# The development of stacked core technology for the fabrication of deep lightweight UV-quality space mirrors

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## ABSTRACT

The 2010 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 4m class or larger monolithic spaceflight UV quality, low areal density, thermally and dynamically stable primary mirrors. A proof of concept 0.43m mirror was completed at Exelis optically tested at 250K at MSFC which demonstrated the ability for imaging out to 2.5 microns. The parameters and test results of this concept mirror are shown. The next phase of the program includes a 1.5m subscale mirror that will be optically and dynamically tested. The scale-up process will be discussed and the technology development path to a 4m mirror system by 2018 will be outlined.

**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 is required. This requires a primary mirror between 4m and 16m to accomplish the minimum science goals outlined. Although it is unclear that a monolithic primary mirror is required, if one was available at a reasonable areal density 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 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 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, 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 processing and gravity 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 and low temperature slumping technology, a lower cost and shorter schedule solution 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.

## 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.

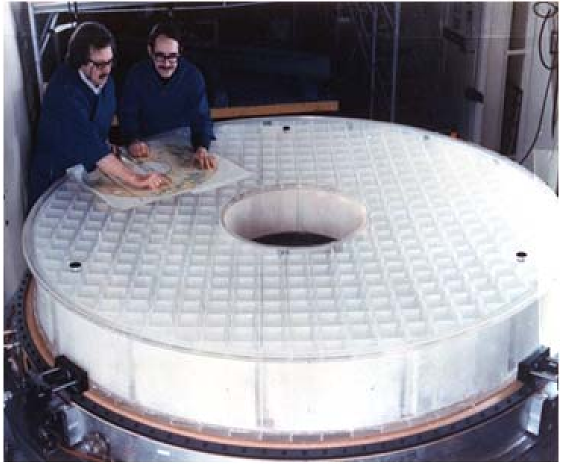


**Figure 1 - The Hubble Space Telescope Primary had a mass of 160 kg/m$^2$.**

As time progressed, the high temperature fusion process was replaced by Frit technology which is a ceramic-like bonding material that attached 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 light-weighting process even further by developing low temperature fusion (LTF) and then the low temperature slumping (LTS) 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 1/6th of a core to be replaced.

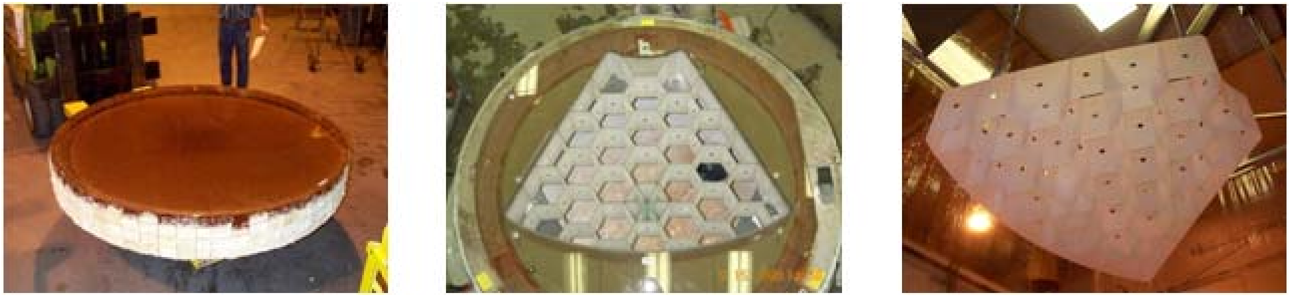


**Figure 2 - Abrasive Waterjet (AWJ) cutting of mirror cores reduced the mass of lightweight mirrors. By segmenting the mirror core, the cost and schedule risk of a catastrophic failure in AWJ was also reduced.**

This cost was further reduced 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 traditionally make up a mirror blank. The blank would be fused as a plano part 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.

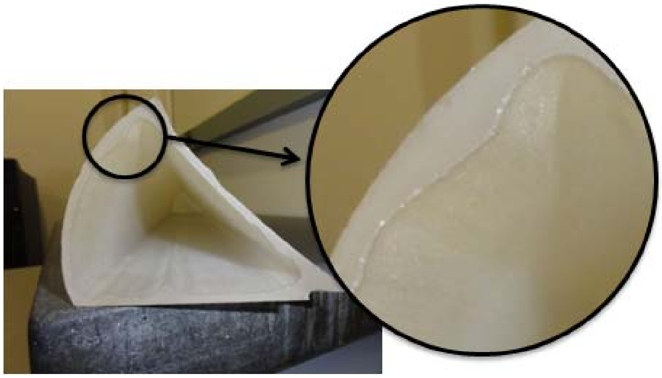


**Figure 3 - An abrasive waterjet cut through about 0.5m of glass. As the cut gets deeper, the abrasive jet wanders leading to non-uniform sections in the core walls.**

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).

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.

