AIAA SciTech
13-17 January 2014, National Harbor, Maryland
Spacecraft Structures Conference
AIAA 2014-1367

MOIRE Gossamer Space Telescope – Membrane Analysis

William D. Tandy Jr.[1]

Larry Campbell[2], Tracy Copp[3], Rusty Schweickart[4], Ryan Thompson[5], and Dave Waller[6]

The views expressed are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

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. The proposed design has traceability to a system with a 20 meter diameter primary optic. As the critical technology of the program, the membrane has received significant analysis and testing time. This paper discusses several 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 the Ball Aerospace 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 1 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 2 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 ground demonstration seeks to image scene data with broadband, incoherent illumination using the complete optical system.

The Phase 2 study also addresses preliminary design, analysis and testing of some aspects of the flight system. Specifically, the on-orbit performance of the membrane and supporting structures are being considered. In this paper, the various analyses are compared using Root Mean Square (RMS) Wavefront Error (WFE). In addition to the analysis, validation of the design of key composite structures is planned to be accomplished through fabrication and testing in a thermal vacuum environment for survivability and deformation characteristics. The results will be used in correlated model analysis.

Finally, Phase 2 activities have begun to characterize the materials used in the system. The membrane, a Novastrat material from NeXolve, underwent tensile, creep, relaxation, micro-yield, and CTE testing. A paper dedicated to the material properties of the membrane is presented in this same conference. ATK has also provided material data for their low thermal expansion composite structures as well as finite element models.

---

[1]Senior Engineer, Structural Analysis, 1600 Commerce Street, Boulder CO 80301, AIAA Senior Member
[2]Principal Engineer, Mechanical Engineering, 1600 Commerce Street, Boulder CO 80301
[3]Senior Engineer, Materials & Process Engineering, 1600 Commerce St., Boulder CO 80301, AIAA Senior Member
[4]Principal Engineer, Cryogenics & Thermal Engineering, 10 Longs Peak Drive, Broomfield CO 80021
[5]Project Engineer II, Mechanisms & RF Technologies, 10 Longs Peak Drive, Broomfield CO 80021
[6]Principal Engineer, Mechanical Engineering, 10 Longs Peak Drive, Broomfield CO 80021

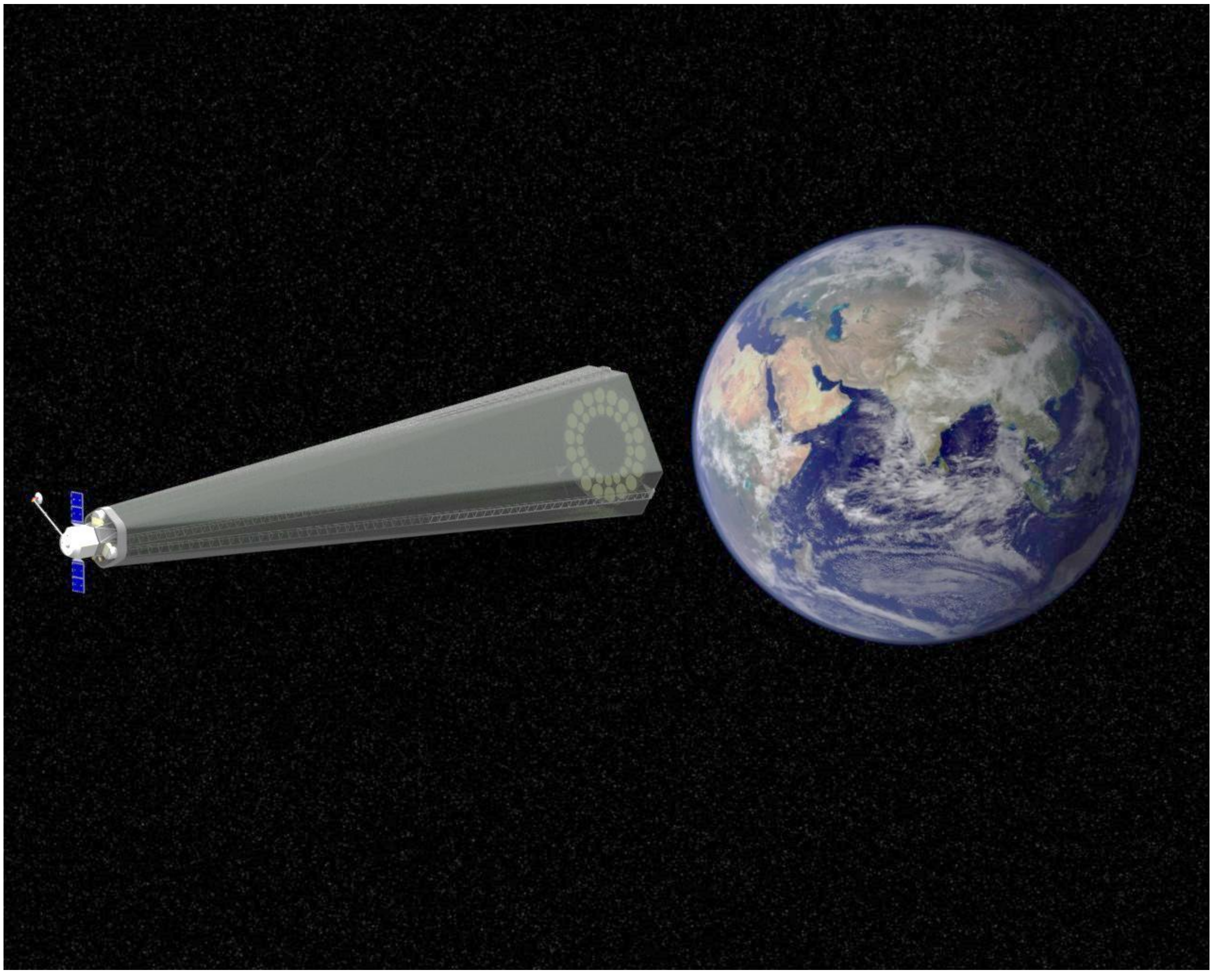


Figure 1. Ball Aerospace's concept of MOIRE based on early efforts in system design

II. Analysis Overview

Structural analysis for the MOIRE program has been ongoing for nearly three years. Through this effort, results and predictions have been collected that have created subject expertise and positioned the team to make well informed technical decisions. Topics of research have been wide-ranging including investigations into membrane and assembly level manufacturing, non-linear material property studies, and environmental predictions. Many of these analyses have highlighted the differences and challenges with membranes versus traditional optical materials like glass. Discussions in this section will cover the need for tight mechanical tolerances as well as introduce WFE as the metric used to compare optical performance impacts.

