

Actively Controlled Membrane Primary Mirrors for Very Large Space Telescopes

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ABSTRACT

Advancing astrophysical research from space or Earth observation capabilities from geostationary orbit beyond current spatial resolution and sensitivity limits requires space telescopes with significantly larger apertures. However, scaling the primary of a space telescope is constrained by carrier fairing dimensions, packaging limitations of segmented mirror architectures, and cost considerations.

To address these challenges, we present a novel approach for fabricating ultra-lightweight primary mirrors based on thin-film polymer membranes. These mirrors are produced via chemical vapor deposition onto a rotating liquid mandrel, yielding high optical quality surfaces with a parabolic surface shape. Owing to their elasticity, the resulting continuous membrane mirrors can be compactly rolled for launch and deployed in space to form a large, continuous aperture. The fabrication process enables areal densities well below 1 kg/m², providing a foundation for highly scalable telescope systems without violating possible mass limits.

Given the nature of these thin membranes, active surface control is essential. We introduce a radiative adaptive optics concept in which spatially modulated illumination induces controlled thermal gradients, enabling localized deformation of the mirror surface. Coupled with wavefront sensing for real-time feedback, this method allows precise shape control. In effect, the primary mirror functions as a deformable adaptive surface with potentially hundreds of thousands of controllable modes, without significant mass penalty.

We present the fabrication methodology and experimental results from a laboratory-scale prototype, demonstrating closed-loop surface control. Finally, we outline a conceptual telescope architecture incorporating this technology, including deployment strategies within launch vehicle constraints, and discuss system-level requirements for illumination control and wavefront sensing in a space-based implementation.

Keywords: Space telescope, membrane primary mirror technology, radiative adaptive optics, deployment technology

1. INTRODUCTION

Space telescopes have become reality now since many years. Exploring astrophysical objects in nearly all regimes of the electromagnetic spectrum, the absence of the earth's atmosphere allows to observe in regimes unseen from ground. But even in spectral windows where the radiation is penetrating the atmosphere, as the optical or near infrared, the absence of absorption and emission provides a significant improvement in sensitivity. Offering an unobscured view into the universe, space telescopes have enabled significant progress in many astrophysical research areas. The Hubble space telescope and the 6.5m sized JWST, both currently in operation, are providing us with an unprecedented rich stream of valuable astronomical data. Probing even much fainter objects as possible today, or increasing the spatial resolution of a space telescope significantly over the current facilities will require mainly a larger primary mirror. In the diffraction limited case, the increase in sensitivity scales approximately with the square of the telescope's diameter. As such, a 20m sized telescope

could outperform a JWST by a factor of ~ 10 . At the blue side of the visible spectrum, this factor becomes even larger as JWST does not reach completely to the diffraction limit.

Apart from an UV optical IR telescope, a 20m sized primary could enable applications in other areas that are impossible with smaller telescopes. An important case could be earth observations from a geostationary orbit (GEO), enabling permanent observation of an area at a spatial resolution that is nowadays provided with smaller telescopes from low earth orbits. Another astronomical application could be the construction of a large baseline sub-mm interferometer, free from water vapor absorption and other disturbances, or a lunar based observatory, requiring similar performance. Obviously, many more applications are thinkable.

While there is a clear need for a large aperture telescope, the scaling of current technology towards significantly larger apertures may hit quickly technologically or financial barriers for realization. Building on the heritage of the current schemes would likely rely on a scaled segmented mirror technology. This always will require to fold, unfold and align the segments to each other, requiring a backing structure, folding actuators and according sensing schemes, rendering a complex and in projection very costly scheme.

To overcome some of the limits of current technology we have developed a completely new scheme of constructing a space telescope system [1]. The architecture is based on the combination of:

- *An extremely lightweight thin sheet primary mirror*, scalable to large sizes in production.
- *A flexible material*, allowing to compactly roll up the large aperture.
- *A novel active optics method*, to radiatively tune the primary to precision optical shape.
- *A foldable telescope structure* to economically fit into launch fairings.

