X-ray Grating Spectrometer Technology Roadmap

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This document presents a roadmap for advancing the critical technology of the *Lynx* X-ray Grating Spectrometer (XGS). The technology roadmap provides a description of the elements of the XGS technology that need to be developed, and identifies the key milestones of the maturation plan, as well as the associated schedule, cost, and risk. XGS is one of three science instruments required for the *Lynx* mission, and will provide high-throughput, high-resolution spectra at soft energies (0.2–2 keV).

1 Introduction

The *Lynx* X-ray Grating Spectrometer (XGS) will provide the spectral resolving power and effective area needed to meet the *Lynx* Pillar II science goals shown in Table 1 and to provide enabling capabilities for General Observer science experimentation.

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

Technology	Science Theme/Goal	Performance Driver	Instrument Requirements	
			Property	Value
X-ray Grating Spectrometer	Science Pillar II: Reveal Invisible Drivers of Galaxy Formation and Evolution	Provide the sensitivity required to observe 80 bright Active Galactic Nuclei sight lines (demonstrated by extraction of 1 mA signal at the representative O(VII) and O(VIII) absorption lines)	Spectral resolving power (R)	>5,000
			Effective Area	4,000 cm^2 at 0.6 keV

Two separate grating technologies have been identified as credible options for the *Lynx* XGS spectrometer: (1) the Off-Plane Reflection Gratings (OP-XGS) described by [Miles et al. 2018, DeRoo et al. 2016, and McEntaffer 2019] and (2) the Critical Angle Transmission Gratings (CAT-XGS) described by [Heilmann, et al. 2019 and Günther & Heilmann 2019]. While the CAT-XGS technology was selected for purposes of the Design Reference Mission (DRM), the OP-XGS is has attained a State-of-the-Art (SOA) Technology Readiness Level (TRL) of 4 with a highly relevant flight demonstration planned for 2021 (see [Tutt et al. 2018], [Donovan et al. 2018], and §1.2.2).

This OP-XGS roadmap was developed by the *Lynx* program as a planning tool that describes the projected development path (technical, schedule, and cost) to mature the OP-XGS to TRL 5 by Q1 2022 and TRL 6 by Q4 2024. Following this path will ensure that the OP-XGS will meet (and likely exceed) all scientific performance and programmatic requirements for the *Lynx* Observatory.

1.1 OP-XGS Overview

Fig. 1 provides a brief introduction to off-plane grating fundamentals. The OP-XGS design is comprised of many individual reflection gratings operating in an extreme off-plane mount (see Fig. 1). Light from the telescope intersects the gratings nearly parallel to the groove direction (as shown in Fig. 1 (left)), creating an arc of diffraction at the focal plane. Given that the exit angle from the gratings is equal to the small, grazing incidence angle of the incoming light (typically 1° to 2°), reflection gratings operating in this geometry can be placed very close to one another to maximize the collecting area of the X-ray Grating Array (XGA). An Atomic Force Micrograph (AFM) of an SOA grating segment is shown in Fig. 1 (center) to provide insight into the physical dimensions of this fundamental building block. Fig. 1 (right) shows an example of the off-plane geometry as applied to three representative reflection gratings (as would be mounted in an OP-XGS module).

The *Lynx* OP-XGS is designed to provide high-throughput, high-resolution spectra at soft energies (0.2–2 keV). As shown in Fig. 2, the *Lynx* XGAs are mounted just aft of the *Lynx* Mirror Assembly (LMA) along the optical path.

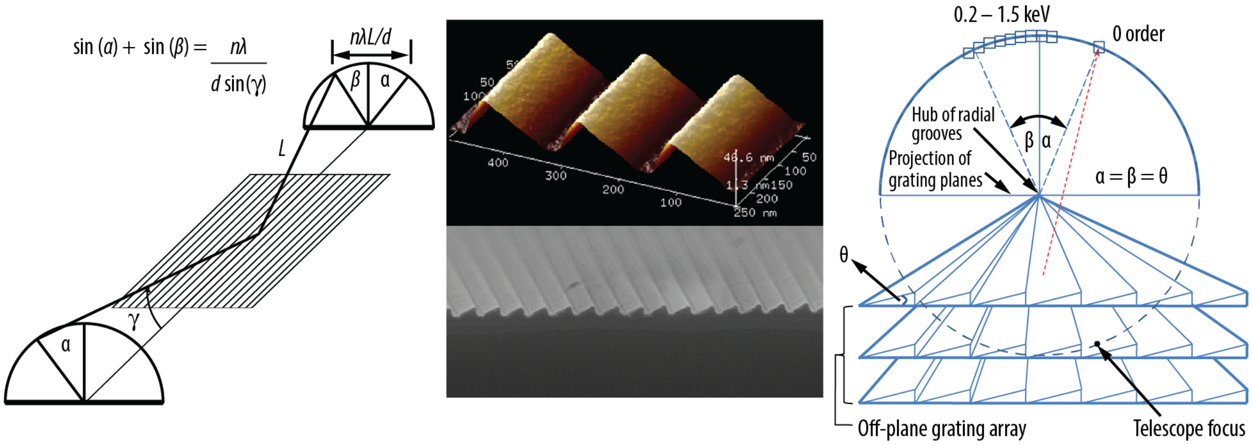

Fig. 1—OP-XGS grating fundamentals. (Left) Diagram illustrating geometry of extreme off-plane diffraction—diffracted orders line along a circular arc at the focal plane. (Center) AFM of an SOA master-blazed *Lynx*-class grating. (Right) Example showing ray tracing with three representative reflection gratings (projections onto the focal plane; taken from [McEntaffer, et al., 2013]).

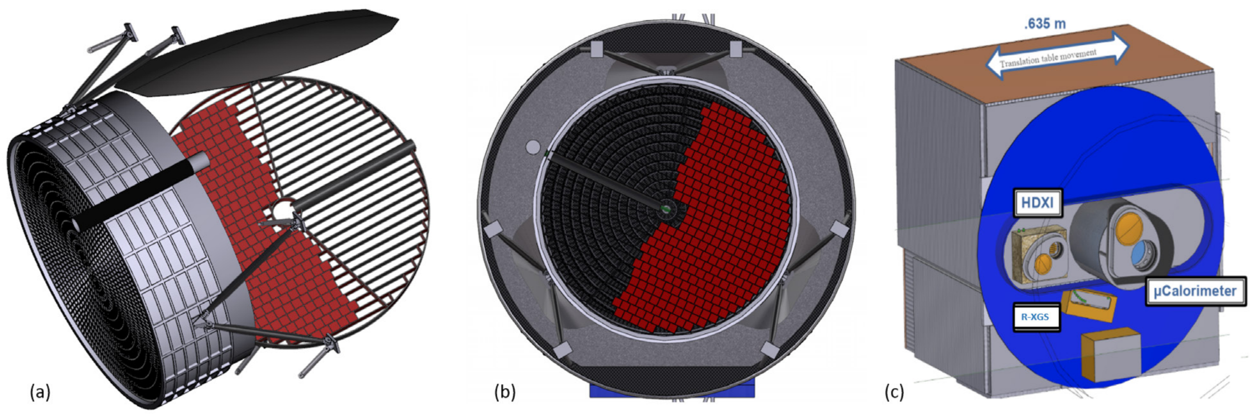

Fig. 2—OP-XGS instrument views. (a) Contamination door (grey) and XGA (red) retracted from the LMA. (b) Focal plane view toward LMA showing the R-XGA actuated into the telescope beam. The array covers 184° in azimuth. (c) View toward the ISIM with the movable focal plane instruments and the stationary OP-XGS readout array.

Flight-proven commercially available actuators are used to rotate the structure into the optical path as required. The sensor readout array is mounted on the *Lynx* Integrated Science Module (ISIM). Sensor array readout technology is essentially identical to that required for the *Lynx* High Definition X-ray Imager (HDXI) and is covered in the separate *HDXI Technology Roadmap*. As noted above, the OP-XGS will have a spectral resolving power of at least R >5,000 (λ/Δλ) in the soft X-ray band and a minimum effective area in excess of 4,000 cm^2 at 0.6 keV.

