Stretched Membrane with Electrostatic Curvature (SMEC) Mirrors for Extremely Large Space Telescopes

Brian Stamper[a], Roger Angel[b], James Burge[a,b], Tom Connors[b], Brian Duffy[b], Neville Woolf[b]

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

ABSTRACT

Very lightweight mirrors can be constructed by stretching a membrane to form a flat surface. Adding tension to the membrane, making it flat, can be done by discrete attachment points, or by using a continuous boundary. Such lightweight mirrors are very attractive for space telescopes where a 100m aperture can be made up of smaller mirror segments.[1] Adding a slight curvature to each segments simplifies the optical train.[2] This article looks at the making of a curved membrane mirror, and demonstrates its use. Measurements of the flat membrane, and the curved figure will be shown.

Keywords: gossamer, space telescopes, ultra-lightweight primary mirrors, membrane mirrors, SMEC

1. INTRODUCTION

1.1. A Case for Large Space Telescopes

To see tiny objects in the sky, or to see faint remnants of our universe's beginning requires ever improving resolution from our telescopes. A reflecting telescope has a resolution limit of λ/D set by diffraction. The wavelength of interest is λ, and D is the diameter of the primary mirror. Using adaptive correction of the atmospheric turbulence, the current class of 6-10m mirrors are reaching image sharpness previously only seen by the Hubble Space Telescope (HST). The Large Binocular Telescope (LBT) is predicted to produce ground based images with ten times better resolution than the HST.[3]

Increasing size of ground telescopes beyond 10m in a single piece of glass is impractical due to the immense weight. Future ground telescopes such as the California Extremely Large Telescope (CELT), or the 20/20 Telescope would have composite primaries with segments based on current technology. Keck is the only facility that has already abandoned monolithic primary mirrors. Ground based telescopes are still limited at wavelengths beyond $2\mu m$ from absorption and the thermal emission from the mirrors and surrounding structure. Even with perfect correction, residual atmospheric effects would blur any faint objects.[4] A telescope outside the Earth's atmosphere would be exposed directly to the entire spectrum of star light, but would necessarily be segmented.

Payload size and mass limits of current launch vehicles dictate what can be put into orbit in one launch. For a large space telescope of 100m, segments must fit into the payload volume available whether assembled or folded. Segments should be light to ship several, or all of them at once. Membranes offer the solution of packing many segments together to be assembled in space. Unlike a rigid optic that must have at least a bed of actuators, membrane mirrors need only be supported at the boundary. This makes packing the segments into a much smaller space very easy.

Further author information: (Send correspondence to BS)
BS: stamper@optics.arizona.edu
RA: rangel@as.arizona.edu
JB: burge@optics.arizona.edu
NW: nwoolf@as.arizona.edu
BD: bduffy@as.arizona.edu
TC: tconnors@as.arizona.edu

1.2. Edge defined mirrors

One method for making lightweight mirrors uses a thin facesheet of glass. The glass is typically one or two millimeter in thickness. A stiff lightweight support structure holds many actuators that shape the mirror by applying a force at points across the surface. This works very well as demonstrated in .5m and 2m prototypes,[5,6] but still requires a structure that covers the same area as the mirror. Another method defines only the boundary of the mirror.

By only defining the boundary, weight is limited to the space around the edge of the mirror. The figure of the mirror is controlled by actuators at the edge of the membrane. Actuators can be connected directly to the mirror surface at discreet points. The surface could also be indirectly coupled to the actuators through a structure such as a pellicle ring. In this case, the membrane is defined by a continuous boundary, and the ring is nudged by actuators attached to the stiff frame around the circumference.

Two approaches stand out when using a continuous boundary. If a very heavy ring is used, tension and optical figure must be adjusted in-situ before being glued to the support. Such a stiff support must be rigid and may be heavy, but no further adjustment can be done. A SMEC mirror uses a lightweight ring, and actuators to compensate for uneven tension and bending in the ring. Assembly and applications for this type of mirror is the focus of the following discussion.

2. ADDING POWER TO MEMBRANES

Simple behavior of the pellicle can be seen if the membrane is uniform in material properties. Applying uniform tension and external pressure produce a spherical curve the details of which have been discussed previously.[7] Errors in this configuration decrease radially as $r^n cos(n\theta)$, where r is the radius and n is the order of control, or the number of points controlled at the boundary. Local deviations at the edge will not significantly decrease the usable area of the mirror. As the diameter increases, the ratio of the useable area to the total area will continue to climb if the density of actuators remains constant.

