Fabrication of the NuSTAR Flight Optics

William W. Craig[c*], HongJun An[a], Kenneth L. Blaedel[a], Finn E. Christensen[b], Todd A. Decker[a], Anne Fabricant[a], Jeff Gum[d], Charles J. Hailey[a], Layton Hale[a], Carsten B. Jensen[b], Jason E. Koglin[a], Kaya Mori[a], Melanie Nynka[a], Michael J. Pivovaroff[c], Marton V Sharpe[d], Marcela Stern[a], Gordon Tajiri[a], William W. Zhang[d]

[a]Columbia University Astrophysics Laboratory, New York, NY
[b]Danish Technical University, Copenhagen, Denmark
[c]Lawrence Livermore National Laboratory, Livermore, CA
[d] NASA Goddard Space Flight Center, Greenbelt, MD

ABSTRACT

We describe the fabrication of the two NuSTAR flight optics modules. The NuSTAR optics modules are glass-graphite-epoxy composite structures to be employed for the first time in space-based X-ray optics by NuSTAR, a NASA Small Explorer schedule for launch in February 2012. We discuss the optics manufacturing process, the qualification and environmental testing performed, and briefly discuss the results of X-ray performance testing of the two modules. The integration and alignment of the completed flight optics modules into the NuSTAR instrument is described as are the optics module thermal shields.

Keywords: Hard X-ray telescope, X-ray optics, thermally-slumped glass, NuSTAR

1. OVERVIEW OF THE OPTICS MODULES

The Nuclear Spectroscopy Telescope Array (NuSTAR) is a NASA Small Explorer (SMEX) satellite mission scheduled for launch in February 2012. The NuSTAR experiment contains two telescopes each consisting of an optic and a CdZnTe focal plane detector separated from each other by a 10-meter deployable mast (figure 1). The experiment is an extension and improvement on the design successfully employed in the HEFT balloon experiment (Harrison et al. 2005[1]). NuSTAR will operate in the 6-79 keV energy band. More details on the mission, the overall instrument design and performance requirements and scientific objectives can be found in Harrison et al. 2010[2].

A blowup of an individual optics module is also shown in figure 1. Each layer of the optic has an upper and lower conic shell (equivalent to the parabola-hyperbola sections of a Wolter-I optic). Each shell is composed of multiple thermally formed glass segments. Each piece of glass is coated with a depth-graded multilayer. The enhanced reflectivity provided by the multilayers, along with the shallow graze angles afforded by the focal length of the optics (10.15 meter) provide high effective area over the NuSTAR energy band of 6-79 keV, and a field of view of 12 arcminutes by 12 arcminutes. There are 133 concentric layers which together form each optic. The glass layers (a glass-epoxy-graphite composite structure) are built up on a Titanium mandrel. Titanium support spiders located on the top and bottom of each optic connect it to the optical bench. The compliant, radially-symmetric spiders accommodate thermal expansion effects as well as dynamic loading. Thin x-ray transparent thermal covers on the entrance and exit apertures of the optic reduce thermal gradients by blocking direct view of the sun and deep space. Two flight modules, FM1 and FM2, were fabricated. A third module, FM0, was fabricated earlier and has Pt/SiC multilayers on the inner 89 layers. FM0 is a potential flight spare and is available to provide for more extensive X-ray characterization than is permitted for either of the flight modules, given the compressed delivery schedule of the optics.

* Correspondence: craig1@llnl.gov

Optics for EUV, X-Ray, and Gamma-Ray Astronomy V, edited by Stephen L. O'Dell, Giovanni Pareschi,
Proc. of SPIE Vol. 8147, 81470H · © 2011 SPIE · CCC code: 0277-786X/11/$18 · doi: 10.1117/12.895278

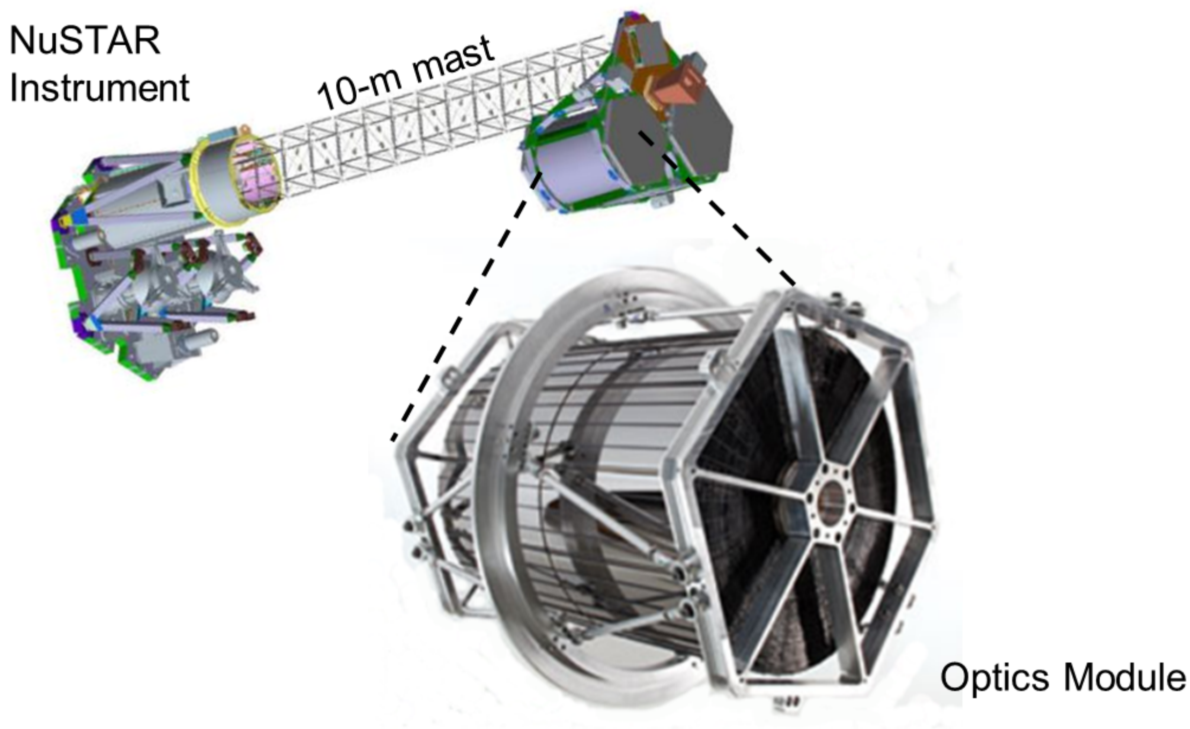

Figure 1: The NuSTAR instrument showing the two telescopes separated by a 10-meter deployable mast. To the lower right is a photograph of an optics module in a handling fixture

2. MANUFACTURE OF THE NUSTAR FLIGHT MODULES

2.1 Optics Design

Table 2: Telescope parameters

Focal Length	10.15 m
Layer Radii	51-191 mm
Graze Angles	1.3-4.7 mrad
Mirror thickness	0.21 mm
Layers per module	133
Mirror segments per module	2376
Multilayer(Layer 1-89)	Pt/C
Multilayer(Layer 90-133)	W/Si
Composite structure	D263 glass; DS-4 graphite; F131 epoxy
Mandrel and Spider	Titanium
Mass per module	37 kg

Table 1 The design parameters for each NuSTAR flight optics modules.