The continuous sheet thin film membrane mirror is based on a polymer carrier with a reflective layer on top. These polymer membrane mirrors are shaped upon production as a paraboloid, suitable to provide an optical surface for a primary in a standard optical telescope design. Being produced by chemical vapor deposition on a rotating liquid, one can scale up the production method economically to very large diameters. The resulting polymer mirrors are intrinsically optically well shaped, but flexible enough to be rolled up in a 'tube' like structure upon packaging, forming a compact and matched geometry for a launch fairing.

By its nature, the thin membrane material cannot provide an optically stiff and solid surface, but requires a method to be tuned into the optical shape. To do so, we have developed a method to adaptively tune the surfaces shape by irradiating it with a spatially variable light source and measuring its shape with a wavefront sensor in real time [2]. Utilizing a digital light projector to irradiate the surface selectively we convert the telescopes primary into a deformable mirror with effectively hundreds of thousands active elements. With these enabling technologies the thin film primary mirror can realize an extremely large space telescope, diffraction limited in the optical wavelength regime.

2. SENSITIVITY

A major motivation to enlarge the aperture of telescopes is the increase in sensitivity. In Figure 1 we have plotted a comparison between the major current and upcoming facilities for space and ground based astronomy. In the diffraction limited case the sensitivity depends mainly on the telescope aperture, collecting a given number of photons per unit integration time. As such a 20m sized telescope could gain an order of magnitude over JWST in the near infrared spectral range. Assuming one could manage to make a future large aperture as well diffraction limited towards the visible spectral range, the sensitivity could increase by a factor of 100. As comparison we have plotted in addition the sensitivity of the upcoming ELT with its first light camera MICADO. Being a ground-based facility, the values given here apply between the atmospheric and thermal OH absorption and emission bands. Averaged over a broader wavelength range, the space facilities will always be significant more sensitive, due to the absence of earth's atmosphere.

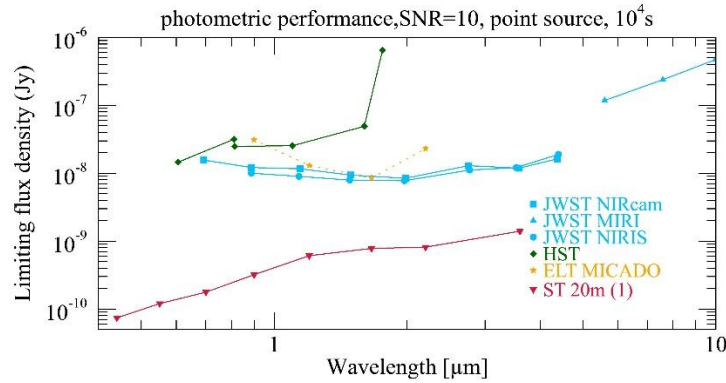


Figure 1 sensitivity of telescopes. Expressed as the limiting flux density in Jansky for a point source to reach a signal to noise ratio of 10 within a 10^4 seconds of integration time. We plot here the comparison of the current and upcoming major astronomical telescopes with a hypothetical 20m diameter space telescope. When being diffraction limited, the increase in sensitivity from JWST to a 20 m sized facility is an order of magnitude. Expanding the range into the visible wavelength region, where JWST is not diffraction limited, a gain of a factor 100 could be achieved in sensitivity. As comparison we have plotted as well the upcoming 40m ELT with the MICADO camera here. The sensitivity values from the ground-based facility are valid in between the atmospheric OH absorption and emission bands.

Thinking the possibilities of a very large space telescope further, such an increase in sensitivity will allow to observe many more objects, currently being unreachable with reasonable integration times. One of the unique compelling science cases is the direct imaging of rocky planets, the study of possible atmospheres and signatures of life. As having the prospect in detecting the signal from such a faint object within reasonable time -as would be a fraction of its revolution period- one could imagine that several of such large telescope could form an array in space, finally being capable to resolve extrasolar planets spatially.

3. MEMBRANE MIRROR PRODUCTION

The above goals in mind we have developed a way to produce thin film membrane mirrors, to serve as primary in a large space telescope. While a mirror's purpose is to reflect light, this requires only a very thin reflective layer. Its thickness usually serves the purpose to maintain the optical shape. With very large mirrors anyway requiring an active shape control, one can drive this concept to an extreme by lowering the thickness to a thin membrane. In this spirit, our mirrors are manufactured to be thin enough to stay flexible and lightweight, but own a thickness and quality to be good enough to be probed by optical metrology. The final optical quality shape is then achieved by an active optics control loop.

