Thermal testing of a stacked core mirror for UV applications

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ABSTRACT

The ASTRO2010 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 and ITT Exelis have developed a more cost effective process to make 4m monolithic spaceflight UV quality, low areal density, thermally and dynamically stable primary mirrors. A proof of concept mirror was built and tested down to 250K which would allow imaging out to 2.5 microns. This mirror was thermally tested at the Marshall Spaceflight Center to understand the thermal changes between the processing temperature of 293K and the potential low end of the operational temperature of 250K. Isothermal testing results and front plate gradient results have been evaluated and compared to analysis predictions. Measurement of gravity effects on surface figure will be compared to analytical predictions. Future testing of a larger Pathfinder mirror will also be discussed.

Keywords: Lightweight Mirrors, Optical Systems, UV Systems

1. INTRODUCTION

In reviewing the Decadal Survey needs for future missions, a large UV system more capable than the Hubble Space Telescope will be required. In reviewing potential concepts, a monolithic primary mirror between 4m and 8m will be needed to accomplish the minimum science goals outlined. Although it is unclear that a monolithic primary mirror is required, if one was available at reasonable areal densities at UV quality, 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 at this class need to 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. 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 quality of the core will suffer. At 4m-8m diameter, the need for a 0.4m class core depth will be 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, monolithic, lightweight, primary mirror.
- At the very deep core depth, the risk also increases. Exelis has used segmented cores for many years, but the depth of this class of mirror further increases the cost and schedule risk of a catastrophic AWJ failure during initial manufacturing.
- The creation of the very deep glass components that are then AWJ cut is expensive with large manpower and energy needs. The raw core boules are about 0.15m thick and have traditionally been stacked and fused together to fabricate the initial core segment. 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 and materials.

- There is a trade between core cell size and processing quilting. In order to reduce the areal density, a lighter core is an easy first step. Making the cells larger easily reduces the mass of the core, but also increases the processing quilting that is observed during processing. At UV quality, this parameter must be minimized.

As the team reviewed 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 and low temperature slumping technology, a more cost and schedule solution was developed. This paper reviews the work done under the NASA Advanced UVOIR Mirror Technology Development (AMTD) Program.

2. HISTORICAL PERSPECTIVE

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/m^2. It used high temperature fusion technology where the sections were very thick in order to survive the high fusion temperatures required to connect the faceplates to the core.

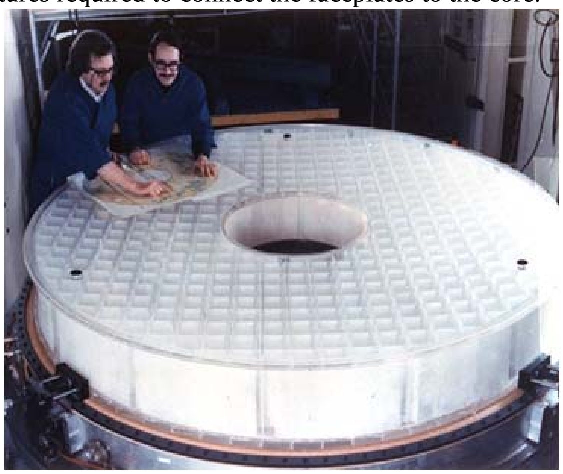

Figure 1 - The Hubble Space Telescope Primary had a mass of 160 kg/m^2.

As time progressed, the high temperature process was replaced by Frit technology which is a ceramic-like bonding material that basically connected the faceplates to the core. This eliminated the need to fabricate the mirror blank at very high temperatures and allowed the section properties to 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. This greatly reduced the mass of the core without impacting the overall stiffness of the mirror which is driven the faceplates themselves. In the 1990's, Exelis took the lightweighting process even further by developing low temperature fusion and then the low temperature slumping process. The low temperature fusion process allowed the cores to not only be lighter, but also segmented. The segmented core reduced 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 $1/6^{th}$ of a core to be replaced.