A. Wavefront Error Discussion

There are many ways to summarize the imaging performance data. One method uses a NIIRS requirement. The acronym NIIRS stands for National Image Interpretability Rating Scales. The NIIRS helps define an overall expectation and, in fact, is used as part of the program goals. However, the scale is based on subjective criteria and many calculations are used to derive a predicted value. Another commonly seen measurement is peak-to-valley wavefront error, which is a valid way of tracking surface deformation. However, the RMS WFE more directly results in actual performance metrics for the system. Plus, it feeds directly into other equations important to optical engineers, such as the Strehl ratio.

Calculating and comparing the WFE across various design concepts is accomplished with Ball's custom software. Figure 2 shows an example output of Ball's in-house optical software. Plots such as these were used to track error sources as the system underwent trade studies. A variety of metrics can be calculated including fringe patterns, derivatives, and the RMS WFE used in this paper.

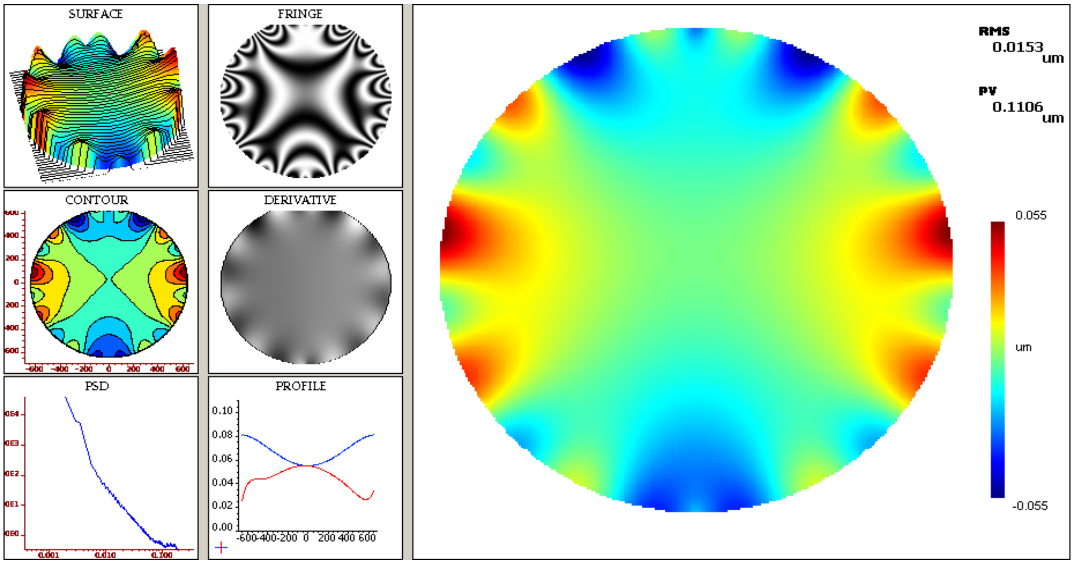


Figure 2. Example WFE plot used to analyze the impact of structural changes. In this case, the boundary of the membrane was displaced to limit values at discrete points. Further discussion of these plots takes place in the analysis sections.

While individual error sources result in a single RMS WFE value, building system level RMS WFE predictions from several sources calls for Root Sum Square (RSS) methods. For instance, the membrane material may have both thickness and CTE variations. Both are randomly distributed and both contribute to a particular type of WFE source. Instead of adding these together the results are RSS'd.

B. Problem Definition

In broad terms, the analysis has three cascading interests:

1) Ensure the membranes survive structurally
2) Ensure the membranes do not wrinkle
3) Minimize the RMS WFE

First and foremost, the membrane must survive the environments to which it is exposed. Figure 3 gives a sample of many of the environments that the membrane would be subjected to, roughly in order. Commonly overlooked areas, such as shipping from site to site and the environment at the launch site, could potentially contribute to a failure mode if not properly prepared for in design and analysis. For instance, humidity changes can tighten or slacken the membrane surface, changing its ability to handle loading that might otherwise be benign. These considerations fed into the design space definition for the mechanical engineering team.

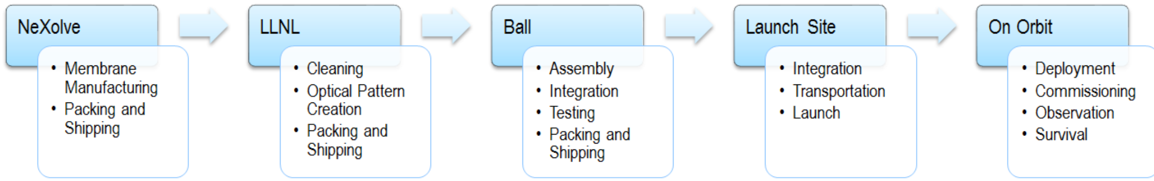


Figure 3. Simplified overview of the environments the membranes would experience, from beginning to end of life. Analysis covered every topic, producing large amounts of data and a detailed understanding of the design space.

After ensuring membrane survival, the second requirement is that there be no wrinkling of the surface. The membrane acts as a diffractive surface; if the surface is wrinkled it will scatter light in uncontrolled directions and reduce the optical efficiency of the system. For this paper, wrinkle onset definition is summarized as a zero stress state in the membrane. Although simplistic, assuming that wrinkles happen when parts of the membrane have no tension does a good job of describing the design space, especially when the trend is increasing and decreasing levels of stress through an environment change. The stress used in the analysis is the minimum stress from the in-plane axes, σ_x and σ_y.

Using internal stress as the wrinkle criteria has the added benefit of often times creating linear relationships between the outcome and the loads. The stress levels in the membrane are typically low, peaking at 2 MPa (200 PSI) or less. For a membrane just 20 μm thick, this represents a low amount of in-plane force. The result is that even though the membrane is a non-linear material, the reponse at the analyzed levels appears to be linear. In fact, all of the analyses presented in the paper assumed non-linear properties, but the results are nearly linear.