To produce such mirrors, we have found a method to deposit a polymer onto a liquid, replicating its surface shape. Aiming for a surface that serves as telescope mirror, we utilize the well-known method to spin a liquid, to form a parabolic surface (see e.g. [3]). Using rotating liquids for deposition of a polymer as well has been tried before [4] with curing epoxy resin. In contrast to those early attempts we combine the rotation method with a CVD process. In Figure 2 a simplified sketch of this process is shown: Within a vacuum process chamber, a rotating container holds a suitable liquid owning a surface acting as optical shape provider. Spinning the container with a controlled angular velocity, with the rotation aligned with the local gravitational vector, a nearly perfect parabolic surface is obtained. On this surface the polymer film grows by chemical vapor deposition. As polymer we are utilizing a Poly(para-xylylene), shortly known as Parylene, that owns some desired properties:

- The material has space flight heritage and is listed in the NASA low outgassing database.
- The deposition takes place at room temperature
- The material deposits pin-hole and tension free, without shrinking or curing issues.
- Parylene owns a not too large CTE, usable for our radiative active optics method.

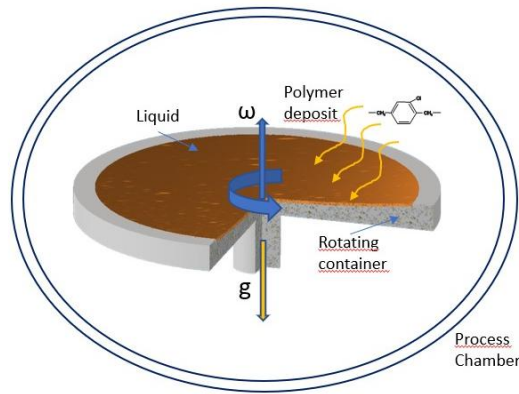


Figure 2: sketch of the mirror deposition method. In a process chamber a rotating container is filled with a liquid to serve as deposition surface. This container is spinning with controlled velocity ω , with the spinning axis aligned to the gravitational vector. As such the surface of the liquid forms a paraboloid with a curvature according to the angular velocity. Onto this surface a polymer film is applied by chemical vapor deposition.

Additionally, this type of process holds several advantages:

- The CVD process takes place in a vacuum environment, keeping the system clean from dust and other unwanted species and away from turbulence or wind velocity effects.
- With the spinning velocity under control, any curvature of the parabola can be obtained.
- By monitoring the deposition process the film parameters as the thickness and quality of the resulting polymer film are tunable to the needs.
- In its clean and controlled environment, the liquid forms an optically perfect surface, as it will do for any diameter by this basic physics process. As such this method can be scaled to any mirror size without exploding costs, as would be the case for an optically polished solid mandrel.

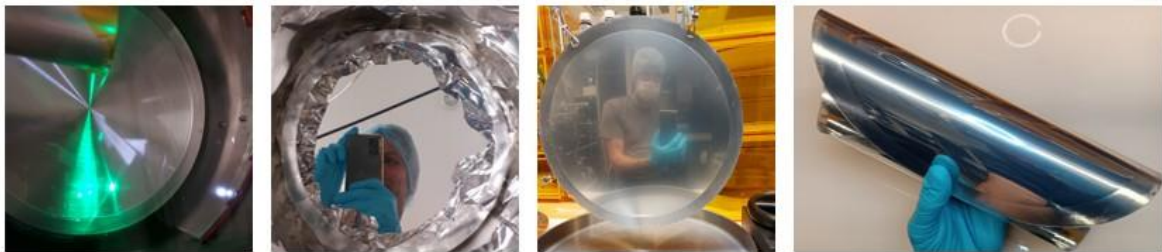


Figure 3: some photographs over the production process. From left to right: view into the polymer CVD chamber while growing a membrane; the freshly aluminized membrane; washing the liquid away on the 'clothesline'; the final flexible membrane mirror.