As shown in Figure 2, the NuSTAR optics modules consist of two zones. These zones, are made up of either sextants (with 60-degree azimuthal segments) or 'twelvetants' (with 30-degree azimuthal segments) and were chosen to constrain the maximum azimuthal span of glass during slumping and coating, The optics were built up layer by layer on a tapered Ti mandrel, and with radial position continually referenced to the axis of rotation of the mandrel.. This allowed each mirror segment to be placed precisely at the correct radial position, thus preventing one key source of systematic error in assembly. Graphite spacers were precision ground in place, which provided the proper spacing between glass layers as well as the setting the desired incidence angle. There are 5 spacers for each azimuthal segment. Two of the three are on the edges creating a double spacer pattern that can be clearly observed in Figure 2.

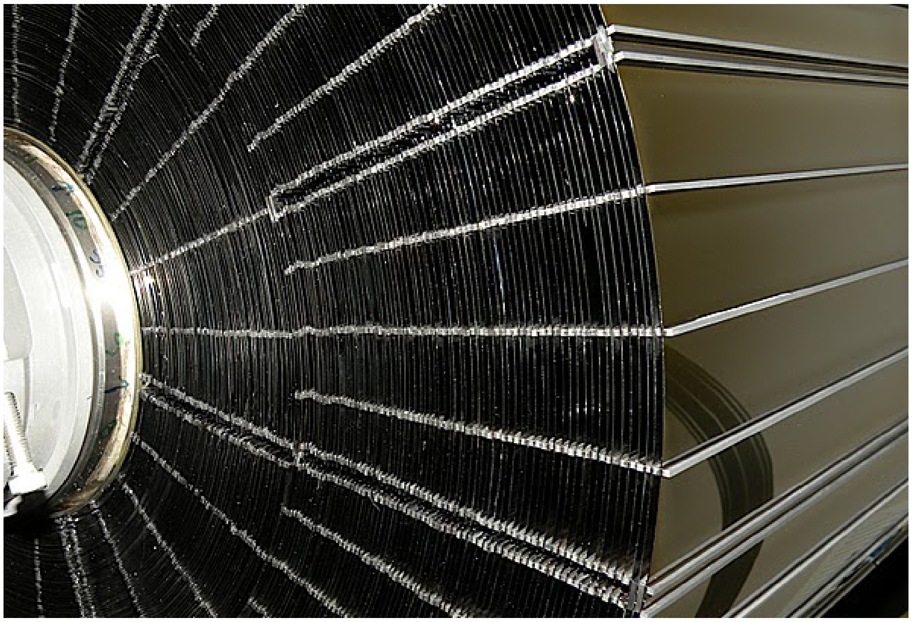

Figure 2: An end view of a NuSTAR optics module showing the 60-degree azimuthal segments (sextants) at the inner radii (the inner 68 layers), and the 30-degree azimuthal segments ('twelvetants') at the outer radii (the outer 65 layers).

2.2 Glass for FM1 and FM2

The glass for the optics modules is Schott D263, with a thickness of 0.2mm. The glass underwent a series of processing steps at the Goddard Space Flight Center to prepare it for use on NuSTAR FM1 and FM2. First the as-received glass sheets from Schott were cleaned by mechanical means followed by an ultrasonic immersion in pH neutral water. The sheets are then cut into flat rectangular pieces in preparation for the thermal forming operation.

Figure 3: The GSFC thermal forming facility. A set of large fused silica mandrels is shown on the rack in front of one of the eight furnaces. The technician is removing a formed glass segment from the mandrel.

The thermal forming process took place in 8 custom built furnaces on 132 fused silica forming mandrels, ground into precise cylinders by Rodriguez Precision and then coated with a BN release layer, which was post-processed to maximize the smoothness of the formed glass. The glass forming was performed in 3 production groups, each covering a particular radial range of the NuSTAR design. For each of the production groups, the furnaces were loaded with mandrels of similar radii during the day and the glass forming cycle took place overnight.

After forming, the cylindrical glass pieces were cut to the final "trapezoidal" shape required by NuSTAR (the glass pieces are cylindrical and are forced into a conical shape by the mounting hardware). A hot wire technique (Zhang 2009) was used to provide high quality cut edges, minimizing the chances of a crack initiating at the edges.

A subset of the glass was measured in an interferometer (Zhang 2009) specifically looking for deviations from cylindrical at ~ few to 10 mm length scale that is characteristic of dust or BN particles on the forming mandrels.

2.3 Coatings for FM1 and FM2

The formed and cut glass was then shipped to the Danish Technical University (DTU) where multilayer coatings were applied (see Christensen et al 2011, these proceedings). For FM1 and FM2, Pt/C multilayers were used through layer 89 (of 133). The 43 outer shells were coated with W/Si multilayers. An extensive glass cleaning program was developed to remove residue from the thermal forming process in preparation for multilayer coating. X-ray measurements at 8keV were performed on witness samples from each run. A complementary set of measurements at higher energy are in progress at the Columbia calibration facility (Brejnholt et al. 2011, these proceedings).

2.4 Assembly

Assembly of the optics modules took place at Columbia University. The coated glass segments were received from DTU and visually inspected. Accepted glass pieces were then measured with a scanning laser reflectometer (Koglin et al. 2005) to determine both short and long length scale figure. These data, biased particularly for the short length scale figure which cannot be removed during mounting, were used to select the pieces to be mounted on the flight optics.

The final inspection and selection, which was performed by the assembly technicians just before mounting, was a dry fit onto the flight optics to select those pieces with the lowest skew, i.e. the best alignment between the as-formed and as-cut axes of the glass segments.

