Generation-X Grating Array Technology Development

A White Paper submitted to the Electromagnetic Observations from Space (EOS) Discipline in response to the Astro2010 Call for White Papers on Technology Development

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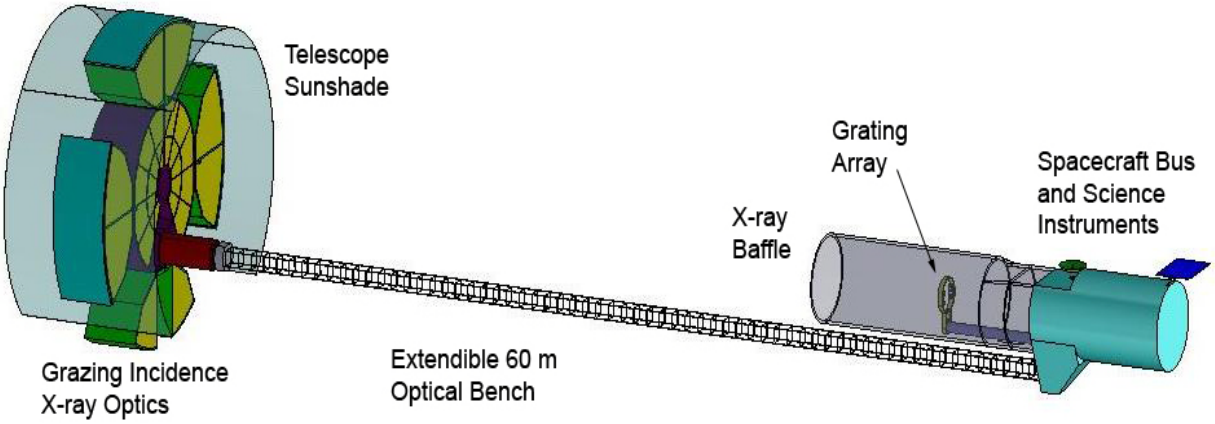

Abstract

The Generation-X Mission (*Gen-X*) is a large area (50 m^2 at 1 keV), high angular resolution (0.1") X-ray telescope tasked with studying a wide range of science topics from the first black holes to the structure of the Universe as it stands today. An integral part of achieving these science goals is the incorporation of a grating array that will be used for high resolution spectroscopy ($E/\Delta E > 10{,}000$) at energies below 1 keV. The technology development for the *Gen-X* grating array will heavily leverage the development for the *IXO* X-ray Grating Spectrometer. However, there are several areas where the development for *Gen-X* will be more advanced given the higher spectral resolution requirement and larger area requirement (10 m^2 at 1keV). This document describes these *Gen-X* specific development efforts.

Introduction

The Generation-X Mission (*Gen-X*) is a large area (50 m^2 at 1 keV), high angular resolution (0.1") X-ray telescope aimed at studying a broad range of science topics including the evolution of stars, galaxies and black holes as well as the physics of matter in the extremes of density, gravity, magnetic fields and kinetic energy. Paramount to achieving these science goals is the incorporation of a Grating Spectrometer (GS) that will be used for high resolution spectroscopy ($E/\Delta E > 10,000$) at energies below 1 keV. As the telescope optics are leveraging technology development for the International X-ray Observatory (*IXO*), so too will the gratings. This document describes the technological challenges involved with making the advancement from *IXO* to *Gen-X*. For an overview of the entire *Gen-X* telescope development effort please see the *Gen-X* Activity response to the Astro2010 Request for Information entitled "Generation-X Technology Development Program", Brissenden et al. (http://www.cfa.harvard.edu/hea/genx/media/papers/astro2010/Astro2010-Brissenden-Gen-X.pdf).

1. Science Goals

The low energy, high resolution spectroscopy offered by the *Gen-X* grating array allows for many unique science goals. A few of these goals are summarized here. First, the detection of diffuse baryonic matter is a major goal of astrophysics. The large effective area of *Gen-X* combined with the high spectral resolution of the gratings allows for not only the detection and mapping of the diffuse intergalactic medium (IGM) but also allows for a determination of the kinematics of these missing baryons. Second, high spectral resolution for soft X-rays will be critical when observing emission from the first galaxies and the first epochs of star formation. Analysis of spectral lines redshifted into this energy range will provide the velocity, temperature and metallicities of these primordial galaxies. Third, quasar winds and outflows can greatly influence the interstellar medium (ISM) of a host galaxy and could contribute to the chemical enrichment of the IGM. The gratings will determine the physical characteristics of these winds such as mass loss rate, abundances and kinematics. Finally, high resolution imaging combined with high spectral resolution at low energies will probe shock physics in supernova remnants including non-thermal emission properties, electron-ion equilibration in shocks, ionization structure in shocks, density of the surrounding medium, and properties of the ejecta. These goals require high spectral resolution and high throughput, which will be achieved using a grating array.