The residual stress, or prevailing tension placed in the membrane during manufacture, determines the pressure on the membrane needed to reach a given curvature. Figure 1 shows the geometry used to make the pellicle for SMEC. The outer diameter of the hole, D, in the support plate is 9.5 inches. Weight, w, can be the ring itself. Changes in the tension, and in the angle between the membrane and ring occur by adding weight across the ring.

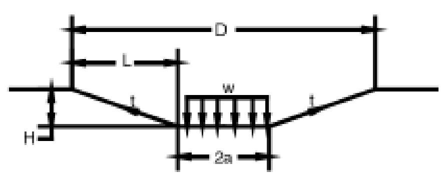

Figure 1. Geometry of pellicle and mount used for manufacturing. The tension can be varied by changing the weight, w, that changes the displacement, H.

To find the tension in the membrane, we start by calculating the angle formed by H and L.

$$\theta = \tan^{-1}(\frac{H}{L}) \tag{1}$$

The pressure per unit thickness of the membrane is the residual stress, or tension in the material. Weight per unit length of contact with the ring divided by the sine of the angle formed as the weight descends gives the pressure around the ring. Divide by the material thickness and simplifying will show the tension in the membrane. Steps are shown below for this calculation:

$$p_r = \frac{w}{c_p sin\theta} \tag{2}$$

$$= \frac{wt}{c_p H} \tag{3}$$

$$\sigma_p = \frac{w}{c_p H} \tag{4}$$

The sagittal depth needed for a specified radius of curvature, R, is given

$$d = \frac{r^2}{2R}. \tag{5}$$

The equation for the pressure required, once the sagittal depth has been specified, follows:[8]

$$P = 1.828\left[\left(\frac{Et}{a^4}\right)d^3 + \left(\frac{1.66t\sigma_p}{a^2}\right)d\right]. \tag{6}$$

Young's modulus, membrane thickness, t, pellicle radius, a, the residual stress, σ_p, and the sag, d, are needed. For SMEC, the pressure is applied electrostatically,[2] but it can also be applied by vacuum. Vacuum, however, would be of no use in space, but the theory is the same for both methods. Finding the pressure and tension by the above method, and using previous theory[2,7] correspond within a few percent.

Using CP1 from SRS Technologies, and a gap of 1.5 mm, the above equation gives the pressure needed to be 4.64 Pa. With $\varepsilon_o = 8.85 \cdot 10^{-12}$ F/m, we get

$$p = \varepsilon_o E^2, \tag{7}$$

where E is the electric field strength in Volts per meter. We then calculate the voltage required by dividing the gap distance into the field strength. For this example, the applied voltage should be 1086 Volts.

3. MAKING A SMEC MIRROR

The rings are six inches inside diameter, and are one quarter inch thick. A cross section of the ring is in Figure 2. A bevel is placed on the top surface. After anodization, the ring is machined to form a land on the inner edge of the top surface. This land will define the boundary of the pellicle ring. The sloping area due to the bevel provides a surface for the glue to adhere without affecting the boundary of the pellicle.

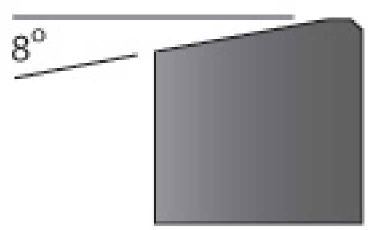

Figure 2. Cross section of ring used for SMEC.

We use rings from National Photocolor that are 6061 Aluminum and come black anodized. The land which controls the boundary of the membrane is lapped flat. Tool marks can still be seen on the land, and although flat, doesn't provide a specular reflection. To take advantage of optical testing techniques, we polish the surface to a much smoother finish. Taking out the roughness of the surface without changing its shape lets us get a reflection we can use for testing. We saw about 4λ of deviation across nearly half of the ring, proving that they are reasonably flat. We use a WYKO 6000 interferometer that has a six-inch aperture. We must piece together two measurements to build a map of the entire land.

Polishing the ring was done by first mounting the ring to a flat plate. We used a half inch thick aluminum plate that matched the 6.5 inch outer diameter of the ring. This is convenient for us, as long as the brackets haven't been glued to the ring, but the whole idea is to find a way to hold the ring during polishing. Putting the ring in contact with a flat lap, typically of iron, worked well when using an abrasive of $5\mu m$ diamond dust suspended in olive oil. India ink was then used to clean, and brighten the polished surface. India ink is often used by itself to polish aluminum, and worked very well for our application.

Further ring modifications have been deemed necessary. If the difference between the membrane angle, and the angle of the bevel is large, the adhesive will wick onto the land. Two grooves were machined into the land.

