror. Visible are the piezo cell top electrodes, the mirror mount, and the six sets of ACF connections for piezo control (again, far fewer connections are necessary with row-column addressing).

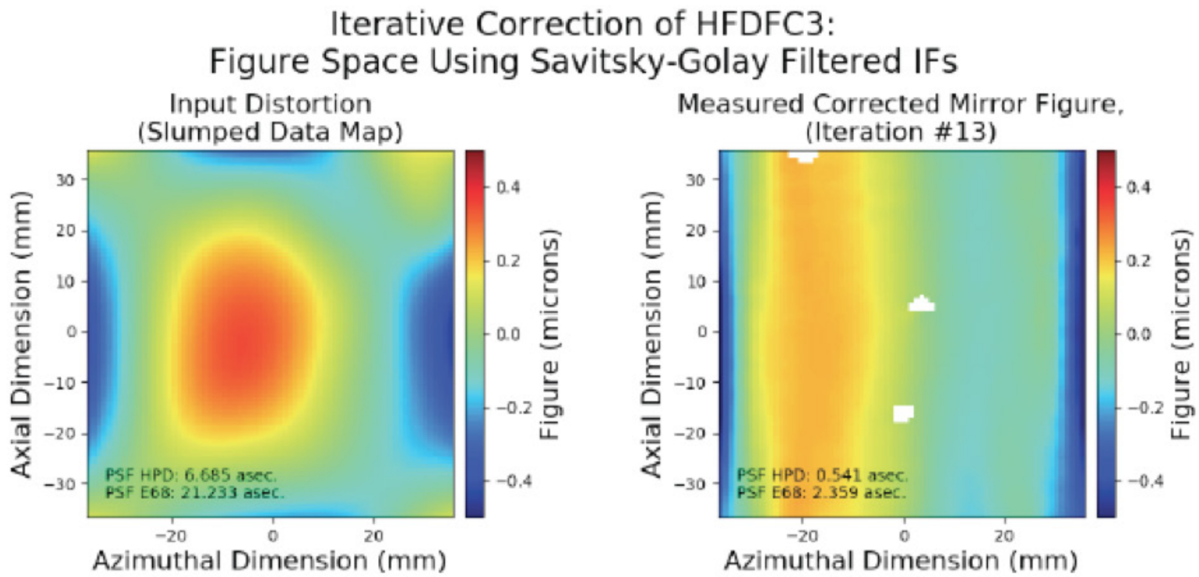


Fig. 3—Results of deterministic figure control test. Left-most color map is the initial figure error; right-most map shows the as-measured figure residual after correction.

The experiment described also demonstrated the ability to successfully connect between electrical control cables and the mirror piezo cells via Anisotropic Conductive Films (ACFs). This is a microelectronics off-the-shelf product designed for producing quick, dense low-voltage connections between many-conductor cables and circuit boards. Electrical contacts as dense as 100 per mm can be achieved—this approach used a much more modest 2 contacts per mm. Ultimately, with row-column addressing, many fewer signal lines will need to be connected to the mirror, but ACF is a strong candidate due to its ease and the lack of measured figure change the cable connections impart to the mirror.

Another major area of technology development is the application of the integrated ZnO thin film transistor (TFT) control electronics. The deposition and use of ZnO TFTs to control piezo cells via row-column addressing has been demonstrated in the past (Wallace 2017). Work continues in that area under a NASA Research Opportunities in Space and Earth Sciences (ROSES) Astrophysics Research and Analysis (APRA) grant led by Penn State University (PSU). In addition, progress continues in development of the insulating layer application with conductive vias to enable closer spacing of piezo cells. Testing is underway on the ability to lithographically align 20-μm-wide features on a cylindrical surface when printing several different mask steps. So far, the ZnO TFTs have been successfully printed, with conductive vias attached to them, and electrical traces to the conductive vias, etc.

Accelerated lifetime testing of the PZT adjusters has occurred, using standard microelectronics testing protocols (testing at elevated temperature and applied voltage). Estimated mean lifetime at present is a ridiculously long ~103 years, although this should decrease at sufficiently low acceptable failure probability.

In the past, there has been some difficulty with the thin film stresses introduced during PZT processing. Conceptually, due to the PZT film thickness and the associated ~125 MPa film stress, stress-related figure distortion is significant. The approach to handling this is to develop a compensating stress on the front (concave) side of the mirror. Compensation does not have to be perfect—in fact, simulations show balancing the stress to about 5%–10% is good enough to reduce the impacts to errors that the PZTs can correct by themselves. That said, initial attempts resulted in much higher PZT film stress on cylindrical optics than on earlier flat test optics, and the stress, which had been uniform, was very non-uniform. Analysis indicated that the Rapid Thermal Annealer (RTA) method of annealing the PZT film on the cylindrical optics was flawed (in a manner it should not be, i.e., malfunctioning), resulting in large and non-uniform stresses. Since returning to annealing in the much slower, less efficient, but simple box furnace, annealed PZT films on cylinders and conical segments appear to have mostly uniform film stress of comparable magnitude as on flats. Changing the PZT annealing method effectively removed 75% of the stress problem. The remaining stress non-uniformity is believed to be the result of measured (and modeled) PZT thickness non-uniformity, itself the result of non-ideal sputter geometry—the PZT sputter chamber at PSU is limited to a 4-inch sputter target, which is small relative to a 4-inch substrate for coating. But there is insufficient funding to modify the PSU chamber to use a larger sputter target. The stress non-uniformity has been modeled based upon the measured thickness non-uniformity, and results are being compared with the apparent measured stress non-uniformity. Current efforts involve trying a different sputter system with an 8-inch diameter target to at least determine if eliminates all or most of the thickness non-uniformity by improving the coating geometry. Moving forward, the switch to Si mirror substrates should significantly reduce both problems of non-uniform annealing stress and the amplitude of distortion due to stresses.

Recent efforts demonstrated mounting a (non-adjustable) 0.4-mm-thick, 100-mm-×-100-mm, 220-mm radius of curvature cylindrical test mirror segment with a side flexure mount, maintaining mirror figure to better than ~1 μm peak-to-valley. This is within the adjuster correctable range, and within a factor of 2 of finite element modeled predictions. Plans call for next mounting a working adjustable conical mirror segment and demonstrating the ability to correct mounting-related distortions.

1.2.2 Progress Toward Achieving Lynx Science Requirements

The selection of Si optics as the baseline XMA technology has changed the thinking about the development of adjustability for *Lynx* mirrors. While the main focus of current development is focused on adding adjustability to component mirrors, options remain open for different mounting and optical design possibilities. These other options both facilitate the use of adjustable optics, and optimize the optical performance to take full advantage of adjustable mirrors. It may be possible that the adjustable mirrors could be a drop-in replacement for the baselined passive Si mirrors (i.e., mounted as described in the Si development roadmap), or a different mounting scheme may be chosen. To that end, the previously developed optical design and mounting scheme for optics will be maintained, albeit with limited additional development unless this development effort is selected in the future. That being said, what follows is a description of the optical design. The tasks, timeline, and costs for developing the alternate mirror mount are discussed elsewhere in this document.

An optical point design was developed that satisfies *Lynx* science requirements, and a detailed imaging error budget is in development. In parallel developments, using internal SAO funds, led to both a mirror mounting scheme that satisfies the demands of minimizing induced distortions and optical alignment metrology and processes that align mirror segment pairs to ~0.35 arcseconds RMS diameter.

The mirror point design makes use of a modular approach as envisioned for Con-X and IXO. The present design, which makes use of preliminary structural plans, includes three radial rows of modules—inner, middle, and outer—with 10 inner modules defining the shells, 20 middle modules, and 40 outer modules. Each mirror segment is 200 mm long (axially). Radii range from a maximum of 1,500 mm to a minimum of 200 mm. The maximum was chosen to be consistent with launch vehicle spacecraft fairing internal dynamic envelopes and spacecraft structure. The minimum is not optimized with respect to the loosely specified high energy performance requirements and mirror mass (the smallest radii shells contribute almost nothing to 1 keV area, but because they can be the most densely packed, can contribute significant mirror mass). Segment azimuthal spans range from ~100 mm to ~220 mm. Corning Eagle XG^{TM} can be produced in sizes up to several meters on a side (current size limitation is due to shipping pallet limits for transport through the Panama Canal). The current design consists of 265 shells (12,720 mirror segments, not including spares). With the modular design, multiple parallel manufacturing lines will likely be employed to reduce mirror assembly fabrication and assembly time. The intent is to explore the structural feasibility of increasing segment size so as to reduce the required number of modules from 40/20/10 (outer/middle/inner) to 32/16/8 or even the original designs 24/12/6, with the concurrent reduction in the number of segments. Reducing the number of segments results in a reduction in mirror fabrication cost, providing motivation for additional structural analyses.