1.2 XGS Description

1.2.1 Overview of Technology

A detailed description of the OP-XGS instrument is given in [McEntaffer 2019] and summarized here. The *Lynx* XGS is designed to provide a spectral resolving power requirement of *R* >5,000 (λ/Δλ) over the 0.2–2.0 keV energy band, with an effective area >4,000 cm^2 at 0.6 keV. As noted above, the OP-XGS is comprised of an array of reflection gratings placed just aft of the LMA. The gratings disperse spectra onto a focal plane camera located on the ISIM. The zero-order reflected image of the telescope focus is located on an individual sensor, while the diffracted orders are located along an arc of sensors azimuthally arrayed from zero-order. The grating array is actuated into the telescope beam for grating science observations and out of the beam for HDXI or LXM dedicated observations. In the current OP-XGS concept design, there are 154 grating modules in the R-XGA containing a total of 9,856 gratings.

Custom groove profiles are required for the OP-XGS. These are fabricated using SOA nanofabrication techniques [Miles et al. 2018a]. For this, the radial pattern is written into a resist using an electron beam lithography tool. This pattern is then transferred into the substrate. Finally, a master grating exhibiting a triangular, radial profile is produced. This master grating can then be replicated hundreds to thousands of times using standard techniques such as Substrate Conformal Imprint Lithography (SCIL). Once the gratings are replicated, they are aligned into modules which are used to populate the XGA. An image of an aligned module of reflection gratings is shown in Fig. 3. This module is comprised of 26 gratings aligned for a suborbital rocket experiment, the *Water Recovery X-ray Rocket* (*WRXR*) [Miles et al. 2018], which launched successfully in 2018.

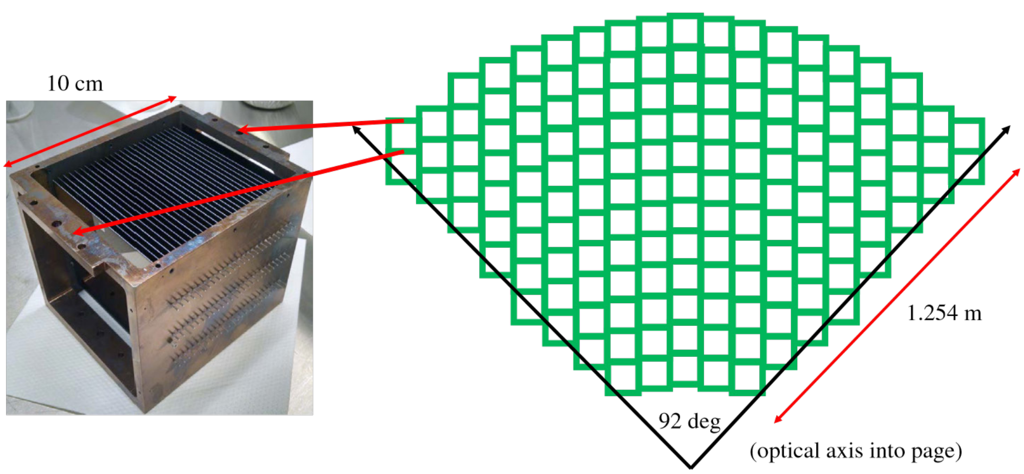

Fig. 3—(Left) Aligned module of 26 replicated, blazed reflection gratings for the *WRXR* mission. (Right) Layout of grating modules (green boxes) over half of the XGA.

Based on these steps, OP-XGS development efforts are focused on four technology elements: (1) the reflection grating master, (2) the replica substrate, (3) the replication methodology, and (4) the alignment methodology. A summary of these elements is shown in Table 2. A detailed discussion of the issues, challenges and risks for each element is provided in §1.2.3.

Table 2—OP-XGS technology maturation elements.

Element	Element Description	TRL	Advancement Description
1	Reflection grating master	4	Selection/refinement of process to fabricate the large-format, blazed grating required for replicate gratings
2	Replica substrates	4	Process improvements to assure availability of both thin and thick substrates required for grating replication
3	Replication methodology	5	Stress reduction in substrates
4	Alignment methodology	4	Processes to align grating within modules and modules within the XGS framework

Element 1 — Reflection gratings have been fabricated with precise blaze profiles capable of high efficiency and have separately been produced with precise radial profiles capable of high resolving power. A master grating needs to be created that exhibits a precise blazed, radial profile over a large format (~10 × 10 cm). There are four fabrication techniques under evaluation for master grating fabrication. All are feasible alternatives requiring straightforward engineering advancement and a downselection to the lowest risk technology under the *Off-plane Grating Rocket Experiment* (*OGRE*) flight program.

Element 2 — Substrates are the fundamental building blocks for the grating replication process. As noted above, SOA replica substrates have been thin 0.5-mm Si wafers or fused silica substrates. Thin substrate technology was used in the *WRXR* flight test. The SOA is not sufficient to meet *Lynx* requirements – improvements in flatness, stress relief and alignment techniques are required. Advancement of thin substrate technology is feasible for *Lynx*. Engineering efforts to ensure acceptable stress relief in the fabrication and improve the alignment process are required and underway. An option employing a thicker substrate technology is also under evaluation. Successful advancement and selection of the thick substrate technology would reduce alignment issues. A down selection will be made under the *OGRE* program and a module will be flown with gratings of similar form, fit and function to *Lynx* will be flight-tested in 2021.

Element 3 — Replication of reflection gratings has been achieved for large format, high groove density, blazed masters. The process has also produced many replicas in a short amount of time to prove the mass-production required for *Lynx* is possible. Engineering efforts are required to reduce stress imparted in the replication process, especially for the thin, flat substrate option. While the planned replication process for the thick, polished substrate option has been demonstrated in the laboratory, the process required for mass production has not been perfected. This is considered straightforward engineering and will be addressed both by *OGRE* and *Lynx* development efforts.

Element 4 — Previous alignment methods can be used for thin, flat substrates if this technology option is selected. This method employs epoxy bonds on the substrate. Straightforward engineering efforts to ensure that the epoxy does not impart unacceptable stress to the flat replica are required. A new alignment method is being developed for the thick, polished substrate option. This alignment method involves coding the tolerances into the polished substrates, which are then stacked to create a module. The stacking process study would leverage from silicon pore optics technologies. A rudimentary error budget has been developed and this will be expanded via both iterative laboratory testing and ray trace model improvements. The error budget will be used to identify alignment issues and optimal resolutions.

1.2.2 State of the Art

The European Space Agency (ESA) launched the *XMM-Newton* Observatory nearly 20 years ago. This platform employed the large reflection grating system pictured in Fig. 4 and is by far the major example of the use of reflection grating technology to date [J.-W. den Herder et al. 2001].

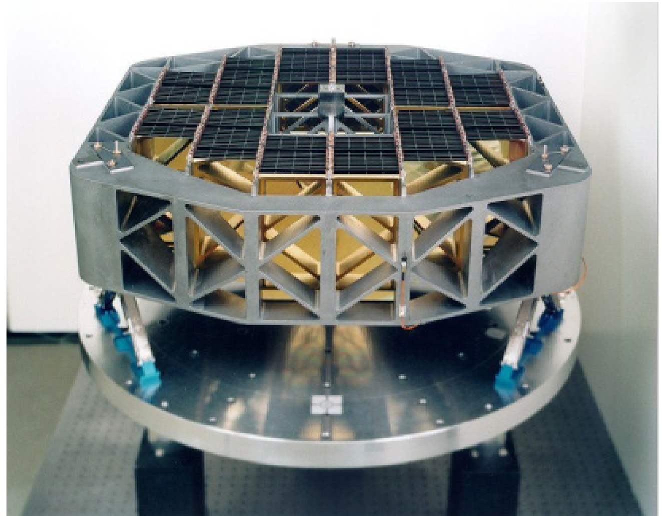

Fig. 4—The *XMM-Newton* Reflection Grating Assembly.

This Reflection Grating Assembly was built when modern photo- and electron beam lithography technologies were in their infancies and not applicable to the *XMM-Newton* system. The *XMM-Newton* RGS was not operated in the extreme off-plane configuration that will enable the truly unprecedented resolution and throughput planned for *Lynx*. Sophisticated lithographic technologies are now SOA for *Lynx*-class fabrications. the keys to successful development of the *Lynx* OP-XGS are (1) the production of the master grating, (2) the mass production of replicated gratings for module assembly, and (3) the alignment of the grating modules in the full grating array. Extensive work has been done in each of these three areas and this heritage is discussed below.

