Full Shell Optics Technology Roadmap

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This technology roadmap of the Full Shell Optics for the *Lynx* X-ray Mirror Assembly provides a description of the elements that need to be developed, tested, and verified; identifies key milestones of the maturation plan; and defines the associated schedule, costs, and risks. Full shell optics technology is one of three optics technologies under consideration for *Lynx* and is a key contributor for the overall *Lynx* mission as it will provide the large effective area and exquisite angular resolution over a large field of view necessary to enable *Lynx* science goals and objectives.

1 Introduction

The Full Shell Optics technology is one of three approaches identified by the *Lynx* study team that conceptually meets the *Lynx* requirements for effective area, angular resolution, and grasp while remaining within system-level mass and geometry contingency reserves. The underlying technology, referred to as *direct fabrication*, holds the pedigree of *Chandra*'s exquisite subarcsecond optics—the only subarcsecond astrophysical X-ray optical system ever produced—namely, grinding and polishing combined with precise metrology to produce finely figured mirrors (see Fig. 1).

Fig. 1—*Chandra* mirror elements shown at different stages of production. Left to right: (Left) Glass substrate prior to grinding and polishing. (Center) Fully polished shell being inspected. (Right) Coated shell.

The phrase "full shell" refers to the individual optical elements that are full-circumference shells, in contrast to shell *segments* that span only small azimuthal portions of a full circumference. Obvious advantages of full shells over segments include the simplified alignment requirements, the inherently greater structural integrity of full shells, and the lower susceptibility to coating-induced stresses and mounting-induced distortions of full shells. Direct-fabrication Full Shell Optics technology is being funded by NASA Marshall Space Flight Center (MSFC) to develop processes based on lightweight metal and metal alloy substrates [Gubarev et al. 2016, Kilaru et al. 2019] and by the Italian Space Agency (ASI) at the Brera Astronomical Observatory (OAB) based on glass and glass-like substrate materials [Civitani et al. 2017, 2018a, 2019]. NASA and the National Institute for Astrophysics (Italy) (INAF) established an agreement in 2016 expressly to develop this technology for future missions such as *Lynx* through cooperative information exchange on technological advancements where beneficial to both development efforts.

1.1 Lynx Optics Overview

The *Lynx* X-ray Mirror Assembly (LMA) must provide a large effective area and exquisite angular resolution over a large Field of View (FOV). The *Chandra* Observatory demonstrated that subarcsecond resolution grazing incidence optics can be fabricated if thick mirror substrates are used, but the mirror thickness must be substantially reduced to permit dense nesting requirements of the *Lynx* mirror shells. Specifically, compared to *Chandra*'s four mirror pairs spanning 0.65 to 1.2 m in diameter and tens of millimeters in thickness, the full shell design for *Lynx* requires 164 mirror pairs spanning diamters from 0.4 m to nearly 3.0 m with 1.6-mm- to 3.4-mm-thicknesses. Anticipating future launch vehicle capabilities, the mirror assembly and supporting structures must also be designed to achieve low mass per unit collecting area, have the structural integrity to withstand launch conditions and the environment of space, and must maintain optical precision throughout the life of the mission. The Full Shell Optics solution for *Lynx* is based upon low-density and low-Coefficient of Thermal Expansion (CTE) materials with high elastic modulus and high yield strength, such as lightweight metal alloys—strictly speaking, metal-based materials under study for *Lynx* mirror substrates are metal matrix composites although the phrase metal alloy is used for simplicity—fused silica, and other glasses. Both OAB and MSFC have developed basic *Lynx* LMA optical designs. Detailed *Lynx*-specific structural, thermal, and mechanical analyses of mirrors and mirror support structures during manufacture, integration, and flight have been provided via the *Lynx* Mirror Assembly Trade (LMAT) study investigations undertaken in 2018 (see also [Civitani et al. 2019]). These studies also included spacecraft accommodation and integration within the then-current Observatory design, including launch load analyses, stray light and thermal baffle design considerations, production schedule and cost estimates, and other assessments. These analyses and simulations show that the full shell design meets all scientific, technical, and programmatic evaluation criteria identified by the LMAT for a feasible LMA concept.

Fig. 2 displays basic predicted imaging performance parameters for the *Lynx* full shell design with Pt+C-coated fused silica as designed by OAB (see also [Civitani et al. 2019]; similar results have been reached assuming metal alloy substrates by MSFC).

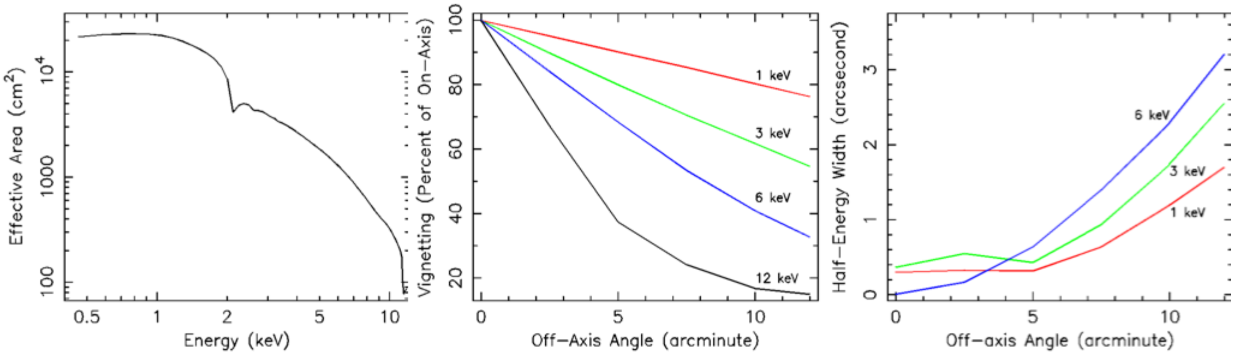


Fig. 2—Predicted full shell design imaging performance parameters. (Left) On-axis effective area against energy. (Center) Vignetting function (percent fraction of on-axis area) vs. off-axis angle for representative energies. (Right) Half-energy point spread function width against off-axis angle for representative energies (see also [Civitani et al. 2019]).

1.2 Full Shell Optics Description

This section provides an overview of the full shell direct fabrication architecture and technology, the State of the Art (SOA), and the foreseen challenges, issues, and risks.

1.2.1 Overview of Technology

Direct fabrication of full shell, subarcsecond X-ray optics was proven decades ago by the development of the *Chandra* High Resolution Mirror Assembly [Weisskopf et al. 2000]. The *Chandra* X-ray mirror assembly was developed using relatively thick mirror shell substrates and comprised only four shell pairs with a maximum diameter of 1.2 m. To meet *Lynx* requirements, a mirror assembly consisting of 164 nested shells with a maximum diameter of a full 3 m is envisioned (see Fig. 3).

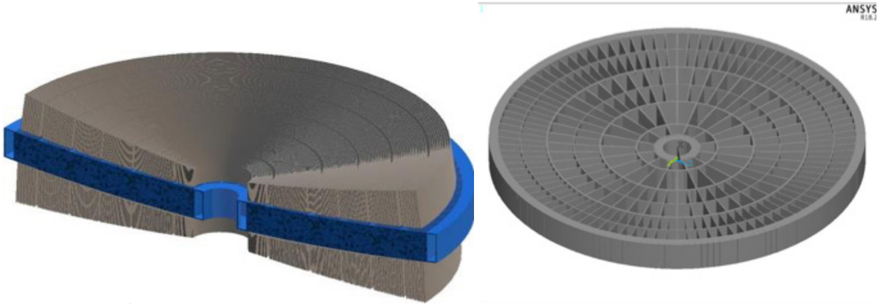


Fig. 3—(Left) Conceptual *Lynx* mirror design with a single supporting structure "spoke wheel" shown in blue separating the nested primary and secondary shells. (Right) Spoke wheel support structure concept.

This planned LMA has shells ranging in height from approximately 350 mm (outermost) to 160 mm (innermost) with a total mass of nearly 2,000 kg. Shell thickness will range from 3.4 to 1.6 mm (again outer to inner), representing a reduction of approximately one order of magnitude compared to *Chandra*. Analogous to directly fabricated segmented designs, these shells must be fabricated to exacting tolerances, film-coated to achieve the required reflectivity, co-aligned, and bonded to a support structure to complete the final assembly. These technology maturation elements are common to both the metal composite and fused silica designs and are shown in Table 1. They are described below in overview. The following sections provide the SOA and the detailed issues, challenges, and risks associated with the planned development effort, with an emphasis on the OAB fused silica design as it is more mature.

Table 1—Full Shell Optics technology maturation elements.

Element	Element Description	TRL	Advancement Description
1	Shell Fabrication	3	Mirror blanks manufactured and characterized, then ground (diamond-turn metal), polished and figured to exacting slope error requirements
2	Shell Coating	3	Application of thin film coating to achieve required reflectance
3	Alignment and Integration	3	Shells individually aligned in the mounting structure framework and integrated to meet Observatory-level optical performance requirements

Element 1: Shell Fabrication — Shell fabrication starts with the production of mirror substrate "blanks" of various dimensions required for each nested shell. Blank substrates made from raw fused silica are available and meet material requirements at a reasonable cost. Metal and metal alloy substrates are also commercially available. Once the blanks are in hand, a three-step process is employed to produce finished mirror shells with the required tolerances. These steps are:

1. Precision grinding or machining of the optical surface — The raw shell blanks are typically procured as cylindrical tubes formed to a single or double (for monolithic primary and secondary shells) conical. A progression of finer and finer grinding/machining is applied in order to bring the optical surface near to the target shape by removing several tens of microns from the surface.

2. Optical surface polishing — To acquire the super-polished surface required (i.e., microroughness of <0.5 nm Root Mean Square (RMS) on millimeter spatial scales), two polishing steps will be employed. Both have been reduced to practice on other programs (see §1.2.2).
3. Post-fabrication figuring — A post-fabrication figure correction process, either ion beam figuring [Civitani et al. 2018b] or differential deposition [Kilaru et al. 2017] is used to produce the final optical performance on a range of spatial scales. As long as the surface microroughness is maintained to less than 0.5 nm RMS, the longitudinal low-frequency profile errors are theoretically correctable with either of these processes.