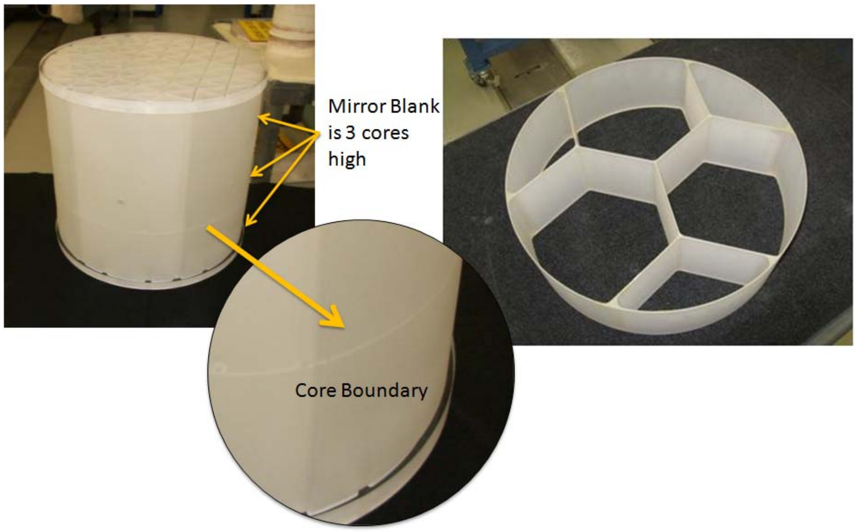


**Figure 4 - The 0.43m demonstration mirror blank shown consists of three independently cut cores sections and two facesheets that were co-fired to create the assembly.**

## 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 impervious 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.

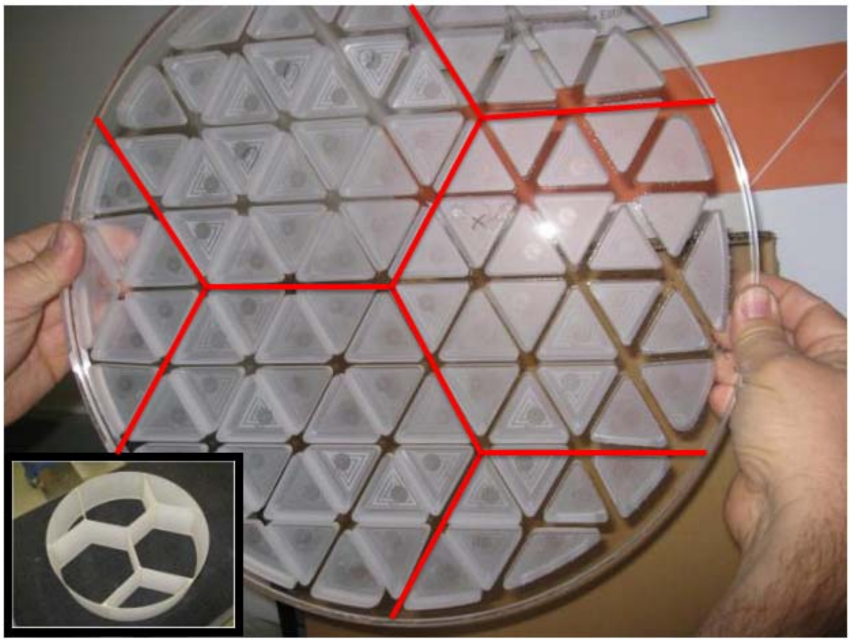


**Figure 5 - The faceplates of the demonstration mirror had a 24 cell structure within each of the larger core interfaces depicted by the red lines.**

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.

This in turn 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 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 results 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 spherical prescription 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 mirror was processed without any issues to a final surface figure of 5.5nm RMS in about 3 weeks. It should be noted that the V-block mounting system was not optimal and the ability to figure the mirror to better than about 5nm RMS was really hindered by the test mount configuration. As can be seen in Figure 8, there is a small amount of low order trefoil still in the part that is residual test noise.

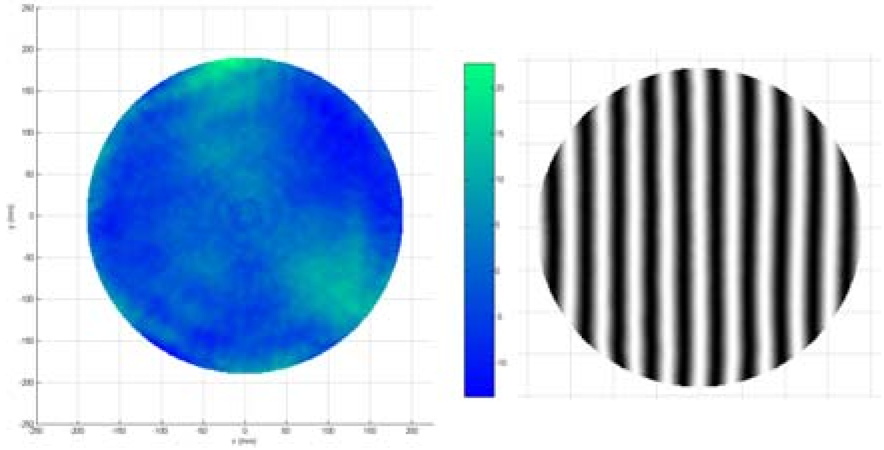


**Figure 8 - The mirror was quickly processed to 5.5nm RMS within a period of about 3 weeks.**

## 7. 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 9 shows a variety mirror diameters at various mirror depth’s sensitivity to first mode natural frequency.

