Thermally formed inflatable reflectors for space telescopes

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Abstract—**Imaging distant objects with increasing spatial resolution is instrumental towards furthering space exploration abilities. Telescopic imaging of exoplanets and other objects requires mirrors with large surfaces which when used at terahertz frequencies can further capture object chemistry, mass structure and dynamics. Membrane mirrors could lead to a dramatic scale up in size of telescope mirrors deployed on orbit. Large membrane reflectors built in the past have had a primary challenge of uncontrolled inflation dynamics and surface shape. A major contribution to such inaccuracies has been attributed to manufacturing techniques employed. The surface shape attained by a tensioned membrane has been described as an oblate spheroid or Hencky surface. Traditionally built out of smaller gore units, membrane mirrors tend to attain faceted final shapes that deviate from the intended. They have unreliable and unrepeatable final surface shapes. This makes the design of corrective optics difficult. Further, complex assembly jigs are required for the precise manufacture of such membrane units. A repeatable and scalable manufacturing method is required to harness the advantages offered by membrane reflectors. Our present work is focused on thermally formed membrane reflectors. This involves heating a whole flat membrane close to its glass-transition region followed by pressurization at a constant fixed temperature. The intent is to induce plastic deformation of the membrane causing a retention of induced curvature when cooled down. This method eliminates breaking down the membrane structure into smaller gore units and can be scaled over to vast membrane sizes. An experimental set-up has been designed and built to thermally form a 1-meter diameter Mylar membrane reflector and conduct shape measurement on its surface. We present development efforts in the design, manufacture and surface shape measurement of thermally formed reflectors. The results are being used to validate thermo-structural simulations conducted on the expected membrane surface behavior. Further analysis is underway to understand optimal circumferential stress distributions to improve the reliability of obtained membrane shapes. Our work contributes towards an understanding of key design variables in the development of tensioned thermally formed membrane reflectors that can provide a potential pathway towards dramatic scale up in size of such mirrors.**

TABLE OF CONTENTS

1. INTRODUCTION 1
2. RELATED WORK 3
3. METHODOLOGY 4
4. RESULTS AND DISCUSSION 6
5. CONCLUSIONS AND FUTURE WORK 7
REFERENCES 7
BIOGRAPHY 8

1. INTRODUCTION

Imaging distant objects in space at increasingly high resolution can greatly enhance our understanding of the solar system. Figure 1 shows enhancements in light collecting abilities over several years. The Hubble space telescope consists of the largest primary mirror currently on orbit with a diameter of 2.4 meters. Scaling up aperture sizes to several meters in diameter in a way that can be launched reliably in space is a challenging engineering problem. The James Webb Space Telescope with a primary mirror spanning about 6.5 meters in diameter currently under development will dramatically improve energy collection abilities as illustrated in the figure.

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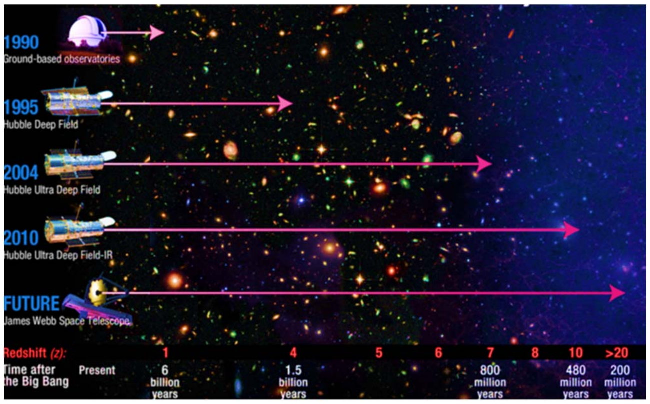


Figure 1. Current and future imaging capabilities (http://hubblesite.org)

Collecting energy from distant bodies, such as exoplanets, would require even larger apertures in size of the order of tens of meters [1]. Figure 2 illustrates a size comparison of mirrors between current and future missions and concepts. Large sizes also help enhance diffraction limited angular resolution which is a function of aperture size. From an Earth observation standpoint, placing a large optical mirror several meters in size in GEO can provide unprecedented coverage time and Earth image resolution [2].