In addition to the production steps required to advance this technology element, measurements must be made throughout the fabrication process to ensure that the desired figure corrections are being made and to target subsequent corrections. These measurements would benefit from in situ metrology that would eliminate the need for reinstallation and realignment between fabrication and metrology steps. Also, for fused silica, an additional annealing procedure to reduce initial stresses and chemical etching to remove grinding-induced surface microfractures may be necessary.

Finally, a Shell Support Structure (S3) is required to hold shells throughout processing and for transportation between various fabrication and testing stations, including coating and post-fabrication processes. An innovative design has been developed for early testing, and this design will be adapted to meet *Lynx* development requirements. The S3 is intended to be released only after the shell has been aligned and bonded in its final mounting position.

Element 2: Shell Coating — After the final polishing phase is complete, a thin film coating is applied to enhance the X-ray reflectivity of the shell. The coating process must maintain stress uniformity within tolerances without increasing surface roughness beyond acceptable limits. An in situ stress measurement technique has been developed that will be applied to aid in optimizing coating process parameters to minimize induced stress.

Element 3: Mirror Alignment and Integration — While the full shell structure provides intrinsic stiffness compared to other concepts, the mirror shells envisioned for *Lynx* are thin and have a high aspect ratio. After the shells are ground, polished, finished, and coated, they are then aligned to the final mounting structure, which must provide the strength and stability for all environmental and X-ray demonstration testing. The team at OAB has designed a "Spoke Wheel" (SW) mounting structure concept as shown in Fig. 3. This design provides greater structural strength under dynamic loads and easier thermal control than mounting structures located at only one or both ends of the mirror assembly [Civitani et al. 2019]. A vertical orientation will be used to align and integrate each shell into the SW. Integration will be accomplished with dummy masses used to simulate the presence of not-yet-integrated shells.

Further, a dedicated offloading system to reduce effects of gravity release will be used, and custom connections will be designed to provide radial decoupling and mitigate potential thermal effects from mismatches in the CTEs of the materials (i.e., shells and SW mount). Dedicated, customized alignment stations will be used.

The alignment and bonding elements proceed alternately; each shell is aligned and bonded before the next shell is mounted. Epoxy used to bond the shells to the SW takes time to cure and has the potential to deform thin shells through shrinkage. The bonding of the semi-shells to the SW is done prior to S3 detachment. In this configuration, vertical integration in a "constant mass" condition can help minimize stress imparted to the individual shells in the epoxy bonding step.

1.2.2 State of the Art

Chandra's High Resolution Mirror Assembly pioneered the direct fabrication and use of Full Shell Optics for high angular resolution [Weisskopf et al. 2000]. The spectacular science return from this Great Observatory has inspired the development of a new generation of Full Shell Optics for *Lynx*. *Chandra*'s four shell system is the SOA with respect to flight-proven Full Shell Optics and it demonstrated the 0.5-arcsecond Half-Energy Width (HEW) angular resolution required to meet *Lynx* requirements. *Lynx*, however, requires an effective area nearly 20× that of *Chandra* and a significantly larger FOV with sub-arcsecond resolution. For this, a full shell system incorporating over 160 shells is envisioned, and significant advancements will be required in each of the three elements discussed in §1.2.1.

The Physics of the Cosmos (PCOS) Technology Management Board in 2017 judged the overall Technology Readiness Level (TRL) of the full shell system at TRL 2 to 3. Advancements by the *Lynx* team (described below) have taken the TRL to 3. While the PCOS review did not assess Advancement Degree of Difficulty (AD^2), internal and independent review sets the AD^2 at 5; because of this, multiple technology paths are being pursued where required to reduce risk.

Element 1: Shell Fabrication — The AD^2 of 5 applies to this element—starting with the development of the large full shell blanks required for processing to fully finish shells. Multiple material options are available. These include raw fused silica substrates and a variety of lightweight metal and metal alloy substrates. All are available commercially at reasonable costs. OAB has focused on the former, and shell blanks have been obtained by from Heraeus Quarzglass GmbH & Co KG as cylindrical tubes, ground to a double-conical configuration with errors of around 50 µm Peak-to-Valley (PTV) and diameters around 400–600 mm, focal length of 5 m, and total length of 200–270 mm. Blanks with diameters up to 900 mm and wall thicknesses between 0.5 and 13 mm are available from this vendor (see Fig. 4).


Fig. 4—A cylindrical tube of fused silica before the grinding to generate a double-conical configuration

Corning, Inc., (USA) has the capability to produce the very large-diameter shells (up to 3 m) *Lynx* requires and is being developed as an alternate vendor. These shells are cut using a waterjet from a solid boule of fused silica and then ground to rough specifications. The largest (outermost) shell lengths, being of the order of 0.5 m, are compatible with the *Lynx* production concept. A hot slumping fabrication technique is also being explored by the OAB, and Heraeus has already produced subscale prototypes. This fabrication technique produces conical blanks requiring significantly less raw grinding compared to the standard conical blanks and is being pursued because successful development would significantly reduce shell processing time/cost.

MSFC has assessed multiple metal and metal matrix composites for shell fabrication and found Be-Al alloys to have excellent potential. Be-Al alloys provide close CTE matching to the full shell NiP coating. Be-Al alloys are machinable using standard techniques and are relatively inexpensive. Based on this analysis, MSFC has selected Axsys Technologies—a company with extensive experience in fabricating high-quality Be-Al optical parts—to use their fabrication technology to produce a low-temperature additive sintering technology to produce low-stress, low-distortion, and low-variability substrates of the desired sizes. Other candidates for substrates include Al-Si-based materials (e.g., Duralcan™ F3S.30S). An advantage of these metallic options is that the material can also be used to fabricate the mounting structure (simplifying thermal design) and are routinely cast as large, high-quality, machinable components for other applications. Thus, the *Lynx* program is exploring multiple promising material options as required with an AD^2 of 5. All are promising, and a downselection will be made in the pre-Phase A timeframe (see §2).

The raw semi-shell blanks are procured with specific conical profiles. After material characterization, several tens of microns (as a minimum) are typically ground from the surface along both the azimuthal direction (errors in the roundness) and along the longitudinal directions. A finer grinding process is then used to provide Out-of-Roundness (OOR) correction and the profiles correction to within some hundreds of nanometers. At OAB, fine grinding of fused silica shells will be done using high-precision lathes (similar to the systems used for diamond turning, available also in vertical configurations for large work pieces). SOA equipment and processes that are adaptable to *Lynx* requirements have been developed. Fig. 5, for example, shows a shell on a lathe at OAB undergoing the grinding process step and the setup for diamond turning at MSFC.

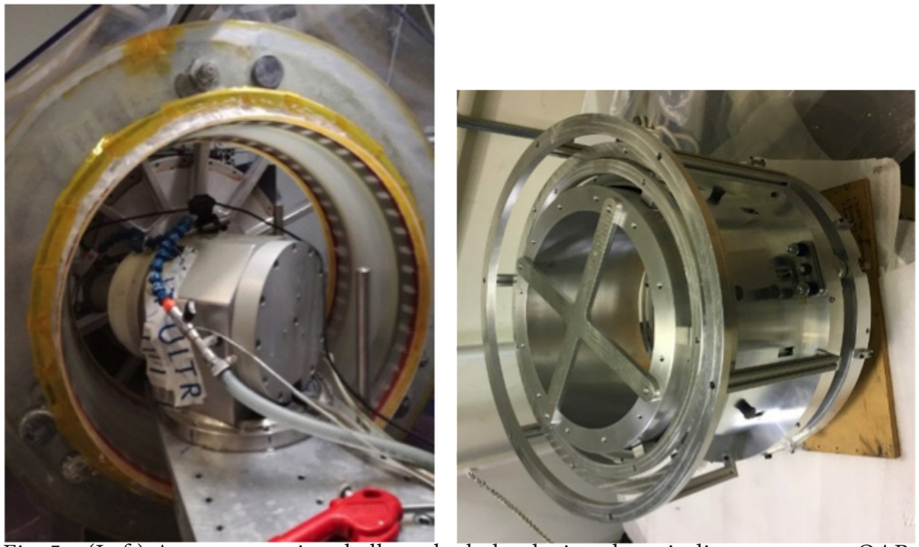


Fig. 5—(Left) A representative shell on the lathe during the grinding process at OAB. (Right) Shell support structure mounted to diamond turning machine at MSFC.

MSFC is using single-point diamond turning on NiP-coated metallic mirror surfaces (Fig. 5) to achieve a 1- to 2-μm surface error and a few hundredths of a micrometer surface finish. The use of metal substrates permits the utilization of this single-point diamond turning, which minimizes subsurface damage compared to grinding and saving the time needed to remove damage. The NiP alloy coating is a hard material that can be easily machined, polished, and super-polished. It is the same coating MSFC uses for all the mandrels fabricated for its electroformed nickel replication X-ray optics program. Therefore, there is considerable experience in machining and polishing this material.

Following the initial grinding step, polishing and super-polishing of the shells is accomplished using polishing equipment (e.g., commercially available Zeeko machines, based on a rotating inflatable tool followed by a long-tool for super-polishing with Trizact™ abrasive pads). An SOA polishing machine is shown in Fig. 6.

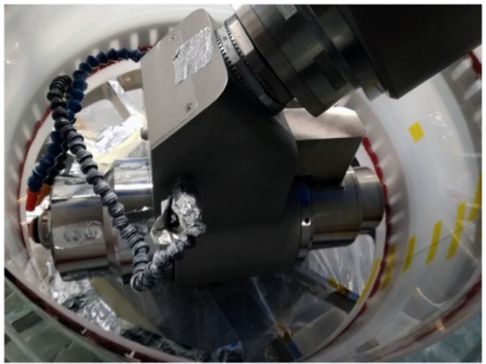


Fig. 6—The Zeeko IRP 1200 equipped with the Bonnet R20 at OAB.