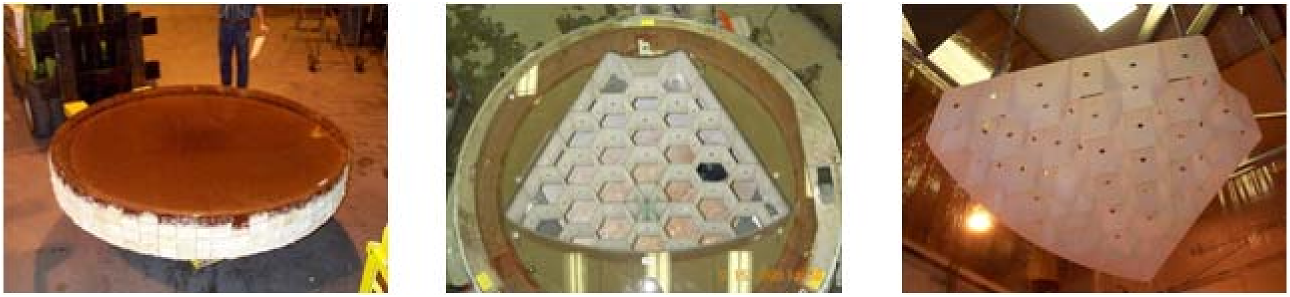

Figure 2 - Abrasive Waterjet (AWJ) cutting of mirror cores reduced the mass of lightweight mirrors. By segmenting the mirror core, the cost and schedule risk of a catastrophic failure in AWJ was also reduced.

This risk reduction was further enhanced with the evolution of the low temperature slumping process. Using this technique, all the mirror parts would be fabricated in the plano state. This is faster and cheaper than making curved parts that would make up a mirror. The mirror blank would then be fused as a plano mirror blank and then slumped to final shape. 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.

3. STACKED CORE TECHNOLOGY

One of the limitations discussed earlier was the overall depth of the core required for 4m-8m monolithic UV quality mirrors. These mirrors would exceed the state of the art achieved via AWJ in both depth and uniformity. Figure 3 shows an AWJ section through about 0.5m of glass. Although deeper than required, one can see that the jet wanders as it cuts sections that are this deep. This leads to non-uniformities in section properties that are difficult to model and require additional mass to insure that minimum sections are achieved.

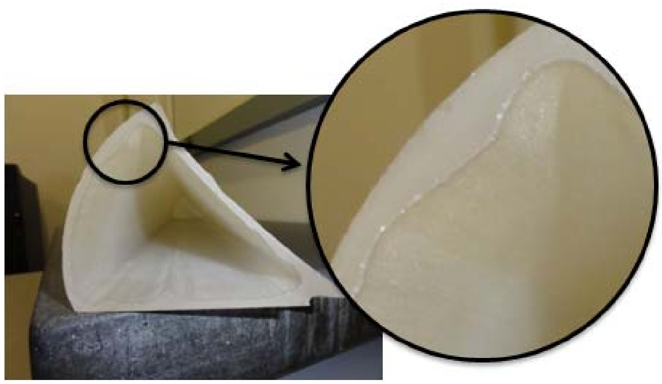

Figure 3 - An abrasive waterjet cut through about 0.5m of glass. As the cut gets deeper, the abrasive jet wanders leading to non-uniform sections in the core walls.

The stacked core concept eliminates the need for these very deep sections to be cut by working at the boule thickness level of about 0.15m. The advantage is that commercial AWJ robots are readily available that can accurately cut this deep. In addition, a finer garnet can be used that reduces the subsurface damage and increases the strength of the final part. To demonstrate the concept, Exelis fabricated a 0.43m mirror that stacked three independently cut cores between two faceplates and co-fired this assembly to create a very deep, sandwich construction mirror blank (Figure 4).

