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High-precision optical systems with inexpensive hardware: a unified alignment and structural design approach.

Edward G. Winrow[1]*, Victor H. Chavez[1]
[1]Sandia National Laboratories, 1515 Eubank Blvd SE, Albuquerque, NM, USA 87123-3453

ABSTRACT

High-precision opto-mechanical structures have historically been plagued by high costs for both hardware and the associated alignment and assembly process. This problem is especially true for space applications where only a few production units are produced. A methodology for optical alignment and optical structure design is presented which shifts the mechanism of maintaining precision from tightly toleranced, machined flight hardware to reusable, modular tooling. Using the proposed methodology, optical alignment error sources are reduced by the direct alignment of optics through their surface retroreflections (pips) as seen through a theodolite. Optical alignment adjustments are actualized through motorized, sub-micron precision actuators in 5 degrees of freedom. Optical structure hardware costs are reduced through the use of simple shapes (tubes, plates) and repeated components. This approach produces significantly cheaper hardware and more efficient assembly without sacrificing alignment precision or optical structure stability. The design, alignment plan and assembly of a 4" aperture, carbon fiber composite, Schmidt-Cassegrain concept telescope is presented.

Keywords: opto-mechanical, alignment, telescope, carbon fiber composite

1. INTRODUCTION

This paper discusses a study whose purpose was to develop and prove a capability to align and bond optics or optical housings with high precision in a cost-effective manner. The study goals were to prove a cost-effective capability to align and hold lens decenters to <30 microns, lens tilts to <18 arcseconds and despaces to <50 microns.

1.1 Scope of the study

The main goals of this study were two-fold: first, to characterize the alignment accuracy achievable with a bonded-lens approach to assembly as an alternate to mechanically located and clamped methods of assembly. The second goal was to demonstrate that, by shifting alignment precision to the tooling (through a bonded-lens approach), flight hardware costs could see a significant reduction. A secondary goal of this study was to attempt to speed up the alignment process through an improved operator interface to the alignment tooling.

The funding for this project was limited, so the following items were **not** addressed in the study, allowing work to focus on the main goals of the program:

1. Optical design optimization – the optical design was tailored to have a variety of components (lenses, mirrors, etc) rather than achieve high quality optical performance.
2. Stray light – no stray light checks were performed.
3. Assembly precision – no adjustments were made to the final design based on as-built optic dimensions.
4. Structural strength for environments – the structure design (bondpad sizes, etc) was not analyzed for any specific environmental loads as the study focused on assembly accuracy, not design robustness.
5. Quality of materials – materials were chosen based on similarity to space-based optical systems where possible (epoxies), but optics were uncoated and carbon fiber components were not space-qualified materials.

*egwinro@sandia.gov; phone 1 505 284-6914

1.2 Design philosophy

The philosophy explored in this study is to replace precisely machined metal components in optical assemblies with cheaper, lighter components without sacrificing alignment precision. Friction based mounts, such as retainer-based lens housings, require tight dimensional controls on lens housing features to maintain alignment tolerances. They also require a long time to fabricate and pose some difficulties in analysis simulations due to the uncertainties in accurately predicting friction effects. This project explores a design where the optical structure is made from loosely toleranced basic shapes, forming a truss structure made from tubes, plates, and highly repeated machined components. Lens centers of curvature (pips) are aligned to a master axis using precision tooling, then are attached to the structure with epoxy bonds. This design method has the benefits of having significantly cheaper hardware, a structural design more readily evaluated with linear finite element analysis (FEA), and can produce higher precision alignments than conventional, integrated alignment mechanisms such as push screws or shimming.

2. DESIGN OVERVIEW

2.1 Optical design

The optical design developed for the study was a Schmidt-Cassegrain telescope. The optical system was designed such that it would connect to a digital single lens reflex camera (DSLR) for imaging tests. The system behaves as a 680mm, F6.7 telephoto lens (35mm camera equivalent). The optical design was tailored such that the secondary mirror (M2) could be bonded directly to the second surface of the second corrector lens (Lens 2). The DSLR camera and field lens can piston in the central tube to adjust focus. Goals of the lens design were to utilize both mirrors and lenses and provide a variety of bonding scenarios in a system with a 4” diameter primary mirror (M1). Optical performance was not a primary goal of the optical design. The alignment and bond configurations evaluated are: convex-plano lens (Lens 1), bi-concave lens (Lens 2) to mirror (M2) (glass-to-glass UV cure), convex mirror with central fiducial (M2/L2 combo), concave mirror via co-aligned reference target (M1), meniscus lens (Field Lens).

