

Status of the Advanced Mirror Technology Development (AMTD) phase 2, 1.5m ULE[®] mirror

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ABSTRACT

The Decadal Survey stated that an advanced large-aperture ultraviolet, optical, near-infrared (UVOIR) telescope is required to enable the next generation of compelling astrophysics and exoplanet science; and, that present technology is not mature enough to affordably build and launch any potential UVOIR mission concept. Under Science and Technology funding, NASA's Marshall Space Flight Center (MSFC) and Exelis have developed a more cost effective process to make up to 4m monolithic spaceflight UV quality, low areal density, thermally and dynamically stable primary mirrors. Under a Phase I program, a proof of concept mirror was completed at Exelis and tested down to 250K at MSFC which would allow imaging out to 2.5 microns. In 2014, Exelis and NASA started a Phase II program to design and build a 1.5m mirror to demonstrate lateral scalability to a 4m monolithic primary mirror. The current status of the Phase II development program will be provided along with a Phase II program summary.

Keywords: Lightweight Mirrors, Optical Systems, UV Systems

1. INTRODUCTION

In reviewing the Decadal Survey needs for future missions such as HabEx, a large UV observatory more capable than the Hubble Space Telescope is needed. Such an observatory requires a primary mirror between 4m and 16m to accomplish the minimum science goals outlined by the decadal committee. Although it is unclear that a monolithic primary mirror (PM) is required, if one was available at a reasonable areal density (approximately half of the Hubble PM) with a surface figure required for UV science, it has the potential to simplify the system architecture.

There are currently several restrictions that limit the ability to fabricate 4m class space based mirrors:

- Space based mirrors in this class must be stiff which drives the need for a classic sandwich type construction using a front and back plate with a lightweight core in the middle. This type of mirror construction has been proven for many different mirror types utilizing Corning ULE[®] Glass. In order to achieve the low mass and high stiffness needed for a UV quality space based system, the depth of the mirror exceeds what has been demonstrated using abrasive waterjet (AWJ) cutting capabilities. Currently the state of the art for core cutting has been limited to 0.28m deep using highly specialized AWJ machines. Updated capabilities could increase this, but at some point the dimensional uniformity (quality) of the core will suffer. At 4m-8m diameter, the need for a 0.4m class core depth is needed. The ability to create a high quality core needs to be addressed in order to confidently achieve the ability to produce a very large, passive, monolithic, lightweight, primary mirror.
- The creation of the very deep glass components that are then AWJ cut is expensive with large manpower and energy needs. The standard ULE[®] core boule is about 0.15m thick and approximately 1.5m in diameter. To manufacture mirrors with cores that are deeper than 0.15m, boules need to be stacked and fused together to fabricate the initial core segment blank. It would require between 3 and 4 layers to achieve the initial height of the mirror core before AWJ could even be started. Heating and cooling this much glass has been done many times, but does add a significant upfront investment in time, materials and cost.
- Manufacturing risk during AWJ also increases as core depths get larger. To mitigate this risk, Harris, formerly Exelis, has used segmented cores, but the depth of this class of mirror further increases the cost and schedule risk of a catastrophic AWJ failure during initial manufacturing.

- There is a trade between core cell size and processing quilting. In order to reduce the areal density making the hexagonal cells larger easily reduces the mass of the core, but also increases the processing quilting that is observed during processing. For a UV quality mirror, processing and gravity induced quilting must be minimized.

As the team evaluated these challenges, it became clear that developing a more cost effective and technically robust solution was required. By building on our history of low temperature fusion (LTF) and low temperature slumping technology (LTS), a technology solution lower cost and risk and a shorter schedule duration was developed. This paper reviews the work done under the NASA Advanced UVOIR Mirror Technology Development (AMTD) Program to develop a solution for future very large, monolithic, lightweight, space based, primary mirrors in the 4m to 8m sized range. Recently, HabEx has been evaluating a 4m system so the thrust of AMTD-II has been to understand the primary mirror parameters around that sized system.

2. THE HISTORY OF LARGE LIGHTWEIGHT MIRRORS

The most famous lightweight space mirror is the 2.4m Hubble Space Telescope mirror (Figure 1). By today's standards, it is very heavy at about 160 kg/m². It used high temperature fusion technology where the core walls were very thick in order to survive the high temperatures required to fuse the faceplates to the core.

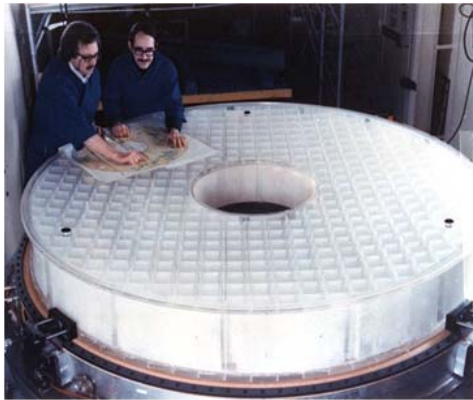


Figure 1 - The Hubble Space Telescope Primary had a mass of 160 kg/m²

As time progressed, the high temperature fusion process was replaced by Frit technology which is a ceramic-like bonding material that is used to attach the faceplates to the core. This eliminated the need to fabricate the mirror blank at very high temperatures and allowed the thicknesses of core ribs be reduced substantially. To fully take advantage of this new process, the cores were AWJ cut to final shape from solid boules of glass instead of fusion welded. The advent of AWJ technology used in conjunction with Frit greatly reduced the mass of the core without impacting the overall stiffness of the mirror which is primarily driven by the faceplates and overall mirror depth. In the 1990's, Harris took the light-weighting process even further by developing the LTF and LTS mirror blank manufacturing processes.. The low temperature fusion process allowed the cores to not only be lighter, but also segmented. The use of segmented cores reduces the cost and schedule risk associated with damage to a monolithic core during AWJ. One can imagine the schedule implications of damaging a Hubble class mirror core late in the AWJ schedule. This would require an entirely new core to be fabricated if it was damaged beyond repair. By segmenting the core as shown in Figure 2, a damaged core would only require 1/6th of a core to be replaced.