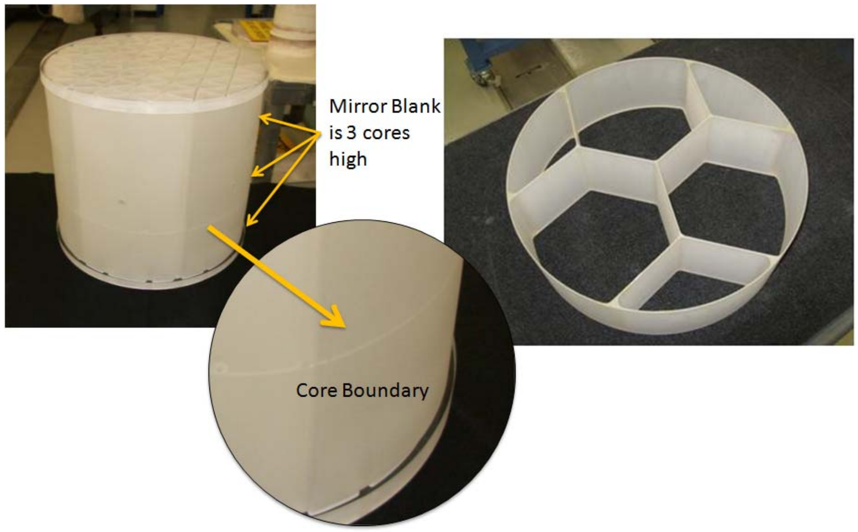

Figure 4 - The 0.43m demonstration mirror blank shown consists of three independently cut cores sections and two facesheets that were co-fired to create the assembly.

The mirror blank fully fused the three cores and two faceplates together during firing with no issues. The joint strength was confirmed through testing moment of rupture samples made during the LTF process. The strength of the core-to-core joints were actually higher than the typical design allowable for the core-to-plate bonds.

This demonstrates that the deep core cutting problem can be mitigated 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 expensive core solid during AWJ since each core is now further reduced in size by at least 1/3. So a damaged core can more easily be replaced 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.

4. POCKET MILLED FACESHEETS

The processing quilting concern was also introduced earlier. This error source is a traditional tradeoff in making lightweight mirrors since the front facesheet is not uniformly supported during processing. Larger core cells increase the processing quilting but allow a lighter mirror. In the 1990's, pocket milling was introduced as a method of creating a mini-core structure within the faceplate. Pocket milling effectively creates an open backed mirror that is more immune to processing quilting while allowing the core cells grow in diameter. Figure 5 shows that in the case of the demonstration mirror, a 24 mini-cell structure was created within the larger central core construction.

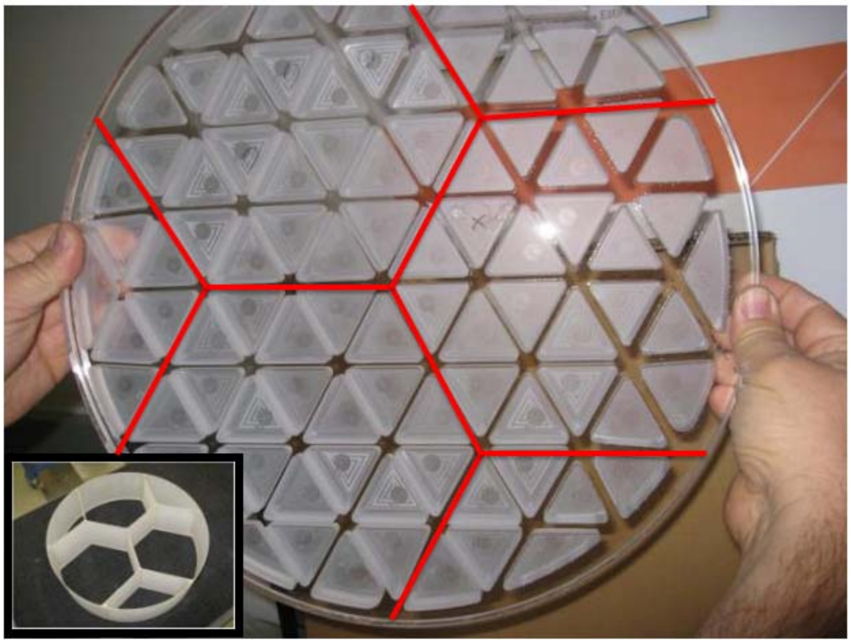

Figure 5 - The faceplates of the demonstration mirror had a 24 cell structure within each of the larger core interfaces depicted by the red lines.