Scaling up the size of space-based mirrors poses formidable challenges due to limited shroud volume of available launch vehicles [3]. The requirement for mirrors with much larger apertures will demand techniques to efficiently package, store and deploy these mirrors without affecting surface precision significantly.

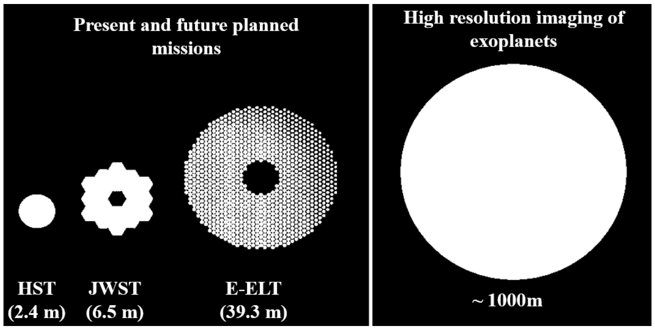


Figure 2. Comparison of mirror sizes

Optical technology such as segmented mirrors and trans-missive diffractive optical elements [4] have shown promise as deployable mirror technologies. They, however, do not scale well in size and exhibit significant structural complexities making them very expensive to launch. Inflatable membrane mirrors can potentially overcome this challenge Table 1 shows a comparison between various deployable mirror technologies [5].

Table 1. Deployable mirror technologies [5]

Mirror technology	**Packing Efficiency**	**Areal Density**	**Scalability**
Fixed Mirrors	1:1	1-2 kg	Low
Linkage Systems	5:1	1-2 kg	Medium
Membranes	20:1	0.3 – 0.5 kg	High

Membrane technology has been shown to hold the greatest potential in terms of areal density and the potential to scale up. The areal density or mass per unit surface area is also the least in the case of membrane mirrors. Conventionally, membrane mirrors are defined as having small enough thicknesses such that compressive stresses minimize to negligible amounts. Hence bending and deflection in membranes is governed principally by tensile stresses. They can be compacted into stowed volumes much smaller than the deployed state as shown by their associated packing efficiencies. In terms of scalability to larger size, membrane mirrors are the least complex mechanically and could potentially be scaled up at a greatly reduced risk of deployment.

Membrane mirrors developed in the past have shown aberrations in attained shapes and exhibit challenges such as the lack of a reliable deployed surface shape. Traditional manufacturing methods employed to build membrane mirrors add to these aberrations. Traditionally, such membranes are built out of membrane units called gores that are sealed together. This leads to a faceted structure with non-smooth seams. Further, assembling such gore units into complex geometries requires tools that can precisely place these units to each other before seams are formed. An alternate strategy towards membrane mirror manufacture is that of thermal forming the membrane. The technique of thermal forming has been explored to some detail in the past [6]. It involves the plastic deformation of a pressurized membrane under temperature ranges resembling a thermal plastic region transition region of the membrane. Elastomers such as polyethylene, polyimide and composites have been studied.

Available literature seems to show a lack of understanding of the reliability and accuracy in final attained shapes using this method. Our present work aims to demonstrate thermal forming on a laboratory scale prototype consisting of 1-meter diameter membranes that we attempt to thermally form and characterize surface behavior. Work is currently underway to develop reliable metrology for such measurements. Measurements will be used to validate thermo-structural models developed to understand the extent of plastic deformation and key design parameters affecting the final shape of the attained membrane mirror element.

2. RELATED WORK

Inflatable membranes have been the subject of investigation for years [7]. The Echo balloon project by NASA in the 1960's [8] was the first successful demonstration of inflatable membranes on a large scale. Echo 1 and 2 were large orbiting spheres constructed out of metallized Mylar and spanned over 30 meters in diameter. They operated as reflectors for radio waves and successfully stayed in orbit for several years. A 16-meter inflatable paraboloid was developed as a part of the inflatable antenna experiment on-board STS-77. It demonstrated the on-orbit deployment of an inflatable membrane reflector [9]. The reflector deployed to expected geometry, but an underestimation of residual gas at packaging led to uncontrolled dynamics in the deployment process.

