Flat Membrane Mirrors for Space Telescopes

Brian Stamper[a], Roger Angel[b], James Burge[a,b], and Neville Woolf[b]

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

[b]Steward Observatory/University of Arizona, Tucson, AZ 85721

ABSTRACT

Current work concentrates on making optically flat mirrors using stretched membranes. Very lightweight mirrors can be made that only require a rigid support at the perimeter of the membrane. Contact with the membrane need not be continuous, only discrete attachment points are required to tension the material. Initial results of useable area as a function of the number of attach points will be given. Experimental fixtures demonstrating methods of forming a flat membrane are shown. The potential for nearly flat mirrors is mentioned including one method of implementation. Surface measurements are also contrasted for different materials.

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

1. INTRODUCTION

1.1. The Need for Large Space Telescopes

Building telescopes that look farther back in time, at objects that are increasingly dim, pushes the ability of current technology. New methods must be developed at if we are to probe more deeply into the history of the universe. The lack of space travel requires that we develop telescopes that will meet these goals without leaving our local solar system. Such an imaging system would create sharper images than available today.

The resolution of a space telescope, providing sufficient optical quality, is fundamentally limited only by the diffractive nature of light itself. The diffraction limited resolution (in radians) is given by λ/D where λ is the wavelength of interest, and D is the primary mirror diameter. Pushed to larger and larger mirrors, space is the only logical place where the scale can be tens or hundreds of meters. The advantages gained outside the atmosphere and gravitational effects let us open the doors to new technology not applicable to ground based systems.

Hubble gave us a factor of 10 increase in sharpness that has dramatically enhanced our ability to look at the universe. Another factor of 10 increase would require a 24m diameter primary. Two NASA programs are in the planning phases that envisage telescopes of this magnitude: the Origins program's Life Finder and Planet Imager missions. Life Finder will use a high sensitivity

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

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spectroscope to probe for biogenic gases in the atmospheres of Earth-like planets around other stars. Another program is the $\sim$ 25m infrared telescope (FAIR), under study by the OSS Large Telescope Systems initiative. The ultimate goal set by NASA for extremely large telescopes in space is the imaging of extrasolar, Earth-like planets by Planet Imager. This could be done by many telescopes of the 40m diameter class in an interferometric array extending over thousands of kilometers. Pushing to 100m apertures, however, provides an alternative to using many telescopes in an array, but introduces other technological hurdles to overcome.

Earth reconnaissance may also benefit from increased telescope size by giving the sharpest possible images of Earth, or to allow broad coverage from a telescope in a higher orbit. For example, a single 30m optical telescope in a 5000km equatorial orbit could reach the same atmospherically limited resolution of 10cm as the current LEO surveillance satellite, but could cover all equatorial and temperate latitudes every orbit. The same satellite in geosynchronous orbit would have diffraction limited resolution of .5m with the added benefit of continuous coverage.

1.2. Producing a Very Large Telescope

The tolerances needed for imaging do not change as the size of the telescopes increase. If they are to reach the diffraction limit discussed above, the accumulated error in the reflected wavefront must be no more than 1/15 of the wavelength under study. For visible light ($\lambda = 550$nm) the tolerance of the mirror surface is 18nm rms. For thermal IR, it is .36μm. Large diffraction limited telescopes for visible light need nanometer accuracy over an entire segment that could be tens of meters across!

A large reflecting primary mirror could be made by using multiple flat elements.[1] Segments could be joined together with the optical surface tangent to a base sphere, or parabola. In space, large flat reflectors could be made from stretched membranes. To provide an accurate optical surface the membrane must have uniform thickness, and its perimeter must be held in a plane. In practice the surface would be controlled by a discrete number of actuators along the boundary. Flatness would be actively maintained using wavefront measurements in a closed-loop system.