Mirror blank fabrication costs for ultra-lightweight mirrors (on the order of 10 kg/m²) were reduced further with the evolution of the low temperature slumping process. Using this technique, all the mirror parts are fabricated in the plano state. This is faster and less costly than making curved parts that would traditionally make up a mirror blank. The blank is LTF'd as a plano part slumped to final shape and subsequently polished to yield the finished mirror. Since the parts are plano, the investment in the parts is kept to a minimum and many of the parts are interchangeable prior to mirror blank fusion. Once the mirror blank is fused and slumped, it is very robust and more immune from damage.

The AMTD program takes these developments one step further by allowing the parts to be further reduced in cost and complexity.

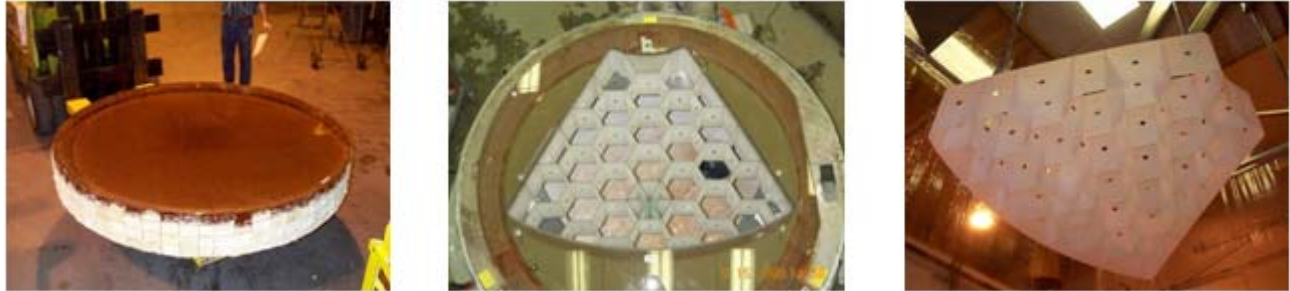


Figure 1 - Abrasive Waterjet (AWJ) cutting of mirror cores reduced the mass of lightweight mirrors. By segmenting the mirror core, the cost and schedule risk of a catastrophic failure in AWJ was also reduced.

3. STACKED CORE TECHNOLOGY

One of the challenges discussed earlier was the overall core depth required for 4m-8m monolithic UV quality mirrors. These mirrors require cores depths that cannot be attained using the current state-of-the-art AWJ technology. Figure 3 shows an AWJ section through about 0.5m of glass. Although the 0.5m is perhaps lightly deeper than what is required for a 4-8m UV PM, one can see that the jet wanders as it cuts sections that are in this depth class. This leads to non-uniformities in section properties that are difficult to model and require additional mass to insure that minimum sections thicknesses are achieved for strength purposes.

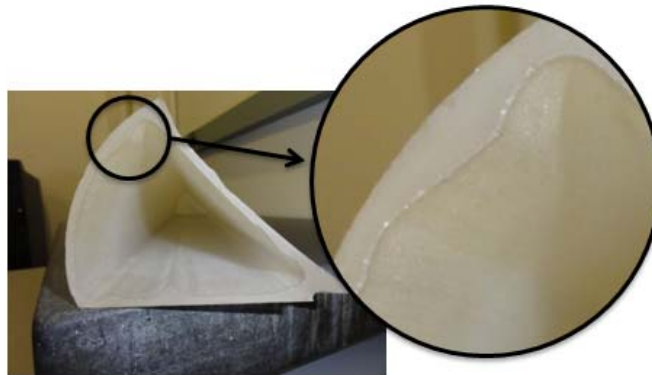


Figure 2 - An abrasive waterjet cut through about 0.5m of glass. As the cut gets deeper, the abrasive jet wanders leading to non-uniform sections in the core walls.

The AMTD stacked core concept eliminates the need for these very deep sections to be AWJ cut by working at the standard ULE[®] boule thickness level of about 0.15m. The advantage is that commercial AWJ robots are readily available that can accurately cut through this depth of glass. Furthermore, a finer garnet can be used that reduces the subsurface damage and increases the strength of the final part. During AMTD Phase I, Harris fabricated a 0.37m deep, 0.4m Ø plano mirror blank that stacked three independently cut cores between two faceplates and low temperature fused all five components together in a single LTF furnace operation. The mirror blank was then low temperature slumped to a 5m sphere and then a 2.5m sphere and subsequently polished to a surface figure quality of ~5 nm-rms. To further minimize mirror mass while maintaining high local stiffness to minimize processing and gravity quilting effects, the facesheets on the mirror fabricated during AMTD 1 were pocket milled with smaller triangular pockets. This can be seen in Figure 4.

The three cores and two faceplates fused together during the LTF furnace firing with no issues. Core-core fusion joint strength was confirmed through testing moment of rupture samples that were co-fired during the LTF process of the plano blank. The strength of the core-to-core joints have been found to be higher than the typical design allowable for the core-to-plate bonds.