Unlike the early development of pocket milling, this latest implementation used a 20mm deep facesheet. This provided the ability to create a very stiff open backed structure to effectively stiffen the unsupported faceplate during processing. In addition, this will also minimize the gravity quilting during integration and test of a telescope system which is also advantageous.

Another more subtle attribute is also involved with deep pocket milled facesheets. The structure of the facesheet is moved further away from the neutral axis which further increases the stiffness of the mirror. Since this is a distance squared term, this small offset of 20mm or so does contribute to the overall stiffness quality of the mirror. So the mirror is not only lighter weight due to the large core structure, the mirror has a higher first mode due to the pocket milled facesheet. These are all positive qualities of a high performance, space based, UV quality mirror.

5. SLUMPING A VERY STIFF STACKED CORE MIRROR

Certainly one concern with the stacked core, pocket milled facesheet approach was the ability to form the mirror over a mandrel to near net shape. Previously the low temperature slumping technology was used on thinner, less stiff active mirrors. Slumping a very stiff mirror like this was a concern. The potential for buckling core cell walls or just the inability to form the mirror to a mandrel due to the inherent stiffness was a risk. To demonstrate the capability, the mirror was initially slumped to a 5m radius of curvature mandrel with very good results and no issues regarding the mirror blank conforming to the mold.

But in order to be able to conduct a center of curvature optical test at 250K inside the Marshall Space Flight Center (MSFC), 1.2m long vacuum chamber, a second slumping cycle was done to a 2.5m radius. This is effect would result in an extremely fast mirror but was an excellent test case to better understand the resulting core characteristics. The resulting mirror shown in Figure 6 had no issues conforming to the mandrel and exhibited minimal core wall deformations.

Figure 6 - The demonstration mirror was slumped to a 2.5m radius of curvature to allow center of curvature optical testing in the Marshall Space Flight Center chamber.

At this point, the mirror blank was complete. The next step in the demonstration process is to determine the ability to polish the mirror to UV quality performance specifications. Longer term, a thermal test would be completed to determine the figure change if the mirror was operated at 250K instead of room temperature.

6. MIRROR PROCESSING

In order to simplify testing at both Exelis and MSFC, a simple sphere was chosen for mirror processing and test. 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.

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.

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.

