

## **Silicon Meta-Shell Optics Technology Roadmap**

## Table of Contents

1	Introduction .....	1
2	Silicon Meta-Shell Optics Overview .....	2
3	Four Key Technical Elements of the Silicon Meta-Shell Optics .....	4
3.1	Fabrication of Mirror Substrates .....	5
3.2	Mirror Coating .....	8
3.3	Mirror Alignment .....	9
3.4	Mirror Bonding .....	10
3.5	State of the Art .....	11
4	Technology Roadmap.....	11
4.1	TRL 4 Development.....	12
4.2	TRL 5 Development.....	13
4.3	TRL 6 Development.....	14
4.4	Milestones, Significance, and Verification .....	16
5	Schedule .....	21
6	Costs .....	23
7	Risks.....	23
8	Summary.....	24
9	Appendices .....	25
9.1	NASA TRL Definitions.....	25
9.2	AD <sup>2</sup> Definitions.....	27
9.3	Risk Definitions.....	28
9.4	Acronyms .....	29
9.5	References .....	30

This document presents a roadmap for advancing the Silicon Meta-shell Optics. It describes an overall strategy and key technical elements to be developed to meet the four-fold *Lynx* requirements: (1) angular resolution, (2) effective area, (3) mass, and (4) production schedule and cost. It also describes the building and testing of an engineering unit whose successful completion will retire all risks, technical, logistical, schedule, and cost, associated with building and delivering a mirror assembly for the *Lynx* mission. All of this work, designed to advance this technology to TRL 6, will be completed by Preliminary Design Review to ensure that the flight mirror assembly production process will be a repetition of a set of well-defined and mature steps, leading to on-time and on-budget delivery of a mirror assembly for the *Lynx* mission.

## 1 Introduction

The challenge of the *Lynx* mirror assembly lies in the combination of, or the simultaneous fulfillment of, four requirements: (1) Point Spread Function (PSF), (2) effective area, (3) mass, and (4) production schedule and cost. The leftmost two columns of Table 1 show the requirements on *Lynx* optics derived from its science requirements. Meeting any one, two, or even three of these four requirements is relatively straightforward, and arguably has been done by existing and past technologies flown on such missions as *ASCA*, *Suzaku*, *XMM-Newton*, *Chandra*, and *NuSTAR*. But as of June 2019, no technology has been able to meet all four requirements simultaneously. The Silicon Meta-shell Optics technology—conceived in 2011 and continually developed by the Next Generation X-ray Optics group at NASA Goddard Space Flight Center—has the potential. By incorporating all knowledge and lessons learned over the last five decades of building and flying X-ray optics in space, Silicon Meta-shell Optics technology uses only commercially available materials (e.g., monocrystalline silicon) and equipment (e.g., the latest deterministic precision polishing machines) developed and made commercially available within the last two decades by the semiconductor industry. The rightmost column of Table 1 shows the basic strategy that Silicon Meta-shell Optics has adopted to meet those requirements.

Table 1—*Lynx* requirements on its mirror assembly derived from its science drivers and the strategy of the Silicon Meta-shell Optics technology to meet them.

Lynx Mirror Assembly Requirements Derived from Science Requirements		Silicon Meta-Shell Optics Strategy to Meet Lynx Mirror Assembly Requirements
PSF (on-axis)	Better than 0.5 arcsec	<ol style="list-style-type: none"> <li>1. Use of deterministic polishing technology and metrology techniques to make and fully qualify each mirror segment.</li> <li>2. Use of kinematic support for alignment and minimal constraint for permanent bonding to realize full performance potential of each mirror segment.</li> <li>3. Use of a Wolter-Schwarzschild optical prescription optimized for best off-axis response.</li> <li>4. Use of mirror segments short in the axial direction (100 mm) to minimize effects of field curvature.</li> </ol>
PSF (10 arcmin off-axis)	Better than 1 arcsec	
Effective area	2 m <sup>2</sup> at 1 keV	<ol style="list-style-type: none"> <li>1. Fabrication and assembly of more than 360 m<sup>2</sup> of mirror surface area.</li> <li>2. Use of mono-crystalline silicon to make thin (0.5 mm) mirror segments to enable efficient packing of the large mirror area into a small volume.</li> <li>3. Coating of the mirror surface with iridium film and possibly other interference coatings to enhance or maximize reflectivity.</li> </ol>

Lynx Mirror Assembly Requirements Derived from Science Requirements		Silicon Meta-Shell Optics Strategy to Meet Lynx Mirror Assembly Requirements
Mass	<2,500 kg	<ol style="list-style-type: none"> <li>1. Use of monocrystalline silicon to make mirror segments that are geometrically thin and lightweight.</li> <li>2. Use of a modular buildup process to minimize the mass of required structural support material.</li> </ol>
Production schedule and cost	<4 years <~\$500M	<ol style="list-style-type: none"> <li>1. Use of commercial off-the-shelf material and equipment to minimize ramp-up schedule.</li> <li>2. Use of mass production technology and processes.</li> <li>3. Reduction of the entire mirror assembly production into a small number of highly mature and efficient routines that are repeated tens of thousands of times.</li> </ol>

As of June 2019, all four basic technical elements of the Silicon Meta-shell Optics technology have been experimentally shown to be viable: (1) fabrication of mirror substrates to required quality, (2) coating of these substrates to maximize reflectivity to meet effective area requirement while preserving figure quality, (3) alignment of mirror segments using a four-point kinematic support, and (4) bonding of mirror segments on the four points using adhesive. However, much remains to be done to refine, mature, and perfect these technical elements to fully meet *Lynx* requirements and retire all risks, both technological and programmatical. This roadmap outlines our approach to advancing this technology to Technology Readiness Level 4 (TRL 4) no later than March 2021, TRL 5 by January 2024, and TRL 6 by January 2027 to support a production process in the subsequent four years, culminating in the delivery of the *Lynx* mirror assembly for integration into the *Lynx* Observatory.

## 2 Silicon Meta-Shell Optics Overview

Silicon Meta-shell Optics is a modular approach to building and testing a mirror assembly, as shown in Fig. 1. It takes four largely independent, major steps to build a mirror assembly, which, in practice, will overlap in time and share facilities and personnel. In the first step, shown in the upper left of Fig. 1, 37,492 mirror segments are fabricated and qualified. Although they are of 914 different optical design prescriptions, 457 primary mirrors, and 457 secondary mirrors, they have similar dimensions (i.e., ~100 mm in the optical axis direction, 100 mm in the circumferential direction, and 0.5 mm in thickness). In the second step, shown in the upper-right panel of Fig. 1, these 37,492 mirror segments are integrated, aligned, and bonded into 611 mirror modules. Each module, in addition to the mirror segments themselves, also includes a mid-plate made of the same material as the mirror segments and onto which all the mirror segments are attached either directly or indirectly via other mirror segments, as well as many non-reflecting stray light baffles. In the third step, shown in the lower-right panel of Fig. 1, the 611 mirror modules are integrated into 12 meta-shells, each of which contains 12 (innermost) to 91 (outermost) identical mirror modules. Finally, in the fourth step, the 12 meta-shells are integrated to create the *Lynx* assembly.

This modular approach has been adopted due to its many advantages. Each step is conceptually, technically, and programmatically isolated from one another, therefore isolating and minimizing technical and programmatic risks. Each step has to build, qualify, and deliver to the next step components that meet well-defined requirements, both in terms of science performance (such as angular resolution and effective area) and of structural and environmental robustness. Another important advantage is that this approach separates and isolates the technology development effort

from engineering and programmatic efforts, which are necessary to successfully build a mirror assembly. This clear separation or compartmentalization enables the most efficient use of technical and financial resources at different stages of mission development. Table 2 shows a top-level angular resolution error budget that is used to guide the technology development effort. The following sections elaborate upon each of the major steps necessary to build a *Lynx* mirror assembly.