Once the dry fitting of the glass segments for the layer was complete, the segments selected, and the travelers updated, the assembly operation could begin.

The assembly flow for the optics is described in detail below:

- Dry re-fit: The previously selected glass segments were again fit onto the machined spacers and, once adjusted by the technician to the proper position, attached to a surrogate for the central load bar (see below) using double-sided adhesive and set aside.
- Graphite spacers: The 1.2mm x 1.2mm x 225mm graphite spacers were manufactured by SST International (Downey, California) of Carbone DS4 material. The appropriate number of graphite spacers for the day's assembly was cleaned using an isopropyl wipe and inspected for visual defects then installed in load bars (see below) and staged for assembly.
- Epoxy: The epoxy used for all but the first layer of the optic was Tra-Bond F131 manufactured by Henkel (Billerica, MA) and packaged in 2.5 gram bipax. The bipax were inspected and then mixed and mechanically agitated and degassed prior to application. The mixed epoxy was loaded into application syringes and air pressure employed to dispense the epoxy. The syringe weight was measured before and after dispensing to allow a precise calculation of the average linear density of applied epoxy. By controlling the linear density precisely we ensured that the entire bonding area of the spacer was fully wetted while minimizing the filets that result when the epoxy is squeezed out during the subsequent assembly steps. A witness sample was also dispensed for each epoxy mix (~1000 individual mixes for each optics module).

Figure 4: Two glass segments are attached to a strongback and are positioned in place. Previously placed load bars are visible to the left of the picture.

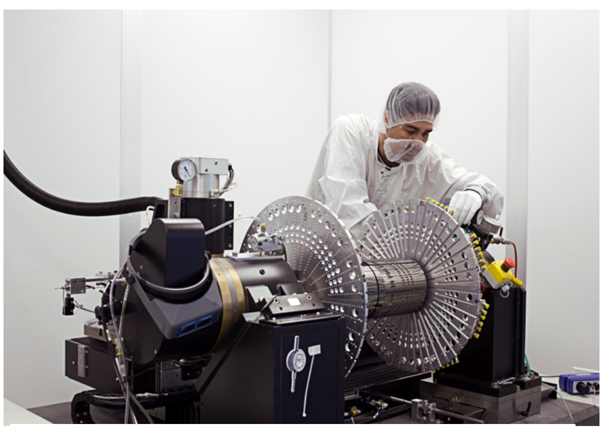

Figure 5: The guide wheels on an assembly machine early in the build of FM1. The slots provide azimuthal clocking to keep the strongbacks aligned with the machined spacers.

- Glass fitting: After the epoxy had been applied to the underlying graphite spacers, the load bars, with the glass segments attached (Figure 4), were installed into the guide wheels by the assembly technicians.
- Load bars: Air pressure-loaded strongback, outfitted with ‘shoes’ which allow for one degree of rotational freedom, were used to ensure that the glass conforms to the underlying spacers and that the appropriate pressure is applied to the epoxy to control its thickness. The strongbacks (each with an, epoxy-wetted graphite spacer in the shoe) were positioned via guide wheels on either end of the optic module under construction as shown in Figure 5. The guide wheels were precisely aligned in azimuth to allow the strongback to compress the glass only directly over a spacer as any load applied to the glass without support underneath acts to distort the glass and impact final figure of the mounted glass piece. (Note that at this point, there is uncured epoxy between the glass and both sets of inboard and outboard graphite spacers.) After load bars were added to apply pressure to the strongbacks, the epoxy was allowed to cure overnight (minimum 8 hours) before the assembly process continued.
- Machining: After the epoxy cured for at least 8 hours, the load bars and strongbacks were removed and preparations for machining of the outboard graphite spacers were begun. Each optics module was mounted in its own assembly machine. Each assembly machine, manufactured by ABTech (Swanzey, NH), is a 3 axis lathe that allows the abrasive wheel used to grind the spacers to the correct figure and smoothness to be positioned to within 1 μm along the entire length of the optic and throughout the radial range. The surface of the grinding wheel is located with respect to the lathe’s axis of rotation at the beginning of each layer. The machined spacers are thereby referenced to the optical axis of the optics module and systematic stack up error in radial position is eliminated.

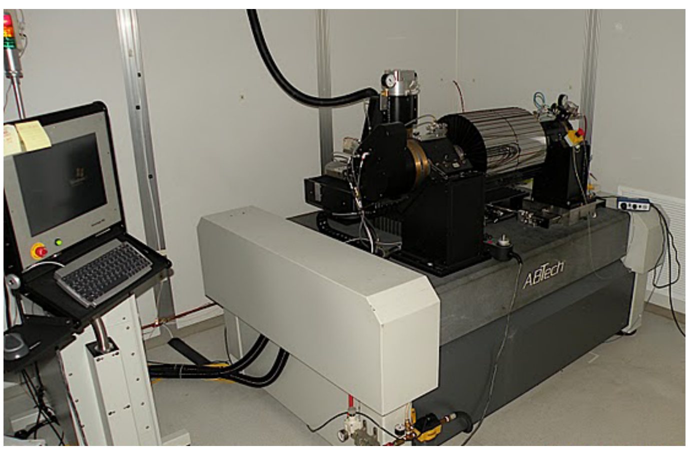

Figure 6: The optics assembly machine is a numerically controlled 3-axis lathe. The spindles are supported by air bearings and the grinding wheel moves in 2 axes to allow the spacers to be machined to the proper figure. The black hose at the upper portion of the figure is a vacuum hose that removes the graphite dust created during machining.

- Metrology: After machining, the figures of both the spacers and the back-side of the glass are measured using a ruby-tipped linear variable differential transformer (LVDT) manufactured by Lion Precision (St. Paul, MN) and Colorado Precision Products (Boulder, CO). This approach exploits the low thickness variation of the glass to predict the eventual x-ray performance of the optic module (see Section 2.5).

This assembly process is the same for nearly all of the 133 layers in the flight modules. There are, however, a few special cases which are detailed below:

- First layer: The spacers are attached to the Ti inner mandrel using Henkel Hysol EA 9394 structural adhesive. These bonds, the most highly stressed in the entire optic, benefit from the intrinsically higher strength of a 9394 bond on a Ti surface prepped with Cytec BR127 primer.

- First 5 layers: As analysis indicated that the first few layers of the optic experienced the highest loading during launch, the width of the first five layers of spacers was increased from the nominal 1.2mm to 1.6mm to provide more bonding area (Figure 7).