The 0.37m deep mirror fabricated during Phase 1 demonstrated that the deep core cutting challenges can be avoided by using the stacked core approach and co-firing the cores together during the fusion process. It should be noted that this solves not only the deep core cutting risk, but also further reduces the risk of damaging the more expensive deep core

solids during AWJ since each core is now further reduced in size by at least 1/3. Hence it is considerably easy to recover from a core that is catastrophically damaged during AWJ since the investment is only at the boule level and not the stacked core solid level. This process actually significantly reduces the labor and energy investment in creating a very large lightweight space mirror as discussed in the introduction.

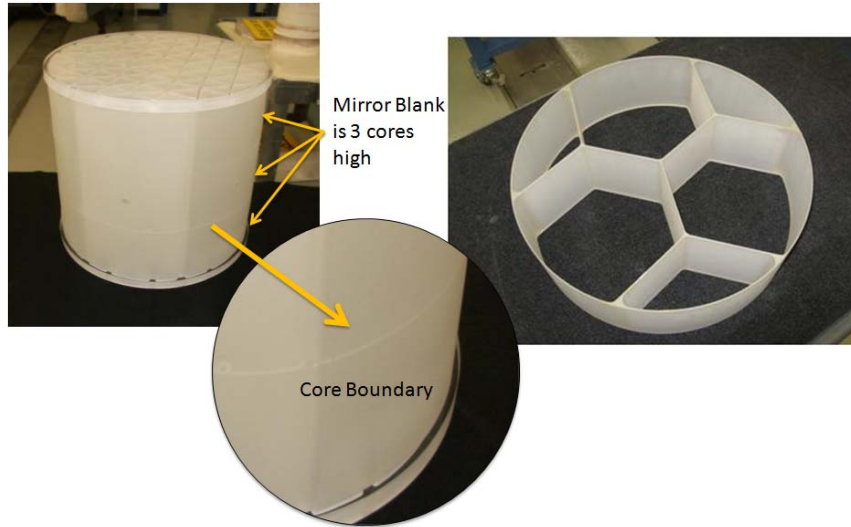


Figure 3 - The 0.43m demonstration mirror blank shown consists of three independently cut cores sections and two facesheets that were co-fired to create the assembly.

4. LARGE SCALE AMTD MIRRORS

The stacked core, pocket milled face sheet mirror fully demonstrated the validity of the concept. The applicability of the AMTD stacked core technology to large scale mirrors can now be discussed. The theory was demonstrated at a small scale and by leveraging this concept; the overall performance of a 4m and 8m diameter mirror was explored. As stated in the introduction, the first mode of space mirrors is always a concern and the ability to cost effectively add depth to the mirror without extensive AWJ development or procurement of expensive, custom water jet machines is attractive. Figure 5 shows a variety mirror diameters at various mirror depth's sensitivity to first mode natural frequency.

As can be seen, at 2.4m, the mirror depth only has to be about 0.2 meters deep to achieve a 225 Hz, first mode frequency. This can easily accomplished with no development against the current state of the art. But as the mirror grows in diameter, it shows that the mirror would have to be about 0.5m deep in order to achieve just 150 Hz first mode. As an example, if the 0.44m diameter by 0.37m deep demonstration mirror that was built was expanded to 4m, the first mode would be about 137 Hz.

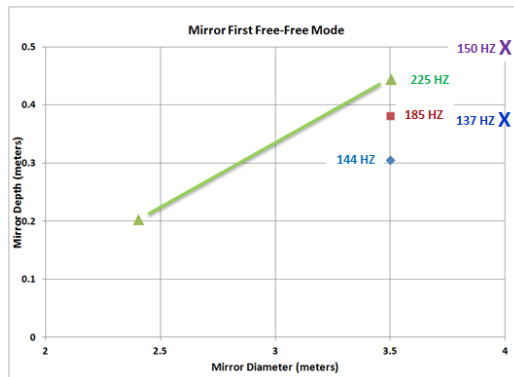


Figure 5 - The first mode frequency of a closed back mirror is driven by the overall depth of the assembly.

A question that is routinely posed is how stiff does a passive monolithic primary mirror have to be? Certainly stiffness and first mode frequency are related so this parameter is an important one. There is no set answer but higher is better and depending on vibration jitter disturbance sources in the final system configuration, there may be keep out zones required. A minimum of about 150 Hz (free-free) is a good starting point. A lower frequency PM requires a robust dynamic control design through the use of both passive and active isolation systems at the observatory and Primary Mirror assembly levels. A higher frequency system will be more forgiving to these isolation schemes. Furthermore, there may be some tonal disturbances like cryo coolers that run at set speeds that create keep out zones that must be factored into the dynamic control solution.

Two designs were completed as a demonstration for stack core, pocket milled face sheet configurations. The first one is a 4m design shown in Figure 6. This mirror design utilizes a segmented core as shown that are configured three core tall. The mirror attributes are as follows:

- Pocket Milled Face Sheet allows larger core cells while controlling quilting
- 12 Core Segments
- 3 Stacked Cores in Depth
- 10m RoC (F#1.25)
- 35 kg/m²
- 137 Hz First Free-Free Mode

This is a very impressive design considering that the Hubble Space Telescope primary mirror has an areal density of 180 kg/m² (828 kg). This 4m mirror would weigh 440 kg or about half of the mass of the HST primary mirror at 2.7 times larger area.