Membrane mirror technology has been investigated more extensively since the early 1990's. Methods such as electrostatically induced membrane curvature has been developed by the University of Arizona. These methods were limited to laboratory scale prototypes which achieved considerable success in demonstrating retention of an induced shape [10]. Developmental prototypes demonstrated considerable success. More stable architectures with low areal densities such as lenticular inflatables have been developed by L'GARDE and SRS technologies [2]. These mainly consisted of a primary membrane mirror supported by lenticular inflatable panels. Primary challenges observed were the persistence of uncontrolled frequency modes and lack of adequate shape control. Apart from membrane mirror technology itself, advancements in associated optical technologies have also received considerable attention in the past few years. Ball Aerospace's and DARPA's MOIRE program [4] aims to place a GEO based 20-m diameter operational telescope for persistent monitoring of the ground on Earth. Advances in transmissive diffractive optics techniques have greatly relaxed surface precision requirements from telescope mirrors. This has enabled technologies being developed for the MOIRE. Figure 3 shows a conceptual image of the MOIRE telescope showing segmented elements.

Figure 3. Proposed MOIRE Space Telescope

A similar investigation of large-scale membrane structures has been with occultors or structures that suppress light from stars. This enables improved imaging. Efficient imaging of distant objects such as exoplanets requires large scale occultors to work in conjunction with telescopes. Once such concept as described in NASA's 2020 decadal survey [11] is the Habitable Exoplanet Observatory (HabEx). The mission is designed to observe exoplanets with the potential of sustaining life. It consists of a deployable occultor termed as 'Starshade.' The Starshade is envisioned as 72m diameter membrane tensegrity structure which deploys from a stowed volume comparable to available payload volumes on conventional launch vehicles. The design consists of a deployable truss structure that acts as a primary support imparting the membrane with stiffness [12]. A network of spokes is used to effect intermediate control on the structure. The Starshade concept highlights the scale and complexity involved in the deployment of space structures of that size.

Among surveyed membrane mirror technologies, it becomes evident that major technology areas need further development before a reliable large scale membrane mirror can operate on orbit. From an optical standpoint, active wave-front control for manipulating shape of the optical signal would be necessary to bring down mirror surface accuracy requirements. This would allow larger tolerances in the sub-millimeter range on surface inaccuracies. From the structural standpoint, design emphasis must extend to include packaging and deployment geometries in addition to final desired shapes. Origami and slip folding techniques have been investigated to aid in packaging and deployment [13]. Their utilization, however, is limited in the case of optical reflectors due to induced creases and folds on the membrane's surface.

Pneumatically inflated membranes have been developed to structures several meters in size. They offer a path to scale to large structures with relatively simple mechanical construction and are highly efficient in compact packaging. Construction of membranes using smaller 'gore' units leads to faceted final shapes which is undesirable and not a very scalable approach. An alternate method of membrane manufacture was studied by Ehrreich et al [6]. This method was applied successfully in the manufacture of meteorological balloons at upper atmospheric altitudes. The aim was to be able to build highly pressurized membrane balloons with the ability to hold inflating gas for long periods of time. Recent investigations at the University of Arizona [14] have shown this to be a promising approach.

Our present work aims to build up thermal forming to a larger scale of about 1 meter in diameter and characterize obtained surface characteristics. A repeatable surface behavior would lead to the design of corrective optics and validating this process as membrane manufacture method that can be scaled up at low cost and relative low complexity.

3. METHODOLOGY

Plastic deformation of membranes

The plastic deformation of thin membranes depends on stresses acting on it at a given operating temperature. Most plastic membranes exhibit a semi-crystalline molecular structure [15]. At a given temperature, a certain stress state causes structural re-organization of chain-like polymer molecules which allows lower energy movement among them. This region is termed as glass transition when the polymer transforms from a hard ‘glassy’ state to a more fluid state. Hence, to induce plastic deformation, applied stress and thermal environments need to be controlled in a favorable region. Figure 4 shows typical stress temperature curves for thin plastic membranes. As can be observed, tensile moduli drop sharply beyond a certain temperature which marks the onset of this transition.

