Stretched Membrane with Electrostatic Curvature (SMEC) Mirrors: A new technology for large lightweight space telescopes

Simona Errico[a], Roger Angel[b], Brian Stamper[a], James Burge[a], Tom Connors[b]

[a]Optical Sciences Center/University of Arizona, Tucson, AZ 85721
[b]Steward Observatory /University of Arizona, Tucson, AZ 85721

ABSTRACT

Exploration of faint distant objects in space has been limited by the power of telescopes. Currently our only option for studying these remote objects is to build larger and better telescopes. These giant telescopes are often constrained by system mass, which is dominated by the primary mirror. It appears that the evolutionary path of using conventional technology to build giant mirrors will not be sufficient to meet the small areal density of approximately 1.5 kg/m^2. Therefore the development of large primary mirrors for space is dependent on innovative approaches and new technology. One approach to building a large primary reflector is to use smaller individual segments and place them along a curve approximating a paraboloid. These smaller segments could be comprised of either flat or curved thin membrane mirrors. These thin membrane mirrors have the potential of meeting the small areal density requirement.

We have started development on a thin membrane mirror. We have built and are testing a 6 inch stretched membrane mirror prototype that uses electrostatic pressure to pull the nominally flat mirror to a 32 m radius of curvature and adaptively correct for aberrations. Preliminary test results of the flat membrane are promising. The surface error for the flat membrane was measured to better than $\lambda/10$ rms for the center four inches and $\lambda/20$ rms over the central three inches. The interferograms for the curved membrane show a residual figure-eight pattern of high order astigmatism, most likely due to tension anisotropy in the mirror. Analysis on the fully curved mirror is still on-going. This paper discusses the SMEC design, development, test results, and current on-going activities.

1. INTRODUCTION

Development of large space telescopes requires innovative approaches and new technology to bridge the performance gap of existing hardware, as shown in Figure 1. Historically, most optical systems have used glass to meet image resolution requirements, but glass is heavy and difficult to stow in a compact configuration within the launch vehicle fairing. The concept of combining multiple segments to form a single coherent image can provide a baseline of a few hundred meters with a collecting aperture of tens of square meters. Segmented thin membrane mirrors, as shown in Figure 2, can provide diffraction limited performance if individual apertures are corrected, coincident in the image plane, and are in phase. There are two approaches for implementing giant segmented telescopes, they include 1) naturally flat mirror segments and 2) electrostatically curved mirror segments. The SMEC mirror can be used as a flat or can be pulled to a desired curvature.

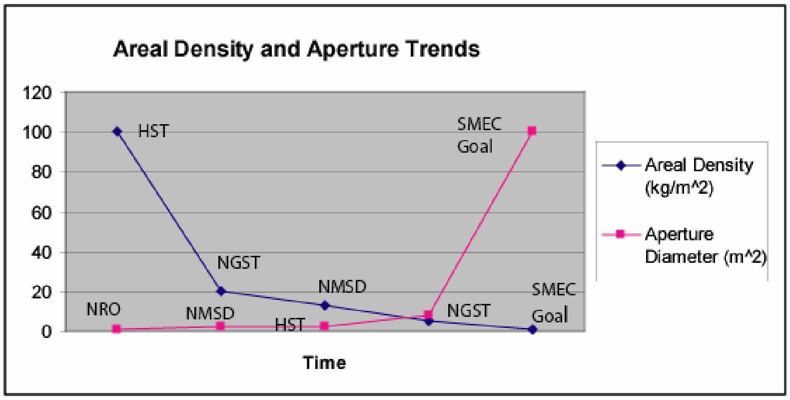

Figure 1. Innovative technologies required for building large light weight space telescopes

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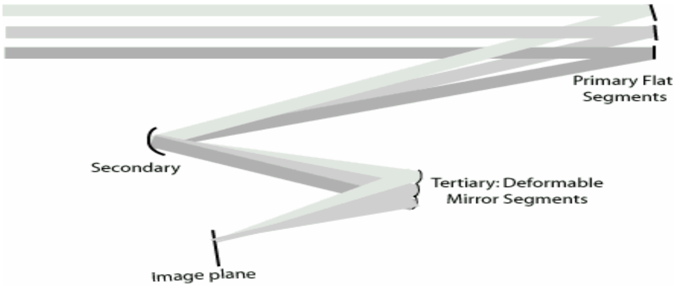