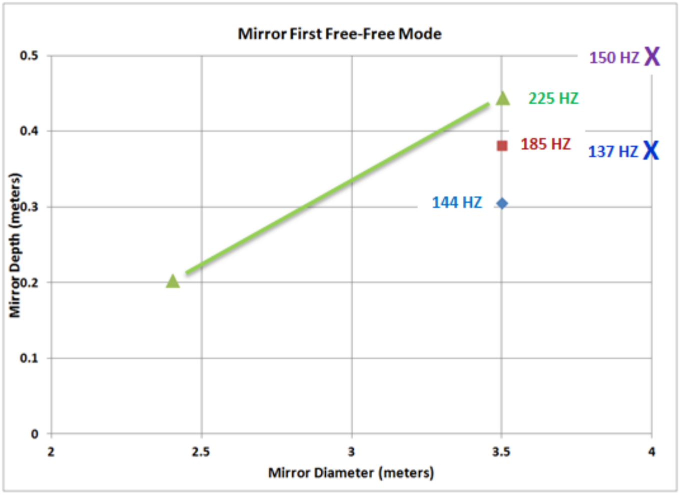


**Figure 9 - The first mode frequency of a closed back mirror is driven by the overall depth of the assembly.**

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 0.43m diameter by 0.31m deep demonstration mirror that was built was expanded to 4m, the first mode would be about 137 Hz.

The question that is always posed is how stiff does the 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 disturbance sources in the final system configuration, there may be keep out zones required. A minimum of about 150 Hz 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. 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 10. 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/m$^2$
- 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/m$^2$ (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.

