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Alignment of the Marshall Grazing Incidence X-ray Spectrometer (MaGIXS) Telescope Mirror and Spectrometer Optics Assemblies

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ABSTRACT

The Marshall Grazing Incidence X-ray Spectrometer (MaGIXS) is a NASA sounding rocket instrument designed and built to observe X-ray emissions from the Sun's atmosphere in the 6–24Å (0.5–2.0keV) range while achieving high spectral and spatial resolution along a 8-arcminute long slit. We describe the alignment process and discuss the results achieved for assembling the Telescope Mirror Assembly (TMA) and the Spectrometer Optics Assembly (SOA) prior to final integration into the MaGIXS instrument. The MaGIXS mirrors are full shell, electroformed nickel replicated on highly polished mandrels at the Marshall Space Flight Center (MSFC). The TMA carries a single shell, Wolter Type-1 mirror pair (primary and secondary) formed on a common mandrel. The SOA includes a matched pair of identical parabolic mirrors and a planar varied-line spacing (VLS) diffraction grating. We performed the subassembly alignment and mounting at the Smithsonian Astrophysical Observatory (SAO) using metrology and precision positioning systems constructed around the Centroid Detector Assembly (CDA), originally built for the alignment of the Chandra mirror shells. The MaGIXS instrument launch has been postponed until 2021 due to the COVID-19 pandemic.

Keywords: X-ray, Alignment, Sounding Rocket, Mirror, Grating

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1. INTRODUCTION

The Marshall Grazing Incidence X-ray Spectrometer (MaGIXS) is a NASA sounding rocket instrument designed and built to observe X-ray emissions from the Sun's atmosphere in the 6–24Å (0.5–2.0keV) range while achieving high spectral and spatial resolution along a 8-arcminute long slit. The MaGIXS instrument optical system includes a 1.09 m focal length Wolter-1 grazing incidence Telescope Mirror Assembly (TMA), a slit at the telescope primary focus, and a 3-element Spectrometer Optics Assembly (SOA). The MaGIXS mirrors are full shells of electroformed nickel replicated on highly polished aluminum mandrels at the Marshall Space Flight Center (MSFC) [ref 1]. The TMA contains a single shell Wolter Type-1 mirror pair (primary and secondary) with an entrance diameter of 150 mm and an overall length of 250 mm. The SOA carries a matched pair of identical parabolic mirrors (84 mm OD at the large end and 79 mm long) and a planar varied-line spacing (VLS) diffraction grating etched onto a fused silica substrate [ref 2]. We mount the 73 mm long grating in the converging beam covering approximately 34 degrees of the full system aperture. Figure 1 shows the layout of the MaGIXS optical system. Both the TMA and the SOA include reference mirrors bonded into their support flanges and removable cross hair reticles used for module alignment. We align the mirrors, mirror modules, and grating for MaGIXS at SAO with custom metrology equipment built around the Centroid Detector Assembly (CDA), originally built for alignment of the Chandra mirror shells [ref 3].

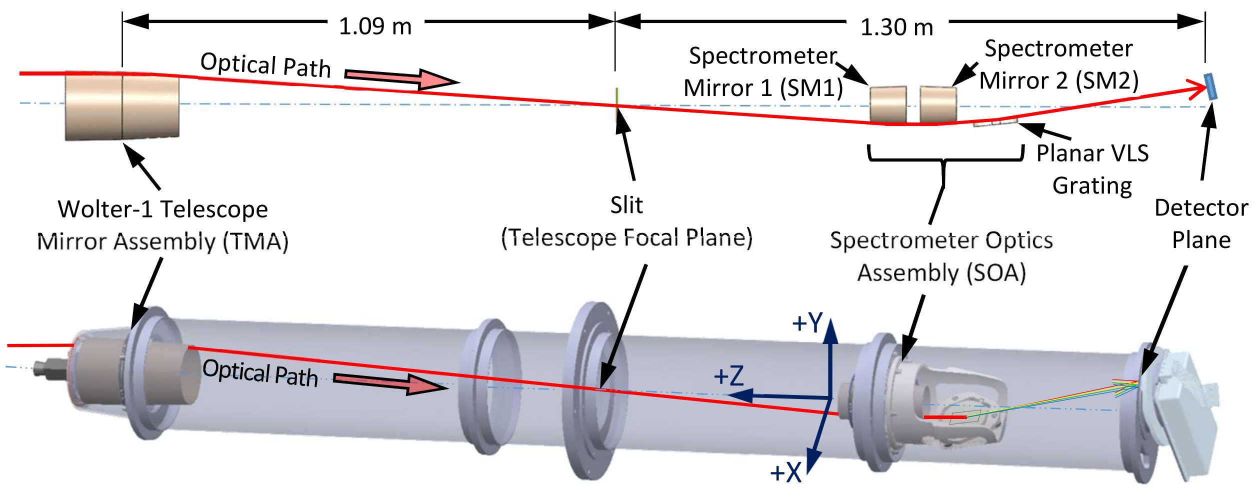

Figure 1: Layout of the MaGIXS Optical System

2. DESCRIPTION of the MaGIXS MIRROR MODULES

Telescope Mirror Assembly (TMA)

The Telescope Mirror Assembly (TMA) is located at the entrance to the MaGIXS Wolter-1 Telescope and contains a single shell optic (paraboloid and hyperboloid) that is supported on a titanium mounting ring by six titanium tangent flexures. We bond the mirror pair at its Center of Gravity (CG) to nickel bonding nubs pressed into the titanium flexures (Figure 2, left). The primary and secondary mirrors are formed on a common mandrel and need no further alignment once they arrive at SAO from MSFC. The TMA carries a flat reference mirror bonded into the mirror mounting ring and a cross-hair reticle that is removable prior to launch (Figure 2, right). During final integration of the mirror modules to the telescope tube assembly at MSFC, we use these integrated alignment features to find the telescope optical axis and to determine the location of best focus for the telescope mirror.