As an example, Figure 4 shows a result of the impact of material choice in the support structure. The assumption is that wrinkle formation will begin when the line crosses the zero-stress axis. Detailed analysis has shown that small wrinkles can form before this point, but the assumption holds true when discussing bulk wrinkling across the surface. Although the analysis assumed non-linear properties, the result is data points best matched with a linear fit.

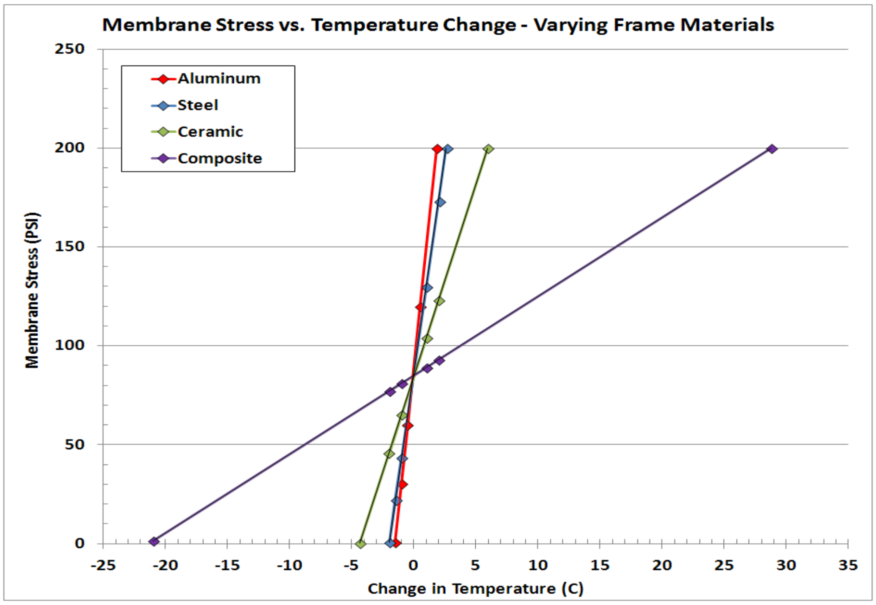


Figure 4. Early design effort results for membrane stresses in frames of various materials. The materials shown were considered for ground testing. Using internal membrane stress to identify wrinkling risk often results in linear relationships for the small stress ranges important to the analysis.

Finally, once the risks of membrane survivability and wrinkling have been mitigated, the analysis seeks to minimize the WFE. The system has a number of built in methods to deal with WFE, but as a starting point the goal is to have 100 nm, or less, of combined RMS WFE.

C. Environments

The MOIRE system is designed to operate in a geosynchronous orbit. This orbit creates a challenging thermal environment due to seasonal exlipses as shown in Figure 5.

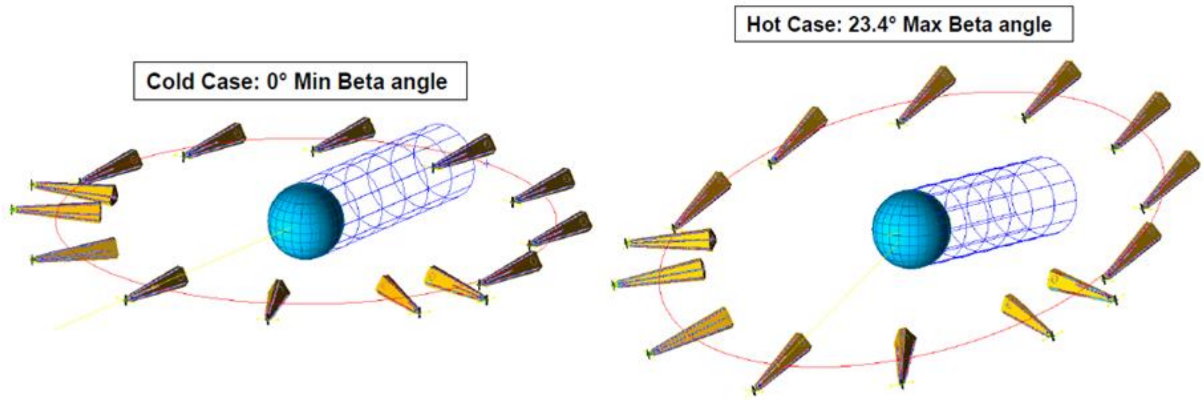
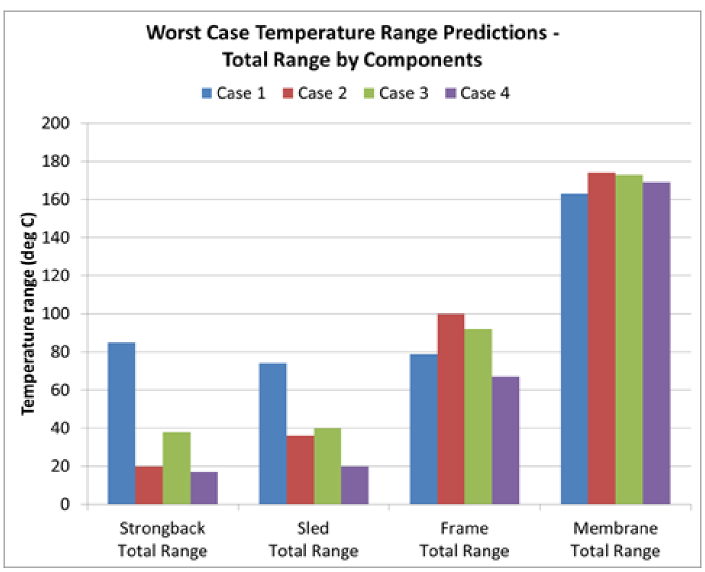


Figure 5. Thermal environment cases. The spacecraft rotates away from the earth during part of its orbit to avoid pointing the optics at the sun.

Some of the thermal effects are reduced through the use of a sunshade covering the optics path, seen as the orange structure in Figure 5. To optimize this effect, one of the variables considered in the trade studies was the sunshade material. Numerous studies were run to come up with comparisons such as those in Figure 6. Through this effort, the expected temperature ranges that the membrane and its supporting structure would need to survive were defined.