Master Grating Fabrication — Reflection gratings have demonstrated diffraction efficiencies with resolving powers that meet and exceed *Lynx* XGS requirements. In fact, blazed, replicated, large-format gratings have produced some of the highest diffraction efficiencies ever measured for X-ray reflection gratings. For example, gratings with blazed profiles have been fabricated at the Penn State University (PSU) Nanofabrication Laboratory [Miles et al. 2018]. Fig. 5 illustrates the high (~90% relative) diffraction efficiency demonstrated in testing of a PSU grating using the Advanced Light Source (ALS) at Lawrence Livermore's Berkeley Laboratories [Miles et al. (2018)]. The grating shown in the inset was developed for the *WRXR* mission, which employed a module of 26 replicated, blazed reflection gratings similar in form and fit to those required for *Lynx*. While the *WRXR* gratings were similar in form and fit to the planned *Lynx* gratings, detailed design aspects (e.g., radial profile prescription) were not. The gratings being designed for the upcoming *OGRE* will be very similar in form, fit and function to *Lynx*. The *OGRE* program directly augments *Lynx* grating development efforts and will lead to the downselection of the master grating technology to be employed by *Lynx*.

Furthermore, gratings with spectral resolving power consistent with the *Lynx* requirement (R ~5,000) have recently been demonstrated [McEntaffer et al. 2019]. Fig. 6 shows an example of the spectral resolving power of a *Lynx*-class radial profile reflection grating. The black histogram in the figure is the data, with model fits as colored solid lines. Each fit includes contributions from the zero-order image convolved with the natural line widths of Al-Kα_2 and Al-Kα_1 (dashed red lines). In addition, a Gaussian component is added to each fit to represent aberrations due to imperfections in the grating grooves. The Gaussian components correspond to the resolutions listed in the legend. The fit stops statistically improving after ~8,000, which is limited by the test telescope PSF.

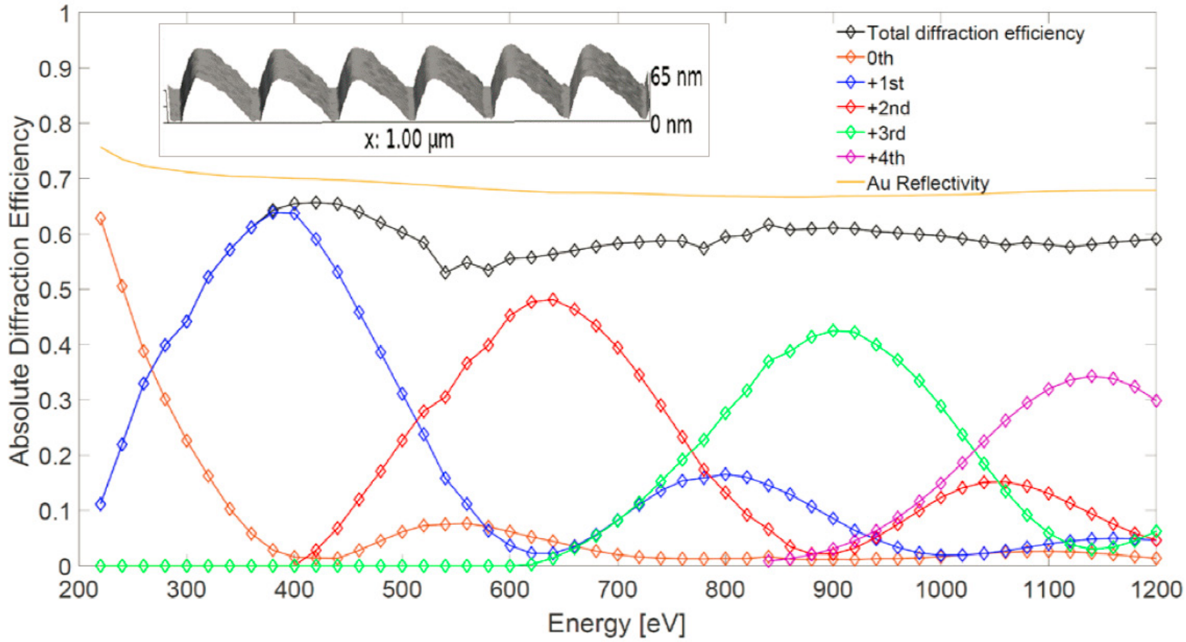

Fig. 5—Diffraction efficiency measurements for a replicated, blazed, reflection grating operated in the extreme off-plane mount. The absolute diffraction efficiency is ~60% across the band with ~90% relative efficiency. (Inset) AFM measurement of the tested groove profile.

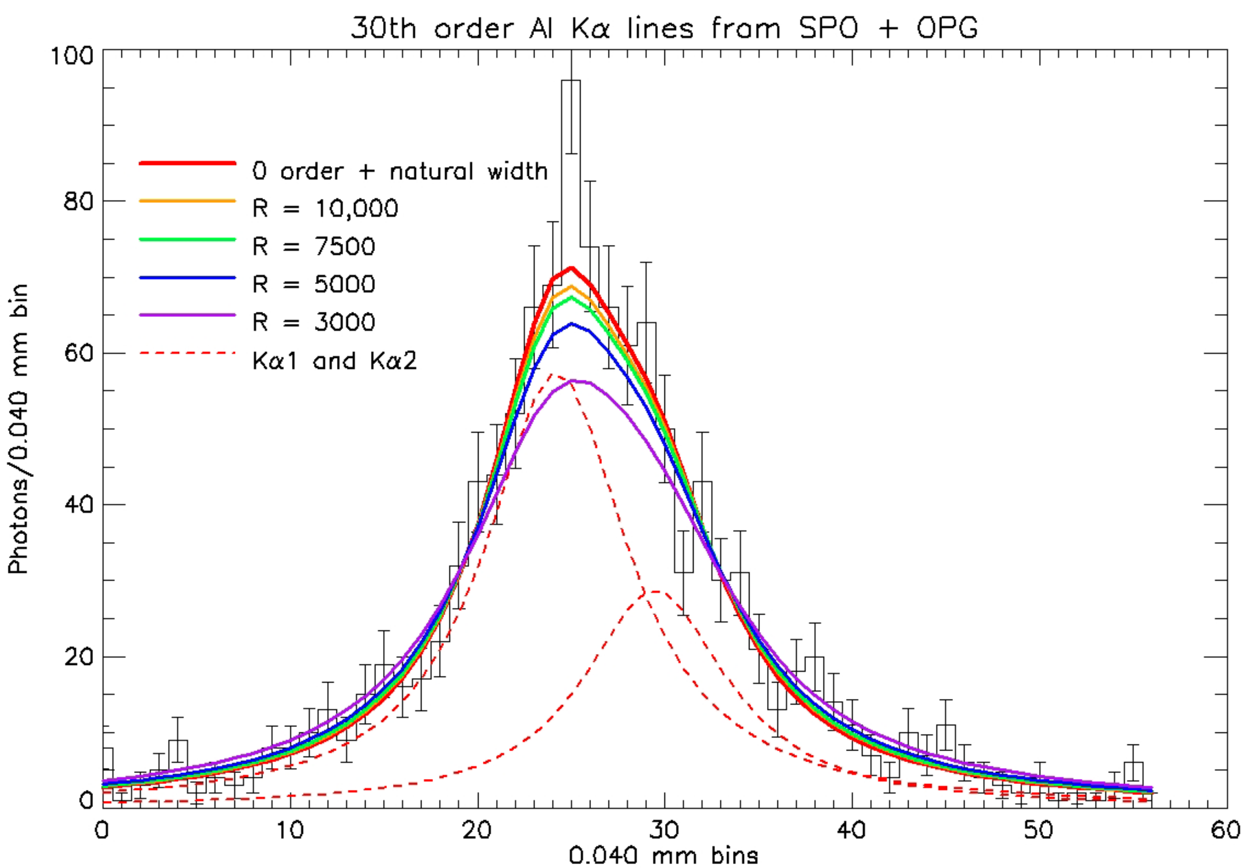

Fig. 6—Spectral resolving power measurement of a radial profile reflection grating.