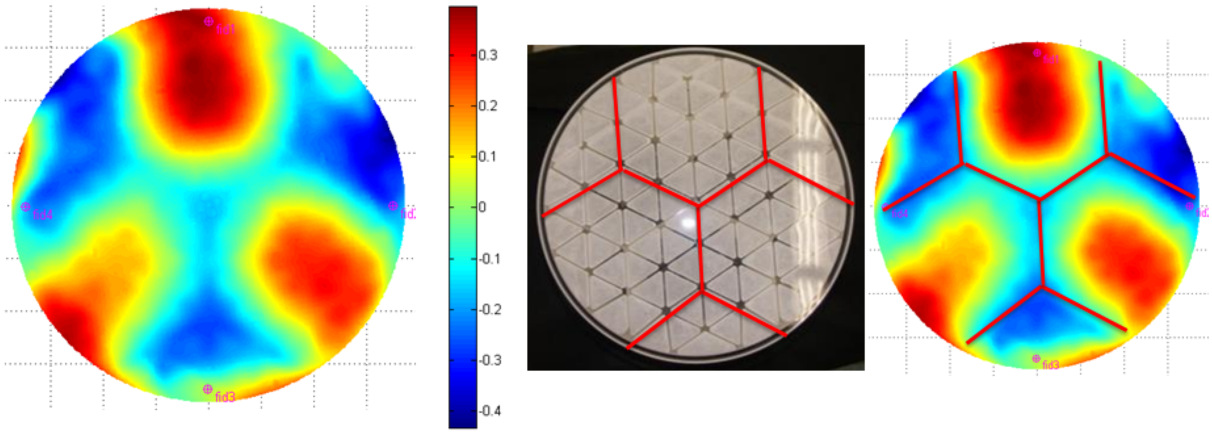

Figure 8 - After initial conventional processing, the part exhibited global quilting due to the unsupported facesheet. This was not unexpected and is easily corrected with the ion figuring process.

As can be seen in Figure 8, there is global quilting that aligns with the core structure. This is not a concern since the Exelis 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.

After the first iteration of ion figuring, the mirror figure error was reduced by over 80% as shown in Figure 9. Even though not all of the global processing quilting was removed the resulting figure error was reduced from

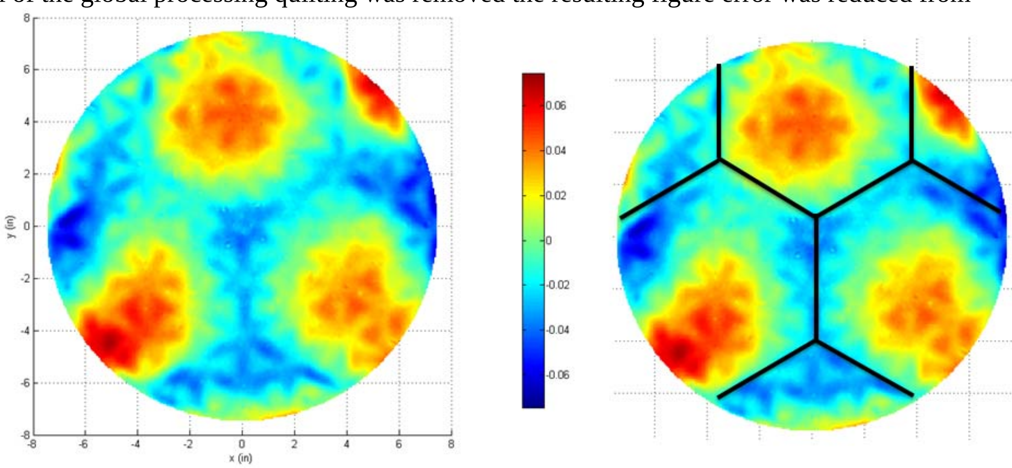

Figure 9 - After the first ion figuring cycle, some global quilting remains. As the figure improves, the pocket milled quilting starts to become visible.

117nm RMS and 524nm P-V to 16nm RMS and 87nm P-V. As the global quilting is reduced, the pocket milled quilting can start to be observed. But before that error is addressed, one additional ion cycle was completed to further reduce the global quilting error as shown in Figure 10. The figure error was reduced by over 60% in this correction cycle which resulted in a surface figure error of 4.9nm RMS and 37nm P-V.

The faceplate pocket milled quilting can now be readily seen but is very small since the overall figure error is only 4.9nm RMS. But even at this small error and reasonably high spatial frequency, the ion figuring process can still address the error. A third ion cycle was completed to specifically address this quilting error.