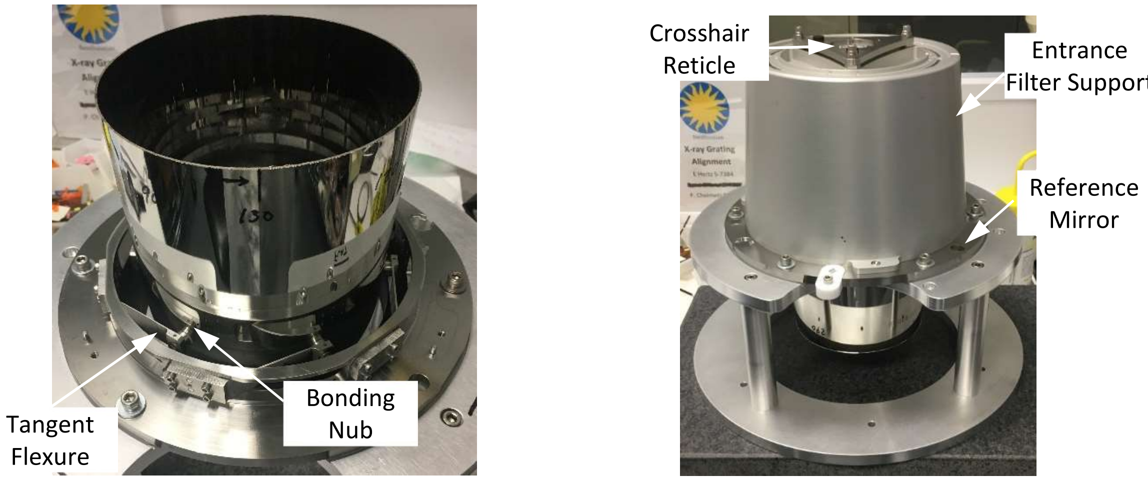

Figure 2: MaGIXS Telescope Mirror Assembly (TMA)

Spectrometer Optics Assembly (SOA)

The Spectrometer Optics Assembly (SOA) consists of two identical paraboloid mirrors precision aligned on either side of a common mounting plate. Each mirror is held in its own titanium ring using three titanium tangent flexures. We bond the mirrors at their CG to nickel bonding nubs pressed into one end of each flexure. Each mirror sub-assembly is fixed to the common mounting plate with an adjustable (for tip, tilt, and decenter) kinematic support consisting of three truncated balls pressed into the mirror mounting plate, trim spacers, and three v-blocks pointed toward the center of each mirror (Figure 3, left). The mirror assemblies carry a flat reference mirror bonded into the mirror mounting ring. We mount the cross-hair reticle at the center of the mirror assembly closest to the grating and remove it prior to launch (Figure 3, right). During final integration of the SOA prior to X-ray test, we use these integrated alignment features to ensure proper alignment and spacing to the TMA [ref 4].

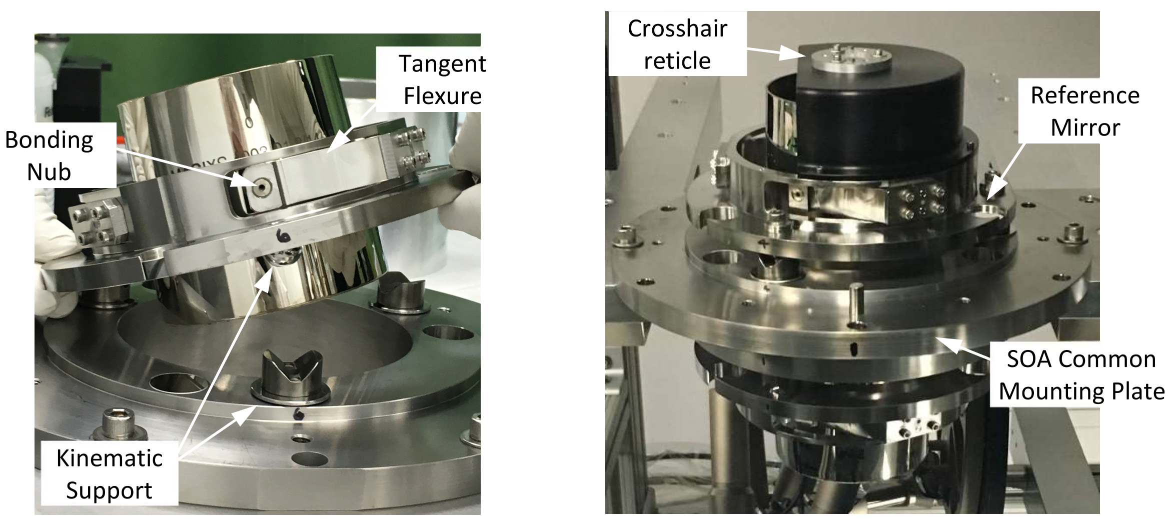

Figure 3: MaGIXS Spectrometer Optics Assembly (SOA)

SOA with Variable Line Spacing Grating

The varied line space (VLS) planar diffraction grating, fabricated at Izentis LLC, is positioned just past the SOA mirror pair and is sized to diffract ~34° of the passing rays (Figure 4, bottom). The 25 x 73 mm grating footprint is patterned on a 100 mm diameter silicon substrate and is held in its grating support frame using three integral wire EDM flexures. We bond the grating substrate to Invar bonding nubs pressed into the integral flexures and mount the grating in its support frame to the housing using a smaller version of the adjustable kinematic support found on the mirror assemblies (Figure 4, left). When bonded, the grating is centered in the support frame with the grating surface flush to the exposed surface of the frame. We assemble the grating housing to one side of the SOA common mounting plate using spacers to control the Z location of the grating footprint in the converging beam.