The mirror prescription is chosen as a Wolter-Schwarzschild (W-S), which offers off-axis imaging advantages over the until-now more typical Wolter Type I (W-I). The 200 mm segment length, along with a system focal length of 10 m, also results in significantly better off-axis imaging than *Chandra*. Using a focal plane situated on a piecewise continuous curved surface optimized for 1 keV X-rays and the full ensemble of shells, and assuming 0.5-arcsecond HPD on-axis imaging, the assembly will provide 1 arcsecond HPD imaging at a 10-arcminute field position, with better performance at smaller field positions. The optimal focal surface is shown in Fig. 4.

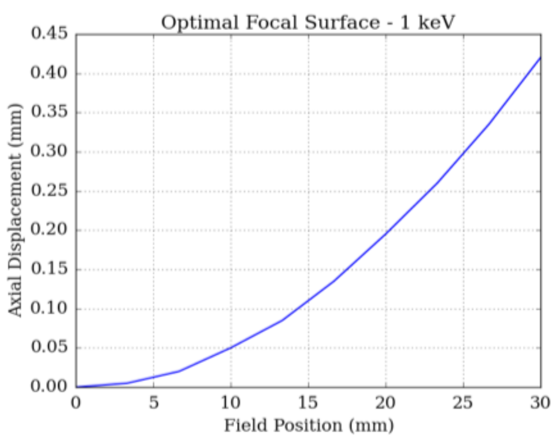


Fig. 4—Optimal focal surface, optimized at 1 keV. The surface has been “segmented to represent reasonable detector chip sizes. Telescope plate scale is 50 µm/arcsec.

On-axis effective area is plotted in Fig. 5 for the mirror assembly. This effective area, ~2.0 m^2 at 1 keV, includes losses in area due to: (1) mirror support structure, (2) allocated secondary to primary mirror alignment, (3) an absorbing thermal shield for the innermost modules, (4) allocated particulate contamination, and (5) large angle scatter outside of the detectors' FOV.

Assuming an on-axis point spread function (PSF) of 0.5 arcsecond HPD, and using the 1 keV optimal focal surface, off-axis performance is better than 1 arcsecond HPD out to a 10-arcminute field position at 1 keV (Fig. 6).

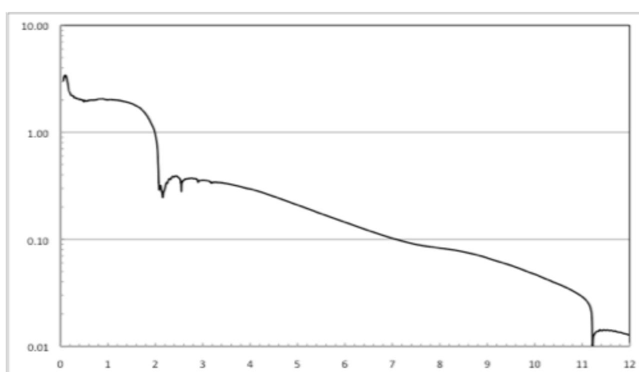


Fig. 5—Effective area as a function of energy, including estimated structural obscurations, misalignment, particulate contamination, and large angle scatter.

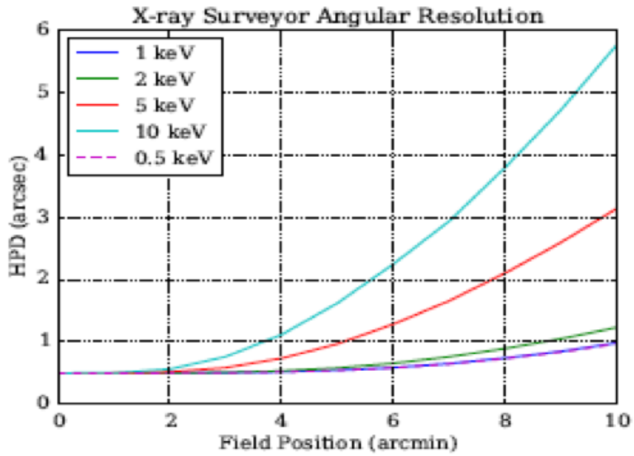


Fig. 6—Off-axis PSF as a function of energy and field position, assuming the focal plane corresponds to the optimal 1-keV focal surface.

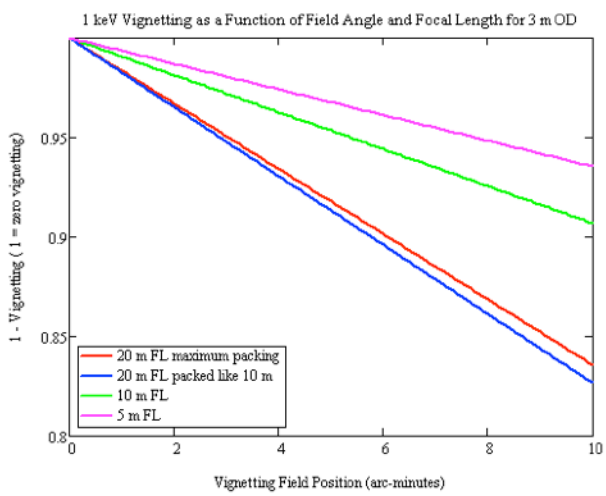


Fig. 7—Vignetting at 1 keV as a function of mirror assembly diameter. The area of interest is along the green curve corresponding to a 10-m focal length.

Vignetting as a function of field is small and linear with field (Fig. 7), such that mirror grasp (the integral of product of image resolution as a function of field angle times the effective area as a function of field angle, for resolution ≤1 arcsecond HPD at 1 keV) marginally missed the required 600 m^2-arcminute^2 with a predicted value of 598.7 m^2-arcminute^2. Besides including allocations for effective area losses, 95% density of the reflecting Ir film is allocated, rather than unachievable 100% density. Also, differences in the optical constants used to calculate reflectance of the Ir can vary the effective area by several percent, plus or minus.

A top-level imaging error budget, shown in Fig. 8, has been developed. The error budget is divided into two elements: imaging and alignment. (The alignment budget is not included in this document, although its contribution to the imaging budget is included.)

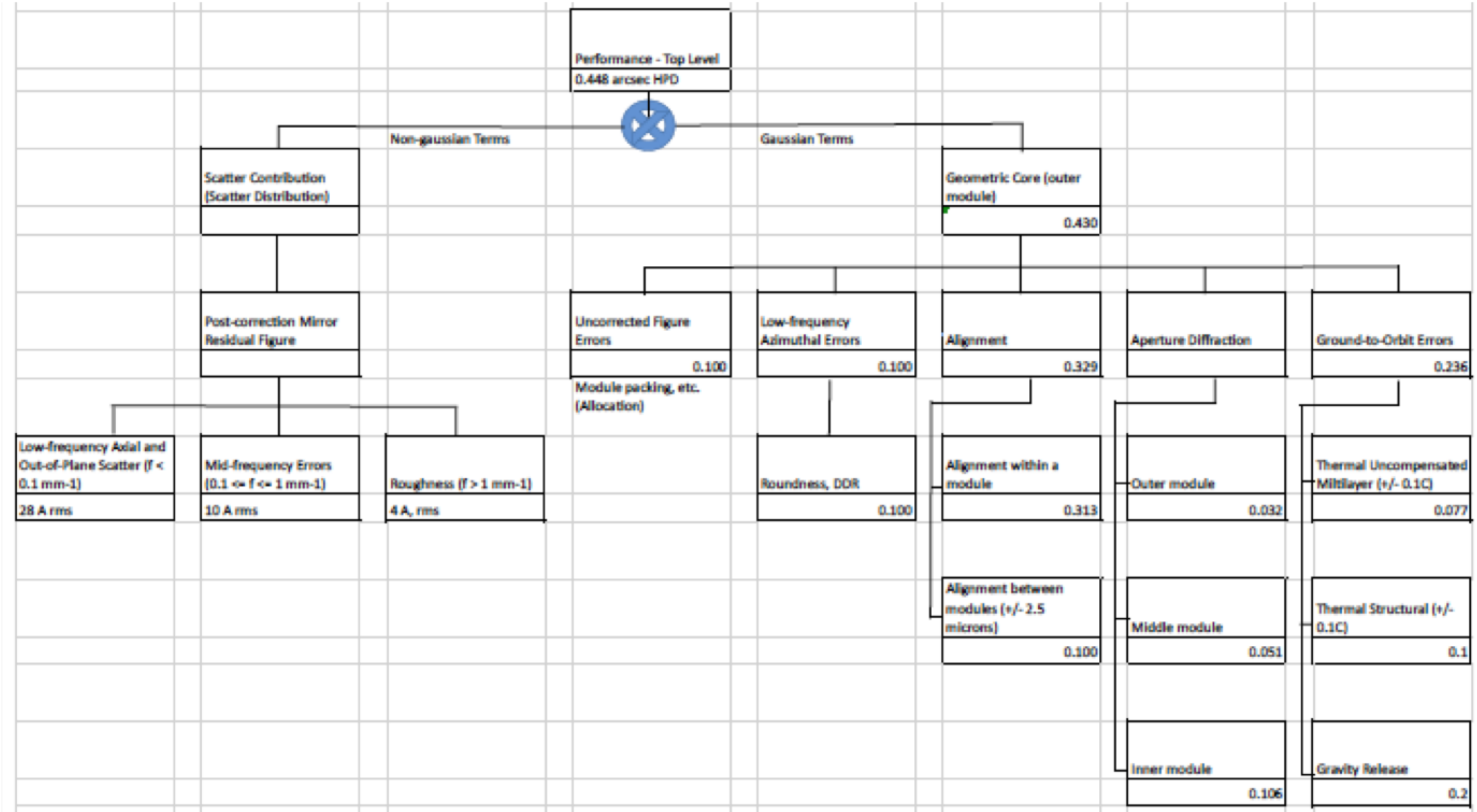


Fig. 8—Imaging error budget. The budget is partitioned into Geometric Core errors on the right-hand side, and Scatter Contributors on the left-hand side. The ⊗ symbol indicates a convolution operation which is performed explicitly, rather than just root sum squaring rms values.