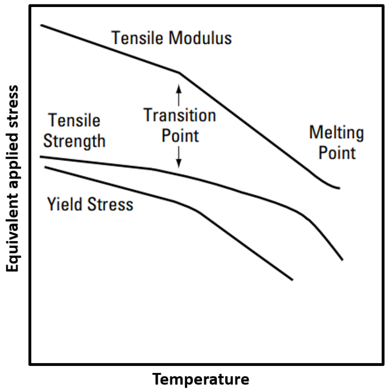


Figure 4. Membrane thermal transition regions

It has been observed that while pre-stress states do affect this region of transition to an extent, a far more sensitive parameter is temperature range. For the purpose our investigation we looked at candidate membranes which included Kapton HN, Mylar and PET. Due to available thermal transition data Mylar was chosen to proceed. From available data an operating temperature of 70°C was chosen for thermal forming. Order of magnitudes of required stress states are a continuing investigation.

Thermal forming of membrane mirror

We attempt to pre-form flat circular membrane elements with a given initial tension. A customized setup has been designed and constructed in the laboratory to achieve this. Figure 6 shows a schematic diagram of our process in detail. The first step is to sandwich a reflective membrane element and a clear membrane element between metal rings that serve to clamp them in place. Clamping provides for an air-tight seal for the passage of pressurizing gas ad also gives the membrane a pre-tension which has a strong bearing on its final shape. This pre-tension needs to be repeatable in order to obtain repeatable inflated shapes and hence the design of the clamping mechanism is a critical design feature. The second step is to inflate the sandwiched mirror elements using compressed air as shown. A final internal pressure of 0.052 psi was provided to obtain a visually wrinkle free surface. The pressure is then held by means of closed loop pneumatic system. The third and final step involves immersing the pressurized membrane mirror and clamp assembly into a water bath held at constant temperature. Temperature settings and loading conditions are membrane specific and discussed in the next section. The water in the immersion tank is drained out and the membrane assembly is assembled onto a stand as shown in figure 7. Shape measurements and metrology apparatus is then installed on the side of the frame opposite to the reflective side of the membrane mirror as shown. Tests are then conducted for surface shape precision and repeatability.

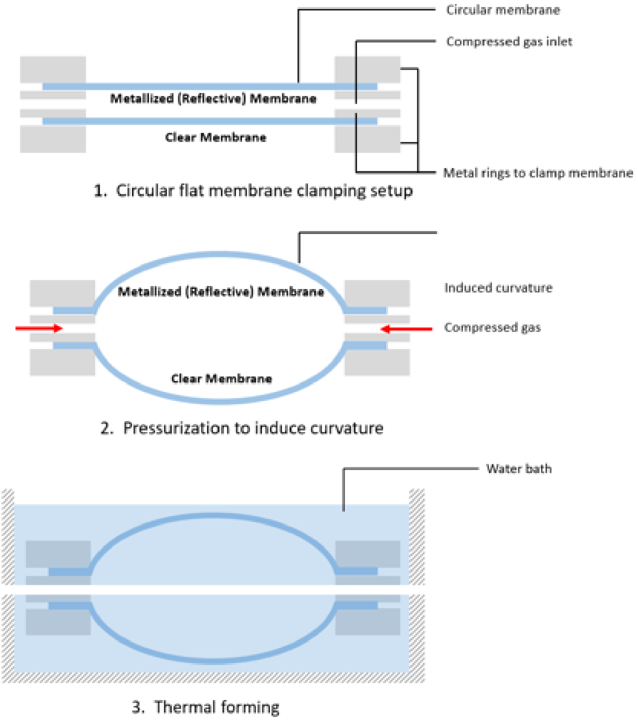
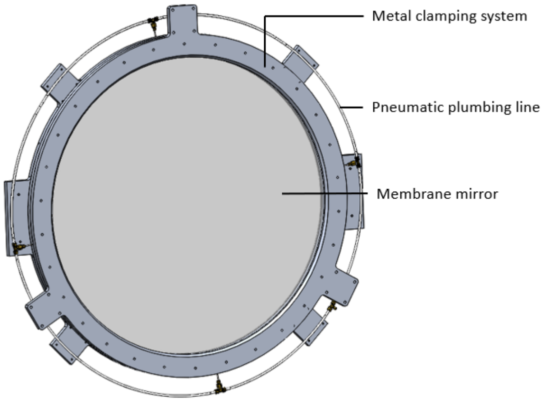