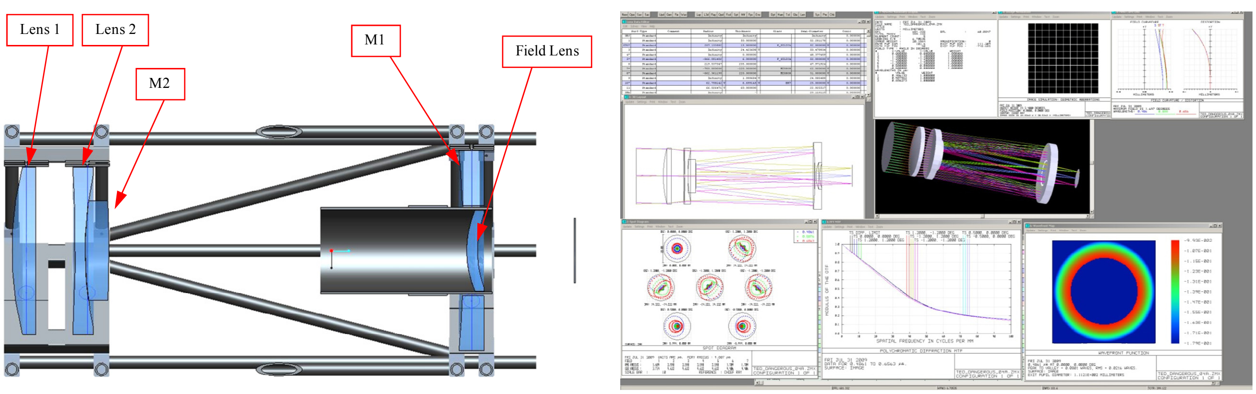

Figure 1. Optical Layout

2.2 Structure design

A tube-truss design was employed for this system for its inherent modularity, stiffness, and low cost components. Corner brackets and spider brackets were machined from aluminum 6061-T6. The central focus tube was machined from titanium 6AL-4V. All other components were made from carbon fiber composite.

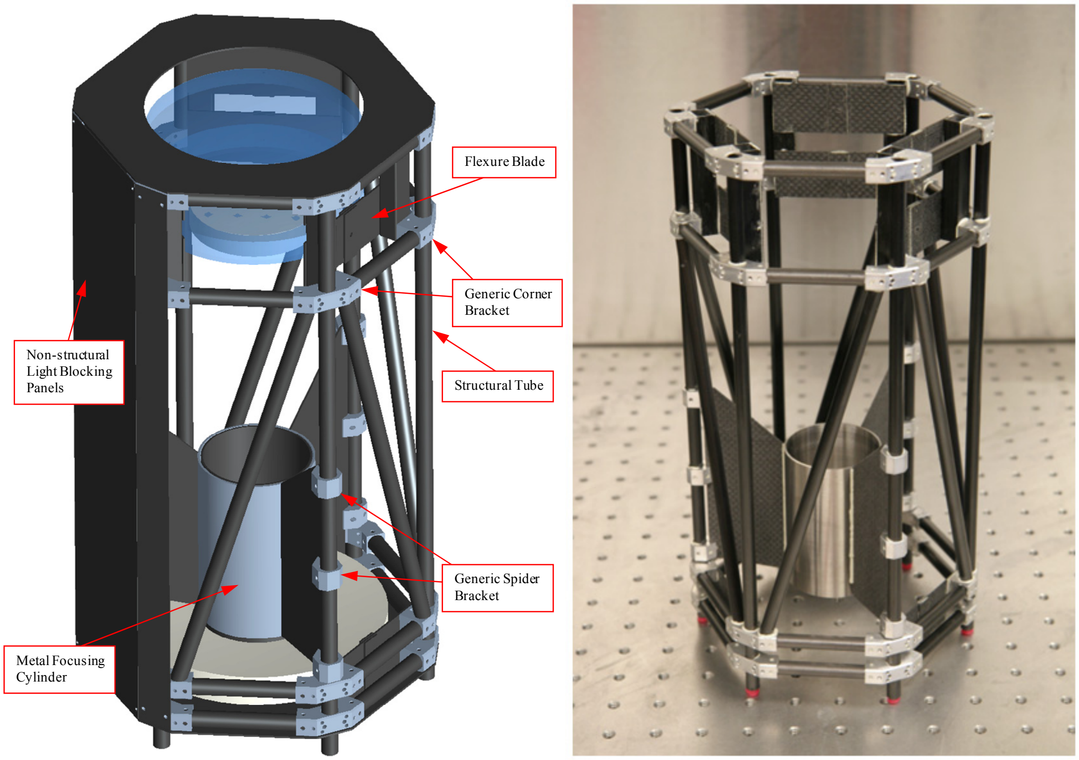

Figure 2. Optical Structure

Trusses were made from pultruded carbon fiber rods, sold as high performance kite spars from hobby stores. Plates are made from multilayer carbon fiber woven fabric. All composite pieces were cut to very loose tolerances by hand with a mitre saw equipped with a diamond cutting blade. Holes were drilled or cut with a hole saw for larger diameters. No CNC machining occurred on any composite hardware. Structure subassemblies were built on assembly jigs and bonded together with a thick structural epoxy (Masterbond EP21TCHT-1).