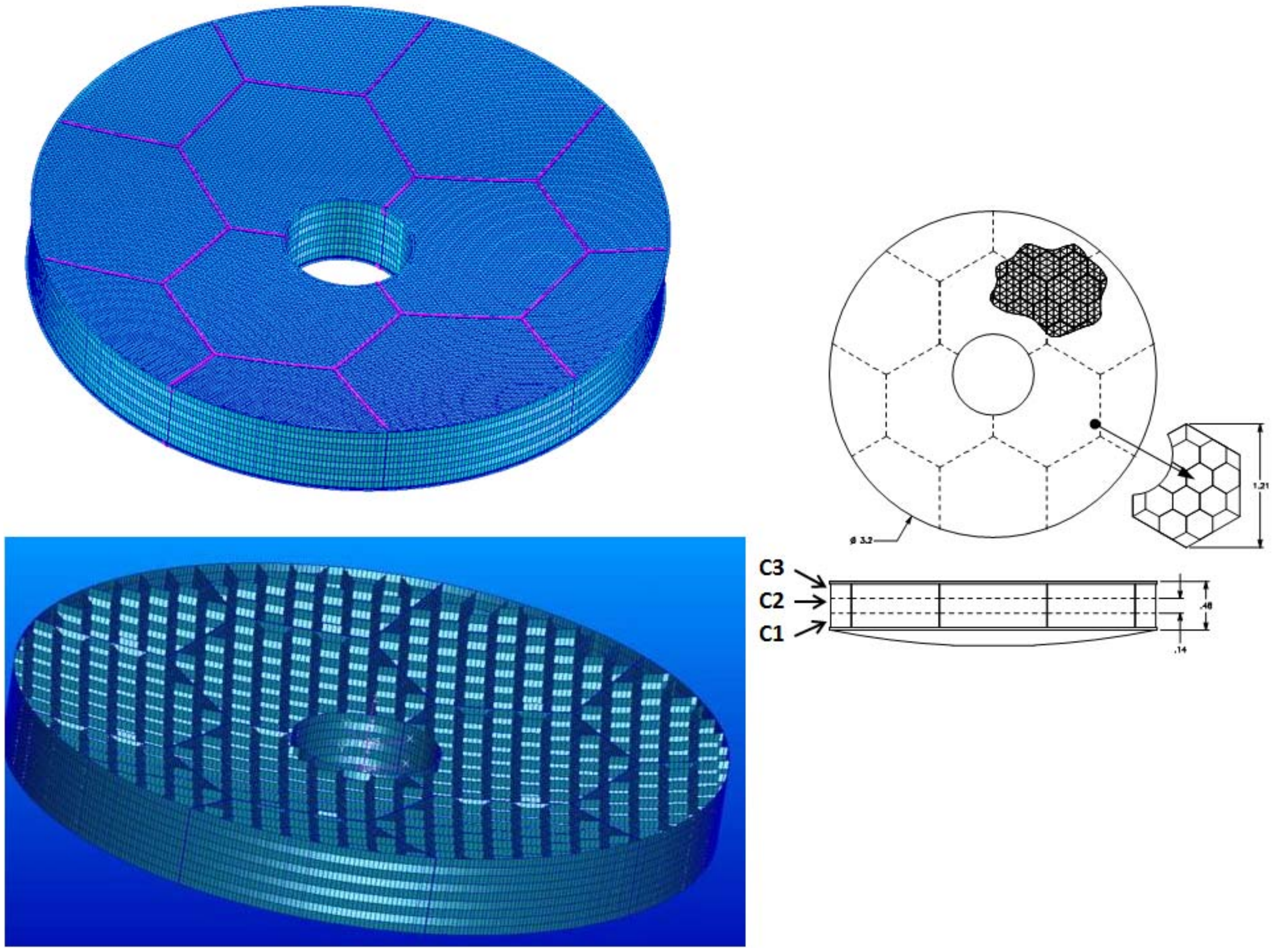


**Figure 10 - 4m design uses 12 boule sized core segments stacked three tall to create a 35 kg/m$^2$, 137 Hz primary mirror.**

The other design was an 8m monolithic design shown in Figure 11. This mirror has the following design parameters:

- Stacked core and Pocket milled face sheet design
- 24.2m RoC (f#1.5)
- The 8 meter mirror modeled to assess performance
    - Model includes light-weighted face plates joined to a light-weighted core.
    - 5% additional mass added to light-weighted sections to account for corner radii.
- Total mass was 3042 kg, 60 kg/m2
- First Free-Free mode at 33 Hz

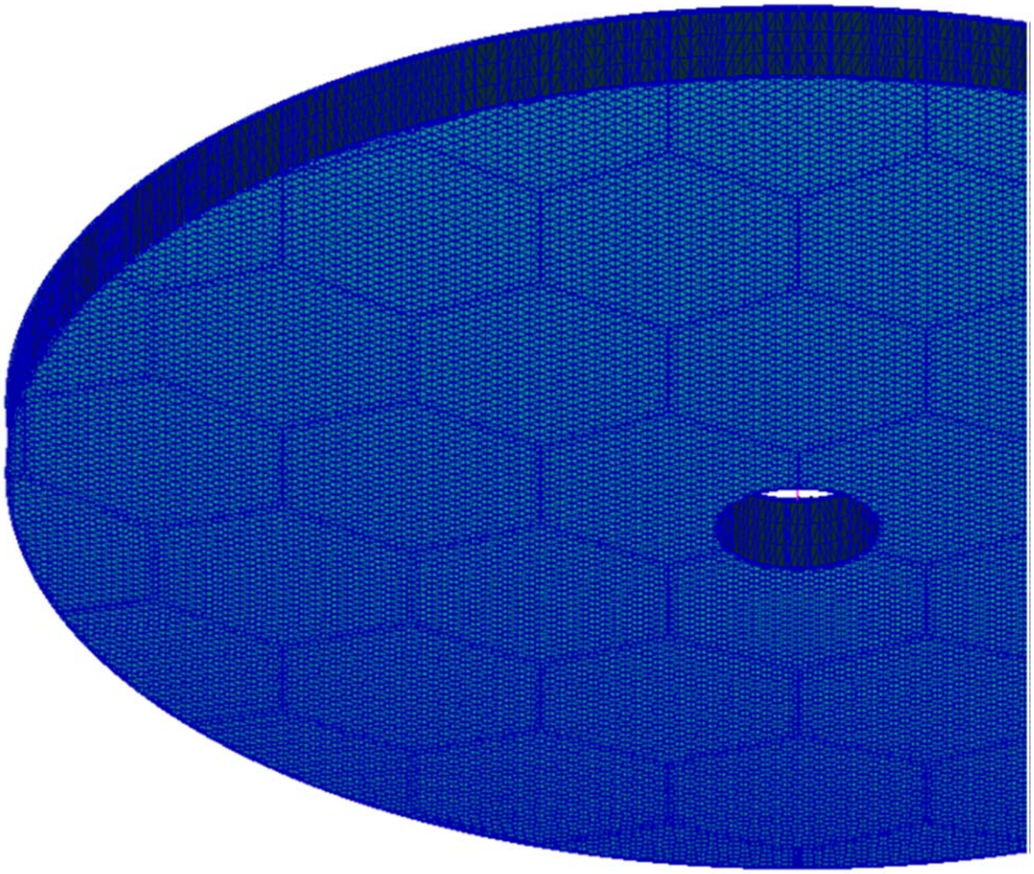


**Figure 11 - The 8m design continues to use boule-sized, stacked core segments. The low 33 Hz first mode would likely require special attention to dynamic control in order to achieve optimum optical imaging performance on-orbit.**

As can be observed, the mirror first mode is quite low and will drive other parameters of the observatory such as the need for careful consideration for vibration disturbances and likely the need for an active dynamics control system. Certainly at some point, the requirement to segment the primary mirror becomes a necessity due to overall mass and dynamic considerations. In addition, shroud diameter will also become a consideration even with the SLS 8m-10m shroud.