Figure 5. Thermal forming process



Membrane reflector and clamp assembly

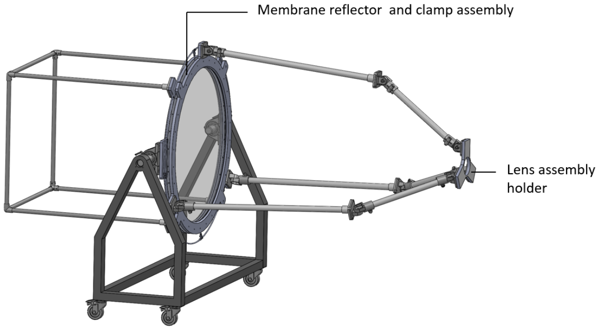


Figure 6. Experimental setup

Expected surface shape

Final pressured shapes attained by circular tensioned membranes were studied by Hencky and extended by Campbell [16] . Distribution of radial and circumferential stresses lead to a surface shape described as an oblate spheroid. Hencky showed that this shape could be expressed in terms of a power series as a function of radius. In the case of small final deflection, the function reduces to the form as described in equation 1.

$$w = \frac{pa^2}{4\sigma t}\left(1 - \frac{r^2}{a^2}\right) \tag{1}$$

Here w represents the deflection at radius r from the center of a flat circular membrane of radius a and thickness t with an initial tensile stress σ for an applied internal pressure p. This deflection has been observed in the elastic region of the membrane. In the case of plastic deformation, a more complex model has been described [17] to predict the shape. Figure 8 describes the model in some details. As can be seen, S1 represents the initial surface or 'flat state' of the circular membrane, S3 represents the final surface of the plastically deformed membrane and S2 represents the hypothetical surface of a perfect sphere of radius R.

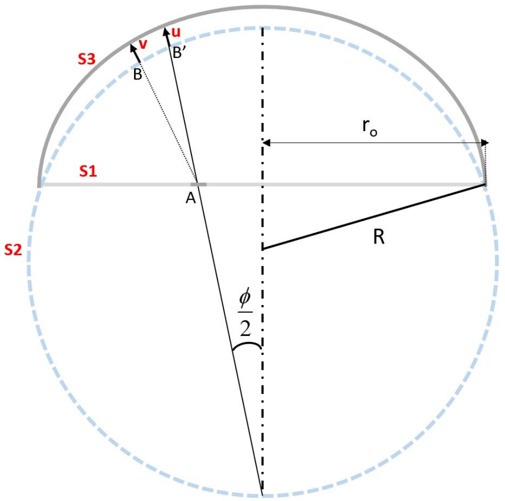


Figure 8. Plastic deformation of circular membranes

Based on initial radial and circumferential stress states, the plastic deformation model predicts a surface composed of two radii, a meridional radius of curvature R_m and a transverse radius of curvature R_t as described by equations 2 and 3.

$$R_m = \frac{\left[(u'-v)^2 + (R+u+v)^2\right]^{2/3}}{(R+u+u')(R+u-u''+2v') + (u'-v)(2u'-v+v'')} \tag{2}$$

$$R_t = \frac{R\sin\phi + u\sin\phi + v\cos\phi}{\sin\left(\phi + \frac{v}{R} - \frac{u'}{R}\right)} \tag{3}$$

Here u and v represent displacements of a section A of the initially flat membrane relative to an ideal sphere S2. Equations 2 and 3 represent differential equations with a strong dependence on initial stress distributions in the membrane. An iterative numerical scheme shall be applied to solve these equations using observed displacement measurements.

Surface shape measurements

Three methods are simultaneously being pursued to accurately measure the surface figure of inflated metalized mylar; an off the shelf laser tracker, custom built laser-galvo scanning system and photogrammetry. A 11 x 11 grid of red dots, each 5 mm in diameter has been printed on the mylar. This grid is used as reference for photogrammetry and provide diffuse reflection for the laser tracker and laser-galvo scanning system.

