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MOIRE Gossamer Space Telescope – Testing Challenges and Solutions

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The MOIRE optical space system, being designed by Ball Aerospace and its partners for DARPA, is a gossamer structure featuring a 10 meter diameter membrane optical element at a distance 50 meters away from the spacecraft bus, with traceability to a system with a 20 meter diameter primary optic. The program is preparing for the space based mission through large scale, ground based testing. As expected, testing an optical system based on precision membrane structures with an exceptionally long focus creates unique challenges. This paper discusses several such challenges and some of the unique solutions and capabilities that Ball Aerospace and its partners are providing.

I. Introduction

THE Membrane Optical Imager Real-time Exploitation (MOIRE) program is sponsored by the Defense Advanced Research Projects Agency (DARPA), as seen in the initial program Broad Area Announcement[1]. Figure 1 depicts a conceptual approach. The MOIRE system seeks to take advantage of recent developments related to large, low cost, lightweight deployable space telescope technologies to provide geosynchronous based earth observation capabilities. Ball Aerospace & Technologies Corp., with its partners Lawrence Livermore National Laboratory, NeXolve Corporation, and ATK, are working to design a 10-m aperture demonstration telescope (ultimately traceable to a 20 meter aperture system[2,3]) with real-time video downlink capability. The concept exploits the benefits of transmissive diffractive optics, which allow for about 3 orders of magnitude relaxation in out-of-plane tolerances in the primary optic when compared to a reflective system. The design is stowed for launch and deployed on orbit.

The MOIRE Phase I study was completed in September 2011, culminating in a Preliminary Design Review and demonstration of the ability to fabricate meter-scale diffractive membrane optical elements. The program is now in a Phase II study to ground validate the telescope design. Ground testing includes building the full optical path, measuring performance relative to changing environmental laboratory conditions, calculating margins based on collected data, and creating manufacturing processes and mechanical designs to lay the groundwork for a flight system. Ultimately, the currently funded Phase II program seeks to image scene data on a real time basis using the complete optical system.

To accomplish the imaging objectives an end-to-end metrology system is being developed. Taking into account temperature and humidity changes, and other such environmental factors, the control system will keep the optics

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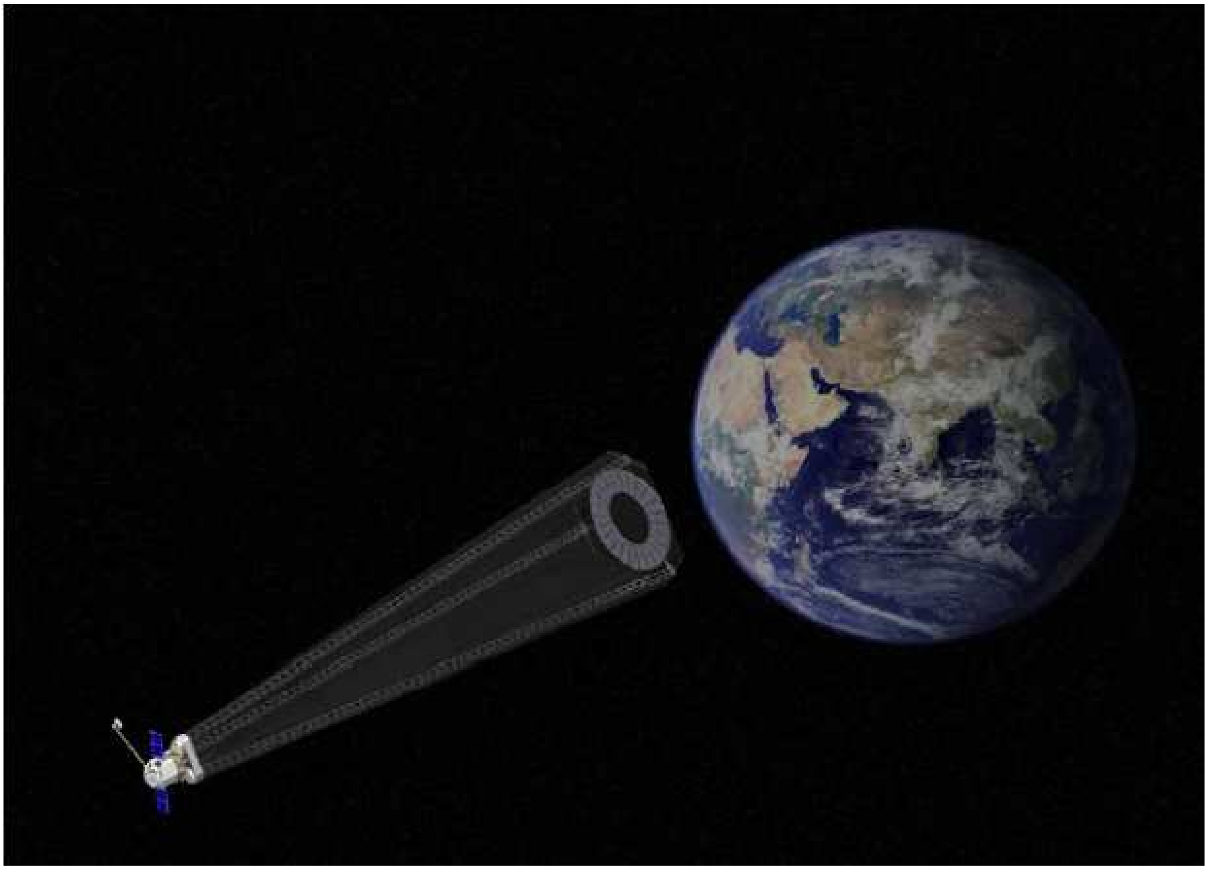
aligned over the imaging period. The metrology system is being designed to measure the relative movement between the primary and aft optical system. It includes three actively controlled optics and has sources and sensors located on the mounting structure of two additional optics. In situ data is being collected in advance so that the system will be best positioned at the start of integration and test. Indeed, a significant achievement of the Phase II program will be a finely tuned understanding of the environmental challenges and how to overcome them to achieve results.