1.2.3 Issues and Challenges

This section identifies the issues, challenges, and risks to achieving TRL 6 in developing adjustable X-ray optics.

1.2.3.1 Issues

Optical Design: Maximum Mirror Size—The current optics point design has an increased number of segments (~12,700) compared to the initial point design (~8,400) presented in October 2017. This increase reflects mirror structural analysis concerns regarding gravity sag for the original design's largest mirror segments based upon preliminary mirror mount analyses. The more segments in a design, the greater the metrology, mounting and alignment costs. Current cost estimates reflect this larger number of segments. In addition, reducing the size (azimuthal span) of the mirror segments decreases the fractional mirror throughput efficiency (due to larger fractional obscuration per segment pair), reducing effective area. This accounts for the reduction in the 1-keV effective area from 2.3 m^2 to 2.0 m^2. Additional analyses and mount design may enable an increase in mirror segment size, reducing mirror cost, but that work falls outside the XMA up-select period timeframe.

Optical Design: Mirror Segment Axial Positions—This issue was described in October 2017 in a presentation of the original optics point design; for a shell (or segment pair) of radius R at the intersection between primary and secondary mirror surfaces, the axial location Z of that intersect is nominally where FL is the focal length.

$$Z(R)=\sqrt{FL^2-R^2}$$

This condition applies if the ratio of primary graze angle to secondary graze angle ξ at an infinitesimal offset from the intersection point is unity. The significance is that every shell (or its component segment pairs) must be situated at different axial positions. Substituting for FL = 10 m with R over a range of 0.2 to 1.5 m, it can be seen that Z varies by ~0.11 m, which is not an inconsequential distance. Having different axial locations for each mirror shell may lead to mechanical/structural and/or alignment implications. A solution to this exists: (optically) redesign each shell over either the full mirror or a range of shells by varying the ratio ξ for each shell such that the axial position of the shells is the same—the smaller the range of mirror $Z(R)$, the smaller the variation from unity required for ξ. Optical design solutions include having all the mirror segments over each module possessing the same axial locations, with axial offsets between inner, middle, and outer modules. Under this approach, there is a small decrease (~10%) in effective area which results from some primary mirror segments having a lower graze angle than in the "nominal" design. The reduction in graze angle provides a small increase in reflectance, but reduces the area of the annular aperture by a larger relative fraction. The reduction in effective area can be mitigated via a hybrid solution of splitting up mirrors within the outermost modules into two or three groups, each with the same axial position within a group but different axial positions from group to group. What's the bottom line? It is a complication that must be addressed to determine if there is an optimal opto-mechanical solution, and what configuration that represents.

1.2.3.2 Challenges

Strain Gauging—Strain gauging development has been proposed for investigation via ROSES 2017.

As described, three operational scenarios exist. The first, AC driving the piezo cells with synchronous detection of strains will enable measurement of the piezoelectric coefficient real time, on orbit. This approach to measuring piezoelectric coefficients has been employed with accuracy better than 1% (Bassiri-Gharb 2005), sufficient to maintain 0.5-arcsecond imaging (based upon Monte Carlo simulations, Aldcroft 2012).

The second operational scenario involves measuring local mirror temperature via semiconductor strain gauges distributed over the surface of many/all mirror segments. This enables detailed modeling of mirror thermal deformations due to a measured temperature map. With these deformations, the figure correction solution (piezo cell voltages) can be updated separately for each mirror segment to correct for the measured change in the thermal environment. Semiconductor strain gauges can measure temperature change to ~0.01 °C, which is about an order of magnitude finer than necessary to maintain corrected figure to 0.5 arcsecond (the imaging error budget allocates an allowable ground-orbit temperature change of 0.1 °C for which no change in mirror correction is required). These two scenarios accommodate both the aging of the piezoelectric material and variation of the thermal environment and maintain imaging performance. The "issue" is the deposition of arrays of semiconductor strain gauges. Arrays of 800 strain gauges have been deposited on flexible substrates (Kevran 2015), and ZnO piezo-resistive strain gauges have been RF-sputter deposited (Ozgur 2005). Development of this capability should be evolutionary, not discovery.

The third operational scenario—the "gold medal" approach—is direct measurement of local strain for use as the mirror figure feedback control. This is the most difficult scenario to implement as it requires the incorporation of both strain insensitive temperature sensing strain gauges (for temperature compensation) and strain-sensitive strain gauges, and it requires the highest precision and stability of the three cases. Implementation of the direct figure feedback approach requires significant development and investigation to determine feasibility (basically, a function of signal-to-noise limits). Failure to achieve direct figure feedback is not a fatal flaw to the technology, however, as the first two operational scenarios should enable maintenance of 0.5-arcsecond imaging. The most challenging operational scenario technology development for strain gauging would afford the least challenging operation of the telescope.

Mounting Timeline — Simply put, there are a lot of mirror segments in the *Lynx* segmented design. To fabricate the mirror assembly within the assembly timeline will challenge mirror mounting, which requires time for epoxy curing. This challenge may entail looking toward different epoxies which can both cure rapidly without shrinkage and incorporate automation into the mounting process.

Thin Film Stress Compensation—Thin film stress from piezoelectric processing results in distortions larger than can be corrected for via the adjusters. Several solutions exist for this issue, but one or several need to be fully demonstrated. A solution that has demonstrated the potential for eventual success is the application of stress compensating coatings. A uniform stress coating has been successfully applied with the same integrated stress (product of film stress and film thickness) as the piezo processing stress, ~190 MPa-µm. This accomplishment occurred via a stressy Cr/Ir front surface coating to balance the back surface piezo film stress. The limitation to demonstrating complete success with this approach has been twofold: (1) the piezo processing stress is not completely uniform, which is likely the consequence of non-ideal deposition geometry (dictated by funding limitations); and (2) by thermal gradients during piezoelectric material annealing. An improved solution would use an axial sputter cathode for depositing both piezoelectric material and the compensating coating, along with a more thermally uniform annealing process. Also, changing to Si mirror segments as substrates for the piezoelectric adjusters enables the use of RTAs, which should reduce the introduction of non-uniform stresses through both greater thermal uniformity and increased thermal conductivity (of the Si with respect to glass). In addition, because Si has approximately twice the stiffness of glass, the amplitude of distortions induced by the film stress will be approximately halved. Significantly, because of the higher anneal temperatures available with Si, the piezoelectric coefficient of the annealed PZT will also be approximately twice as large. This "cancels out" a loss of correction dynamic range due to the stiffer material. Thus, the distortion amplitudes are reduced by both an increase in stiffness and reduction in gradients and higher annealing temperatures, and the correction range of the adjusters is unchanged. Alternative variations to be explored include increasing piezoelectric cell voltage limits (currently operating at a maximum voltage less than one-third the breakdown voltage) and changing the ground electrode material to a more crystalline material, which has been shown to as much as double the piezoelectric coefficient. This approach would increase the piezo correction dynamic range to encompass the non-uniform stress component of the thin film stress.

Another potential solution examined briefly with glass substrates is called "post-processing"—namely using surface figuring technologies such as Magneto-Rheological Finishing (MRF) or ion machining to correct the mirror figure, thereby refiguring the mirror to account for the stress-related distortion. Preliminary experiments with MRF (Harris Corp.) and IBF (INAF OAB) look promising, but are certainly not considered "demonstrated" technologies (yet). More development would be needed for those approaches. Thus, while coating stresses are an issue, multiple prospective solutions exist that require additional funding to realize.

Table 2—Adjustable optics technology maturation elements.