Figure 7: A close up view of the first 25 layers of FM2 showing the wider spacers on the first five inner layers and also providing a view of the typical width of the epoxy filet at the outer radius. For scale, the outer spacer is 1.2mm in width.

- Intermediate circumferential structural zone: The transition from 30 degree to 60 degree azimuthal glass segments requires special spacers for two layers of spacers. These wide spacers allow two pieces of glass to be supported on single spacers, tying the optic together azimuthally, albeit with a degradation in mounted figure.
- Outer circumferential structural zone: The outer two layers are also tied together azimuthally by wide spacers similar to those used in the intermediate circumferential structural zone.

Quality assurance was a significant focus during the assembly of the optics modules. Daily inspections of parameters across all of the manufacturing organizations were performed and trended throughout the build. Parameters included glass cut quality, cleanliness and chemical state (pH) of solvents used in glass cleaning, spacer machining, epoxy mix and witness samples, as-applied epoxy linear density and cured bond lines. A cross-institutional QA team met weekly to review the data and make corrections as required throughout the flight optic build.

Work schedule was driven by overall program schedule. GSFC formed glass at up to 6 days per week. DTU coated glass at an ever increasing rate, eventually operating their chamber continuously with up to 11 coating runs completed per week with rotating shifts of technicians and operators. Assembly technicians at Columbia worked 6 days per week throughout the optics build, averaging 11 assembled layers per week between the two flight optics.

2.5 Performance

As described in Section 2.4 a number of measurements are collected during the build. The individual glass segments are selectively sampled via interferometry and fully sampled with a laser reflectometer that measures the instantaneous slope of the unmounted glass segments. The LVDT scans described earlier and shown in Figure 8, were calculated daily for each layer and were used throughout the build to track performance and make corrections to process and/or hardware as appropriate. The area weighted half power diameter (HPD) projection from the LVDT data is 50” for FM1 and 49” for FM2. The NuSTAR top level requirement for HPD is 58”.

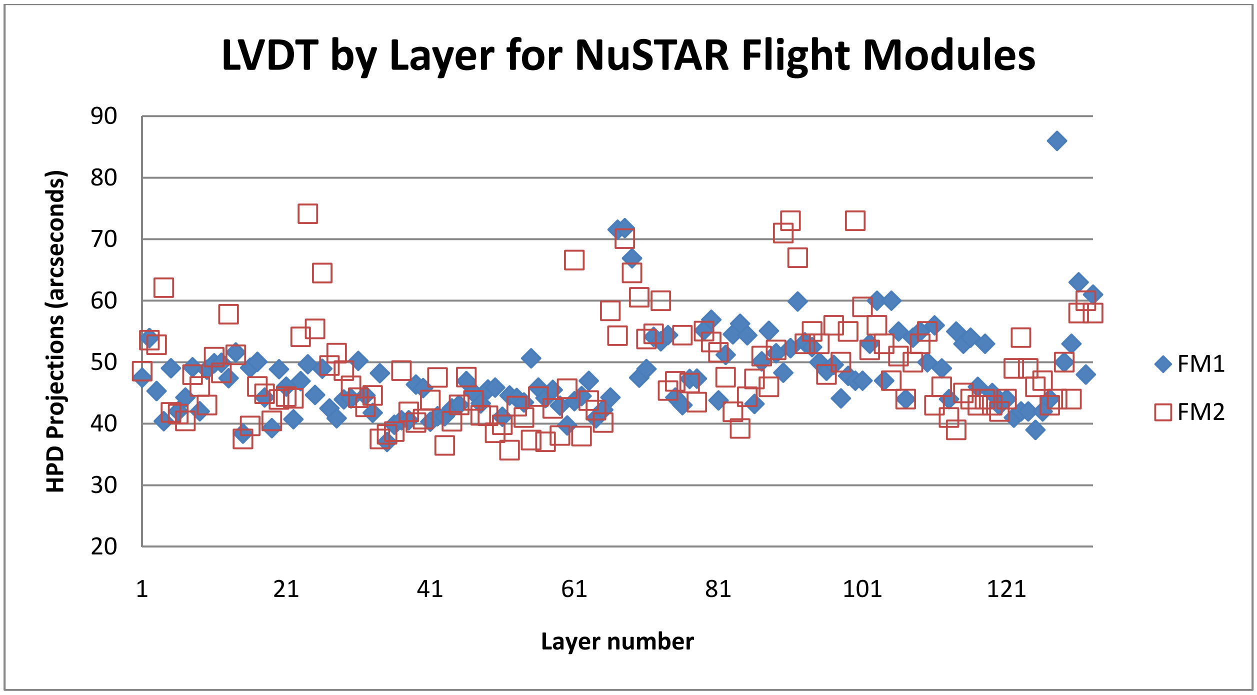

Figure 8: Performance projections from LVDT scans of the two NuSTAR flight optics modules. The increase in HPD of both modules at the circumferential structural zones is evident (layers 66-68 and 131-133).

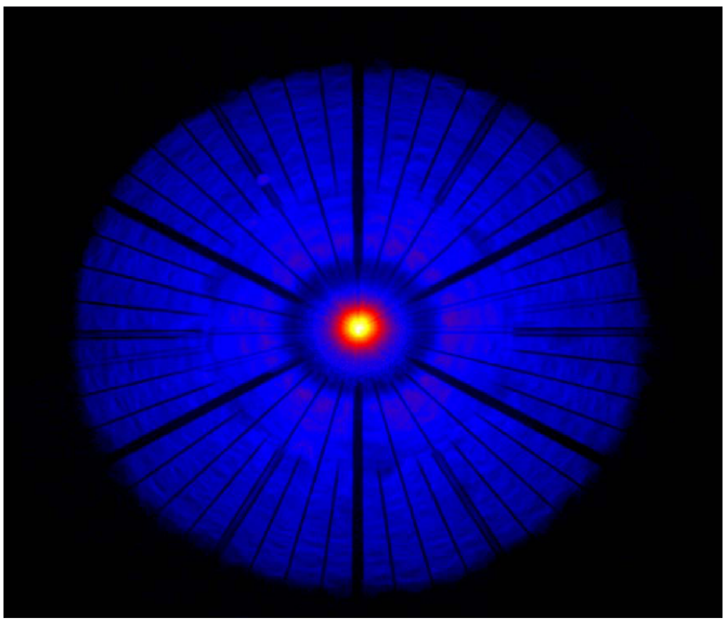

Figure 9: A composite image of a full aperture flood illumination of FM2 showing the central spot and the shadowing from the support spider and the graphite spacers. See Vogel et al 2011 for a complete description

