

X-ray Grating Spectrometer Technology Roadmap

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This *Lynx* technology roadmap details the plans for maturing all aspects of the *Lynx* X-ray Grating Spectrometer to TRL 6. For this, three technology elements will need to be advanced from TRL 4 to TRL 6. The document contains an overview of the instrument with an assessment of the state of the art and the issues and challenges faced by the *Lynx* team. This is followed by a description of the development plans with key milestones. A section on the major program risks is also provided along with program cost projections through Phase A.

1 Introduction

The *Lynx* X-ray Grating Spectrometer (XGS) will provide the spectral resolving power and effective area needed to meet the Pillar II science goals shown in Table 1 and to provide enabling capabilities for General Observer (GO) 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 (XGS)	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) Critical Angle Transmission Gratings (CAT-XGS; e.g., Heilmann, et al. 2016, 2017, 2018, 2019, and Günther and Heilmann 2019) and (2) the Off-Plane Reflection Gratings (OP-XGS) described by [Miles et al. 2018, DeRoo, et al. 2016, and McEntaffer 2019]. Both are at a similar stage of development and were vetted at Technology Readiness Level (TRL) 4 in 2016. The CAT-XGS technology was selected for purposes of the Design Reference Mission (DRM), and this document provides the CAT-XGS technology development roadmap planned to achieve TRL 5 by Q1 2022 and TRL 6 by Q4 2024. OP-XGS technology development is described in the OP-XGS roadmap in the *Lynx Concept Study Report*.

Unlike typical Ultraviolet (UV)/Infrared (IR) gratings that are relatively easy to manufacture, XGS-class gratings are much more complex (see Fig. 1). X-rays are easily absorbed in transmission, and reflection is only effective at small angles of grazing incidence. Fig. 1(a) shows a schematic of the CAT grating, where small angles of grazing incidence are used and transmission is maximized. As will be discussed below, these gratings are etched from silicon wafers, and a Scanning Electron Micrograph- (SEM-) generated image of a cleaved State-of-the-Art (SOA) CAT grating membrane is shown in Fig. 1(b) to provide insight into their dimensions and intricacy.

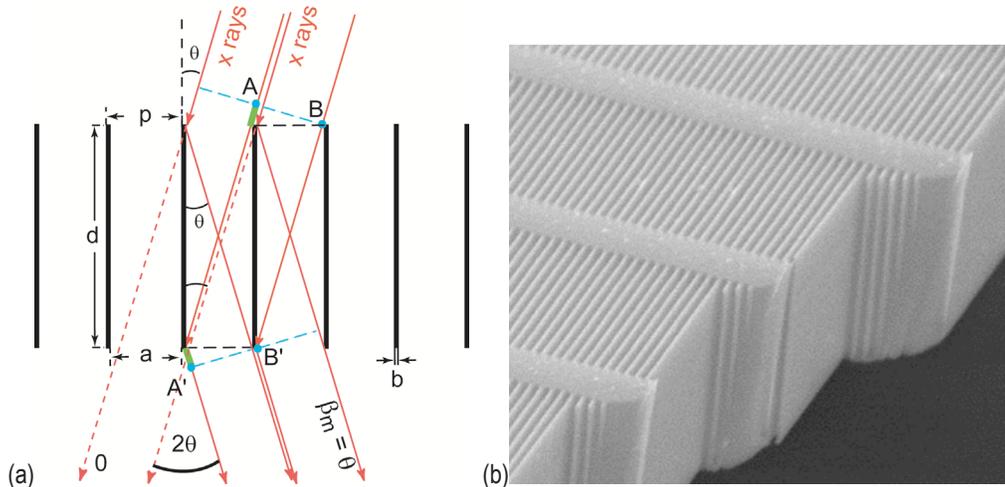


Fig. 1—(a) Schematic cross section through a CAT grating of period p . The m^{th} diffraction order occurs at an angle β_m , where the path length difference between AA' and BB' is $m\lambda$. Shown is the case where β_m coincides with the direction of specular reflection from the grating bar sidewalls ($|\beta_m| = |\theta|$), i.e., blazing in the m^{th} order. (b) Cleaved CAT grating membrane showing top, cross section, and sidewall views of the 200-nm-period silicon grating bars and their monolithically integrated 5- μm -period cross supports (X-rays enter from the top and leave out the bottom).

Furthermore, X-rays are easily scattered, and sub-nanometer surface roughness is required to maximize transmission. X-ray transmission grating-based spectrometers can, however, be operated in high orders, and this greatly increases their resolving power. Because of this, the *Lynx* goal of $R > 5,000$ is well within (in fact, well below) projected limits, and actual resolution (with 5,000 as an absolute minimum) will be determined based on consideration of cost, schedule, and final instrument location with respect to the *Lynx* microcalorimeter. While the planned CAT-XGS development efforts build on *Chandra*'s High- and Low-Energy Transmission Grating (HETG) Spectrometer [Canizares et al. 2005] and *XMM-Newton*'s Reflection Grating Spectrometer [den Herder et al. 2001] heritage, *Chandra* and *XMM-Newton* technologies are inadequate for *Lynx*-class measurements, and the required technology advances are detailed below. The Rowland torus configuration employed on *Chandra*, for example, provides a quality starting point—*Lynx* requirements necessitate an advanced tilted Rowland torus design [Günther and Heilmann 2019]. The CAT-XGS was selected as the DRM baseline in part because its transmission geometry is comparatively insensitive to grating misalignment and grating non-flatness, leading to relaxed alignment and figure tolerances as compared to other technology options.

1.1 XGS Overview

As stated above, the CAT-XGS will provide the spectral resolving power and energy resolution necessary to reveal the sought-after information on galaxy structure formation and evolution. Specifically, the spectrometer will provide high-throughput, high-resolution spectra in the soft X-ray energy band centered around 0.6 keV. The instrument consists of a retractable array of lightweight, co-aligned CAT gratings and a stationary linear silicon pixel sensor readout array. The retractable XGS assembly is mounted just aft of the *Lynx* Mirror Assembly (LMA), as shown schematically in Fig. 2.