One groove is halfway down the bevel, and the other is between the first groove and the outer edge of the ring as shown in Figure 3. It is important to have a sharp tool, or the anodization may splinter. The tool will be dulled some since it must cut through the anodization first. Quick cuts that remove small amounts of material work best. Otherwise, heat builds up that could warp the ring. If grooves are needed, polishing should be done as the last step.

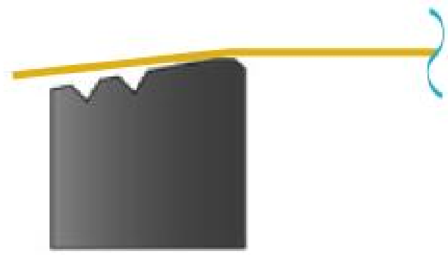

Figure 3. Location of grooves that limit capillary action between the ring and the film. Note the contact point of the film that defines its boundary.

3.1. Control Point Attachment

The current iteration of the mount uses moment-neutral spring assemblies to bias a point against a New Focus picomotor actuator. We fix three points as a plane of reference. These three control points are modified so they form a kinematic mount. This keeps the entire ring positioned laterally.

It was found that contact between the ring and the mount points was establishing a conduction path to ground for the high voltage charge we were trying to place on the membrane. The picomotor and/or springs make a perfect conduction path from the mount point to the backplane.

The epoxy used to attach the mounts to the ring is an insulator as is the oxide formed in anodization. Even a very high resistance can allow enough conduction to bleed the high voltage to ground. This happens when the mounts come in contact with the anodized ring. We now put small insulating spacers between the mounting points and the ring. Strips of PVC tape make great insulating points, and they also provide uniform glue joints around the ring.

3.2. Membrane Gluing

We require that the membrane be able to deflect under pressure, electrostatic or vacuum, as much as $200\mu m$. This is a much larger sag than most pellicles can deflect before being plastically deformed. Most pellicles have a large tension, and are not used in an application that requires any deflection. Since we are making a mirror we must use as little tension as possible that will still keep the membrane from wrinkling while it is flat and doesn't have a pressure applied.

We start by attaching the membrane to a frame with an 9.5 inch hole cut in the center. The material is spread flat over the hole, and clamped to the frame at 12 locations. It is important to keep from putting any asymmetric tension in the material as we want it with zero strain at this point. The film and the mount are sprayed with dry nitrogen through a deionizing nozzle until it is clamped to minimized static charges on the membrane. We then set the ring on the center of the membrane as shown in Figure 4. Weight from the ring alone provides enough tension to pull out wrinkles from static electricity, or from stress in the membrane. At this point, if we want more tension we can add weight to the ring.

Glue is then flowed into the gap left between the bevel and the membrane. A generic cyanoacrylate was used first since it will easily flow into the gap, but it tends to cause some puckering. It is so thin that application is only done at two points, and capillary action pulls it around the rest of the ring. Cyanoacrylate and other solvent based glues attack the membrane, and shrink as they dry. This makes it nearly impossible to get a uniform boundary. We feel that a more viscous glue would result in a better boundary condition for the optical surface.

Figure 4. The ring is lying on the membrane. Tension is due only to the weight of the ring.

Dental adhesive is UV cured, decreasing the cure time from 24 hours to 30 seconds. The chances of causing a problem before it is cured are eliminated. It will even be possible to put a thin coat of the adhesive on the ring before it is set onto the membrane. This would decrease the wrinkling problem caused by the glue wicking around the ring from one or two application points. A jig could be made to ensure that the ring was lowered evenly.

Unfortunately, UV curing is impractical with most of our materials. They are used for UV protection in space, and block nearly all UV wavelengths. Since our rings are aluminum and not transparent, we must apply UV light through the membrane to cure the adhesive. It does not even become tacky after 24 hours of exposure so a new glue technique must be found.

A more viscous glue that is a two-part epoxy designed for attaching connectors to fiber optic cable seems to work best. The combination of increased viscosity, and two grooves on the rings has kept this from disturbing the boundary conditions. We want the land to be the only part of the ring contributing to the defining boundary. Another benefit is very low shrinkage as the epoxy cures. A bead of epoxy is placed on the membrane a couple millimeters from the outer edge of the ring. It will then slowly flow down to the ring, and onto the bevel up to the first groove. The increased viscosity decreases the chance of jumping the grooves so the gluing area is limited to the outer edge of the bevel. This works great due the the smaller gluing area, and the superb adhesion of the epoxy to the membrane and ring.