Laser tracker- An off the shelf TackLife Laser Distance Gage with an accuracy of +/- 2 mm is used to scan across the sagittal and tangential plane by aiming at the printed dots to get an estimate of the radius of curvature (RoC) of the inflated metalized mylar. Distance from the laser tracker ***r***, azimuthal angle $\boldsymbol{\theta}$ and altitude $\boldsymbol{\varphi}$ are measured over several trials. The averaged data is then used to calculate sag.

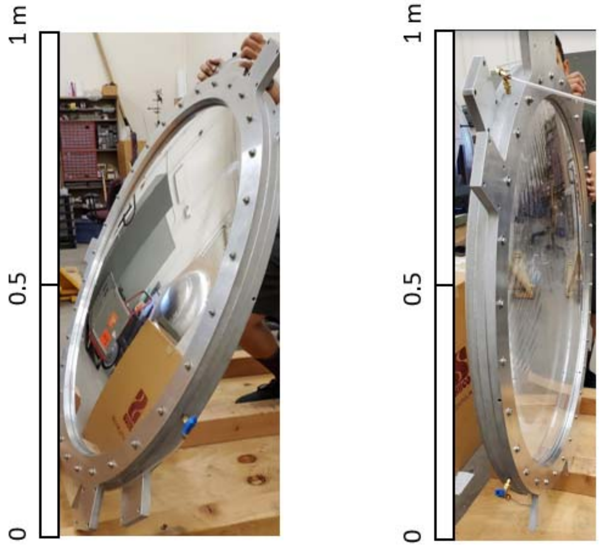
Laser galvo scanning system- A laser-galvo scanning system is used to project a grid of dots on the surface under test. The reflected images are captured for every dot and centroiding is employed to form a point cloud of all the dots. A ZEMAX model of the set up uses the point cloud as its input and optimizes the surface to fit the point cloud. The specular reflections from the mylar results in multiple reflections of similar intensities and to avoid this the laser has to be aimed accurately at the printed dots which acts as a diffusive surface. This method is still in development stage.

Photogrammetry- A DSLR camera is used to image the printed dots on the mylar from two locations with a known separation distance. A MATLAB program is used to identify the dots, apply centroiding and then form a point cloud of locations of the centroid of all the printed dots. This is then used to determine the surface figure of the inflated metalized mylar. This method is also under development and a relative displacement accuracy of +/- 1.3 mm has been achieved so far. The absolute measurement of surface figure with this set up is still being researched.

4. RESULTS AND DISCUSSION

Membrane mirror assembly

Reflective and clear Mylar sheets of 1 mil thickness each were cut to 1-meter circular shape and clamped between metal rings The membranes were then inflated using an air compressor to an internal pressure of 0.62 psi at which point the reflective surface visually appears wrinkle free. A maximum deflection of 2.7 mm on either side was observed. Each of the individual inflated sides can be seen in Figure 9.



(a) **(b)**

Figure 9. (a) Reflective surface of inflated membrane mirror (b) Clear surface of inflated membrane mirror

Before thermal forming, it was necessary to have an accurate and calibrated shape measurement system in place. The next section details our efforts to date towards getting an accurate estimate of surface shape. The conclusion of this effort will be followed by thermal forming and a repeat measurement post thermal forming.

Membrane shape measurement

Laser tracker- Figure 10 shows the laser tracker setup. As shown in figure 10 (a) the laser tracker is mounted on an alt-azimuth stage. Figure 10 (b) shows the mounted membrane mirror being scanned along the sagittal plane by aiming the tracker at printed red dots.