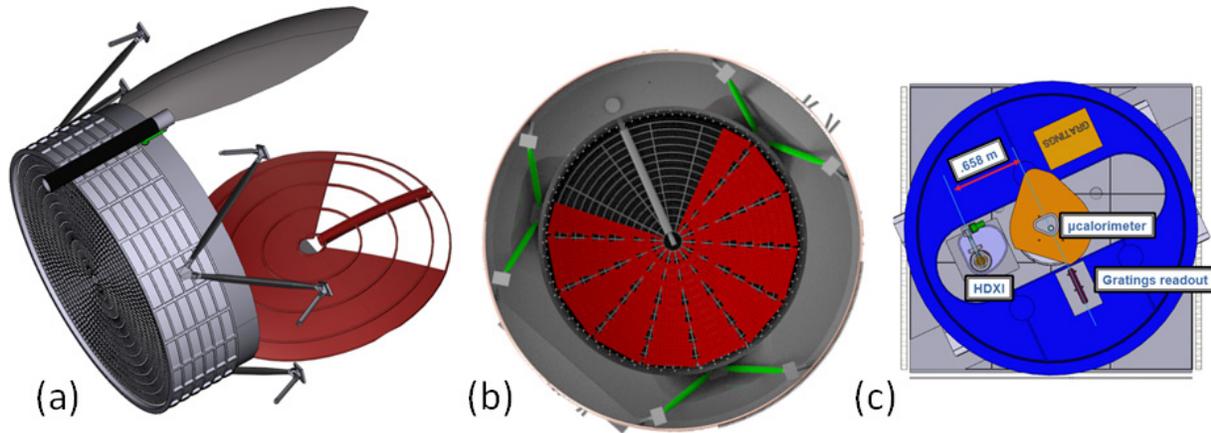


Fig. 2—CAT-XGS instrument views: (a) Contamination door (shown in grey) with retracted CAT XGS in red; (b) upstream view of the deployed CAT-XGS array, covering $\sim 264^\circ$ in azimuth; and (c) downstream view of the ISIM. Shown is the configuration with the microcalorimeter instrument in the focus position and the High Definition X-ray Imager moved to the side. Image credit: NASA MSFC/M. Baysinger.

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 previously, the CAT-XGS will have a spectral resolving power of at least $R > 5,000$ ($\lambda/\Delta\lambda$) in the soft X-ray band and a minimum effective area in excess of $4,000 \text{ cm}^2$ at 0.6 keV.

1.2 XGS Description

1.2.1 Overview of Technology

The CAT-XGS grating membranes are the key to the efficacy of the instrument. They consist of 200-nm-period, freestanding, ultra-high-aspect ratio silicon grating bars that are inclined by an angle less than the critical angle of total external reflection relative to the incident X-rays, resulting in efficient blazing of diffraction orders near the angle of specular reflection from the grating bar sidewalls. The membranes are fabricated from Silicon-on-Insulator (SOI) wafers—see again Fig. 1(a) for an SEM-generated image of a cleaved SOA CAT grating membrane.

The grating membrane is bonded to a narrow frame and the combination comprises a grating facet. Following production, the facets are mounted to a Grating Array Structure (GAS) in co-aligned fashion. The ultimate number of facets required will depend on *Lynx* technology advancement (mostly a combination of facet size and throughput). The target based on current projections is 800, but more than 2,000 might be needed to meet science requirements within the available real estate. The resulting grating array, when deployed, densely tiles a fraction (target $\sim 2/3$) of the mirror array aperture.

Thus, the CAT-XGS is composed of three basic technology elements: (1) the grating membrane, (2) the grating facet, and (3) the integrated grating assembly that includes the grating facets, properly aligned on the GAS. To meet *Lynx* requirements, advancement of all three grating technology elements is required. These technology elements are shown in Table 2 with top-level advancement descriptions in the right-hand column. Brief descriptions of each element are shown below, and the SOA and advancement plans for each element are described in following sections.

Table 2—XGS technology maturation elements.

Element	Element Description	TRL	Advancement Descriptions
1	CAT grating membrane	4	Deeper, thinner bars, reduced L1 and L2 blockage and increased membrane size
2	CAT grating facet	4	Facet structure reduction to decrease blockage; improvements in alignment and attachment capabilities
3	Integrated grating assembly	4	Analytical model and test article development to assure final <i>Lynx</i> -required alignment capability

- Element 1:** Key aspects of the CAT grating membrane design are illustrated in Fig. 3. Grating bars are etched out of a $\sim 6\text{-}\mu\text{m}$ -thick SOI device layer at the same time as the Level 1 (L1) cross-support mesh that holds the grating bars in place. A high-throughput Level 2 (L2) support mesh of millimeter-scale is etched out of the $\sim 0.5\text{-mm}$ -thick SOI handle layer, and the Buried Oxide (BOX) layer that separates device and handle layers is removed from the open areas. Key features are the grating bar layer etched from the SOI device layer with monolithically integrated L1 supports and the L2 layer etched from the SOI handle layer. The two layers are connected via the SOI BOX layer in areas where the structures overlap. For increased effective area, the grating bar depth needs to be increased (leading to higher diffraction efficiency), and L1 and L2 structure widths need to be minimized (to reduce X-ray blockage) to the extent possible while maintaining acceptable structural integrity.

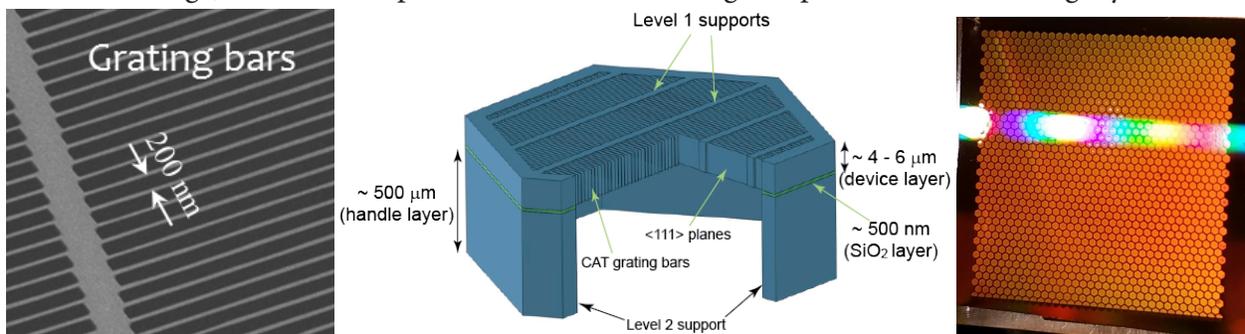


Fig. 3—CAT membrane basics. (Left) Top down SEM of grating membrane, showing thin grating bars and high throughput ($\sim 90\%$) L1 supports. (Middle) “Unit cell” schematic showing the structural hierarchy (not to scale). (Right) Photograph of an existing $32\text{-x-}32\text{ mm}^2$ CAT grating membrane with back illumination to show the hexagonal L2 mesh, and with visible light diffraction due to the L1 device layer mesh.

- Element 2:** CAT grating facets consist of the silicon membrane etched from an SOI wafer, and the frame to which the membrane is bonded. The frame must be minimized with respect to X-ray blockage and permit both distortion-free bonding of the silicon membrane and effective alignment on the GAS. The facets must maintain adhesion and alignment both through launch and in-space.
- Element 3:** The integrated grating assembly consists of the facets and GAS, and is mounted on the actuators which rotate it in and out of the optical path for grating array insertion and retraction. The fully integrated XGS will require the precision alignment of between 800 and 2,000 facets. This alignment is crucial to resolving power performance. There are multiple sources of alignment errors, and a detailed error assessment (error budget) is required to optimize the XGS alignment strategy. The basis for this optimization lies in the high-fidelity ray tracing model developed for *Lynx*.