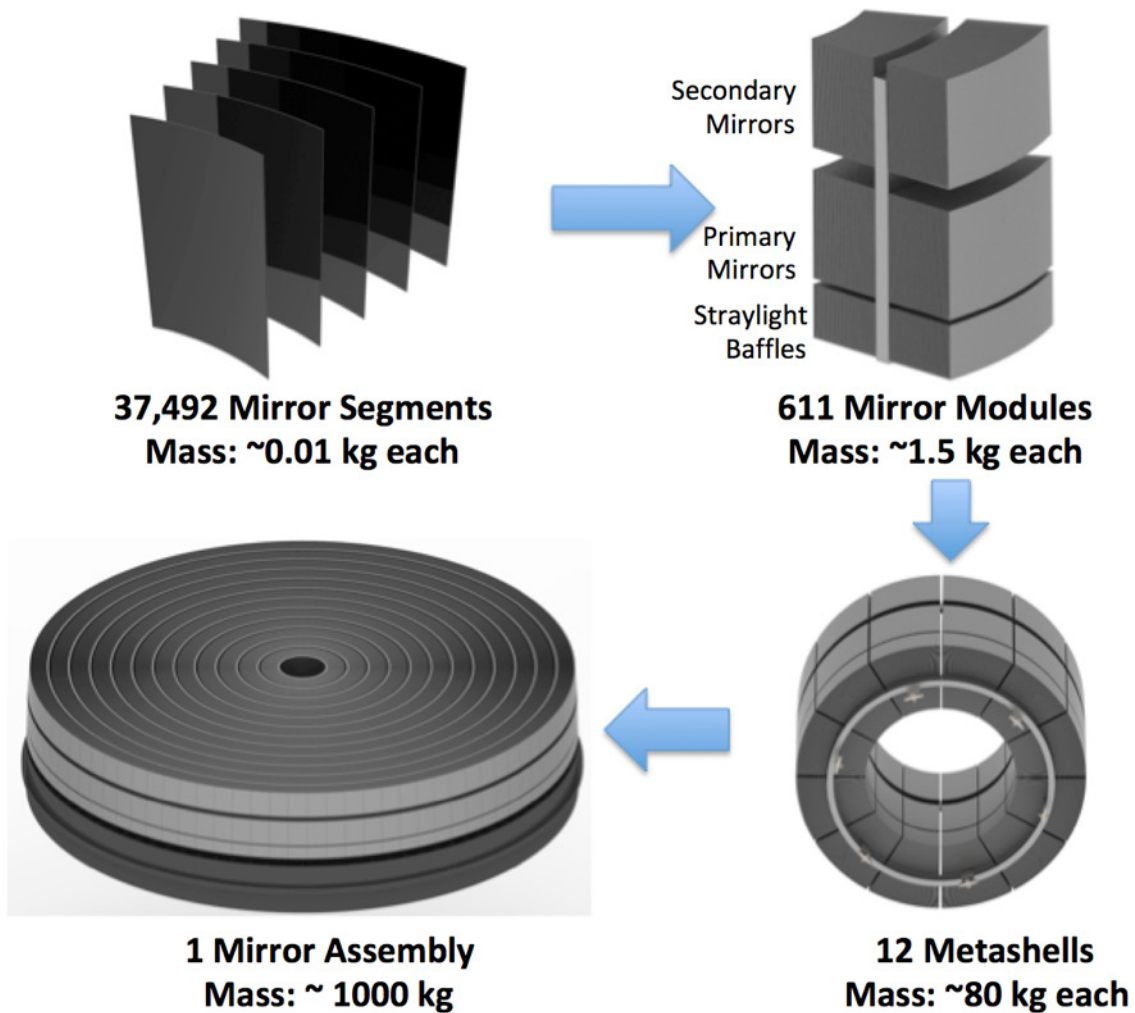


Fig. 1—The four major steps of building a mirror assembly for *Lynx*. (Upper-left) Fabrication and qualification of mirror segments, each measuring  $\sim 100\text{ mm} \times 100\text{ mm} \times 0.5\text{ mm}$ . (Upper-right) Those mirror segments are integrated into 611 mirror modules, each of which is independently built and tested. The current *Lynx* design calls for a minimum of 21 mirror segment pairs per module and a maximum of 75 pairs per module. (Lower-right) The 611 mirror modules are in turn integrated into 12 meta-shells, each of which again is individually and independently built and tested. (Lower-left) Finally, the 12 meta-shells are integrated into a mirror assembly that will then be qualified for spaceflight.

Table 2—Top-level angular resolution error budget guiding technology development to meet *Lynx* requirements. The hierarchical meta-shell approach isolates the technology development to the rows with bold-faced letters (i.e., fabrication of mirror segments, and alignment and bonding of them to make mirror modules). All other items such as integration of modules into meta-shells and, in turn, integration of meta-shells into assembly are challenging engineering tasks but require no technology development. Substantially similar tasks have been repeatedly done for past missions.

Major Steps	Cumulative HPD Req (arcsecond, 2 reflections)	Error Sources	Allocation (or Req) (arcsecond HPD, 2 reflections)	Technology Status as of March 2019 (arcsecond HPD, 2 reflections)	Notes
Optical prescription	0.11	Diffraction	0.10	0.10	At 1 keV, weighted average of diffraction limits of all shells.
		Geometric PSF (on-axis)	0.05	0.05	On-axis design PSF is slightly degraded to achieve best possible off-axis PSF.
Fabrication of mirror segments	0.25	Mirror Substrate	0.20	0.40	Each pair of mirror segments must have a PSF better than 0.2-arcseconds HPD, based on optical metrology.
		Coating	0.10	0.20	Coating that maximizes X-ray reflectance must not degrade the mirror pair's PSF by more than 0.1 arcseconds.
Integration of mirror segments into modules	0.34	Alignment	0.10	0.30	Each pair's image must be located within 0.1 arcseconds of the module's overall image.
		Bonding	0.20	0.30	Bonding of a mirror pair must not degrade its PSF by more than 0.2 arcseconds.
Integration of modules into meta-shells	0.36	Alignment	0.10	0.10*	Each module's image must be located within 0.1 arcseconds of the meta-shell's image.
		Bonding	0.10	0.10*	Bonding must not shift the module's image by more than 0.1 arcseconds.
Integration of meta-shells into mirror assembly	0.39	Alignment	0.10	0.10*	Each meta-shell's image must be located within 0.1 arcseconds of the overall assembly's image.
		Attachment	0.10	0.10*	Permanent attachment of the meta-shell must not shift its image by more than 0.1 arcseconds.
Ground-to-orbit effects	0.43	Launch shift	0.10	0.10*	Launch shift must not degrade PSF by more than 0.1 arcseconds.
		Gravity release	0.10	0.14*	Disappearance of gravity must not degrade PSF by more than 0.1 arcseconds.
		On-orbit thermal	0.10	0.16*	On-orbit thermal disturbance must not degrade PSF by more than 0.1 arcseconds.
Mirror assembly on-orbit performance			0.43	0.70	On-axis PSF of the optics. Add effects of jitter and other effects to get the final observatory-level PSF.

\* Model performance estimates

### 3 Four Key Technical Elements of the Silicon Meta-Shell Optics

Of the steps required to build the *Lynx* mirror assembly, only two are unique, have never been done, and therefore require technology development; the others are straightforward engineering exercises. These two steps are (1) the fabrication of mirror segments, and (2) the alignment and

bonding of mirror segments to make the mirror modules. These steps are unique to the building of a large X-ray mirror assembly. They must meet the four-fold requirement of angular resolution, effective area, mass, and production schedule and cost. These two steps can be further divided into four technical elements: (1) fabrication of mirror substrates, (2) coating of these substrates to make mirror segments, (3) alignment of these mirror segments, and (4) bonding of these mirror segments to make modules. Table 3 includes a brief description of these four elements and their development status as of June 2019, with the focus of the work in coming years to mature them enough to fully meet *Lynx* requirements. In what follows, each of these four elements is described in detail.

Table 3—Brief description of the technical elements of the Silicon Meta-shell Optics technology and their status as of June 2019.

Key Technical Elements		Technical Approach	Status as of March 2019	Current & Future Development Work
Buildup of Mirror Modules	Fabrication of Substrates	Precision polishing and slicing of monocrystalline silicon.	Substrates have been made repeatedly nearly meeting all requirements: optical, structural, schedule, and cost.	<ol style="list-style-type: none"> <li>1. Refine and perfect process to increase efficiency and reduce cost;</li> <li>2. Further improving figure quality and ability to measure figure quality optically.</li> </ol>
	Coating	Standard iridium coating with a chromium binding layer; precision compensation of coating stress with SiO <sub>2</sub> stress.	Concept fully proven with several mirror segments.	<ol style="list-style-type: none"> <li>1. Refine process to achieve more precise stress compensation;</li> <li>2. Verify and establish coating stability over time.</li> </ol>
	Alignment	Use of four spacers to kinematically support a mirror segment; grinding the heights of four spacers to achieve alignment.	Concept fully proven with multiple trials of aligning single mirror segments as well as pairs of primary and secondary mirror segments.	<ol style="list-style-type: none"> <li>1. Refine the optical beam used for alignment to further reduce effect of diffraction and systematics associated with it;</li> <li>2. Speed up the alignment measurement process; and further automate the grinding process to deterministically set spacer heights.</li> </ol>
	Bonding	Precision application of epoxy between mirror surface and spacers.	Proof of concept with repeatedly bonding mirror segments.	<ol style="list-style-type: none"> <li>1. Improve the epoxy application process to ensure that all four spacers get equal amounts;</li> <li>2. Minimize figure distortion and alignment disturbance caused by epoxy shrinkage;</li> <li>3. Build and test repeatedly mirror modules with progressively more mirror pairs.</li> </ol>
Integration of modules into meta-shells	Each module is treated as a rigid body, aligned and bonded in all 6 degrees of freedom to a forward and an aft ring: X, Y, Z, pitch, yaw, and roll.		Work to commence once mirror modules are successfully and repeatedly built and tested.	
Integration of meta-shells into assembly	Each meta-shell is treated as a rigid body, aligned and flexure-bonded to a spider in all 6 degrees of freedom: X, Y, Z, pitch, yaw, and roll.		Work to commence once mirror meta-shells are successfully built and tested.	

### 3.1 Fabrication of Mirror Substrates

We have chosen direct fabrication as the method for making mirror segments because of two

considerations. First, of all techniques that have been used for making optics in general, and X-ray optics in particular, direct fabrication—also known as grind-and-polish—makes the best possible optics. Second, direct fabrication technology has progressed by leaps and bounds in the last 20 years, since the *Chandra* mirrors were fabricated in the 1990s. Many then-esoteric techniques have matured and have become commercially available in the form of turnkey machines. In particular, ion beam figuring technology has become widely used in the semiconductor industry for making high-precision wafers meet more stringent device fabrication requirements. Perhaps most important of all, some of these polishing processes exert little to no shear stress or normal pressure on the substrate being polished, making it possible to fabricate extremely thin optics without breaking them.

In conjunction with choosing the direct fabrication method, we have chosen monocrystalline silicon as the mirror material for several reasons. First of all, monocrystalline silicon is free of internal stress, unlike other materials that are full of internal stress because of domain boundaries between crystal grains (as in metals) or because of super-cooling (as in glass). This lack of internal stress makes it possible to use the deterministic material removal techniques to make precision optics: any figure change is determined and only determined by the removal of material. In contrast, for a material with internal stress, the removal of material causes figure change in two ways: (1) the disappearance of the material itself and (2) the disappearance or appearance of stress as a result of the material removal. The figure change due to stress is unpredictable. While an unpredictable, stress-induced figure change is totally negligible for a thick (~10 mm) substrate, it is not so for a thin (~0.5 mm) substrate.

Second, silicon has highly desired material properties. It has a relatively low density of 2.33 g/cm<sup>3</sup>, lower than most glasses and aluminum. Its elastic modulus is approximately 150 GPa, twice that of the typical glass and aluminum alloys, making it relatively stiff. Equally important is its high thermal conductivity, that is, 150 W/mK at room temperature—more than 100 times higher than typical glass—minimizing thermal gradients caused by the hostile thermal environment of space. Compounding the benefit of high thermal conductivity is its low coefficient of thermal expansion, 2.6 ppm/K at room temperature, lower than typical glass and much lower than typical metals. All of these material properties make silicon almost the ideal material for making X-ray mirrors for spaceflight. It would be ideal if its coefficient of thermal expansion were zero.