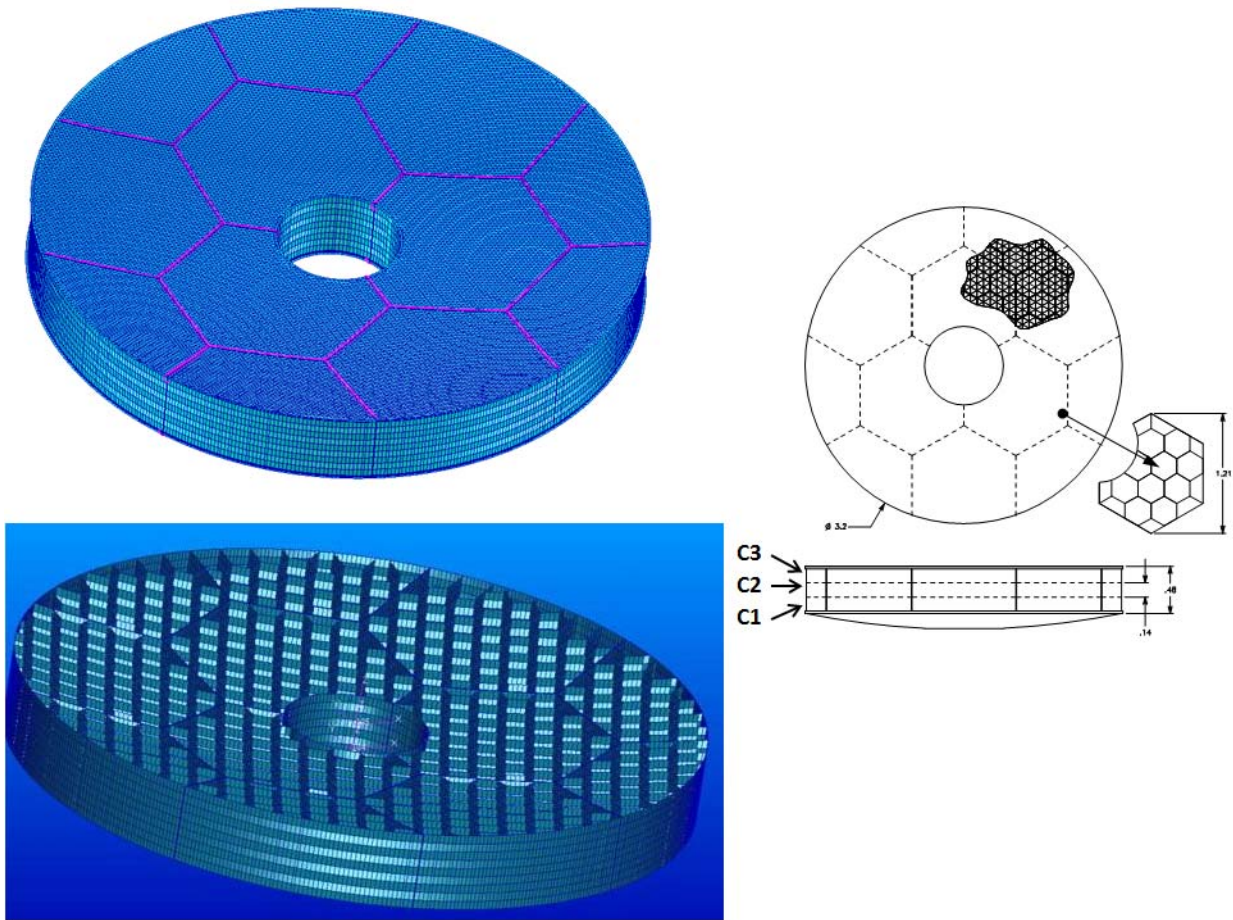


Figure 6 - 4m design uses 12 boule sized core segments stacked three tall to create a 35 kg/m², 137 Hz primary mirror.

5. AMTD PHASE I MIRROR AND RESULTS

As discussed in Section 3, Harris developed a small 0.4m diameter mirror in Phase I. This mirror was essentially a cookie cutter section of a full scale, 4m diameter stacked core mirror. In order to simplify processing and testing at both Harris and MSFC, a simple sphere was chosen for the mirror prescription. In order to minimize the effect of gravity quilting during test, a multiple orientation, horizontal test was determined to be the most advantageous configuration with a minimal number of analytical backouts for the optical test data. A simple V-block mount shown in Figure 7 was designed to hold the mirror and allowed the mirror to be easily rotated to multiple orientations. The initial processing involved the final generation of the spherical surface with a rigid tool followed by conventional grind and polish to remove the resulting subsurface damage. The first light test shown in Figure 8 revealed a mirror with 117nm RMS and 524nm Peak-to-Valley (P-V) of surface error. Note that in all cases, power was removed from the data.



Figure 7 - A simple V-block mount was used to test the mirror horizontally during processing. This minimized the gravity effects during in-process testing

As can also be seen in Figure 8, there is global quilting that aligns with the core structure. This is not a concern since the Harris ion figuring process can easily remove this low order figure error. Since the resulting figure error is well within the capture range of ion figuring and the subsurface has been removed, the conventional processing was complete and only ion figuring would be required to finish the part.