1.2.2 State of the Art

The CAT grating design was invented in 2005 and has undergone NASA-supported technology development since 2007. Diffraction efficiency is well-predicted and described by theory. Development of the final gratings will be an iterative process to reach a final design and manufacturing process. Simply put, membrane size needs to be increased to reduce the number of gratings and cost. The CAT-XGS instrument will benefit from significant heritage from *Chandra*, *XMM-Newton*, *Arcus* [Smith et al. 2017], and other programs. The SOA stems both from these programs and from the step-wise advancement achieved to date in support of *Lynx*. The following points illustrate heritage/progress to date on the CAT-XGS elements and form the basis for the TRL and Advancement Degree of Difficulty (AD²) assessments (i.e., the SOA):

- **Elements 1 and 3:** Both high (HEG: 200-nm period) and medium (MEG: 400-nm period) gratings were required by *Chandra*, and the proposed grating fabrication process (a precursor to *Lynx*) was considered revolutionary. Facilities were constructed and fabrication tools were installed and tested by the mid-1990s. The effort resulted in the successful fabrication of 336 flight transmission gratings (1995–96) and final delivery of the final fully populated/ tested grating array for *Chandra* in the fall of 1996. While the labor-intensive approach used for *Chandra* is not practical for *Lynx*, the *Chandra* program laid the groundwork for many aspects of the grating and structure design necessary to make the *Lynx* requirements possible.
- **Elements 1 – 3:** Transmission gratings fabricated at the Massachusetts Institute of Technology's (MIT's) Space Nanotechnology Laboratory (SNL) and successfully flown on the *Solar and Heliospheric Observatory (SOHO)*, *IMAGE*, *Geostationary Operational Environmental Satellite (GOES—N, O, P, R)*, *Two Wide-Angle Imaging Neutral-Atom Spectrometers (TWINS) A and B*, and the *Solar Dynamics Observatory (SDO)* [Schattenburg 1990, Carter 1992, Scime 1995, Balkey 1998, van Beek 1998, Pollock 2000, Schattenburg 2001] all provide technology background and lessons learned applicable to *Lynx* development.
- **Element 1:** Recent applicable advancements in the semiconductor/Micro-Electromechanical Systems (MEMS) industrial sector directly impact the *Lynx* SOA. These industries have undergone enormous growth over the past three decades and advances in both tool design and fabrication process used for the large-scale production of a wide array of products. Fortunately, tool and process technologies will directly benefit *Lynx*. For example, the development of automatic loaders for 200–300 mm wafers and highly repeatable, nanometer-precision patterning and manufacturing process steps are directly applicable.
- **Element 1:** Grating membranes developed under *Arcus* represent the current SOA with a 4- μm etch depth (example shown previously in Fig. 3). Recent developments produced membranes with L1 transmission close to 90%, and have shown that multiple gratings (approximately up to 16 demonstrated, depending on size) can be patterned on a single 200-mm wafer. Very recently under the *Lynx* program, Samco, Inc., produced grating bars and integrated L1 supports with an etch depth of 6 μm (shown in Fig. 4) that is beyond the *Lynx* target of 5.75 μm .

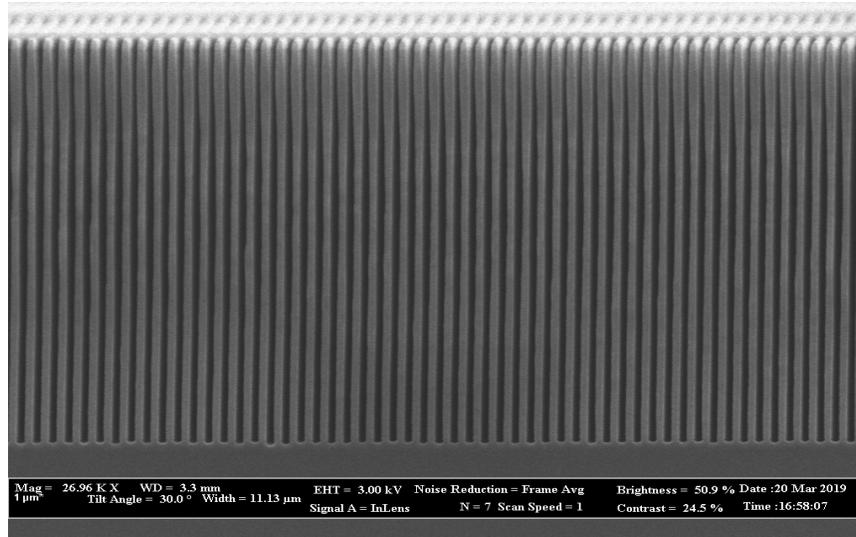


Fig. 4—Silicon 200-nm-period CAT grating bars with 6- μm etch depth and integrated L1 supports etched on a Samco Deep Reactive-Ion Etch (DRIE) tool.

- **Elements 1 – 3:** *Arcus* was proposed as a high-resolution X-ray Grating Explorer with roots dating to *IXO* [Bookbinder 2010] and won a MIDEX Phase A study that included technology development in 2016–18 [Smith 2017]. Technology development under the *Arcus* program resulted in the advancement in the SOA of many Figures of Merit (FOMs) relevant to the *Lynx* XGS. Table 3 shows *Lynx* target FOMs compared to those demonstrated under *Arcus*, which represents the SOA with respect to most features.

Table 3—Demonstrated (*Arcus*) and goal future (*Lynx*) grating geometric parameters and diffraction efficiency for a CAT-XGS.

Mission	Grating depth (μm)	Blaze angle* (deg)	Grating Bar Duty Cycle	L1 Transmission	L2 Transmission	L3 Transmission	Total Geometric Transmission	Blaze Efficiency (incl. L1 blockage)
<i>Arcus</i>	4.0	1.9	0.3	0.82	0.81	0.7	0.46	>35%
<i>Lynx</i>	5.75	1.6	0.2	>0.9	>0.9	0.98**	>0.79	>50%

*Optimum blaze angle for given grating bar depth and duty cycle.

**L3 structures assumed to be mostly “shadowed” by mirror array support structures.

- **Elements 1 – 3:** Recent efforts have produced CAT grating facets with 200-nm-period, 60-nm grating bar width, and 4- μm depth with a size of $32 \times 32 \text{ mm}^2$ and >30% blazed absolute diffraction efficiency at a wavelength near the *Lynx* target (0.52 keV vs. 0.6 keV [Heilmann et al. 2018]). Absolute diffraction efficiency measurements included absorption by L1 and L2 structures. Four gratings of this size were co-aligned into an array with a laser-based technique (no vacuum required) and illuminated with two co-aligned silicon pore optics X-ray optical units (2.1 arcseconds Full Width at Half Maximum (FWHM) in the dispersion direction) using a relevant calibrated radiation source (Mg-K α at 1.25 keV) (see Fig. 5). The testing demonstrated $R > 3,500$ in 14th order [Heilmann et al. 2018]. Earlier testing results of a single facet with a single mirror pair (~ 1 arcsecond FWHM) are shown in Fig. 6, demonstrating $R > 10,000$ [Heilmann et al. 2016, 2019].