A segmented primary made from flat mirrors would need the wavefront returned to a continuous surface. A segmented, or scalloped, corrector is placed at an image of the primary. It is faceted so that an equal and opposite amount of departure resulting from the segmented primary, is added to the wavefront.[2] A small amount of curvature added to the segments eliminates the need for wavefront correction downstream, such as a scalloped tertiary. A near flat, but concave reflector can be made by configuring the mirrored surface as one plate of a capacitor. A small pressure can then be applied electrostatically, forcing the mirror into a curved shape.[3] Similar mirrors have been used for years as corrective elements,[4] and have been recently used as primary surfaces in large scale optical systems. If a parabola is chosen as the base surface, an off-axis parabolic surface can be induced. Varying the potential across the surface can add the needed astigmatism very easily.

The support structure is the dominant weight factor. Efficient structures to accurately define the boundary conditions are an integral part of a successful space telescope system. Making larger segments will also help since fewer actuators would be needed over the entire primary mirror. Larger backing structures would still have to meet the optical tolerances of the system.

2. MEMBRANE MATERIALS

The material is the basis for the entire segment. It must have a stiffness that is negligible so that it behaves as a membrane and not as a plate. Polyimide plastic and nickel are already being used for reflectors in space. Solar reflectors and multilayer insulation are made from polyimide. Electroformed nickel has been used for X-ray telescopes such as the XMM satellite. Both materials can be formed using glass as a mandrel. The quality of the mandrel determines the surface finish of the replicated membrane and flatness on smaller scales.

Polyimide films by Dupont and SRS with thicknesses of $10-20\mu m$ are available today and have thickness variations of about $1\mu m$ and widths up to two meters. Equation 1 relates the thickness variation, Δt, the surface, s, the wavefront, ΔW, and is illustrated in Figure 1. Thickness uniformity will need a factor of 10 increase to meet the needed surface tolerance for large space telescopes. Plastic films do have drawbacks such as viscous flow properties, tensile strength, and the tendency to slowly deform when a constant force is applied. This slow deformation, or creep, can help heal creases, but can adversely affect the boundary constraints if tension is relieved. Other boundary issues will be discussed in the next section.

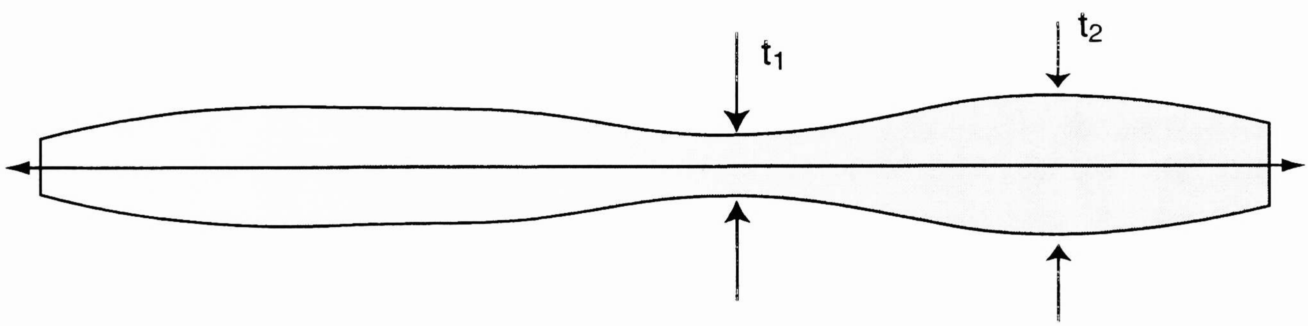

Figure 1. Thickness variations of a planar membrane.

$$\begin{aligned} \Delta t &= t_1 - t_2 \\ \Delta W &= 2s = \Delta t \end{aligned} \tag{1}$$

Electroformed nickel is appealing as a membrane material because of its strength and stability. A smaller area can be used to attach an actuator since it doesn't deform as easily as the plastic materials. This also allows a much larger applied tension enhancing the surface control. Actuator pads could be shaped during the electroforming to improve the coupling with the support structure. Unfortunately, it can crease easily even when being pulled of the mandrel after fabrication. The manufacturer, Media Lario, is working to improve the process to stay within the constraints dictated for optical surfaces. Post manufacture processing to eliminate the surface irregularities could be done if necessary.