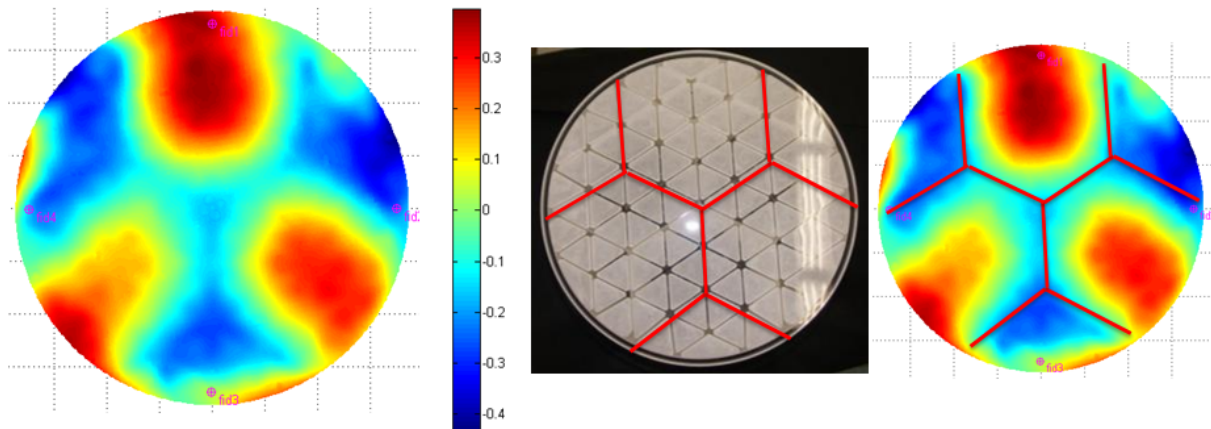


Figure 8 - After initial conventional processing, the part exhibited global quilting due to the unsupported facesheet. This was not unexpected and is easily corrected with the ion figuring process.

After three ion runs, the final mirror figure was 5.4nm RMS and 37nm P-V. The mount repeatability is insufficient to further reduce the figure error which drives only low order figure errors. As can be seen in Figure 9, the figure error is driven by low order aberrations from mount repeatability.

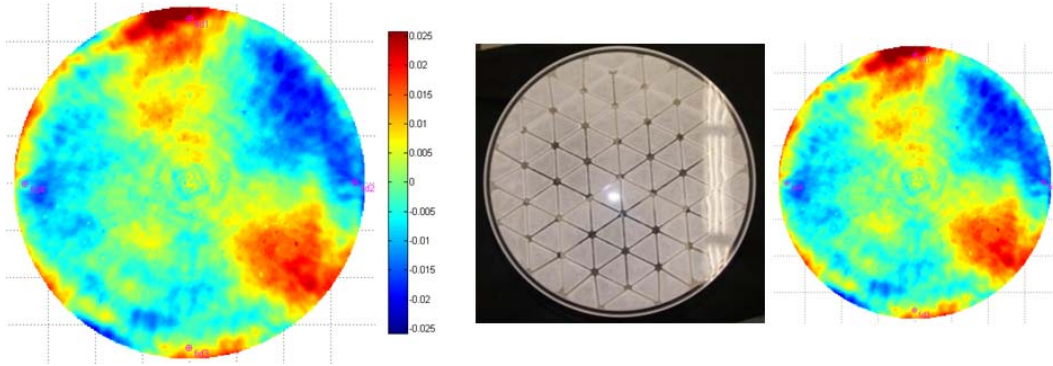


Figure 9 - The last ion run was focused on removal of the pocket milled quilting which was very successful.

Once the mirror was completed, it was transported to Marshall Space Flight Center for cold testing in their small, 1-meter vacuum chamber shown on the right in Figure 10. The thermal testing was designed to evaluate changes in the mirror figure between room temperature (293K) and 250K. Five temperature stabilization temperatures (293K, 285K, 275K, 265K, 255K) over three thermal cycles were used to collect data.

Figure 10 also shows the mirror in the vacuum chamber and ready for center of curvature testing through the small window in the front of the chamber. Note that the mirror is sitting in a V-block mount and is not kinematically mounted. This is less than ideal but was driven by the limited budget on the program. During the temperature transition phase, the mirror was photographed with an uncooled microbolometer FLIR camera as shown in Figure 11. The core structure can easily be seen in the picture since the deeper core structure holds heat longer than the much thinner front faceplate. This was to be expected and does not represent an issue when the mirror is at a stabilized temperature. At each of the five temperatures, the mirror was allowed to stabilize overnight.

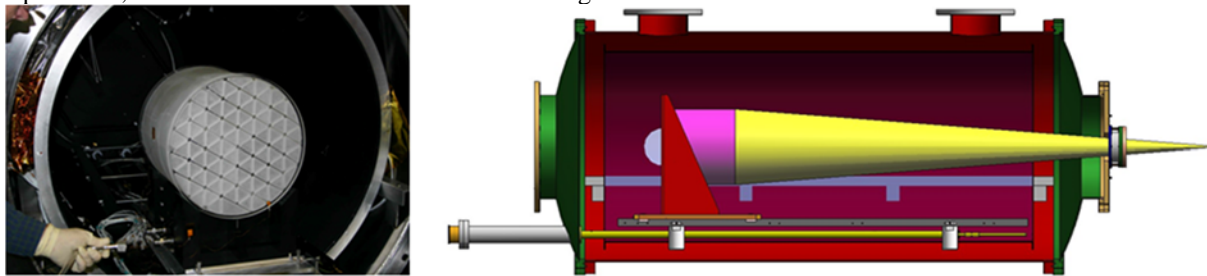


Figure 10 - The mirror inside the vacuum chamber is shown in the left. The test of the sphere will be done from the center of curvature through a small window as shown on the right.