2. Mission Overview

The *Gen-X* mission concept consists of a large effective area (50 m^2) X-ray telescope capable of providing unprecedented spatial resolution (0.1" half power diameter). The large envelope of the optics will be unfolded on-orbit and then extended from the focal plane instruments. These instruments include an X-ray Microcalorimeter Spectrometer for high spectral resolution at high energy and a Wide Field Imager (WFI) consisting of a self triggering active pixel detector. An overview of the technology development for each of these instruments is given in the following white papers: "Development of Low-Temperature Detectors for Generation-X and Other Missions Requiring High-Resolution, Large-Format, X-ray Detector Arrays," Bandler et al. (http://www.cfa.harvard.edu/hea/genx/media/papers/astro2010/Astro2010-Bandler-XMS.pdf) and "Active Pixel X-ray Sensor Technology Development for the Generation-X Wide-Field Imager," (http://www.cfa.harvard.edu/hea/genx/media/papers/astro2010/Astro2010-Bautz-WFI.pdf), Bautz et al.

The grating array will disperse onto an active pixel detector (similar to the WFI) supplying the necessary requirements for high spectral resolution at low energy.

3. Grating Spectrometer (GS)

The performance requirements for the mission that are addressed by the GS are

- Spectral resolution E/ΔE > 10,000 below 1 keV
- Effective area > 10,000 cm^2 below 1 keV
- Energy range 0.1-1.0 keV

To achieve these requirements, *Gen-X* will study two different options for the GS, a Critical-Angle Transmission GS (CATGS) and an Off-Plane Reflection GS (OPGS). Regardless of the gratings, the reference candidate design for the GS places the gratings in the converging telescope beam, 8 m from the focal plane and requires actuation in and out of the beam. Both options will utilize an active pixel detector at the focal plane. A summary of the two different layouts follows.

3.1 CATGS configuration

The CATGS is based on the heritage of the optical design for the HETGS (High Energy Transmission Grating Spectrometer) and ACIS (AXAF CCD Imaging Spectrometer) instruments on *Chandra*. The two transmission grating arrays consist of support structures that hold a number of grating facets in a fixed position and orientation relative to the detector spacecraft when deployed. A moveable mechanism similar to that employed on *Chandra* can swing the grating arrays out of the telescope beam when they are not needed. In the deployed position the gratings cover ~ 57% of the mirror aperture. The coverage is limited to two juxtaposed azimuthal segments of ~ 110 degrees each. In contrast to the phase-shifting transmission gratings on *Chandra*, CAT gratings are blazed. They blaze very efficiently for wavelengths with a critical angle of total external reflection that is greater than the angle of incidence onto the grating bar sidewalls. The summed diffraction efficiency of all blazed orders for a given wavelength is on the order of 50% and therefore leads to high effective area.

The 200 nm-period silicon gratings disperse X-rays according to wavelength and focus them along a straight line (dispersion axis) into a spectrum that is recorded by the camera. Figure 1 shows a cross section of an early CAT grating prototype. The center of each grating facet touches a Rowland torus that also contains the telescope focus and the fixed blaze position in the spectrum. Blazing in the case of CAT gratings means that the diffraction efficiency is maximized around the direction of specular reflection off the sidewall of a grating bar. The direction of specular reflection coincides with the direction of the blaze position, which is 3° from transmitted 0^{th} order. Since the CAT gratings are blazed, shorter wavelengths contribute in higher diffraction orders and can therefore be detected with higher resolution. In addition, the CATGS takes advantage of the anisotropic projected scattering from the grazing-incidence mirrors through sub-aperturing. This can improve resolution by a factor of 2-3 or more, depending on the details of the telescope mirror error budget.

The gratings only have to be a few micrometers thick, and are therefore light-weight. The mass of the grating array is dominated by the supporting structures that hold the membrane-like gratings in place. The two grating arrays have a total mass on the order of 20 kg. The mount is relatively alignment insensitive, especially for diffraction orders that lie within a few degrees of the directly transmitted (0th order) beam. Typical angular alignment tolerances are therefore in the range 2-15', despite the 0.1" arcsec telescope PSF. However, distances along the optical axis need to be maintained to within tens of micrometers to preserve the required high spectral resolution.