Vapor Deposited Material
Two layers - Aluminum
Silver
Aluminum
Nickel
Germanium
Chromium
Silver-Teflon (not VD)
Iron Oxide
None (black Kapton)

Figure 6. Example case study looking at the effect of sunshade materials on the thermal environments of the primary optic. The table on the right lists coatings considered in Rusty Schweickart's work. Some were applied on the internal side of the sunshade, others externally, and some were applied to both sides.

III. Analysis

With an understanding of the environments the membrane would be exposed to, analysis next looked at ways to optimize membrane shapes, manufacturing tolerances, and supporting structure.

A. Frame Warping Requirements

One of the detailed analyses looked at how optical performance changed with frame flatness. In this scenario the membrane is manufactured perfectly flat by NeXolve and then bonded to a frame with various deformations. Figure 7 is an example of a deformation. In this figure the frame creates a saddle shape with the red regions being held fixed and the blue points being deflected upwards by varying amounts.

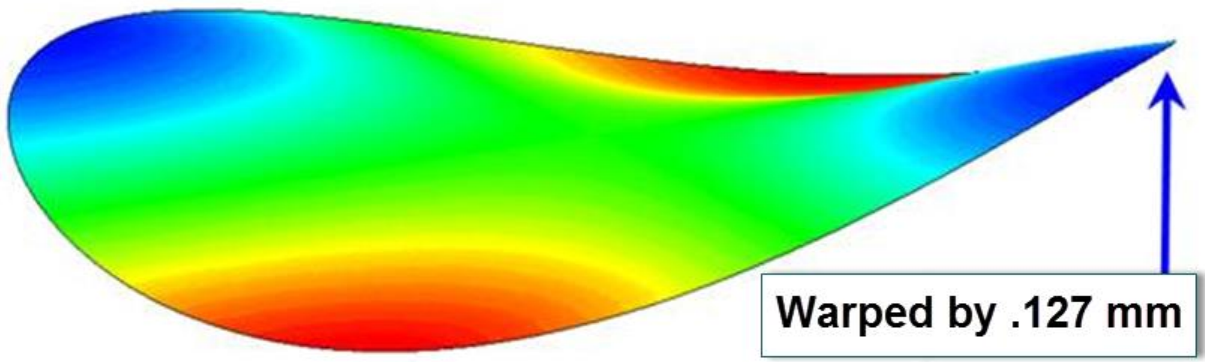


Figure 7. Example deformation analyzed in this section, in this case a saddle shape.

Several different types of displacements were used, with some being saddle shaped as in Figure 7 where two points are held fixed, and others assuming different numbers or locations of the fixed points. The intent was to try to capture what kinds of manufacturing deformations could be expected. The distortion results from these cases were run through Ball Aerospace's custom WFE software to produce results like those shown in Figure 8. In this case, this WFE results corresponds to the deflection shape from Figure 7.

It turned out that the result in Figure 8 is the worst-case result. The combination of a high amplitude with the saddle shape produced overall worse results than the other shapes investigated. The bounding case of 67.4 nm of RMS WFE helped establish the tolerance requirement for frame flatness. An inter-discipline effort of mechanical and optical engineers resulted in a design with a final expected performance hit of less than 7 nm of WFE.

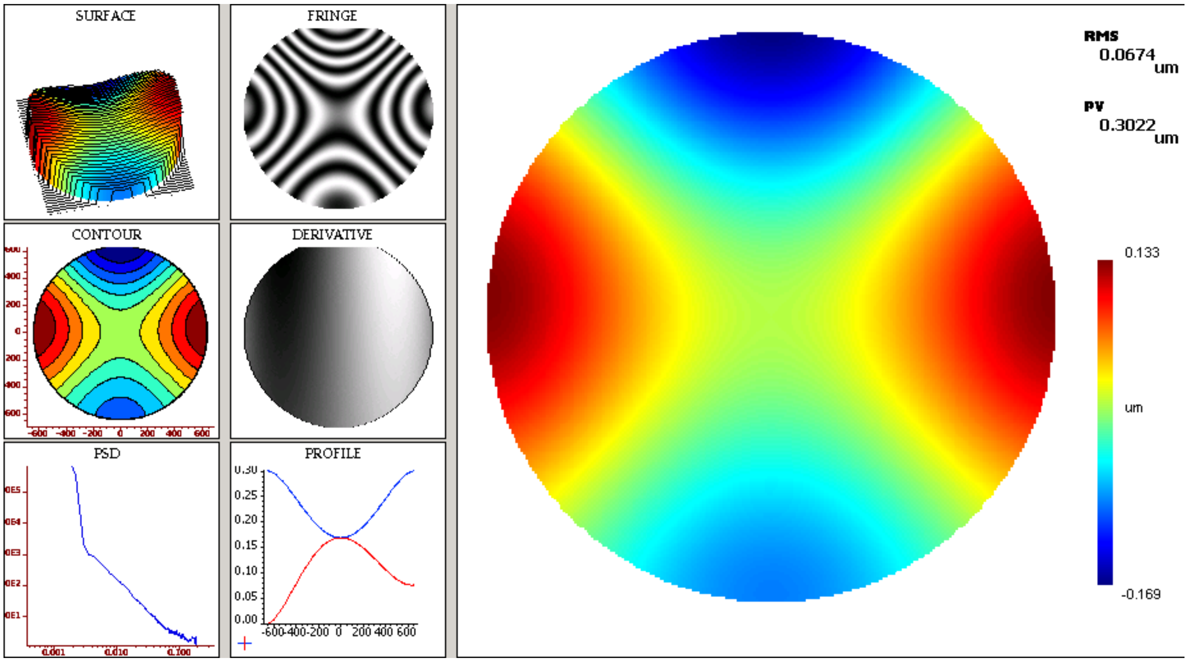


Figure 8. WFE analysis result of the shape in Figure 7. This was the worst-case result and led the team to a better understanding of the optical and mechanical requirements.

B. Membrane Thickness Variation

The membranes produced for Phase 2 were able to meet the thickness requirement of 20 ± .5 μm. While future fabrication techniques are are expected to reduce even this small variation, the team was interested in understanding the effect of thickness variability on the WFE. In response, a thickness variation code was developed.