A pre-polishing phase with the bonnet tool has been successfully tested to show efficient polishing of fused silica shells. Both OAB and MSFC have procured and programmed Zeeko machines for polishing full shells. These machines are 7-axes-of-motion robotic polishers, capable of polishing directly fabricated thin shells of moderate diameter held in a vertical orientation. It is noted that in addition to the OAB work with fused silica substrates, MSFC has recently demonstrated polishing of NiP-coated, vertically oriented cylindrical mandrels to a surface roughness of 1.5 to 2.0 nm and is expected to reach the 0.5-nm goal. Additional super-polishing option developments are focused on reducing polishing time by adding an additional step to drive the tool with high frequency: while the shell rotates around the optical axis, a linear stage oscillates parallel to the surface of the shell. The optimization of multiple parameters (e.g., abrasive type and grain, length of the movement, pitch tool size, oscillation frequency, and exerted force) is under study independently at both OAB and MSFC. An example of polishing capabilities is provided in Fig. 7. It is noted that extensive modeling efforts are also in place to guide process development. Mechanical simulations predict that the stress values during this process are not high. The principal tensile stress peak is between 2.28 and 3.79 MPa for shell diameters between 400 and 3,000 mm. In the simulations, the pad width ranges between 20 and 60 mm for the larger shell, while the applied pressure is set to 0.3 N/cm^2.

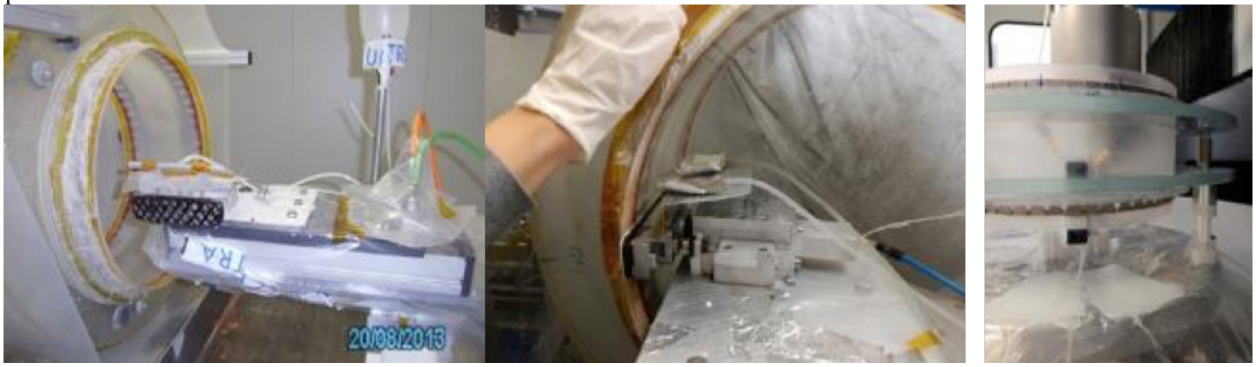


Fig. 7—Shell polishing at OAB showing: (Left) Polishing with a pitch tool. (Center) 3MTM Trizact™-equipped pitch tool in contact with surface of shell. (Right) 3MTM Trizact™ tool fixed on the Zeeko robotic arm (visible through the thin fused silica shell) with shell in vertical orientation.

Following the final polishing step, post-fabrication figure correction is planned to improve the final optical performance on a range of spatial scales. As long as the surface microroughness is lower than 0.5 nm RMS, the longitudinal low-frequency profile errors are theoretically correctable with an ion beam figuring process and/or with a differential deposition process, without degrading the microroughness. At INAF/OAB, tests have been carried out using a large ion beam facility developed in recent years. The facility, originally designed for large aspheric optics with diameters up to 1.3 m, has been upgraded and can now accommodate ion beam figuring of full shells; an ion source is mounted on a vertical translation stage, while the shell is rotated to treat the surface.

Differential deposition has also proven to be a viable post-fabrication figure correction technique to improve the angular resolution achieved with the X-ray mirrors. The technique involves depositing varying amounts of material on the surface of the mirror with a goal of minimizing figure errors.

In the past, an iterative approach was used where broader features with higher amplitudes were corrected first, followed by the correction of progressively smaller features. A factor of 2 improvement has been demonstrated through X-ray testing, and a factor of 3 through figure metrology [Kilaru et al. 2017]. Current efforts are focused on improving the efficiency of the process. One approach to achieve this is the use of active slits that can correct multiple spatial frequencies along an axial scan. The design and fabrication of this slit is complete and algorithms to operate the slit are being developed. The second approach uses a custom mask with varying hole sizes that can correct the entire mirror surface in a single pass without having to scan along various positions. The design and fabrication of this mask is complete and testing will soon commence.

Element 2: Reflection Coatings — Magnetron sputtering is the SOA for depositing the high-reflectivity Iridium (Ir) coatings and will be used for the *Lynx* optics. This process can induce differential stress that can deform the substrate's figure and degrade imaging resolution. To help identify mechanisms for reducing the film stress, MSFC has developed an in situ method for measuring the film stress during film growth. The method employs a high-resolution fiber optic displacement sensor to measure the displacement of the tip of a cantilevered substrate during the deposition of the film. The integrated stress is then a function of the measured substrate curvature as given by the Stoney equation. This device has helped to identify and exploit the microstructural evolution in iridium films deposited by magnetron sputtering. Specifically (Fig. 8), measurements have led to optimization of the argon process pressure to achieve a reduction of the stress by nearly three orders of magnitude [Broadway et al. 2015] accompanied by surface roughness increases within acceptable limits.

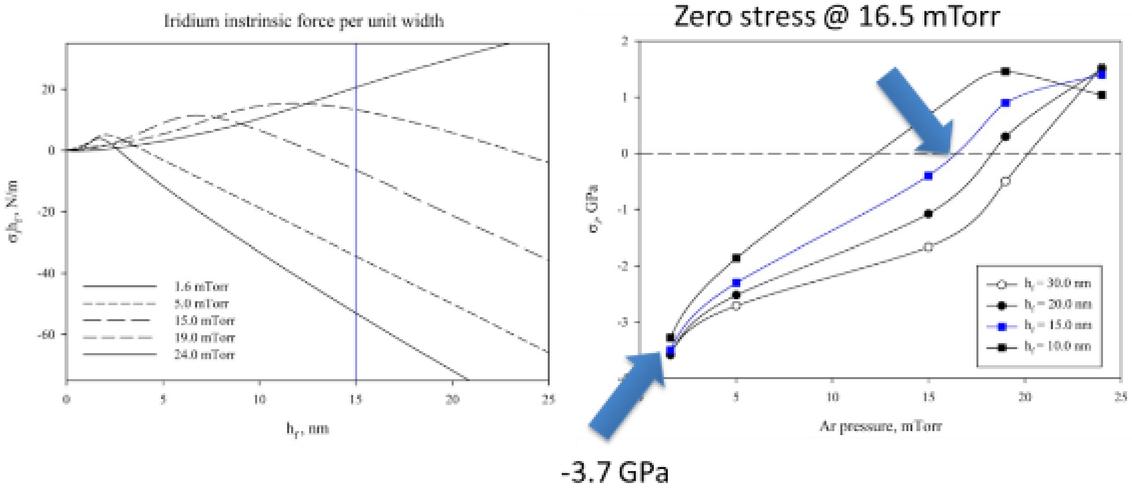


Fig. 8—Thin film stress reduction. (Left) In-situ stress in Ir films as a function of film thickness for the indicated Ar process pressures. (Right) Stress as a function of Ar pressure for the indicated film thicknesses (e.g., blue line indicates that zero-stress is indicated at 16.5 mTorr for a 15-nm-thick Ir film.

MSFC is currently adapting this technology to measure the change in the curvature of figured optics caused by film stress and as a method of in situ metrology for figure correction. It is anticipated that incremental, *Lynx*-specific advancements will be required to ensure the coatings meet *Lynx* requirements.

Element 3: Alignment and Integration — Analysis indicates that a vertical configuration, with shell mass surrogates, is optimal and has been demonstrated for the final process of alignment and integration of the shells to the SW and releasing the S3 from the shell. There will be process modifications when transitioning from breadboard to flight-like SW structures to best account for "missing" shells as each shell is aligned and integrated; an offloading system to counteract the force of gravity will be needed. To advance the SOA, MSFC has developed "hanging wire" systems that offload the mirror weight between support points during alignment and assembly of mirror shells into the SW (see Fig. 9).

Preliminary work at OAB shows that connectors allowing some radial decoupling between the shell and the SW are necessary to mitigate thermal effects due to shell and SW CTE mismatch. Similar benefits apply to gravity release effects and to stress peaks in the mirror shells at the SW connection points. However, the decoupling cannot be so large as to cause springback phenomena when passing the shell from the S3 to the SW.

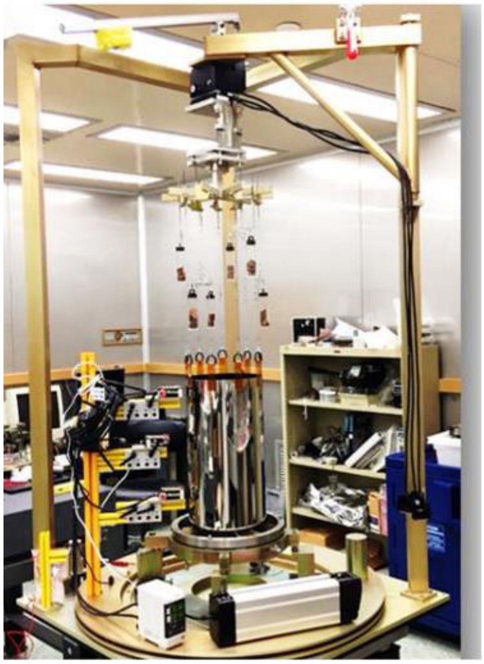


Fig. 9—Hanging wire station for final stage bonding at MSFC.