E#	Element Description	SOA Element TRL
1	Mirror Development: Fabricate a Si mirror that has a back surfaced polished well enough to accept our actuators, and demonstrate mirror figure performance within the capture range of the actuators to achieve required optical correction	3
2	Electronics/Control Development: Apply PZT actuators to a full-size substrate	3
3	Electronics/Control Development: Apply PZT support electronics (insulating layers, patterned contacts, vias to the other electronics on the mirror back) to a full-size substrate	3
4	Electronics/Control Development: Develop ZnO transistors and row-column addressing on a full-size substrate	3
5	Electronics/Control Development: Validate strain gauge/temperature monitoring methodology, and apply strain gauges to full-size substrate	3
6	Electronics/Control Development: Define and realize an on-mirror ASIC design	3
7	Coating Development: Apply a grazing incidence X-ray coating (either stress compensating or low stress, to be determined) to a full-size substrate	3
8	Mount Development: Develop full-size frames to hold individual mirror pairs	3
9	Mount Development: Develop module design for full-size mirrors	3
10	Assembly Process Development: Align modules to build up the EM	3
11	Scaling: Slumping, electronics, coating, and assembly scale-up	3

The following are descriptions of each element to be matured:

1. **Mirror Development: Fabricate a Si mirror than has a back surface polished well enough to accept the actuators and also demonstrate mirror figure performance within the capture range of the actuators to achieve required optical correction**. The current process for fabricating Si mirror segments includes saw cutting the mirrors off a larger block of

Si, then acid etching the back of the mirror to remove residual surface damage and stress. An additional polishing step will be needed to prepare the back surface to accept the actuators. This polishing step may be necessary in any case, as a polished surface is both stronger and easier to clean than a brought surface.

2. **Electronics/Control Development: Apply PZT actuators to a full-size substrate**. Applied an array of 5-×-10-mm "pixels" of PZT on the back of test mirrors. These mirrors had all of the electrical connections run between the "alleyways" between the pixels. Current fabrication efforts involve a new mirror with more pixels, each 5 × 5 mm, and the electrical connections come off the back of the mirror through vias and over an insulating layer. There is more area for each pixel, less dead space between the pixels. Ultimately, the technology needs to be matured for mirrors with potentially larger area. This will require new sputtering equipment (or at least a new sputtering supplier to deposit the PZT) and scaling up the support electronics backplane.
3. **Electronics/Control Development: Apply PZT support electronics to a full-size substrate**. Same discussion as the previous element (apply PZT actuators). This maturing element refers to the support electronics that accompany the PZTs—insulating layers, patterned contacts to the PZTs, vias, and routing to the other electronic components on the mirror back.
4. **Electronics/Control Development: Develop ZnO transistors and row-column addressing on a full-size substrate**. ZnO transistors on glass substrates have been successfully deposited, and this technology is very mature. For *Lynx* purposes, validate depositing the requisite circuitry on a full-size substrate, and that this circuit can enable row-column addressing, which will greatly reduce the wire count coming off the mirror, and reduce the complexity of the mirror assembly.
5. **Electronics/Control Development: Validate strain gauge/temperature monitoring methodology**. There are several possible ways to use strain gauges to monitor mirror figure. They range from periodic poling of the gauges in AC mode (which will allow periodic correction of the mirrors as the PZT actuators age) up to real-time, relatively high-frequency adjustment of the mirror figure by constant monitoring of the strain gauges. The option chosen will be a function of the actual performance of the stain gauges for the application, including the temperature sensitivity of the gauges. Understanding of strain gauge capabilities in this specific application needs to mature, and it is critical to validate a methodology that assures the mirror figure is maintained throughout the life of the mission. Once a strain gauge-based figure monitoring methodology is worked out, the next step will be to apply the requisite gauges in the quantities and required locations on a full-size mirror.
6. **Electronics/Control Development: Define and realize an on-mirror ASIC design**. Having an ASIC integrated into the patterned electronics already on the back of each mirror will serve to distribute the mirror control electronics, thereby avoiding additional mass and volume for a central controller. Such a distributed control system would result in much simpler electronics and reduced cabling coming off the mirrors. That being said, it is not absolutely necessary to distribute the controls, so the use of an ASIC is an area of interest and possible system-level improvement but is not a showstopper if not selected as part of the control system.

7. **Coating Development: Apply a grazing incidence X-ray coating (such as stress compensating or low stress) to a full-size substrate**. Depending upon the condition of the mirror's figure after the slumping, post-slump processing, and electronics integration, a stress compensating coating or an ultra-low stress coating may be applied. To date, since a post-slump polished mirror hasn't been made and tested, a stress-compensating coating has always been used on the developmental mirrors. No matter which option is chosen, the equipment for and process to reliably coat a full-size mirror substrate with the requisite X-ray coating is needed.
8. **Mount Development: Develop full-size frames to hold individual mirror pairs**. The point design is to mount the primary mirror into a frame, align the secondary to the primary, and mount it in the same frame structure. Current efforts involve testing a proof of concept primary mirror-only frame. Ultimately, a mirror pair frame needs to be designed and validated.
9. **Mount Development: Develop module design for full size mirrors**. The point design is to mount mirror pairs (PM and SM) onto a frame, align the outermost pair from any given module to the next pair, and so on, thus building a module from the outside-in. The frames that hold the mirror pairs will serve to form the structure of the module. This methodology must be matured in order to validate aligning mirror pairs to each other and hold them in place throughout module build and the mission lifecycle.
10. **Assembly Process Development: Align modules to modules to build the EM**. The last step in the EM assembly process is to assemble modules onto a master framework, aligning modules to the assembly. The apparatus and methodology must be developed to align, test, and validate the EM assembly process.
11. **Scaling: Electronics, coating, and assembly scale-up**. As progress is made toward the mass production of thousands of mirrors, work with industry will need to continue in order to prepare the infrastructure to support this mass build. Several optical companies have been contacted to estimate the time and dollars it will take to scale up. It is a matter of timing this scale-up to coincide with *Lynx* needs based on the build schedule.

Efforts with electronics fabricators and PZT sputtering industry experts has occurred to assess the time and costs associated with scaling up to build actuated mirrors. At present, there are no showstoppers here, if there is a lab-demonstrated process for applying the necessary materials to the backs of the mirrors. This maturation step is more about understanding the timing and costs to scale-up.

The buildup of modules (and ultimately the EM) will require a substantial investment in facilities and equipment, especially an X-ray test facility. This maturation element involves understanding existing facilities' capabilities and availability, and adapting *Lynx* build methodology accordingly.

2 Detailed Technology Roadmap

Moving through the TRLs, each of the 11 maturation elements needs to be addressed. The TRL definitions provide the guidelines for expected performance. Achieving each TRL performance level requires that the key elements be matured in a stepwise fashion. Those steps, and key milestones along the way, are covered in detail in the following TRL sections. Table 3 addresses each of the 11 maturity elements' milestones necessary to achieve that particular TRL level.

2.1 Key Milestones

Table 3—Adjustable optics TRL milestones.

<table>
<tr><th>NASA TRL 3</th><th colspan="3">Analytical studies place the technology in an appropriate context. Laboratory demonstrations, modeling, and simulation validate analytical predictions.</th></tr>
<tr><th>Lynx Optics TRL 3 Exit Criteria</th><th colspan="3">Adjustable Optics Development/Maturation Milestones</th></tr>
<tr><td rowspan="12">Must demonstrate a credible technology development path to the required on-orbit performance of the XMA. Demonstrations must trace to the on-orbit performance requirement in the operational environment.