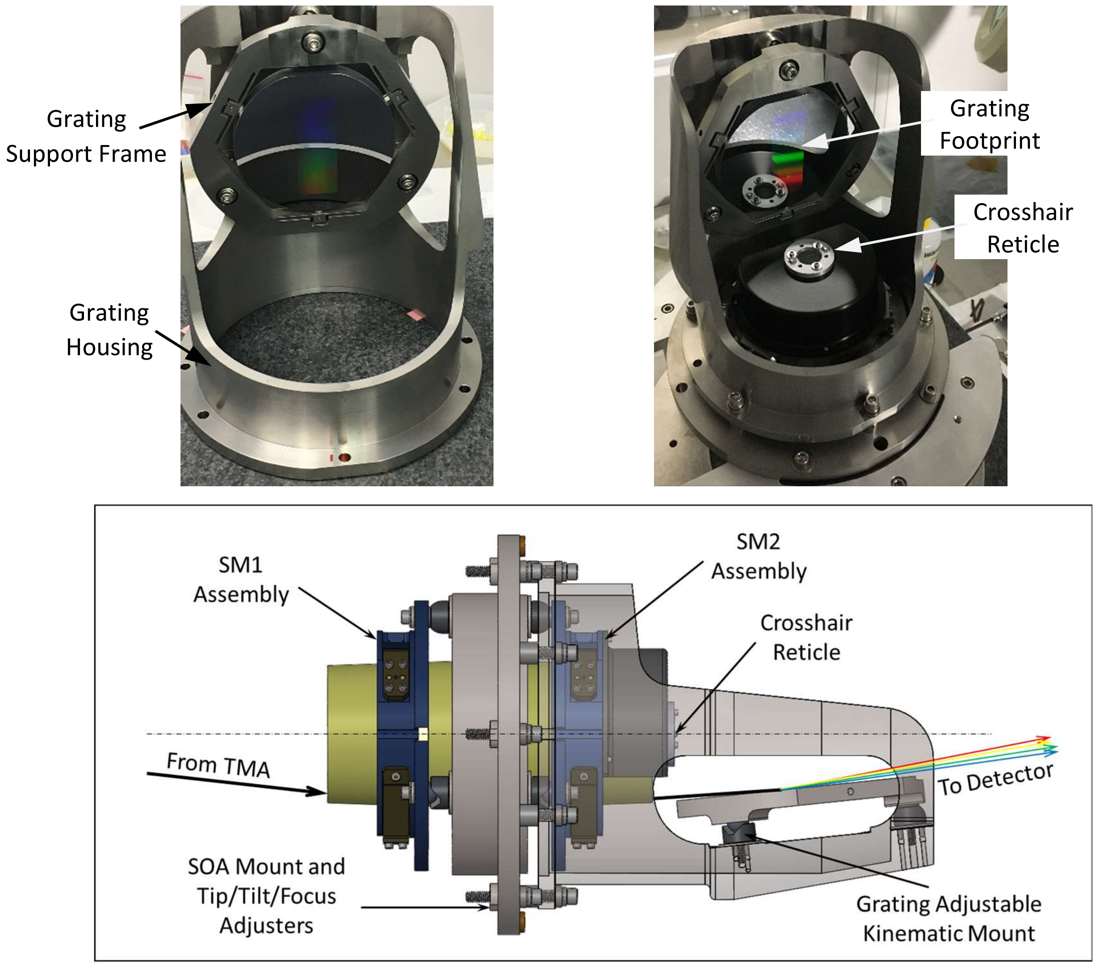

Figure 4: MaGIXS SOA with Grating

3. ALIGNMENT REQUIREMENTS

The sensitivity of the MaGIXS instrument performance with respect to misalignments is discussed in detail in Champey et al. (2016) [ref 5]. The included alignment analysis shows that the MaGIXS optical system performance is most sensitive to misalignments between the spectrometer mirror pair and to the position of the grating. The most challenging tolerances are the tip/tilt alignment between the two spectrometer mirrors which must be limited to 5 arcseconds or better and the rotational alignment of the grating about the X axis with respect to the telescope optical axis which must be better than 50 arcseconds. The location of the grating along the Y and Z axes must be controlled to better than 100 µm and 200 µm respectively with respect to the telescope focus and the optical axis.

We assembled and aligned the TMA and the SOA separately at SAO and integrated them to the Telescope Tube assembly at MSFC using the recorded positions of the onboard fiducials (reference mirrors and crosshair reticles) for each assembly [ref 4]. The TMA optical axis defines the optical axis for the entire telescope, and since the primary mirror and secondary mirror are fabricated on the same mandrel, alignment between the two segments of the Wolter-1 mirror pair is fixed. The only alignment requirements for the TMA are to understand the angle between the TMA optical axis and the reference mirror mounted to the TMA mirror cell (better than 5 arcseconds) and the distance of the mirror optical axis to the center of the TMA crosshair reticle (better than 25 µm).

With three optical components requiring precision alignment, the SOA includes a much more elaborate assembly and alignment process. Table 1 shows the alignment tolerances associated with the SOA and grating assembly. Refer to Figure 1 for the instrument coordinate system. The tolerances highlighted in bold are described in more detail below while the majority of the remaining alignment tolerances are easily met through specified machine part tolerances and good-practice assembly techniques.