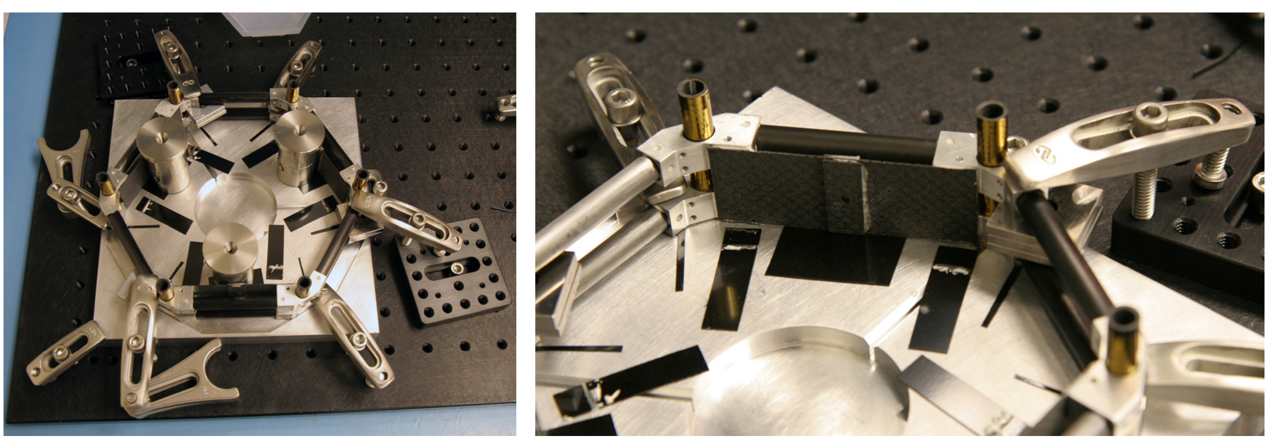

Figure 3. a) M1 frame on assembly jig, b) flexure bonded to truss hoop.

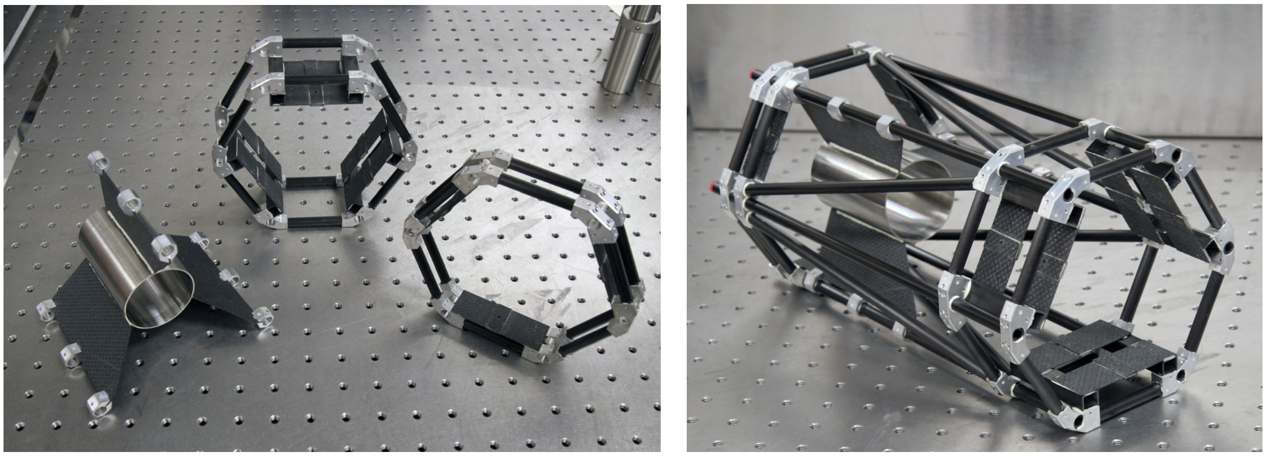

Figure 4. a) Structure Subcells, b) Fully Assembled Structure.

Lenses were edge-bonded to three blade flexures which allow for thermal expansion of the glass, relative to the housing, without introducing lens movements or inducing excess stress into the optic. Alignment tooling then positioned each optic in five degrees of freedom inside the structure, leaving a small (0.020”) gap between the optic and the flexure blades. A thick epoxy is then injected radially through holes in the flexures to fill the gap and lock the lens into its aligned position.