Upon completion of assembly the optic modules were installed in the Columbia calibration facility (Brejnholt et al.2011) and illuminated by a beam whose energy spanned the NuSTAR pass band. One dimensional scans were performed using high resolution Ge and Si detectors and two dimensional imaging scans were performed with an imaging device (Vogel et al. 2011). The detailed X-ray performance of the two flight optics is described in detail in Koglin et al. 2011 (these proceedings) and analysis is ongoing; here we briefly summarize the results. The X-ray generated HPD at energies above 12 keV for both of the two flight modules is 52" with systematic errors estimated at 4". The effective area of both modules is still being analyzed but first results indicate that the area meets NuSTAR requirements. Effective area and HPD below 12 keV has not yet been analyzed due to complications imposed by facility systematics, although no significant deviations in these results are expected.

3. QUALIFICATION TESTING

Because the NuSTAR mission schedule precluded the development of a full qualification model in advance of a flight build, the qualification program for the optics modules was quite dependent on developing and testing representative models of the NuSTAR structural components. This required the development of a large finite element model (effort led by P. Rapacz at JPL), which in turn guided the selection of representative witness coupons that were used to test the NuSTAR manufacturing processes.

The key concern was the strength of the compound bonds, particularly in the inner part of the optic. As NuSTAR will launch on a Pegasus launch vehicle, the loads on those bonds are both transverse and axial and required a detailed technical performance trade as the number of bonding points (spacers) and the width of the bonding area (which blocks x-ray transmission) was optimized with respect to overall throughput. This optimization resulted in 1.6mm width spacers for the first 5 layers of the optic, where launch stresses were calculated to be higher, and 1.2 mm spacers throughout the bulk of the optic (with the exception of the circumferential structural zones (layers 66-68 and 131-133).

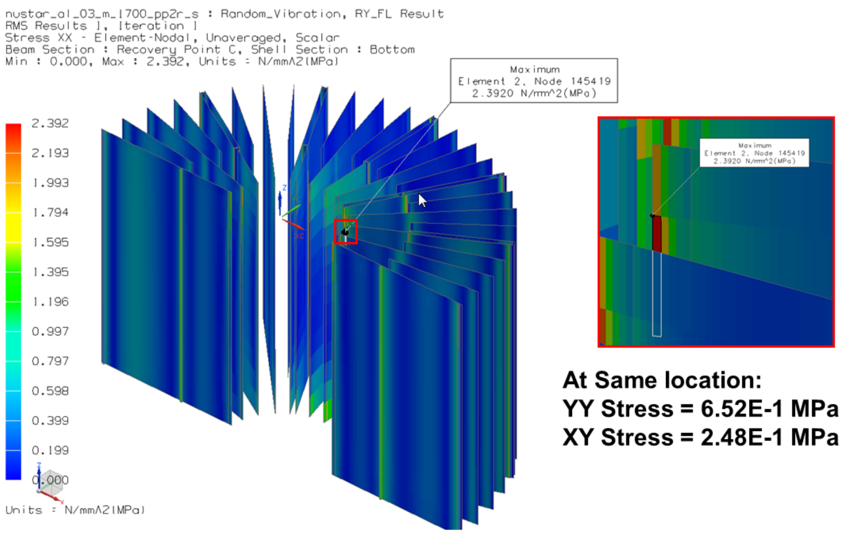

Figure 10: A view of the finite element model results showing the peak stress areas on the optic. The inner few shells see the highest load during launch; the circumferential structural zones (layers 66-68 and 131-133) also experience higher loads than the bulk of the optic, although they still experience a factor of 2 lower than the innermost layers.

3.1 Strength

A detailed finite element model of the NuSTAR optics modules showed that the composite structure would be subject to both shear and peel stresses during launch and also during required dynamical testing prior to launch. After considering several approaches, a coupon was developed that tested all of the key bonds in the optic. Both the optics module and the coupon were similarly analyzed to ensure that failure stresses that were calculated (from the failure loads) for the coupon

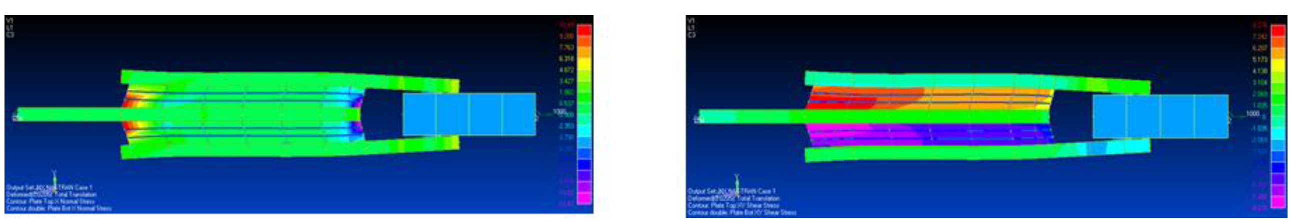

Figure 11: A finite element model representing the qualification coupons showing both peel and shear stresses. The dimensions of the coupons were set to provide the appropriate peel to shear ratio.

could be used as the failure stresses for the optics module. The coupon employed a central Ti bar with spacers attached to both sides (the spacers were affixed with Hysol EA 9394 adhesive as in the flight optic) and then two layers of