A credible demonstration must comprise the following for these Wolter-Schwarzschild optics:
1. Realistic end-to-end error budget for Lynx telescope angular resolution.
2. Laboratory demonstration of measured angular resolution of mirror elements performing less than a factor of 6 away from their required performance (as stated in the error budget), executed under the following conditions:
• Mirror figure and the ability to correct mirror figure for a single mirror segment demonstrated via metrology or X-ray testing.
• Early proof-of-concept of mirror mounting and all essential hardware elements demonstrated.
3. Models, Analogies, or Lab Demonstrations
• All elements related to the as-corrected mirror error contributions (e.g., coatings, thermal, g-release) must be validated.)</td><th>#</th><th>Milestone Description</th><th>Date</th></tr>
<tr><td>1</td><td>Mirror Development: Fabricate a 100-x-100-mm glass substrate (glass was used in this early development) that demonstrates both requisite mirror figure (6x allocated error budget) and a smooth back ready to accept PZT material.</td><td>COMPLETE</td></tr>
<tr><td>2</td><td>Electronics Development: Apply PZT material to the back of a 100x100mm slumped glass substrate. Verify yields and test actuator authority and the correctability afforded by the actuators</td><td>COMPLETE</td></tr>
<tr><td>3</td><td>Electronics Development: Apply requisite patterned electronics on top of the PZT layer on a 100-x-100-mm substrate. Determine yields and effectiveness of the process. Measure the mirror figure, by a normal-incidence optical test. Verify that we are within 6X the requirement.</td><td>COMPLETE</td></tr>
<tr><td>4</td><td>Electronics Development: Proof of Concept - Apply ZnO transistors to a representative piece of glass to validate that process feasibility.</td><td>COMPLETE</td></tr>
<tr><td>5</td><td>Electronics Development: Proof of Concept - Apply stain gauges to a representative material to determine the feasibility in this application and the capabilities of the gauges</td><td>COMPLETE</td></tr>
<tr><td>6</td><td>Electronics Development: Proof of Concept - Develop/procure an ASIC on a representative material to prove feasibility to our application</td><td>COMPLETE</td></tr>
<tr><td>7</td><td>Coating Development: Apply a grazing incidence X-ray coating to the front of a 100-x-100-mm substrate, matching stress induced by the PZTs.</td><td>COMPLETE</td></tr>
<tr><td>8</td><td>Mount Development: Mount a 100-x-100 mm mirror in a proof of concept. Verify acceptable mount-induced figure error pre- and post-correction on the mirror, per structural analysis and the error budget, at the 6X level.</td><td>COMPLETE</td></tr>
<tr><td>9</td><td>Mount Development: Model how the proof of concept frame would ultimately be assembled.</td><td>COMPLETE</td></tr>
<tr><td>10</td><td>Assembly Process Development: Model the alignment of modules to create the EM</td><td>COMPLETE</td></tr>
<tr><td>11</td><td>Scaling for Production: Supplier/Industry survey to determine scale-up possibilities</td><td>COMPLETE</td></tr>
<tr><td colspan="4">TRL 3=>4 Advancement Degree of Difficulty: AD = 2

Our plan to achieve TRL 4 is to continue to use smaller mirrors (100 x 100 mm) because without investment in larger PZT deposition and other processing equipment or finding and developing other suppliers, we are currently limited to this size. The key areas we would need to mature are the addition of ZnO transistors to facilitate RC addressing, the alignment of a mirror pair in a proof of concept frame, the testing of this mirror pair in an X-ray beamline, and validation of the performance to within 3x the requirement.</td></tr>
<tr><td colspan="4">Anticipated date to achieve TRL 4: Q1 2020</td></tr>
</table>

NASA TRL 4	**A low-fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.** **Breadboard: A low-fidelity unit that demonstrates function only, without respect to form or fit in the case of hardware, or platform in the case of software. It often uses commercial and/or ad hoc components and is not intended to provide definitive information regarding operational performance**

Lynx Optics TRL 4 Exit Criteria

Must demonstrate a credible technology development path to the required on-orbit performance of the *Lynx* Mirror Assembly. Demonstration must be traceable to the on-orbit performance requirement in the operational environment.

A credible demonstration must comprise the following for these Wolter-Schwarzschild optics:

1. Realistic end-to-end error budget for *Lynx* telescope angular resolution.
2. Laboratory demonstration of measured angular resolution of mirror pairs executed under the following conditions:
   - Must be able to repeatedly build and X-ray test single-pair mirror modules and achieve 0.5” HPD at 1 keV.
   - The effective areas must match predictions based on standard atomic data.
   - The mirror segments must be of the right thickness and appropriately coated.
   - A breadboard lab mount can be used.
   - The focal length and radius of curvature of these mirror segments can be different from *Lynx*’s.
3. Models, Analogies, or Lab Demonstrations
   - All elements related to the as-corrected on-orbit mirror error contributions (e.g., thermal, g-release, etc.) must be validated.

Adjustable Optics Development/Maturation Milestones

#	Milestone Description	Date
1	Mirror Development: Fabricate a 100 x 100 mm Si substrate with appropriate curvature that demonstrates both requisite mirror figure and a polished back ready to accept PZT material.	Q2 2020
2	Electronics Development: Apply PZT material to the back of a 100 x 100 mm Si conic substrate.	Q1 2020
3	Electronics Development: Apply requisite patterned electronics on top of the PZT layer on a pair of 100 x 100 mm Si conic substrates. Determine yields and effectiveness of the process. Measure the mirror figure by a normal-incidence optical test and an X-ray test. Verify effort is within 3X the requirement.	Q3 2020
4	Electronics Development: Incorporate ZnO transistors on a pair of 100 x 100 mm Si substrates to validate RC addressing efficacy.	Q3 2020
5	Electronics Development: 1. Demonstrate strain gauge direct deposition on representative substrates. 2. Demonstrate accuracy limits and thermal sensitivity of strain gauges.	Q3 2020
6	Electronics Development: No additional development needed on an ASIC at this level.	COMPLETE
7	Coating Development: Apply a grazing incidence X-ray coating to the front of a pair of 100 x 100 mm Si substrates, matching stress induced by the PZTs on the backside. Verify that reflectivity/scatter meet require-ments of the coating in X-ray testing.	Q3 2020
8	Mount Development: Mount a pair of 100 x 100 mm mirrors (PM and SM) in a proof of concept frame. Verify acceptable mount-induced figure error on the mirror, and alignment of the mirrors to each other, via normal incidence optical testing, optical alignment testing, and X-ray testing, per the error budget at the 3x level.	Q4 2020
9	Mount Development: No additional development needed at this level; module development will occur as a part of TRL 5 efforts.	COMPLETE
10	Assembly Process Development: No additional development needed at this level; assembly process will be developed as a part of TRL 5 demonstrations.	COMPLETE
11	Scaling for Production: Continued supplier involvement to determine scale-up requirements, costs, and lead times.	Q1 2021

TRL 4=>5 Advancement Degree of Difficulty: AD = 6

TRL 5 will require going to full-sized mirrors (point design max size is 200 x 208 mm). This will require either an investment in larger processing equipment at PSU, or the development of an industry supplier. Other key maturity elements that need to be demonstrated include the addition of strain gauges to monitor mirror figure, the partial buildup of at least two modules (including mass simulators as needed) to X-ray test both inter and intra-module alignment methodologies to within 1.5x the requirements.

Anticipated date to achieve TRL 5: Q3 2024

NASA TRL 5	**A medium-fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrate overall performance in critical areas. Performance predictions are made for subsequent development phases.** **Brassboard: A medium-fidelity functional unit that typically makes use of as much operational hardware/ software as possible and begins to address scaling issues associated with the operational system. It does not have the engineering pedigree in all aspects, but is structured to operate in simulated operational environments in order to assess performance of critical functions.**

Lynx Optics TRL 5 Exit Criteria

Must demonstrate a credible technology development path to the required on-orbit performance of the XMA. Demonstrations must trace to the on-orbit performance requirement in the operational environment.

A credible demonstration must comprise the following for these Wolter-Schwarzschild optics:

1. Realistic end-to-end error budget for *Lynx* telescope angular resolution.
2. Laboratory demonstration of measured angular resolution of medium-fidelity mirror brassboard subassemblies, as defined below:
   - Repeatedly build and X-ray test >2 mirror modules each with ≥2 pairs and achieves 0.5-arcsecond HPD at 1 keV.
   - Effective areas must match those predicted based on standard atomic data.
   - The mirror segments must be the right thickness and appropriately coated.
   - The focal length and radius of curvature of these mirror segments can differ from *Lynx*'s.
   - Mounting hardware must be flight-like—that is, being of identical design and procedure to that planned for the flight article, although different materials may be used (i.e., machined metal in place of graphite epoxy, etc.).
   - Must demonstrate alignment of modules.
   - Must demonstrate capability to perform necessary metrology for the assembly.
   - Assemblies must be tested in operational environment that includes shock, vibration, and thermal vacuum. For missing mirror shells, mass simulators should be used.
3. Models, Analogies, or Lab Demonstrations
   - All elements related to the as-corrected mirror error contributions (e.g. coatings, g-release) must be validated.