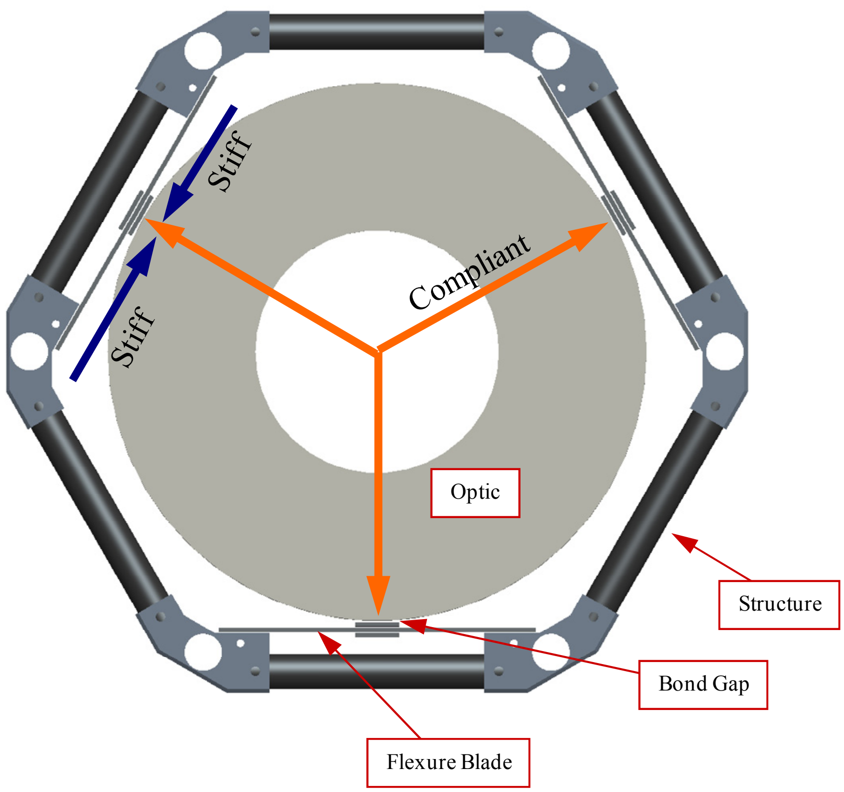

Figure 5. Optical Mount Diagram

2.3 Alignment / assembly plan

The primary method for aligning lenses in this study utilized the pip returns from the centers of curvature of the lenses. A theodolite with an autocollimator source was used to project a "+" of light that was then focused, in space, at the center of curvature of the lens. The focused beam then reflected off the lens surface to return as an image in the theodolite (called a pip return). Every lens produces 2 pips (one from each surface) which define the optical axis of the lens. For the case of the primary mirror (M1), a mirrored crosshair was aligned in the hole of M1 which provided a pip at infinity from the flat target mirror and another point at the center of the crosshair. By using pip returns from the lens surfaces, tolerance errors are minimized compared to using the edge or face-flats of the lens as references since the optical surfaces are measured directly.

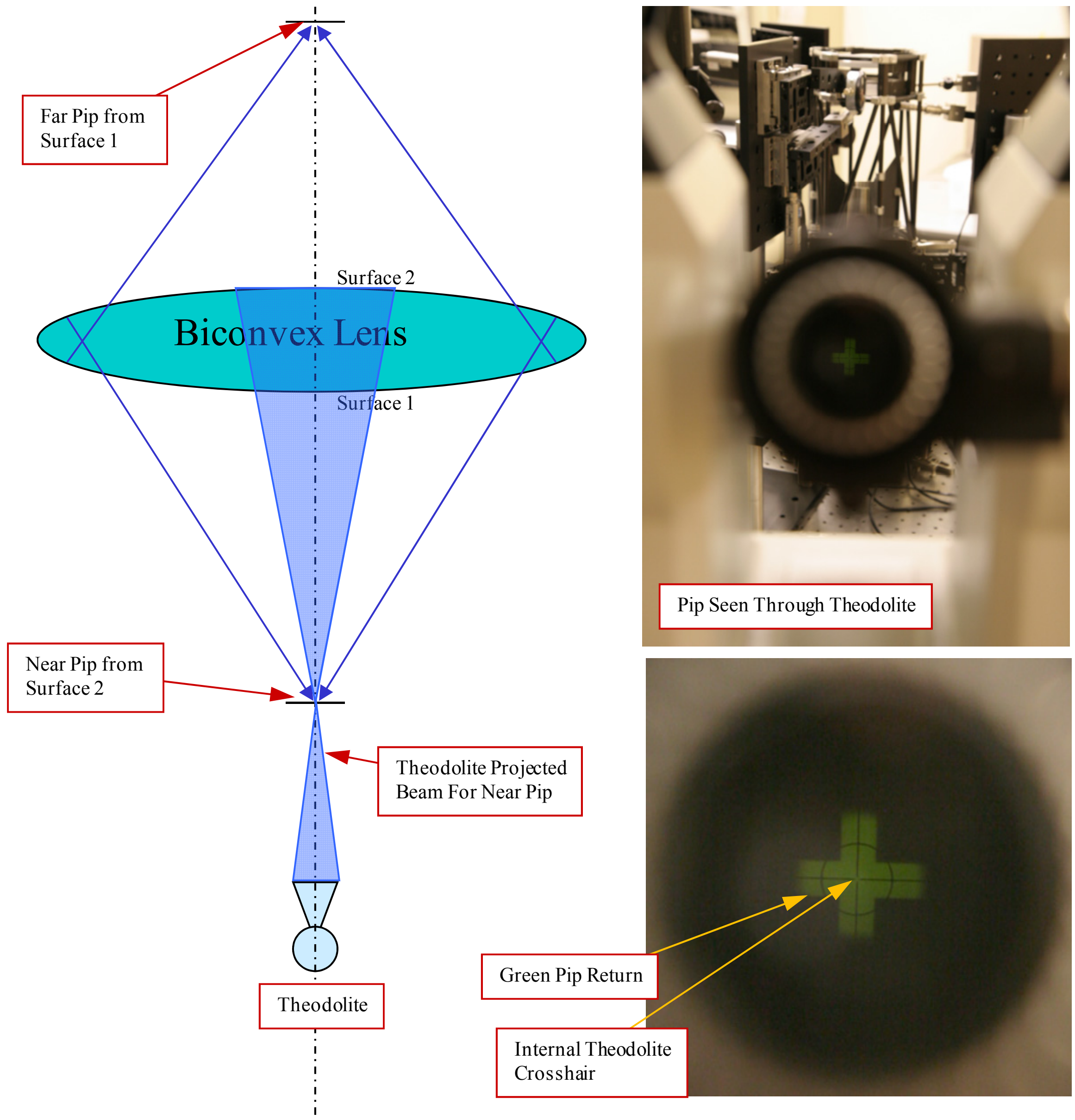

Figure 6. Pip Return Diagram

In this study, the theodolite defined a "master axis" based on crosshairs strung inside the optical structure. Each optic was then placed inside the structure then held and maneuvered by three motorized alignment towers that gave tip/tilt, decenter and piston movements. In this manner, the optic was aligned to the master axis. Piston distances were set with an inside micrometer. Once the optic was positioned, it was bonded with epoxy. Alignment tweaks were made as the epoxy cured to help minimize any drift of the optic.