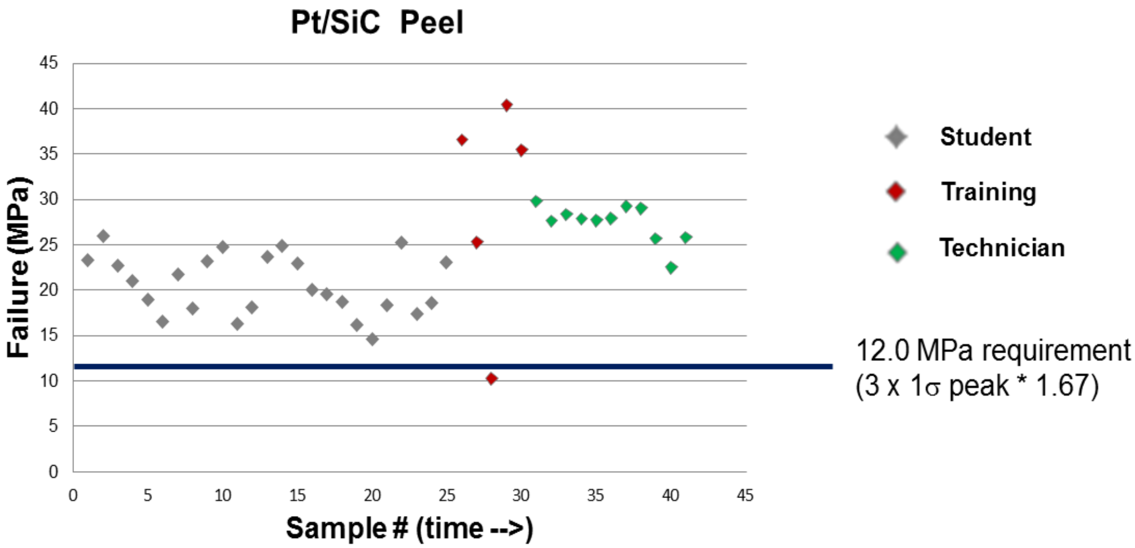

Figure 12: Results from a series of coupon tests showing the margins above the strength floor required by JPL. The trend in the data represents the refinement of the process with a set of common materials.

multilayer coated glass, graphite and F131 epoxy were built up on each side to simulate the inner two layers of the optics modules. Another Ti bar was added on both sides to allow the application of force and the entire unit was allowed the cure for 100 hours and was then pull tested to failure. Inspection of the specimen after testing revealed the mode and initiation site of the failure. Because all of the components of the key bonds were tested in an ensemble, this coupon testing provided a simultaneous qualification of the materials (e.g. glass, graphite, multilayers and processes used in the modules. Over 400 of these coupons were constructed and tested during the FM1 and FM2 preparations and build. The primary mode of failure was the failure of the F131 epoxy and graphite bond. Bulk graphite failure had a significantly lower probability of being the failure mode. Multilayer adhesion was not a significant failure mode, nor was the glass or the Hysol EA 9394 epoxy itself.

As described in Hailey et al 2010, additional process validation models (PVMs) were also constructed. These models were built to validate the bond strength calculations and qualification and faithfully replicated both the bonds and loading on the inner layers of the flight optics. Both PVMs were vibrated to NuSTAR qualification loads with no issues.

4. ENVIRONMENTAL TESTING

4.1 Overview of program

As noted previously, the NuSTAR program schedule was extremely challenging and was a key driver in the planning of the environmental testing program. Each flight optic, and the qualification unit (FM0) underwent thermal vacuum and vibration testing, but only FM0, was tested in the X-ray before and after environmental testing.

4.2 FM0 qualification testing

FM0 assembly was completed in August of 2010. The module was installed in the Columbia calibration facility and the point spread function measured throughout the NuSTAR band. The module was then transported to National Technical Services (NTS) and installed in a stiff fixture which allowed the primary optics modes to be exercised. Three-axis force-limited vibration testing to NuSTAR qualification levels was successfully performed December 14th and 15th 2010. The module was then transported to the UC Berkeley Space Sciences Laboratory and thermal vacuum (TVAC) testing was begun. A long ~150 hour soak at 35C was followed by hot and cold survival and operational temperature cycles at NuSTAR qualification levels. At the completion of TVAC the optic was transported to Columbia where a subset of the earlier X-ray testing was completed. As expected, particularly given the relatively benign environments, no change in X-ray response was noted.

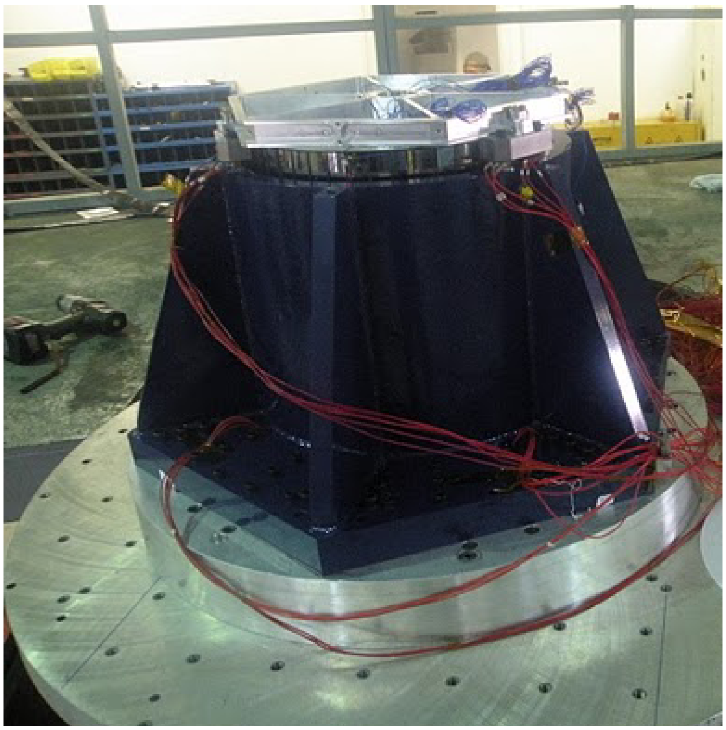

Figure 13: FM0 in its vibration fixture on a shake table at NTS. The glass and spacers are visible just under the spider at the top of the fixture. Force gauges between the spider and fixture allow force-limited test sequence.

4.3 FM1 and FM2 program

After the completion of assembly for FM1 and FM2 in February and March 2011, they were tested in the X-ray (see Koglin et al 2011) and then individually transported to UC Berkeley Space Science Laboratory where they underwent TVAC testing similar to that described earlier for FM0. The modules were then transported to National Technical Systems (NTS) Los Angeles where they were vibration tested using the same fixturing as for FM0 but at the somewhat lower levels appropriate for flight acceptance. All testing was completed successfully and both modules were delivered to JPL for installation on March 31, 2011.

5. INTEGRATION AND ALIGNMENT

5.1 Overview

The optical axis of the modules, i.e. the axis that produces maximum X-ray throughput, was established mechanically by the assembly manufacturing tooling and process described in Section 2. At the end of assembly a precision alignment cube was bonded to each end of the optic, positioned against a diamond turned surface. The cube was attached using Hysol EA 9394 and remained on the optic throughout the rest of I&T (and in flight). During X-ray testing at Columbia, the axis of maximum throughput was determined by scanning the optic in pitch and yaw around the mechanical axis. Once the correct position was found, the orientation (in pitch and yaw) of the top face of the cube, as determined by an autocollimator (see Brejnholt et al 2011) was recorded. A later operation used two autocollimating theodolites to measure the angle of the top cube with respect to the lower one to provide redundancy if a cube were to be lost or damaged during handling or environmental testing.