In addition to slope errors, we are concerned with small scale roughness. Initial surface rms values are shown in Table 1. Surface profiles are one way of comparing many different materials. We are working to develop a technique for mapping a surface contour to its thickness variation. This would confirm the wavefront deviations believed to be caused by thickness fluctuations.

Material	rms surface
Mylar (Al coated)	121.10
Kaptan-Dupont	67.96
Melinex-Dupont	7.01
Polyimide-SRS	40.03
Nickel (Au coated)	10.01

Table 1. Typical rms surface roughness in nm (values over $1mm^2$).

2.1. Boundary Conditions for Flat Membranes

Membranes have no stiffness so tension is required to make them flat. The simplest method of controlling the surface of the membrane is to constrain the entire boundary, similar to a pellicle. The support would have to be massive to maintain a planar shape in this fashion. Flexing the entire frame would be the only way to make any corrections. While this works great for small pellicles, it is utterly impractical for a 10m class mirror. A corollary of this method revisits the method of pressurizations mentioned earlier. If you enclose a boundary whose method is completely defined then pressurizing the internal space provides control over the shape of the reflecting surface. An assembly that uses this principle was demonstrated by Boeing.[5] A complex structure and a pressure source would be needed, but this is also a lot of extra weight per segment to launch into space. Pressure maintenance could limit the lifetime especially if punctures occurred.

Our ideal membrane would be flat with both surfaces coplanar. The surface would be free of creases and bumps. We consider several methods to couple the membrane to a support. Figure 2 shows a very simple six-point mount using an elecroformed nickel membrane. Tabs are currently soldered to the nickel, but could actually be formed as part of the membrane during manufacture. A spring couples the tab to a support post that in this case has a small adjustment perpendicular to the plane of the membrane. To ensure no moment is introduced, the neutral axis of the tab should be coincident with the central axis of the membrane.

If the attachment is not done in a stress free manner, wrinkles can propagate into the surface from the tabs. Fortunately, small error will die out quickly as they propagate toward the center of the membrane.[3] One way to predict wrinkles is to equate them with compressive stress. Since membranes by definition are tension-only members, any compressive forces will buckle the material. Folding of the surface results, and the reflection from this area becomes scattered.

Our initial models show that using more than six attachment points doesn't result in a greater useable area. Table 2 shows the percentage of useable area versus number of attach points. The useable area is the percentage of the entire membrane surface that does not scatter light out of the system. If we consider inducing a shape by systematically moving actuators out of plane, then more attach points increases the resolution of the deformation. An example would be astigmatism for an off axis paraboloidal segment. Of course, adding actuators also increases weight and complexity of the system. We must balance the additional control with the lack of increase in useable surface area.