A key focus of the current phase is investing resources in a more comprehensive understanding of the materials that will make up the flight system. The membrane optic receives a lot of attention, but the support structure will likely be a composite of some type. Understanding how these two materials behave on their own and in their interactions with each other is a critical driver of the program. Challenges with accurately measuring the properties and an overview of where we stand today are discussed in this paper.



II. Testing Overview

Testing the MOIRE optics system creates challenges in available floor space as well as in the control of environmental conditions within that space. Additionally, deciding what information is important to gather for analysis and what information can be used to control the metrology system influences the hardware requirements in the systems controlling the test. Finally, choosing how much of the final system needs to be built in order to accomplish the test objectives feeds directly into cost and schedule budget decisions. The following sections address these challenges and Ball's solutions.

A. Floor Space

Although a 10 meter optic is baselined for the on orbit mission, a 5 meter optic allows for a test bench capable of proving out the technical challenges involved in the larger diameter optic while scaling down distances to more practical scales. Despite this scaling down of the focal length, a significant amount of floor space is still required. Figure 2 below maps out the general dimensions of the test area and some of the key components. Ball Aerospace has invested significant resources recently to greatly expand its floor space for processing large space systems. The

MOIRE program is taking advantage of these new facilities and has become the first program to move into the new additions. By being a first-use program MOIRE has been able to influence the design of the facilities to better optimize the space for the testing of large scale optical systems.

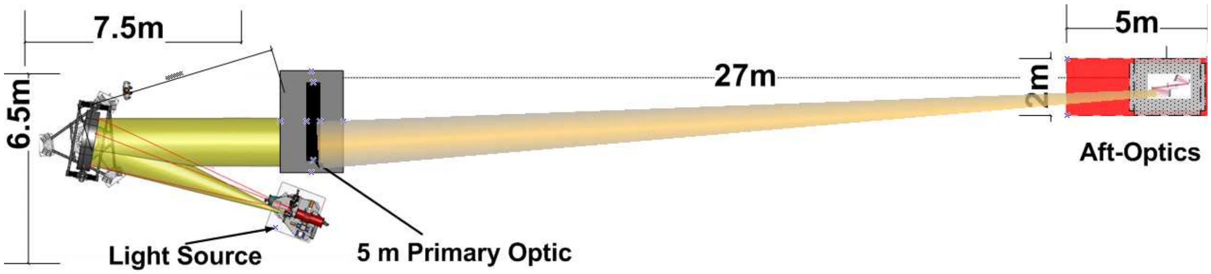


Figure 2. General Layout and Dimensions of the Test Area

B. Required Environmental Control

The membrane has a coefficient of thermal expansion near zero, but the ground based equipment that supports the membranes has higher thermal coefficients. The membrane's properties were designed with NeXolve in anticipation of on orbit operations. Supporting materials, such as the memrbane's metal frame, were chosen based on cost and schedule. Additionally, while the membranes are susceptible to humidity changes, the metal frames in the test are not, which helps prevent large changes throughout the system. All ground based optic systems are also influenced by turbulence in the room's air which diffracts the signal. MOIRE's long focal length provides for a greater potential for this error than smaller systems. Air turbulence can be mitigated by shutting off sources of air flow, but optical averaging can also be used in this case to help remove the effects of nominal turbulence over time.