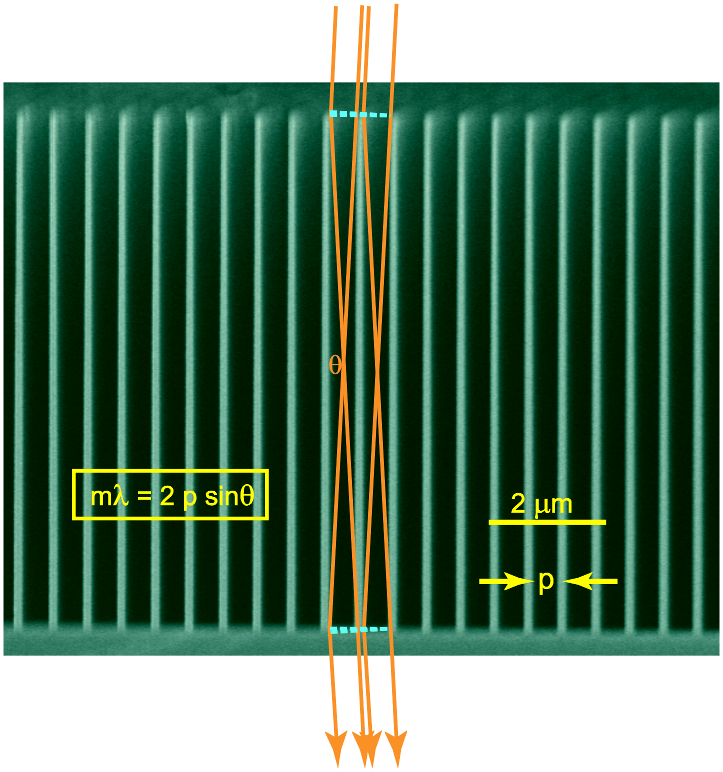

Figure 1: Scanning electron micrograph of a cleaved cross section through an early CAT grating prototype, showing the high aspect ratio of the grating bars.

Since the CAT gratings are so thin, they also become almost completely transparent at higher photon energies. This leads to the welcome effect that other focal plane instruments (such as the calorimeter) that have better energy resolution at higher energies lose very little effective area and can operate simultaneously with the CAT-GS, even if the gratings were to cover the whole mirror aperture.

The grating arrays are passive devices that do not require any power except for thermal control and insertion. We estimate that temperature gradients across the grating arrays need to be kept below +/- 3K.

The camera consists of a linear array of active pixel detectors and its housing, detector electronics and power supply, and a digital processor. The active pixel detector array extends from ~ 190 mm to 620 mm in the radial/dispersion direction from the telescope focus.

3.2 OPGS configuration

The OPGS utilizes reflection gratings in the extreme off-plane mount. In this configuration the telescope beam intersects the grating in a direction nearly parallel to the grooves and is then dispersed into a cone of light with half-angle equal to the graze angle of incidence, typically <3°. This maximizes the illumination efficiency on the grating face and allows for high throughput when the gratings are stacked into an array. The grooves on each grating can be customized to obtain optimal performance. First, the groove profile can deviate from parallel grooves and assume a profile that fans out to match the convergence angle of the telescope. This negates any aberration due to varying incidence angles with respect to the groove direction. Furthermore, as with the CAT gratings, off-plane reflection grating grooves can be blazed as opposed to the typical sinusoidal profile. This leads to most of the light being dispersed on only one side of zero order thus nearly doubling efficiency in either plus or minus orders. The off-plane array can also take advantage of sub-aperturing, but given the high quality of the telescope focus of *Gen-X*, this technique is not necessary to obtain the resolution requirement. A resolution of > 10,000 can be met with a grating groove density of 5500 grooves/mm and a blaze of 21°. Furthermore, since dispersion is constant in wavelength, this gives a factor of ten increase in resolution at 0.1 keV.

The array will consist of a number of modules that each holds a number of gratings. Figure 2 shows a CAD model of the grating modules being designed for *IXO*. A nearly identical design will be employed for *Gen-X*. The gratings are aligned to one another in each module which is then aligned with the other modules forming the array. The array will cover ~73% of the beam in two opposing (either side of the optical axis) sections. Each section will cover 132° of azimuth over the outer radii of the telescope beam. By covering only outer radii, the array will conserve the high energy throughput of the center of the telescope even when the gratings are deployed. To obtain 10,000 cm^2 of effective area, the array will utilize 219 modules that will weigh ~0.8 kg each leading to an array mass of ~180 kg.