Grating Replication — The SOA in rapid master grating replication was demonstrated in the *WRXR* program. Here, the master grating was replicated 50 times in one day using SCIL replication technology to provide replicas for the *WRXR* module (shown in Fig. 3). The *WRXR* gratings measured $100 \times 110 \times 0.5$ mm^3 with triangular blazed grooves - characteristics similar to the gratings planned for the *Lynx* OP-XGS concept. As with the master grating fabrication, the *OGRE* program will be a pathfinder for *Lynx* grating replication. To date, thin substrates have been used and represent the SOA. This technology is being considered for *Lynx* because of its heritage. In addition, the used of thick/wedged, highly polished, ribbed substrate technology is under consideration. This technology is under development at PSU and results to date indicate that this technology could ease the alignment and stress-in-fabrication issues encountered with the thin substrate alternative. The *OGRE* program will downselect to a single technology for flight demonstration, and this decision will carry over to *Lynx*. Further discussion can be found in §1.2.3. Improvements in manufacturing processes will also be required to identify and mitigate stresses that would result from SOA resist, coating, dicing, and bonding processes.

Grating/Module Alignment — Multiple recent and ongoing projects contribute to the SOA for reflection grating alignment. Reflection gratings were originally proposed for the *Arcus* program and a reflection grating module (shown in Fig. 7) that is similar to the modules envisioned for *Lynx* was designed, fabricated and demonstrated [Allured et al. 2015].

Fig. 7—*Arcus* Off-Plane Grating Module.

For the *WRXR* mission, the 26 gratings in the flight module were aligned to one another to ~10s of arcseconds in the rotational degrees of freedom [Tutt et al. (2019)]. This module was similar to those proposed for *Lynx* in both form and fit and represents the SOA. While the roll tolerance will have to be improved (by less than a factor of 10 for *Lynx*), the *WRXR* effort demonstrated the fundamentals of the alignment methodologies needed for *Lynx*. Advancement of these technologies should be straightforward. In fact, many of the advancements required at the module level will be completed in the ongoing *OGRE* program. Overall alignment of the many grating modules will require the development of a precise error budget, alignment and test facilities, and an advanced ray tracing model for development and testing at the component and system levels. A rudimentary error budget has been developed and will be advanced for *Lynx* using straightforward engineering practices. The required test facilities are at the required SOA. Similarly, a module-class ray trace model has been developed for *OGRE* and this SOA model will serve as the starting point for *Lynx*. The model will be upgraded to incorporate the system issues associated with the large *Lynx* framework for TRL 5 and TRL 6 development.

It is noted that in addition to *XMM-Newton* and *Arcus*, reflection gratings have been studied for *Constellation-X*, *IXO*, and multiple other programs. Further, since the last Decadal both the NASA Strategic Astrophysics Technology (SAT) and Astrophysics Research and Analysis (APRA) programs have provided funding since 2011 to increase the OP grating TRL from 3 to nearly 5. These latter development efforts are directly applicable to *Lynx* based on the fact that the performance and development goals for these studies are tailored to *Lynx*-class technology targets. This technology development roadmap extends these efforts, as necessary, to achieve first TRL 5 and then TRL 6 based on the strong foundation provided by these NASA-funded efforts.

The NASA PCOS Technology Review Board vetted reflection gratings at TRL 4 with acknowledgment of a clear path toward TRL 5. The *Lynx* program agrees with this assessment with two notes. First, the replication methodology (Technology Element 3) is considered to be TRL 5 and second, the *OGRE* program is anticipated to provide significant advancements in master grating fabrication, replication technology, and in-module alignment capabilities that will be flight-proven outside of the *Lynx* program in 2021. While the PCOS board did not assess Advancement Degree of Difficulty (AD^2), the *Lynx* program performed an internal non-advocate assessment that placed the overall AD^2 for advancement to TRL 5 at a level between 3 and 4. Moving from the demonstrated SOA to the *Lynx* goal for all three technology elements currently rated at TRL 4 (i.e., master grating fabrication, replication substrate advancement and alignment) will require arduous, stepwise advancements. There are, however, no known physical barriers (e.g., formulating the process(es) to meet *Lynx* requirements). All developments will take time, patience, and quality engineering, but no fundamental "breakthroughs" are required. It is noted that for the TRL 4 to TRL 5 advancement programs, multiple technology paths are being explored for element advancement. All options under consideration are considered to be feasible – the program is carrying more than one in order to identify the lowest cost/risk approaches only. The advances made in the TRL 4 to TRL 5 path should significantly reduce risk going forward and an AD^2 of 2 is anticipated for the TRL 5 to TRL 6 development effort.

1.2.3 Issues, Challenges, and Risks

As described above, there are four main technical challenges that must be addressed in the development of the *Lynx* OP-XGS: the (1) fabrication of large-format, radial, blazed gratings that demonstrate both the efficiency and resolving power required to meet *Lynx* science goals; (2) development of substrates of sufficient quality to meet *Lynx* tolerances; (3) the development of the replication processes necessary to mass produce replicate gratings; and (4) the development of the alignment processes necessary to populate the extreme off-plane mount effectively. While substantial progress has been made toward meeting these challenges, methodical, stepwise advancement is required to meet all TRL 4 exit criterial for 1, 2, and 4 (3 is already considered TRL 5) and then move to TRL 6. It is noted that there are no known physical barriers to meeting the technology development targets but rigorous advancements of modeling (e.g., ray tracing), grating fabrication, and alignment techniques will be required.

There are multiple approaches to meeting the first challenge (i.e., creation of a large-format, radial, blazed grating), and these are briefly described here. Research and development efforts to date indicate that all of these approaches are projected to produce quality gratings through relatively straightforward engineering advancement efforts. Four alternatives are being explored in this relatively inexpensive stage to identify which provides the best path (i.e., lowest cost/risk) to the end product. Method 1 employs KOH etching of Si wafers to produce the precise blaze profiles required [McEntaffer et al. 2013, Miles et al. 2018a]. The challenge with this method lies in the fact that the continuously varying groove direction of a radial profile does not follow the crystal structure of the Si. Development efforts are required to assure fabrication with both acceptable scatter and resolving power. In Method 2, ion milling is employed to transform a laminar patterned grating into a blazed profile. The radial profile is first dry-etched into the Si wafer to create a rectangular (laminar) profile. The ion milling tool then physically ablates the features to create the desired blazed profile. The major challenge with this method is obtaining the facet surface smoothness necessary to attain the required scatter and sensitivity figures of merit. Method 3 is based on the mechanical manipulation of the substrate to create the desired radial pattern. Here, a parallel grating profile is written and etched into Si to create a precise blazed profile. This profile is then replicated onto a flexible stamp (typically made from polydimethylsiloxane (PDMS)). The stamp is differentially stretched perpendicular to the groove direction to create a continuously variable groove density. Replication of the stretched pattern will result in a radial, blazed grating of the quality necessary for *Lynx*. The challenge lies in developing the process to the degree necessary to reduce the inherent differential stretching to the point that the radial profile necessary to provide the required resolving power can be obtained. Finally, Method 4 involves thermal processing of a pattern recorded by an electron beam. In this technique, the electron beam is used to expose the resist to varying levels using grayscale lithography. The pattern is then smoothed into a blazed facet using thermal reflow in which the resist relaxes from the grayscale pattern into a smooth triangular profile. The challenge with this method is in the creation of a high-quality replica from the resist. Each of these methods have been deemed feasible by experts in the field. Each will require the application of rigorous engineering practice. The program is investigating each in order to select the "best" (read: lowest cost/risk) technology to carry forward. Development efforts are currently focused on development of the *OGRE* flight test article. A downselection will be made in the near term, and this decision will carry over to *Lynx* pre-Phase A and Phase A development methods.

The challenges associated with developing the required substrate for the replicate grating lie in achieving the required flatness and in developing the methodology necessary to reduce stress to acceptable levels. As noted above, thin wafer technology is the SOA and has been successfully applied/demonstrated on the *WRXR* flight. *WRXR*-class alignment technology is not sufficient to meet *Lynx* requirements and continuing engineering efforts are required and planned. An alternative, thick substrate technology has emerged, and this is being explored for both *OGRE* and *Lynx*. This technology uses thicker (~2 mm) Si substrates that have been polished into a wedge that carries the alignment tolerances within the precise shape of the substrate. Most of the material of the wedge is removed leaving the flat face sheet that carries the grating along with several ribs on the backside to maintain the precise wedge shape. These substrates are then stacked and bonded together in the same way as Silicon Pore Optics (SPOs) such as those used for the *Athena* mission (Collon et al. 2018). As with the master grating efforts, both of these options are feasible and will require straightforward engineering attention to meet *Lynx* goals. Similarly, *Lynx* will benefit from *OGRE* developments; one of these methods will be selected for this *WRXR* follow-on experiment that will demonstrate *Lynx*-class (form, fit, and function) module technology in 2021.