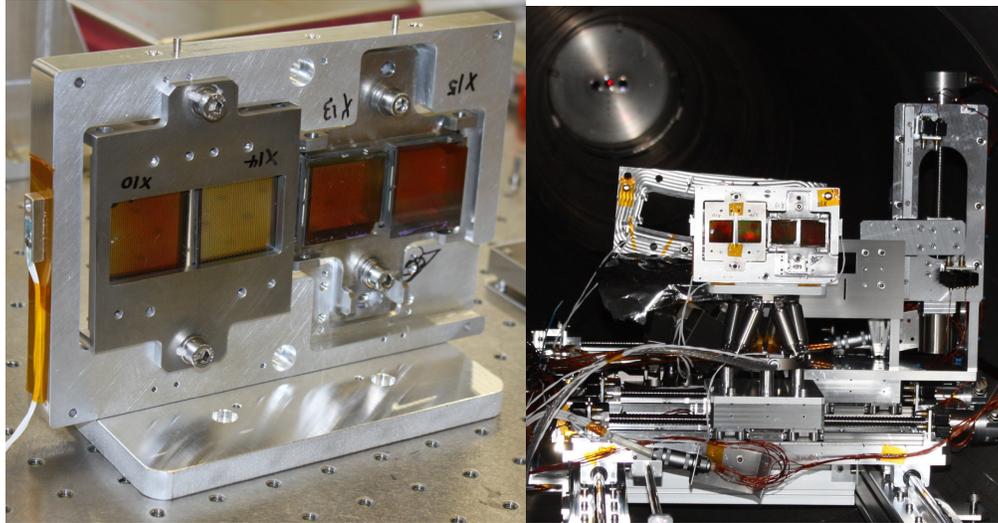


Fig. 5—(Left) Grating petal holding four co-aligned CAT grating facets. (Right) Grating petal inside the Panter X-ray facility in Neuried, Germany, aligned in front of two co-aligned silicon pore optics X-ray optical units (hidden upstream of the gratings).

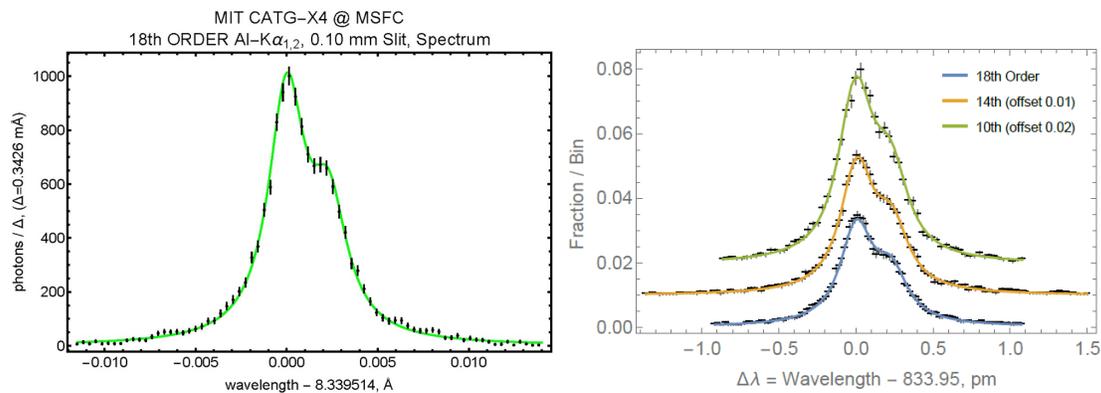


Fig. 6—(Left) Spectrum of Al-K α doublet (1.49 keV) in 18th order from a single Pt-coated CAT grating, measured at the NASA MSFC Stray Light Test Facility (SLTF), demonstrating $R > 10,000$. (Right) Spectra in 10th, 14th, and 18th orders. Solid lines are the best fit to the combined data from the three orders and also give $R > 10,000$ in 18th order.

- **Element 2:** A grating facet alignment and bonding station has been developed for the aligned bonding of CAT grating membranes to frames, and flexure-based frames have been developed [Heilmann et al. 2018].
- **Element 3:** A detailed ray tracing model has been developed for investigation of the CAT-XGS system, and a realistic alignment error budget has been developed. Modeling to date shows good agreement with test data. Both point to the fact that achieving $R > 5,000$ with the 0.5-arcsecond Point Spread Function (PSF) *Lynx* mirrors does not present a challenge, and $R \sim 7,500$ or greater is expected. Tradeoffs between grating size, optical aberrations, and cost are under investigation to provide program design options [Günther and Heilmann 2019].
- **Element 3:** In addition to the aligned grating structure technology and lessons learned from both *Chandra* and *Arcus*, a small-scale GAS for alignment testing purposes was developed for *Arcus* and is being used as a starting point for *Lynx*. This test fixture is shown in Fig. 7.

CAT grating technology was assessed to be TRL 4 by the NASA PCOS Technology Review Board in June 2016. The *Lynx* program agrees with this assessment with the note that the recent demonstration of etching capability beyond that required to meet *Lynx* goals moves the technology significantly closer to TRL 5. While the PCOS Board did not assess AD², the *Lynx* program performed an internal non-advocate assessment that placed the overall AD² between 3 and 4. Carrying the OP grating option at this point is a prudent program decision. Moving from the demonstrated SOA to the *Lynx* goal for all three technology elements will require arduous, step-wise advancements in grating fabrication, facet assembly, and precision alignment on the integrated grating assembly. There are, however, no known physical barriers (e.g., formulating the process(es)) to produce the required number of finished grating bars with the required tolerances in spacing and surface roughness—to the development of the required capabilities. All developments will take time, patience, and quality engineering, but no fundamental “breakthroughs” are required.

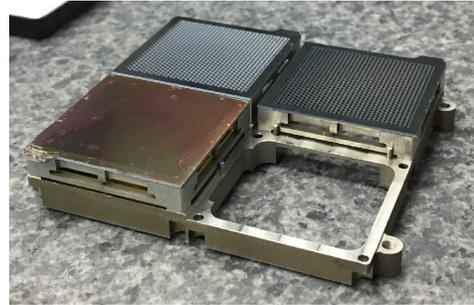


Fig. 7—Grating structure “window” for *Arcus* [Heilmann et al. 2018], designed to hold four 30- \times -31-mm² grating facets in precise alignment to each other. The photo shows the window populated with one grating facet and two mass simulator facets.