4. LABORATORY TESTING

Testing started with flatness measurements over the entire six inch clear aperture. Once the mirror is flat, we know the condition of the ring used as the boundary. The system shown in Figure 5 has 12 actuators at the boundary that work perpendicular to the plane of the mirror. All astigmatic orders up to 6θ can theoretically be corrected as well as the low order aberrations of piston, tip, tilt, and focus. Remaining errors result from displacements or moments that can only be corrected with a higher density of actuators.

The 6-inch membrane was quantified flat so the boundary position was known. A flat surface is one method of building a very large space telescope.[9] Figure 6 shows an interferogram of a flat SMEC mirror. Edge effects from higher order aberrations are still present, but rapidly decrease toward the center. Any dust or debris on the land will contribute errors as well. Surface error of the membrane over the central four inches is better than $\frac{\lambda}{20}$ RMS.

4.1. Electrostatic Curvature

Mirror figure was tested while curved by electrostatic pressure. The configuration is shown in Figure 7. A radius of curvature of 32m is used in the SMEC telescope. To keep the testing distance reasonable, a lens is used to bring the focus closer to the mirror. The focus coincides with the focal point of a reference sphere on an interferometer

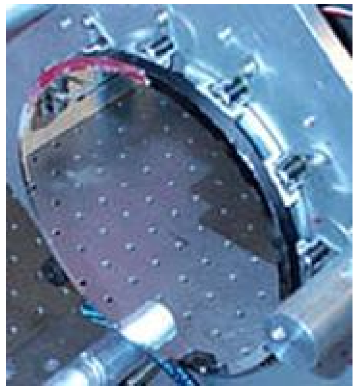

Figure 5. Six-inch SMEC mirror showing picomotor actuators at edge.

Figure 6. Interferogram of a six-inch SMEC mirror optimized for flatness.

for very accurate surface profiles. The system requires 1090 volts to pull a 32m radius of curvature, if the gap is 1.5mm between the electrode pad and the membrane. Theory previously discussed corresponds to experiment surprisingly well. A uniform potential across the entire electrode board is used first.

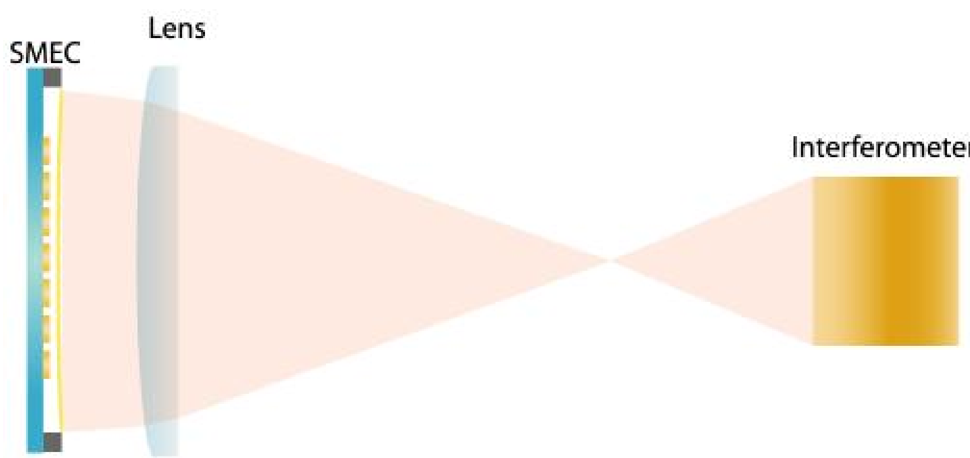

Figure 7. Setup to test 32m radius of curvature. A lens enables the test to be done in a four meter space.

Figure 8 shows the change in the membrane as the voltage increases from zero to 1200. The potential is larger here because the electrode board was tilted away to make the gap more symmetric. This required slightly more voltage since the gap has increased. The rightmost picture shows a figure-eight astigmatism. Focus is at the circle of least confusion, but this is not pure third order astigmatism. The astigmatism is constrained by the planar circular boundary of the ring. An error of this shape is most likely due to anisotropic tension in the membrane. Of course, the same effect would appear if the material properties were not isotropic.

If the tension is different along perpendicular axis of the membrane, the radii of curvature must be different. The fixed circular boundary is also a factor in defining the shape. Pure astigmatism would require the boundary to deviate from planar. The figure-eight pattern can be modelled as a combination of several higher orders of astigmatism. Surface error over a four inch subaperture is better than $.16 \pm .02$ waves RMS. An equation to model the actual shape of the surface would be a simpler approach to model the figure-eight astigmatism. This requires finding the shape of astigmatism constrained by a circular boundary.