Figure 2. Segmented thin membrane mirrors bridge the technology gap

The SMEC mirror was developed to surpass current limitations in aperture size, areal density, and compact stowage of high quality optical space systems. The current SMEC mirror design and control system provides several degrees of image correction capabilities. The SMEC mirror is characterized by influence functions, which are determined experimentally for both the flat membrane and the fully curved membrane. These influence functions, typically Gaussian in shape, correspond to the overall influence that each node potential has on the shape of the membrane. Testing is underway to characterize the static and dynamic properties of the mirror.

2. SMEC DESIGN

The basic principle of the SMEC mirrors is to use electrostatic pressure to maintain a desired shape (either flat or curved) and correct aberrations in a reflective, uniformly stretched mirror. The mirror operational concept is to achieve a spherical curvature by using various control parameters, such as:

1. Establishing uniform tension across the entire thin film membrane during the manufacturing phase
2. Defining a circular boundary condition during the manufacturing phase
3. Using piezoelectric motor actuators along the boundary condition to provide real time real-time control of the membrane
4. Applying sufficient real-time electric potential to the flat membrane to correct for aberrations.
5. Applying a high voltage to pull the flat SMEC mirror to full curvature and correcting for additional errors

The SMEC hardware and functional block diagrams are combined in Figure 3 and describe the lower level functional details of each piece of hardware. For example the control computer has a GUI interface that allows the user to select an input voltage from 0-280 volts. The computer then takes the user input and converts it into an 8-bit number ranging from 0-255 and then outputs an analog signal from 0-5 volts to the high voltage control system. The high voltage control system reads the analog signal, identifies the selected channel(s) and the corresponding voltage, and outputs the specified power on the appropriate channels.

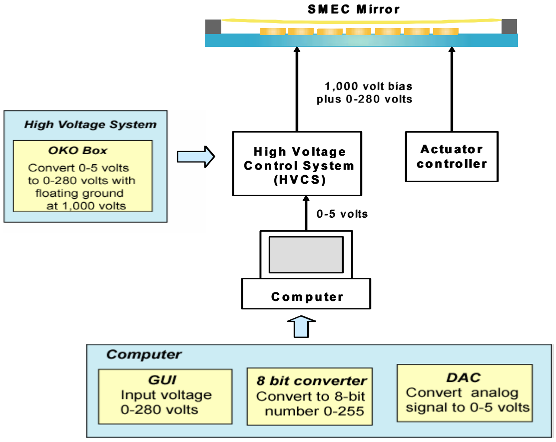


Figure 3. SMEC hardware and functional block diagram

2.1 SMEC governing principles and design parameters

The key design parameters for the SMEC mirror are derived from Coulomb's law of electrostatic fields. We assume the SMEC mirror film has uniform thickness and elastic properties. In addition we assume that it has uniform tension, with a force T per unit length, and uniform external pressure p. We have chosen the simplest solution by making the boundary circular such that the membrane takes on a uniform spherical curvature, with a radius given by:

$$R = 2T / p \tag{1}$$

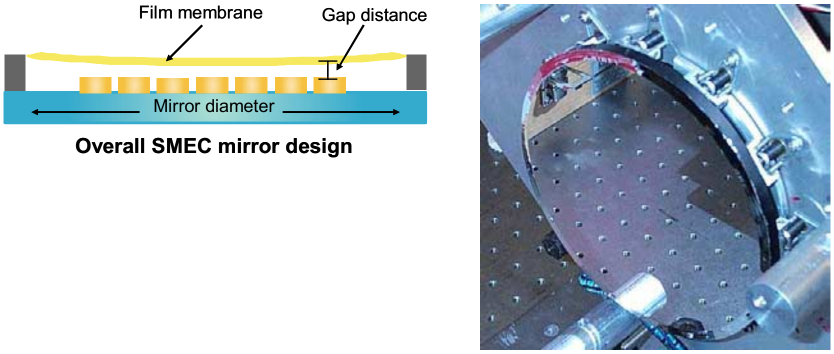
The applied potential is given by the following equation where d is the gap distance between the electrode pad and the membrane and $\varepsilon_o = 8.8510^{-12}$ F/m:

$$V = \sqrt{\frac{d^2 p}{\varepsilon_o}} \tag{2}$$

The displacement or sag of the concave spherical mirror with a diameter r and radius of curvature R is given by:

$$sag = \frac{r^2}{2R} \tag{3}$$

The overall SMEC mirror system design is shown in Figure 4. The key design parameters for the SMEC mirror, derived from the above equations, are summarized in Table 1. SMEC uses a 10 μm thick CP-1 polyimide membrane made by SRS Technologies. This polyimide has been flight tested for over 10 years and had historically been used to protect satellites from ultraviolet rays. SRS Technologies is making significant strides at achieving a CP-1 material with demonstrated optical quality.



Overall SMEC mirror design

SMEC mirror

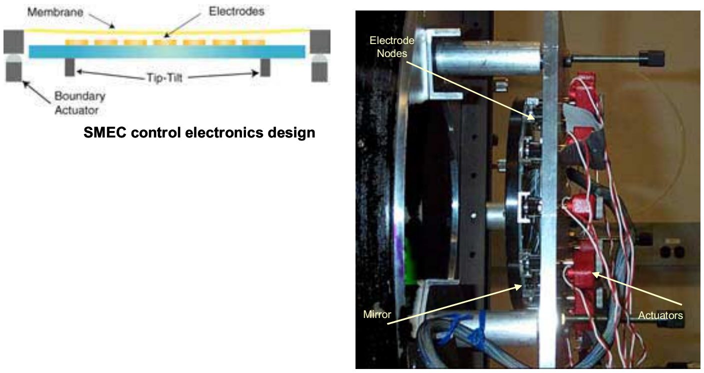
Figure 4. Overall SMEC mirror design

Parameter	Value
Membrane sag/displacement	90 μm
Radius of curvature (R)	32 m
Pellicle radius (r)	77.1 mm (3 inches)
Gap distance (d)	1.5 mm
Pressure (p)	4.64 Pa
Applied voltage (v)	1090 volts

Table 1. Summary of key SMEC mirror parameters

2.2 SMEC electronics

The shape of the SMEC mirror is controlled using the SMEC electronics. The SMEC mirror uses three essential elements to control the shape of the mirror including: actuators, an electrode pad, and a high voltage control system (HVCS). Two of the three primary elements (actuators and the electrode pad) are highlighted in Figure 5.



SMEC control electronics design

SMEC control electronics

Figure 5. SMEC control electronics design

The piezoelectric pico-motor actuators are made by New Focus. These twelve actuators are evenly placed along the boundary of the mirror and exert a force perpendicular to the mirror boundary ring to establish a nominally flat boundary condition. For an ideal control system an infinite number of actuators are desirable, however in reality the number of possible actuators is limited by the available mounting space along the mirror ring. To determine the optimal number of actuators, an analysis was performed to determine the maximum useable area of the membrane as the number of actuators increased. The result of this analysis, shown in Figure 6, indicates that the useable area of the mirror plateaus using six actuators. However, the SMEC mirror design uses twelve actuators to allow a 100% growth margin, which is acceptable during the initial development and test phase. The position of the actuators along the boundary have been optimized to provide the best control:

- Three static actuators are used to set gap distance between the membrane and the electrode pad in addition to serving as kinematic mounts
- Three active actuators are primarily used to correct trefoil error
- The remaining six actuators are used in concert to correct for astigmatism and other low order aberrations

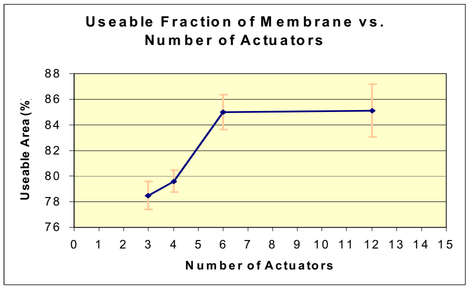


Figure 6. Useable fraction of SMEC membrane with respect to the number of necessary actuators

The second element of the SMEC electronics is the electrode pad that resides directly behind the SMEC mirror. The gap distance (1.5 mm) between the membrane and the electrode pad was selected to prevent arcing. The electrode pad, shown in Figure 7, has thirty-seven nodes arranged in a keystone pattern to ensure full coverage of the membrane. Each node on the electrode pad can be individually controlled. To control the shape of the flat mirror selective nodes are energized from 0-280 volts. To pull the membrane to full curvature all the nodes are energized at a high potential, and then based on the influence function inputs additional selective nodes are used to correct for aberrations.