1.2.3 Issues, Challenges, and Risks

Meeting *Lynx* requirements will require significant advances in the SOA for all three technology elements discussed above. Simply put, meeting the *Lynx* goals of $R > 5,000$ with an effective area of 4,000 cm² at 0.6 keV will require (1) larger, “chirped” gratings and grating bars with higher aspect ratios and thinner support structures, (2) larger facet structures with lower blockage, and (3) improved modeling and alignment capabilities. Fortunately, model and experimental testing show that $R > 5,000$ with the projected 0.5-arcsecond PSF *Lynx* mirrors does not present a significant challenge, and $R > 10,000$ has been demonstrated. This means that tradeoffs between grating size, optical aberrations, and cost can be considered as development progresses. Key issues, challenges, and risks associated with the required advancements are discussed here, followed by the technology development roadmap (milestones and schedule) and an expanded risk discussion.

While the unchirped, 4- μ m etch depth CAT grating technology was considered TRL 5–6 for *Arcus* purposes, it falls short of meeting *Lynx* requirements. Covering the whole *Lynx* aperture with today’s CAT gratings would provide $\sim 3,000$ cm² effective area (well below the *Lynx* minimum of 4,000) and requires more than 8,000 gratings, which is impractical from a manufacturing and cost standpoint. For gratings above a certain size, optical aberrations due to deviations of large flat gratings ($> \sim 50 \times 50$ mm²) from the Rowland torus surface must be mitigated by introducing small variations in the grating period (a method known as chirping – producing a “chirped” grating) to achieve $R > 5,000$. To meet *Lynx* cost and schedule goals, it is estimated that the total grating count needs to be $\sim 2,000$ or below, with 800 set as the goal. For this, grating diffraction efficiency must be improved, blockage from support structures must be reduced, and grating size must be increased beyond the SOA through stepwise improvements in effective fabrication, alignment, and integration techniques.

Diffraction efficiency must be increased over the SOA, and the desired increase from $\sim 33\%$ to $\sim 50\%$ (L1 blockage included) can be achieved by increasing grating depth from 4 to ~ 5.75 μ m.

Etching ultra-high aspect ratio structures on the nanometer scale is a fabrication challenge. While the recent demonstration of etching to $\sim 6\ \mu\text{m}$ (Fig. 4) provides confidence that this goal will be met with margin, the fabrication of large “finished” grating bars with the required parameters (e.g., bar width, surface roughness) represents a key challenge. For *Lynx*, the goal is to achieve an aspect ratio of ~ 140 ($5.75\ \mu\text{m}$ deep, $40\ \text{nm}$ wide). Deep Reactive-Ion Etching (DRIE) leaves the grating bar sidewalls rough. Grating bars are patterned parallel to $\{111\}$ planes in the SOI $\langle 110 \rangle$ device layer, such that a short “polish” in KOH solution creates nanometer-smooth sidewalls. *Arcus* gratings feature bars with aspect ratios of ~ 70 . Prototype $6\text{-}\mu\text{m}$ -deep DRIE CAT grating structures have been demonstrated, but large-area freestanding gratings with the required aspect ratio have not been attempted yet and may require further DRIE recipe development. Geometric throughput can be increased through reduction of L1 and L2 blockage to 10% each. Reducing the blockage from L1 and L2 structures can be achieved through reduction of the widths of the structures, which is simply done by patterning smaller-width mask features. The risk in doing so is the mechanical weakening of the structures, and the fabrication challenge lies in producing structural features that will provide the required throughput while maintaining the structural integrity to survive both the fabrication process and launch. CAT grating bars and L1 structures are etched simultaneously from silicon using DRIE, and fabrication process improvements will require DRIE recipe enhancement—this is an iterative process that has been successfully employed to reach the current SOA.

Larger gratings have the advantage of lower cost/area (fewer gratings; less labor for fabrication, qualification, alignment, integration). Some fabrication processes have not yet been demonstrated for sizes greater than $32 \times 32\ \text{mm}^2$. The *Lynx* baseline is $80 \times 80\ \text{mm}^2$ and if this is met, ~ 800 gratings would be required. The *Lynx* threshold of $50 \times 50\ \text{mm}^2$ gratings would increase this number to a still manageable ($\sim 2,000$) grating count based on current assumptions. For efficient fabrication, most of the process steps will be performed with 200-mm SOI wafers. To obtain the maximum possible resolving power, such large gratings need to be chirped. Using the planned projection lithography for patterning should make the production of chirped gratings straightforward based on the SOA in similar applications.

Once the final detailed design of the flight mirror assembly is complete, the grating facet shapes and GAS can be designed to place much of the large-scale mechanical structures in the X-ray “shadows” of passive mirror support structures.

2 Detailed Technology Roadmap

All the basic concepts of a CAT grating spectrometer have been demonstrated. Grating facets that simultaneously meet resolving power requirements and provide $\sim 30\%$ diffraction efficiency near $0.6\ \text{keV}$ have been fabricated and environmentally tested without performance degradation. A *Lynx* XGS built with SOA CAT gratings would meet resolving power requirements but fall short of effective area requirements by $\sim 25\%$. Technology development efforts to advance from the SOA to *Lynx* requirements are expected to be incremental in nature. A number of independent parameters need to be improved/optimized, with relative improvements typically in the range of 10% – 50% and requiring straightforward engineering approaches. Many of these developments can be undertaken in parallel. Parallel efforts reduce risk by allowing more time for design optimization, and the schedule shown in Table 4 is designed with parallel efforts to the extent possible given program budget targets and the need to address the most challenging technical issues early in the development cycle.

Table 4—XGS TRL 4 to TRL 6 milestones.