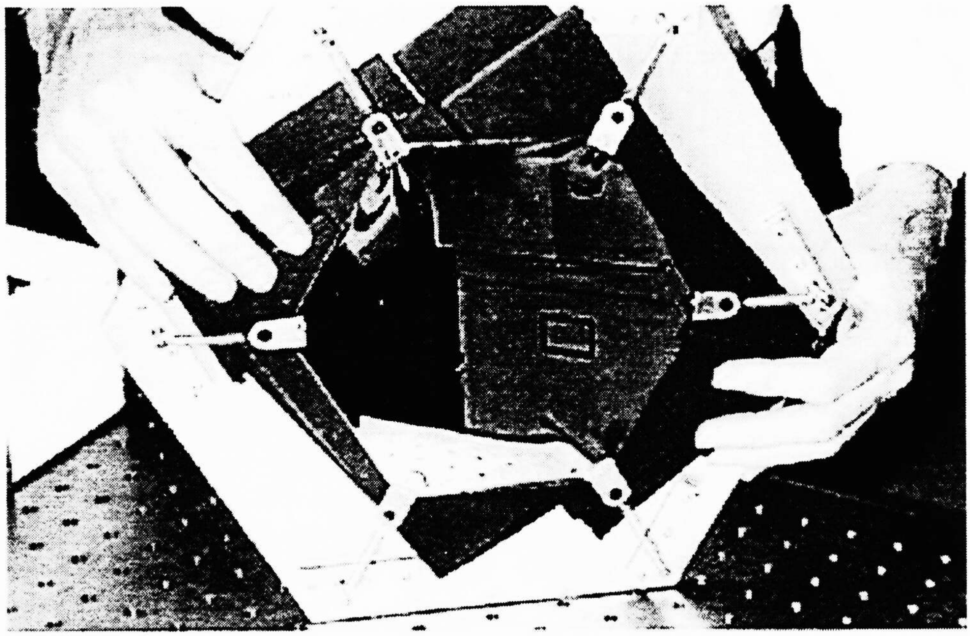

Figure 2. Gold coated nickel membrane mounted on six discrete contact points.

Attachment Points	Useful Area
3	78.5% ± 1.10
4	79.6% ± 0.85
6	85.0% ± 1.35
12	85.1% ± 2.05

Table 2. Percentage of useable area versus number of attachment points.

2.2. Electrostatic Curvature

A stretched membrane* can also be deformed with electrostatic pressure. The coated side is positioned down and provides the second plate of a capacitor. Reflection is done off the back side, through the membrane. Since the material is only 5μm thick, and the focal ratio is so slow, we can ignore aberrations due to propagation through the membrane.

We will show a model that predicts the surface by knowing the boundary. The boundary is approximated by a function that we can modify then recalculate the change of the surface. Derived for a continuous boundary, the solution works remarkably well for a boundary constrained at a finite number of points. This solution is from work previously done at UA by Angel, et al.[3]

A three-inch stretched membrane mirror with electrostatic curvature (SMEC) is shown in Figure 3. Let the membrane have uniform thickness, be uniformly tensioned by a force T per unit

*A six inch pellicle with a nitrocellulose membrane was used with an aluminum coating on the front side.

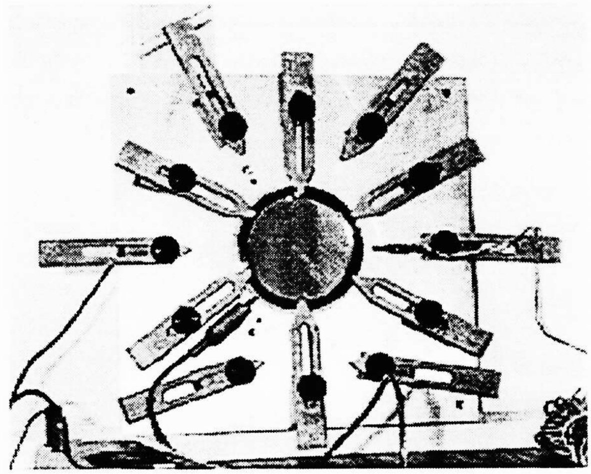

Figure 3. Three-inch SMEC in fixture.

length, and respond to an external uniform pressure p. If the material is homogenous, deformation can be predicted by balancing the force with the pressure at each point:

$$T \cdot \nabla z = p. \tag{2}$$

When the boundary is circular, the membrane follows a uniform spherical curvature with the radius of curvature given by the following:

$$R = \frac{2T}{p}. \tag{3}$$

This simple solution holds for any boundary that can be drawn on the surface of a sphere of radius R. For other boundaries, the non-uniform curvature is more complicated and depends on the specific shape of the boundary. If the boundary is a circle of radius a, lying in the r,θ plane, we can input an out-of-plane displacement, z(a,θ), along the boundary. The shape across the surface of the membrane, z(r,θ), can be determined by expressing z(a,θ) as a Fourier series:

$$z(a, \theta) = \sum_n A_n cos(n\theta) + B_n sin(n\theta). \tag{4}$$

The solution of Equation 2 with boundary condition, z(a,θ), is given by a linear superposition of terms:

$$z(r, \theta) = \sum_n A_n (r/a)^n cos(n\theta) + \sum_n B_n (r/a)^n sin(n\theta) + \frac{p(r^2 - a^2)}{4T}. \tag{5}$$