Element and Error Name		Allowable	Measured	Units	Notes
SM1	Decenter ±X	50.0	45.00	*µm*	with respect to SOA optical axis
	Decenter ±Y	50.0	40.00	*µm*	with respect to SOA optical axis
	Despace ±Z	500.0	250.00	*µm*	knowledge of focal length to center of optical surface
	Tilt ±X (about centroid)	**5.0**	**1.50**	***arcseconds***	**with respect to SOA optical axis**
	Tilt ±Y (about centroid)	**5.0**	**1.50**	***arcseconds***	**with respect to SOA optical axis**
SM2	Decenter ±X	50.0	3.50	*µm*	with respect to SM1
	Decenter ±Y	50.0	3.00	*µm*	with respect to SM1
	Despace ±Z	500.0	250.00	*µm*	knowledge of focal length to center of optical surface
	Tilt ±X (about centroid)	**5.0**	**1.50**	***arcseconds***	**with respect to SM1**
	Tilt ±Y (about centroid)	**5.0**	**1.50**	***arcseconds***	**with respect to SM1**
SOA	Decenter ±X	50.0	45.00	*µm*	with respect to SOA crosshair reticle
	Decenter ±Y	50.0	40.00	*µm*	with respect to SOA crosshair reticle
	Despace ±Z	100.0	100.00	*µm*	knowledge of focal length for best part of optic
	Tilt ±X (about centroid)	180.0	3.00	*arcseconds*	with respect to SOA reference mirror
	Tilt ±Y (about centroid)	180.0	3.00	*arcseconds*	with respect to SOA reference mirror
Grating	Decenter ±X	250.0	150.00	*µm*	with respect to SOA optical axis
	Decenter ±Y	**100.0**	**32.00**	***µm***	**with respect to SOA optical axis**
	Despace ±Z	**200.0**	**40.00**	***µm***	**with respect to SM2 (telescope) focus**
	Tilt ±X (about centroid)	**50.0**	**15.00**	***arcseconds***	**with respect to SOA optical axis**
	Tilt ±Y (about centroid)	270.0	3.00	*arcseconds*	with respect to SOA optical axis
	Roll ±Z (about centroid)	180.0	35.00	*arcseconds*	about SOA optical axis

Table 1: SOA Alignment Tolerances

4. ALIGNMENT STATION AND METROLOGY

The essential tool used to align the MaGIXS mirror assemblies is the Centroid Detector Assembly (CDA). We designed our mirror alignment and bonding station around the CDA providing us with a convenient way to achieve the required precision demanded by the MaGIXS optical alignment. The CDA was originally built in 1994 by Bauer Associates, Inc. to align the Chandra (AXAF) mirror elements [ref 3]. In 2014, the CDA at SAO was re-calibrated and upgraded with a 488nm, 20 mW laser and new beam shaping lenses to provide a smaller, higher power probe beam. The CDA works on the principal of a Hartmann test where a pencil beam is sent from the nominal focal point of the optical system being tested (Figure 5). A centered beam that is projected on axis defines the optical axis for the test. In general, the pencil beam reflects off a grazing incidence mirror at a mirror dependent radius and focal length to a retro-reflection flat mirror. The beam retraces its path back to the nominal focal point where its lateral position is measured on the detector within the CDA. The CDA beam is steered around the mirror shell so that many sub-apertures (typically in 15° increments) for each shell are tested and the slope error for each measurement is integrated to give the total wavefront error for the mirror at the measurement position. We make corrections to the mirror position tilt, decenter, and focus to minimize the size and optimize the shape of the “spot” at the CDA detector until our budgeted tolerances are met. When used properly with a carefully aligned retro-reflecting mirror, alignment of a mirror centroid can be achieved to much better than 5 arcseconds.

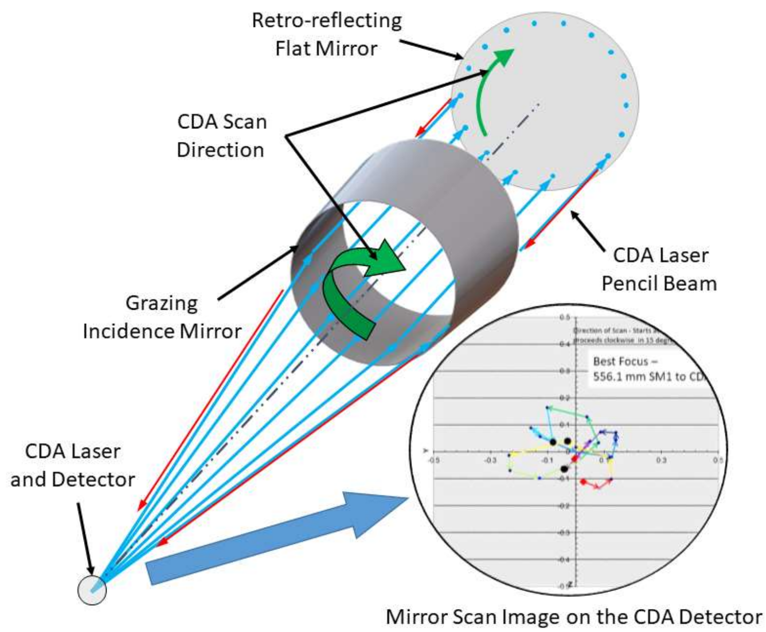

Figure 5: CDA Alignment Scan

We use the CDA as described for aligning the telescope mirror and the spectrometer mirrors while bonding them into their cells; the pencil beam is sent back on itself as shown in Figure 5. For alignment of the spectrometer mirror pair, we introduce a second or satellite camera at the focus of the second spectrometer mirror taking the place of the CDA’s built in detector. We steer the CDA laser using the CDA control software and use purpose written MatLab code with the satellite camera to perform the calculations needed for determining the centroid of the refocussing CDA beam to better than 0.1μm (see Figure 6).

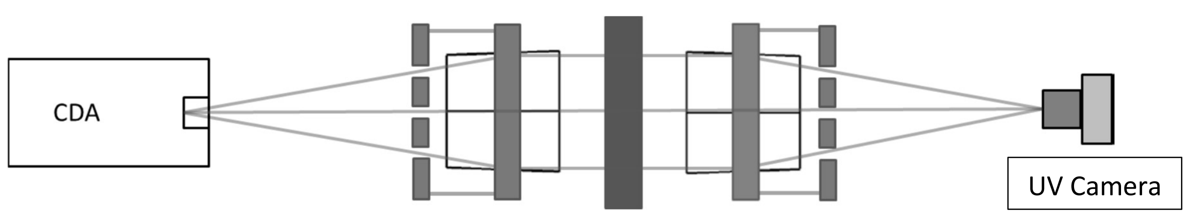

Figure 6: Schematic of the CDA Alignment Scan with Satellite UV Camera

For MaGIXS, we introduce a flat fold mirror between the CDA and the first optic in order to place the CDA horizontally on our large vibration isolated optical bench while allowing the optics to be supported vertically. Supporting the optics on three points vertically minimizes gravity induced mirror distortion (see Figures 7, 8, & 9). We also incorporate a Leica T3000A Theodolite into the alignment station for measuring vertical and horizontal angles with an accuracy of better than ±1 arcsecond. We use a Hexagon

Technology model 7530 6-Axis Romer Arm for making point to point linear measurements to better than 25µm. We make precision adjustments of the unmounted and mounted optics in increments as small as 1 µm or 1 arcsecond using a suite of precision micrometers or a PI H-840 Hexapod, depending on the particular operation.