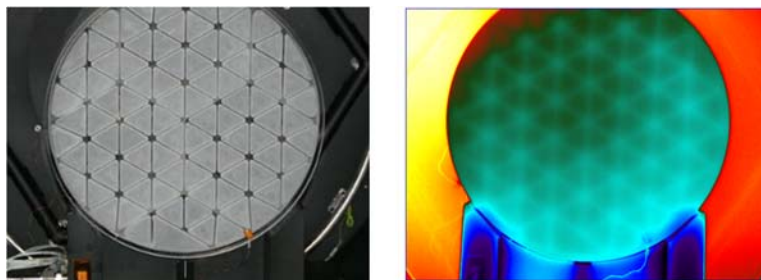


Figure 11 - A FLIR SC655, 640x480 pixel, 16-bit uncooled microbolometer looking through a ZnSe window recorded this image during warm-up

The results show that for the 38K temperature change, a change of about 4nm RMS was observed. As can be seen in Figure 12, this change is dominated by the friction around the V-block non-kinematic support in the vacuum chamber. No core quilting can be seen in the surface maps. A reference picture of the mirror with the larger core structure outlined in red in the left hand frame of the figure.

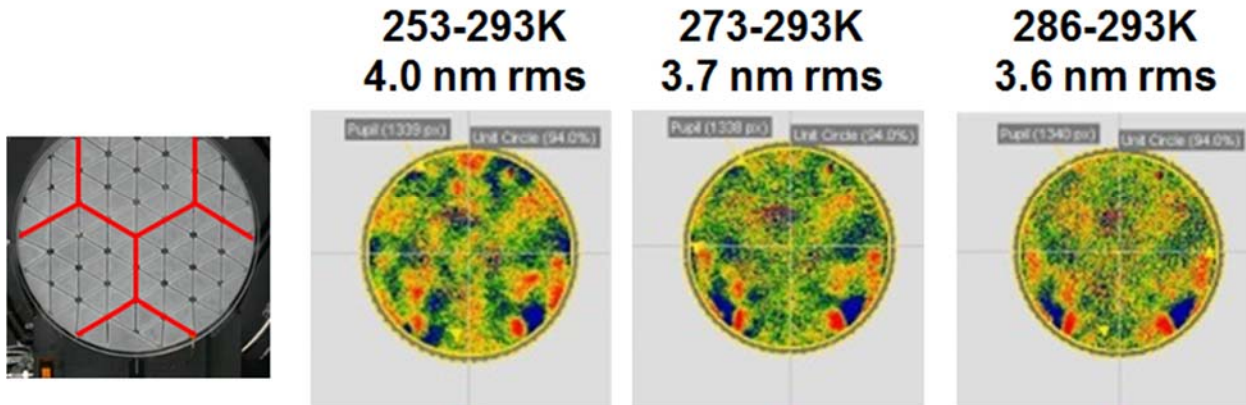


Figure 12 – The difference maps between ambient and temperatures down to 253K are shown. Very small changes were observed and were driven by the non-kinematic mount system.

6. PHASE II MIRROR DESIGN

A Phase II Science and Technology contract has been awarded to the MSFC/Harris team. Under this contract, the team will build and test a 1.5m on-axis, stacked core mirror. Like the demonstration mirror produced in Phase I, the Phase II mirror will have a three-layer stacked cores high m as well as 6 segments circumferentially to create the overall lightweight core as shown in Figure 13. This mirror blank will be fabricated as a plano substrate to reduce cost and then slumped to the near net shape in a subsequent furnace firing. But unlike the Phase I mirror which was a effectively a 0.4m cored section of a larger 4m mirror system, the 1.5m Phase II mirror has been designed to have comparable stiffness to a 4m design in order to demonstrate the lateral scalability of the LTS process. After processing at Harris, the mirror will be shipped to Marshall Space Flight Center and optically tested at both ambient and 250K. Longer term plans include performing additional environmental tests to increase the Technology Readiness Level of the LTF/LTS segmented stacked core mirror design.

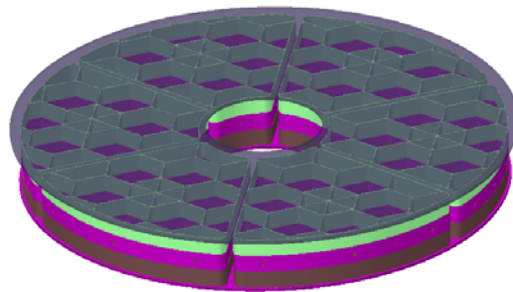


Figure 13 – A 1.5m, on-axis mirror will be fabricated and tested.

Prior to starting the detailed design of the 1.5m segmented-stacked core Low Temperature Fused (LTF) / Low Temperature Slumped (LTS) mirror blank, Harris completed the fabrication, testing and documentation of Modulus of Rupture (MOR) test samples to determine the design allowable strength for the core-to-core bonds. A total of 72 test samples were fabricated and tested. The MOR samples were cut from Abrasive Water Jet LTF samples as shown in Figure 14 and then tested in a standard 4 point bend configuration as shown in Figure 15. The A-basis Weibull 99% Confidence strength allowable based on 49 of the samples was found to be 17.5MPa which is approximately 50% higher than the strength of core-to-plate LTF bonds. This information was used in developing the mirror plano blank design to verify the mirror strength integrity.