The two environmental variables that the program can best control are temperature and humidity. When controlling for thes two variables, the first step is understanding how they impact the optical performance so that limits can be set. Figure 3 below shows a trade study used to determine the stress in the membrane due to changes in temperature for various frame materials. By understanding the stress in the system the team can understand the optical performance and thus set temperature limits in the room. For instance, for the ground based system the temperature during testing can be readily controlled to ±3 °C and to tighter limits when required. So while the composite material provides for low stress changes for a given temperature change, its cost and schedule impacts aren't worthwhile because the team doesn't need that much margin. On the other hand, the space based system will have much larger swings in temperature as well as mass lmit requirements so the composite is a likely choice for that mission.

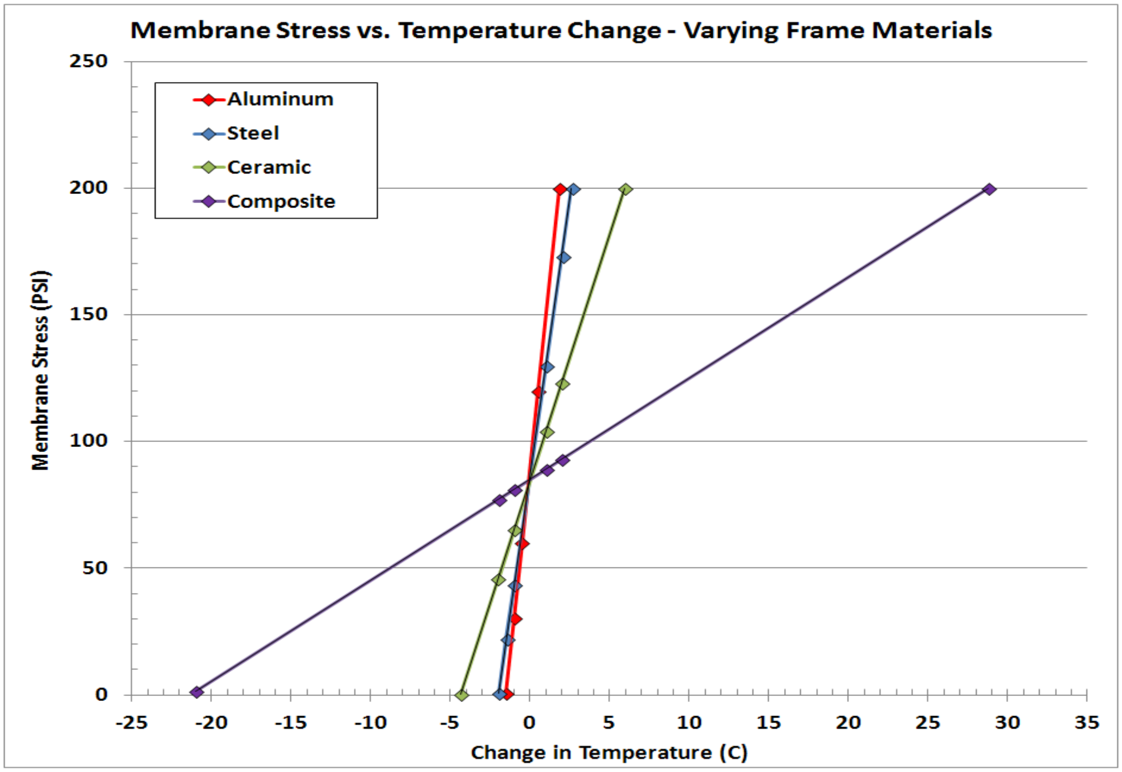


Figure 3. Membrane stress through temperature changes for sample materials.

Humidity is important because it can change the stress in the membrane without affecting the frame. The expansion/retraction of the membrane relative to the frame can cause wavefront errors in the optic. However, humidity is often closely tied to the temperature. Analysis thus needs to consider both effects simultaneously. Figure 4 shows a chart where humidity effects are combined with temperature to help judge constraints for that particular frame material.