When replicating a grating master onto the substrates mentioned above, there is a challenge in ensuring minimal induced stress from the processing. Substrate conformal imprint lithography is a proven replication technique that can produce high-quality replications with high volume. This process was used to produce 50 replicas for the *WRXR* mission in a day. The requirements for the optical figure on the substrates for *Lynx* are much tighter than those for *WRXR*, however, so additional characterization of stress during processing is required. Replicas are made via imprinting the master grating into a resist. The resist then hardens, and the pattern is preserved on the replica substrate. This hardened resist can impart stresses into the substrate thus changing its figure. Minimizing this effect is a challenge that needs to be addressed, especially for the thin substrates. It may not affect the thick substrates, but the appropriate testing needs to be performed. Following replication, the final grating will need to be cut out from the substrate. Again, this has been performed successfully many times previously, but the induced stress has only seen limited study. The stress of this process needs to be determined and minimized for the thin and thick substrates. The methods of determining the stress at these steps is well known and straightforward. *Lynx* will benefit from the previous studies in these areas and only need incremental engineering advances to address this challenge.

The OP-XGS will require the alignment of nearly 10^4 gratings in approximately 400 modules across a large area mounting structure. The final *Lynx* design will likely have a translational tolerance on the order of 100 μm (1 σ) and an angular tolerance around 5 arcseconds (1 σ). The angular tolerances are challenging and beyond the SOA. Large reflection gratings have been aligned successfully (e.g., *XMM-Newton*) and the tools, methodologies and lessons learned from past programs (*XMM-Newton*, *Arcus*, *WRXR*, *OGRE* and others) will be used to meet the *Lynx* alignment challenges. The *Lynx* approach is based on the development of a detailed, accurate error budget incorporating a detailed requirements matrix. The error budget will build upon previous (e.g., *WRXR, Arcus*) and ongoing (e.g., *OGRE, Lynx*) efforts. The development will start with detailed assessments of all anticipated major alignment factors including (1) within module (grating-to-grating) alignment, (2) inter-array (module-to-module) alignment, (3) array to LMA alignment, and (4) alignment at the system level (LMA+R-XGA) alignment. These assessments, along with knowledge of factors such as the telescope PSF, pointing, and detector pixilation will provide a foundation for the error budget. The development of this budget also requires a detailed ray trace of the system, including detailed knowledge of the telescope PSF, a major contributor to the LSF. A first-generation model is already in place and has been demonstrated in the *OGRE* development. This model is currently being expanded to the system level required for *Lynx*—this is relatively straightforward engineering and should be low risk. Extensive testing is required but the facilities and instrumentation required for the anticipated iterative testing is proven and available.

2 Detailed Technology Roadmap

The key elements of the *Lynx* R-XGA, reflection gratings, and their alignment have been studied extensively in recent years. These investigations have identified fabrication methods for the gratings and shown improving alignment methodologies. Projections using the current techniques show that achieving *Lynx* requirements is straightforward given appropriate development. Given the advanced TRL of reflection gratings, the development path is well-established with incremental advancements required in each area.

2.1 Key Milestones

Milestones defined by the *Lynx* Instrument Team for specific activities necessary to develop and/or mature the technology elements have been identified in Table 3. Approximate dates for reaching each milestone is provided. Key milestones are defined as those critical to the advancement of the technology to the next TRL level.

Table 3—XGS TRL milestones.

TRL 4=>5, Advancement Degree of Difficulty: AD^2 = 3-4
Advancing from the demonstrated SOA to the *Lynx* goal for all three technology elements currently rated at TRL 4 will require stepwise advancements but there are no credible physical barriers to meeting *Lynx* requirements. Multiple technology paths are being explored for element advancement to TRL 5 in order to identify the lowest cost/risk approaches from the various feasible options.

<table>
<tr><td>NASA TRL 5</td><td colspan="2">A medium-fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrate overall performance in critical areas. Performance predictions are made for subsequent development phases.

Brassboard: A medium-fidelity functional unit that typically 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 operate in simulated operational environments in order to assess performance of critical functions.</td></tr>
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***Lynx* XGS TRL 5 Exit Criteria**
Must demonstrate a credible technology development path to the required on-orbit performance of the *Lynx* XGS. Demonstrations must trace to the on-orbit performance requirement in the operational environment. Performance is consistent with the expected flight performance, given no worse than a 30% uncertainty in lab demonstrations and/or models, consistent with the medium-fidelity system required for TRL 5. A credible demonstration must comprise the following for the XGS: 1. Realistic end-to-end error budget for *Lynx* XGS resolving power and effective area. 2. Laboratory demonstration of resolving power and effective area of medium-fidelity grating subassemblies as defined below. Lab demonstrations will be executed under the following conditions: • X-ray test of an aligned array of representative CAT grating facets illuminated by an aligned array of high-quality mirrors. Gratings are placed in representative positions across the array, with mass simulators in place of missing gratings. The array and grating dimensions are about 1/4 the size of the gratings array in the point design. • The module is integrated with a medium-fidelity array structure with realistic mechanical interfaces. • The grating array is integrated with a high-quality telescope capable of producing a PSF consistent with achieving the required performance. • Assemblies are tested in an operational environment that includes vibration and thermal vacuum. • The effective area of the aligned gratings are measured while illuminated by a telescope. The source beam and the telescope response are quantified prior to this test. 3. Models • Performance is validated based on performance measurements of individual gratings, alignment results, and ray-trace models that incorporate the results of these measurements. • Ray-trace model of resolving power for *Lynx* and the given test configuration. • Diffraction efficiency modeling and structure modeling for predictions of effective area testing. • Mechanical modeling of the grating and support structures. • Validation of error budget based on modeled and measured performance. • Use results to predict performance during TRL 6 developments and quantify appropriate scaling.

XGS Development/Maturation Milestones

#	Milestone Description	Date
1	Blaze a radial master grating	Q4 2019
2	Complete stress study on thin, flat substrates and replicas	Q1 2020
3	Complete stress study on thick, polished substrates and replicas	Q1 2020
4	Complete non-advocate SME interim progress review on component technology	Q1 2020
5	Complete alignment study of thin, flat replicas	Q2 2020
6	Complete alignment study of thick, polished replicas	Q2 2020
7	Complete non-advocate SME review prior to TRL 5 test module production	Q3 2020
8	Complete analyses of alignment study results and produce a module of replicas for TRL 5 testing.	Q1 2021
9	Complete TRL 5 module specific ray trace model	Q1 2021
10	Perform TRL5 tests and analyze results.	Q2 2021
11	SME review on TRL 4 exit criteria.	Q3 2021

TRL 5=>6, Advancement Degree of Difficulty: $AD^2 = 2$
The advances made in the TRL 4 to TRL 5 path should significantly reduce risk going forward and an AD2 of 2 is anticipated for the TRL 5 to TRL 6 development effort.

Anticipated date to achieve TRL 5: Q3 2021

<table>
<tr><td>NASA TRL 6</td><td colspan="3">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.</td></tr>
<tr><td rowspan="11">Lynx XGS TRL 6 Exit Criteria
The system must demonstrate using a high-fidelity, scalable, flight-like prototype which adequately addresses all critical scaling issues and ensures that all Lynx performance requirements are met in critical environments.