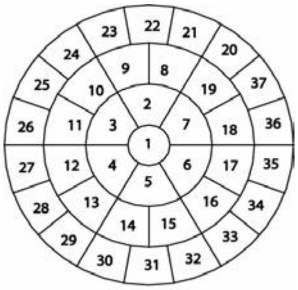
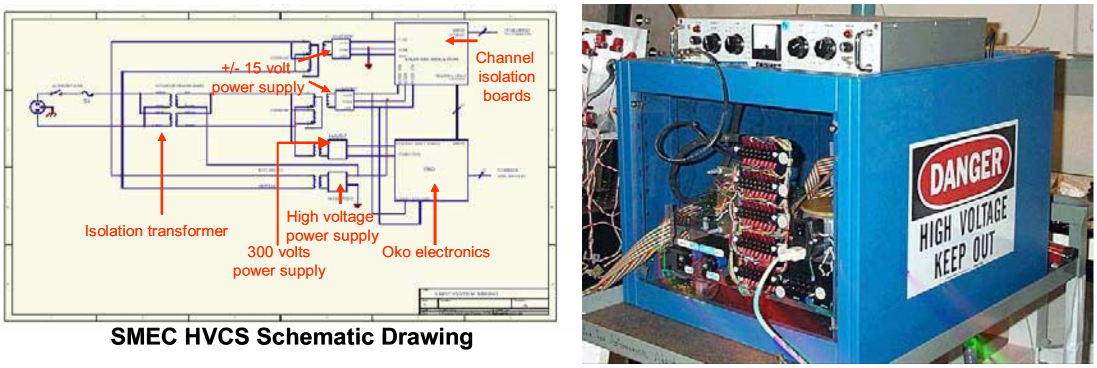


Figure 7. SMEC electrode pad uses key stone pattern to ensure full membrane coverage

The last component of the SMEC electronics includes the high voltage control system (HVCS) that works in concert with the electrode pad. The purpose of the HVCS is to provide sufficiently high voltage (up to 1200 volts) to the electrode nodes to deform the mirror to the desired 32 m radius of curvature. The HVCS design is based on a floating ground scheme, shown in Figure 8, such that ground is biased at a desired high voltage. An additional potential of 0-280 volts can be applied to the existing biased high voltage, to correct astigmatism and other low order aberrations on the mirror.



SMEC HVCS Schematic Drawing

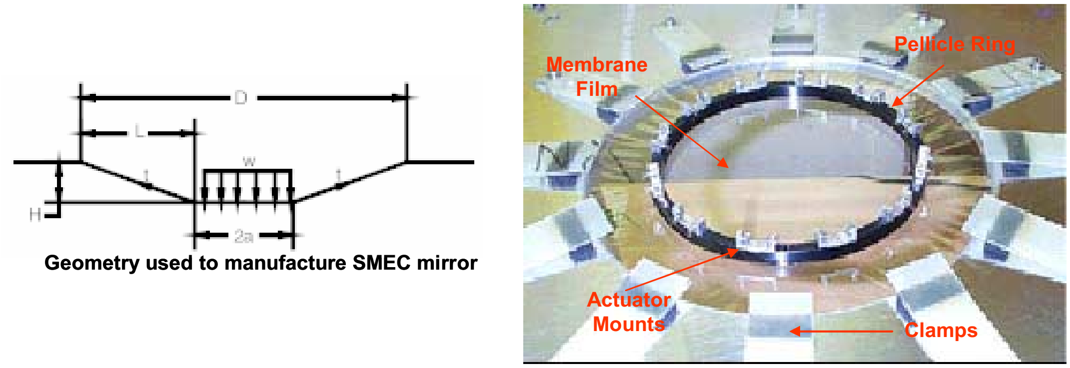
SMEC High Voltage Control System

Figure 8. SMEC high voltage control system is used to pull mirror to full curvature and correct aberrations