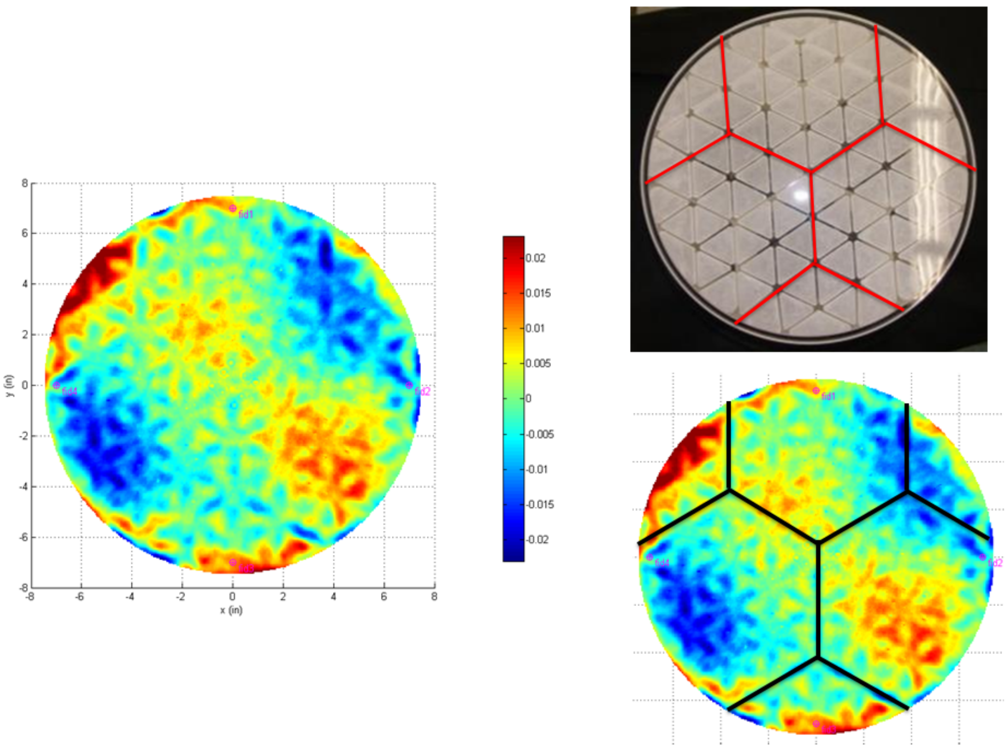

Figure 10 - After the second ion cycle, the pocket milled quilting can be observed.

Figure 11 shows the results of this final ion figuring cycle. The quilting error is notably reduced even though the figure error increased slightly to 5.4nm RMS and 37nm P-V. This is due to test errors associated with the V-block mount shown earlier. The repeatability of this mount is insufficient to further reduce the figure error. As can be seen in Figure 11, the increase in the figure error is driven by low order aberrations from testing.

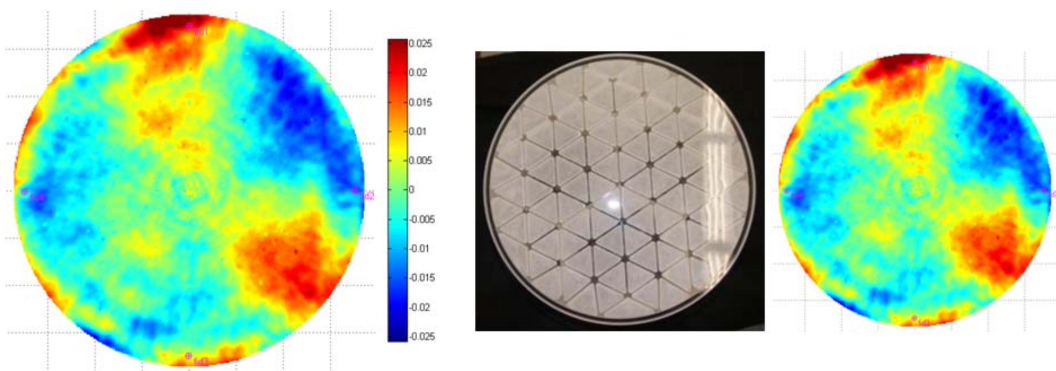

Figure 11 - The last ion run was focused on removal of the pocket milled quilting which was very successful.