When the optics are installed and aligned, the objective is to orient the optics such that the optical axis, as set by the cube offset angle, is aligned to the normal of the NuSTAR optical bench.

5.2 FM1 and FM2 alignment

The optics modules were setup in a mount that had previously been adjusted to reflect the dimensions of the as-built optical bench. The optical bench was then hoisted and lowered over the two optics modules with contact between the optic modules and the bench prevented by Delrin guide disks affixed to the top (entrance) side of the modules. After the bench has been lowered and attached to the lower spiders, a laser tracker is used to measure the angle of the alignment

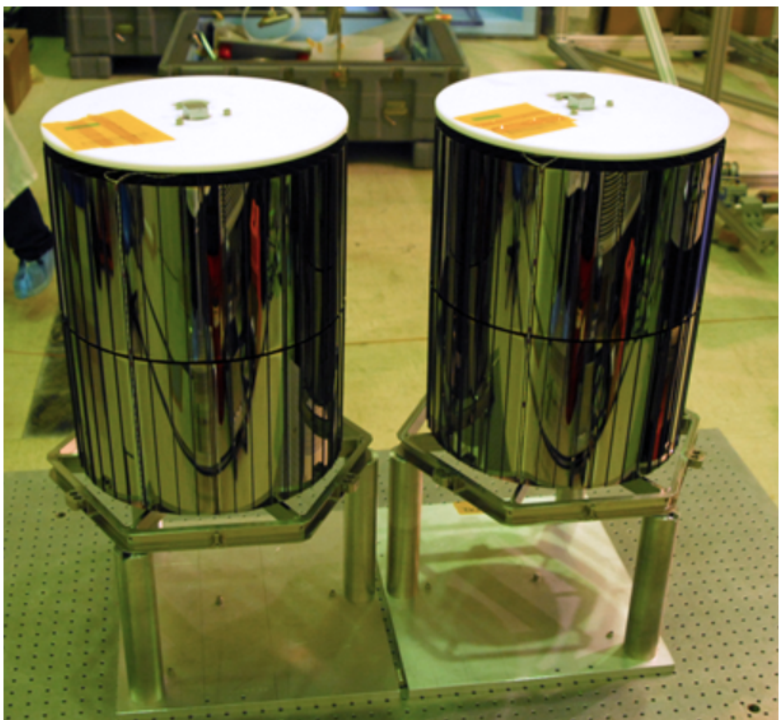

Figure 14: FM1 and FM2 modules on their kinematic mount before installation of the optical bench. The Delrin guide disks and alignment cubes can be seen on the top of each module.

cube on each module with respect to the fiducial plane defined by monuments on the optical bench. Set screws are used to make fine adjustments to the lateral position of the upper spider. Measurements are repeated and the process iterated until the upper spiders are torqued to the optics bench and the optics modules are aligned to within ~10" of their nominal position as determined during X-ray calibration.

Figure 15: The optics bench lowered on to the optics modules. The optics are surrounded by a composite shell which contains the thermal control hardware for the modules.

6. OPTICS THERMAL COVERS

6.1 Overview

The NuSTAR optics modules have angular resolution driven requirements that mandate a maximum gradient of 10C axially and 5C radially under all on-orbit operating conditions (the survival temperature range is higher. Nominal median operating temperature for the optics is 18C with an acceptable range of +10C to +25C (check). To maintain these thermal conditions the optics modules are mounted within a thin-walled carbon composite cylinder that is fitted with heaters (both operational and survival) and thermal sensors and switches. Each optics module is also instrumented with 6 thermistors located at the outer, middle and inner shells on both the entrance and exit end of the module. The bench is, in turn, blanketed with multilayer insulation.

Two other factors are important in driving the overall thermal design. 1) NuSTAR must be able to point directly at the Sun and 2) The configuration of the Observatory places the two optics module entrance aperture in the ram direction during launch with no protective covers. These factors drive a design which has both the high reflectivity to reject solar load as well as high emissivity to survive the free molecular heating experienced during launch.

To meet both operating range and gradient requirements, the entrance and exit apertures of the optics modules must be covered with a material that provides acceptable thermal and physical properties while maintaining transparency throughout the NuSTAR band. The design that was adopted for NuSTAR is a novel implementation of spin cast polyimide developed by NeXolve Corporation with thermal properties set by coatings developed and applied by Surface Optics Corporation.

6.2 Design and Fabrication

The thermal covers for NuSTAR are based on a carrier film of spin cast polyimide of nominal thickness 7 microns. A rip stop layer, which is fused with the carrier film, is also manufactured of polyimide of the same thickness. A gridded rip stop, which maps onto the spider obscuration where possible, is created by cutting open patterns into a cured film. The two layers are film and then fused together creating a composite film carrier. The film is lightly stretched over an aluminum frame and bonded in place with NuSil CV-2289. The mounted carrier films are then mounted in a large coating chamber at Surface Optics. The front surface of the cover, which points toward space, is coated with 0.08μm of

Al then 1.2 μm of SiO_X. The back surface, which faces the optics module, is coated with 0.08μm of Al. The combination of carrier film and coating is >97% transmissive at 6 keV for a single layer (the requirement for the combination of entrance and exit covers is 94%). The frame, which incorporates flexures at the 6 mounting points, is then mounted to the spiders on each end of the optics modules. The final product of this process is shown in Figure 16 below.

6.3 Testing

The covers tested for survival to 300C by locally heating the surface of the film. This verifies survival during launch when free molecular heating briefly raises the temperature of the membrane. A qualification model of the assembled covers underwent stand-alone acoustic testing at JPL to Pegasus qualification levels, surviving with no physical damage. All flight covers underwent thermal vacuum cycles at UC Berkeley to survival and operational extremes. All environmental testing to date has been successful. Observatory level acoustic and vibration testing is scheduled but not completed as of August 2011.