The analysis started with a membrane of uniform thickness, then seed points were added that changed the local thicknesses. The thickness was changed by using a random distribution based on Gaussian probabilities. From there a smoothing algorithm applied thicknesses to the elements between the points. All other properties, such as modulus and CTE were held constant so that the only parameter that changed was the thickness. Figure 9 demonstrates an example result, showing that the displacement of the circle varies across the surface when a thermal load is applied.

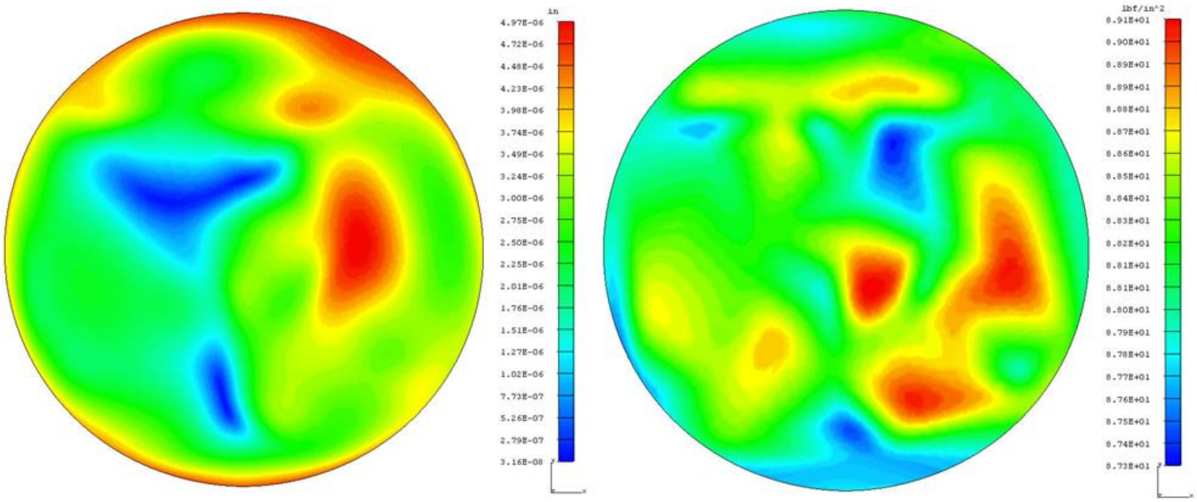


Figure 9. Example deformation plots of two membranes with thickness variations subjected to a temperature change. The analysis used a number of randomly generated thickness distributions to investigate optical performance.

A displacement map was calculated at three temperatures and these were fed into the WFE calculations. This process was repeated with new random thickness models and the results tabulated. Figure 10 shows the averaged results from the multiple runs. Note that a membrane of uniform thickness would have zero contributions to WFE for this type of analysis. The result then is that the 0.5 micron thickness variation could lead up to 10 nm of RMS WFE.

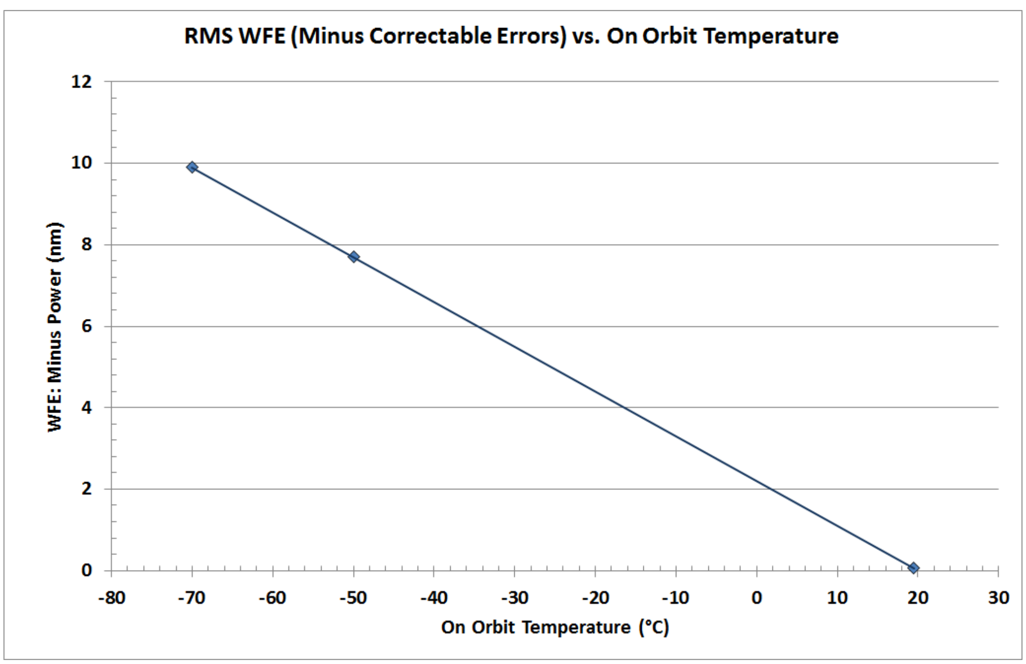


Figure 10. The chart provides the RMS WFE of the membrane due to thickness variation effects. The results shown are averaged across all the samples.

C. Frame Fastening

One of the assembly concepts involved bolting a membrane between two halves of a frame. However, a typical concern with fasteners and optics is that small changes in torque or load distribution can warp even thick glass components. To understand what kind of impact the membrane may see from this type of load input, a small analysis was run. In this study a preload from the fasteners was applied at numerous proposed fastener locations around the circumference. Very small changes in distribution were applied to simulate cases where the fasteners were at random extremes of their hole clearances. Figure 11 shows the result with a displacement map. It is seen that a displacement distribution can be created through this type of loading, although it's fairly small. A WFE analysis showed a RMS WFE contribution of about 5 nm, although the bulk of the error was from one region. The conclusion from this one-off study was that if fasteners were to be used it would be important to tightly control the preload and location, but even without those controls the impact would be relatively minor.