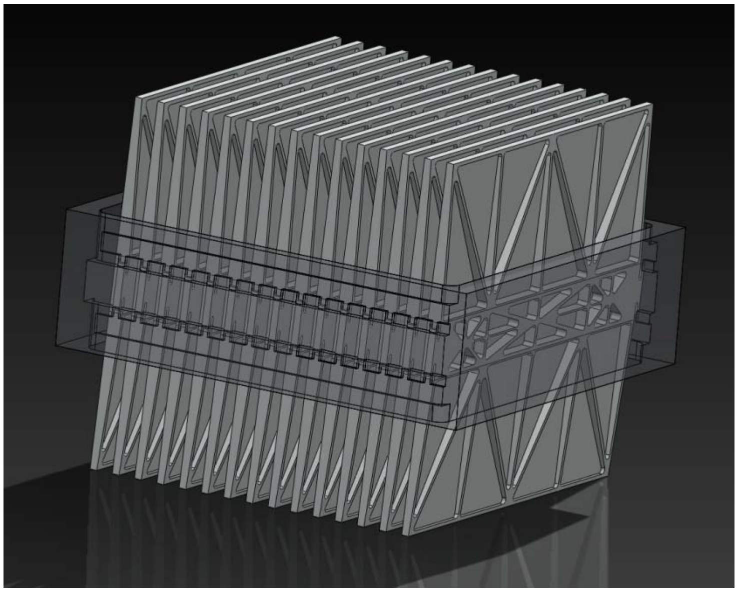

Figure 2: OPGS CAD module showing multiple gratings aligned within the module structure (shown transparent). The lighweighted backs of the gratings are visible with the groove surface on the opposite side.

The aligned grating array will form an arc of diffraction at the focal plane. The OPGS will utilize the same active pixel detector technology as the CATGS. However, contrary to the linear, radially spanning array of the CATGS, the OPGS will have an array at a constant radius, 1.43 m, and span 180 mm in azimuth. To cover the required wavelength range the active pixel array will monitor zero order as well as capturing the dispersion arc.

4. *Gen-X* Technology Plan

Technology development plans for the two GS options:

OPGS

1. Verify design via detailed raytrace and develop accurate tolerance matrix
2. Develop thin substrate gratings with robust, high quality surface figure and roughness
3. Develop replication process that does not alter the optical quality of the substrate
4. Develop alignment and assembly technology
5. Align, assemble, and test an array

CATGS

1. Develop silicon CAT gratings with low-obscuration integrated support mesh
2. Develop coarse level-II silicon support mesh
3. Develop level III metal support mesh & facet frame
4. Increase grating facet size to ~ 5 cm x 5 cm
5. Design and build grating support structure

In both cases, steps 1-5 overlap with technology development for *IXO*, with *IXO* TRL 6 achieved by early 2014, and instrument delivery by the end of 2017. While the grating instruments for *IXO* and *Gen-X* are conceptually very similar, there are several areas where technology development for *Gen-X* needs to move beyond *IXO* requirements. This is driven by the higher spectral resolution requirement, $E/\Delta E > 10{,}000$ compared to 3000 for *IXO*. TRL 6 for *IXO* can be interpreted as TRL 5 for *Gen-X*.

Table 1 below gives a rough comparison between assembly, alignment, and placement tolerances for the grating spectrometers on *IXO* and *Gen-X*. The largest challenges for the CATGS will be in assembly and repeated placement of the grating facets to within 60 micron of nominal positions relative to the telescope mirrors, and placement of the (curved!) detector surface within < 15 micron of the Rowland torus surface. These requirements place high demands on deployment accuracy, and tighter demands on grating period control and thermal control over a roughly 2.5 times larger grating area than for *IXO*.

OPGS Tolerances	*IXO*	*Gen-X*	**CATGS Tolerances**	*IXO*	*Gen-X*
grating surface figure	$\lambda/4$	$\lambda/10$	Δz (μm)	394	62
grating-to-grating pitch (arcsec)	1	0.3	grating roll (arcmin)	22	13
grating yaw (over array; μm)	20	7	grating pitch (worst; arcmin)	6	2.3
Temp. gradient (along groove; K)	1	0.3	grating pitch (on blaze; arcmin)	20	7.7
			detector "depth of focus" (μm)	500	15
			Rowland sag over 1 CCD (μm)	8	30
			period variation Δp (pm)	4	1.5
			Temperature gradient (K)	7.7	3

Table 1: Comparison of selected tolerance estimates between instruments on *IXO* and *Gen-X*.