7. ION FIGURING IMPACT ON SURFACE ROUGHNESS

Certainly one of the historical factors regarding the ion figuring process is its impact on various spatial errors. Primarily the change in surface roughness due to the ion ablatement of material from the surface of the part is the concern. Clearly the ion figuring process addresses low order errors very well with deterministic removal rates and fast convergence to the final figure. The ion process also addresses what would typically be term mid-spatial frequency errors as shown in Figure 12. The spatial range shown is between 50mm and 10mm. In the image on the left, the pocket milled processing quilting can easily be seen. On the right hand side is the result of one ion run that addressed that spatial frequency. The pattern is now more random in nature with little structure associated with the resulting figure error map with the error reduced from 1.27nm RMS to 0.89nm RMS.

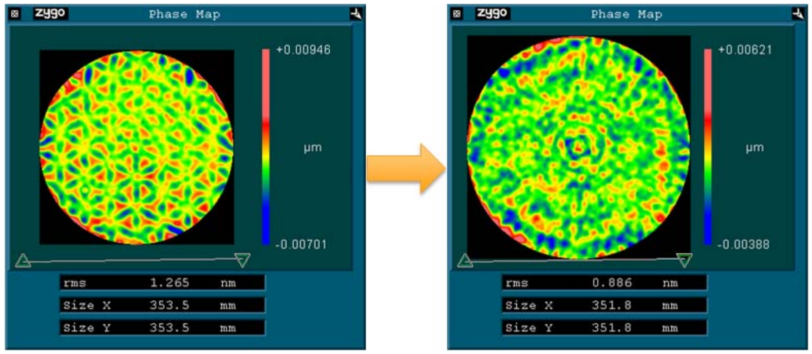

Figure 12 - The ion figuring cycle focused on removing the pocket milled quilting produced a final random error that was 0.9nm RMS.

Figure 13 shows the high spatial errors less than 10mm. This is the area of surface roughness and the result shows no increase in this high spatial frequency error of 0.26nm RMS pre to post ion figuring.

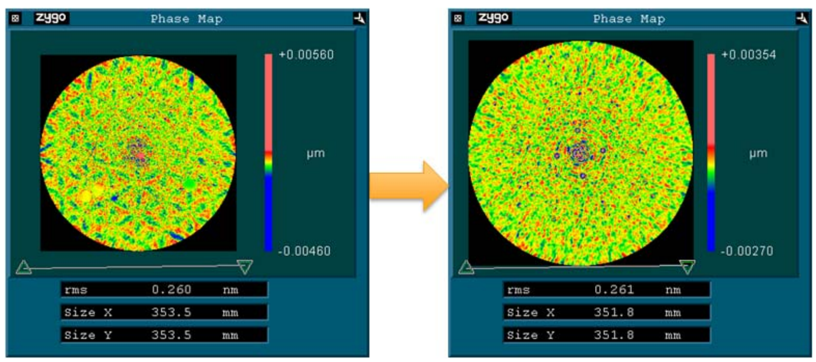

Figure 13 - No change in the high frequency error was observed after ion figuring.

This provides data that demonstrates that a UV quality mirror can be ion figured to remove low and mid spatial frequency errors with little impact to the overall surface roughness qualities of the final mirror.

There are two related SPIE papers that discuss the processing and thermal testing of this AMTD mirror:

- The Development of Stacked Core Technology for the Fabrication of Deep Lightweight UV-Quality Space Mirrors [8838-23]
- Cryogenic Optical Performance of a Lightweighted Mirror Assembly for Future Space Astronomical Telescopes: Optical Test Results and Thermal Optical Model [8837-11]

8. SUMMARY

The processing of the stacked core, pocket milled facesheet mirror converged within a 3 week period using ion figuring. The results show no significant PSD change due to ion figuring in spatial periods smaller than 10mm. And while the global surface figure limited by mount repeatability, the ability to demonstrate that UV quality (5nm RMS) could be achieved and verified with a stacked core, pocket milled facesheet mirror was demonstrated.

A Phase II proposal has been submitted to NASA to continue this development by building a 1.3m stacked core mirror.

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