In addition, monocrystalline silicon is an industrial material. Very large blocks of it are commercially available at low costs. Along with material availability comes a large body of knowledge accumulated over the past 50 years, as well as the industrial equipment required for processing. No other material enjoys these advantages. As a matter of fact, a key aspect of this technology development is to maximize the use of these advantages to make the best X-ray optics at the lowest possible cost.

Once the fabrication technique and material are determined, the thickness of the mirror segment can be determined by three parameters: (1) mass allocated for the mirror assembly, (2) mirror surface area, and (3) density of the material. For *Lynx*, these three parameters lead to a thickness of 0.5 mm. The dimensions of the mirror segment are then determined by finite element analysis requiring that gravity distortion, while the mirror is supported at four locations, be sufficiently small to meet angular resolution requirements. All things considered, the dimensions of the mirror segment are determined to be 100 × 100 × 0.5 mm. This size happens to be similar to a 150-mm-diameter wafer that is commonly produced and processed by the semiconductor industry, enabling the use of commercially available equipment and silicon blocks to facilitate mirror segment production and minimize cost.

The mirror substrate fabrication process, illustrated in Fig. 2, starts with a commercially procured



block of monocrystalline silicon measuring  $150 \times 150 \times 75$  mm, shown in the upper-left panel. In the next step, (upper-middle panel), a conical approximation contour is cut into the block with a band saw. The surface is then lapped on a precision conical tool to generate a precision conical surface that is a zeroth and first order approximation to an X-ray mirror segment. Then, the block is brought back to the band saw again to slice off a thin silicon shell, as illustrated in upper-right panel. This silicon shell, because of the cutting and lapping process, has damage to its crystal structure. To remove the damage, it is etched in a standard industrial process with a solution of hydrofluoric acid, nitric acid, and acetic acid. After this etching step, the thin shell is a single crystal where practically every atom is on its lattice location. The entire shell is free of internal stress. At this point, the shell's surface is matte and not capable of reflecting X-rays at all.

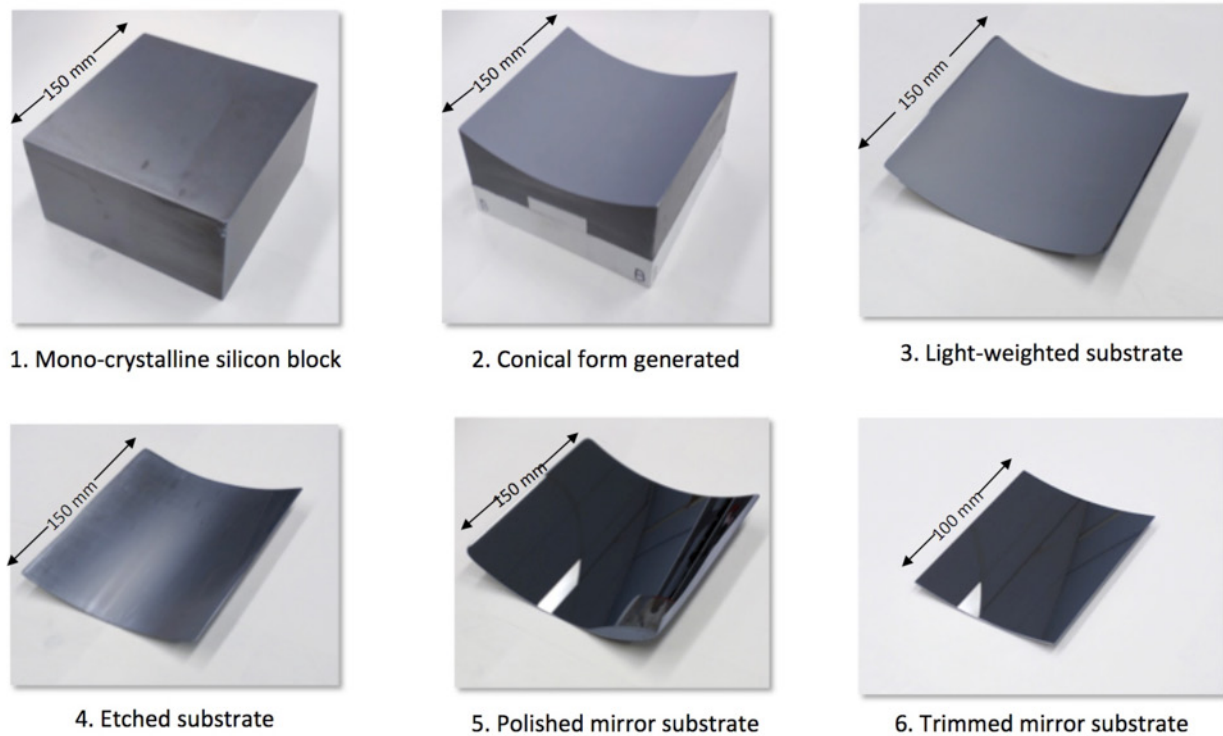


Fig. 2—Six major steps of fabricating a mirror substrate. This entire process, using no special equipment other than what is commonly available in the commercial market, takes about 15 hours of labor time and one week of calendar time. The process is highly amenable to automation and mass production, leading to high throughput and low cost.

Then, the conical substrate is polished with synthetic silk on a cylindrical tool to achieve required specularly and micro-roughness. In order for the reciprocation to be random in both the circumferential direction and axial direction to avoid grooving, the conical substrate is elastically bent into a cylindrical shape. This is equivalent to the stress-polishing process that was successfully used for making aspheric mirrors for the Keck telescopes. This step results in a mirror substrate whose clear aperture is  $\sim 100 \times 100$  mm, with roll-off errors near the four edges that are typical of full-aperture polishing processes, shown in the lower-middle panel of Fig. 2. The areas near the edges are removed on a dicing saw, resulting in a mirror substrate of the required size, shown in the lower-right panel. The monocrystalline nature of the substrate is such that the figure of the remaining mirror does not change at all as a result of the operation, as long as the damage caused by the cutting process is properly removed. The damage along the cut edges is removed via etching.

The final step of the mirror substrate fabrication is a figuring process using an ion beam. The mirror substrate is measured on an interferometer to produce a topographical map that is used to guide the ion beam to preferentially remove material where the surface is high. As of June 2019, mirror substrates have been fabricated repeatedly and have consistently met requirements. Fig. 3 shows the parameters of one of the mirror substrates. Its overall quality is similar to *Chandra's* mirror. Two mirrors like this one, when properly aligned, are predicted to achieve images of 0.4-arcseconds HPD at 1 keV. In the coming years, every step of the entire substrate fabrication process will be examined, refined, and perfected to achieve better substrates, reaching the diffraction limit by sometime in the late 2020s.

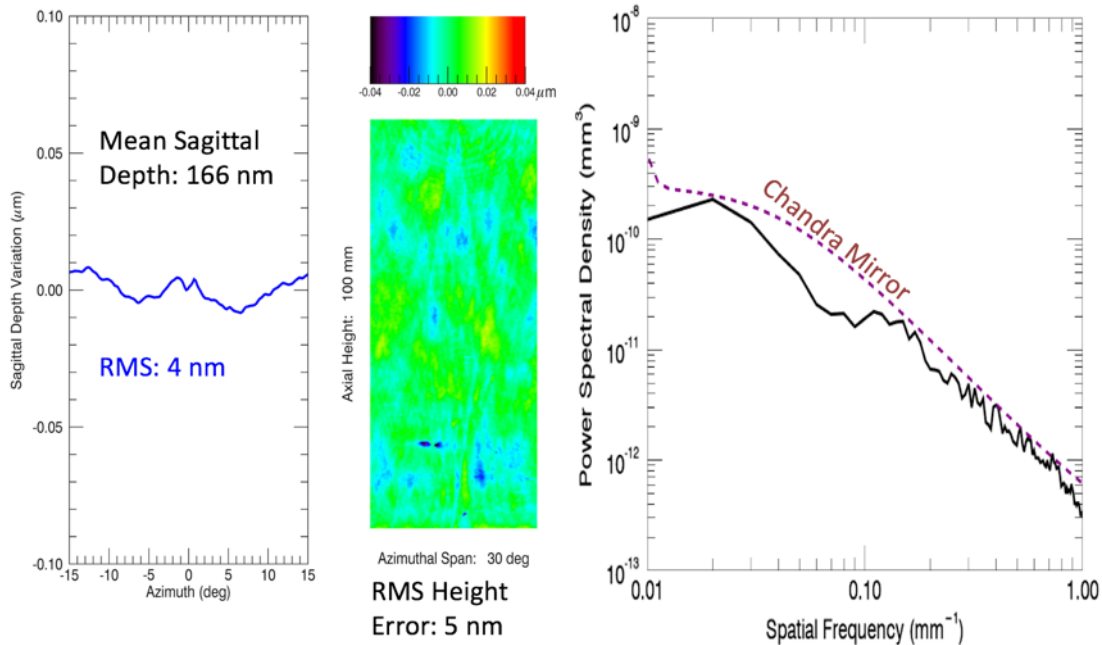


Fig. 3—Measured properties of a finished mirror substrate. (Left panel) Sagittal depth variation as a function of azimuth. This substrate's average sagittal depth of 166 nm differs from the design value of 174 nm by 8 nm. The RMS variation of the sagittal depth is 4 nm. (Middle panel) Surface error topography. After removal of the sagittal depth, this mirror has an RMS height error of only 5 nm. (Right panel) Power spectral density (black solid curve) in comparison with *Chandra's* mirror (purple dashed curve). All of the errors combine to make this mirror substrate have an image quality of 0.4 arcseconds HPD (two-reflection equivalent).

## 3.2 Mirror Coating

Bare silicon is a poor X-ray reflector. It needs to be coated with thin films to enhance its reflectivity. There are potentially many different ways of coating a bare silicon surface to achieve high reflectance, but for the purpose of this technology development, we assume the use of the traditional iridium coating. Other coatings, when fully demonstrated, can be implemented with little to no change to the process presented here. The major issue related to coating is that coating introduces stress that can severely distort the figure of a mirror substrate. The preservation of the substrate figure requires a way to cancel or otherwise compensate for the effect caused by the coating stress.