## 8. 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. 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 12 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.

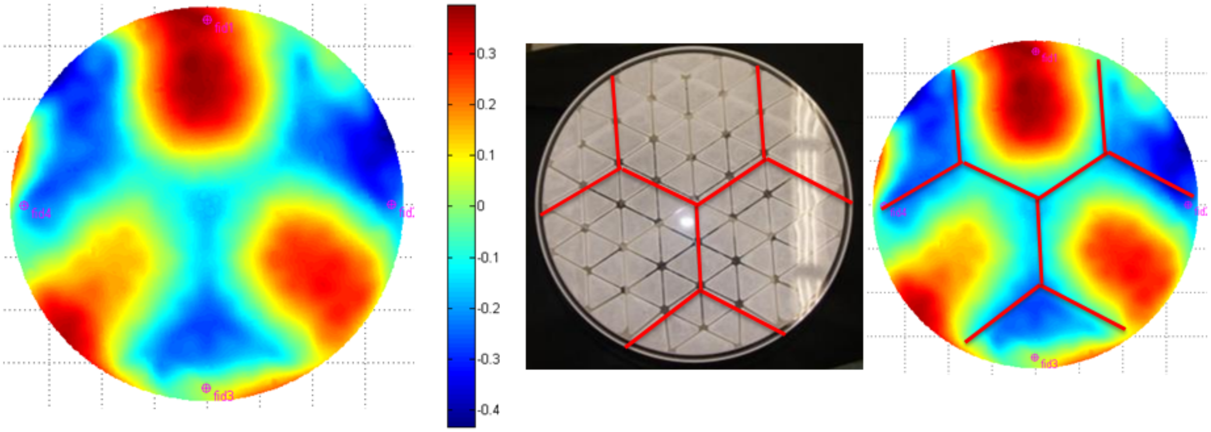


**Figure 12 - After initial conventional processing, the part exhibited global quilting due to the unsupported facesheet. This was not unexpected and is easily corrected with the ion figuring process.**

As can be seen in Figure 12, 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 13. Even though not all of the global processing quilting was removed the resulting figure error was reduced from 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 14. The figure error was further reduced by over 60% in this correction cycle which resulted in a surface figure error of 4.9nm RMS and 37nm P-V.

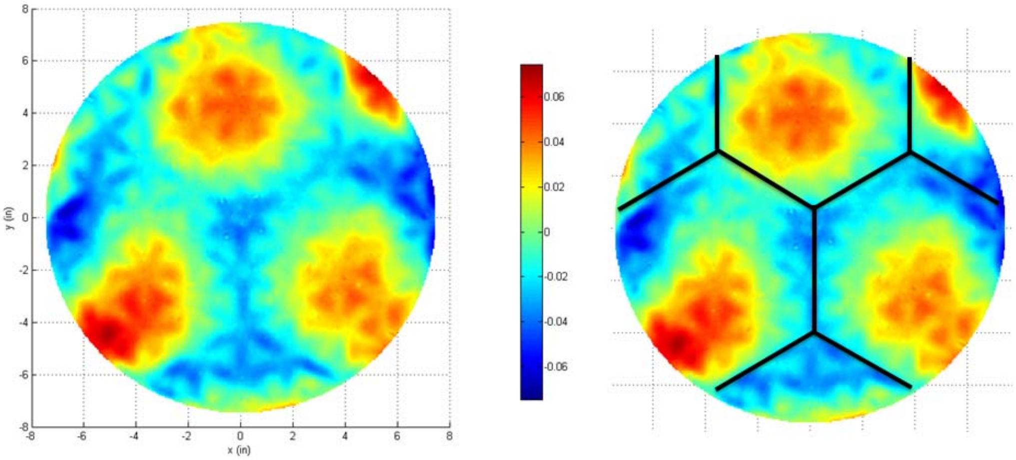


**Figure 13 - After the first ion figuring cycle, some global quilting remains. As the figure improves, the pocket milled quilting starts to become visible.**

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.