In the case of Lens 2 and the secondary mirror (M2), which are bonded surface-to-surface, the tip/tilt of M2 was determined by the curvature matching of the optics and the centering of M2 on the Lens 2 surface. First, the theodolite and alignment tower system were then used to align the theodolite to the axis of Lens 2 via its surface pips, then M2 was aligned to the theodolite axis by sighting the mirror pip and adjusting M2 in centration until the pip coincided with the master axis. Norland 61 UV cure epoxy was used to affix the mirror to the lens once aligned. A small epoxy dot was placed at the center of the M2 surface to aid in aligning the Lens2/M2 doublet into the full system later. A coordinate measuring machine (CMM) was used to probe the perimeter of the lens and find the center, then the CMM probe tip was lightly dipped in epoxy and driven down to probe the calculated center of the optic, creating the fiducial.

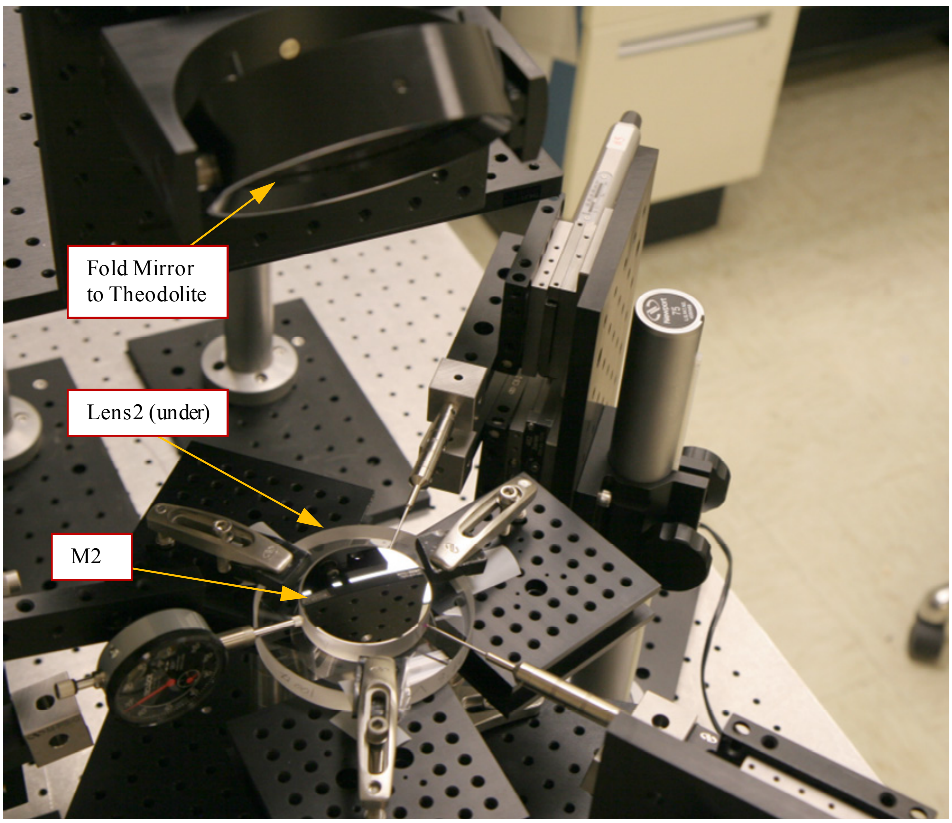

Figure 7. Secondary mirror (M2) to Lens 2 alignment and bonding.

2.4 Alignment tooling

The alignment tower system known as OMAR (Opto-Mechanical Assembly Robot) consisted of 3 towers, each with 2 precision motorized actuators pushing precision linear stages. Each tower had a vertical actuator and a radial actuator. The 3 vertical actuators provided piston and tip/tilt movements and the 3 radial actuators provided decenter. The towers were made from consumer-off-the-shelf (COTS) opto-mechanical hardware. The actuators were COTS DC servo products with submicron accuracy and repeatability. Each actuated stage moved an arm fitted with a ruby-ball-tipped coordinate measuring machine (CMM) probe at the end. The CMM probes were the interface to the optic. Gravity held the optics against the 3 tip/tilt adjusters and the 3 decenter adjusters pushed radially on the edge of the optic. The motion controller for the actuators had a remote console such that the theodolite operator could directly manipulate the lens while watching the pips, which greatly reduced the time to align each optic. Through the use of modular opto-mechanical hardware and the vast array of available CMM probe tips and sizes, this alignment tool (OMAR) is readily reconfigurable for many different optics sizes and structure configurations. The system can handle optics as heavy as 60 lbs.

The theodolite used in this study was a Leica Total Station TM5100A. The theodolite contained a built-in autocollimation device, had a two inch diameter, and provided 13x magnification at its nearest focus at two feet. The theodolite sat on a Brunson translation stage attached to a custom mount anchored to the optics assembly table (not floor mounted). The custom mount was height adjustable using COTS lab posts and post extensions.