The coating process, shown in Fig. 4(1), starts with a bare silicon substrate cleaned of particulate and molecular contaminants. Using the standard semiconductor industry's dry oxide growth process, the backside (i.e., the convex side or the non-reflecting side) is coated with a layer of silicon

oxide. The silicon oxide exerts compressive stress on the substrate, causing it to distort as shown in Fig. 4(2). Then a thin film of iridium, with an undercoat of chrome serving as a binding layer, is sputtered on the front side. The compressive stress of the iridium film counteracts the silicon oxide stress, cancelling some of the distortion (shown in Fig. 4(3)), but still significant distortion remains. The final step (shown in Fig. 4(4)) is to trim the thickness of the  $\text{SiO}_2$  layer to achieve precise balance of stresses and restore the figure of the substrate. The trimming is guided by precise figure measurement and finite element analysis.

One way of trimming the thickness of the silicon oxide layer is by using chemical etching, which has been recently demonstrated (Yao et al. 2019). Another way is using an ion beam, the same as figuring the silicon substrate. Since this is a dry process, as opposed to the wet chemical etching process, it has the advantage of being cleaner. It is expected that this will be experimented with in 2019.

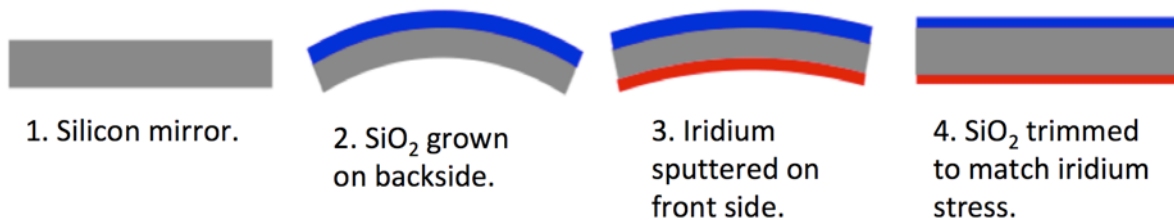


Fig. 4—Illustration of mirror coating process to enhance X-ray reflectance while preserving the figure quality of the silicon substrate. The distortion caused by the stress of the iridium thin film is precisely balanced by the stress of the silicon oxide on the other side of the mirror substrate.

### 3.3 Mirror Alignment

A mirror segment needs to be aligned and bonded to form part of a mirror module. A mirror segment will be supported at four optimized locations, as shown in Fig. 5. Four supports, as in the case of three supports for a flat mirror, *necessarily* and *sufficiently* determine the location and orientation of a curved mirror such as an X-ray mirror. Using gravity (i.e., the weight of the mirror segment) as the nesting force, the alignment of the mirror segment is determined by the heights of the four supports, which are interchangeably called “posts” or “spacers.” The alignment task is reduced to the precision grinding of the heights of these spacers.

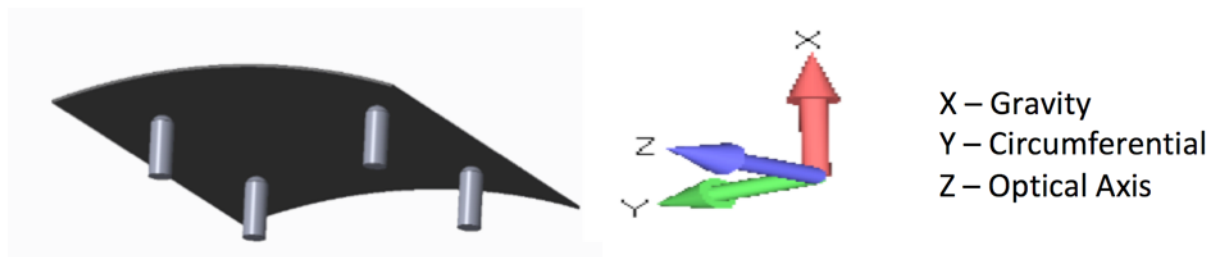


Fig. 5—Illustration of the 4-point kinematic support of an X-ray mirror. The four supports, also known as spacers or posts, are approximately located one quarter of the way inboard from each corner. See text for a discussion of the advantages of aligning and bonding a mirror segment using these four supports.

The alignment process is an iteration of Hartmann measurements using a beam of visible light monitored by a CCD camera (shown in Fig. 6) and precision grinding of the heights of the spacers. The precision of the spacer heights required depends on the radius of curvature of the

mirror segment. In the worst case for *Lynx* for the largest radius of curvature of 1,500 mm, the 0.1-arcsecond alignment error budgeted in Table 2 translates into a spacer height error of 25 nm. With a deterministic material removal process, this precision is easily achievable. Over the course of the last two years, many mirror segments have been repeatedly aligned—both primary and secondary ones individually and primary and secondary segments combined—achieving alignment accuracy of approximately 1-arcsecond HPD, which is dominated by the diffraction effect of the visible light, limiting the precision of alignment determination. The plan forward is to refine this process by using visible light of a shorter wavelength to minimize the diffraction effect to achieve 0.1-arcsecond alignment precision.

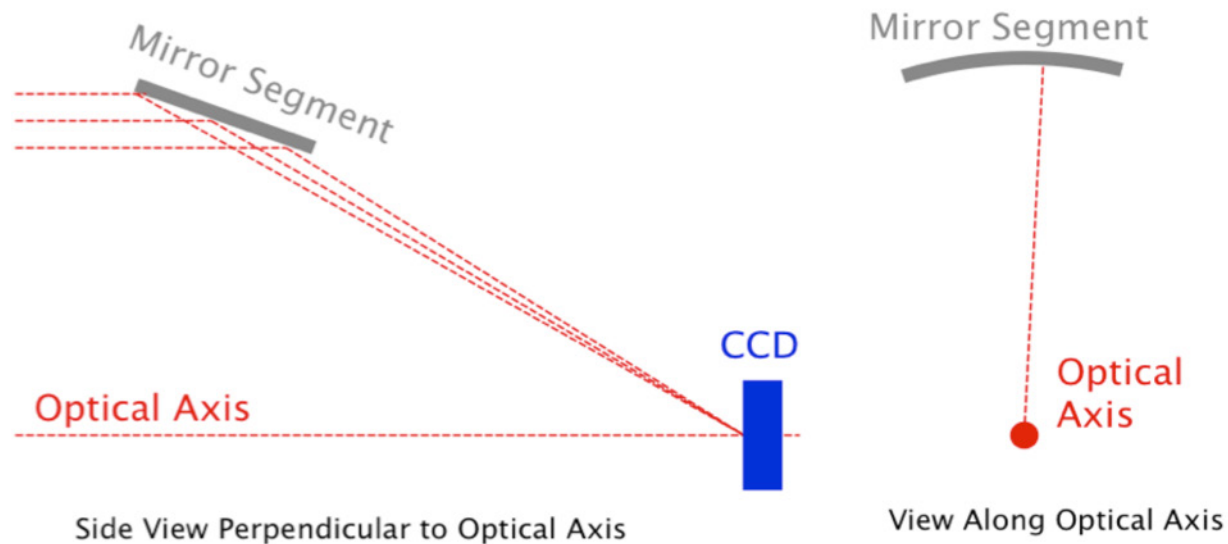


Fig. 6—Illustration of the Hartmann setup using a beam of visible light to measure the location and orientation of the mirror segment being aligned.

### 3.4 Mirror Bonding

Bonding the mirror segment is a direct extension of the alignment process. Once the four spacers have the correct heights, as determined by the Hartmann measurement, the mirror segment is removed, a small amount of epoxy is applied to the top of each of the four spacers, and the mirror segment is re-applied. Finally, vibrations are applied to help the mirror segment settle in its optimal configuration, the same way as during the iterative alignment process. During the settling process, because of the weight of the mirror and the vibrations, the epoxy on each spacer is spread and compressed. The mirror segment is permanently bonded when the epoxy has cured.

Supporting and bonding the mirror segment in this way has many advantages. First, the gravity-induced distortion is not frozen permanently. Because of the optimization of the locations of the four spacers, the gravity distortion disappears once the gravity is released. Second, the epoxy bonds do not affect the alignment of the mirror segment. Third, any local distortion caused by epoxy cure is minimal, as the diameter of the spacer is only a few times larger than the thickness of the mirror segment. The mirror segment, being 0.5 mm in thickness, is very stiff over the length scale of several millimeters similar to the diameter of the spacers.

### 3.5 State of the Art

The validity of the entire process, from mirror substrate fabrication to alignment and bonding, has been demonstrated through the successful repeated building and testing of mirror modules, as shown in Fig. 7. A module was placed in the 600-m X-ray beam line at NASA Goddard Space Flight Center and produced images with 1.3-arcseconds HPD, as shown in the right panel. A similar module was tested at the PANTER 130-m X-ray beam line and measured for its effective areas at several different energies, agreeing within 2% with calculations based on atomic form factors independently measured.

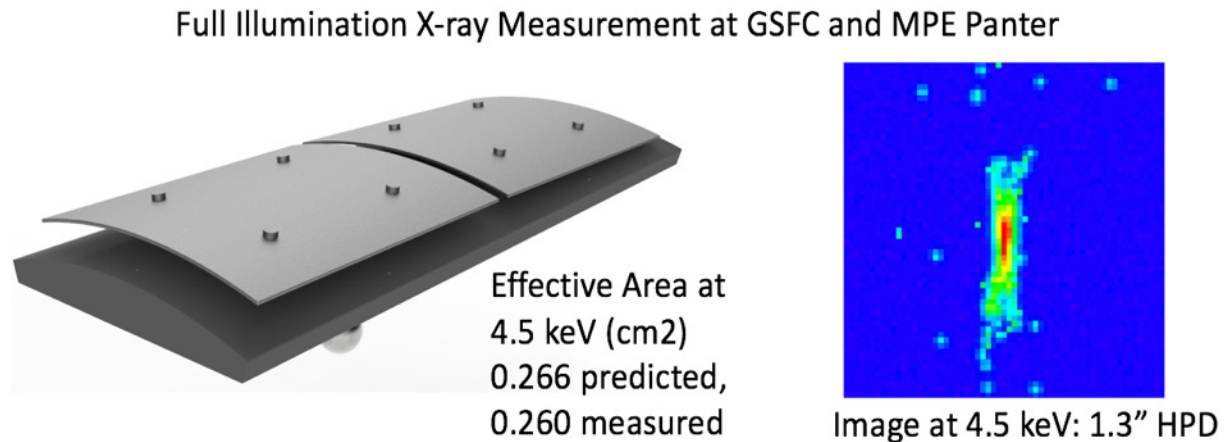


Fig. 7— (Left) A pair of mirror segments aligned and bonded on a silicon plate. Each mirror is bonded at four locations with silicon spacers (not visible in this view). The four spacers on the back of each of the two mirrors are there to mount the next pair of mirror segments. (Right) An X-ray image obtained with a beam of 4.5-keV (Ti K) X-rays with a half-power diameter of 1.3 arcsecond. Simulations show that the equivalent performance in the absence of gravity is close to 0.5 arcsecond. The effective areas at several energies were measured of a similarly built module at MPE's PANTER X-ray beam line, thanks to Dr. Vadim Burwitz and his team, to agree with theoretical expectations.