3. SMEC MIRROR MANUFACTURING

The SMEC mirror was built at the University of Arizona, Optical Sciences Center. The mirror is comprised of a thin membrane film and a circular boundary ring. The membrane is a 10 µm thick polyimide material developed by SRS Technologies. It is assumed that the membrane has uniform thickness. In reality the membrane has some inherent thickness variations, however these variations were not analyzed prior to building the mirror. Presently SRS Technologies continues to improve their spin-casting process to reduce the membrane thickness variations. The mirror pellicle ring is a black anodized 6061 aluminum ring built by National Photocolor. The aluminum ring has an 8 degree bevel along the top surface intended to prevent arcing. In addition, two grooves were machined out of the pellicle ring to prevent the glue form entering the landing area and affecting the membrane shape.

The key requirement to building a flat SMEC mirror was to ensure uniform tension across the mirror. The technique used stretches a sample of 10 µm thick CP-1 film, twelve inches in diameter, across the pellicle ring. The membrane was stretched using twelve discrete moment-neutral attachment points to prevent asymmetric tension in the membrane. Once the membrane was uniformly stretched, the pellicle was placed on top of the membrane as shown in Figure 9. Weight from the pellicle provided adequate tension to pull out wrinkles in the membrane caused by static electricity. Glue was then flowed into the gap between the bevel and the membrane. Several glues were tested until a viscous glue, made of two-part epoxy, appeared to work the best. The two-part epoxy exhibited very desirable characteristics. The two-part epoxy did not appear to disturb the boundary condition, displayed low shrinkage during curing, and demonstrated superb adhesion to the membrane.



Geometry used to manufacture SMEC mirror

Stretching SMEC membrane

Figure 9. Stretching technique for building the SMEC mirror

4. SMEC TESTING

The challenge of very large space telescopes is to reach a diffraction limited resolution which implies that the accumulated rms error in the reflected wavefront must be no more than about 1/10 of the wavelength under study. To characterize the SMEC mirror control system, we derive the mirror influence functions and Zernike polynomials for both the flat and fully curved mirror configurations. A WYKO 6000 phase shifting interferometer is being used to test and characterize both configurations of the SMEC mirror system. The test procedures and results for each mirror configuration are described below.

4.1 Flat Mirror Testing

We first measured the flatness of the mirror using a WYKO 6000 phase shifting interferometer. The SMEC mirror is mounted to a black cylindrical tube to ensure testing repeatability and improve membrane stability during testing. Test results indicate that the center portion of the SMEC mirror provides excellent performance, as shown in Table 2. We have been able to compare membrane temporal performance over a period of a year. The performance degradation over a period of a year is believed to be due to recent membrane defects that were observed during recent testing. During the period of a year, it was observed that the coating in one area of the membrane has started to crack. It is believed that these cracks are most likely due to temporal fatigue or the inherent hydroscopic properties of the CP-1 membrane. In addition to the coating cracking, there is a permanent indentation on a small region near the perimeter of the membrane that looks like a "thumb print" potentially caused by improper handling over a year's time. The surface roughness interferograms of the flat mirror, shown in Figure 10, demonstrate that the "thumb print" is causing local yielding across the membrane. Further analysis on how the local yielding affects the membrane strain is currently being analyzed.

A year ago performance	Current performance
Central 4 inches better than $\lambda/20$ rms	Central 4 inches about $\lambda/10$ rms
	Central 3 inches about $\lambda/20$ rms

Table 2. Summary of temporal flat membrane performance

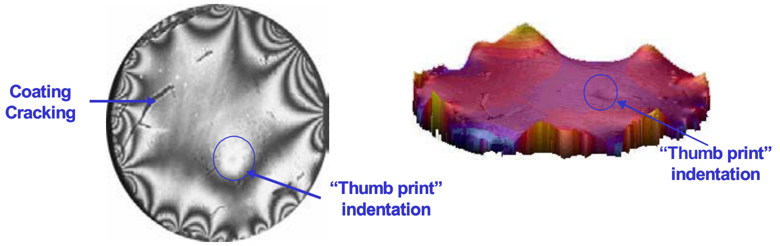


Figure 10. Interferograms of the current flat membrane a) intensity plot b) 3-D contour plot