The production process for such a polymer mirror goes mainly along the following steps:

- **Chamber preparation:** as the process takes place in a vacuum chamber, this chamber requires careful cleaning and surface treatment. A pre-test on vacuum tightness is usually conducted, pressure gauges and vacuum pumps tested and calibrated.
- **Liquid Preparation:** since the deposition of the polymer is done on top of the process liquid, the grade and handling of the liquid plays an important role for the mirror surface quality. Particles on the surface or bubbles need to be strictly avoided. As such we are pre-treating the liquid for careful de-gassing and surface particle avoidance.
- **Turntable preparation:** the liquid is placed on a turning table and the rotation defines the optical surface, a precision alignment of the table wobble against rotation axis and against the gravitational vector is required. With a set of tilt actuators we usually align the wobble to be of-order $1..5 \mu\text{m}$ reflecting the current precision of the used table.

- *Pre-Process conditions*: this step contains the application of the required amount of liquid onto the table, including an optical measurement of the border conditions, avoiding effects from surface tension. If passed, the process chamber is closed, a sequence of evacuation steps applied and a thorough de-gassing time allowed.
- *Polymer CVD coating*: in this process step the CVD process is conducted by mainly following the known Gorham process [5], which takes several days for the 200 μ m thick mirror membranes.
- *Reflective layer application*: once finished with the polymer growth, a reflective layer is applied on the surface. Currently we evaporate an Aluminum or Gold layer on top. This could be done by other processes upon needs, e.g. sputtering.
- *Liquid removal*: Finally, the mirror is cut off the turntable, and the remaining process liquid is washed away.

Until now we have exercised this process to grow 30cm diameter membrane mirrors, with the size limit currently being the available process chamber. These 30 cm prototypes for the moment are ideal to gain knowledge on the process, improve on surface quality, roughness or influence of border tension effects. The 30cm F#3 mirrors, as currently available, are a matching size to research the optical control process with the radiative method, outlined in chapter 4.

Process upgrades

While we have been using the prototype chamber now to grow several of the membrane mirrors, we have started to implement several improvements to the system. In the light of a future larger system, we can test with the 40cm chamber how process parameters can improve the mirrors and ensure a continuous quality. Two major parameters are currently on the way to be implemented: a polymer dimer supply system into the process without breaking the chambers vacuum and a process buffer gas supply to improve on surface quality. The dimer supply system already has passed a first test, and we could grow a membrane with a continuous high vacuum quality over the full process duration. The buffer gas supply system is under preparation and it follows the parameter space that has been discussed by [10], having shown that an Argon buffer gas can effectively suppress volume polymerization, resulting in improved surface qualities. A typical surface quality that we can reach with our prototypes without special process care is shown in Figure 4.

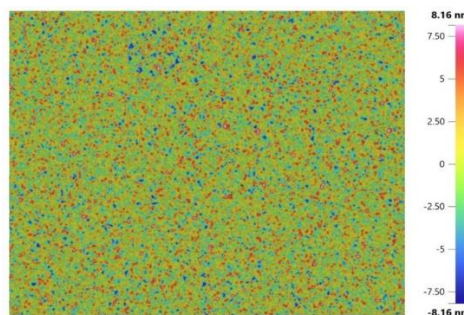


Figure 4 Surface topology of a membrane mirror test area. The measurement was performed with a white light interferometer (Sensofar) and shows a $\sim 800 \times 700 \mu\text{m}$ area of an aluminized Parylene-C sheet. The measured surface RMS amounts to 2.7nm. While already matching requirements for an optical telescope surface, the 'spotted' surface indicates that some volume polymerization is still present in the reactor. With the envisioned upgrade to a controlled Argon mass flow we expect even better results.

4. RADIATIVE ADAPTIVE SURFACE TUNING

With the membrane mirrors coming out of the production process already in good 'optical' quality, and being pre-shaped as a parabolic concave mirror we can probe the mirrors with optical metrology tools. For this, we are using a commercial Shack Hartmann system (Optocraft) with high dynamic range to probe the surface. The surface measurement system is laid out in Figure 6. With a single mode fibre matching the F# and being located at the radius of curvature of the mirror, we can use the back reflected light to probe the mirrors surface. With splitting the returning light with a cube beam splitter and an imaging lens in front of the SH lenslet array, the reflected wavefront can be measured.