5. ALIGNMENT SUMMARY

Mirror Bonding

The first step in the alignment process is to bond the mirrors to the nubs pressed into their support flexures while ensuring that alignment to the embedded reference mirrors is maintained. We align the large fold and return mirrors of the alignment and bonding station using the theodolite and ensure that the pencil beam projected from the CDA is properly aligned at its central position. This establishes the optical axis for the assembly and is rechecked throughout the alignment process as every CDA alignment scan is centered on this axis. We place the mirror and the mirror cell assembly onto the adjuster assembly. The mirror and the mirror cell assembly each sit on three micrometer adjusters that provide tip, tilt, and focus adjustment for the mirror and the mirror cell independently. Three additional micrometers provide lateral translation adjustment for each (see Figure 7).

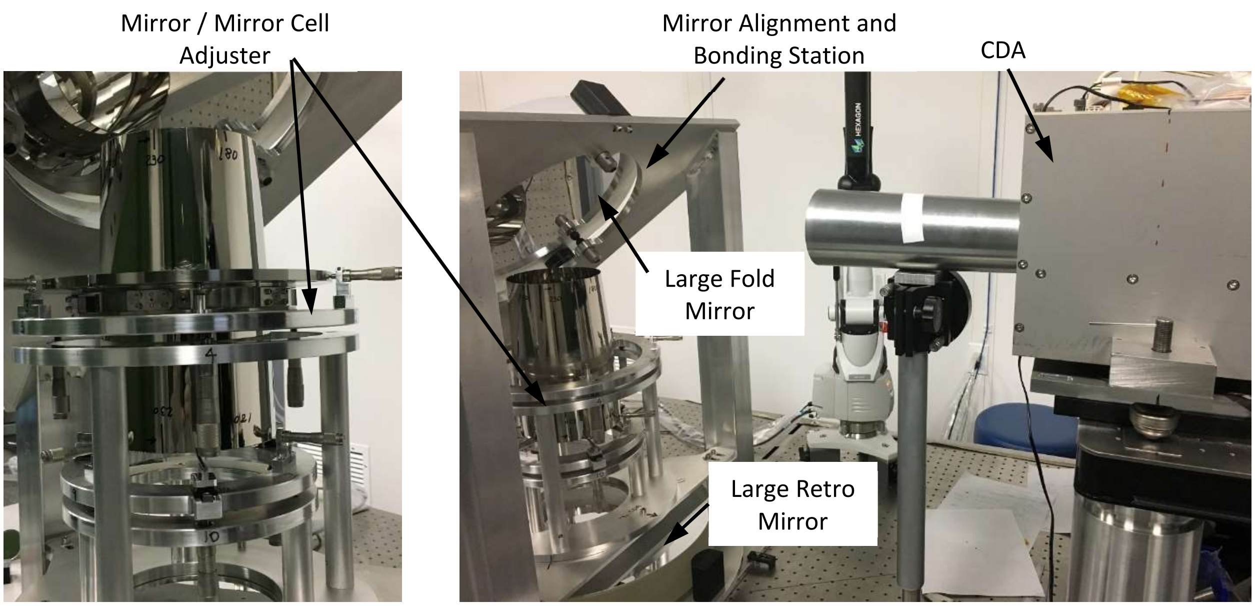

Figure 7: Aligning and Bonding the TMA

After aligning the mirror cell assembly with the theodolite by spying the embedded reference mirror and turning the micrometers until the mirror cell is aligned to the optical axis, we use the CDA to align the mirror to the same axis. This process is iterated until the mirror is properly aligned to the CDA and well centered in the mirror cell assembly. Once accomplished, we inject epoxy into the flexure assemblies and allow the epoxy to cure for 3 days. Small adjustments to the mirror position can be made immediately after making the first tack bond to the mirror without affecting the mirror's shape. CDA scans of the mirror assemblies, before injecting epoxy, immediately after, and after a full 3 day cure indicate very little change in mirror alignment or in the shape of the optic. Figure 8 shows a progression of aligned CDA scans for one of the spectrometer mirrors. The better definition seen in the shape of the last scan of the group is the result of changing the location of the CDA scan from the leading edge of the mirror to the center of the mirror. Note that the RMS diameter of the scan has actually decreased in the last scan (from 358 µm RMSD to 252 µm RMSD). The portion of the mirror that feeds the MaGIXS grating is the ~34°

section highlighted at the center of the final image. Each segment of the scan corresponds to 15° of the full mirror perimeter.