To completely characterize the flat membrane, we look at the changes each electrode induces on the membrane surface. The compilation of the deviation caused by each electrode node is referred to as the influence function. The influence function is generated by initially taking a reference measurement of the wavefront when the mirror is flat, and then re-measuring the wavefront change when each electrode node energized. Subtracting the two measurements for all the electrode nodes results in the Gaussian shaped influence function. Figure 11 shows the surface change from a single electrode. To derive the SMEC mirror system influence function in a flat configuration we first selected the ideal voltage increment that would be applied by each node. This voltage increment was selected by identifying the applied potential that has the greatest influence on the membrane. It was observed that the greatest change to the membrane wavefront occurred at 280 volts. Next we identified the region on the electro-pad that imparted the greatest wavefront deviation. As expected, the inner most electro-nodes have greatest influence on the membrane. Finally, to build the influence function and find the wavefront correction inputs, we used the phase shifting interferometer to collect wavefront changes induced by each node energized at the maximum potential, shown in Figure 11. This wavefront data was reformatted and used to calculate the influence function which is then used to find the input voltages needed to correct the mirror shape. The wavefront correction inputs for a sample flat membrane are plotted in Figure 12. It appears that the central portion of the membrane (nodes 1-20) was indeed flat and did not require any correction. The sharp deviations along the perimeter of the mirror (nodes 21-37) are due to boundary effects.

Node 1 **Node 7** **Node 8**

Figure 11. Influence input from an each electrode energized at 280 volts

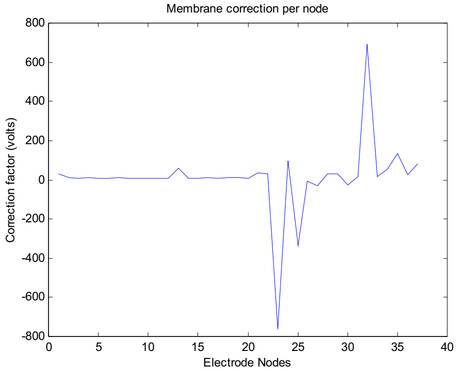


Figure 12. Wavefront correction inputs for a sample flat mirror verifies that the central portion (nodes 1-20) of the mirror is flat

4.2 Fully-Curved Mirror Testing

To completely characterize the fully-curved membrane we began by applying a biased uniform potential to pull the flat membrane to full curvature and used the interferometer to measure the surface roughness. The set-up used for testing fully-curved mirror is shown in Figure 13. A high quality null lens is inserted between the interferometer and the SMEC mirror in order to reduce the mirror focal length so that all testing can be performed on a standard optical test bench.

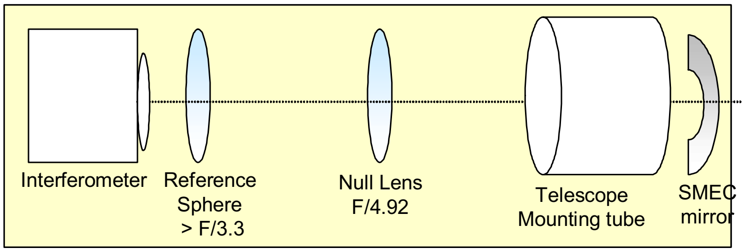


Figure 13. Test set-up for the fully curved membrane

During the most recent testing of the fully-curved mirror, two principle performance variations were observed. First, we noticed that the amount the voltage required to pull the mirror to full curvature was only about 78% of the voltage required by the mirror a year ago, shown in Figure 14. Second, we noticed that the wavefront produced by the mirror no longer matched the wavefront produced by the membrane a year ago. Figure 15, shows the resulting interferograms as the membrane is gradually brought to full curvature for the most recent tests and the tests performed a year ago. The performance of the current membrane breaks down between 800 and 900 volts.