Radiative Surface Control

Being a thin material, the membranes are subject to many deformation sources: On ground, gravity will change the shape, depending on the way how the mirror is hold in place. Mounting or the border seat precision has an impact onto the mirrors

performance, as well as thermal variations cause the material to change its shape. All of those influences will appear in one or the other way when deploying such a mirror in space.

To counteract such surface deformations active systems have been proposed for membrane optics. Based on electrostatic, piezoelectric, or magnetic actuation [6][7][8][9][10]. All of these methods do require either backing structures, high voltages, extensive wiring or complicated structured materials.

As a novel shape-tuning method, we have proposed to utilize the thermal expansion of the mirror material itself to actuate the local shape. By simply radiating light onto the mirror, the absorbed portion of energy will increase the temperature of the thin film. When applying a local increase in temperature to the concave mirror shape, the material will react with a local increase in curvature. Controlling spatially the amount of energy radiated over the mirrors surface, the surface shape of the mirror can be controlled actively. This method does not require any backing structure, nor complicated wiring or electronics, nor is touching the membranes surface at all. Utilizing a digital light projector to illuminate the membranes surface we add very little weight to the system, but can make use of the huge number of active pixels such a projector offers. With each of the pixels being a locally intensity tunable light source, we turn the primary of the telescope into a deformable mirror with possibly millions of actuators.

In Figure 5 a sketch is shown how such a system could be set up in a telescope assembly. A star in the field of view could be used as reference, delivering a flat wavefront towards the telescope. With collecting distortions from the primary (and other parts of the mirror train) the resulting wavefront is measured by a suitable sensor system. To counteract the distortions, a light source with a DLP illuminates the mirrors surface, altering its shape. With an active control loop commanding the illumination distribution, the wavefront distortions can be minimized.

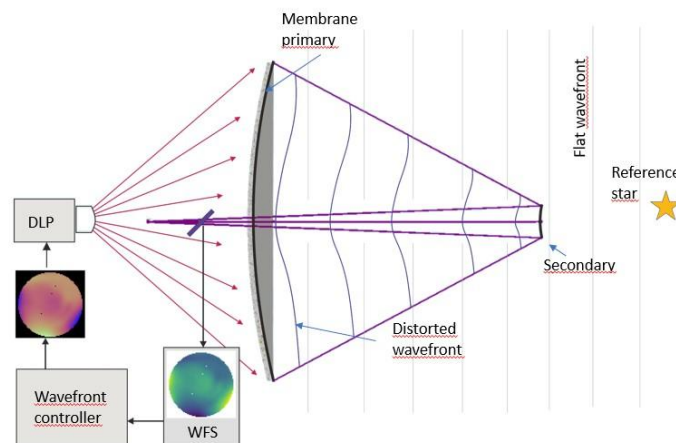


Figure 5 schematics of the wavefront control, as would be conducted in a telescope system. A reference star within the field of view supplies an undisturbed flat wavefront to the telescope. The light from this reference star is picked and directed towards the wavefront sensor. Any membrane deformations and alignment errors are accumulated and seen by this wavefront sensor. The wavefront controller calculates an irradiation pattern which is applied via a digital light projector on the membrane primary mirror. With the absorbed light causing a local increase in temperature, the local surface curvature increases by thermal expansion, again seen by the wavefront sensor and controlled in closed loop.

Experimentally testing this method is currently conducted with the usage of our 30cm prototype mirrors. In Figure 6 the schematics of the optical setup is shown. The measurements from the Shack Hartmann sensor provide the reflected wavefront, that are read into the control computer. The mirrors shape is changed by irradiating the light from a commercial laser DLP onto its surface. Geometry matching between sensor and DLP is done by dialing known patterns of irradiation into the DLP, while recording the resulting wavefront with the SH sensor.