Adjustable Optics Development/Maturation Milestones

#	Milestone Description	Date
1	Mirror Development: Fabricate a 100 x 100 mm Si substrate with appropriate curvature that demonstrates both requisite mirror figure and a polished back ready to accept PZT material.	Q3 2022
2	Electronics Development: Apply PZT material to the backs of several Si substrates at various radii; mirrors representative of multiple modules. Verify yields. Test actuator authority and the correctability afforded by them. Also, run realistic PZT in real time (as opposed to accelerated) lifetime testing to demonstrate acceptable PoF	Q1 2023
3	Electronics Development: Apply requisite patterned electronics on top of the PZT layer on several full-size substrates at various radii. Determine yields and effectiveness of the process. Measure the mirrors' figure, by a normal-incidence optical test and an X-ray test, at operational environment(s).	Q1 2023
4	Electronics Development: Incorporate ZnO transistors to several full size and various radii substrates to validate RC addressing efficacy; test in operational environment(s).	Q1 2023
5	Electronics Development: Incorporate strain gauges to several full-size mirrors of different size and radii to validate efficacy; test in operational environment(s).	Q2 2023
6	Electronics Development: Design and incorporate a control ASIC on several mirrors and demonstrate functionality (control). Verify insignificant impact on pre-corrected mirror figure.	Q2 2023
7	Coating Development: Apply a grazing incidence X-ray coating to the front of a substrate, matching stress induced by the PZTs on the backside. Verify the reflectivity/scatter meet requirements of the coating in X-ray testing.	Q3 2023
8	Mount Development: Mount a pair of mirrors in a flight-like mount. Verify acceptable mount-induced figure error on the mirror, and alignment of the mirrors to each other, via normal incidence optical testing and X-ray testing, before and after environmental testing, per the error budget.	Q4 2023
9	Mount Development: Build full size mirrors into a module, partly populated (with aligned, corrected mirrors), employing mass dummies for missing "shells," using the assembly concept. Verify the mirror figure and alignment (S to P) is maintained, and alignment achieved from segment pair to segment pair in optical and X-ray testing, before and after environmental testing.	Q4 2023
10	Assembly Process Development: Build a second module from the same ring as the first. Some mass simulators can be used but require enough mirrors to verify that the modules can be aligned to each other within 1.5x the tolerances of the alignment error budget. Verify alignment and optical performance is held in operational environment.	Q1 2024

	11	Scaling for Production: Continued supplier involvement to determine scale-up requirements, costs, and lead times.	Q1 2024

TRL 5=>6 Advancement Degree of Difficulty: AD = 4

The logic for claiming AD = 4 for this section is that achieving TRL 5 (which has a higher AD), will advance those things needed to get to TRL 6 with less difficulty. The main hurdle to overcome to achieve TRL 6 is to repeat what was accomplished for TRL 5 in terms of building several partial modules and testing both inter and intra-module alignment. The difference between TRL 5 and 6 is that 6 will require a higher-fidelity, full-size prototype, and will need to meet the actual *Lynx* requirements (no 1.5x factor).

Anticipated date to achieve TRL 6: Q1 2027

NASA TRL 6	**A high-fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.** **Prototype: Unit demonstrates form, fit, and function at a scale deemed representative of the final product operating in its operational environment. A subscale test article provides fidelity sufficient to permit validation of analytical models capable of predicting the behavior of full-scale systems in an operational environment.**

Lynx Optics TRL 6 Exit Criteria

Must demonstrate using a high-fidelity, scalable, flight-like prototype which adequately addresses all critical scaling issues so that all *Lynx* performance requirements are met in critical environments.

A credible demonstration must comprise the following for these Wolter-Schwarzschild optics:

1. Realistic end-to-end error budget for *Lynx* telescope angular resolution.
2. Laboratory demonstration of measured angular resolution of flight-like prototype that demonstrates form, fit, and function that is representative of the flight unit and executed under the following conditions:
   - Build and X-ray test 9 fully populated modules: 3 in the innermost meta-shell, 3 in a middle meta-shell, and 3 in the outermost meta-shell.
   - These modules should have *Lynx*'s focal length. In principle, these modules can be flight modules. Assembly procedures should follow those used on flight hardware.
   - The modules, meta-shells, and spider must be a flight-like representation and include mass dummies appropriate for validating in a flight-like environment.
   - HPDs must be 0.5 arcsec or better and effective areas must match predictions based on standard atomic data.
   - All modules must pass X-ray tests before and after environmental tests: vibrations, thermal vacuum, acoustic, and shock.
3. Models Calculations/Predictions
   - All elements related to the as-corrected mirror error contributions (e.g., g-release) must be validated.

Adjustable Optics Development/Maturation Milestones

#	Milestone Description	Date
1	Mirror Development: No further development needed on the individual mirrors at this level. Mirrors will have been fully developed in earlier TRL development efforts.	Q3 2022
2	Electronics Development: Continue with realistic PZT real-time lifetime testing (as opposed to accelerated lifetime testing) to demonstrate acceptable PoF.	Q1 2025
3	Electronics Development: No further development needed on the PZT deposition on individual mirrors at this level. Mirrors will have been fully developed in earlier TRL development efforts.	Q1 2025
4	Electronics Development: No further development needed on the ZnO transistors on individual mirrors at this level. Mirrors will have been fully developed in earlier TRL development efforts.	Q1 2025
5	Electronics Development: No further development needed on the strain gauges on individual mirrors at this level. Mirrors will have been fully developed in earlier TRL development efforts.	Q2 2025
6	Electronics Development: No further development needed on the ASIC at this level. ASIC will have been proven at TRL 5.	Q2 2025
7	Coating Development: No further development needed at this level.	Q3 2025
8	Mount Development: No further development of the individual mirror frames is needed at this level. The mirror frame concept will have been proven at TRL 5.	Q3 2025
9	Mount Development: Build full-size mirrors into nine modules, fully populated with aligned, corrected mirrors and using the flight assembly concept. Verify that the mirror figure and alignment (S to P) is maintained, and alignment achieved from segment pair to segment pair in optical and X-ray testing, before and after environmental testing.	Q2 2026
10	Assembly Process Development: Build nine modules, three each from the inner, outer, and middle rings. Using mass simulators for the other modules, build a “testable” EM. Verify alignment and optical performance is held in operational environment.	Q1 2027
11	Scaling for Production: Continued supplier involvement to determine scale-up requirements, costs, and lead times.	Q1 2027

2.2 TRL Development Schedule

Maturing each of the 12 key maturation elements to TRL 6 is covered extensively in the previous section. Each of the TRL levels is met simultaneously by all of the maturation elements. For example, successfully testing the three modules aligned to the optical axis in X-rays and in operational environmental conditions will result in all of the maturation elements simultaneously achieving TRL 6. The projected dates for the TRLs are:

- TRL 3 – our current status
- TRL 4 – Q1 2021
- TRL 5 – Q3 2024
- TRL 6 – Q1 2027

After TRL 6, ramp up to production starts immediately. In order to meet the program milestone of the XMA ready for calibration on June 1, 2032, a few long lead items need to begin right after TRL 6 is achieved, before Critical Design Review (CDR); specifically, mandrel production and the preparation of the production facilities for slumping, mounting, and telescope assembly. Actual slumping and all other hardware activities will begin just after CDR.

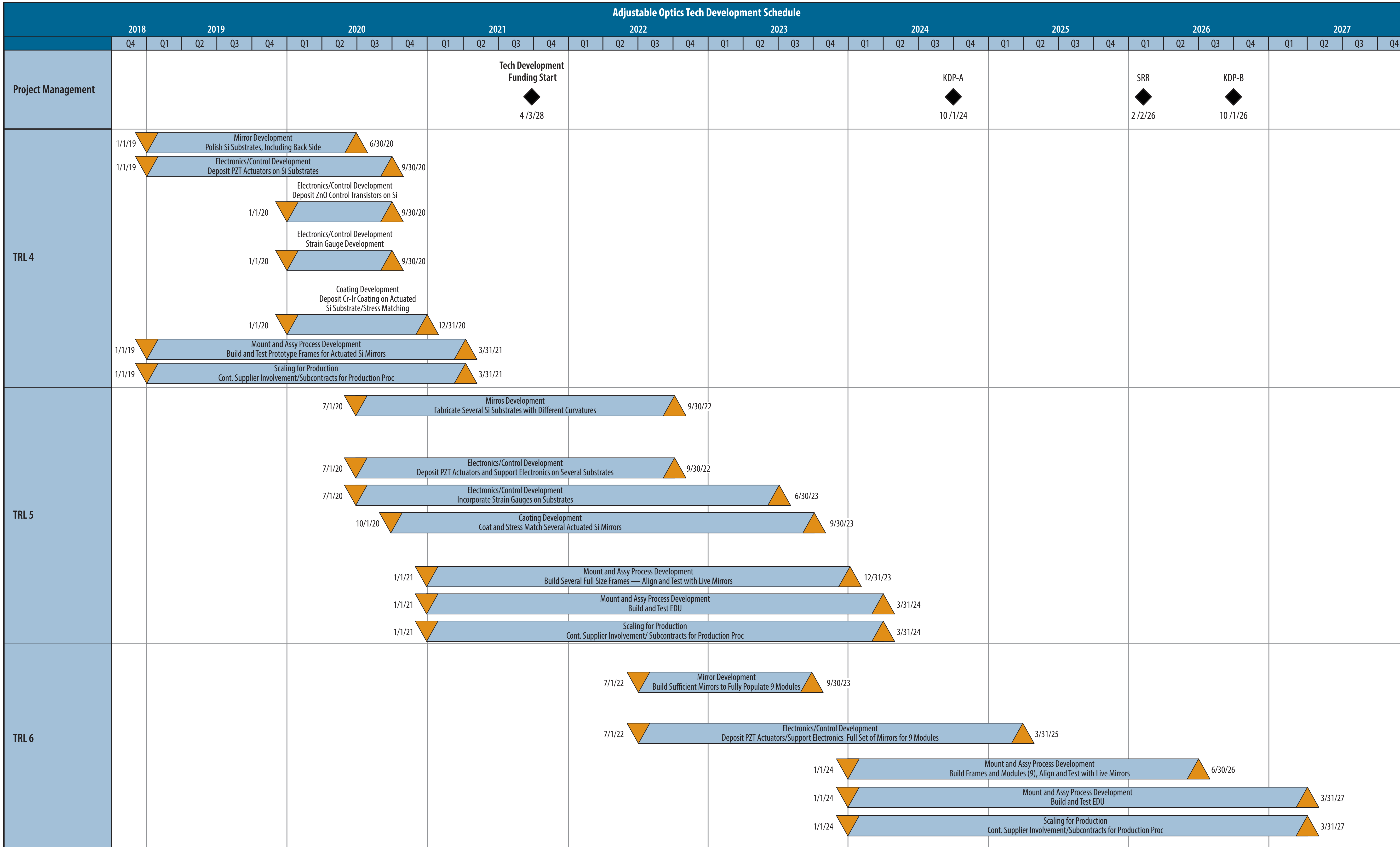


Fig. 9—High-level Gantt chart for XMA fabrication.