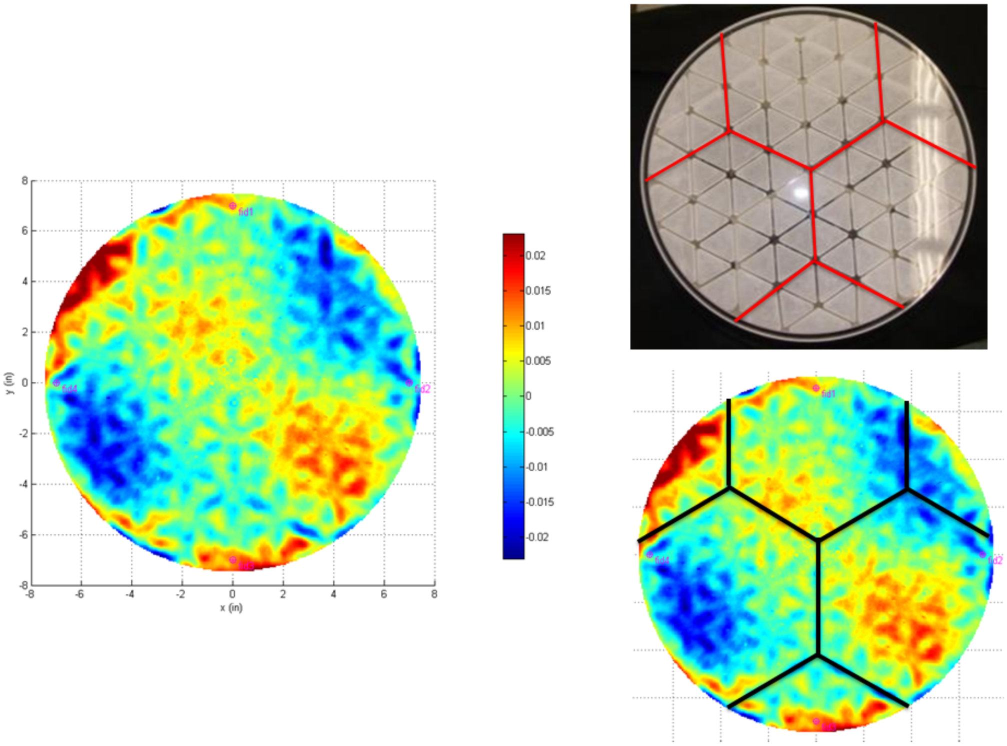


**Figure 14 - After the second ion cycle, the pocket milled quilting can be observed.**

Figure 15 shows the results of the 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 repeatability of the V-block mount shown earlier. This mount repeatability is insufficient to further reduce the figure error which drives only low order figure errors. As can be seen in Figure 15, the increase in the figure error is driven by low order aberrations from testing.

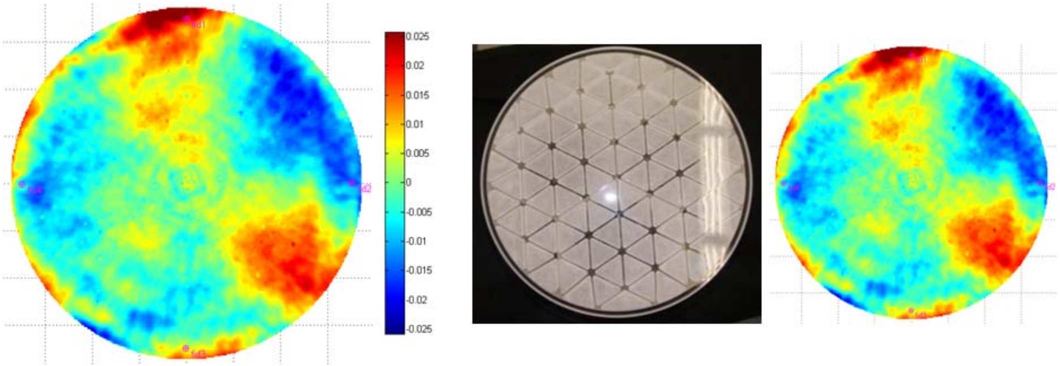
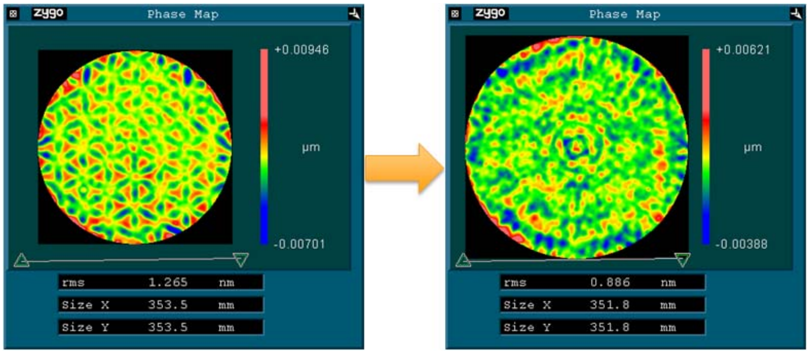


**Figure 15 - The last ion run was focused on removal of the pocket milled quilting which was very successful.**

## 9. ION FIGURING IMPACT ON MID-SPATIAL SURFACE ERRORS

Certainly one of the historical factors regarding the ion figuring process is its impact on various spatial errors. Primarily the concern is the potential degradation of the mid to high frequency surface errors due to ion ablatement. 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 16.