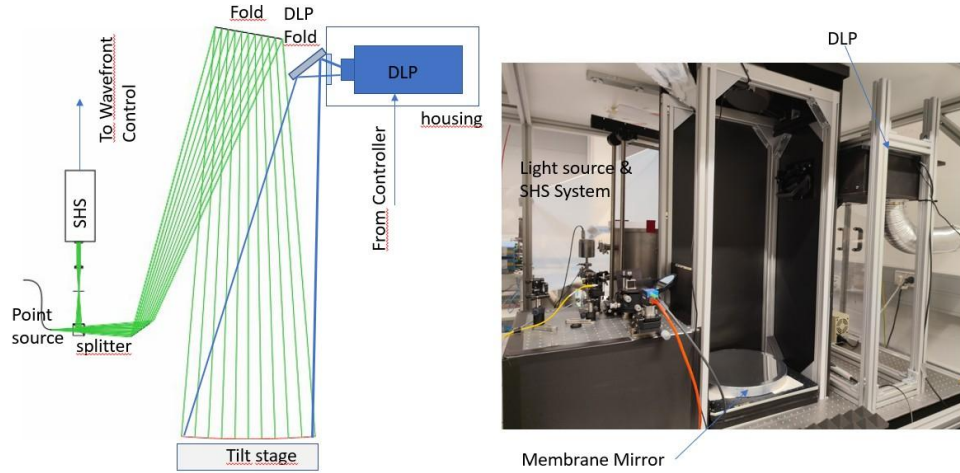


Figure 6 optical setup of the membrane mirror measurement and control. A fibre based point source is placed at the radius of curvature of the mirror, with the back reflected light being split towards the Shack Hartmann wavefront measurement system. A lens in front of the SHS images the membrane onto the lenslet array of the SHS. The controlled deformation of the mirror is conducted with the laser based DLP projector, illuminating the membrane from the front side. The DLP is contained in a housing structure with active heat removal, while the rest of the system is closed against environment to minimize external turbulence distortion. To the right a photograph of the setup with opened housing is shown.