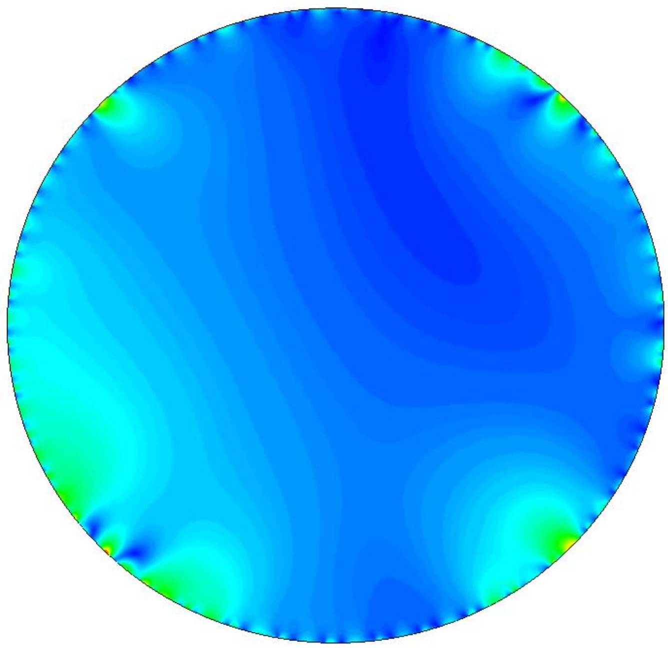


Figure 11. Example deformation plot from bolt preloads. The maximum displacement is about 500 nm. Small variations in fastener locations, within mechanical tolerances, create small changes in membrane tension and displacement.

D. Bonding Flatness

Another approach to holding the membrane to the frame is a bondline. The bondline approach is considered more likely than a fastener approach so a trade study was run to understand the design space. In this case, the goal was to understand how sensitive the optical performance was to variations in the bondline thickness. Additionally, the goal was to understand what frequency in variation would be acceptable. For instance, was it better to have many variations in thickness over a small area, or larger stretches of gently changing variations?

To control the study an assumption was made about the type of thickness variations that might be observed. Three different types were studied: infrequent and gently varying differences, a moderate variation, and a variation where the thickness changed often. Within these groups, peak to valley bond thickness of different amounts were run. Custom code written in Matlab helped setup and run the test. Figure 12 shows the different setups and the sinusoidal assumption used. Like many other tests, the goal was to determine results indicative of what an actual assembly may achieve and a sinusoidal approach is a reasonable approximation.

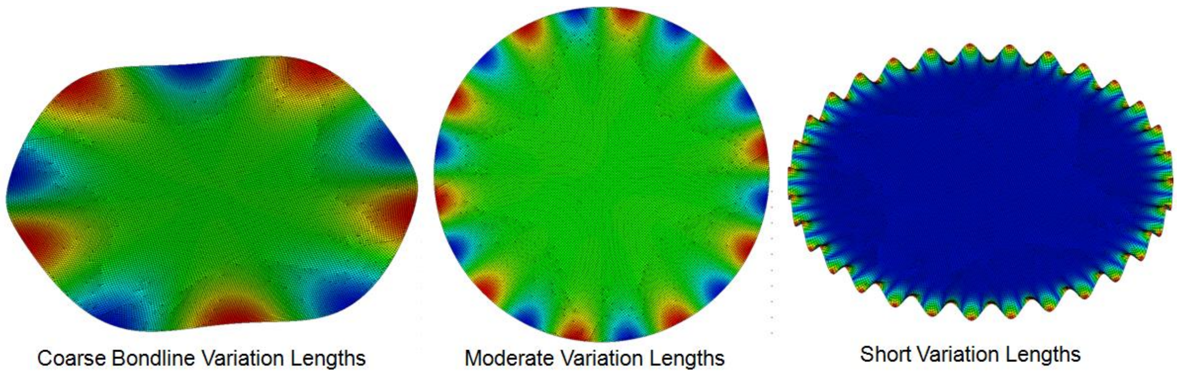


Figure 12. The bondline thickness variation analysis assumed sinusoidal variations thickness with three different wavelengths. Within each wavelength, a variety of amplitudes were applied. In this way the team could investigate the impact of bondline thickness on the WFE.

These various configurations were run and the results analyzed using Ball Aerospace's custom WFE analysis software. An example result is shown in Figure 13. The fringe pattern in particular was useful for understanding how a boundary distortion interacted with the optical performance in the center.

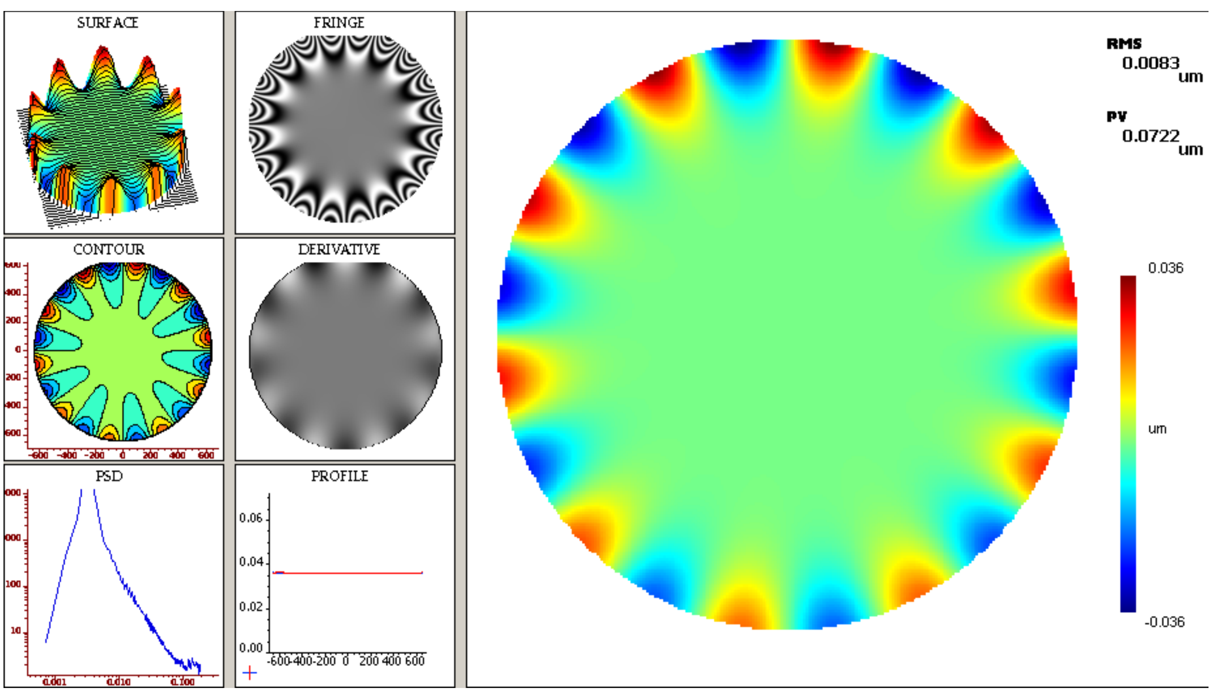


Figure 13. Example WFE plot showing the various metrics collected in the trade study. This example is from the moderate wavelength bonding thickness variability assumption.