<p>NASA TRL 5</p>	<p>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.</p> <p>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. 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.</p>			
<p style="text-align: center;">Lynx XGS TRL 5 Exit Criteria</p> <p>Must demonstrate a credible technology development path to the required on-orbit performance of the <i>Lynx</i> 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.</p> <p>A credible demonstration must comprise the following for the XGS:</p> <ol style="list-style-type: none"> 1. Realistic end-to-end error budget for XGS resolving power and effective area. 2. Laboratory demonstration of measured angular resolution of resolving power and effective area of medium fidelity grating sub-assemblies as defined below. Lab demonstrations will be executed under the following conditions: <ul style="list-style-type: none"> • X-ray test 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 will be integrated with a medium fidelity array structure with realistic mechanical interfaces. • The grating array are integrated with a high-quality telescope capable of producing a PSF consistent with achieving required performance. • Assemblies are tested in 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 <ul style="list-style-type: none"> • 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 <i>Lynx</i> 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. 	<p>XGS Development/Maturation Milestones</p>			
	#	Milestone Description	Date	
	1	Increase grating bar depth to 5.75 μm using SOIs with 5.75-μm-thick device layers. Goal for grating bar width ~60 nm. Measure diffraction efficiency on ~30 x 30 mm ² membranes and compare to model predictions.	Q4 2019	
	2	Optimize L2 design and reduce blockage to ~0%.	Q2 2020	
	3	Design and fabricate facet frames with smaller blockage (goal ~2%).	Q2 2020	
	4	Complete concept and metrology infrastructure development for facet/GAS mounting and alignment conforming to <i>Lynx</i> alignment error budget requirements.	Q3 2020	
	5	Complete facet fabrication and build a brassboard GAS for TRL 5 tests. Complete diffraction efficiency measurements and map the period of the GAS brassboard facets.	Q2 2021	
	6	Complete ray-trace model enhancements with inclusion of all features necessary for TRL 5 testing.	Q2 2021	
	7	Perform TRL 5 tests and analyze results.	Q3 2021	
	8	SME review on completion of TRL 5 exit criteria	Q4 2021	
<p>TRL 4 to TRL 5 Advancement Degree of Difficulty: AD² = 3–4 (20%–30% Development Risk)</p> <p>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 steps are incremental developments and improvements relative to the SOA. As noted in §1.2.2 above on the SOA, the development of all three elements followed by their integration and testing will require substantial development. All anticipated development efforts, however, rely on the application of known engineering practices and there are no known physical barriers to the completion of all milestones on the planned development path to meeting TRL 4 exit criteria.</p>				
<p>Anticipated date to achieve TRL 5: Q1 2022</p>				

NASA TRL 6	<p>A high-fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.</p> <p>Prototype: The prototype unit demonstrates form, fit, and function at a scale deemed representative of the final product operating in its operational environment. A subscale test article provides fidelity sufficient to permit validation of analytical models capable of predicting the behavior of full-scale systems in an operational environment.</p>		
Lynx XGS TRL 6 Exit Criteria	XGS Development/Maturation Milestones		
<p>The system must demonstrate using a high-fidelity, scalable, flight-like prototype which adequately addresses all critical scaling issues and all <i>Lynx</i> performance requirements are met in critical environments.</p> <p>A credible demonstration must comprise the following:</p> <ol style="list-style-type: none"> 1. Realistic end-to-end error budget for <i>Lynx</i> 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: <ul style="list-style-type: none"> • X-ray test an aligned array of representative gratings illuminated by an aligned array of high-quality mirrors (~1 arcsecond or better HPD in dispersion direction, consistent with the X-ray optics at 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. 	#	Milestone Description	Date
	9	Reduce grating bar width to 40 nm. Increase grating membrane size to ~60 x 60 mm ² . Measure diffraction efficiency and map period.	Q4 2022
	10	Design frames for larger grating size.	Q4 2022
	11	Fabricate large membranes with period chirp.	Q42022
	12	Fabricate large, "chirped" facets for TRL 6 testing. Measure diffraction efficiency and map period.	Q3 2023
	13	Design and fabricate prototype GAS. Populate prototype GAS with aligned facets and mass simulators.	Q4 2023
	14	Perform TRL 6 tests and analyze results.	Q2 2024
	15	SME review on completion of TRL 6 exit criteria	Q3 2024
<p>TRL 5 to TRL 6 Advancement Degree of Difficulty: $AD^2 = 2-3$ (10%–20% Development Risk)</p> <p>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 steps are incremental developments and improvements relative to the SOA. The advances made to meet the TRL 5 exit criteria will demonstrate an understanding of all engineering aspects (modeling and fabrication) sufficient to make advancements needed to meet TRL 6 exit criteria straightforward engineering practice.</p>			
<p>Anticipated date to achieve TRL 6: Q4 2024</p>			

2.1 Key Milestones

Milestones defined by the *Lynx* Instrument Team for specific activities necessary to develop and/or mature the technology elements are identified in Table 4. Approximate dates for reaching each milestone are provided. Key milestones are defined as those critical to the advancement of the technology to the next TRL level.

Milestone 1 — Increase grating depth to 5.75 μm .

Significance — Increasing the grating bar depth from 4 μm to 5.75 μm is predicted to increase diffraction efficiency from ~30% to ~50%. This will increase the effective area proportionally to meet the *Lynx* effective area goal.

Verification — Diffraction efficiency will be measured using synchrotron (ALS) and/or laboratory sources (MIT polarimetry beamline) in straightforward and established experimental testing. Direct comparison of physical measurements (SEM of grating bar and L1) and Rigorous Coupled-Wave Analysis (RCWA) will be made.

Milestone 2 — Optimize L2 design and reduce blockage to ~10%.

Significance — Development will increase the open area beyond the current SOA (i.e., the current L2 hexagonal structure mesh with ~81% open area). The predicted increase will augment the effective area gains from increasing the etch depth (Milestone 1) to make the required open area goal achievable with margin and while maintaining the required structural integrity

Verification — Level 2 structures are in the 0.1 to 2 mm range and are therefore easy to measure using standard (well-proven) laboratory instrumentation. Test components will be shaken to demonstrate structural integrity on the vibration table available at MKI.

Milestone 3 — Design and fabricate frames with smaller blockage.

Significance — Frame design will be reduced to minimize the frame footprint to the extent possible without compromising requirements for minimal grating distortion, stability in launch and operational environments, and effective alignment

Verification — Frame footprint is simple to verify via standard measurement techniques. Finite element modeling will be used to assess environmental stability (launch, thermal), and custom metrology in the SNL will measure potential grating distortions from bonding.

Milestone 4 — Complete concept and metrology infrastructure development for facet/GAS mounting and alignment conforming to *Lynx* alignment error budget requirements.

Significance — The CAT-XGS grating array consists of ~800 to 2,000 CAT gratings. All of these gratings have to be arrayed according to the XGS optical design (i.e., on the surface of a common Rowland torus) with well-defined roll, yaw, and pitch angles. The efforts toward this milestone will provide the capabilities necessary to design to the anticipated design constraints (e.g., tolerances currently predicted to be in the 6-arcminute to 1 degree range for rotations, and 0.2 to 2 mm for translations (1σ)).

Verification — Past and ongoing technology and engineering development in this area for the *Arcus* mission concept provides a solid foundation for alignment metrology and assembly. Verification of performance will be obtained from laboratory tests of resolving power and effective area (see Table 4).

Milestone 5 — Complete facet fabrication and build a brassboard GAS for TRL 5 tests.

Significance — Meeting this milestone demonstrates the capability to fabricate (repeatably) the multiple grating membranes required for TRL 5 demonstrations of resolving power and effective area. These will be bonded to medium-fidelity frames without significant distortions, followed by final assembly of the GAS for TRL 5 level testing.