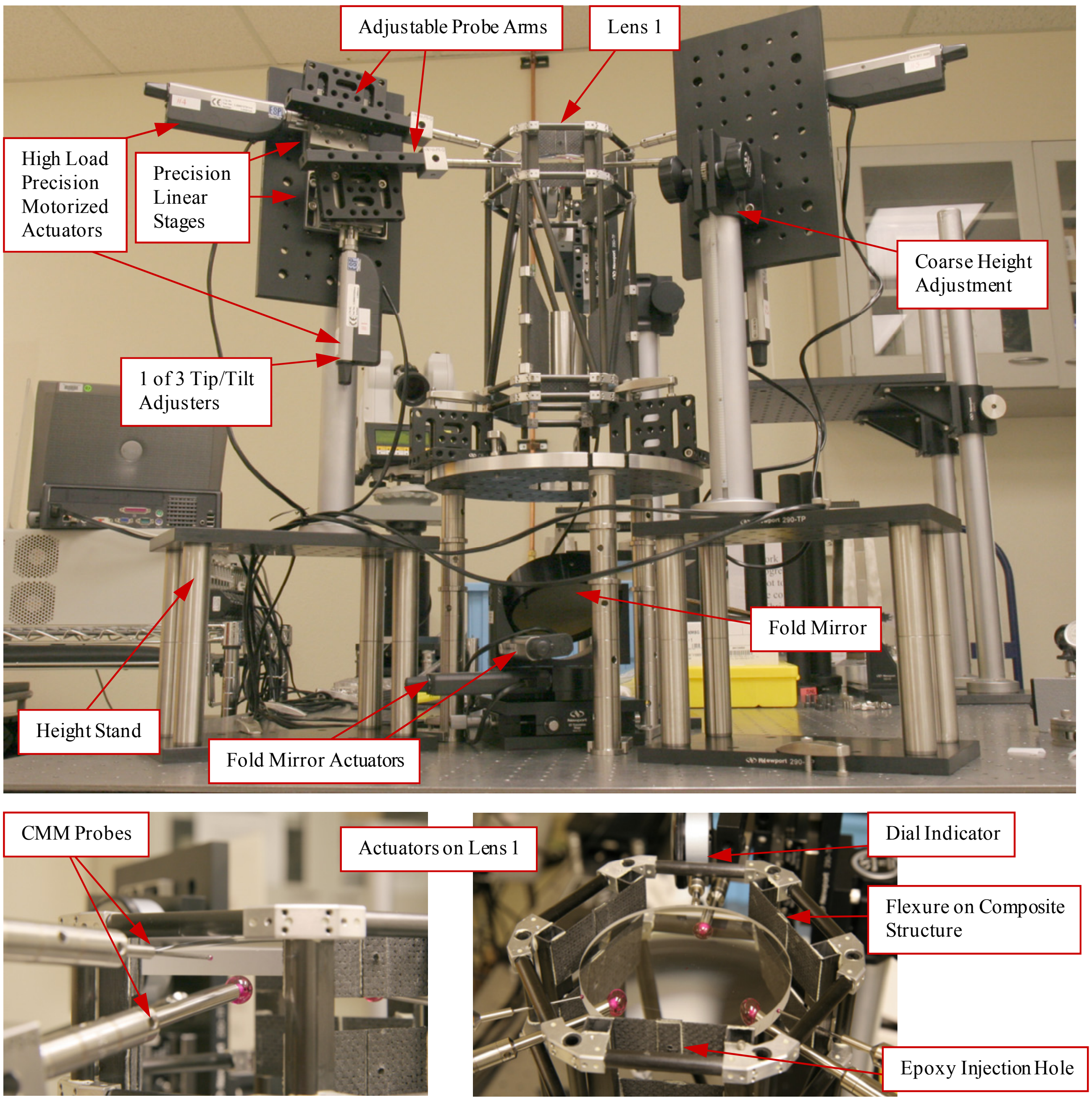

Figure 8. a) Alignment Station with OMAR. b) CMM probe contact with lens. c) Lens 1 alignment.

2.5 Hardware Costs

The hardware and labor costs of this study's optical system were compared to a theoretical, equivalently sized, titanium lens housing with retainers holding the elements in place, as is common for lens assemblies in space-optic systems. Costs and labor times for the titanium structure were estimated based on past experience of the author with similar designs and tolerances. Comparative weights are also shown between the titanium structure, the new structure, and a commercial Canon 600mm f/4 telephoto lens. The weights of the optics alone are also displayed for comparison.

	Optics Only (for comparison)	Canon 600mm f/4 Telephoto Lens (comparison)	Ti Structure (no optics)	Composite Structure (no optics)	Improvement (Composite compared to Ti Housing)
Weight (lbs)	1.8	11.8	4.3	1.7	60.5%
Estimated Hardware Cost (k$)	13*	9.2**	35	5.35*	84.7%
Time to assemble structure (hours)			1	40	
Labor Cost to assemble at $100 an hour (k$)			0.1	4	
Total Cost with Labor (k$)			35.1	9.35	73.4%
* actual cost	**retail price				

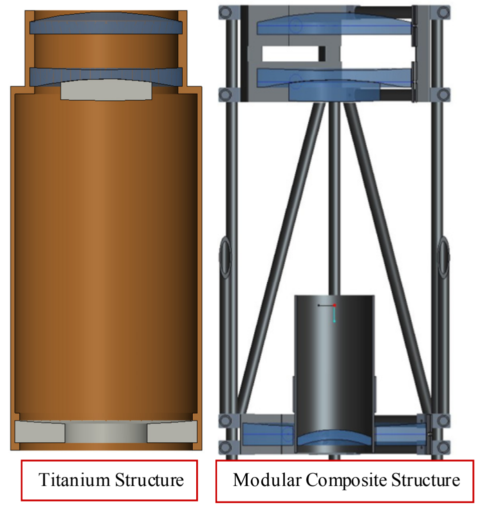

Figure 9. Cost comparison and structural schematic.