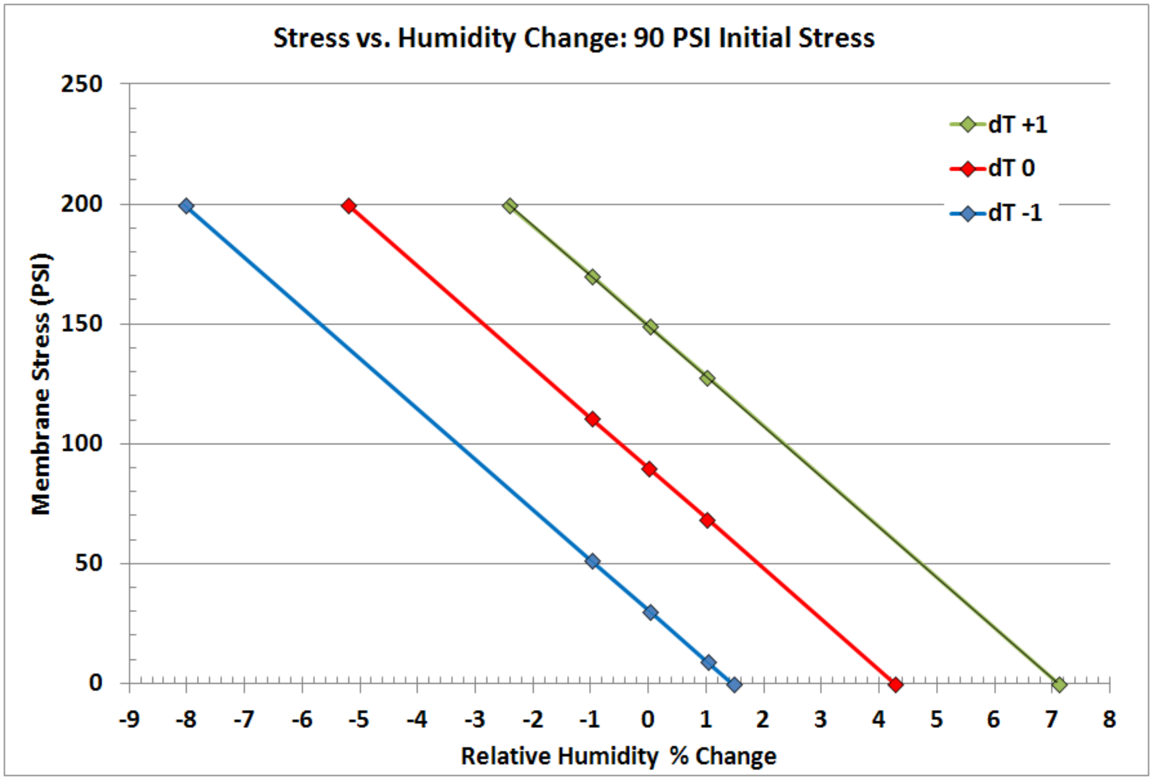


Figure 4. Membrane stress through temperature and humidity changes for an aluminum frame.

It is seen that humidity can actually play a helping role in performance. When temperatures drop it causes a reduction in membrane stress. Losing too much stress will cause wrinkles. However, a temperature reduction most often corresponds with a humidity reduction and this causes an increase in membrane stress. The same logic works in reverse for a temperature increase: increasing temperatures cause stress increases, but also increases the humidity which decreases membrane stress. The interaction of temperature and humidity can therefore increase the robustness of a system relative to a scenario where only one of the variables is considered.

C. Testing Hardware

The MOIRE ground test components can be broken up into three broad categories: the light source or scene generator, the primary optic, and the aft optics. Figure 2 above labeled the components on the floor space diagram. The light source controls the quality of the light input into the system. It is also the source of the images projected through the system to measure performance. The primary optic systems represent the diffractive optics and their supporting testbeds. Environmental control and flexibility to changing needs are key design principles in this region. The aft optics area is the collection of optics used to receive, refine and process the image. It includes a number of custom optics with designed-in adjustment capabilities as well as the computer systems and software used to report the final results.

The goal for the light source component is to create realistic and high quality inputs into the system. Ball Aerospace has a long history in the design and manufacture of precision optics, making this one of the most certain aspects of the test program. Light is provided by a high powered source in wavelengths relevant to the program and then collimated with a 1.45 meter diameter finely tuned reflector.