A credible demonstration must comprise the following:
1. Realistic end-to-end error budget for Lynx XGS resolving power and effective area.
2. Laboratory demonstration of measured resolving power and effective area of high-fidelity grating array prototype, as defined below, and executed under the following conditions:
• An X-ray test of an aligned array of representative gratings illuminated by an aligned array of high-quality mirrors (~1 arcsec or better HPD in dispersion direction, consistent with the X-ray optics at a TRL 5). Grating modules should fill a portion of the full array and be placed in representative positions across the array, with mass simulators in place of missing gratings/modules. The prototype units must be tested in an operational environment that includes vibration and thermal vacuum.
• Performance is validated based on performance measurements of individual gratings, alignment results, and ray-trace models that incorporate the results of these measurements.
3. Environmental testing (acoustic, thermal vacuum, vibration) and X-ray testing in operational environments.</td><td colspan="3">XGS Development/Maturation Milestones</td></tr>
<tr><td>#</td><td>Milestone Description</td><td>Date</td></tr>
<tr><td>12</td><td>Complete fabrication of the Lynx OP-XGS grating master</td><td>Q1 2022</td></tr>
<tr><td>13</td><td>Complete SME review on grating master fabrication versus specifications</td><td>Q2 2022</td></tr>
<tr><td>14</td><td>Complete fabrication of the Lynx grating modules and array structures</td><td>Q3 2022</td></tr>
<tr><td>15</td><td>Complete fabrication of the grating substrates</td><td>Q3 2022</td></tr>
<tr><td>16</td><td>Complete replication of the gratings and their alignment within modules</td><td>Q3 2022</td></tr>
<tr><td>17</td><td>Complete pre-alignment SME review</td><td>Q1 2023</td></tr>
<tr><td>18</td><td>Integrate grating array with TRL 6 mirror assembly and readout array</td><td>Q2 2023</td></tr>
<tr><td>19</td><td>Perform TRL 6 tests and analyze results</td><td>Q4 2023</td></tr>
<tr><td>20</td><td>SME review on TRL 5 exit criteria</td><td>Q1 2024</td></tr>
<tr><td colspan="4">TRL 5=>6, Advancement Degree of Difficulty: AD^2 = 3–4
20–30% Development Risk—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. All the steps are incremental developments and improvements relative to the SOA</td></tr>
<tr><td colspan="4">Anticipated date to achieve TRL 6: Q2 2024</td></tr>
</table>

Milestone 1 — Blaze a radial master grating

Significance — Blazing a radial master of the required quality demonstrates the capability to achieve the effective area and resolving power requirements for *Lynx*.

Verification — The groove profile will be measured using Scanning Electron Microscopy (SEM) and AFM. The diffraction efficiency will be tested at the ALS and Lawrence Berkeley National Lab, or a similar synchrotron facility. The spectral resolving power can be measured at the Stray Light Facility (SLF) at NASA Marshall Space Flight Center (MSFC). Measuring high diffraction efficiency and high spectral resolving power over a ~10-×-10-cm area will verify this milestone.

Milestone 2 — Complete stress study on thin, flat substrates and replicas

Significance — Demonstrates capability to produce the thin (0.5 mm), flat (<2 μm peak-to-valley) substrates required for *Lynx*. Two candidate substrates developments (one using Si and the other using fused-silica wafers) will be evaluated based on cost, risk, and schedule considerations for input to the final selection process.

Verification — Each of the candidate substrates will go through typical replication processing steps – i.e., spin-on replication resist, imprint master, cure resist, dice out grating, coat with metal, and bond into a module. Step results will provide the understanding of stresses needed to develop the final production process—process condition limits, requirements for stress relief (e.g., annealing), etc. Surface figure stress measurements will be taken at each process stage using standard, proven interferometer. All data will be analyzed and reported.

Milestone 3 — Complete stress study on thick, polished substrates and replicas
Significance — Confirmation that the thick, polished substrates required for *Lynx* can be manufactured.
Verification — Wedge-polished Si on both sides to will be created to <5 Å RMS using processing steps including, for example, spin-on imprint resist, imprint master, cure resist, dice out grating, dice out ribs on back of grating, metallic coating, and stack bonding. It is anticipated that most of the stress is imparted in the process of dicing out the ribs on the back of the grating. Surface figure interferometric stress measurements will be taken between each process step to determine standard processes (e.g., chemical or ion etching) will be required to meet *Lynx* goals.

Milestone 4 — Complete interim SME review
Significance — Assurance of progress on component readiness prior to completion of alignment studies.
Verification — OP-XGS team to provide review materials to non-advocate SME panel. SMEs review with validation, recommendations, and/or other comments.

Milestone 5 — Complete alignment study of thin, flat replicas
Significance — Demonstrated required capability to align thin, flat replicas necessary to proceed to TRL 5 module production.
Verification — Alignment methodology will follow protocols developed for the *WRXR* mission. Upgrades will include upgrades to metrology and staging required to achieve the *Lynx* tolerances, adapted for *Lynx* as necessary. Six degrees of freedom will be tracked for each grating during population of the module. All test results will be documented.

Milestone 6 — Complete alignment study of thick, polished replicas
Significance — Demonstration of the thick, polished substrates required for *Lynx*. This study will demonstrate that the new alignment methodology (with heritage from SPO technology development) can be successfully implemented. Specifically, completion of this milestone will show that wedged, ribbed replicas can be stacked onto one another and that the treated Si forms bonds between the ribs and the adjacent grating in the stack to create a single-piece, robust module with alignment tolerances encoded into the polished substrates.
Verification — Six degrees of freedom will be tracked for each grating during population of the module, mostly through interferometer measurements. The bonding jig constrains the translation tolerances and the yaw, while the substrate figure constrains pitch and roll. Standard testing will ensure that all specifications are met.

Milestone 7 — Complete non-advocate module development readiness review
Significance — Provides assurance that the OP-XGS team is ready to proceed to the TRL 5 test module fabrication stage.

Verification — Non-advocate review of all relevant module-development testing to date with comments and recommendations.

Milestone 8 — Analyze alignment study results and produce a module of replicas for TRL 5 testing.

Significance — To meet this milestone, one of the two processes will be selected alongside a fully populated grating module in preparation for TRL 5 level testing.

Verification — Specific figures of merit relating to technical quality, schedule, risk, and cost will be analyzed with module production based on highest rated of the two competing technologies.

Milestone 9 — Develop ray trace model for TRL 5 test

Significance — Development of a predictive ray trace model is critical to design and development efforts for advancement to both TRL 5 and TRL 6. Meeting this milestone will demonstrate the efficacy of the ray trace model for TRL 5 design efforts.

Verification — The ray trace model predictions will be compared to the LSF for multiple diffracted orders to verify the model's predictive capability (e.g., prediction of the LSF given the alignment tolerances achieved during grating module production).

Milestone 10 — Perform TRL 5 tests and analyze results

Significance — The TRL 5 tests will verify required system-level throughout a comprehensive environmental test program. Post-environmental verification of performance will demonstrate successful achievement of the TRL 5 exit criteria.

Verification — Both spectral resolving power testing and efficiency testing will be performed. The efficiency testing will take place at a synchrotron facility at the individual grating level. The module effective area may also be tested (if deemed necessary) at the same beamline facility where the resolving power tests are performed. Environmental testing will consist of appropriate vibration and thermal testing. The LSF will be detailed at several diffraction orders using an X-ray beamline facility. The effective area will be measured via diffraction efficiency measurements at a synchrotron facility and can also be measured during beamline testing. X-ray testing will take place at MSFC SLF or another equivalent facility. Several facilities have capabilities for environmental testing (MSFC, GSFC, Wallops Flight Facility (WFF), etc.).

Milestone 11 — Non-advocate SME review of TRL 4 exit criteria testing

Significance — Provides a non-advocate assessment showing that the OP-XGS team successfully completed the testing and analyses required to meet TRL 4 exit criteria and graduate to TRL 5.

Verification — The program will provide the SME panel with a full report of all relevant test results and analyses. The SME panel will compare these with the TRL 4 exit criteria and provide concurrence and recommendations.

Milestone 12 — Complete fabrication of the *Lynx* OP-XGS grating master

Significance — The program will now have the flight-like *Lynx* master grating required for the creation the necessary grating replicas.

Verification — The groove profile will be measured using SEM and AFM. The diffraction efficiency will be tested at the ALS and Lawrence Berkeley National Lab, or a similar synchrotron facility. The spectral resolving power can be measured at the SLF at MSFC. Measuring high diffraction efficiency and high spectral resolving power over an ~10-×-10-cm area will verify this milestone.

Milestone 13 — Non-advocate SME review of master grating development

Significance — Provides a non-advocate assessment showing that the OP-XGS team has produced the required master grating.

Verification — The program will provide the SME panel with a full report of the master grating development and testing efforts to be reviewed against OP-XGS master grating specifications.

Milestone 14 — Complete fabrication of the *Lynx* grating modules and array structures

Significance — At this point, the flight-like array structure with flight-like grating modules necessary for TRL 5 exit criteria testing will be fabricated, verified, and available.