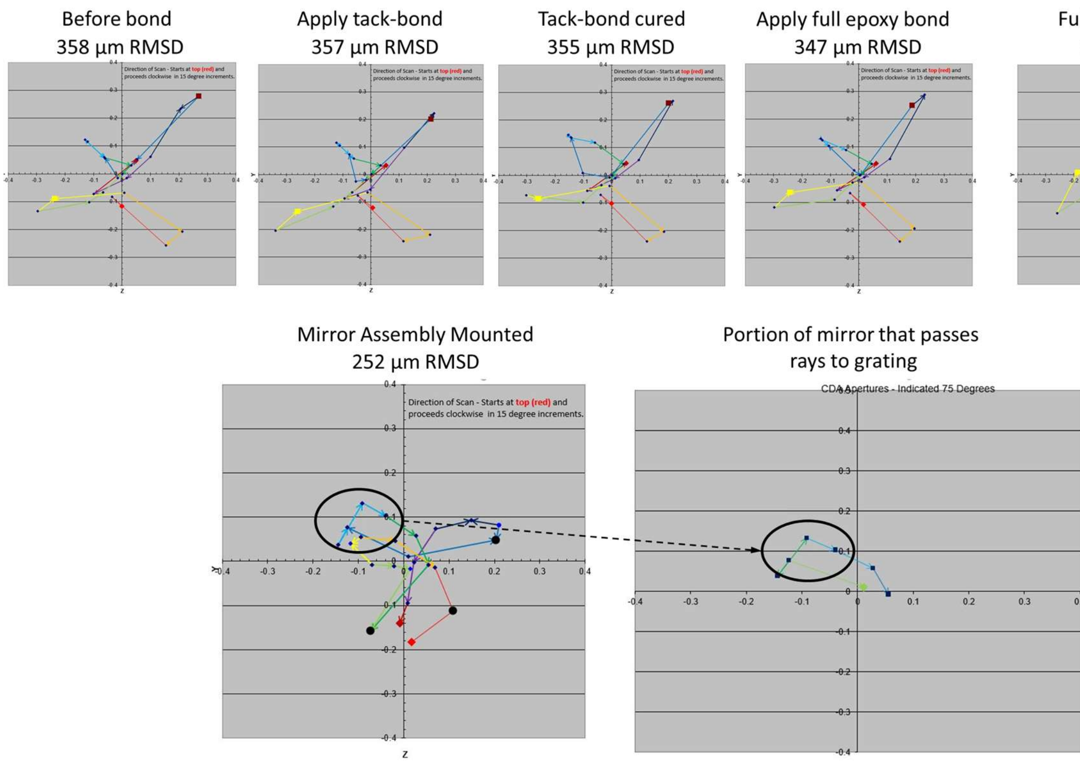

Figure 8: CDA Alignment Scans for Spectrometer Mirror Bonding (SM2)

We also use the CDA to determine the focal length of the mirror. We program the CDA with the intended focus distance and aperture scan diameter for a mirror and begin a series of scans (see Figure 9). By continuing to realign, change the physical distance between the CDA and the mirror, and alter the programmed focus distance, we arrive at a best image focus for the mirror. Please note that the scale for these images is different from that shown in Figure 8. Having data for the physical characteristics of the mirror (i.e. height, radius at the leading and trailing edges, and the design focal length) is needed in order to establish a starting point for our CDA measurements. We use a gantry-type coordinate measuring machine (CMM) with high accuracy (~3µm) to carefully survey the non-reflective surfaces of each mirror prior to beginning alignment.

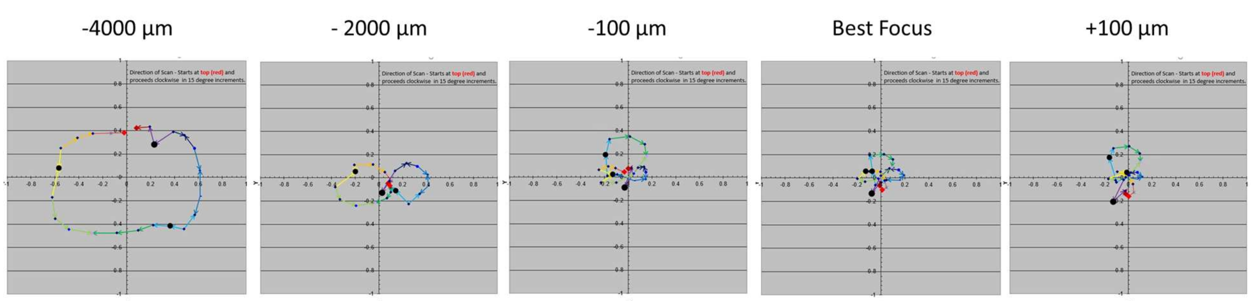

Figure 9: CDA Focus Scans for Spectrometer Mirror (SM1)

With the mirrors bonded into their cells and properly aligned using the CDA, we measure the difference in angle (pitch and yaw) between the reference mirror embedded in the mirror cell and the mirror optical axis using a theodolite. We then mount the crosshair reticle at the center of the mirror module and align it to the center beam of the CDA. The satellite camera (Mightex) aligned to the central CDA beam picks up an image of the reticle illuminated by the CDA laser (see figure 10) when the reticle is aligned. Once the bonding operations are complete, the aligned position for each mirror assembly is measured with respect to its onboard references (reference mirror and crosshair reticle) and known to better than the requirements of 25 μm decenter and 5 arcsec pitch and yaw.