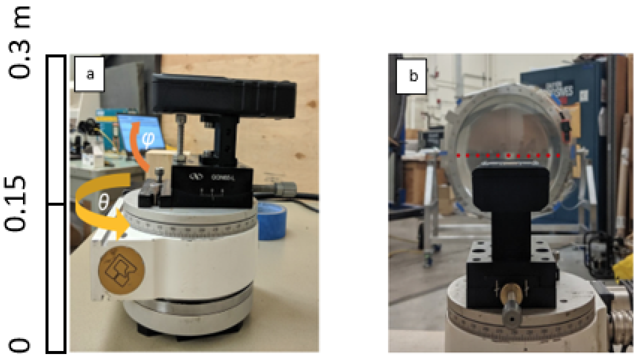


Figure 10. Laser tracker setup

mirror being scanned along the sagittal plane by aiming the tracker at printed red dots. Figure 11 shows average sag plotted for differential pressures of 0.052 psi and 0.1 psi. A best estimate radius of curvature (ROC) fits results to 3.46m for 0.052 psi and 2.79m for 0.1 psi.

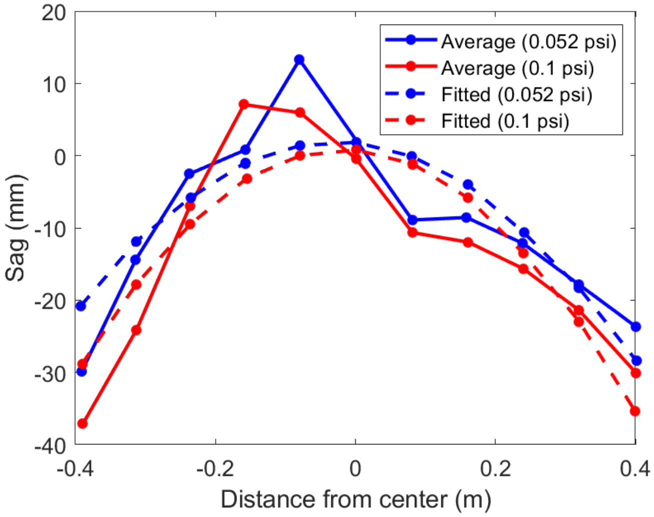


Figure 11. Average sag plots

Figure 12 shows two images taken of the reflective surface using a DSLR camera with a 240 mm separation between locations. A circle finding algorithm is used to identify all the dots and point cloud is formed after centroiding.

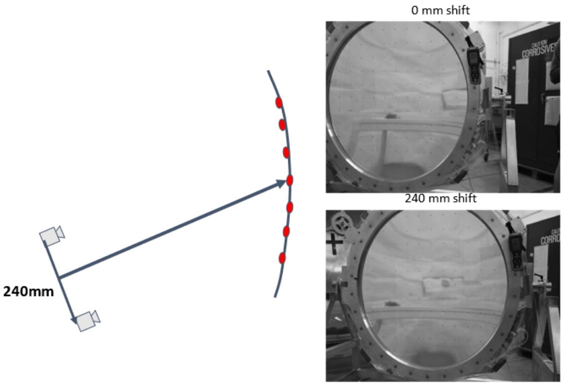


Figure 12. Photogrammetric setup

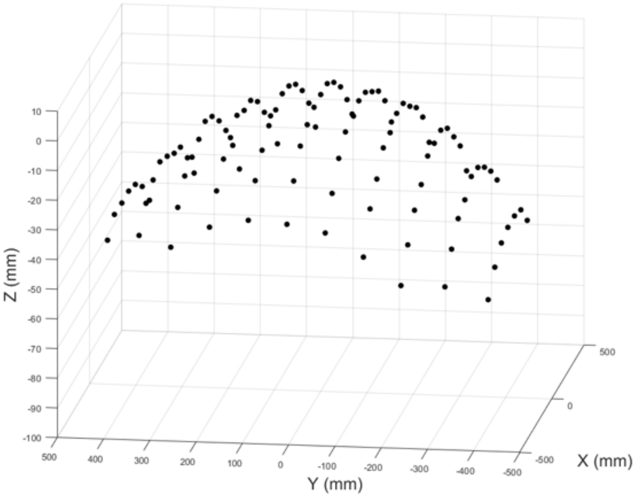


Figure 13. Point cloud of measured surface

Figure 14 shows the generated point cloud of the printed dots where the Mylar is inflated at a differential pressure of 0.052 psi. As can be seen, two ROCs are visible. These are 3.39 m along x-direction and 2.15 m along y-direction. The existence of two ROCs points to the possibility of plastic deformation having taken place due to stresses of pressurization. This needs to be verified through further measurements.