Other Considerations: Development of a Shell Support Structure — The S3 is designed at OAB to hold the shell using an innovative, metallic thin "comb," providing a radial flexure at the connection between the mirror shell and the support structure. Fig. 10 shows locations of the flexures on the shell (left) and a relevant operational jig in use for X-ray testing (right). This design substantially reduces the elastic and thermal distortions transmitted to the shell during fabrication compared to other existing mounting concepts. Essentially, this design offloads stresses that can occur in grinding and polishing operations from the mirror shell to the S3 to reduce the likelihood of shell damage.

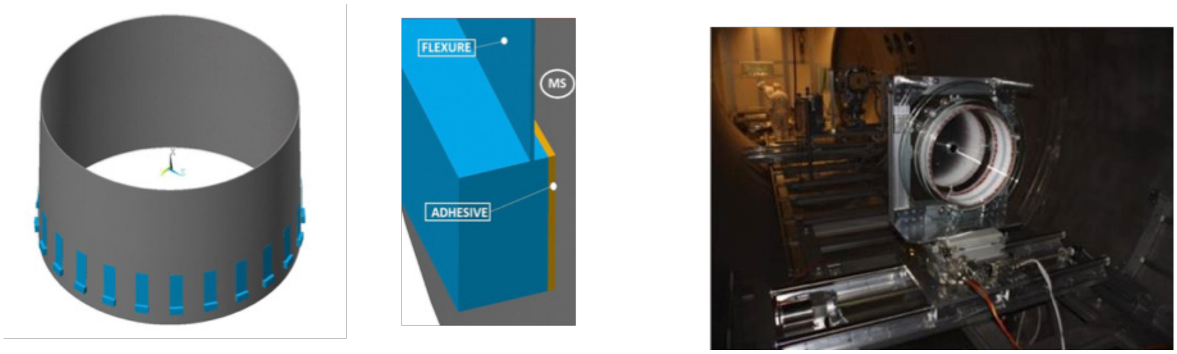


Fig. 10—Shell supporting structure design. (Left) Conceptual design of the azimuthally distributed flexures (blue) that are bonded on the glass surface (gray) and connect the shell with the S3. (Center) Close-up showing layer of adhesive attaching the flexure to the shell. (Right) Photograph of shell in S3 attached to a translation table for X-ray calibration at PANTER.

An astatic support system will be used to mount the shell onto the S3. A pathfinder system has been developed at OAB (see Fig. 11) and successfully tested with laboratory-grade test articles to demonstrate the proof-of-concept. It is anticipated that straightforward engineering advancements will be needed as the project progresses to TRL 6.

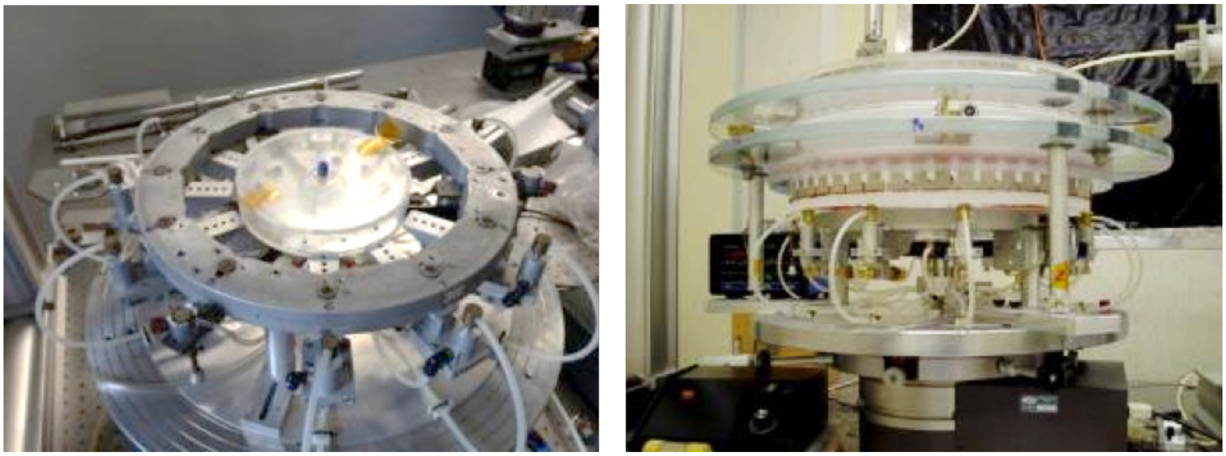


Fig. 11—The astatic equipment used to support the shell during integration into the S3. (Left) Twelve-point support with three fixed points and nine pre-loaded (as required based on shell mass). (Right) A representative shell being integrated into an S3 using the astatic support.

The connections of the mirror shell to the S3 are realized with adhesive. Two possibilities are under evaluation. Epoxy could be used to increase the natural frequencies of the system, which could be helpful during the manufacturing process; however, better performance is expected from silicon (like RTV 566) for the decoupling from the external influences and in terms of shrinkage. As the effect on the optical performances of the silicon adhesive is at least a factor 10 lower than the epoxy and the lowest natural frequency of the shell is still compatible with the manufacturing, the use of silicon bonding is considered the baseline.

Epoxy bonding of the shells to the SW is anticipated. There are several space-qualified epoxies on the market that can guarantee very low shrinkage. As a consequence, there are no limitations in the epoxy selection based on the curing time, which enables the setup of a reliable and smooth bonding process.

Other Considerations: Metrology — The direct fabrication process requires precise metrology within nearly all phases of fabrication. Ideally, metrology is performed in situ with the fabrication station(s) in order to minimize production time by eliminating the need for reinstallation and realignment between fabrication and metrology steps. The accuracy and precision of the metrological system define the limits of error corrections. The maximum measurement error amplitudes must be no more than a few tens of nanometers on large scales and a few nanometers RMS on small scales. The metrology for grinding can be an optical probe (which guarantees high accuracy and low noise) directly mounted on the central tree of the grinding lathe and following a configuration already

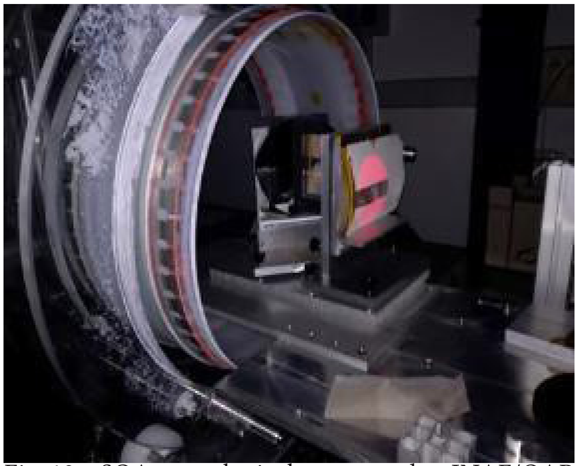


Fig. 12—SOA metrological setup used at INAF/OAB during polishing.

successfully tested by INAF/OAB in collaboration with the LT-Ultra (Fig. 12). This measurement setup can be used for the early phases of the process, when the surface is rough.

The measurement setup at OAB for latter phases combines profilometric and interferometric measurements (Fig. 13). While the profilometric approach is sufficient for the phases of the manufacturing process prior to polishing, the interferometric approach is very attractive for the latter phases because it is fast and provides a two-dimensional surface map rather than a set of traces in only one dimension. While the SOA for this technique does not meet *Lynx* requirements, the measurement setup is being actively improved in parallel with advances in shell manufacturing procedures.

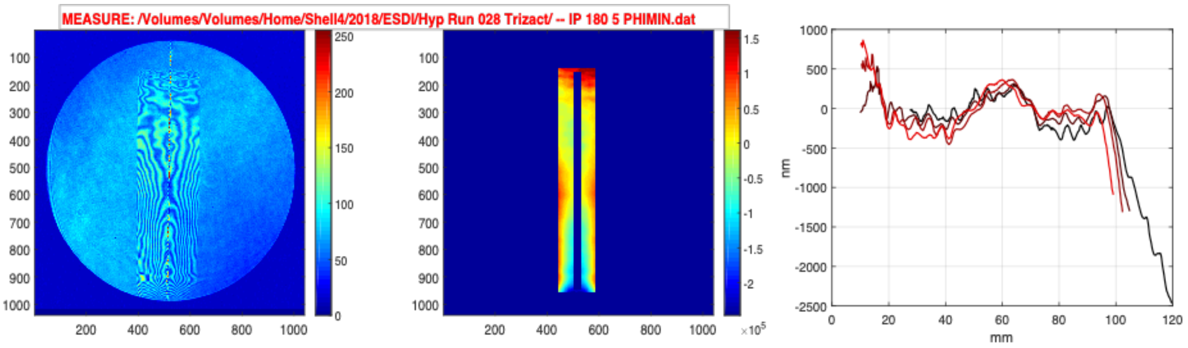


Fig. 13—Typical metrological results at OAB (left to right): Interferometric fringe pattern, corresponding reconstructed error map, and longitudinal profilometer traces corresponding to four polishing passes.

For *Lynx*, techniques and facilities will have to be improved to ensure the availability of the measurement capabilities. There are no apparent physical barriers to development, and the team is focusing on the development of in situ measurements wherever possible to reduce process steps, risk, and cost.