The primary optic contains a mosaic of membranes about .4 m^2 each that create the larger optic. Because the primary optic is segmented, the team can test individual optics and extrapolate performance to a full set of optics. This allows Ball to build a subset of the full diameter of optics across a wider range of conditions than would be allowed if a full set of membranes needed to be adjusted for each test. Figure 5 shows a concept drawing using six membranes in an adjustable fixture. The ability to move and rotate the membranes allows for testing a large number of configurations and provides the data required to understand full system level performance.

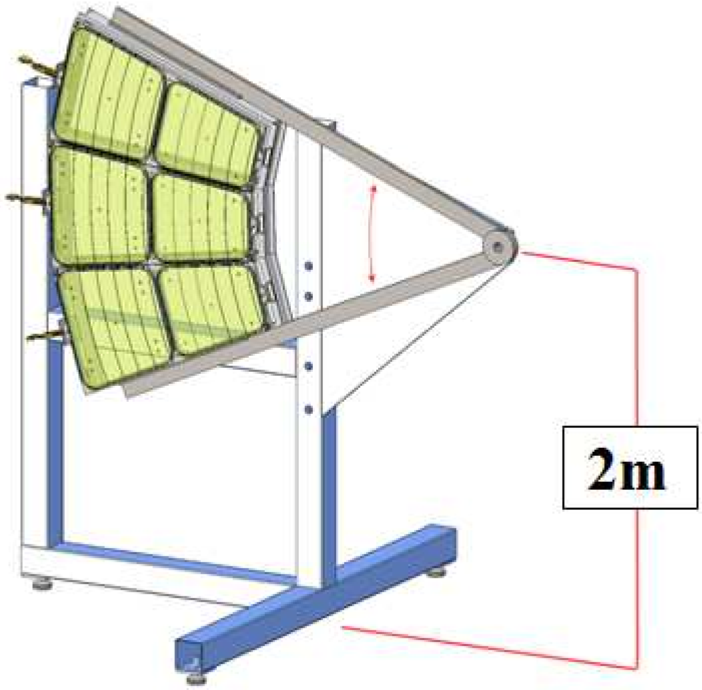


Figure 5. Concept Drawing of Ground-Test Membrane Fixtures

The aft optics system is designed to collect and refine the projected images. One of its most difficult tasks is correcting for error sources through optic movements and software algorithms. In fact, the metrology system in the aft optics contains many of the most complex design efforts. It is discussed further in more detail in its own section.

D. What's Measured and How

For the performance demonstration, a set of Air Force bar targets and complex scenes will be imaged. After removal of turbulence effects, the processed images are expected to demonstrate image quality equal to about 50% of what can be obtained with a diffraction-limited optical system. The bar targets will demonstrate image performance based on spatial MTF. Complex scenes will demonstrate imaging performance based on point spread function analysis and image structure.

III. Metrology System Design

The image quality captured by the system is influenced by a number of independent variables. The metrology system designed to control these variables is therefore an engineering challenge in and of itself. This section discusses what the metrology system is built to control and lays out the general approach to how this is accomplished.

A. Metrology System Overview

As discussed in previous sections, temperature, humidity, and turbulence all impact the overall image quality. Precise alignment of the components in the optical path is required to maintain imaging performance through each of these potential sources of error. Temperature and humidity influence the focus and translation of the image while turbulence influences the image directly. To address the alignment of the telescope, the metrology system is built to measure the displacement of the optical beam and then compensate for it by adjusting up to three different optics with actuators. Figure 6 gives a high level overview of a basic metrology control loop that Ball is building. Based on closed-loop analyses, the loop is designed with a control bandwidth of about 1 Hz.