5. CONCLUSIONS AND FUTURE WORK

An experimental setup has been designed and built to test thermal forming characteristics of thin membranes. Work done to date shows the ability of the setup to adequately hold internal pressures required for a wrinkle free membrane mirror. Laser tracker measurements have been used to provide and ROC estimate as a data point for corroboration with future measurements. Photogrammetry has shown most promising results in generating a point cloud of reference points on the reflector surface. A composite ROC surface hints towards plastic deformation possibly having taken place.

Further work is required in the form of a detailed thermo-structural analysis to determine a standard operating procedure for inducing thermal forming. This would be particularly useful in re-design the clamping mechanism to ensure symmetric and quantifiable initial conditions. Further refinements to the photogrammetric measurements will lead to data that can be used to validate the plastic deformation model leading to an understanding of its repeatability in space like conditions.

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BIOGRAPHY

Aman Chandra *received an MS in Aerospace Engineering at Arizona State University. He is currently a PhD student at the Univeristy of Arizona department of Aerospace and Mechanical Engineering. His master's thesis dissertation is on the design and optimization of gossamer space structures for small satellites. His research interests include structural dynamics, optimization.*

Siddharth Sirsi *is a PhD candidate in Electrical Engineering and a MS student in Optical Sciences at the University of Arizona. His main areas of research are superconducting transistors, teraHertz astronomical instrumentation design and optical design and metrology of inflatable telescopes. He is part of the Steward Observatory Radio Astronomy Lab and Large Optics and Fabrication and Testing Lab at UofA. He completed his MS in ECE from Arizona State University in 2014.*

Heejoo Choi *is a post-doctoral researcher at the James C. Wyant College of Optical Sciences at the University of Arizona. He has studied the nonlinear optical harmonic generation and optical metrology. His current research covers various optical engineering such as metrology for science and industry and UV and spectroscopy space telescope design, LiDAR and active optics system of Larger Binocular Telescope.*

Phuoc Andy Phan *is a bachelor and master's graduate of the James C. Wyant College of Optical Sciences at the University of Arizona. His experiences involve designing, fabricating, and testing optical system which proceeded from his work involving a prototype Mylar mirror. His thesis consisted of scalable fabrication and thermal processes for membrane mirrors that assisted in the planning phase of OASIS, Orbiting Astronomical Satellite for Investigating Stellar Systems, building the 1-meter Mylar reflector.*

Yuzuru Takashima *is an Associate Professor at College of Optical Sciences of University of Arizona and has been on the faculty since 2011. Prior to joining to the University of Arizona, he was employed as a research staff by Stanford University where he has been actively involved in the field of novel optical system design and engineering, particularly for high density page-based and bit-based holographic data storage systems and Nano-photonic electron beam generators. He was employed as an optical engineer at Toshiba Corporation in Japan where he conducted research and development of ultra-precision manufacturing of optical components and products. He received B.S. in Physics from Kyoto University and M.S. and Ph.D. in Electrical Engineering from Stanford University.*

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Christopher Walker *is a professor of Astronomy at Steward Obervatory at the University of Arizona. He has served as dissertation director for ten Ph.D. students and is a Topical Editor for IEEE Transactions on TeraHertz Science and Technology. Prof. Walker has worked in industry (TRW Aerospace and JPL) as well as academia. As a Millikan Fellow in Physics at Caltech, he worked on the development of low-noise, SIS waveguide receivers above 400 GHz and explored techniques for etching waveguide out of silicon. Prof. Walker led the effort to design and build the world's largest (64 pixels) submillimeter-wave heterodyne array receiver. He is PI of the NASA funded long duration balloon project "The*

Stratospheric THz Observatory (STO)'', which had a successful Antarctic flight earlier this year. The follow-on project to STO, called GUSTO, was recently selected by NASA as the first balloon-borne mission under the auspices of the Explorer Program. He is also PI of the "10 meter Suborbital Large Balloon Reflector (LBR)" project, selected by the NASA Innovative Advanced Concepts (NIAC) program for a Phase I and II study. He recently authored Terahertz Astronomy, the first textbook in his field of study.