The OPGS does not share some of the tight tolerances in position as the CATGS does, however it does have strict requirements on the individual grating surfaces. For *IXO* the off-plane gratings must hold an optical surface figure of $\lambda/4$ (measured at $\lambda = 6563$Å) along the grooves. This is particularly difficult due to the thinness of the grating substrates. Currently, the *IXO* requirement is just within machine tolerances, but advancement to a figure of λ/10 for *Gen-X* will take considerable study on how to alter or completely change the substrate fabrication and grating replication processes to remove sources of mechanical stress. An alternative is to fly thicker gratings, but the increased mass and increased coverage of the beam (due to the thickness) may not be the optimal solution.

Other challenges for the OPGS come from alignment of the gratings relative to each other and pointing accuracy. When performing the alignment for *IXO*, the off-plane gratings will need to have their surfaces aligned in pitch to within an arcsecond of each other. This tolerance will tighten by a factor of three for *Gen-X* which will require a much more precise alignment strategy that will require study. In terms of pointing the off-plane grating array cannot yaw more than ~20 microns at one end of the array (yaw is rotation about the grating surface normal) for *IXO*. Again, this is currently achievable, but tightening the tolerance to ~7 microns over a larger array for *Gen-X* will require more study than what will be done for *IXO*.

The final factor that affects resolution is temperature. Temperature deviations along the grating grooves causes pitch errors, which are the tightest tolerance. *IXO* temperature control for the gratings is 1 K. Again, this is currently achievable using standard heaters and thermal control, but making the requirement 0.3 K will probably require a different thermal control strategy and qualification testing to ensure this small range of temperatures.

5. Grating Spectrometer Budget Estimate

Table 2: Gen-X grating array technology program costs ($M) in fixed FY09 dollars showing TRL with time.

FY:	11	12	13	14	15	16	17	18	19	20	21	22	23		Total
Gratings	0.5	0.5	0.5	0.5	1.0	2.0	2.0	2.0	2.0	1.0	🟩	🟩	🟩	🟩	12.0

TRL Legend	2	3	4	5	6

(As a point of reference, the total cost of all contracts for fabrication & manufacture, testing, and integration of the Chandra HETGS was $39.6M in 1995 dollars, detectors excluded.)

In summary, while grating alignment and assembly tolerances for certain degrees of freedom are expected to be met with typical machining tolerances for both spectrometer designs of *IXO*, active alignment with customized high-precision metrology during assembly might be necessary for most degrees of freedom in the case of *Gen-X*. The stricter tolerances on position, figure, pointing and temperature will require further study than will be done for *IXO*. These issues need to be investigated carefully before an accurate cost estimate for technology development, grating and array fabrication, assembly, integration, and testing can be made.

The cost estimate for the grating spectrometer technology development program assumes that the development for *Gen-X* will leverage heavily off of the development for the *IXO* X-ray Grating Spectrometer (XGS). A summary of *Gen-X* grating array program costs is given in Table 2. The color code indicates that a particular TRL has been reached. The transitions between TRL are marked by Technology Gates where the grating performance and TRL will be verified. The schedule for *IXO* development has the XGS obtaining TRL 6 in FY2014. However, given the increased requirements, this will only be a TRL of 5 for the *Gen-X* grating array. The grating development work for both projects will run parallel during this time period and minimal additional funding will be required for *Gen-X*. The $0.5M funding level during these years is to initiate development efforts that will be distinctly different between *IXO* and *Gen-X*. This will be split between to two grating technologies being studied. Most of this money will go towards the staffing required to perform the technology studies. After FY2014, development efforts for *IXO* will have ended and a jump in funding will be necessary to take the *Gen-X* gratings to TRL 6. Again, this will be split between the two technology groups. Most of the funding will be directed towards various studies that are required to achieve the high resolution and area requirements of *Gen-X*. These include assembly of the gratings into arrays, repeated placement tolerances as the arrays are flipped in and out of the beam, placement of the active pixel detector at the focal plane/possibility of curved detectors, optical surface requirements, pointing accuracy, and temperature control. The tolerance levels for these areas are a step above the current state-of-the-art and will require significant study.

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