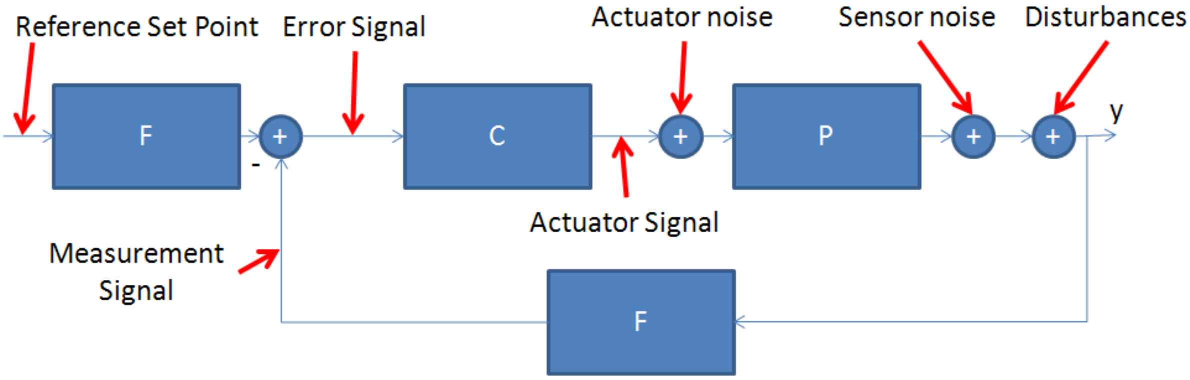


Figure 6. Basic Metrology Control Loop

Not all components of the metrology system act on a closed loop cycle. The wavefront error induced by the control opticsis are compensated for by feedforward control. For instance, the focal length of the primary optic changes with both temperature and humidity. This changes the imaging beam footprint in the aft optics. The metrology closed-loop system correct the beam position and as a consequence induces wavefront error in the imaging path. Instead of calculating the residual wavefront error in real time, the sensitivity of these values are collected in a pre-test phase and used in the feedforward operation to cancel the second-order effects of the closed-loop system. The optical beam bulk changes can thus be quickly mitigated while a less precise system deals with second order effects. Using a combination of closed and open loop systems allows for a flexible and responsive approach to the complex interplay of error sources.

The metrology system consists of laser sources on the primary mirror whose beam positions are measured by position sensing photo-detectors in the aft optics. Once final optical alignment has been achieved, the digital control system keeps the primary aligned to the aft optics via dc servo motors acting on the optics through four-bar flexures.

B. Aft Optics Flexures

In order to provide the adjustability in the optics required to run the metrology system key optics need to be flexured and, in some cases, actuated. Figure 7 displays an example optical mounting system that provides for translation both laterally and vertically. The flexures are optimized by understanding the displacement requirements and the available displacement loads. In the case of this particular optic the displacement range is measured in millimeters and the load in the single digits Newtons. This combination lead to relatively long and thin flexures that were still stiff enough to provide stability. Similar efforts also designed mounts that required rotational degrees of freedom. By optimizing each mount in the same way the optics have the capability required to satisfy the metrology requirements.

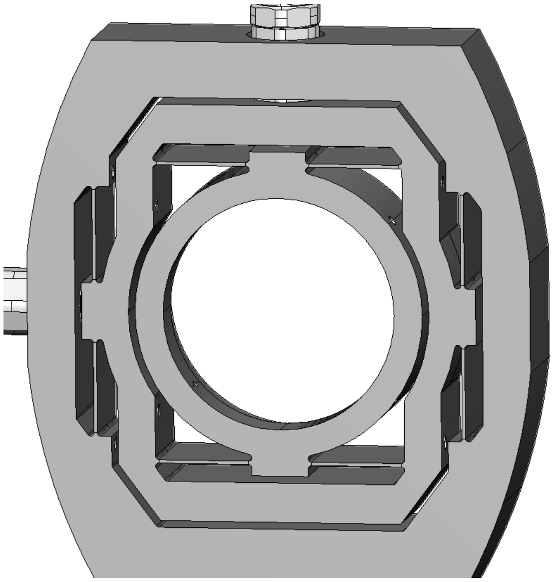


Figure 7. Example optical mount built to translate vertically and laterally.

IV. Summary and Conclusions

The MOIRE program is continuing to understand and overcome the technical challenges of the Phase II testing program to demonstate the feasibility of ultra-lightweight diffractive optics for space applications. For instance, while environmental changes on the membrane and the structures can strongly influence image quality, by understanding at a high level what the environmental impacts can be the metrology and alignment system has been designed to address any potential problems. Additionally, by completing complex and detailed optics design the team has been able to understand the testing requirements and develop enough floor space, hardware and software in order to efficiently meet the program objectives. The Ball team will continue to develop the ground based system through the rest of Phase II as it progresses towards the image capture and testing stage. Successful demonstration of the MOIRE optical technology will create a new class of ultra lightweight, low-cost alternatives for designers of large space telescope systems.

V. Acknowledgments

The authors would like to express our appreciation for all the hard work provided by the MOIRE team – at Ball Aerospace, DARPA, and our partners Nexolve and ATK.

VI. References

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