1.2.3 Issues, Challenges, and Risks

The LMA is the heart of the *Lynx* Observatory, and the full shell LMA concept offers several advantages if successfully developed. While in-depth assessments to date indicate that there are no fundamental physical barriers to the development of the *Lynx*-class full shell concept, the *Lynx* team faces several major development issues/challenges that will require exacting attention to both engineering detail and fabrication processes in order to stretch the SOA to meet *Lynx* requirements. Major challenges include (1) handling of the mirror blanks from acceptance from the vendor to final nesting in the LMA; (2) developing/refining the processes needed to grind, polish, and figure the individual mirror shells to *Lynx* tolerances; (3) applying the X-ray reflective coating without inducing unacceptable stress levels or microroughness; (4) aligning and bonding of the individual segments into the SW; and (5) ensuring accurate and precise metrology as required from the initiation of the grinding process to the final nesting of the mirror segments. The current collective TRL 3 shows that the full shell concept is more than just an idea, and significant progress has been made over the last several years as indicated in §1.2.2 above. Plans for development of each critical element are in place and the multiple paths to success will be pursued in areas in which an AD^2 above 4 is indicated. The following is a brief, general discussion of the major issues, challenges, and risks facing the *Lynx* Full Shell team. A more detailed discussion of the major identified risks is provided in §2 below.

The *Lynx* full shell challenge starts with the substrate blanks. While multiple commercial entities (e.g., Heraeus Quarzglass GmbH & Co KG and Corning, Inc.) have the technology needed to produce the large, raw monolithic shells required, there are only subscale prototypes at this time. While the full shell concept provides significant structural stability once assembled, production issues for full-sized shells (especially the largest) are not well-established. For fused silica, two fabrication methods are being evaluated at this point at OAB. Development of optics made from metal matrix composites is being funded to provide a program option should the fused silica prove problematic.

Development of the S3 support structure(s) with subsequent shell integration will present multiple engineering challenges. The S3 itself must be designed to provide the flexibility to offload shell-deforming stresses inherent to the mounting process. The required characterization phase must be optimized in order to prevent overestimating processing time and to reduce the possibility of breakage. Employment of the "astatic" support system developed for integration will require careful engineering support.

The shell machining process presents multiple challenges. While all of the processes have been demonstrated on samples, their application on *Lynx*-scale test articles and in the production mode that will be required to produce the full LMA has not been demonstrated. It is likely that machining capability shortfalls and the need for process improvements will be uncovered as work progresses. The management challenges here will be to (1) identify potential issues and develop contingency plans in early stages, (2) maintain strict oversight of the development efforts to catch issues as they occur, and (3) be decisive in implementing remediations. Examples of challenges include adapting the grinding process to a vertical orientation for large-diameter shells without introducing unacceptable reduction in grinding time (requiring engineering-directed adjustments in grinding grain size, etc.); improving the accuracy in the positioning of the Zeeko robotic arm; and modifying the ion-beam figuring process based on thermal loads experienced in the ongoing test program.

Shell coating will also present unique challenges. While sputter coating technology is a proven, entrenched technology across the industry, *Lynx* plans for coating multiple shells which requires careful stress management. The technique developed for in situ deposition monitoring is a true advancement in the SOA. Its application on the *Lynx* scale has not been demonstrated.

The adopted metrology must be of high accuracy and repeatability as well as applicable within the manufacturing environment. The in situ measurement schemes planned for *Lynx* are elegant and should provide the required solution. Returning to the labor/time-intensive processes of transporting between fabrication and metrology stations as used in *Chandra* is not an option due to the large numbers of shells in the *Lynx* design. As with the shell fabrication processes discussed above, the management challenge will be to identify potential weaknesses in the metrology scheme, monitor results for shortfalls (especially early in the development effort), and identify and implement engineering upgrades in a timely manner.

Finally, the assembly process of mating the shells to the final mounting structure represents a significant engineering challenge. The current *Lynx* scheme of using S3 to support the shells through the entire fabrication process is efficient and should be effective. There are many potential issues associated with the precision alignment and bonding (misalignment due to epoxy shrinkage, unanticipated deformation due to mounting stresses, etc.), and all must be accounted for with a plan that includes mitigations that must be developed as the program progresses.

The top-level error budget (Table 2) specific to the OAB full shell design captures many of these issues and challenges.

Table 2—Top-level error budget.

Element	Value	Description
Optical Configuration	0.31	
Design	0.30	On-axis design slightly degraded to achieve best off-axis PSF
Diffraction	0.09	Shell-by-shell weighted by effective area
On-orbit Loads	0.33	
Thermal	0.20	From finite element modeling (FEM) analysis
Gravity Release	0.26	From FEM analysis using current mounting structure design; material-dependent shell manufacturing
Shell Manufacturing	0.24	
Metrology	0.05	Assumes adequate thermal environment control
Primary Figure	0.15	Mainly longitudinal profile errors; azimuthal errors and microroughness small to negligible
Secondary Figure	0.15	Mainly longitudinal profile errors; azimuthal errors and microroughness small to negligible
Shell Support System	0.05	From FEM analysis of shell support structure design
Coating	0.10	From FEM simulations assuming 35 nm Ir on fused silica
Integration	0.18	
Alignment	0.15	Dominated by tilt between primary and secondary
Bonding	0.10	Assumes long-cure epoxies to reduce shrinkage
Final	**0.55**	

Based on both internal and external (independent) review of these issues, challenges, and risks, the program has developed a list of the major risks to the Full Shell Optics development plan and mitigation strategies for each. These risks are discussed in detail below.

2 Detailed Technology Roadmap

2.1 Key Milestones

Table 3 outlines the milestones and approximate schedule for specific activities necessary to develop and/or mature the technology elements identified above within the overall *Lynx* maturation plan.

Table 3—Full Shell Optics TRL milestones.

TRL 3 to TRL 4 Advancement Degree of Difficulty: 5 Advancement to TRL 3 requires the acquisition of an acceptable full shell blank, fabrication of an S3 mount, successful blank/mount mating, demonstration of all steps of the shell fabrication process (grinding, polishing, figuring, coating) with X-ray calibration to demonstrate success. The baselined fused silica blanks are commercially available. All of the fabrication steps have been demonstrated on relevant material samples and an initial design for the S3 mount has been developed. The required X-ray calibration capability is in place. The full end-to-end (blank/S3 attachment through finished shell) demonstration is new and there will be a learning curve for each step in the process. The overall yield is unknown – e.g. it is possible that the blank quality and/or blank/S3 mounting issues make fused silica a difficult choice. This uncertainty leads to the AD2 assessment of 5 and the program will carry a material option (Al-infused Be requiring machining rather than grinding) at least until the TRL 3 exit criteria are met. Similarly, multiple options exist for each phase of the fabrication process (e.g. grit selection in polishing step) and the TRL 3 to TRL 4 campaign will explore these options as necessary to 1) ensure successful fabrication in this phase and 2) reduce risk for larger shell development through the demonstration of TRL6.
Anticipated date to achieve TRL 4: Q1 2021

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 LMA. 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 elements performing less that a factor of 3 away from their required performance (as stated in the error budget), executed under the following conditions:
   - An X-ray test of a single coated full shell using a breadboard lab mount must be demonstrated. Mirrors must have nominal thickness consistent with their point design.
   - Functional breadboard mounting and all essential hardware elements (such as fixture to hold and transport full shell elements) demonstrated.
   - Full shell demonstration of the alignment of a single primary shell, aligned to optical axis as defined by the mount.
3. Models, Analogies, or Lab Demonstrations
   3.1 All elements related to the as-corrected mirror error contributions (e.g., coatings, thermal, g-release) must be validated.

Full Shell Optics Development/Maturation Milestones

#	Milestone Description	Date
1	Delivery and material acceptance of raw silica blank(s) for shell fabrication	Q4 2019
2	SME review of readiness to demonstrate fabrication process	Q1 2020
3	Successful mating of a shell blank to the S3 jig	Q1 2020
4	Demo the end-to-end fabrication process	Q3 2020
5	Single-Shell Coating	Q4 2020
6	SME review to confirm TRL 3 exit conditions met	Q1 2021

TRL 4 => 5 Advancement Degree of Difficulty: 5

Advancement to TRL 5 requires the extension of TRL 4 proven fabrication processes to larger facilities and the development of larger machinery. It also requires the first mounting of multiple, two-reflection shells (with diameters up to 1 m) on a single SW structure with X-ray calibration. While all of these advancements require new development (e.g., larger grinding machines, modified mounting procedures), none of the advancements are considered to be outside of normal engineering practices and no known fundamental barriers exist. Similarity to existing experience is substantial. Epoxy shrinkage is an issue and multiple paths will be considered. Further, while a single shell development path may be sufficient for the OAB design, issues may be encountered in moving to the large size needed for TRL 6 demonstration. Thus, three options (primary/secondary, monolithic, and segmented) will remain under consideration in this phase. single development path can be taken with a high degree of confidence for success.

Anticipated date to achieve TRL 5: Q1 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 demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.** **Brassboard: 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 able 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 LMA. Demonstrations 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 medium fidelity mirror brassboard sub-assemblies as defined below, performing less than a factor of 1.5 away from their required performance (as stated in the error budget), executed under the following conditions:
    - X-ray test of co-aligned, coated, realistically mounted mirror pairs (p-s) of 2 diameters with the one diameter being ~1-m. Focal length must be in the range of 6 to 10 m. Mirrors have nominal thickness and size consistent with their point design. Metrology, alignment, and mounting hardware and design 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.).
3. Test Conditions: Assemblies must be tested in operational environment that includes vibration and thermal vacuum. For missing mirror shells, mass simulators of sufficient fidelity must be used in the subassemblies.
4. Models, Analogies, or Lab Demonstrations
    - All elements related to the as-corrected mirror error contributions (e.g., coatings, g-release) must be validated.