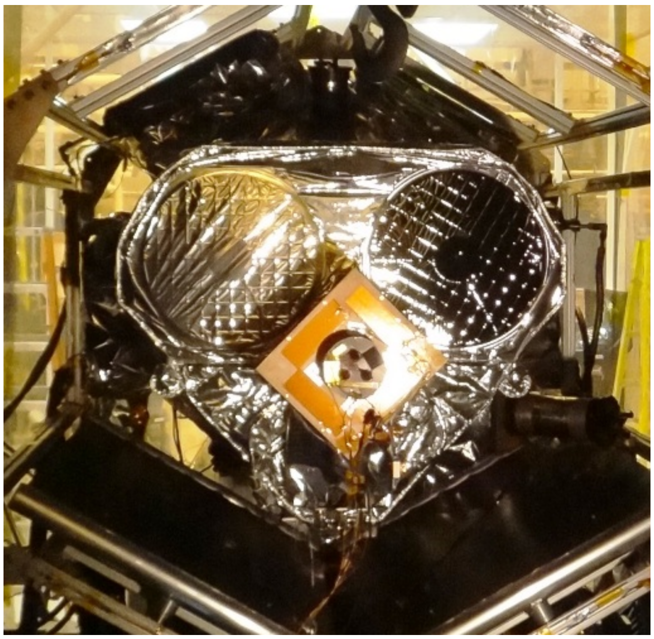

Figure 16: The two optics modules, with thermal covers, as viewed from the top side of the NuSTAR Observatory during thermal vacuum testing in July of 2011.

7. SUMMARY AND CONCLUSIONS

NuSTAR flight optics modules FM1 and FM2 and their thermal covers have been completed, tested and installed into the Observatory and are ready for flight. Testing to date indicate that all requirements have been satisfied.

ACKNOWLEDGEMENTS

This work is supported by a NASA contract to Columbia University, NNG08FD60C, "The Nuclear Spectroscopy Telescope Array (NuSTAR): Bringing the High Energy Universe into Focus". Part of this work was funded by the Technical University of Denmark (DTU Space). Part of this work was also performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL contributions included support from LDRD project 10-SI-007. The use of the RMD X-ray detector for optics calibration was made possible thanks to NASA SBIR Grant NNX11CH32P.

REFERENCES

[1] F.A Harrison, F.E. Christensen, W.W. Craig, C.J. Hailey, W. Baumgartner, C.M.H. Chen, J. Chonko, W.R. Cook, J. Koglin, K.K. Madsen, M. Pivavoroff, S. Boggs and D. Smith, “HEFT and NuSTAR focusing telescopes”, Experimental Astronomy, Volume 20, Issue 1-3 (2005) 131-137.

[2] F.A. Harrison, S. Boggs, F.E. Christensen, W.W. Craig, C.J. Hailey and D. Stern, “The nuclear spectroscopic telescope array (NuSTAR)”, Proc. SPIE 7732, (2010).

[3] J.E. Koglin, H. An, K.L. Blaedel, N.F. Brejnholt, F.E. Christensen, W.W. Craig, T.R. Decker, C.J. Hailey, L.C. Hale, F.A. Harrison, C.P. Jensen, K.K. Madsen, K. Mori, M.J. Pivovaroff, G. Tajiri, W.W. Zhang, “NuSTAR Hard X-ray Optics Design and Performance”, Proc, SPIE 7437, (2009).

[4] C.J. Hailey, S. Abdali, F.E. Christensen, W.W. Craig, T.R. Decker, F.A. Harrison and M.A. Jimenez-Garate, “Investigation of substrates and mounting techniques for the High Energy Focusing Telescope (HEFT)”, Proc. SPIE 3114, (1997).

[5] J.E. Koglin, C.M.H. Chen, J. Chonko, F.E. Christensen, W.W. Craig, T.R. Decker, K.S. Gunderson, C.J. Hailey, F.A. Harrison, C.P. Jensen, K.K. Madsen, M. Stern, D.L. Windt, H. Yu, E. Ziegler, “Production and calibration of the first HEFT hard X-ray optics module”, Proc. SPIE 5168 (2004a), 100-111.

[6] J.E. Koglin, C.M.H. Chen, J.C. Chonko, F.E. Christensen, W.W. Craig, T.R. Decker, C.J. Hailey, F.A. Harrison, C.P. Jensen, K.K. Madsen, M.J. Pivovaroff, M. Stern, D.L. Windt and E. Ziegler, “Hard X-ray Optics: from HEFT to NuSTAR”, Proc. SPIE 5488 (2004b), 856-867.

[7] W.W. Zhang, “Manufacture of mirror glass substrates for the NuSTAR mission”, Proc SPIE 7437, (2009).

[8] W.W. Zhang, K. Chan, D.A. Content, R. Petre, P.J. Serlemitsos, T.T. Saha and Y. Soong, “Development of Mirror Segments for the Constellation-X Observatory”, Proc. SPIE 4851, 58 (2002).

[9] F. Christensen, A. Hornstrup, P. Frederiksen, P. Grundsee, S. Henrichsen, E. Jacobsen, M.M. Madsen, C. Nilsson, H.W. Schnopper, N.J. Westgaard and P. Orup, “Studies of multilayers and thin-foil X-ray mirrors using a soft X-ray diffractometer”, X-ray Science and Technology, vol. 2, issue 2, (1990), 81-94.

[10] K.K. Madsen, F.E. Christensen, C.P. Jensen, E. Ziegler, W.W. Craig, K. Gunderson, J.E. Koglin and K. Pedersen, “X-ray study of W/Si multilayers for the HEFT hard x-ray telescope”, Proc. SPIE 5168 (2004), 41-52.

[11] J.E. Koglin, F.E. Christensen, W.W. Craig, T.R. Decker, C.J. Hailey, F.A. Harrison, C. Hawthorn, C.P. Jensen, K.K. Madsen, M. Stern, G. Tajiri and M.D. Taylor, “NuSTAR Hard X-ray Optics”, SPIE 5900, 33 (2005).

[12] C.J. Hailey, F.E. Christensen, W.W. Craig, F.A.Harrison, J.E. Koglin, R. Petre, D.L. Windt and W.W. Zhang, “Overview of Segmented Glass Optics Development for the Constellation-X Hard X-ray Telescope”, Proc. SPIE 4851, (2003), 519-527

[13] N. Brejnholt, H. An, F.E. Christensen, T.A. Decker, M. Doll, C.J. Hailey, K. Mori, J.E. Koglin, and G. Tajiri, Proc. SPIE 8147, (2011) .

[14] H. An, F.E. Christensen, M. Doll, C.J. Hailey, C.P. Jensen, J.E. Koglin, K. Mori and G. Tajiri, “Evaluation of epoxy for use in NuSTAR optics”, Proc. SPIE 7437, (2009).