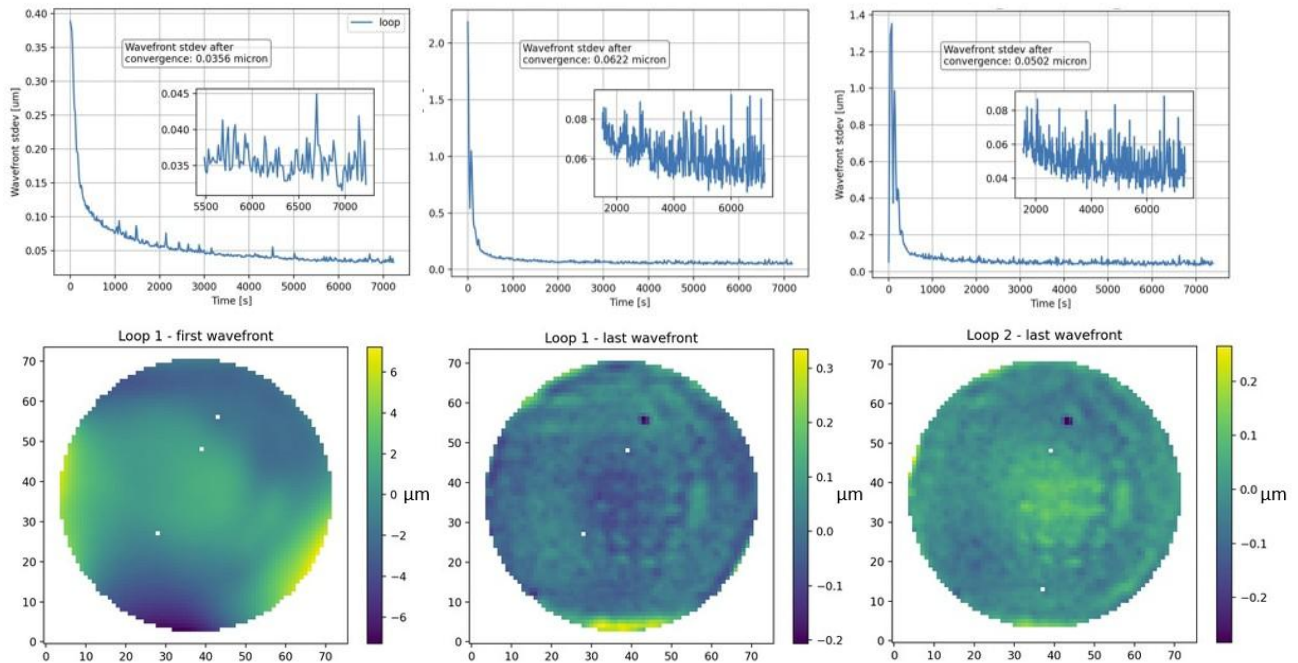


Figure 7 In the top row on the loop convergence with different parameters is shown. To the left a dataset from 2024 is shown with one of the first control attempts. In the middle a current control system with a new DLP set up, and to the right a version that includes an outer border extrapolation in the control loop, smoothing boundary effects. In all cases we usually start at wavefront distortions of around 2 to 3 μm RMS that can be improved by at least a factor 50. In all cases we still see noise in the measurement and control of order 20nm, originating from a not yet optimal Shack Hartmann setup (visible in the center of the maps) that will be improved for further tests. The bottom row shows wavefront maps in reflection from the controlled membrane. The left is the wavefront without control, middle the 'standard' control settings, the right panel with border extrapolation. The slightly unstable measurement in the center, causing the major amount of noise, originates from a recently recognized measurement issue at the 20nm level, that will be removed for the next tests. Expecting the noise issue to be solvable, a reflected wavefront of-order 30 to 40nm RMS can be achieved.

The closed loop control is based on a zonal feedback and has been implemented with a framerate of 15s, and an integral control with a $\sim 3\text{dB}$ bandwidth of $\sim 1\text{mHz}$, as already used in the first publication of this aspect[2]. Figure 7 shows examples of three closed loop convergences. The left panel is a reference to our 2024 publication, where the first closed loop performance has been achieved. With recently re-starting the program we now can reliably close the loop with an upgraded laser DLP any time. The final converged wavefront performances are of-order 40 to 50nm RMS, but within the current measurement noise comparable to each other. Since the step response is of order 40s and a small gain is applied, the convergence takes several hours. In the current laboratory environment disturbances are present in the measurement. Two factors currently limit the final performance, that will be improved in further tests: since we apply a relatively large bias radiation to the membrane, the generated heat and turbulence from un-absorbed radiation adds noise to the measurement. In addition, a measurement issue which is only seen at the $\sim 20\text{nm}$ level, adds uncontrolled background to the SH. Getting both effects under control will improve the system and lead to an even higher surface quality in the next tests.

5. DEPLOYABLE TELESCOPE STRUCTURES

Being a thin structure, the membrane mirrors will easily deform under its mounting conditions. As such the structure holding the mirror in place will play an important role in system performance. As the closed loop control discussed in the previous chapter will enable the ‘high order’ or fine wavefront control, it will require to off-load large deformations to the mirror mounting system. Following a comparable scheme that is commonly used in ground-based telescopes, the low order deformations are compensated by the ‘telescope system’: a secondary mirror that can be positioned, and a mirror border control system, capable to align its global position and ensures the distortion free position adjustment of the mirrors outer border. We propose to install a system of positioners that can adjust the border position and force, controlling the low order wavefront. Those positioners will require to compensate for telescope structure variations, leaving the mirror optically in good shape. This requirement will call for a multi-axis stage at μm resolution, and several cm in travel range. Some mirror mounting possibilities are discussed in [11], proposing a load-distribution structure and a wire mount to the solid telescope beams. Rolling the primary mirror for packaging allows for a fairly compact arrangement of this telescope, being longer than wide, matched to fairing geometries of a rocket system. In Figure 8 we show a deployment sequence of such a compactly storable telescope assembly.