## 4 Technology Roadmap

The Silicon Meta-shell Optics technology is nothing more than *four sets of procedures*, each of which is repeated many times to produce the *Lynx* mirror assembly. These four sets of procedures are:

1. **Procedures to manufacture a mirror segment**—This set of procedures starts with a block of monocrystalline silicon and ends with a coated mirror segment that measures approximately  $100 \times 100 \times 0.5$  mm. This set of procedures needs to be repeated 37,492 times to make all the mirror segments for flight and additional times to make spares.
2. **Procedures to align and bond a mirror segment into a module**—This set of procedures needs to be repeated 37,492 times to make the 611 modules.
3. **Procedures to align and bond a module into a meta-shell**—This set of procedures needs to be repeated 611 times to integrate all the 611 modules into 12 meta-shells.
4. **Procedures to align and flexure-bond a meta-shell onto a spider to form the final mirror assembly**—This set of procedures needs to be repeated 12 times.

Technical maturity and robustness of these procedures lead directly to minimal technical risk of making the *Lynx* mirror assembly. Higher efficiencies of these procedures, both in terms of time and cost, directly leads to shorter schedule and lower cost for making the *Lynx* mirror assembly. This technology development work is nothing more than developing, refining, and perfecting these procedures to pass progressively each of the following criteria:

1. Science performance to meet PSF and effective area requirements
2. Structural integrity to meet spaceflight environment requirements
3. Efficiency to meet production schedule and cost requirements

This development work will involve a large number of iterations of building and testing many hardware pieces at many different levels of integration, such as single mirror segments, modules with one or more pairs of mirror segments, and will be guided by optical, thermal, and structural analysis every step of the way. The following section describes the issues to be addressed at each stage of the development effort to reach TRL 4, TRL 5, and TRL 6. At the end of the development effort, this technology will be ready for building a mirror assembly for the *Lynx* mission with little to no technical, schedule, or cost risk.

The development work described in the previous section, including analysis, building, and testing of single-pair mirror modules to achieve a 1.3-arcseconds HPD image, has demonstrated that the Silicon Meta-shell Optics technology is at TRL 3 as of early 2019. The goal of development efforts over the next few years is to continually advance this technology first to TRL 4 and then to TRL 5, before culminating in reaching TRL 6 by January 2027, before the start of *Lynx* project Phase B, and facilitating an early start of mirror production, which is on the project critical path.

## 4.1 TRL 4 Development

The objective of TRL 4 work is to refine and perfect the four technical elements such that modules containing at least *three co-aligned pairs* of mirror segments can be repeatedly built and tested and shown to meet *Lynx* PSF, effective area, and field-of-view requirements. TRL 4 is expected to be reached by March 2021.

**Mirror Substrate Fabrication** — As of June 2019, mirror substrates meeting requirements have been repeatedly fabricated. The development work in this aspect will be to refine the fabrication process to achieve highest efficiency at the lowest cost.

**Coating** — As of June 2019, the basic concept of coating bare silicon substrates with chromium and iridium on the front and silicon oxide on the back to compensate for iridium stress has been proven to work. This process will be refined by experimenting with the precision removal of the SiO<sub>2</sub> layer using hydrofluoric acid (Yao et al. 2019) and using ion beam figuring. Both methods are expected to work and meet stress compensation requirements. In the end, the method with the higher efficiency and lower cost will be used. This work is expected to be completed by March 2020.

**Alignment** — As of June 2019, an X-ray mirror that can be precisely supported by four spacers and aligned to about 1 arcsecond has been repeatedly shown. This precision is currently dominated by two factors: (1) the size of the light source and (2) the diffraction of the visible light which degrades the ability to locate the centroids of Hartmann maps, therefore degrading the precision of mirror alignment. Solutions to both of these problems have been identified: a smaller pinhole will be used to reduce the light source size from its current 100 μm to 5 μm, and beam-reducing optics will be used to focus the diffraction spot size from about 30 mm down to 5 mm, significantly increasing

the centroiding precision. This work is expected to be completed by March 2020.

**Bonding** — As of June 2019, mirror segments have been repeatedly bonded using different epoxies and have found multiple variables that can affect the bonding quality: (1) epoxy type, (2) cure strain of the epoxy, (3) epoxy viscosity, (4) diameter of the spacer, and (5) surface geometry of the spacer in contact with the mirror segment. These effects are easily understandable intuitively. Also, many finite element analyses have reproduced these effects. Numerous experiments will be conducted in combination with finite element analysis to quantify the relationships among the variables and arrive at an optimal specification. This work is expected to be completed by March 2020. By June 30, 2020, it is expected that single-pair modules that consistently meet *Lynx* PSF and effective area requirements, as well as field-of-view requirements, will be successfully built and tested.

The strategy is to experiment, analyze, test, and then iterate the process as many times as possible. In particular, the four technical elements are pursued in parallel simultaneously. As of June 2019, single-pair mirror modules of various degrees of perfection have been continually built and tested. This process is expected to continue into early 2020, when building and testing of single-pair modules that meet the exact *Lynx* requirements will start (i.e., mirror segments with the correct dimensions and thickness and are coated with iridium). These modules will be tested for PSF, both on- and off-axis, as well as effective areas. These tests will allow the identification of problems and the devised solutions to be tested in the next iteration. At least three single-pair modules are expected to be built and tested, most likely more than a dozen, in 2020. By the end of 2020, it is expected that single-pair modules that fully meet *Lynx* science performance requirements will be built consistently.

Building on the knowledge and experience of making and testing single-pair modules, in late 2020 we will begin building and testing modules that contain three co-aligned and bonded pairs of mirror segments. Successful building and testing of these modules will conclusively demonstrate that we can make mirror segments to have precisely the same focal length and co-align and bond them to achieve confocality. We expect to be able to repeatedly and reliably build and test 3-pair modules meeting *Lynx* science performance requirements, thereby reaching TRL 4 by September 2021.

## 4.2 TRL 5 Development

The TRL 4 work has shown conclusively a process of mirror substrate fabrication, coating, alignment, and bonding that can successfully build multiple-pair mirror modules that meet *Lynx* science performance requirements in PSF, effective area, and mass. TRL 5 is to develop this technology to meet *spaceflight environment requirements*: thermal vacuum, vibrations, acoustics, and shocks. Detailed TRL 5 requirements are specified in Table 4.

Once TRL 4 is reached, there is little doubt that multiple pairs of mirrors can be co-aligned and bonded to perform at the required levels of image quality and effective area, as well as field of view. The only question is whether a module so built can pass a battery of spaceflight environmental tests (including thermal vacuum, vibration, acoustic, and shock) without degrading its science performance (i.e., PSF). Preliminary finite element analysis, based on epoxy strength and spacer diameter, has shown that such a module should be able to sustain a “reasonable” launch environment; TRL 5 work will start with this premise. First, a module that resembles a typical innermost *Lynx* module in terms of number of mirror segments and radial span will be built using best practices developed in the TRL 4 work: diameter of spacers, epoxy, cure time, etc. A battery of tests will be conducted with emphasis on environmental tests and an X-ray test before and after the environmental tests. Accelerometer data will be analyzed and compared with finite analysis expectations. Then, based

on these results, another module will be built and tested. The expectation is to be able to iterate this way at least four times, such that progressively more knowledge and confidence will be acquired in the module passing both performance and environmental tests.

During these iterations, the main experimental variable is the diameter of the spacer and the surface contour of the spacer in contact with mirror segment. The working hypothesis is that a larger diameter spacer will lead to stronger bonds but will demand a more precise surface contour matching the mirror segment surface to minimize distortion caused by epoxy cure and shrinkage. Increasingly more sophisticated methods of material removal techniques will be used to modify the height and surface contour of the spacer surface until sufficiently strong bonds are achieved without causing unacceptable distortion to the mirror segment's figure. The material removal techniques used will include:

1. Grinding and buffing with fine compound, which has been shown to have height repeatability of better than 50 nm.
2. Ion beam figuring, which has been shown to be capable of achieving a precision of better than 5 nm.

Grinding and buffing using fine compound has the advantage of taking place outside a vacuum chamber. The ion beam figuring, however, can for sure meet the height and surface contour requirements. Though having to be done in a vacuum chamber is a significant inconvenience, work has been done to show that the amount of time required for pump-down and venting, as well as the amount of time for ion beam figuring each spacer, is acceptable.

### 4.3 TRL 6 Development

At the conclusion of TRL 5 development, there will be a set of procedures to build modules that meet *Lynx* requirements in all aspects: PSF, effective area, field of view, and passing all spaceflight environmental tests, including vibration, acoustic, thermal vacuum, and shock tests. The TRL 6 development will combine all knowledge into making an engineering model X-ray mirror assembly that demonstrates the following:

- Mirror modules can be accurately aligned and integrated into meta-shells.
- Meta-shells can be accurately integrated onto a spider.
- The finished X-ray mirror assembly engineering model meets all PSF, effective area, field of view, and spaceflight environmental requirements.
- The entire production logistics, schedule, and cost risks are retired.

As such, successful completion of the TRL 6 development as defined in Table 4 will essentially guarantee that the *Lynx* mirror assembly can be made not only to meet science performance and spaceflight environment requirements, but also meet schedule and cost requirements outlined in the project implementation plan.