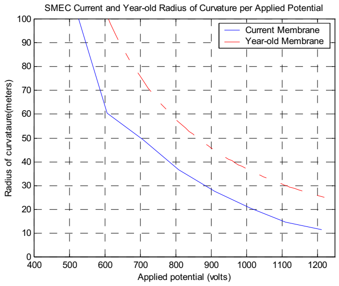


Figure 14. SMEC current and one year old radius of curvature performance

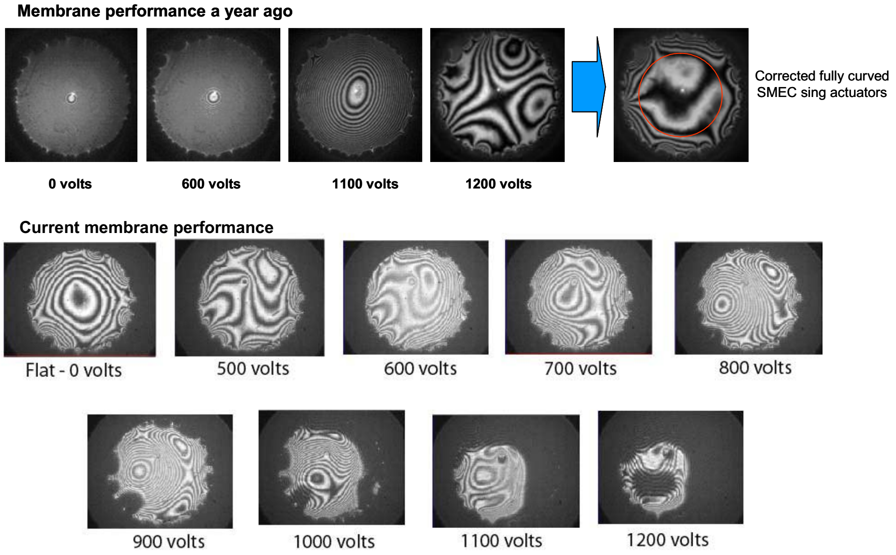


Figure 15. Comparison of the SMEC mirror interferograms while being gradually pulled to full curvature

We have identified potential causes for the performance discrepancy of the fully curved mirror including:

1. The electrode pad is no longer positioned at the defined position of 1.5 mm
2. "Thumbprint" induces local strain into the membrane
3. CP-1 membrane is self-inducing a temporal strain relief
4. Hydroscopic properties of the CP-1 material
5. SMEC mirror creep along the boundary ring caused by the glue

We have started to look at each of these causes. We have contacted SRS technologies regarding the CP-1 material properties. SRS Technologies has indicated that the properties of the polyimide are such that it would not induce an internal strain relief. We have developed a simple NASTRAN model of the SMEC mirror to simulate the results caused by the "thumb print" during test. These issues are currently being analyzed. We believe that the most likely cause is related to the positioning of the electrode pad.

5. CONCLUSION

Since the diffraction-limited angular resolution of a telescope is directly related to the aperture diameter, larger and larger space telescopes are desired. However while the desired telescope aperture size is increasing, the size of the launch vehicle remains the same. These opposing requirements demand the introduction of innovative approaches and new technologies.

The SMEC mirror is one such technology that can be used in segmented giant space telescopes. The flat SMEC mirror preliminary test results are very promising. The fully-curved SMEC mirror requires additional testing and analysis to explain the discrepancy of performance.

We are in the process of acquiring newly characterized CP-1 from SRS Technologies to build another 6 inch mirror. In addition we hope to use the model created from the 6 inch SMEC mirror results to build a larger 1 foot SMEC aperture.

6. REFERENCES

1. J.H. Burge, E. Sabatke, J.R.P. Angel, N.J. Woolf ,"Optical Design of Giant Telescopes for Space" in *Novel Optical Systems Design and Optimization III*, J. Sasian, Eds., Proc. SPIE **4092**, 2000
2. B. Stamper, R. Angel, J. Burge, T. Connors, B. Duffy, N. Woolf, "Stretched Membrane with Electrostatic Curvature (SMEC) Mirrors for Extremely Large Telescopes"
3. J.R.P. Angel, J.H. Burge, and N.J. Woolf, "Extremely large space telescopes and interferometers made with flat primary mirrors," *Gossamer Optics Workshop* http://origins.jpl.nasa.gov/meetings/ulsoc/angel.pdf
4. B. Stamper, R. Angel, J. Burge, and N. Woolf, "Flat Membrane Mirrors for Space Telescopes", in *Imaging Technology and Telescopes*, Proc. SPIE **4091**, 2000