2.3 Cost

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2.4 Risks

An assessment of risks and risk mitigations follows. A summary is provided in Table 5. Fig. 10 presents the risk in the standard 5-×-5 format.

Table 5—Summary of adjustable optics technology maturation risks.

Risk	Title	L	C	T	S	$
1	Coating Stress	2	3	✓		
2	Strain gauge resolution/temperature dependency	3	3	✓		
3	Single mirror mount in a frame	3	3	✓		
4	Mirror pair alignment	3	3	✓		
5	Intra-module alignment	4	3	✓		
6	Inter-module alignment	4	4	✓		
7	PZTs on full-size wafer	3	3	✓		
8	Modeled gravity release prediction	2	4	✓		
9	Fabrication duration	3	2	1	✓	

L = likelihood of occurrence; C = consequence; T = technical risk, S = schedule risk, $ = cost risk

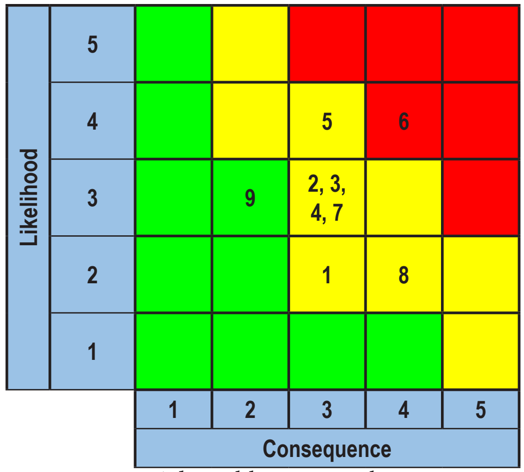


Fig. 10—Adjustable optics risk impact.

Risk 1 — Unable to coat an X-ray reflective surface on the mirrors without distorting the mirrors out of the capture correction range of the actuators due to stresses induced by the mirror coating, the mirror figure will be degraded, resulting in degraded telescope resolution.

Mitigation — The actuators are good at correcting low-frequency figure errors associated with coating stress. The actuators themselves are good mitigations against coating stress deformation. The probability of failure to tailor the coating stress to within the capture range of the actuators is fairly low.

Risk 2 — Unable to adequately control the mirror figure due to either lack of sufficient resolution of the strain gauges or strain gauge temperature dependencies beyond compensation, the mirror figure will be degraded, resulting in degraded telescope resolution.

Mitigation — The are several different ways to run the strain gauges. If the piezoelectric actuators are operated in AC mode with the strain gauge resistance monitored synchronously (phase loop locked), the temperature dependency is eliminated. It would be possible to poll the strain gauges periodically (say every ±6 months) while operating the piezos in AC mode and use that information to change the drive voltage on the actuators as the PZT ages. Another way to use the gauges is to orient the strain sensitive direction of gauges along the direction normal to the mirror surface (which is unstrained) and use those gauges as temperature gauges. This approach can be used in two ways: (1) monitor temperature at the 0.01 °C accuracy level and use this information to update structural-thermal-optical performance (STOP) models and the piezo solution as required, and/or (2) close the loop with other strain gauges oriented along the piezo strain direction—parallel to the mirror surface—which will change due to temperature changes. In this mode, mirror control can be real time, and updated at relatively high frequency. However, the need to monitor and update rapidly is not anticipated because changes in mirror temperature are expected to be slow, resulting from temperature control system and multi-layer insulation aging on-orbit, and significant changes in sun exposure to the spacecraft. Because of the demonstrated capabilities for measuring the piezoelectric coefficient and measurement of temperature, the first two modes (piezo aging and mirror temperature) are expected to be low risk applications. Only strain gauge signal-to-noise limits in measuring for the direct figure change mode represents a "stressful" application (although there are several approaches for "pulling" the signal out of the noise that can be applied in this case). In any case, there is a need to investigate strain gauges to control the mirrors, an activity planned between TRL 4 and TRL 5.

Risk 3 — Unable to mount the full-size mirror with the point design's edge mounting clips without distorting the mirror beyond the capture range of the actuator correction due to epoxy shrinkage or mechanical forces applied to the mirror during mounting, which leads to mirror figure degradation, resulting in degraded telescope resolution.

Mitigation — The focus of current efforts to get from TRL 3 to 4 is to validate the models that predict mount performance; in this case for the proof of concept edge mounting clips and frame for a 100-×-100-mm mirror. Current models of the same mounting technique for full-size mirrors shows that the larger mirrors can be mounted within error budgeted targets. Focus is now on validating the models.

Risk 4 — Unable to align and hold the mirror pair position relative to each other as mounted in the frame due to epoxy shrinkage, mechanical forces applied during assembly, or mount temperature dependence, compromising telescope resolution.

Mitigation — The effort to get to TRL 4 will include a proof of concept of a 100-×-100-mm mirror pair mounted in a frame and X-ray tested. This will go a long way toward validating the models that predict mount performance. Further effort to TRL 5 will involve testing a full-size mirror pair.

Risk 5 — Unable to align and hold a mirror pair to mirror pair alignment within a module due to mechanically induced stress during assembly, epoxy shrinkage, or mount temperature dependence, compromising telescope resolution.

Mitigation — Current models show the frames can be built up into modules while holding the alignment to error budgeted tolerances. Mitigation will be to validate those models throughout the development, culminating in empirical verification during the TRL 5 testing.

Risk 6 — Unable to align and hold module to module on the telescope superstructure due to mechanically induced stress during assembly, epoxy shrinkage, or assembly temperature dependence, compromising telescope resolution.

Mitigation — Current models show the modules can be aligned to other modules on the telescope support structure while holding the alignment to error budgeted tolerances. Mitigation will be to validate those models throughout the development, culminating in empirical verification during the TRL 5 testing.

Risk 7 — Unable to apply PZT (the piezoelectric material) and anneal it to the back of the full-size mirror while still keeping the mirror figure within the capture range of the actuators due to non-uniform stress produced by PZT processing, leading to degradation of the mirror figure and resulting in degraded telescope resolution.

Mitigation — The current plan is to allow for post-slump mirror correction to also serve as post-PZT mirror correction. The mirror front will not be polished for final correction until all of the depositions on the back of the mirror are complete. The test mirror polished at Harris Corp to date did have all of the electronics on the back. Results are not in at the time of this writing, but the mirror appears to have survived the correction run and the electronics are intact. In addition, there are several other risk mitigation approaches. One approach is to increase the correction dynamic range of the PZTs by: (1) increasing the operational voltage range and (2) changing the ground electrode from Pt to lanthanum nickel oxide. At present, the PZT is limited to a maximum electric field of ~70 kV/cm: the breakdown voltage of the PZT films as deposited are in excess of 250 kV/cm.

This can readily double the correction dynamic range without risk of electrical breakdown. It would come at the expense of piezo lifetime, but, based upon accelerated lifetime testing, would reduce lifetime from hundreds of years to ~100 years, well beyond a mission lifetime, including Phases B/C/D. Lanthanum nickel oxide as a ground electrode can result in a doubling of the piezoelectric coefficient. The combination of both of these factors may increase our correction dynamic range by as much as a factor of 4.

A second approach is to improve thermal uniformity of the oven used to anneal/crystalize the PZT (currently done in a university lab as opposed to a production environment), as well as improve the deposition uniformity by using an axial sputter source (e.g., how *Chandra* was coated), rather than the planetary approach currently employed because of the use of existing sputter chambers at PSU.