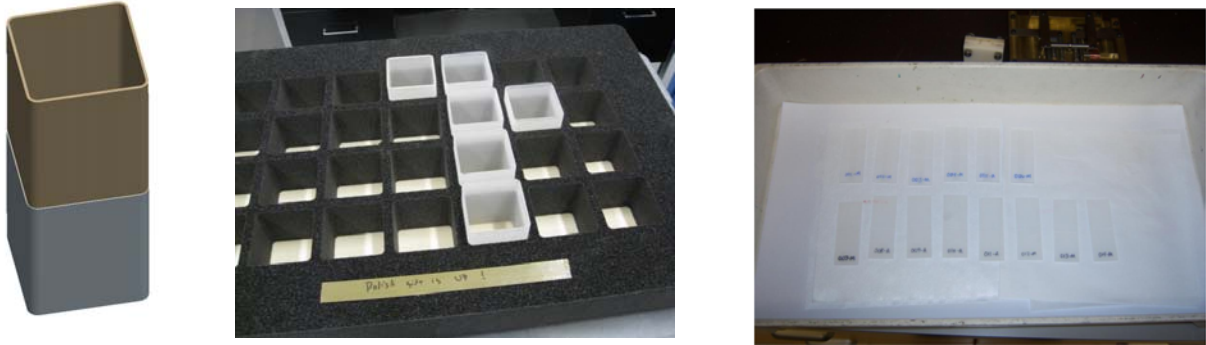


Figure 14 – AWJ LTF Boxes from which MOR samples (right image) are fabricated

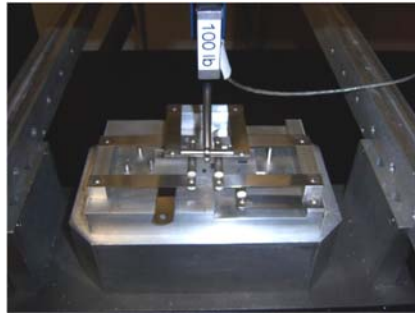


Figure 15 – - MOR Sample in Test Fixture

The blank design was developed iteratively using the non-linear finite element tool Abaqus (by Dassault Systèmes) to understand how the mirror blank distorts visco-elastically during the LTS process. Results from the LTS analyses were used to develop the required plano blank inner and outer diameters so that the slumped mirror blank has the proper diameters, as the back plate stretches and thins during slumping and the front plate compresses and gets thicker. The Abaqus analyses were also used to assess the amount of core wall bowing that is expected during the LTS process. These results were used to develop the size of the core segments and the required segment boundary gap to ensure that adjacent cores will not come into contact with each other during LTS (if adjacent cores were to contact during LTS, an unacceptable stress concentration would exist). Figure 16 shows the predicted deformed shape of the slumped mirror blank (using a 30 degree symmetric Finite Element Model (FEM)) and the contours indicate the areas at the core segment boundary that are bowing (red in, blue out towards the adjacent segment).

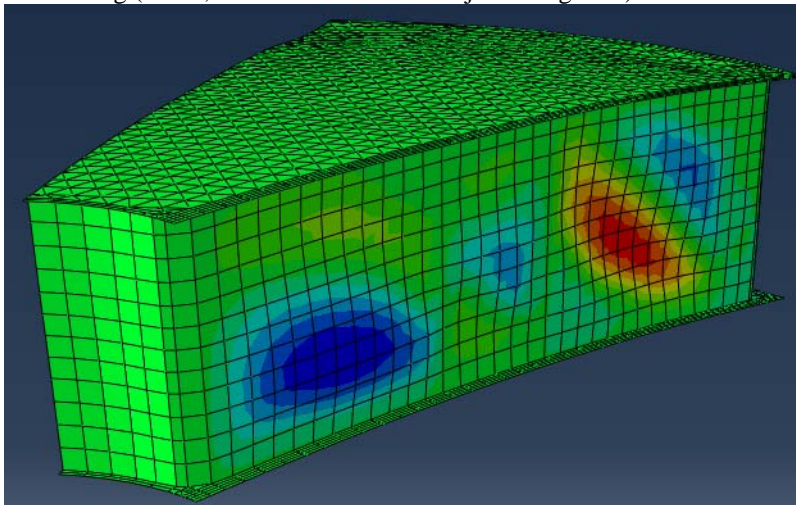


Figure 16 – LTS Blank Geometry from Abaqus Viscoelastic FEM

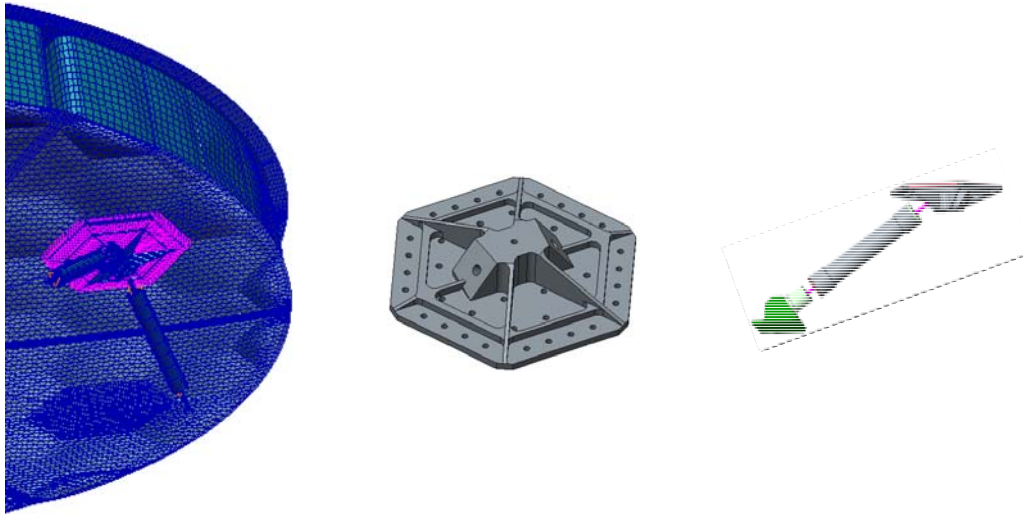


Figure 17 – FEM model of mount pad with simplified strut, Detailed Mount Pad,& Mount Strut Design
Note in left picture of FEM, back quilting from the LTS process is apparent