Verification — Diffraction efficiency of fabricated facets will be measured using standard synchrotron equipment and techniques and the MIT polarimetry beamline. The grating period distribution across each facet will be mapped with the MIT custom period mapping tool. Results will be compared to both model predictions and *Lynx* requirements to assure the acceptability of the unit for TRL 5 testing.

Milestone 6 — Complete ray-trace model enhancements with inclusion of all features necessary for TRL 5 testing.

Significance — The TRL 5 test will use a custom setup different (small with minor detail variations) from the full flight XGS design incorporated into the model. At this milestone, the program will have

a detailed predictive ray trace model for the analysis of the outputs of TRL 5 testing.

Verification — Usual coding best practices. Incorporate feedback from earlier or preliminary tests, as well as feedback during TRL 5 testing.

Milestone 7 — Perform TRL 5 tests and analyze results.

Significance — TRL 5 tests will be performed according to Table 4. Measured performance and model predictions for the tests will be compared for consistency. Successful testing will provide the information necessary to demonstrate TRL 5 exit criteria and will be submitted for a non-advocate review.

Verification — The imaging system (X-ray source, focusing optics, detectors) will be characterized in detail (flux as a function of wavelength, PSF). The partially populated GAS will then be incorporated into the system and aligned. Line spread functions (informing about resolving power) and intensities of relevant diffracted orders (informing about effective area) will then be measured at relevant wavelengths. The GAS will then be removed and subjected to environmental testing (vibration, thermal under vacuum, etc.). Finally, the GAS will be reinstalled in the imaging system, and the full measurement suite will be repeated. Note: X-ray testing will take place at the NASA MSFC SLTF or an equivalent facility (e.g., SAO, Draper).

Milestone 8 — SME review on completion of TRL 5 exit criteria.

Significance—This is a non-advocate review of the TRL 5-level testing performed to meet Milestone 7. Successful completion signifies that TRL 5 exit criteria have been met.

Verification—The non-advocate SME panel will review the TRL 5 test results with respect to pre-established TRL 5 exit criteria.

Milestone 9 — Reduce grating bar width to 40 nm. Increase grating membrane size to $\sim 60 \times 60$ mm². Measure diffraction efficiency and map period.

Significance — Meeting the grating bar width goal value will increase throughput. This will increase effective area (one of several improvements required to meet the overall XGS effective area goal). Further, the iterative testing planned will provide the information required to assess the ultimate structural limits associated with increasing aspect ratios (i.e., how far reductions can be pushed while maintaining required strength margins. Increasing the grating membrane size leads to a lower grating count (i.e., lower cost) and less area lost to frames and mounting structures, but it can also change the mechanical properties of the facets (analysis and testing will be done to optimize support structures for larger gratings). This also tests the uniformity of the different fabrication steps (patterning, pattern transfer, i.e., etching) across a larger surface.

Verification —Grating bar width will be measured with an SEM and/or an Atomic Force Microscope (AFM), and these are both available to the program. Cleaved samples will show the grating bar profile. Comparing X-ray diffraction efficiency measurements with predictions based on the measured geometrical grating parameters will provide the information required to assess grating bar width. X-ray measurements at different points of a large membrane will demonstrate the uniformity of the achieved structures. Finally, environmental testing, bracketed by diffraction efficiency measurements and period mapping, will set the limits for future large, thin-wall grating fabrication (based on survivability with respect to anticipated launch and space environmental conditions).

Milestone 10 — Design frames for larger grating size.

Significance — Larger membranes require larger frames, and efforts toward this milestone will build on the lessons learned from Milestone 3. Planned testing will provide the information on mechanical and thermal stability needed for large frame fabrication.

Verification — Frame footprint will be measured using standard laboratory and measurement techniques. Finite element modeling will be used to assess design with respect to environmental stability (launch, thermal). Existing custom metrology in the SNL will be used to measure potential grating distortions from bonding.

Milestone 11 — Fabricate large membranes with period chirp.

Significance — Systematic variation in grating period across the grating will be introduced and demonstrated. This advancement is required to mitigate the aberrations that would result from the use of large conventional “non-chirped” gratings.

Verification — Validation of the fabrication of gratings with the targeted “chirp” will be verified through period mapping of an etch mask and/or of a finished grating membrane or facet.

Milestone 12 — Fabricate large, “chirped” facets for TRL 6 testing. Measure diffraction efficiency and map period.

Significance — Meeting this milestone will provide the large “chirped” grating facets required for TRL 6-level testing (i.e., demonstrations of resolving power and effective area). The required bonding to high-fidelity frames without significant distortions will be demonstrated. Finally, the performance of these individual facets will demonstrate the required repeatability of fabrication needed to produce the large grating membranes (with predictable performance) in the quantity required for the XGS.

Verification — Diffraction efficiency of fabricated facets will be measured, and the grating period across each facet will be mapped using the custom MIT period mapping tool. Results will be compared to model predictions and requirements to ensure XGS goals are attainable.

Milestone 13 — Design and fabricate a prototype GAS for TRL 6-level testing. Populate prototype GAS with aligned facets and mass simulators as required to meet TRL 6 test standards.

Significance — Meeting this milestone demonstrates the capability to fabricate/integrate a prototype GAS of the fidelity needed to meet TRL 6 testing requirements (i.e., form, fit, and function at a scale deemed representative of the final product for operational environmental testing with a demonstration of alignment and mounting methods that address all critical scaling issues).

Verification — Alignment metrology will serve as the verification method; all key attributes will be confirmed. Other verification methods will be considered (e.g., Coordinate Measuring Machine (CMM) testing) and employed if deemed necessary by non-advocate SME review.

Milestone 14 — Perform TRL 6 tests and analyze results.

Significance — TRL 6 tests will be performed according to Table 4. Measured performance and model predictions for the tests will be compared for consistency. Successful testing will provide the information necessary to demonstrate TRL 5 exit criteria and will be submitted for a non-advocate review.

Verification — As in the TRL 5 testing, the imaging system (X-ray source, focusing optics, detectors) will be characterized in detail (flux as a function of wavelength, PSF). The partially populated

GAS will then be incorporated into the system and aligned. Line spread functions (informing about resolving power) and intensities of relevant diffracted orders (informing about effective area) will then be measured at relevant wavelengths. The GAS will then be removed and subjected to environmental testing (vibration, thermal under vacuum, etc.). Finally, the GAS will be reinstalled in the imaging system and the full measurement suite will be repeated. During these tests, partial illuminations with smaller PSFs/higher resolving power (“sub-aperturing”) will also be utilized for more detailed diagnostics, compared with ray trace predictions, and numerically combined for comparisons with “full” illumination measurements. Note: X-ray testing will take place at the NASA MSFC SLTF or an equivalent facility (e.g., Panter).

Milestone 15 — SME review on completion of TRL 6 exit criteria.

Significance — This is a non-advocate review of the TRL 6-level testing performed to meet Milestone 14. Successful completion signifies that TRL 6 exit criteria have been met and that the XGS is ready for Phase A.