The preparation work for TRL 6 work begins during the TRL 5 development. This is so mainly because of the long-lead time capital equipment needed for the TRL 6 work: CNC machines, ion beam figuring machines, and outfitting of space to accommodate mirror production, coating, and integration work. By the beginning of the formal TRL 6 work (i.e., January 2024), facilities and equipment will be ready for production. The TRL 6 work entails the following specific tasks:



1. Planning the production and qualification of the X-ray mirror assembly engineering model.
2. Hiring and training of a team of production workers to fabricate, coat, align, and bond mirror segments to make mirror modules.
3. Establishment of a team of engineers to develop the process of integrating mirror modules into meta-shells, including design, analysis, and implementation.
4. The same team of engineers will also integrate the three meta-shells into a mirror assembly.
5. Finally, the establishment of a team of engineers and test conductors to X-ray test and environmentally test the engineering model.

The outcome of the TRL 6 work is as follows:

1. An engineering model of a *Lynx* mirror assembly that contains three meta-shells: the innermost one, a middle one, and the outermost one, each containing three modules that are fully populated with optically qualified mirror segments capable of meeting *Lynx* science performance requirements. This engineering model passes all environmental tests as well as science performance tests before and after the environmental tests.
2. A team of scientists, engineers, quality control personnel, and managers who are fully knowledgeable of the entire *Lynx* mirror production process, including logistical as well as technical aspects. In particular, this team may include people from commercial companies that are potential bidders for the contract to manufacture the *Lynx* mirror assembly.
3. A list of potential suppliers and contractors that are technically ready to implement one or more production lines for making mirror segments, modules, and for integrating and testing those modules as well as the final *Lynx* mirror assembly.
4. An implementation plan that, with minor modification, can be used for making and delivering the *Lynx* mirror assembly.

For all intents and purposes, the TRL 6 work is a dress rehearsal of the complex work of making and qualifying a mirror assembly for the *Lynx* mission. The technical development is a three-pronged approach.

The first prong is the making of mirror modules whose parameters span the full range of the *Lynx* mirror assembly. This is a rigorous exercise of the procedures developed in the TRL 5 work. The production of mirror segments and production of mirror modules will be done at a much larger scale, possibly at industrial contractor facilities, depending on contractual and other logistical arrangements. In particular, industrial contractors are expected to be invited to participate in all aspects of this work; this will serve as an opportunity to inform them and possibly as a first step of a technology transfer process. In addition to more thorough X-ray performance testing, the environmental testing of these modules will be of higher fidelity and specific to the *Lynx* Observatory design and its launch vehicle.

The second prong is the engineering development of a process to integrate mirror modules into meta-shells, and in turn to integrate meta-shells into a mirror assembly. This represents a new and more advanced phase of the mirror technology development. Experienced personnel—who have worked on other spaceflight projects, such as *Chandra*, *JWST*, and *WFIRST*, and who have extensive experience in integrating space optics—will be brought on board to design, analyze, and implement a process for module and meta-shell integration. In particular, this integration process may occur

at one or more contractor facilities where previous missions' integration has taken place, leading to savings in both facilities and personnel costs.

The third prong is the development of the mirror testing and qualification process, including both science performance and environmental testing. Given the mass production nature of making the *Lynx* mirror assembly, it is critical that there are three separate, efficient qualification processes: one for the modules, one for the meta-shell, and finally, one for the full mirror assembly.

As part of the production process, each mirror module will be X-ray tested for its performance. Once they are qualified, they will not be changed as subsequent integration steps will, and, indeed, will be required to, preserve their performance. A beam of visible light is used to verify that all modules have been correctly aligned and integrated into the spider to be confocal. The *Lynx* Team is considering the value of X-ray testing the TRL 6 mirror assembly at XRCF at several X-ray energies and off-axis angles to verify that performance has not changed, as a dry run for the final calibration.

#### 4.4 Milestones, Significance, and Verification

All key milestones of the development effort are listed in Table 4. This section describes the technical significance and verification of each milestone.

Table 4—Silicon Meta-shell Optics TRL milestones.

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.		
<b>Lynx Optics TRL 4 Exit Criteria</b> 1. End-to-end error budget for <i>Lynx</i> telescope angular resolution. 2. Laboratory demonstration of measured angular resolution of mirror pairs executed under the following conditions: <ul style="list-style-type: none"> <li>• Must be able to repeatedly build and X-ray test mirror modules each containing three pairs of mirror and achieve 0.5-arcseconds HPD at 1 keV.</li> <li>• The effective areas must match predictions based on standard atomic data.</li> <li>• The mirror segments must be of the required thickness and appropriately coated.</li> <li>• A breadboard lab mount can be used.</li> <li>• The focal length and radius of curvature of these mirror segments can be different from <i>Lynx</i>'s.</li> </ul> 3. Models and analogies <ul style="list-style-type: none"> <li>• All elements related to the as-corrected on-orbit mirror error contributions (e.g., thermal, g-release, etc.) must be validated.</li> </ul>	<b>Silicon Meta-shell Optics Development/Maturation Milestones</b>		
	#	Milestone Description	Date
	1	Fabrication of mirror substrates meeting performance requirements based on optical metrology: Fizeau interferometer, Zygo profiler, and optical Hartmann tests.	Done as of Q1, 2019
	2	Coating of mirror substrates with 20 nm of iridium and compensating coating stress with an appropriately thick layer of silicon oxide on the back to reduce figure distortion caused by coating to <0.1-arcseconds HPD.	Q1, 2020
	3	Alignment and bonding of a single pair of mirror segments into a module and X-ray test it to achieve 0.5-arcseconds HPD images at 1 keV.	Q2, 2020
	4	Build and test three more single-pair modules as described above to achieve 0.5-arcseconds HPD images at 1 keV.	Q3, 2020
	5	Begin building and testing two-pair modules to demonstrate robustness of the process: mirror fabrication, mirror coating, co-alignment between two pairs, and bonding.	Q4, 2020
6	Build and test the first three-pair modules. Iterate at least two more times with two additional three-pair modules. Q2 is reserved as schedule margin for fully meeting TRL 4 requirements.	Q2, 2021	

<p><b>TRL 4 =&gt; 5 Advancement Degree of Difficulty (AD<sup>2</sup>): 4</b></p> <p>The pathway from TRL 4 to TRL 5 is straightforward; no difficulties are anticipated. Once 3-pair modules have been done repeatedly (as required for TRL 4), aligning and bonding additional pairs is but a repetition of the same procedure. The only significant difference is in the optical prescriptions of the mirror segments. The difference only entails the use of different tooling which is procured commercially, which does not present any technical issue.</p> <p>The reason for assigning an AD<sup>2</sup> of 2 is to account for a possibility of having to make the diameter of the spacer larger than that used in demonstrating TRL 4 to ensure that the module can sustain the vibrational environment. If indeed larger diameter spacers have to be used, the spacer grinding process would need to be refined to ensure an accurate top surface. There is no intrinsic technical difficulty, but additional time and effort would be needed to ensure the completion of TRL 5 demonstration.</p> <p>Anticipated date to achieve TRL 4: March 31, 2021</p>
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<b>NASA TRL 5</b>	<p>A medium-fidelity system/component brassboard is built and operated to demonstrate overall performance in critical areas in a simulated operational environment with realistic support elements. Performance predictions are made for subsequent development phases.</p> <p><b>Brassboard:</b> A medium-fidelity functional unit that typically tries to make 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 be capable of operating in simulated operational environments in order to assess performance of critical functions.</p>		
<b>Lynx Optics TRL 5 Exit Criteria</b>	<b>Silicon Meta-shell Optics Development/Maturation Milestones</b>		
<p>TRL 5 demonstrations comprise the following:</p> <ul style="list-style-type: none"> <li>• Build, X-ray test, environmentally test (vibration, thermal-vacuum, and shock), and the X-ray test again at least two mirror modules that are similar to one or more <i>Lynx</i> mirror modules: dimensions, number of mirror segments, etc. Of all the mirror segments aligned and bonded in these modules, at least two pairs of mirror segments are optically qualified and are capable of achieving 0.5-arcseconds HPD at 1 keV.</li> <li>• The mirror segments used (optically qualified or structural dummies) must be 0.5 mm thick and coated with iridium.</li> <li>• Effective areas measured in X-ray tests of these modules must match those predicted based on standard atomic data.</li> <li>• Modules must be X-ray tested in different orientations with respect to gravity with results understood based on finite analysis.</li> </ul>	<b>#</b>	<b>Milestone Description</b>	<b>Date</b>
	7	Build modules with only two pairs of optically qualified mirror segments that can survive vibration tests.	Q4, 2021
	8	Build, X-ray test, environmentally test, and X-ray test modules each containing three pairs of mirror segments, achieving 0.5-arcseconds HPD at 1 keV.	Q1, 2022
	9	Fabrication and coating of a sufficient number (>100) of mirror segments for making multiple mirror modules.	Q3, 2022
	10	1st iteration: Build and test the first mirror module that may or may not meet all requirements.	Q4, 2022
	11	2nd iteration: Build and test the second mirror module that may or may not meet all requirements.	Q1, 2023
	12	3rd iteration: Build and test the third mirror module with required number of mirror segments. Conduct a complete battery of tests: X-ray, environmental, X-ray again in different gravity configuration.	Q2, 2023
	13	4th iteration: Build and test the fourth mirror module with required number of mirror segments. Conduct a complete battery of tests.	Q3, 2023
	14	Document and report the case for TRL 5 completion.	Q4, 2023
<p><b>TRL 5 =&gt; 6 Advancement Degree of Difficulty: 2</b></p> <p>Once TRL 5 is reached, the path to TRL 6 is logistic preparations and repetitious work.</p> <p>Anticipated date to achieve TRL 5: January 2024</p>			