The first six Zernike terms† can now be changed by adjusting the pressure and displacement around the boundary. This demonstrates how an off axis segment could be corrected as mentioned above. The accuracy needed in defining the perimeter can be inferred from the radial dependence of Equation 5. Because the radial displacement of the nth order term falls off as r^n, the low order terms dominate the shape of the membrane. This effect can be seen in Figure 2. It is important

†piston, tip, tilt, focus, and astigmatism[6]

to control low order displacement very accurately, but significant high order displacements can be ignored if an appropriate amount of the membrane's edge is masked off. For example, if we have a perimeter accurately defined at 12 points, errors propagating into the center of the membrane will fall of at least as fast as $(r/a)^6$.

Electrostatic pressure is created when the conductive membrane is held at a potential, and an electrode is held at a different potential. The pressure in this case is

$$p = \varepsilon_o E^2, \tag{6}$$

where $\varepsilon_o = 8.85 \cdot 10^{-12}$ F/m and E is the electric field in V/m. Note that since the force between the membrane and the electrode is proportional to the inverse square of the gap, arcing and catastrophic failure of the membrane can occur if the sag of the membrane is comparable to the gap. In practice, keeping the maximum sagittal depth at 10% or less of the membrane to electrode spacing works well.

3. LABORATORY TESTING

Membranes couple easily to motion of the surrounding air. Any local acoustic vibrations can be seen in the membrane if it is free to oscillate. This makes testing on a large scale difficult since we want to study the surface defined solely by the actuators. Testing on three different size scales helps eliminate some of the coupling between multiple effects. Small scale test as mentioned earlier cover the one millimeter size. Intermediate tests between from 6-12 inches will be mentioned below as well as experiments on the one meter scale. Electrostatics offer one method of damping out vibration, and it adds an extra element of control. Test of a three inch SMEC will also be discussed.

3.1. Large Scale

Even pellicles of an inch or two in diameter can be seen to oscillate if looked at by interferometry. Low contrast usually results where large deflections occur, such as the center of the membrane. We look to analysis that can tolerate much larger magnitudes of aberration.

We start by setting up a membrane support in a Ritchey-Common[7] configuration. Just by looking at an image in the focal plane, any power (curvature) in the surface will show up as astigmatism. Figure 4 shows the arrangement used where the laser and sensor are as close as possible. The laser is 632.8 nm, and the sensor is a CCD based camera. One source is a pressure on one side from air currents. Averaging over several seconds is often necessary to compensate for the membranes sensitivity to acoustic vibration. By masking the membrane down to 60 cm, we have a 13 arcsec FWHM image.

A phase diversity method based on the image transport equation can be used to reconstruct and measure the wavefront at the pupil of the test system.[8,9] The reduction is done by taking two images that must be on opposite sides of focus by an equal amount. Laplace's equation is solved, and the output can be in a table of Zernike terms.[6] Wavefront reconstruction, however, will give us the complete phase front. Care must be taken to properly define the system parameters, or the iterative algorithm often begins to diverge. The $f/\#$, focal shifts to within a few microns, and pixel size must be known, or the resulting accuracy will suffer.