Verification — The non-advocate SME panel will review the TRL 6 test results with respect to pre-established TRL 6 exit criteria.

2.2 TRL Development Schedule

Redacted

2.3 Cost

Redacted

2.4 Risks

Redacted

3 Summary

The *Lynx* XGS is 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 CAT grating technology can meet requirements for resolving power and effective area with ample margins. The technology is well on its way to TRL 5. Steady and reasonable investment in technology development through NASA SAT funding, followed by *Lynx* technology development funding, will bring a CAT-XGS to TRL 6, well within the schedule for *Lynx* and with manageable risks.

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 8.

Table 5—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 AD² Definitions

AD² 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. AD² is what it takes, in terms of cost, schedule, and risk to advance to the next TRL. AD² is defined on a scale of 1–9 in a manner similar to TRL. The description of the AD² levels is shown in Table 9.

Table 6—AD² 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. 10.

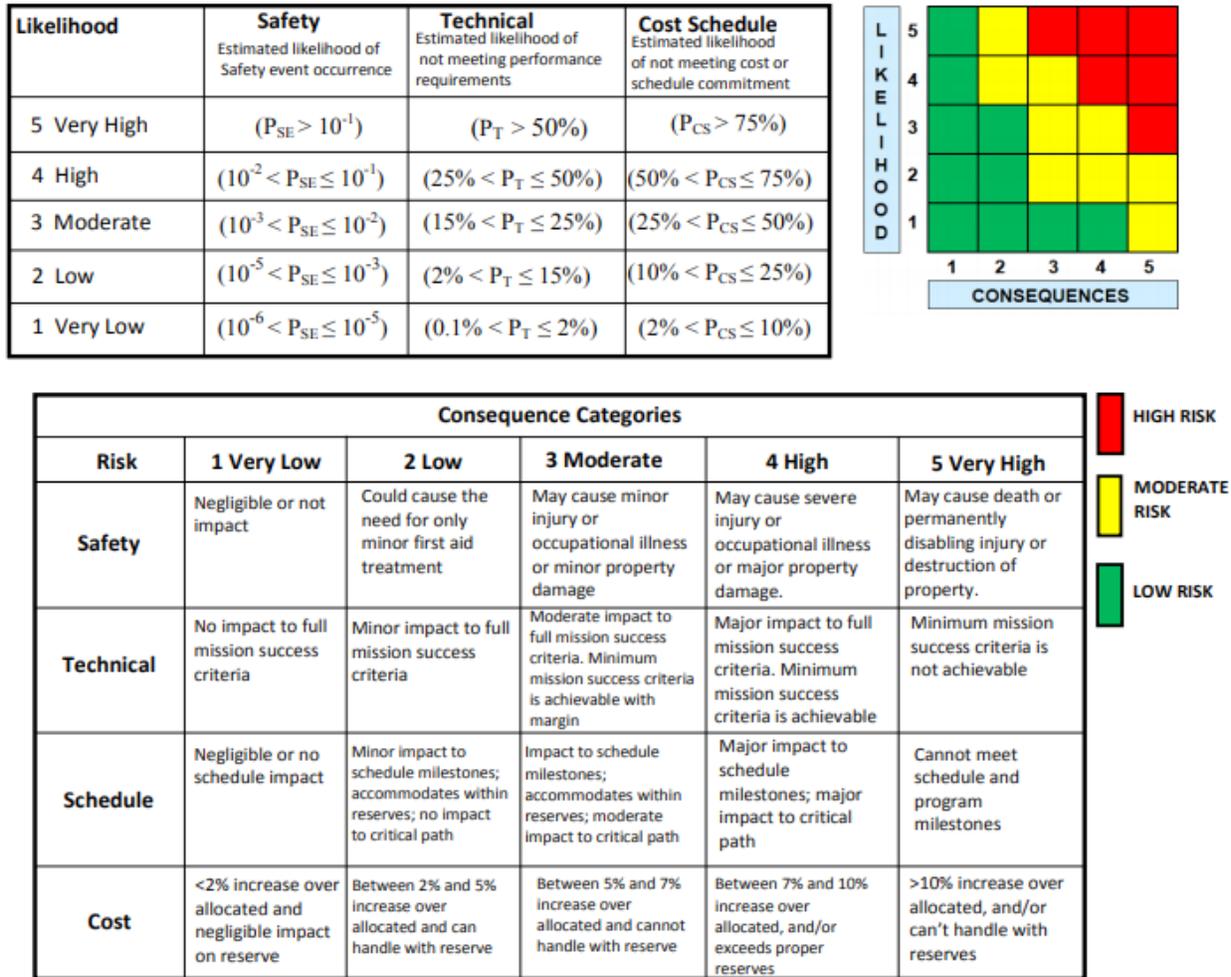


Fig. 8—Risk matrix standard scale.

4.4 Acronyms

AD ²	Advancement Degree of Difficulty
AFM	Atomic Force Microscope
APRA	Astrophysics Research and Analysis
BOX	Buried Oxide
CAT-XGS	Critical Angle Transmission X-ray Grating Spectrometer
CMM	Coordinate Measuring Machine
DDT&E	Design, Development, Test, and Evaluation
DRIE	Deep Reactive-Ion Etching
DRM	Design Reference Mission
FWHM	Full Width at Half Maximum
GAS	Grating Array Structure
GOES	Geostationary Operational Environmental Satellite
GPR	Goddard Procedural Requirements
HDXI	High Definition X-ray Imager
HETGS	High-Energy Transmission Grating Spectrometer
HPD	Half-Power Diameter
ISIM	Integrated Science Instrument Module
KDP	Key Decision Point
L1	Level 1
L2	Level 2
MCR	Mission Concept Review
MEMS	Micro Electro Mechanical Systems
MIT	Massachusetts Institute of Technology
MKI	MIT Kavli Institute for Astrophysics and Space Research
NPR	NASA Procedural Requirement
OP-XGS	Off-Plane Reflection Gratings
PCOS	Physics of the Cosmos
PDR	Preliminary Design Review
PPBE	Programming, Planning, Budgeting, and Execution
RCWA	Rigorous Coupled-Wave Analysis
SAT	Strategic Astrophysics Technology
SDO	Solar Dynamics Observatory
SEM	Scanning Electron Micrograph
SLTF	Stray Light Test Facility
SNL	Space Nanotechnology Laboratory
SOHO	Solar and Heliospheric Observatory
SOI	Silicon-On-Insulator
SOTA	State of the Art
TRL	Technology Readiness Level
TWINS	Two Wide-Angle Imaging Neutral-Atom Spectrometers
WFIRST	Wide Field Infrared Survey Telescope
XGA	X-ray Gratings Array
XGS	X-Ray Grating Spectrometer
XMA	X-ray Mirror Assembly

4.5 References

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