NASA TRL 6	<p>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.</p> <p>Prototype: The 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.</p>		
<p><b>Lynx Optics TRL 6 Exit Criteria</b></p> <p>TRL 6 demonstrations comprise the following:</p> <ul style="list-style-type: none"> <li>• Build and qualify nine fully populated modules: three innermost ones, three middle ones, and three outermost ones. The qualification tests include environmental tests as well as X-ray tests before and after environmental tests. In particular, these modules must be tested in different configurations with respect to gravity with results understood using finite elements analysis.</li> <li>• These modules must be according to <i>Lynx</i>-specific design and prescription. In principle, they can be flight spares. As such, they must meet all requirements, including PSF and effective area.</li> <li>• The nine modules must be integrated into their respective meta-shells, using mass dummies for the rest of modules. Then, the three meta-shells must be integrated to form a mirror assembly called the engineering model, which must be subject to and pass a battery of X-ray performance and environmental tests as if it were a flight mirror assembly.</li> <li>• All terms in the overall PSF and effective area budget are empirically verified and shown to be valid.</li> </ul>	<p><b>Silicon Meta-shell Optics Development/Maturation Milestones</b></p>		
	#	Milestone Description	Date
	15	Preparation work for TRL 6 development completed: procurement of major capital equipment, outfitting of laboratory space for production work, etc.	Q3, 2023
	16	Test production of one of each of the three types of mirror modules: innermost, middle, and outermost.	Q1, 2024
	17	Completion of making all fully qualified modules, three of each type: three innermost modules, three middle modules, and three outermost modules.	Q4, 2024
	18	Integration of the nine modules into three respective meta-shells completed.	Q1, 2025
	19	X-ray and environmental testing of the three meta-shells completed.	Q2, 2025
	20	Integration of the three meta-shells into the X-ray mirror assembly.	Q3, 2025
	21	X-ray and environmental tests of the X-ray mirror assembly.	Q1, 2026
	22	Nine-month schedule reserve for the following: one more iteration of building an X-ray mirror assembly if test results deem necessary. Otherwise, this time will be used for documenting TRL 6 work and for planning flight production.	Q4, 2026
Anticipated date to achieve TRL 6: January 2027			

**Milestone 1** — Fabrication of mirror substrates meeting performance requirements.

**Significance** — This is the foundation of the Silicon Meta-shell Optics technology, on which subsequent development steps are based.

**Verification** — Each substrate is measured optically on two independent instruments: an Fizeau interferometer and a Zygo surface profiler. Between these two instruments, all characteristics of the substrate are quantified. In addition, each mirror substrate is also measured with a set of Hartmann sub-aperture measurements. As of March 2019, mirror substrates have been repeatedly fabricated that, according to these measurements, meet *Lynx* requirements.

**Date of Completion**—Q1, 2019.

**Milestone 2** — Coating of mirror substrates with 20 nm of iridium and compensating coating stress with a silicon oxide layer.

**Significance** — After the substrate fabrication, this is another one of the most significant steps. It indicates that this technology is fully capable of meeting *Lynx*'s effective area requirements at the various energies.

**Verification**—Measurement of the Fizeau interferometer and the Zygo surface profiler to ensure figure and microroughness requirements are met. Measurement in an X-ray beam to ensure that the effective reflectance requirement be met.

**Date of Completion**—Q1, 2020

**Milestone 3** — Alignment and bonding of a single pair of mirror segments into a module and X-ray test it to achieve 0.5-arcsecond HPD at 1 keV.

**Significance** — The realization of this milestone will persuasively demonstrate that this technology can meet the *Lynx* PSF requirements as well as its effective area requirements.

**Verification** — Full-illumination X-ray test at NASA Goddard Space Flight Center and MPE's Panter X-ray Beam line in Germany. Both PSF and effective area will be measured at 1 keV and other energies.

**Date of Completion:** Q2, 2020.

**Milestone 4** — Build and test three more single-pair modules that meet PSF and effective area requirements.

**Significance**—This is a repeat of Milestone 2 to ensure that the procedures developed are robust and reliable.

**Verification**—The same as for Milestone 2.

**Date of Completion**—Q3, 2020.

**Milestone 5** — Build and test two-pair modules.

**Significance** — This is one significant step beyond Milestones 3 and 4, accentuating the point that not only the process of building and testing single-pair mirror modules works technically, but also that it works for co-aligning a second pair.

**Verification** — The same as for the previous milestones.

**Date of Completion**—Q4, 2020.

**Milestone 6** — Build and test three-pair modules that meet PSF and effective area requirements.

**Significance** — This is a natural continuation of Milestone5, adding another pair to the module. The completion of this milestone will demonstrate that we can build a module with many pairs of mirror segments. This milestone completes the TRL 4 work. The on-time completion of this milestone leaves us with Q3 as schedule margin as our overall plans calls for the completion of TRL 4 demonstration by Q3 of 2021.

**Verification** — The same as for the previous milestones.

**Date of Completion** — Q2, 2021.

**Milestone 7** — Successful build and test of a module with two pairs of mirror segments that can survive vibrations.

**Significance** — The realization of this milestone signifies that the basic procedure co-aligning and bonding another pair of mirrors to the first pair works, and such mirror modules are robust against vibrations.

**Verification** — Full-illumination X-ray test to ensure that both PSF and effective areas are reasonable before and after a well-define vibration test.

**Date of Completion** — Q4, 2021.

**Milestone 8** — Successful build and test of a module with three pairs of mirror segments that achieve 0.5-arcsecond HPD at 1 keV that can sustain environmental tests.

**Significance** — This is the same as Milestone 6, but with one more pair of mirror segments and with the PSF quality requirements.

**Verification** — The same as for Milestone 6.

**Date of Completion** — Q1, 2022.

**Milestone 9** — Fabrication and coating of a sufficient number (>100) of mirror segments for making multiple mirror modules.

**Significance** — This represents the first success of mass production of mirror segments. Most, if not all, problems associated with making and qualifying a large number of mirror segments in a relatively short time will have been solved, demonstrating that the tens of thousands of mirror segments required for *Lynx* are ready to be mass produced.

**Verification** — Optical surface metrology, the same as for Milestone 1.

**Date of Completion** — Q3, 2022.

**Milestones 10, 11, 12, 13, and 14** — Repeatedly build and test mirror modules, and document the process and results.

**Significance** — These five milestones repeatedly build and test mirror modules, culminating in a report documenting the process and making it as a base for starting a much larger effort of advancing this technology to TRL 6. The realization of these milestones will conclusively demonstrate that knowledge of how to build mirror modules that meet *Lynx* requirements.

**Verification** — All of these modules will be subject to X-ray tests, environmental tests, and X-ray tests again. X-ray tests are full-illumination as well as Hartmann tests where only a relatively small part of a module is illuminated. The environmental tests include vibrations, thermal vacuum, acoustics, and shocks. The levels of these tests will be based on the observatory design and launch vehicle information available at that time.

**Date of Completion** — Q4, 2023. (Nine months ahead of *Lynx* project requirement of Q3 2024.)

**Milestone 15** — Preparation work for TRL 6 development.

**Significance** — While this milestone is not technical or technological, it is nonetheless very important in the sense that it is part of this technology's requirement to meet *Lynx*'s schedule and cost requirements. Its realization will demonstrate that the logistical aspects of the technology are sound and also ensure that this technology will be able to fulfill all of its promises.

**Verification** — There will be a standard review process to scrutinize whether logistical assumptions made for and under this technology's paradigm are valid.

**Date of Completion** — Q3, 2023.

**Milestone 16** — Test production and qualification of each of the three types of mirror modules: innermost, middle, and outermost.

**Significance** — These modules are no longer "generic" in the sense that they are bona fide *Lynx* modules. As such, they can in principle be qualified and flown as part of the flight mirror assembly. These will be significant steps in demonstrating the maturity of this technology.

**Verification** — X-ray tests before and after environmental tests; full environmental tests.

**Date of Completion** — Q1, 2024.

**Milestone 17** — Production and qualification of nine mirror modules: three innermost ones, three middle ones, and three outermost ones.

**Significance** — As Milestone 15, this is another step in the technical maturity and readiness direction, further demonstrating that this technology is ready for production of *Lynx* flight mirror modules.

**Verification** — The same as for Milestone 15. X-ray tests before and after environmental tests; full environmental tests.

**Date of Completion** — Q4, 2024.

**Milestones 18 and 19** — Integration of the nine modules into three respective meta-shells, meeting science performance and environmental requirements.

**Significance** — This will represent the first time that multiple modules are aligned and bonded into meta-shells, demonstrating an important engineering aspect of this technology. Although no technical difficulties are expected in accomplishing this milestone, it is recognized that accomplishing this milestone requires significant coordination among many different people using many different tools. Its realization is another significant step in maturing this technology to manufacture readiness.

**Verification** — Perform optical metrology and coordinate measuring machine to guide and verify the steps and the final meta-shells. X-ray tests before and after environmental tests, environmental tests based on *Lynx* Observatory design and launch vehicle.

**Date of Completion** — Q1 & Q2, 2025.

**Milestones 20 and 21** — Integration of the three meta-shells into the X-ray mirror assembly, called the engineering model. Successful performance and environmental tests.

**Significance** — This milestone marks that this technology has reached TRL 6. The realization of this milestone retires all risks associated with the *Lynx* mirror assembly: technical, schedule, and cost. Reaching this point guarantees that this technology can make the *Lynx* mirror assembly on schedule and on budget and meets all requirements.

**Verification** — Full X-ray performance and qualification-level environmental tests.

**Date of Completion** — Q1, 2026.

**Milestone 22** — Schedule reserve for accomplishing Milestones 19 and 20.

**Significance** — It is recognized that things may not always go according to plan. As such, this is a 9-month schedule reserve for realizing Milestones 19 and 20. This reserve will afford the time to repeat the work for Milestones 19 and 20 in case the results are not as expected. The objective is to ensure that this technology is fully ready to support the *Lynx* project implementation schedule.

**Verification** — The same as for Milestones 19 and 20.

**Date of Completion** — Q4, 2026.

## 5 Schedule

A schedule laying out the major milestones for silicon optics technology development is shown in Fig. 8.