The alignment tooling costs were non-recurring costs that were not rolled up in the comparison above. Specific assembly tooling such as jigs and consumables were included in the hardware costs listed above. Alignment tooling consisting of the motion controller, actuators, COTS opto-mechanical hardware, etc. summed to approximately $45,000.

3. STUDY RESULTS

3.1 Alignment accuracy measurements

In this study, each raw theodolite measurement was repeated five times. Average values were processed along with standard deviation representing the "eyeball accuracy" of the operator. Error bounds on the measurements were the 2-sigma values from the raw theodolite measurements.

Pip location (radius of curvature of the optic) and the distance of the pip from the theodolite affect the relationship between raw theodolite angular measurements and the actual tip/tilt or decenter of the optic. For example, biconvex lenses with large surface radii have a long distance between pips which yield much more sensitive tip/tilt measurements.

Note that any optic alignment accuracy will be affected by the pip location, distance to the theodolite, operator precision, coatings, and measurement system stability. The results presented in this paper are examples of achievable accuracies and characterizations of typical operator error. Due to limited funding for the project, only data for the direct theodolite measurements are presented (Lens 1, Lens 2/M2, M1). Alignment errors for the glass to glass bond of the secondary mirror (M2) to Lens 2, the alignment of the reference target for the primary mirror (M1), and the centering of the field lens were not calculated.

Piston distances for all optics were set with an inside micrometer. Piston accuracies were not evaluated in this study and are estimated to be +/- 50 microns. The inside micrometer published tolerance was +/- 25 microns.

3.2 Alignment accuracies

Results presented below are the alignments of the optics prior to epoxy bonding, after epoxy injection and a re-alignment to correct for any movements during the injection, and after the epoxy cured. Note that the "bounds" are actual limits of the measurement, not +/- values.

The theodolite support stand configuration was changed prior to the M1 bonding to remove the theodolite translation stage which was proving to be a significant source of instability in the system. Note the improvements of the M1 alignment compared to the previous optics resulting from this change. Fold mirror movements were used to achieve the axis translation motion that the translation stage originally provided.

Table 1: Alignment accuracies

		Initial Alignment		Wet Epoxy		Cured Epoxy (final)			
Optic	**Alignment Details**	**Tip/Tilt**	**Decenter**	**Tip/Tilt**	**Decenter**	**Tip/Tilt**	**Bounds**	**Decenter**	**Bounds**
		(arcsec)	(microns)	(arcsec)	(microns)	(arcsec)	(+/-)	(microns)	(+/-)
Lens 1	Convex/Plano Lens	0.4	11.7	0.0	11.8	1.8	2.3	21.1	21.6
	2x Pip Returns						1.6		16.4
Lens 2 / M2	Convex Mirror	13.9	7.0	15.4	8.5	10.5	29.7	8.5	34.3
	Pip and Fiducial						4.3		2.7
Mirror 1	Flat Mirror	15.4	8.5	0.3	2.8	3.3	3.8	3.7	16.0
	Pip and Fiducial						2.7		3.7

Eyeball accuracies presented are for a single operator (the author) over 22 alignments. Each alignment constituted the alignment of an optic to the master axis. The "average" value is the average of the final alignment accuracy of the 22 alignments. Each alignment had five independent measurements.

Table 2: Operator "eyeball" accuracies.

		Horizontal	Vertical
		(arcsec)	(arcsec)
Eyeball Accuracy	average	0.56	0.56
(22 alignments)	stddev	0.77	0.73
	2 sigma value	2.10	2.03

In summary, this project showed that it is possible to achieve tip/tilt alignment accuracies of 1.8 (+0.5 -0.2) arcseconds and decenter alignment accuracies of 3.7 (+12.3 -0.0) microns using the methods described.

3.3 System images

The optical system was attached to a Canon 20D DLSR camera (8.2 megapixel) to acquire images through the completed system. An additional stray light baffle was included into the system to block an unexpected direct illumination path to the detector. Images below show one side of the exterior panels removed to show interior detail.