Full Shell Optics Development/Maturation Milestones

#	Milestone Description	Date
7	Complete design and fabrication of flight-like SW	Q1 2021
8	Shell Integration into the Mounting Structure (SW)	Q4 2021
9	Fabrication and verification of 2nd (intermediate size) shell	Q1 2022
10	Assembly of co-aligned mirror pair on SW using next generation S3 jig.	Q2 2023
11	X-ray calibration of co-aligned mirror pair on SW and SME readiness review prior to environmental testing	Q3 2023
12	Environmental Test Campaign and SME review	Q1 2024

TRL 5 => 6 Advancement Degree of Difficulty: 5

TRL 6 is an extension of the TRL 5 milestone to larger diameter mirror shells. Attaining TRL 6 requires additional (larger) machines that can fabricate mirrors aligned in a vertical orientation. Conceptually, TRL 6 is merely a scaling from TRL 5, but costs are substantial as are estimated lead times to procure shells and manufacturing hardware. These are considered new developments but similarity with experience from the TRL 5 development sufficient to make this straightforward engineering advancement. There are, however, enough concern over the fabrication and testing of very large (~ 3 m) thin shells that continued evaluation of both the fully monolithic and segmented is warranted.

Anticipated date to achieve TRL 6: June 2026

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: 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.**

Lynx Optics TRL 6 Exit Criteria

Must demonstrate using a high-fidelity scalable flight-like prototype, which adequately addresses all critical scaling issues 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. A detailed flowed down error budget must exist and X-ray test performance must meet or surpass the budgeted allocations
2. Laboratory demonstration of measured angular resolution of flight-like prototype that demonstrates form, fit, and function representative of the flight unit and executed under the following conditions:
   - X-ray test of co-aligned, coated, flight-mounted mirror pairs (p-s) of 4 or 5 diameters with the two shells being the two outermost of the optical design, two being the two innermost of the optical design, the fifth being the mirror diameter assessed as most difficult to fabricate, measure, and mount, all with a 10 m focal length. (If the "most difficult" mirror is determined to be among the innermost and outermost total of 4 shells, then only 4 shells are required). Mirrors have nominal thickness and size consistent with their point design. Flight assembly and procedures must be employed, including flight materials and coatings etc. This mirror assembly should demonstrate mechanical feasibility. Ideally, mirror shells should be removable from the assembly structure, with as many components as feasible available for re-use in the flight article (but minimally including the mirror shells and SW (or equivalent)).
3. Environmental testing (acoustic, thermal vacuum, vibration, radiation) and X-ray testing in operational environments. For missing mirror shells, mass simulators of sufficient fidelity must be used in the subassemblies.

Full Shell Optics Development/Maturation Milestones

#	Milestone Description	Date
13	Fabrication of large diameter shell pair	Q3 2024
14	Assembly of large co-aligned mirror pair on SW using next generation S3 jig	Q2 2025
15	X-ray calibration of co-aligned mirror pair on SW and SME readiness review prior to environmental testing	Q3 2025
16	Environmental test campaign and SME review	Q1 2026

Details are provided below for the milestones listed in Table 3. It is assumed that Subject Matter Experts (SMEs) will be available to provide oversight at key points in the development schedule. In addition, although not milestones in the sense used here, several cost and schedule challenges are noted that will have a bearing on the ultimate success of the full shell effort: (1) identifying one or, preferably, several suppliers of substrates of the desired quality and geometries needed to demonstrate TRL 4, 5, and 6; and (2) obtaining upgrades to fabrication machinery as needed for the larger shells, including grinding and polishing machines that operate on shells held in the vertical orientation, larger vacuum chambers for ion beam and/or differential deposition and coating, and larger (vertical) mounting facilities (and requisite alignment metrology).

Milestone #1 — Delivery and material acceptance of raw silica blank(s) for shell fabrication.

Significance — The shell development process starts with the delivery and acceptance of the raw blank. This milestone will demonstrate that acceptable shell blanks can be obtained from a commercial vendor.

Verification — A complete material evaluation screening will be performed on the delivered blank(s). This will include chemical composition and surface quality characterization with pre-established acceptance criteria set by the full shell team.

Milestone #2 — SME review of readiness to demonstrate fabrication process.

Significance — The shell fabrication process is complex and failure in any of the process steps could result in program delays (and cost impacts). This review will cover all aspects of the process to provide assurance that all reasonable steps are being taken to manufacture a test article to the desired figure.

Verification — The full shell team will formally present the details of the planned fabrication and test campaign to the SME reviewers. This presentation will include (1) specific details of each manufacturing step and (2) a list of potential issues/unknowns and mitigation plans. The SME panel will review plans and provide concurrence and/or recommendations for changes in writing.

Milestone #3 — Successful integration of a mirror shell to the S3.

Significance — The S3/shell alignment and integration process is fundamental to the full shell concept as it enables handling the shell throughout the fabrication process.

Verification — Precision measurements of the newly fabricated S3 components and the shell blank to ensure mating tolerances are met. Behavior under load will be verified with a dedicated metrological campaign. The results will be compared with FEM model output. Epoxy bonding followed by measurements to ensure alignment is maintained with acceptable stress levels.

Milestone #4 — Demonstrate the end-to-end fabrication process.

Significance — Completion of all the necessary fabrication steps will result in a mirror shell ready for reflective coating. This milestone will demonstrate the efficacy of the fabrication process and provide confidence that the process can be applied for all the shells needed for the LMA. Recommendations for process improvement, if any, will be available for implementation in the next development phase.

Verification — Metrology of the finished shell will be compared to error budget allocations. Timing for each process step will be reported and compared to pre-fabrication estimates. Issues identified and process modifications will be described in detail.

Milestone #5 — Single-shell coating

Significance — Meeting this milestone will demonstrate that the required reflective coatings can be applied to produce a shell without inducing unacceptable stresses.

Verification — At a minimum, metrology will be carried out before and after the coating process to determine mirror figure. The in situ stress monitoring system developed at MSFC will also be applied to monitor stress during coating. Measurements will be compared with FEM simulations and verified by X-ray calibration.

Milestone #6 — SME review to confirm TRL 3 exit conditions met.

Significance — This independent review will confirm that the program-negotiated requirements to attain TRL 4 have been met.

Verification — The full shell team will provide a detailed review of the metrology and X-ray calibration results obtained in the Milestone 5 testing and a comparison of those results to the program-specified TRL 3 exit criteria. The team will also provide a list of lessons learned and an overview of plans for the next phase of development (TRL 4 to TRL 5 advancement). The SME panel will confirm that the exit criteria have been met and give recommendations for the next phase.

Milestone #7 — Complete design and fabrication of flight-like SW.

Significance — The individual shells must be aligned and integrated into an SW to within error budget tolerances. Meeting this milestone will produce the SW needed for TRL 4 to TRL 5 demonstrations.

Verification — Detailed measurements to demonstrate budgeted allocations are not exceeded. FEM simulations made and verified to the level necessary to provide confidence in mounting scheme for all shell sizes.

Milestone #8 — Shell integration into the SW.

Significance — Meeting this milestone will demonstrate that the S3-to-SW transfer procedure is successful, repeatable, and scalable. Review of this first integration will be needed to refine the models and procedures as the development proceeds from TRL 4 (breadboard mount) to TRL 6.

Verification — A full alignment verification sequence (physical measurements, metrology, and X-ray calibration) will be performed on the integration of a shell pair (or monolithic shell). Comparisons to FEM model predictions will be made. X-ray calibrations will be made before and after mounting in order to determine the change in figure due to separation from the S3 and mounting in the SW.

Milestone #9 — Fabrication and verification of second (intermediate size) shell.

Significance — Demonstration that the fabrication process developed in the TRL 3 to TRL 4 advancement can be extended to larger test fixtures, equipment, and facilities as needed to produce intermediate-size shell pairs (diameter ≥1 m). This delivery is required to proceed with the integration and demonstration testing planned to meet TRL 4 exit criteria.

Verification — Measurements of the fully finished shell pair (including coating) will be taken and compared to preset required tolerances. Timing for each process step will be reported and compared to pre-fabrication estimates. Issues identified and process modifications will be described in detail.

Milestone #10 — Assembly of co-aligned mirrors on SW.

Significance — Demonstrates that a second intermediate-size mirror pair can be assembled on the SW. This will be the first production of a co-aligned mirrors of different radii for environmental testing.

Verification — Physical measurements and metrology.

Milestone #11 — X-ray calibration of co-aligned mirrors on SW and SME readiness review prior to environmental testing.

Significance — Provides independent confirmation that the co-aligned mirror pair on the SW is ready for the full environmental testing required to meet TRL 4 exit criteria.

Verification — X-ray testing to verify alignment and mounting has been performed to specifications. Results of this testing along with a review of the shell fabrication and shell assembly to the SW will be provided to the SME panel. The panel will provide concurrence and recommendations for upcoming environmental testing and future TRL 5 to TRL 6 development efforts.

Milestone #12 — Environmental test campaign and SME review.

Significance — The planned environmental testing will demonstrate the survivability of the co-aligned mirror pair under flight-like dynamic and thermal conditions.

Verification — Successful completion of a full environmental qualification test (thermal vacuum and vibration test campaign). Testing to be conducted using the flight-like (brass board) mounting developed for Milestone 10 and X-ray calibrated for Milestone 11. Comparison of X-ray calibration results acquired before and after testing that are coherent, with no degradation of the optical performance. Agreement of in-test metrological data (thermocouple and accelerometer data) with the values obtained from simulations. Presentation of test results to SME review for concurrence that TRL 4 exit criteria passed.

Milestone #13 — Fabrication of large-diameter shell pair.

Significance — Demonstrates the feasibility of fabrication, alignment, and mounting of large-diameter (2 to 3 m) mirror shell pair. This will demonstrate the large-scale facilities (including vertical fabrication) and equipment needed for full-scale production of the many large shells for the LMA.

Verification — Measurements of the finished shell will be taken and compared to preset required tolerances; alignment will be confirmed. Timing for each process step will be reported and compared to pre-fabrication estimates. Issues identified and process modifications will be described in detail. X-ray alignment testing will be made in accordance with TRL 6 requirements. Agreement with metrological data should be verified for all the shells.

Milestone #14 — Assembly of large co-aligned mirror pair on SW using next-generation S3.

Significance — Demonstrates that alignment and integration is fully scalable. This will be the first production of multiple co-aligned mirror pairs for environmental testing and will demonstrate the feasibility of many nested pairs for final LMA development.