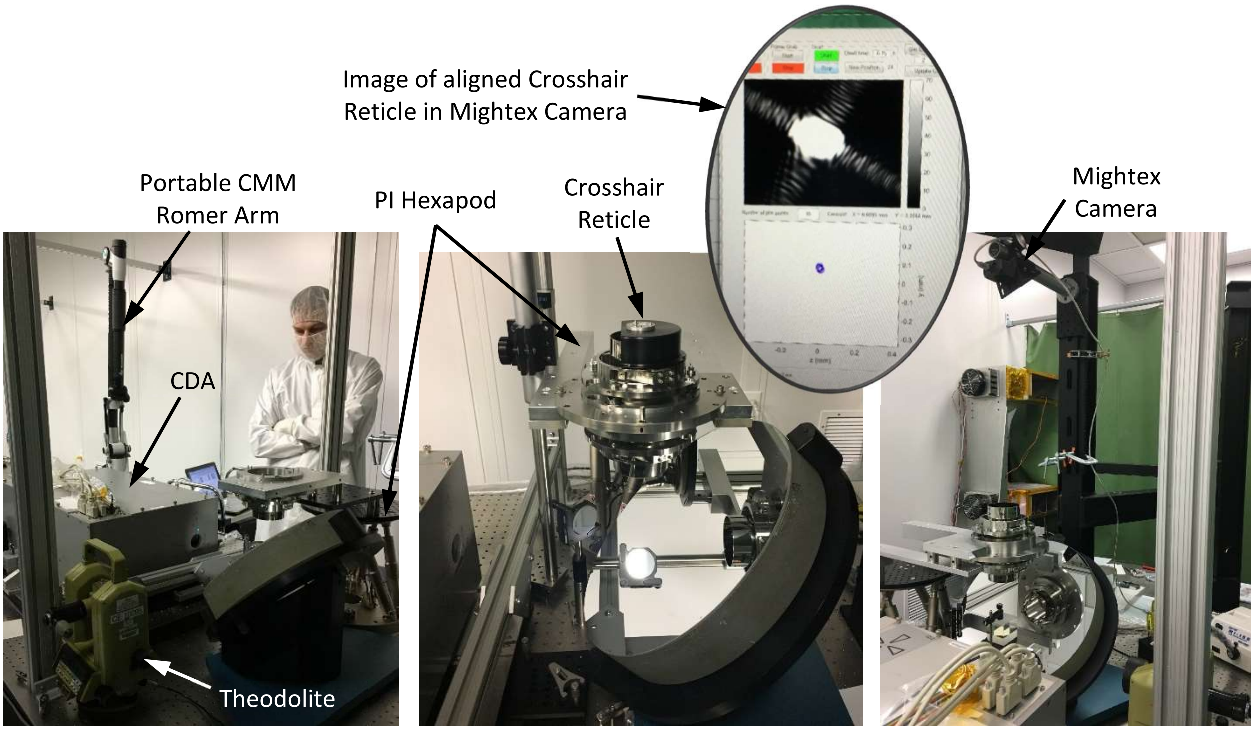

Figure 10: Aligning the SOA

SOA Mirror Alignment

The next step in SOA alignment is to align the first spectrometer mirror (SM1) and the second (SM2). By having the knowledge of the aligned position for each mirror, we calculate the correct thickness for our six shims (3 for each mirror) to provide a first alignment of the two mirrors to the optical axis and mounting surface of the SOA assembly. In order to achieve the required alignment for the two mirrors (5 arcseconds), we will perform multiple CDA scan iterations and repeated fine polishing of the shim thickness. We mount SM1 onto its kinematic mount on the common mounting plate and align it to the optical axis established by the CDA (Figure 10, left panel). We then mount SM2 onto the other side of the common plate and begin alignment (Figure 10, center and right panels). With each successive CDA scan, we remove and polish the required trim spacer until we have achieved the desired shift in angle and focus. Because we only use a small portion of the beam that passes through the SOA, we elected to optimize that portion of the beam as it falls on the telescope focus. This results in a longer recommended focal length for the SM2 mirror (+1.5 mm) than the best focus for the entire mirror. The focal length for the SM1 mirror remains unchanged. Figure 11 shows the CDA scans of the aligned SOA at the two different focal distances.

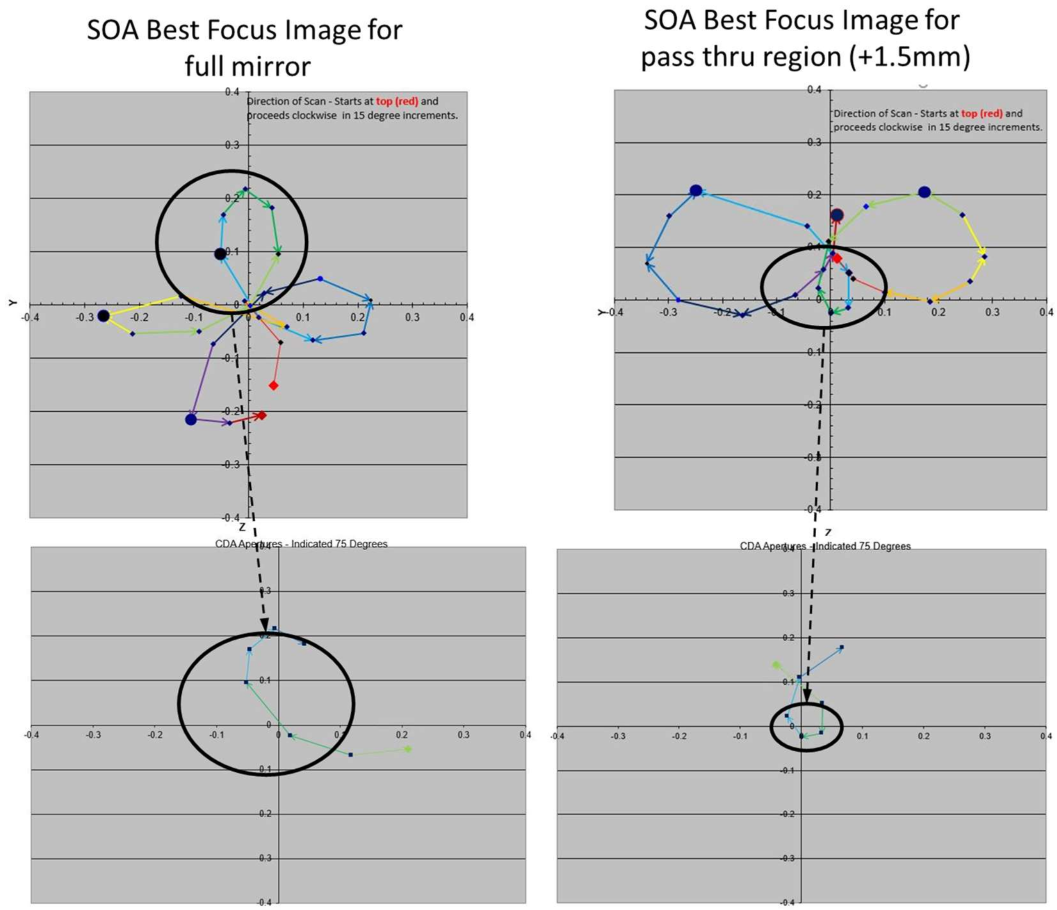

Figure 11: CDA Scans of the SOA

Grating Alignment

With the SOA mirror aligned and the grating already bonded to its mounting plate, we move on to mounting and aligning the grating housing assembly to the SOA common mounting plate. We will perform the fine alignment of the grating pitch/yaw and set the proper offset of the grating to the spectrometer mirror pair by polishing spacers on the grating kinematic mount and between the housing and SOA common plate