The spatial range shown is between 50mm and 10mm. In the image on the left, the pocket milled processing quilting can easily be seen. 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 spatially filtered phase map. The quilting error was reduced from 1.27nm RMS to 0.89nm RMS.

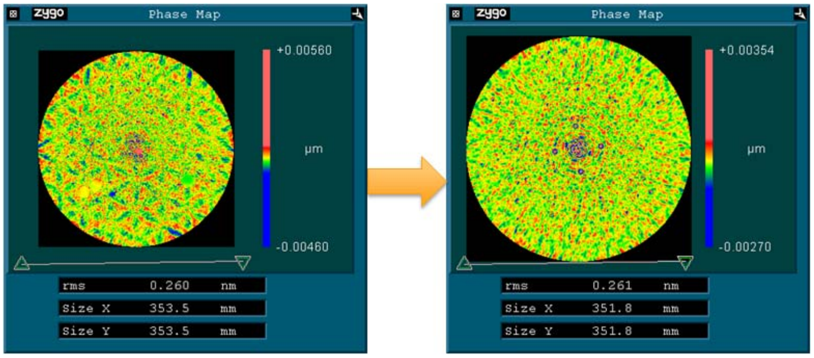


rms 1.265 nm
Size X 353.5 mm
Size Y 353.5 mm

rms 0.886 nm
Size X 351.8 mm
Size Y 351.8 mm

**Figure 16 - The ion figuring cycle focused on removing the pocket milled quilting produced a final random error that was 0.9nm RMS.**

Figure 17 shows the high spatial errors of less than 10mm. This would include the higher order spatial frequency surface errors and the result shows no change in this error value of 0.26nm RMS pre to post ion figuring.



rms 0.260 nm
Size X 353.5 mm
Size Y 353.5 mm

rms 0.261 nm
Size X 351.8 mm
Size Y 351.8 mm

**Figure 17 - No change in the high frequency error was observed after ion figuring.**

This data 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.

## 10. THERMAL TESTING

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 18. 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.

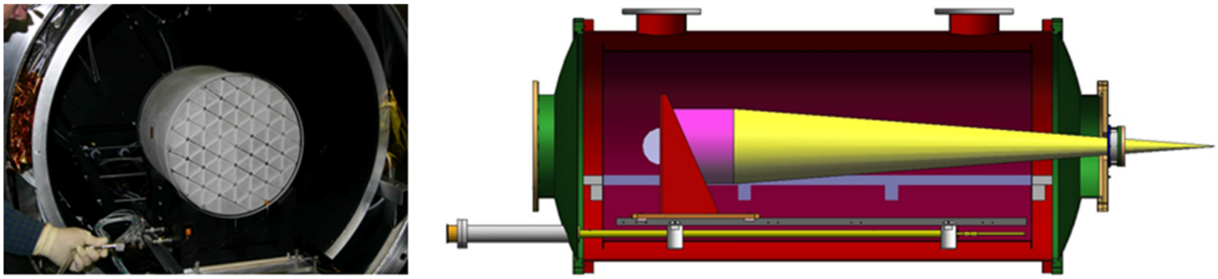


**Figure 18 - The mirror inside the vacuum chamber is shown in the left. The test of the sphere will be done from the center of curvature through a small window as shown on the right.**

Figure 18 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 19. 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.

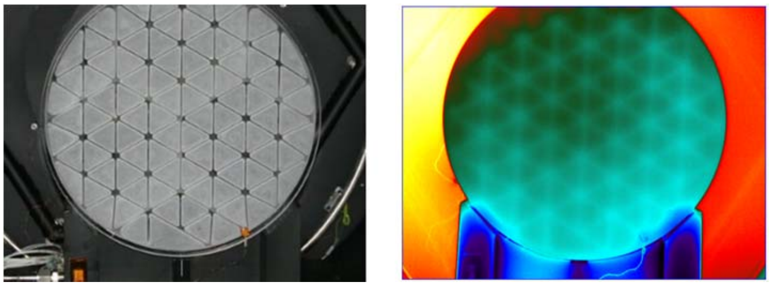


**Figure 19 - A FLIR SC655, 640x480 pixel, 16-bit uncooled microbolometer looking through a ZnSe window recorded this image during warm-up**