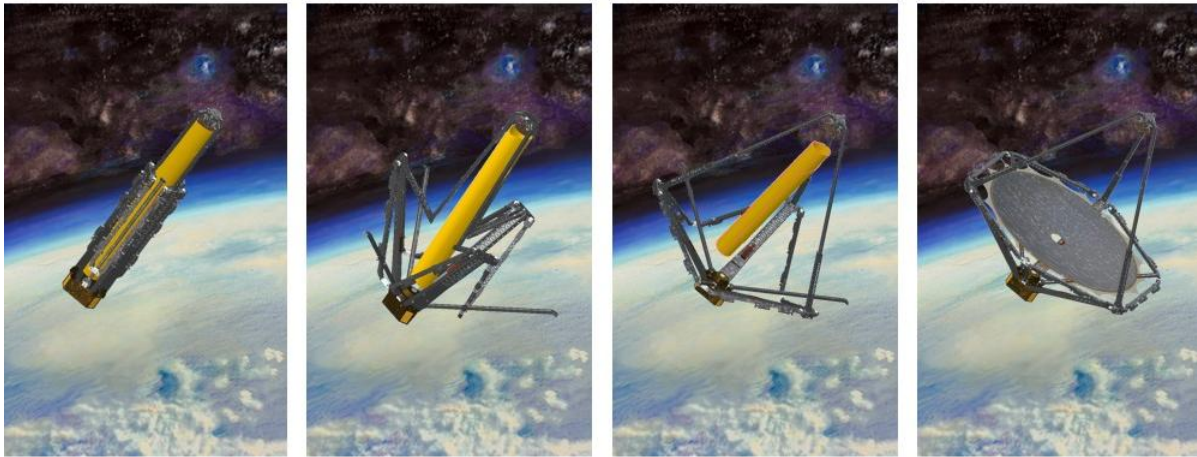


Figure 8: artists impression of a deployment sequence with a rolled primary mirror. The telescope structure is folded around the stored mirror and fits in a launch fairing. In its deployed state it forms a ring like structure around the primary, allowing to place actuators to precisely align the pulling directions of the wire mounted membrane mirror.

A telescope based on the active membrane mirror does superimpose requirements and unique architecture needs. Amongst those are the following considerations:

- **Mounting the thin film membrane primary:** In contrast to a solid system, the flexible nature of the thin material will require a mounting method that does not deform the shape. We have been looking at a system where a load distribution structure is attached to the mirror circumference, spreading the load from the mirror diameter onto wires that attach to a solid structure. Within such a system one needs to ensure that the forces on the mirror are equally distributed, and the pulling directions do hold the mirrors outer diameter in a plane. Being an optical surface, this plane must be maintained to the level where the radiative active loop can correct the shape, i.e. within

an expected $\sim 5\mu\text{m}$ precision level. As such a controlled three degree of freedom stage could be required at each of the wire locations.

- *Locating the DLP sources for the radiative shaping:* There are two basic possibilities to locate the radiation sources for the active surface shaping. Illuminating the front side, or the backside of the mirror. Illuminating the front side from the secondary mirror position possesses the beauty that a symmetric small cone of illumination would be needed. On the other hand, the front side of the mirror will hold a coating dictated by the science needs, which might reflect the light over a wide wavelength regime. As such, the power needs of the DLP source will increase. Illuminating the backside, one can choose a mirror coating matched to the DLP illumination wavelength, decreasing the power needs. Nevertheless, this backside illumination may be geometrically more demanding. The cone might be larger, or for obscuration reasons multiple DLP sources have to share the task.
- *Oscillation suppression:* In contrast to a solid stiff mirror substrate, the thin film membrane is likely to be more sensitive to vibrations. While we do prepare an analysis to cover this topic, it is worth mentioning here that special care on isolation and suppression of vibrations can be expected.
- *Solar shielding:* as many space flight systems do require a shielding from solar radiation, the thin film primary does in particular. As we are using the polymers expansion to control its shape by radiation, any uncontrolled additional radiation needs to be avoided. There will be no problem with a certain amount of leakage through a sun shield, warming the primary mirror, as long as the DLP radiation source is able to even it out and keeping its surface under control. To achieve this, a careful radiation management and shielding will be a major requirement.

6. CONCLUSION

Thin film membrane mirrors offer a unique possibility to create very large space telescopes. This technology offers extremely low areal weight optics, a compact way to roll those mirrors for packaging and an economic production path. With the production method, to grow mirrors by chemical vapor deposition on a rotating liquid in vacuum we have developed a method to make high quality parabolic pre-shaped optics. In conjunction with the adaptive shaping via the radiative method we found a pathway that can lead to a new generation of very large optical telescopes in space.

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