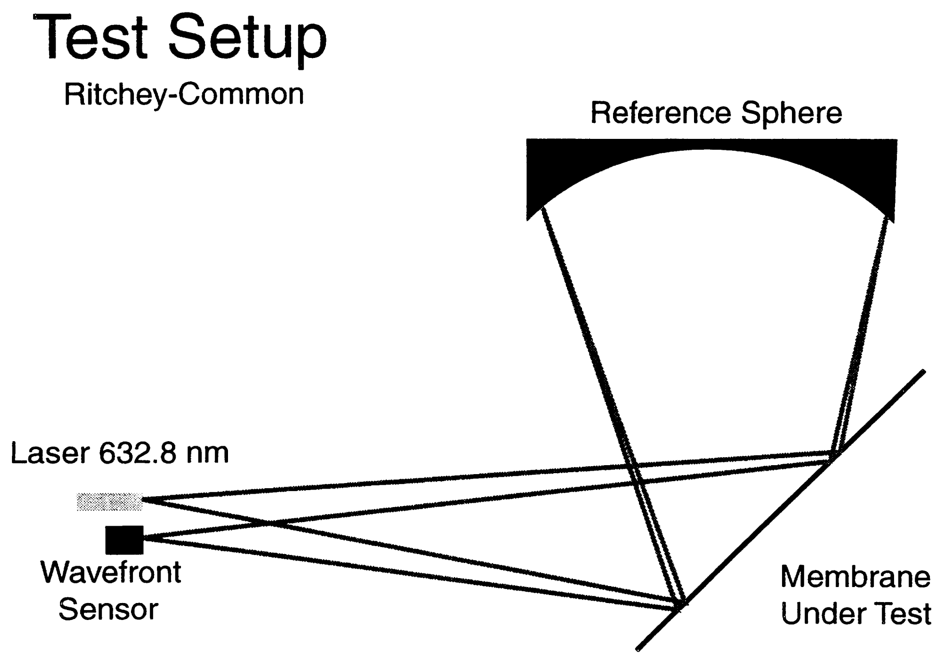

Figure 4. Ritchey-Common test used for large membranes.

A Shack-Hartmann system is another option when large wavefront errors[‡] are present. Both methods require some way to illuminate the entire surface and gather the reflected light. We use a reference sphere that is larger in diameter than the test piece. This allows us to observe the free edges, and the behavior of our defined boundary conditions.

3.2. Intermediate Scale

Interferometry is still a very good way to measure surfaces once the errors are smaller than roughly 10 waves. Figure 5 shows a demo six-inch test fixture. A six-inch optical flat with surface errors less than $\lambda/10$ is used to define the boundary of the membrane before testing. Figure 6 shows the orientation of the flat and membrane. The flat has been recessed 50μm so that in the center five inches the membrane is suspended. Having the small air space behind the membrane helps to damp any acoustic vibrations. The flat is lightly pushed into the membrane when the measurements are taken, and this also allows for a small amount of tip-tilt adjustment to make alignment easier.

Stopping a six inch SMEC down to the four inch circle shown in Figure 7 eliminates non uniformities around the boundary. Discontinuities around the boundary cause the surface to be a distorted as evident at the edge of the interferogram. The low contrast in the center is due to air movement and the resulting oscillation. Notice that the high order errors at the boundary are almost nonexistent by the four inch circle, and the remaining area is within a few waves of perfectly flat.

[‡]Tens of waves up to $\sim$ 100 waves of aberration

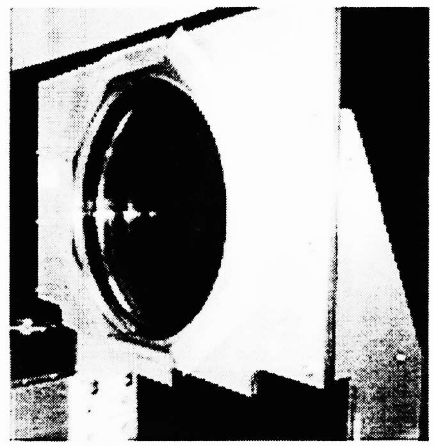

Figure 5. Fixture for interferometric testing using an optical flat. The side in front comes in contact with the flat, and the back side is positioned toward the interferometer.