Verification — The final grating modules and array will be measured for compliance using pre-specified fabrication/machining requirements.

Milestone 15 — Complete fabrication of the grating substrates

Significance — Grating substrates created using the technique selected and reviewed in Milestone 7 and available to populate the modules for TRL 5 exit criteria testing.

Verification — Substrate production will be tracked and verified using appropriate quality control/assurance practices. Six degrees of freedom will be tracked for each grating during population of the module. Upgrades to metrology and staging will be completed and employed to ensure achievement of all *Lynx* tolerances.

Milestone 16 — Complete replication of the gratings and their alignment within modules

Significance — The required number of replicate grating aligned in test modules for TRL 5 exit criteria testing. (Note: meeting this milestone will also demonstrate the automated industrial process for mass grating replication.) The alignment will dominate this milestone and use the same method as the TRL 5 module.

Verification — Module alignment will be verified using the same methodology used in the development of the module for TRL 5 exit criteria demonstration.

Milestone 17 — Non-advocate SME review of master grating development

Significance — Provides a non-advocate assessment showing that the OP-XGS team is ready the grating integration required for TRL 5 exit criteria testing.

Verification — The program will provide the SME panel with a presentation detailing all relevant accomplishments to date and plans for proceeding to full integration. The SME panel will provide concurrence and recommendations.

Milestone 18 — Integrate grating array with TRL 6 mirror assembly and readout array

Significance — The numbers and positions of modules necessary to accurately assess final grating performance will be determined by a detailed ray trace analysis using the SOA model created for TRL 5 exit testing. The grating array will be populated and integrated with an appropriate mirror assembly to create a flight-like optical subsystem for TRL 5 exit criteria testing.

Verification — The position of each grating module relative to the array will be measured and monitored using optical and mechanical fiducials on the modules and the array. These same fiducials will be used to position the grating array relative to the optics using similar fiducials on the mirror assembly. A similar exercise is currently being implemented on the *OGRE* suborbital rocket (Donovan et al. 2018b), which uses a polished Si mirror assembly and an array of reflection grating modules.

Milestone 19 — Perform TRL 5 exit criteria testing and analyze results

Significance — The planned test sequence (similar to the TRL 4 exit criteria tests but on a larger scale) will demonstrate that the OP-XGS has met TRL 5 exit test criteria.

Verification — The LSF will be detailed at several diffraction orders using an X-ray beamline facility. The contributions from each module to the LSF will be characterized individually and as an entire array. Comparisons to ray trace will verify performance while providing predictions for the *Lynx* OP-XGS flight performance. The effective area of the mirror/grating assembly will also be measured at several energies. These measurements will be similar to those performed during pre-flight calibrations. X-ray testing will take place at the MSFC SLF or another equivalent facility. Several facilities have capabilities for environmental testing (MSFC, GSFC, WFF, etc.). Negligible changes in these measurements during post-environmental testing will verify TRL 6.

Milestone 20 — Post-test SME review

Significance — Provides a non-advocate assessment showing that the OP-XGS team successfully completed the testing and analyses required to meet TRL 5 exit criteria and graduate to TRL 6.

Verification — The program will provide the SME panel with a full report of all relevant test results and analyses. The SME panel will compare these with the TRL 5 exit criteria and provide concurrence and recommendations.

2.2 TRL Development Schedule

The *Lynx* program has developed a comprehensive schedule for the OP-XGS instrument that is based on the milestones and development path shown in Table 3. Fig. 8 provides a high-level, one-page version of the program schedule.

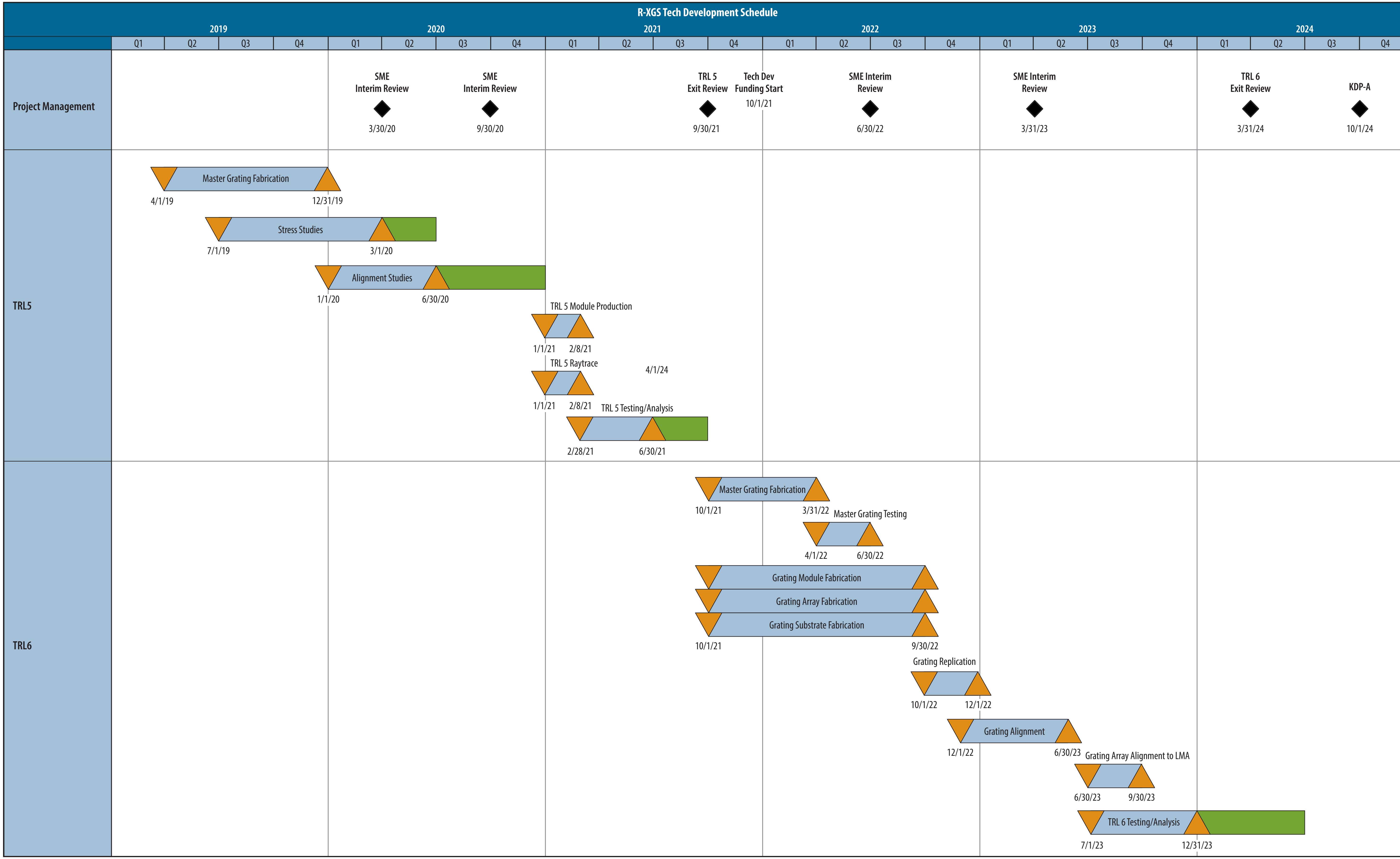


Fig. 8—XGS technology maturation schedule.

2.3 Cost

Redacted.

2.4 Risks

The *Lynx* program has performed an in-depth risk assessment with the support of non-advocate SME's. 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 latest (June 2019) PCOS inputs. Table 5 shows the major risks identified to date. Fig. 9 presents the risk in the standard 5-×-5 format.

As shown in the table, risk mitigation strategies have been developed for each risk. One common risk-reduction theme involves interim reviews by SMEs. Past inputs from PCOS reviewers have indicated concern over a lack of detail leading up to meeting the TRL 5 and TRL 6 exit criteria. In fact, meeting these criteria typically requires multiple iterations with extensive testing at varying levels of fidelity. While the nature (and number) of these tests precludes roadmap inclusion, interim SME review is inserted to ensure progress is on schedule and that issues are identified in a timely manner.