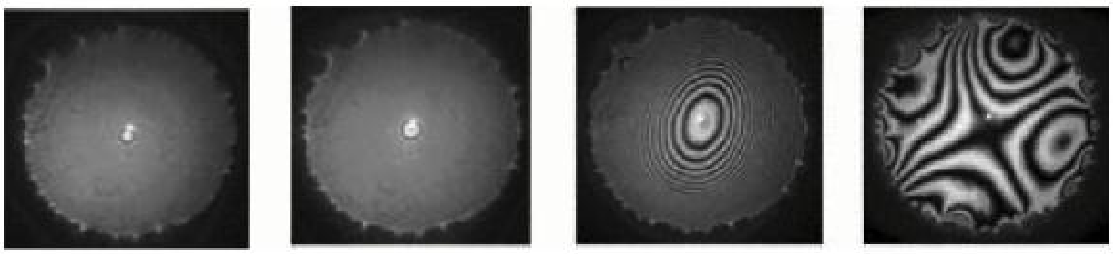

Figure 8. Voltage increases from left to right starting at zero volts. The potential increases to 600, 1100, and 1200 volts ending on the right.

We can improve central portion of the membrane by letting the boundary deviate from planar. If we manipulate the edge actuators appropriately we can significantly improve the central portion of the membrane. Figure 9 shows how well the center four inch section can be improved. Any residual errors would not make the membrane useless. We can recover good imaging over most of the surface.

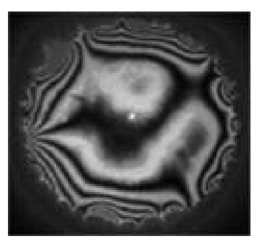

Figure 9. Center improved by changing the boundary shape. Mirror is deformed by 1200V, with power removed.

If we start from a flat membrane again, we can look at the changes each electrode can make to the surface. The change is called the influence function of the parameter we are manipulating. We take a reference measurement when the surface is flat, then take another measurement with a single electrode energized. Subtraction between the two leaves the change that the electrode induced. The left map in Figure 10 shows the surface change from a single electrode. Dotted lines indicate the location of the individual electrode pads. Change in surface when the entire electrode board is tilted is the right of Figure 10. The tip-tilt control is located at three equidistant points on the electrode board.

We now have two levels of control input to the surface shape. Larger off-axis errors, such as coma, can be improved with tip and tilt. Small, local errors can be changed by varying the potential on individual electrodes. A very high level of aberration control is now available, and the electrode density could be increased if needed.

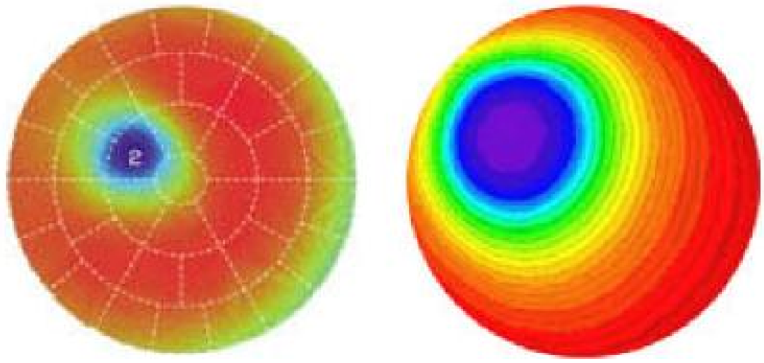

Figure 10. Influence function from a single electrode at left. At this location on the membrane, the maximum surface change is 2 waves. Influence due to tip-tilt of the electrode board is shown at right.

5. CONCLUSION

We have seen that membrane mirrors can produce regions of very good surface quality. All methods do date have some edge condition that prohibits using one hundred percent of the surface. Larger membranes have a smaller area lost to these effects. Increased size, and lighter support structures make membrane mirrors very attractive for space telescopes.

Membrane mirrors are very susceptible to acoustic vibrations. Testing is more difficult as a result, but in space the effect is not present. Extremely large membranes would not sag under their own weight in space either. These problems make membrane mirrors impractical for ground based applications, but perfectly suited to space.

Getting to 100m class telescopes is a difficult path. Large enough pieces of membrane material aren't currently available for six meter class segments. The surface quality must be of optical quality, and is being continually improved by the manufacturers. Most membrane materials have applications that don't require an optically smooth surface. Components must be packaged with care not to cause any defects in the membrane. At this point in time, assembly in space would be the only way to get 100m class telescopes into orbit.

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