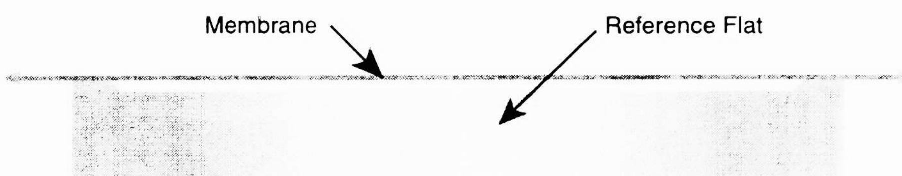

Figure 6. Configuration of reference flat.

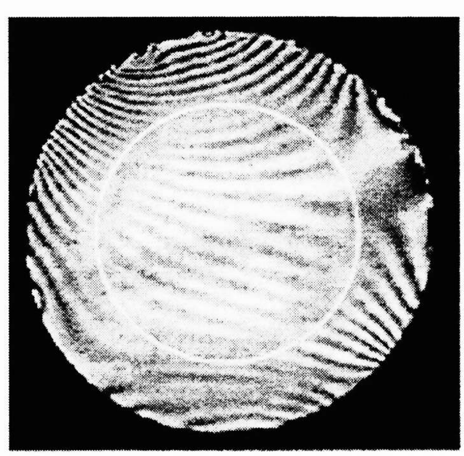

Figure 7. Interferogram of six-inch pellicle ($\lambda = 632.8nm$). The inner circle represents a four-inch aperture.

3.3. Electrostatic Solution

We can characterize a bound membrane, such as a pellicle, by adding a small known potential and measuring the resultant curvature. The sagittal depth is related to the curvature:

$$s \approx \frac{\rho^2}{2R} \tag{7}$$

where ρ is the radial coordinate measured from the center of the membrane, and R is the radius of curvature. An interferometer can be used to measure small curvatures, and is a good way to start as it allows small potential. One can also illuminate it with a diverging laser, or white light source. If we measure the distance from the source to the mirror, z, and the distance from the source to the focal spot formed by the mirror, z', we can use the mirror formula[§] to find the radius of curvature

$$\frac{2}{R} = \frac{1}{z} + \frac{1}{z'}. \tag{8}$$

Using ρ as the membrane radius, we can now find the sag. The electric field is calculated from what is now the gap and the applied potential. From Equation 6 we can find the resulting pressure since we now have the electric field. Equation 5 allows us to calculate the tension in the membrane.

We can confirm the tension by measuring the resonant frequency. The membrane will oscillate if we apply an acoustic impulse close to the surface. It will have a longer delay at resonance, and we can measure that frequency by looking at the spectral components during the decay via a fourier transform. Equipped with the resonance frequency, we can find the tension using[11]

$$T = \left(\frac{2\pi f}{2.405}\right)^2 \sigma A. \tag{9}$$

where f is the measured frequency, σ is the density per cross sectional area, and A is the surface area of the membrane . If these two methods of measuring tension agree, then we can be confident in our predictions of how the membrane will act while in use. With only initial trials done to date, discrepancy betwen theory and practice is several percent. It looks very promising that as we refine our procedures, the experimental error will become very small.

4. CONCLUSION

Large flat segments lend themselves well to space based telescopes. Each mirror could be assembled adjacent to another building up a much larger reflecting surface. The lack of gravity would keep the material from sagging under its own weight. Membranes could then be stretched completely flat. Individual pieces of multiple segments can be packed together and assembled in space, one key to launching much larger telescopes.

Continued work will focus on improving the contact between actuators and the membrane. Better control of all the degrees of freedom at the contact area will be developed and characterized. Work with vendors to improve surface quality will be monitored. Effort will be put into making the tests of the optical figure as accurate as possible, including the refinement of measuring single-piece membranes where only the actuators at the boundary are available to adjust the surface.

[§]We use the sign convention given in Modern Optical Engineering.[10]

Once eight meter class segments become a reality, the bulk of one assembly is more than current rocket shrouds can accommodate. Launching raw materials with a facility in space to produce trusses and supporting structures is an alternative to larger rockets. Issues of building and launching large structures must be considered for them to become a reality.

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