After the blank was sized through the LTS analyses, a Nastran FEM was generated directly from the Abaqus model. This approach yields a Nastran FEM that has the proper geometry as well as the proper shell thicknesses due to the stretching and compressing of the glass during the LTS process. A mount pad design was developed using this finite element model and a simplified strut was integrated to it to determine the required strut stiffness to achieve a first mounted mode that is greater than 60 Hz (see Figure 17). With the required stiffness known, the final mount strut design was developed leveraging a legacy Harris design updated to meet AMTD requirements and modified to be athermal about 250K. Stress analysis was performed to verify that core wall thicknesses were acceptable. A CAD image of the plano blank design is shown in Figure 13.

7. PHASE II MIRROR FABRICATION STATUS

Harris acquired 3 pieces of glass for the mirror plates from Corning. Two of the plates have gone through processing to prepare them for the LTF process. (The third piece of glass will be used as a loading body during the LTF). Plate preparation started with an AWJ step to reduce the plates in diameter to be slightly oversized from what is required for the finished Plano Blank. Four large pieces of residual glass were generated during this AWJ process for each plate. Half of the residuals were sent to Ormond for use in AWJ technology development. Images of the AWJ process and the 4 residuals (~50mm thick) are shown in Figure 18.



Figure 18 – One of the AMTD mirror plates (face sheets) being rounded in AWJ (left) shown with residual glass sent to Ormond (right)

After the plates were rounded to the required size, they were Blanchard ground to achieve the desired thickness. This was followed by additional grinding to remove subsurface damage and then polishing to achieve the required shine needed for the LTF process. An image of one of the plate in polish is shown if Figure 19. Both of the mirror facesheets are now in queue to be AWJ to their final pre-LTF dimensions.

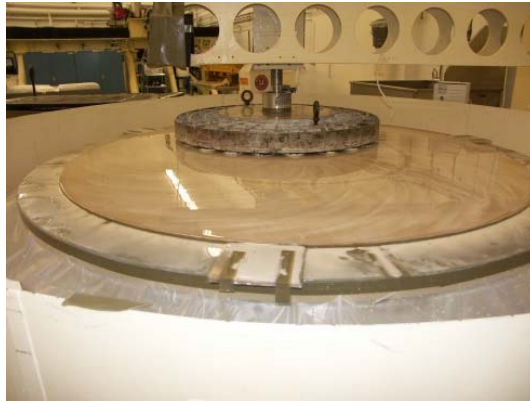


Figure 19 – One of the AMTD mirror plates receiving an LTF shine (Polish)

Harris also acquired 3 boules of ULE[®] glass that were donated to the AMTD program from another government agency. These boules will be utilized to make the 18 AWJ segments that make up the core of the mirror blank. The three boules were sliced in half by Corning to yield 6 slices of glass. Four and a half of the slices are needed to yield the requisite 18 core segments. One of the slices will be used as a spare. The other half slice will be used for AWJ process verification prior to light weighting the core segments. Harris has received all 6 slices and is in the process of thinning them to thickness and polishing them with an LTF shine. The processing of the core slices is analogous to the process utilized for the plates. Currently the cores are on track to be ready for AWJ light weighting at Corning at the end of September 2015.

8. SUMMARY

To date, the stacked core approach shows great promise to reduce the cost and schedule for building large, 4m-8m, closed back, mirror blanks. The mirror blanks can be lower cost by leveraging the ability to accomplish parallel work on multiple, lower cost waterjet robots and saving the time and energy required to create very thick core solids that are subsequently cut to create the lightweight core.

Harris has demonstrated the ability to fabricate and process a lightweight, stacked core mirror and control the spatial frequency figure errors needed to produce a lightweight, UV quality mirror.

During Phase II NASA and Harris will continue this development by building and process a 1.5m stacked core mirror. Environmental testing will be completed to understand the performance in a launch and flight environment.

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BIBLIOGRAPHY

1. Stahl, H. Philip, *Overview and Recent Accomplishments of the Advanced Mirror Technology Development (AMTD) for large aperture UVOIR space telescopes project*, SPIE Conference on UV/Optical/IR Space Telescopes and Instrumentation, Optics & Photonics, San Diego 2013.
2. Stahl, H. Philip, W. Scott Smith, Marc Postman, *Engineering specifications for a 4 meter class UVOIR space telescope derived from science requirements*, SPIE Conference on UV/Optical/IR Space Telescopes and Instrumentation, Optics & Photonics, San Diego 2013.

3. Matthews, Gary, et al, *Processing of a stacked core mirror for UV applications*, SPIE Conference on Material Technologies and Applications to Optics, Structures, Components, and Sub-Systems, Optics & Photonics, San Diego 2013.
4. Matthews, Gary, et al, *Development of stacked core technology for the fabrication of deep lightweight UV quality space mirrors*, SPIE Conference on Optical Manufacturing and Testing X, Optics & Photonics, San Diego 2013.
5. Eng, Ron, et. al., *Cryogenic optical performance of a lightweighted mirror assembly for future space astronomical telescopes: correlation of optical test results and thermal optical model*, SPIE Conference on Material Technologies and Applications to Optics, Structures, Components, and Sub-Systems, Optics & Photonics, San Diego 2013.