To align the grating, we use the CDA's UV laser to take advantage of the in-plane diffraction geometry of the grating where both a specularly reflected beam (grating zero order) and a back diffracted beam (grating 1st order) are produced. We use the zero order beam to align the grating in pitch and yaw while we use the back diffracted beam to perform the roll alignment [ref 7]. First, we perform a series of reference and calibration alignments in order to place satellite cameras in their proper locations. One camera will receive the back diffracted beam from the grating while the other will view the reflected beam (see Figure 12) of the grating. We use the theodolite along with the CMM Romer Arm to accurately place fold mirrors at the location and angles corresponding to the aligned grating (reflected and back diffracted) and verify the location of the satellite cameras by illuminating them with the CDA's UV laser. In this configuration, we can only use the CDA pencil beam that strikes the center of the 25 mm wide grating for our alignment. Later we will scan to either side of the 25 mm wide footprint to ensure that the grating is well centered.

We make sure that the SOA mirrors are aligned to the optical axis using the CDA and perform a CDA scan without the grating. We repeat the scan with the grating in place. The scan points that are not blocked by the grating substrate must be replicated exactly on the satellite camera with the grating mounted to be sure that the SOA has not moved (Figure 12, right panel). We use the theodolite to measure the angle of the grating with respect to the optical axis and polish the grating trim spacers in order to achieve both pitch and yaw alignment. We verify that the SOA has not moved by performing additional CDA scans with the grating in place and iterate our pitch yaw adjustments as necessary. The grating roll alignment camera is placed in the path of the 1st order diffracted beam so that roll alignment is demonstrated by the beam falling on the Y axis of the camera (Figure 12, right and center panels). We polish the appropriate shims between the grating housing and the SOA common mounting plate until all alignment conditions are met. Once this is achieved, we use the CDA to scan to either edge of the 25mm wide grating and ensure that the grating footprint is centered properly. Following completion of all adjustments, we made final measurements to the SOA with the grating assembly to verify that all alignment tolerances were met and that the SOA mirror alignment had not moved. The images in Figure 12 are from these final verifications prior to SOA shipment to MSFC.

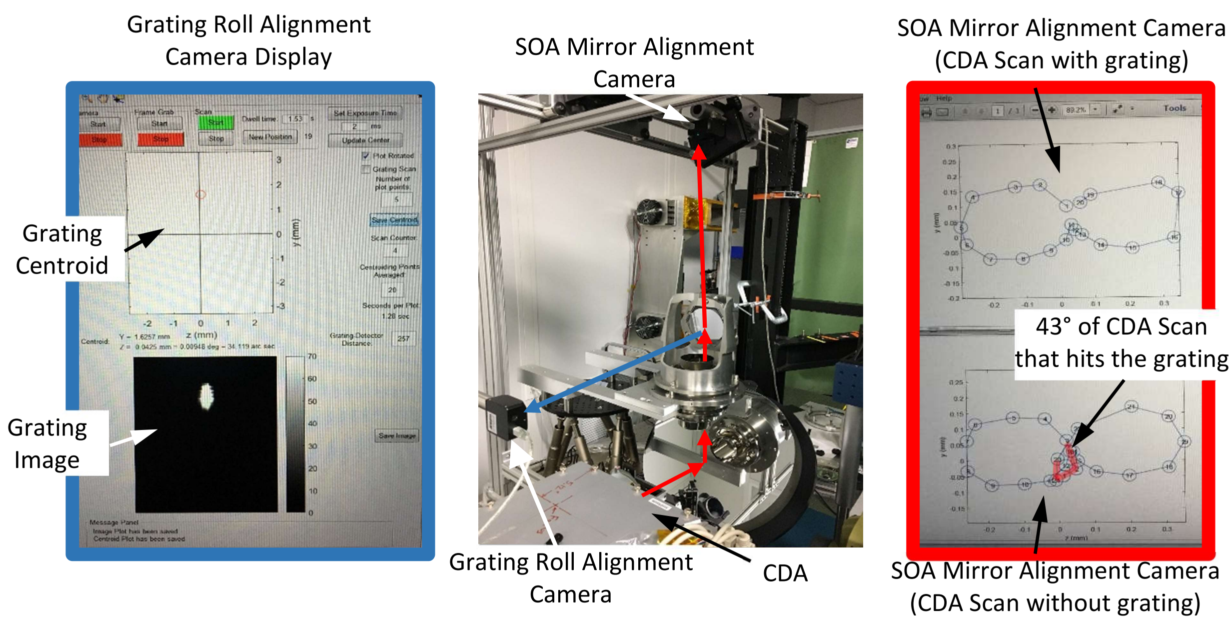

Figure 12: Aligning the Grating

6. CONCLUSIONS

The MaGIXS mirror modules and grating assembly were successfully aligned to the specified tolerances using a refurbished Centroid Detector Assembly at SAO. We were also able to demonstrate new alignment techniques for full shell grazing incidence optics that may be used for other missions currently planned or under development. The measured values shown in Table 1 demonstrate that we can achieve the very tight alignment tolerances demanded by the MaGIXS optical assembly. As of this writing, the MaGIXS instrument has been fully integrated, aligned, and tested at MSFC and awaits a successful launch in 2021.

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