Verification — Measurements of the finished mounted shells will be taken and compared to preset required tolerances; alignment will be confirmed. Agreement between predictions from simulations and full-suite metrological data will be verified for each shell pair.

Milestone #15 — X-ray calibration of co-aligned mirror pair on SW and SME readiness review prior to environmental testing.

Significance — Provides independent confirmation that the co-aligned multi-mirror pairs on the flight-like SW are ready for the full environmental testing required to meet TRL 5 exit criteria.

Verification — X-ray testing to verify mirror figure and alignment will be performed. Results of this testing along with a review of the shell fabrication and shell assembly to the SW will be provided to the SME panel. The panel will provide concurrence and recommendations for upcoming environmental testing.

Milestone #16 — Environmental test campaign and SME review.

Significance — The planned environmental testing will demonstrate the survivability of the co-aligned mirror pairs under flight-like dynamic and thermal conditions.

Verification — Successful completion of a three-shell environmental qualification test (thermal vacuum and vibration test campaign). Testing to be conducted using the flight-type mounting developed for Milestone 14 and X-ray calibrated for Milestone 15. Comparison of X-ray calibration results acquired before and after testing that are coherent, with no degradation of the optical performance. Agreement of in-test metrological data (thermocouple and accelerometer data) with the values obtained from simulations. Presentation of test results to SME review panel for concurrence that TRL 5 exit criteria passed.

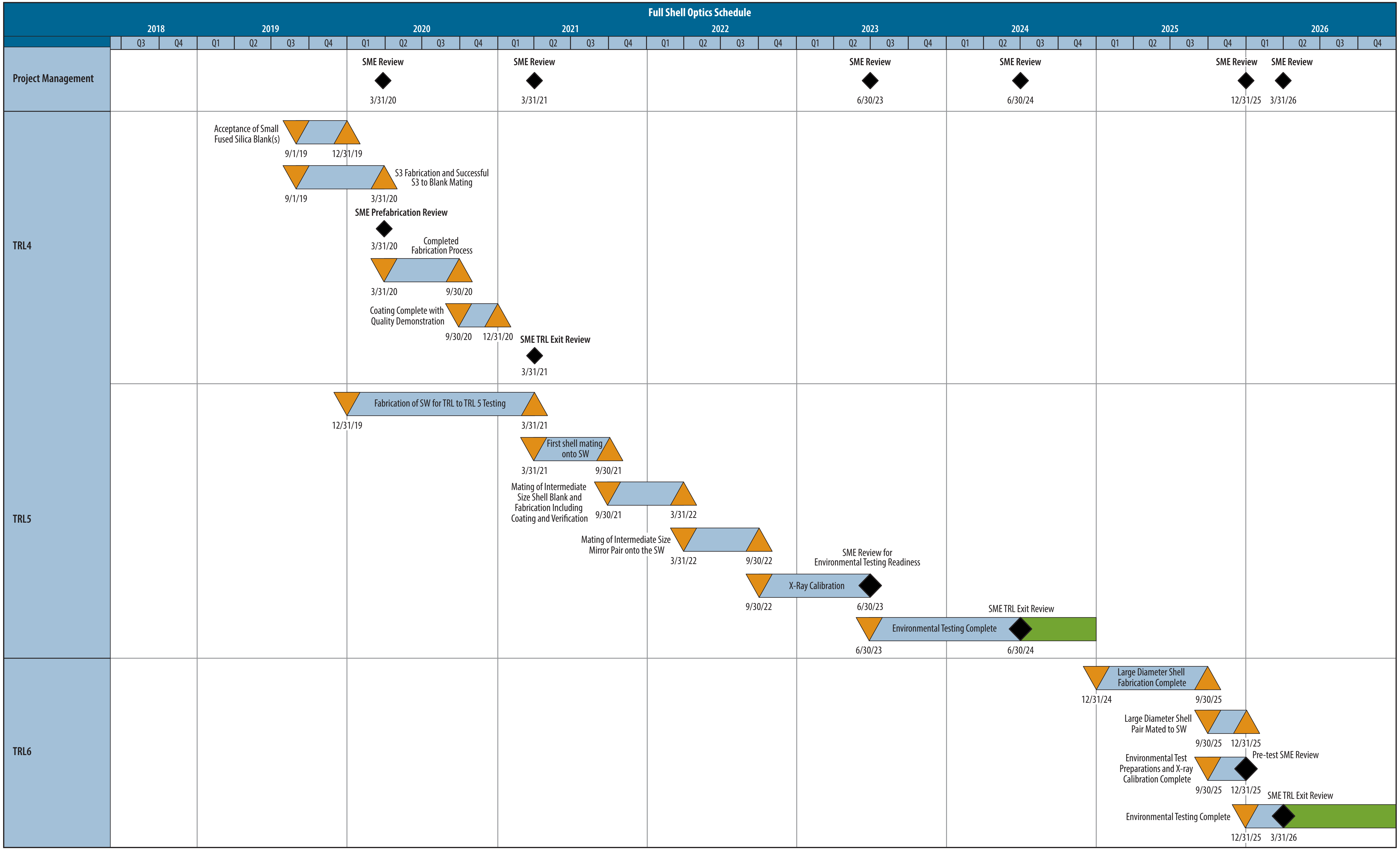


Fig. 14—Full-shell optics technology development schedule to meet TRL 6.

2.2 Cost

Redacted.

2.3 Risks

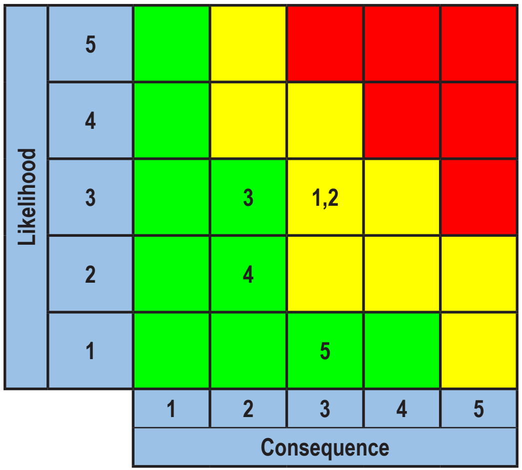
The *Lynx* program has performed an in-depth risk assessment with the support of non-advocate SMEs. The assessment has been revisited with each external review and as the various technology development efforts have advanced. The most recent revision was performed after the LMAT study in 2018. The top 5 risks are shown in Table 5. Fig. 15 presents the risk in the standard 5-×-5 format.

As shown in the table, risk mitigation strategies have been developed for each risk. The full shell development program builds from small to large diameter shells. Recognizing that new or revised procedures and facilities are thus needed to advance the technology to TRL 5 and 6, it is noted here that overall risk could be lowered by reverting to either segmented shells or to thicker full shells beyond some large diameter. Either alternative would substantially lower fabrication, handling, alignment, and survivability risk, and there are no physical differences fabricating segments or thicker shells compared to thin full shells. These alternatives would, however, reduce the aggregate effective area and increase the mass of the mirror assembly.

Table 5—Summary of Full Shell Optics technology maturation risks

Risk #	Risk Title	Risk Statement	Risk Type	Risk Assessment			Mitigation Plan
				L	C	Score	
FSO-1	Shell Production	Breakage, distortion during fabrication leads to low shell yield or production timescales nonlinearly with shell diameter.	T,S	3	3	9	1. Funded evaluation of multiple shell material options 2. Scheduled SME reviews to quality control and fabrication process scaling issues 3. Funded schedule reserve
FSO-2	Shell Alignment on Spoke Wheel (SW)	Aligned and bonded shells on SW do not meet the required error budget.	T,S	3	3	9	1. Mid-2021 SME review focused on mounting process (then biannual) 2. Multiple shell alignment and SW design options until large shell alignment/bonding demonstrated 3. Funded schedule reserve
FSO-3	Shell Support Structure (S3)	Initial S3 design insufficient to prevent deformation of shells during fabrication and transportation and/or release to SW induces unacceptable stress.	T,S	3	2	6	1. Flexible S3 design—intense early lab test campaign with funded schedule for multiple iterations 2. Early S3 SME progress review then (minimum) biannual review until acceptable design achieved
FSO-4	In Situ Metrology	In situ metrology insufficient to support planned mirror processing schedule.	S	2	2	4	1. Extensive, SME-reviewed early (pre-shell) testing of metrological capabilities 2. Funded evaluation of alternate, metrology implementations 3. Funded schedule reserve
FSO-5	Reflection Coating Process	Inability to produce reflection coatings with required surface microroughness and within coating-induced deformation tolerances requires change in coating process.	T,S	1	3	3	1. Use in situ stress measurements to refine coating processes 2. Schedule for multiple iterations in coating process development 3. SME reviews – First single-shell and first multiple-shell coating runs

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



Likelihood					
5	🟩	🟨	🟥	🟥	🟥
4	🟩	🟨	🟨	🟥	🟥
3	🟩	🟩 3	🟨 1,2	🟨	🟥
2	🟩	🟩 4	🟨	🟨	🟨
1	🟩	🟩	🟩 5	🟩	🟨
	1	2	3	4	5
	Consequence				

Fig. 15—Full shell optics risk ranking.

Risk 1 **—** The full shell design requires roughly cylindrical mirror shell geometries ranging from approximately D × t × L = 400 mm × 1.6 mm × 150 mm to 3,000 mm × 3.4 mm × 330 mm (primary or secondary). Such large, thin shells are unwieldy at best and, depending on the substrate material, may be susceptible to breakage or large-scale distortions (e.g., OOR) during the manufacturing and handling processes. Moreover, fabrication advances (e.g., increasing facility and fabrication equipment size) required for TRL 5 and 6 are untried, and delays in the necessary advancements would impact schedule.