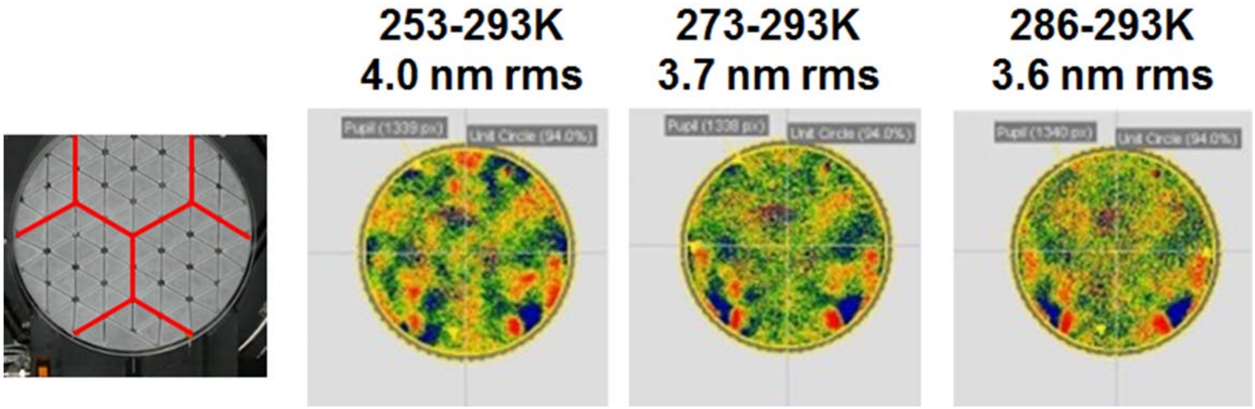


**Figure 20 – The difference maps between ambient and temperatures down to 253K are shown. Very small changes were observed and were driven by the non-kinematic mount system.**

The results show that for the 38K temperature change, a change of about 4nm RMS was observed. As can be seen in Figure 20, 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 is shown in red in the left hand frame of the figure.

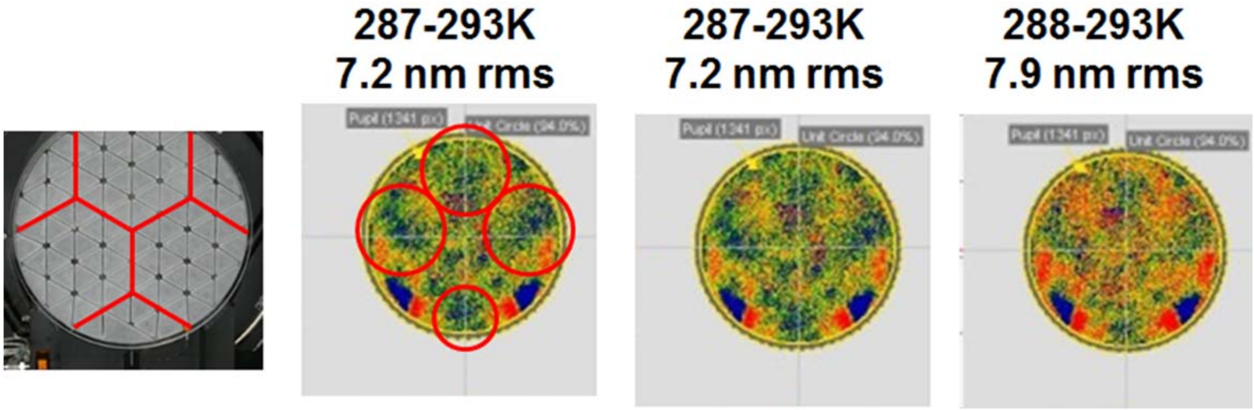


**Figure 21 – During the final thermal cycle, tests were done while a transient gradient was present in the mirror. This caused a slight increase in surface error but again was driven by the mount induced friction.**

On the final thermal cycle, a gradient was driven into the mirror to better understand thermally induced quilting. As expected, the figure did degrade more than for the isothermal environment. But as can be seen in Figure 22, the change was still only 8nm RMS and was still dominated by the mount effects. Using the picture of the mirror as a reference, a very small amount of thermally induced quilting can be observed as shown in Figure 21.

## 11. PHASE II DEVELOPMENT

A Phase II Science and Technology contract has been awarded to the MSFC/Exelis 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 be stacked with three cores high and multiple segments peripherally to create the overall lightweight core as shown in Figure 22. 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.

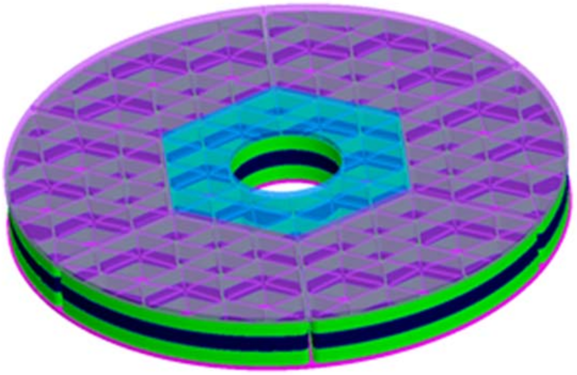


**Figure 22 – A 1.5m, on-axis mirror will be fabricated and tested.**

After processing at Exelis, the mirror will be shipped to Marshall Space Flight Center and environmentally tested.

# 12. 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.

Exelis 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 Exelis 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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