As a global risk reduction strategy, the *Lynx* program has maintained a target for baseline coverage of only one half of the *Lynx* mirror aperture to meet the effective area goal. This provides conservatism in design—the area of coverage could be increased significantly if technology advancement in any/all elements falls short of expectations. While increasing the coverage area would increase mass and cost, all science requirements would be met and the "off-ramp safeguards" built into the *Lynx* XGS roadmap (shown in Table 3) minimize risk of the XGS becoming a critical path issue.

Further conservatism is built into the program by the fact that the XGS roadmap is based on the SOA as described in §1.2.2. Aggressive development efforts are in progress across the technology elements and significant advances are anticipated. The fact that there has been one successful flight test with OP grating technology (similar form and fit but not function) and that a second flight test of a very relevant (close form, fit, and function) grating technology is planned in 2021 provides high confidence in the ultimate advancement of the technology via the roadmap described in this document.

Table 5—Summary of XGS technology maturation risks.

Risk #	Risk Title	Risk Statement	Risk Type	Risk Assessment			Mitigation Plan
				L	C	Score	
XGS-1	Grating Master Quality	Inability to manufacture target blazed radial groove profile	T	3	2	6	1. Parallel development of 4 grating fabrication methods 2. Scheduled checkpoints with SME review for progress against specific grating quality metrics (see schedule) 3. Funded schedule reserve for unplanned process refinement iterations 4. Off-ramp to increased XGS coverage area
XGS-2	Grating Substrate Flatness	Substrate flatness insufficient to produce required LSF quality	S	3	2	6	1. Scheduled checkpoints with SME review for progress against signal processing metrics (see schedule) 2. Funded schedule reserve for unplanned process refinement iterations 3. Off-ramp to increased XGS coverage area
XGS-3	System-Level Alignment	Unacceptable alignment tolerance due to collected alignment issues (e.g., grating-to-grating, module-to-module, XGA-to-LMA)	S	2	2	4	1. Scheduled checkpoints with SME review for progress against signal processing metrics (see schedule) 2. Program emphasis (funding) on development of advanced ray tracing model for system-level assessment 3. Ad-hoc SME reviews of specific alignment issues as they arise 4. Funded schedule reserve for unplanned process refinement iterations 5. Off-ramp to increased XGS coverage area

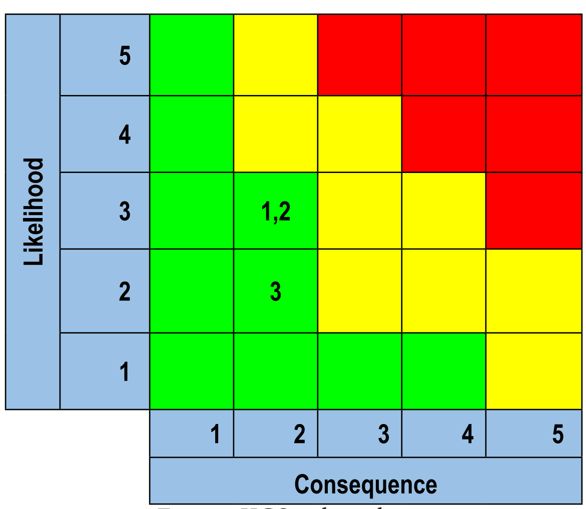


Fig. 9—XGS risk ranking.

Risk XGS-1: Master Grating Quality Issues — The quality of the blazed, radial profile on the master grating determines the performance of the replicas. Inability to meet target requirements for this key feature would limit the performance of the grating as currently envisioned (50% coverage) to less than *Lynx* requirements.

Mitigation strategies — The program will continue to support four grating fabrication methods at least up to the pre-Phase A start. At this point, all of these techniques have been reviewed by experts and deemed feasible. Funding requirements are relatively small in this stage of development, and each will be evaluated to determine which is optimal from a cost/risk perspective. The program has scheduled multiple SME reviews to evaluate progress and identify issues and solutions. Further, as shown in Fig. 7, the OP-XGS team is carrying significant funded schedule reserve to address issues and provide for additional fabrication process iterations if required. Last, the current design requires only 50% coverage area. If the reflection grating design targets are not met, this area can be increased to preserve science goals.

Risk XGS-2: Substrate Flatness Issues — Failure to meet grating substrate flatness targets would degrade alignment and negatively impact the LSF quality.

Mitigation strategies — The program has scheduled multiple SME reviews to evaluate progress and identify issues and solutions. To address the grating flatness issue, this will be extended to ad hoc vendor evaluation and root cause analysis with recommendations if required. Funded schedule reserve is planned into the program to address issues and provide for additional fabrication process iterations if required. Flatness issues potentially affect LSF, and hence resolving power. Thus, a further mitigation is to subaperture the telescope PSF in the dispersion direction.

Risk XGS-3: System-Level Alignment Issues — The OP-XGS is a large, complex assembly requiring the assembly of many parts. Errors propagate across the system and reduction in alignment quality anywhere in the system (e.g., grating-to-grating, module-to-module, XGS-to-LMA) will reduce resolving power.

Mitigation strategies — As with the other risks, multiple SME reviews will be performed to assess progress and make recommendations. Funded reserve is carried to account for potential delays. Alignment issues also affect LSF and hence resolving power. Thus, a further mitigation is to subaperture the telescope PSF in the dispersion direction.

2.5 Summary

The proposed OP-XGS development program will provide *Lynx* with a soft X-ray grating spectrometer with unprecedented spectral resolution and effective area. It will reveal the invisible drivers of galaxy and structure formation through absorption line spectroscopy of plasmas in galactic halos and the intracluster medium. An XGS design based on reflection grating technology can meet requirements for resolving power and effective area with ample margins. The technology is well on its way toward TRL 5. Steady and reasonable investment in technology development, through NASA SAT/APRA programs, will bring the OP-XGS to TRL 6 well within the schedule for *Lynx* and with manageable risks.

3 Appendices

3.1 NASA TRL Definitions

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

Table 6—NASA TRL definitions.

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

TRL	Definition	Hardware Description	Software Description	Exit Criteria
6	System/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.

3.2 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.

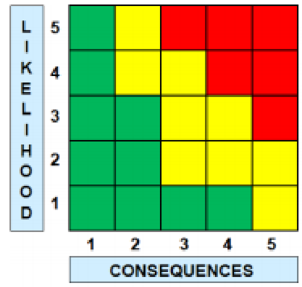
Table 7—AD^2 level definitions.

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)

3.3 Risk Definitions

The standard risk scale for consequence and likelihood are taken from Goddard Procedural Requirements (GPR) 7120.4D, Risk Management Reporting. The definitions for likelihood and consequence categories are provided in Fig. 10.

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



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

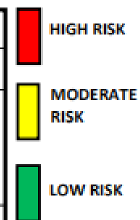


Fig. 10—Risk matrix standard scale.

3.4 Acronyms

AD^2	Advancement Degree of Difficulty
AFM	Atomic Force Microscope
ALS	Advanced Light Source
APRA	Astrophysics Research and Analysis
CAT	Critical Angle Transmission
DDT&E	Design, Development, Test, and Evaluation
DRM	Design Reference Mission
DSMT	Decadal Survey Management Team
GPR	Goddard Procedural Requirements
GSFC	Goddard Space Flight Center
HPD	Half-Power Diameter
ISIM	Integrated Science Instrument Module
JWST	James Webb Space Telescope
KDP	Key Decision Point
LMA	*Lynx* Mirror Assembly
LSF	Line Spread Function
MCR	Mission Concept Review
MSFC	Marshall Space Flight Center
NPR	NASA Procedural Requirement
OP-XGS	Off-Plane X-ray Grating Spectrometer
PCOS	Physics of the Cosmos
PDMS	Polydimethylsiloxane
PPBE	Programming, Planning, Budgeting, and Execution
PSF	Point Spread Function
RMS	Root Mean Square
SAT	Strategic Astrophysics Technology
SCIL	Substrate Conformal Imprint Lithography
SLF	Stray Light Facility
SOA	State of the Art
TRL	Technology Readiness Level
WFIRST	Wide Field Infrared Survey Telescope
WRXR	Water Recovery X-ray Rocket
XGA	X-ray Grating Array
XGS	X-ray Grating Spectrometer

3.5 References

[1] Allured, R. et al., "Optical and x-ray alignment approaches for off-plane reflection gratings," Proceedings of the SPIE, 9603, 960315, 2015.

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