The database of results were compiled to create Figure 14. A critical conclusion from this plot is that, in terms of overall performance, it was better to have many peak-to-valley distortions than to have a handful of longer wavelength distortions. The short wavelenths interfered with each other, whereas coarse variations lead to cases where the distortion could reach further towards the center of the membrane.

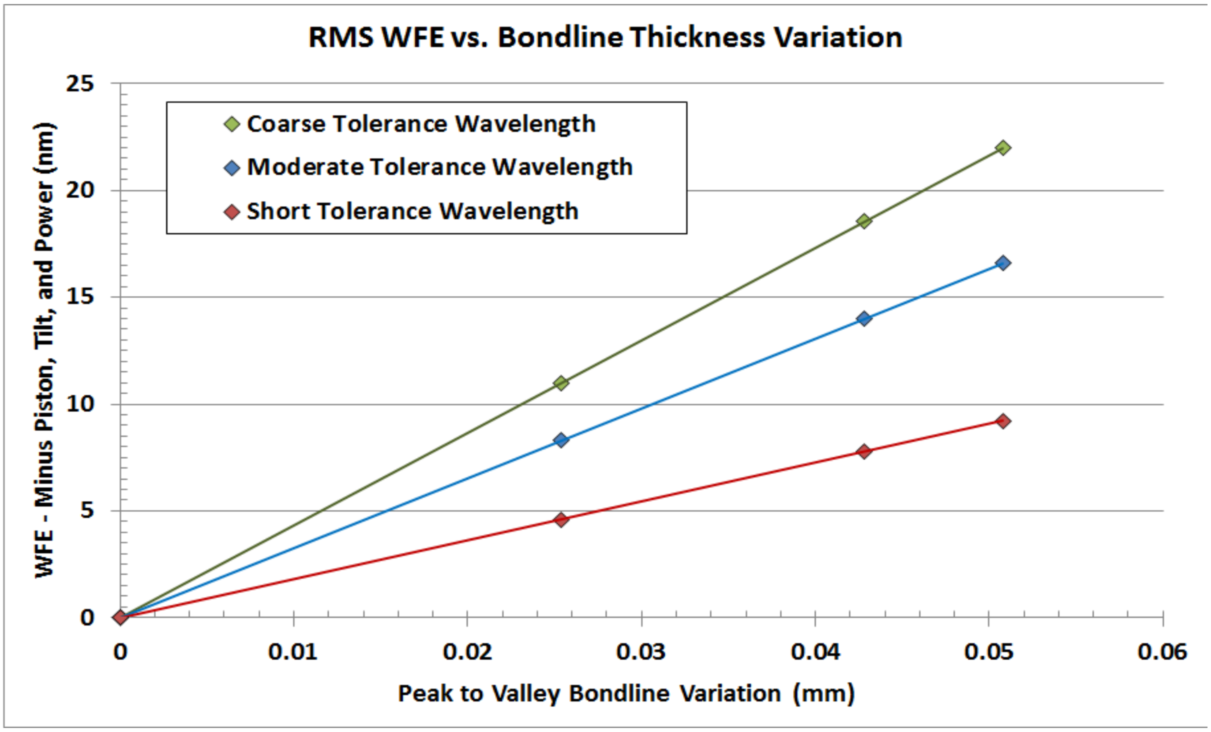


Figure 14. The optical performance can be impacted by distortions at the edges, which is what a bondline variation creates. This study indicated it's better to have many variations due to the distortions interacting with each other.

E. Results Summary

Many trade studies were conducted in this phase of the program. Indeed, those shown in this paper are a small sample of a large body of work. The bottom line result from all analyses is shown in Figure 15. This plot combines all the many types of analyses, including variation considerations, permanent deformation allowances due to launch, and more. This plot is for a single optic WFE, not the entire DOE performance. Also note that many of these individual sources of error are not linearly added together. In most cases, results are RSS'd together per standard optical engineering practice. Finally, this assumes no commissioning improvements on-orbit.

Because the design of the telescope allows for a commissioning period, the results can be improved further. Figure 16 demonstrates a perfect commissioning at -50 °C. As most observations tend to happen around this temperature, correction for errors also centers on this temperature. One of the key benefits gained by the commissioning is that one-time errors, such as gravity and humidity loss effects, can be corrected permanently. Many of these, especially the gravity terms, lead to the non-linearity in Figure 13. By removing these during the commissioning process the remainder is primarily the linear thermal effects.