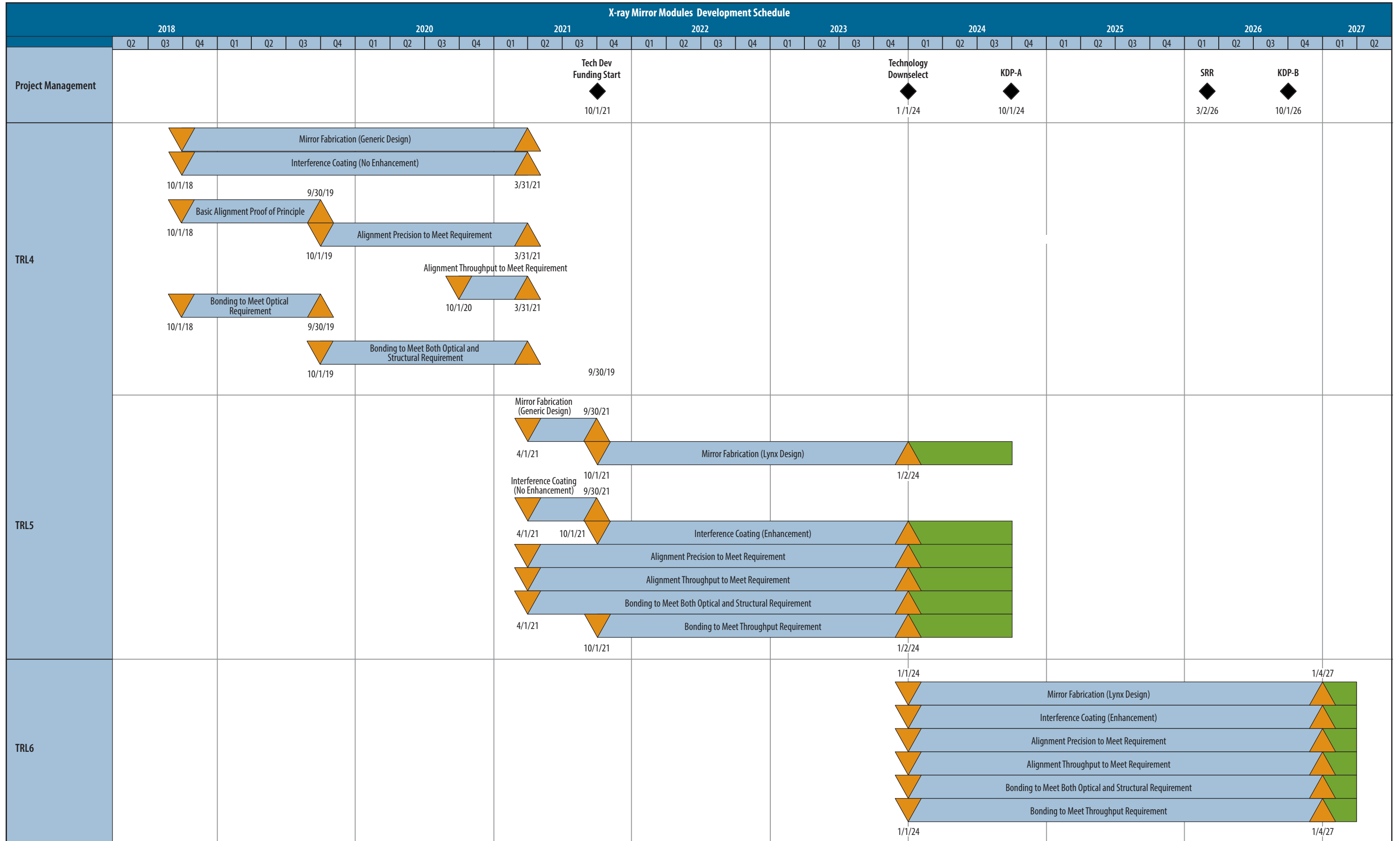


Fig. 8—Silicon optics technology maturation schedule.



## 6 Costs

Redacted.

## 7 Risks

The essential elements of this technology have been empirically demonstrated. The only risk is a quantitative one in development. At this time, there is only one foreseen risk that has the potential of causing mild disturbance to *Lynx* science performance and project implementation schedule.

Table 6—Summary of the silicon optics technology risks.

Risk	Title	L	C	T	S	\$
1	Epoxy shrinkage	3	2	X		

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

Likelihood	5					
	4					
	3		1			
	2					
	1					
		1	2	3	4	5
		Consequence				

Fig. 9—Silicon Meta-shell Optics risk ranking.

**Risk 1** — Epoxy shrinkage during cure causes large than expected figure distortion.

If this risk materializes, the number of mirror segments bonded to a module will be reduced, therefore increasing the number of modules. This will effectively reduce strength requirement and allows use of much smaller amount of epoxy, leading to less distortion. The net consequence of this is a slight reduction in the effective area of the mirror assembly as more modules will lead to a slightly lower packing efficiency.

## 8 Summary

This document has described a technical approach with the potential of meeting the requirements of the *Lynx* mission. The basic elements of this approach have been empirically demonstrated. Further technical and engineering development in the coming years (summarized in Table 4) will ready this technology for implementing the *Lynx* mission. The salient features of this technology (e.g., use of mass production processes and commercially available equipment and materials) have the potential of significantly reducing the mirror cost from what is estimated today.

## 9 Appendices

### 9.1 NASA TRL Definitions

TRL definitions per NASA Procedural Requirement (NPR) 7123.1B, Appendix E, are reproduced in their entirety in Table 7.

Table 7—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/sub-system 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.

## 9.2 AD<sup>2</sup> Definitions

AD<sup>2</sup> (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<sup>2</sup> is what it takes, in terms of cost, schedule, and risk to advance to the next TRL. AD<sup>2</sup> is defined on a scale of 1–9 in a manner similar to TRL. The description of the AD<sup>2</sup> levels is shown in Table 8.

Table 8—AD<sup>2</sup> level definitions.

AD <sup>2</sup>	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)

### 9.3 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. 10.

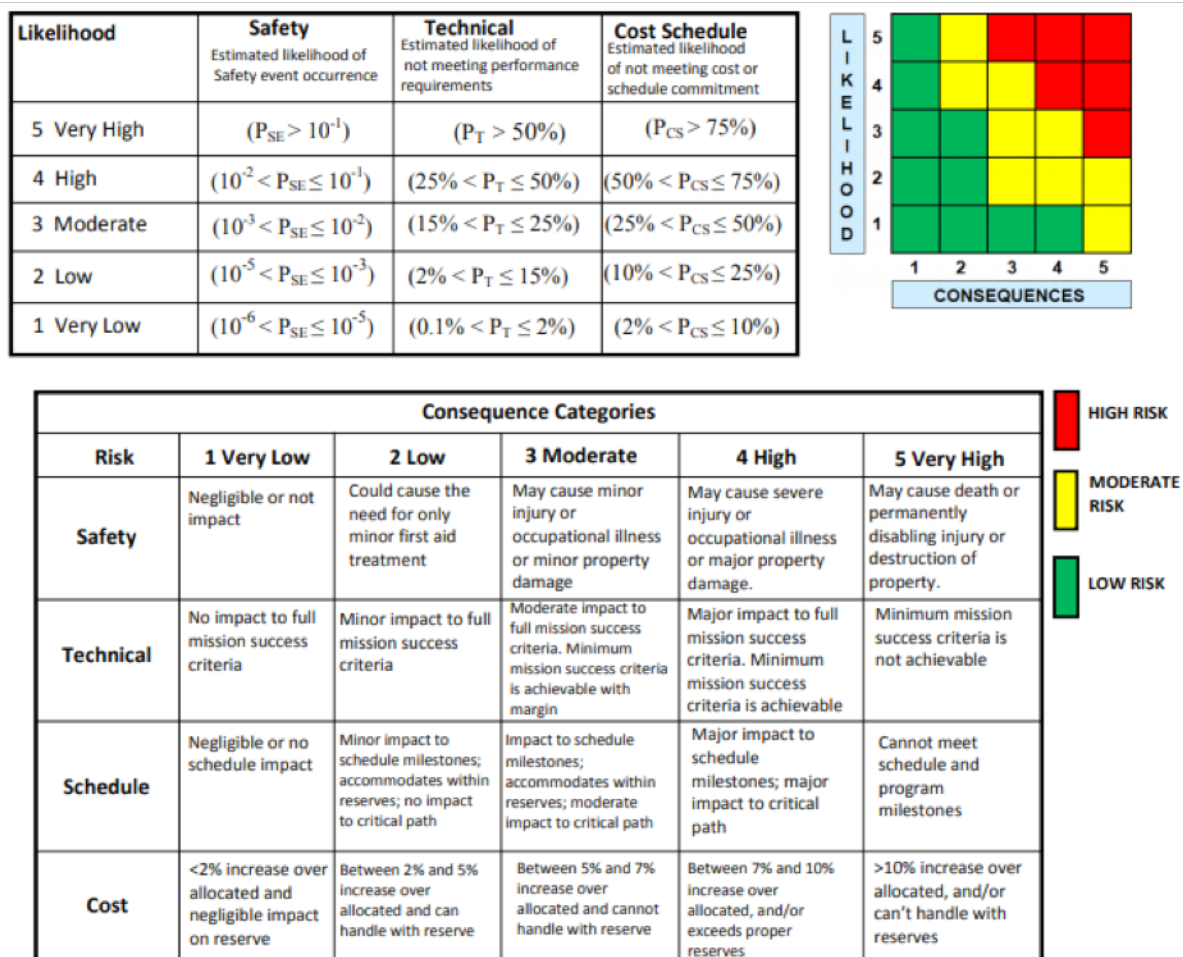


Fig. 10—Risk matrix standard scale.

## 9.4 Acronyms

ASCA	<i>Advanced Satellite for Cosmology and Astrophysics</i>
AD <sup>2</sup>	Advancement Degree of Difficulty
CNC	Computer Numerical Control
HPD	Half-Power Diameter
<i>JWST</i>	<i>James Webb Space Telescope</i>
PDR	Preliminary Design Review
PSF	Point Spread Function
RMS	Root Mean Square
SiO <sub>2</sub>	Silica
SMO	Silicon Meta-Shell Optics
TRL	Technology Readiness Level
<i>WFIRST</i>	<i>Wide Field Infrared Survey Telescope</i>

## 9.5 References

- [1] Yao, Y., et al., “Progress of coating stress compensation of silicon mirrors for the *Lynx* X-ray telescope mission concept using a thermal oxide patterning method,” *JATIS*, In Press.