Mitigation strategies — Although FEM undertaken by both OAB and MSFC and known material properties indicate low yield is unlikely, the full shell team is pursuing multiple design options to mitigate this risk. Alternative substrate materials are currently under investigation. A segmented shell approach (for large diameters) could also be considered should the current full shell options prove impractical. It is also noted that thicker shell substrates (of a given material) are much easier to handle and are less likely to fracture or distort but will have lower effective area and higher system mass. An independent SME review will be held prior to the initiation of the TRL 5 shell fabrication process to assess progress and plans and provide recommendations.

Risk 2 **—** Effective alignment and bonding of the individual shells to the SW is critical to meeting the performance requirements of the LMA. While laboratory results to date are promising, bonding of large shells to a large SW has not been done. While this is considered an engineering issue, if multiple iterations on either the SW design or bonding process are needed, the program schedule would be impacted.

Mitigation strategies — An early SME review will be performed in each TRL advancement cycle to assess SW development and alignment and mounting procedures. The review will focus directly on the efficacy of the SW design, and the proposed alignment/bonding process and outputs will include specific recommendations for both the ongoing advancement cycle and what are perceived as risk reduction actions needed for the next TRL. Funded schedule margin is included to allow for at least one SW redesign in each phase.

Risk 3 **—** The manufacturing processes and environments experienced by shells held within backing S3s induce stresses within the shells. If the shells distort upon release from the support structures, then the shells may not meet the figure error budget allotted.

Mitigation strategies — The full shell team will use their FEM and lessons learned to continue to iterate the S3 design. An SME review will be conducted after each fabrication and laboratory test results have been reported to provide feedback and recommendations for improvements. Funded reserve is included to provide the team with margin for iteration on the S3.

Risk 4 **—** Measurements of the mirror shell figure must be made during the manufacturing process to monitor progress and target further processing. If metrology cannot be performed in situ, then the production schedule will need to be extended to account for delays due to installation and realignment between metrology and fabrication stations.

Mitigation strategies — Development of in situ metrology is ongoing at both OAB and MSFC. Multiple promising techniques that provide measurements without physical contact with the test article (to minimize contamination) do not require precise alignment of the test article and/or can be integrated into the machining device itself (such as commercially available displacement sensors). The multiple paths will have continued funding until the required metrology capabilities are in place. The metrology progress will be a point of discussion at each planned SME review.

***Risk 5* —** If the planned process to produce reflection coatings meeting *Lynx* tolerances for deformation due to coating-induced stress, iterations in the process will be required that will impact the development schedule.

Mitigation strategies — Funded schedule reserve is provided for iterations in the coating process to ensure stress uniformity and adhesion/lamination lifetime testing prior to coating of the full shell. In situ stress measurements will be made during coating tests and used to help optimize the process. If necessary, a post-facto thermal oxidation process could be added to help correct distortion induced by coating stress.

3 Summary

The Full Shell Optics technology development plan has been contributed by developers at INAF/OAB and MSFC. It describes the direct fabrication Full Shell Optics technology that combines traditional grinding and polishing with precise metrology to produce finely figured, full-circumference mirrors. The advantages of full shells are the simplified alignment requirements, the inherently greater structural integrity of full shells, and the lower susceptibility to coating-induced stresses and mounting-induced distortions of full shells. This technology development plan provides a review of the SOA; a description of the technical elements that need to be developed, tested, and verified; statements of TRL 4, 5, and 6 specific to Full Shell Optics; an assessment of the key milestone elements (with AD^2 evaluations) needed to advance each technology to successive TRL levels; and an estimate of the associated schedule, cost, risks, and risk mitigations.

4 Appendices

4.1 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.

4.2 AD^2 Definitions

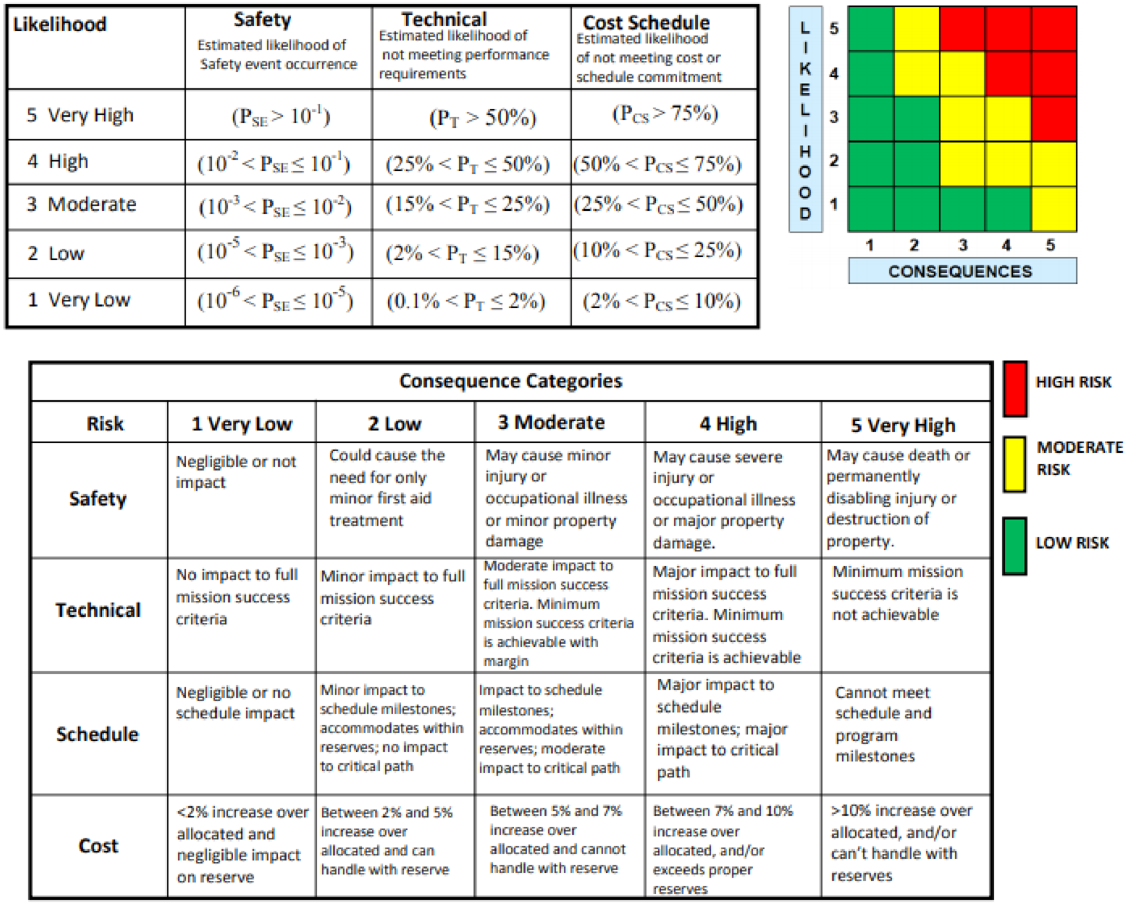
AD^2 is a description of what is required to move a system, subsystem, or component from one TRL to the next. TRL is a static description of the current state of the technology as a whole. AD^2 is what it takes, in terms of cost, schedule, and risk to advance to the next TRL. AD^2 is defined on a scale 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)

4.3 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. 16.



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	$(10^{-6} < P_{SE} \leq 10^{-5})$	$(0.1\% < P_T \leq 2\%)$	$(2\% < P_{CS} \leq 10\%)$

LIKELIHOOD					
5	🟩	🟨	🟥	🟥	🟥
4	🟩	🟨	🟨	🟥	🟥
3	🟩	🟩	🟨	🟨	🟥
2	🟩	🟩	🟨	🟨	🟨
1	🟩	🟩	🟩	🟩	🟨
	1	2	3	4	5
	CONSEQUENCES				

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

🟥 HIGH RISK
🟨 MODERATE RISK
🟩 LOW RISK

Fig. 16—Risk matrix standard scale.

4.4 Acronyms

AD^2	Advancement Degree of Difficulty
ASI	Italian Space Agency
CTE	Coefficient of Thermal Expansion
FEM	Finite Element Method
FOV	Field of View
GPR	Goddard Procedural Requirements
HEW	Half-Energy Width
INAF	National Institute for Astrophysics (Italy)
LMA	*Lynx* Mirror Assembly
LMAT	*Lynx* Mirror Assembly Trade
MSFC	Marshall Space Flight Center
NPR	NASA Procedural Requirement
OAB	Brera Astronomical Observatory (Italy)
OOR	Out-of-Roundness
PCOS	Physics of the Cosmos
PDR	Preliminary Design Review
PTV	Peak-to-Valley
RMS	Root Mean Square
S3	Shell Support Structure
SME	Subject Matter Expert
SOA	State of the Art
SW	Spoke Wheel (mounting structure)
TRL	Technology Readiness Level
UV	Ultraviolet

4.5 References

[1] Gubarev, M. et al., "Development of a direct fabrication technique for full shell x-ray optics," 2016 SPIE 9905, 99051V

[2] Kilaru, K. et al., "Full shell x-ray optics development at Marshall Space Flight Center," 2019, JATIS 5, 021010

[3] Civitani, M.M. et al., "Thin fused silica shells for high-resolution and large collecting area x-ray telescopes (like *Lynx*/XRS)," 2017, SPIE 10399, 103990W

[4] Civitani, M.M. et al., "*Lynx* optics based on full monolithic shells: design and development," 2018a, SPIE 10699, 1069911

[5] Civitani, M.M. et al., "*Lynx* optics based on full monolithic shells: design and development," 2019, JATIS 5, 021014

[6] Weisskopf, M.C. et al., "Chandra x-ray observatory: overview," 2000, SPIE 4012, 2

[7] Civitani, M.M. et al., "Probing 3M Trizact abrasive pads in the polishing and super-polishing phase of fused silica," 2018, SPIE 10706, 107063K

[8] Kilaru, K. et al., "Improving x-ray optics via differential deposition," 2017, SPIE 10399, 103991F

[9] Broadway, D.M. et al., "Achieving zero stress in iridium, chromium, and nickel thin films," 2015, SPIE 9510, 95100E