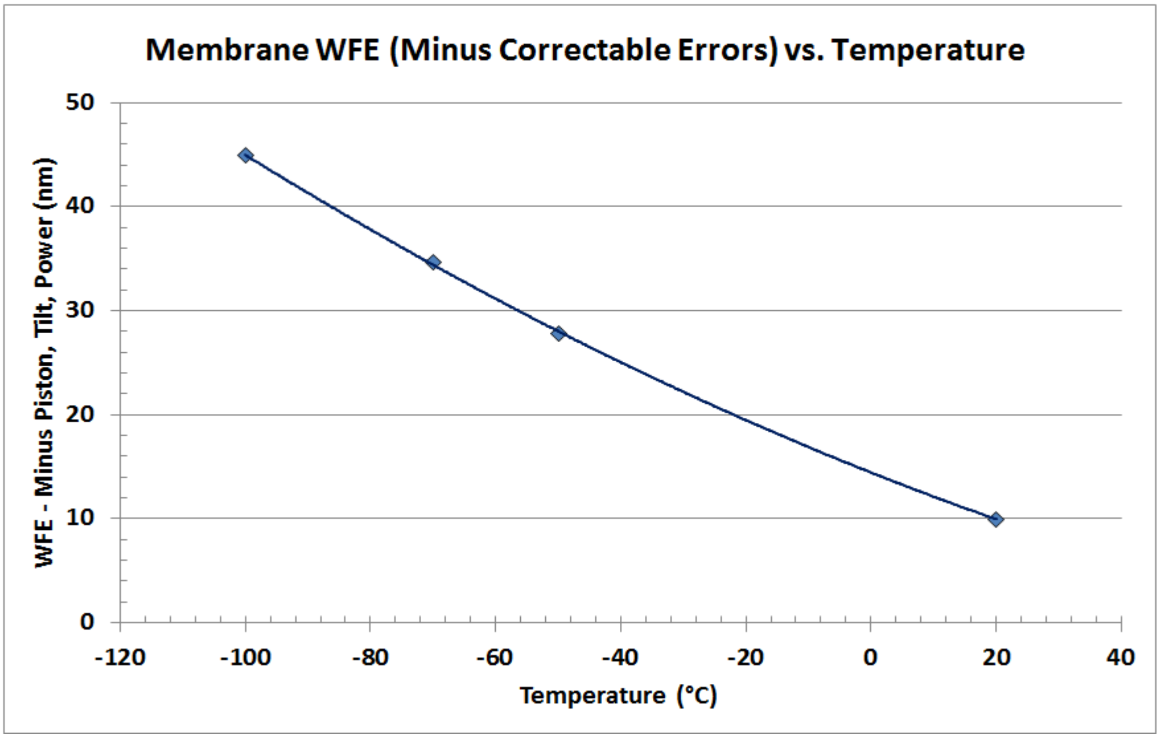


Figure 15. Plot showing how the WFE changes with temperature. The results include all of the various sources of error that come from the membrane and frame assembly.

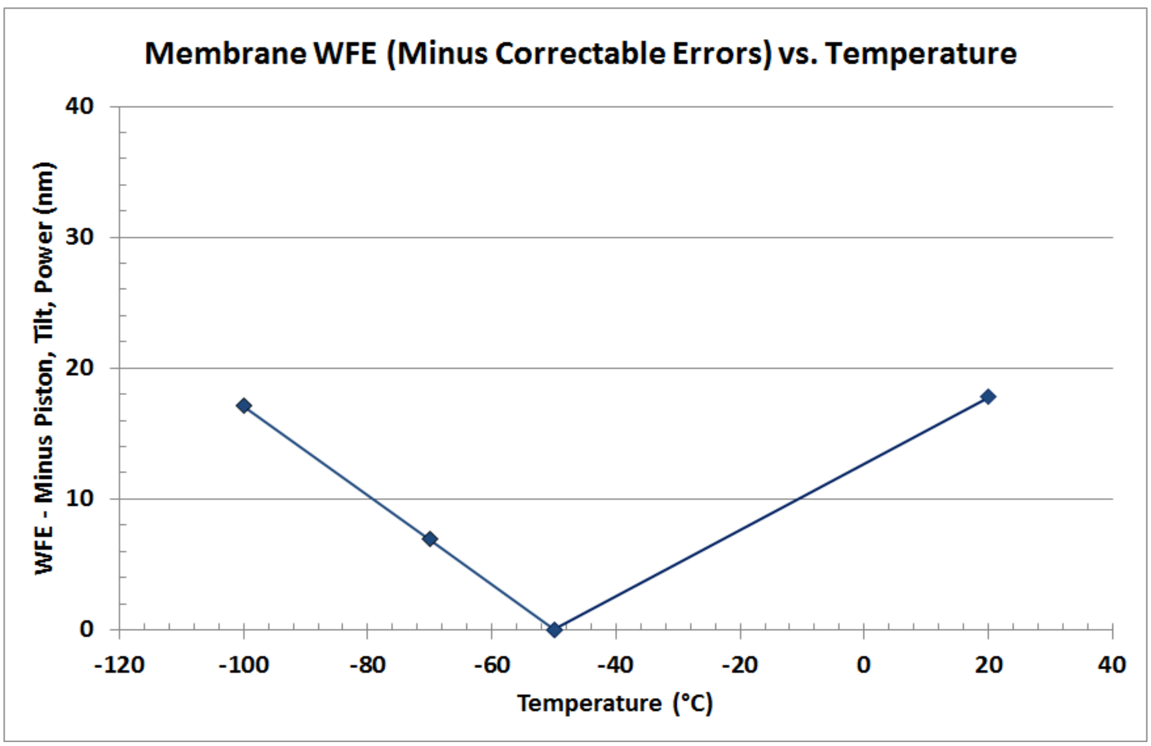


Figure 16. Performance expectation assuming perfect commissioning correction on-orbit. Although optimistic, it demonstrates the best possible performance the design can deliver.

IV. Summary and Conclusions

The MOIRE program is continuing to understand and overcome the technical challenges of the system level performance as it changes through environments. The team continues to iterate the designs as new solution spaces are opened. In tracking down greater efficiencies and robustness, significant amounts of resources from which to draw technical solutions from have been developed. Along the way expertise in membrane and gossamer systems has also been gained.

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 LLNL, Nexolve, and ATK.

VI. References

[1]Solicitation Number: DARPA-BAA-10-51, "MOIRE - Membrane Optic Imager Real-Time Exploitation", URL: https://www.fbo.gov/index?s=opportunity&mode=form&id=5dea37072f51f629ef3f152128856c5b&tab=core&_cview=1

[2]R.A. Hyde, "Eyeglass. 1. Very large aperture diffractive telescopes," Applied Optics, Vol. 38, No. 19, July 1999, pp. 4198-4212

[3]J. Early, R. Hyde and R. Baron, "Twenty meter space telescope based on diffractive Fresnel lens," Proc. SPIE, Vol. 5166, 2004, pp. 148-156.

[4]P.A. Lightsey, "James Webb Space Telescope – A large deployable cryogenic telescope in space," Proc. SPIE, Vol. 6720, Paper 6720-22, 2007.

[5]W. Tandy, "MOIRE Gossamer Space Telescope – Structural Challenges and Solutions," 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Paper 1224028, 2012.

[6]W. Tandy, "MOIRE Gossamer Space Telescope – Challenges and Solutions in Large Scale Testing," 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Paper 1514119, 2013.