A third approach would be to employ the one used in the commercial thermal forming industry for optical lenses—adjust the shape of the mandrel until the desired shape is achieved post-thermal forming. In this case, it would be necessary to bias the mandrel shape to account for the effects of PZT uniform and non-uniform stresses post annealing. Such an approach cannot be tested at this point in time. Once transferred to industry, the process might be far more amenable to such an approach as commercial deposition processes yield highly constant stress (within a percent or 2) over many parts. This would result in a repeatable, known deformation from PZT deposition/annealing stresses which may be readily accounted for before-the-fact by biasing the slumping operation (the mandrel) to accommodate the stress induced change in shape. This last approach would clearly be one most readily explored during pre-Phase A through Phase A.

Risk 8 — Unable to predict the gravity release on orbit to within the error budgeted tolerances due to large gravity release terms, leading to degraded telescope resolution.

Mitigation — Perform multiple tests in the course of the development to validate the models. The only solution for this issue is to have models that can be trusted to predict on-orbit performance, and in order to get that the models will be validated. This risk is considered low given past experience with model verification on *Chandra* (AXAF) conical shells and Con-X segments.

Risk 9 — Cannot build the flight unit in the time allocated due to longer production times for the high number of mirror segments needed or cannot install and align the high number of mirrors in time, causing LMA delivery to be delayed.

Mitigation — Working with industry will ensure that capacities are balanced so that a process flow, at the requisite rate will be possible. If that means more equipment and more personnel, that will be reflected in the project costs and schedules.

3 Appendices

3.1 NASA TRL Definitions

TRL definitions per NASA Procedural Requirement (NPR) 7123.1B, Appendix E, are reproduced in their entirety in Table 6.

Table 6—NASA TRL definitions.

TRL	Definition	Hardware Description	Software Description	Exit Criteria
1	Basic principles observed and reported	Scientific knowledge generated underpinning hardware technology concepts/ applications.	Scientific knowledge generated underpinning hardware technology concepts/ applications.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated	Invention begins, practical applications is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Practical application is identified but is speculative; no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations, and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental critical function and/or characteristic proof-of- concept	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/ experimental results validating predictions of key parameters.
4	Component and/or breadboard validation in laboratory environment	A low fidelity system/ component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to final operating environment.	Key, functionality critical software components are integrated and functionally validated to establish interoperability and begin architecture development. Relevant environments defined and performance in the environment predicted.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment
5	Component and/or Breadboard validation in relevant environment.	A medium fidelity system/ component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrate overall performance in critical areas. Performance predictions are made for subsequent development phases	End-to-end software: Elements implemented and interfaced with existing systems/ simulations conforming to target environment. End-to-end software system tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements

TRL	Definition	Hardware Description	Software Description	Exit Criteria
6	System/subsystem model or prototype demonstration in a relevant environment.	A high fidelity system/ component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale, realistic problems. Partially integrated with existing hardware/ software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions
7	System prototype demonstration in an operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test performance demonstrating agreement with analytical predictions
8	Actual system completed and "flight qualified" through test and demonstration	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space)	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed.	Documented test performance verifying analytical predictions.
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All documentation has been completed. Sustaining software support is in place. System has been successfully operated in the operational environment	Documented mission operational results.

3.2 AD^2 Definitions

AD^2 (Advancement Degree of Difficulty) is a description of what is required to move a system, subsystem, or component from one TRL to the next. TRL is a static description of the current state of the technology as a whole. AD^2 is what it takes, in terms of cost, schedule, and risk to advance to the next TRL. AD^2 is defined on a scale of 1–9 in a manner similar to TRL. The description of the AD^2 levels is shown in Table 7.

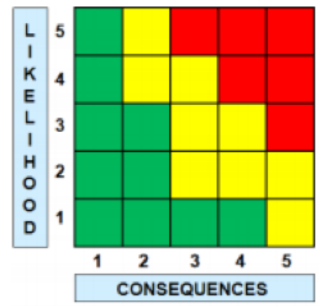
Table 7—AD^2 level definitions.

AD^2	Definition	Risk	Category	Success Chance
1	Exists with no or only minor modifications being required. A single development approach is adequate.	0%		Guaranteed Success
2	Exists but requires major modifications. A single development approach is adequate.	10%		
3	Requires new development well within the experience base. A single development approach is adequate.	20%		
4	Requires new development but similarity to existing experience is sufficient to warrant comparison across the board. A single development approach can be taken with a high degree of confidence for success.	30%	Well Understood (Variation)	Almost Certain Success
5	Requires new development but similarity to existing experience is sufficient to warrant comparison in all critical areas. Dual development approaches should be pursued to provide a high degree of confidence for success.	40%	Known Unknowns	Probably Will Succeed
6	Requires new development but similarity to existing experience is sufficient to warrant comparison on only a subset of critical areas. Dual development approaches should be pursued in order to achieve a moderate degree of confidence for success. Desired performance can be achieved in subsequent block upgrades with high confidence.	50%		
7	Requires new development but similarity to existing experience is sufficient to warrant comparison in only a subset of critical areas. Multiple development routes must be pursued.	70%		
8	Requires new development where similarity to existing experience base can be defined only in the broadest sense. Multiple development routes must be prepared.	80%	Unknown Unknowns	High Likelihood of Failure (High Reward)
9	Requires new development outside of any existing experience base. No viable approaches exist that can be pursued with any degree of confidence. Basic research in key areas needed before feasible approaches can be defined.	100%	Chaos	Almost Certain Failure (Very High Reward)

3.3 Risk Definitions

The standard risk scale for consequence and likelihood are taken from Goddard Procedural Requirements (GPR) 7120.4D, Risk Management Reporting. The definitions for likelihood and consequence categories are provided in Fig. 11.

Likelihood	Safety Estimated likelihood of Safety event occurrence	Technical Estimated likelihood of not meeting performance requirements	Cost Schedule Estimated likelihood of not meeting cost or schedule commitment
5 Very High	$(P_{SE} > 10^{-1})$	$(P_T > 50\%)$	$(P_{CS} > 75\%)$
4 High	$(10^{-2} < P_{SE} \leq 10^{-1})$	$(25\% < P_T \leq 50\%)$	$(50\% < P_{CS} \leq 75\%)$
3 Moderate	$(10^{-3} < P_{SE} \leq 10^{-2})$	$(15\% < P_T \leq 25\%)$	$(25\% < P_{CS} \leq 50\%)$
2 Low	$(10^{-5} < P_{SE} \leq 10^{-3})$	$(2\% < P_T \leq 15\%)$	$(10\% < P_{CS} \leq 25\%)$
1 Very Low	$(10^{-6} < P_{SE} \leq 10^{-5})$	$(0.1\% < P_T \leq 2\%)$	$(2\% < P_{CS} \leq 10\%)$



Consequence Categories					
Risk	1 Very Low	2 Low	3 Moderate	4 High	5 Very High
Safety	Negligible or not impact	Could cause the need for only minor first aid treatment	May cause minor injury or occupational illness or minor property damage	May cause severe injury or occupational illness or major property damage.	May cause death or permanently disabling injury or destruction of property.
Technical	No impact to full mission success criteria	Minor impact to full mission success criteria	Moderate impact to full mission success criteria. Minimum mission success criteria is achievable with margin	Major impact to full mission success criteria. Minimum mission success criteria is achievable	Minimum mission success criteria is not achievable
Schedule	Negligible or no schedule impact	Minor impact to schedule milestones; accommodates within reserves; no impact to critical path	Impact to schedule milestones; accommodates within reserves; moderate impact to critical path	Major impact to schedule milestones; major impact to critical path	Cannot meet schedule and program milestones
Cost	<2% increase over allocated and negligible impact on reserve	Between 2% and 5% increase over allocated and can handle with reserve	Between 5% and 7% increase over allocated and cannot handle with reserve	Between 7% and 10% increase over allocated, and/or exceeds proper reserves	>10% increase over allocated, and/or can't handle with reserves

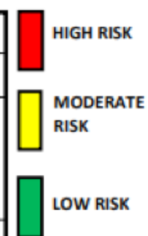


Fig. 11—Risk matrix standard scale.

3.4 Acronyms

ACF	Anisotropic Conductive Films
AI&T	Assembly, Integration, and Test
APRA	Astrophysics Research and Analysis
ASIC	Application-Specific Integrated Circuit
CDR	Critical Design Review
COG	Chip-on-Glass
FOV	Field of View
GSFC	Goddard Space Flight Center
HPD	Half Power Diameter
HRMA	High Resolution Mirror Assembly
IXO	International X-ray Observatory
MRF	Magneto-Rheological Finishing
PCOS	Physics of the Cosmos
PDR	Preliminary Design Review
PSF	Point Spread Function
PSU	Penn State University
ROSES	Research Opportunities in Space and Earth Sciences
RTA	Rapid Thermal Annealer
SAO	Smithsonian Astrophysical Observatory
SOA	State of the Art
TFT	Thin Film Transistor
TRL	Technology Readiness
XMA	X-ray Mirror Assembly

3.5 References

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