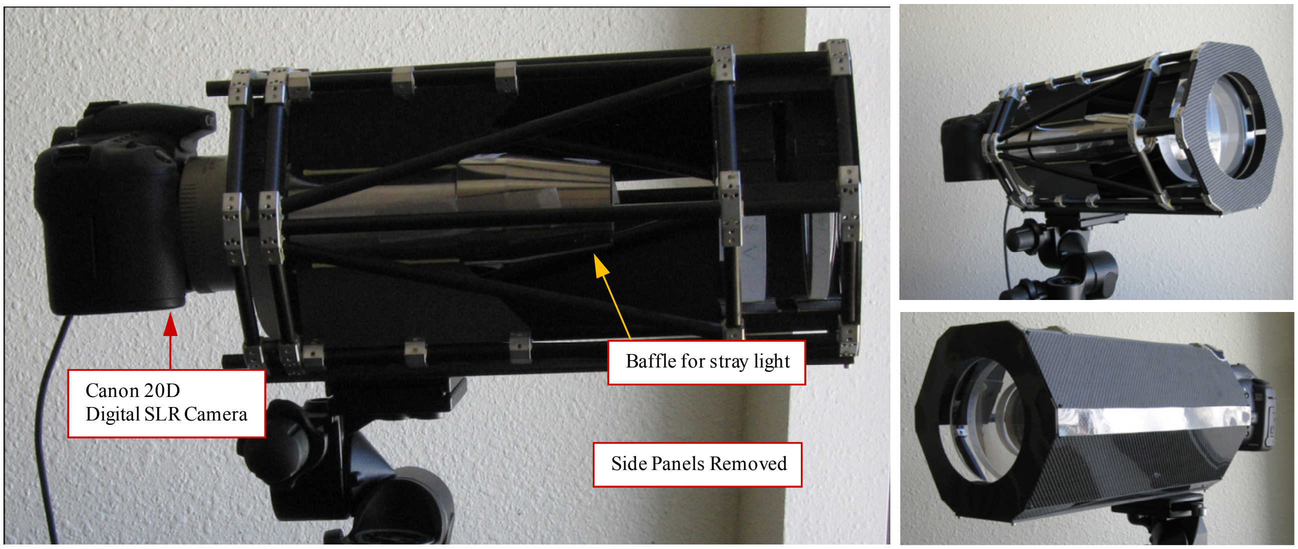

Figure 10. Imaging system with DLSR camera attached.

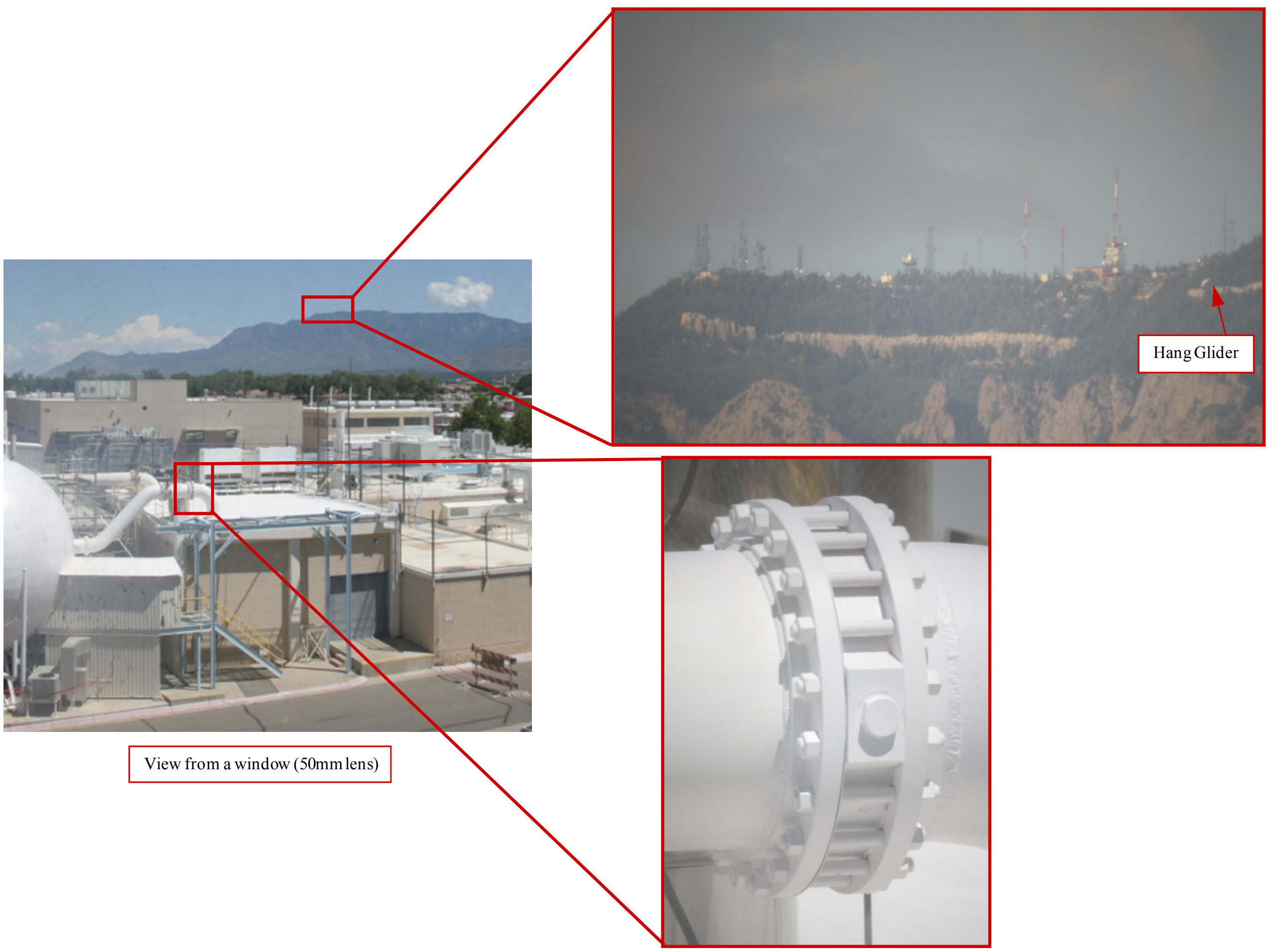

Figure 11. Raw images from the system. Sandia Crest is ~15 miles from telescope.

Figure 12. Composite panorama from the system. 25 images stitched and contrast enhanced.

4. CONCLUSIONS

4.1 Lessons learned

Although fairly limited in scope due to funding requirements, this project did provide valuable lessons in alignment setup and structure design. Although not discussed in this paper, several techniques were developed for the bonding of the structural components. Lessons learned included the following:

1. Concurrent development of the optical system, alignment plan, and optical structure plays a key role in having an efficient design cycle, functional hardware, and mitigation of issues during assembly.
2. Alignment tooling stability can play a key role in alignment accuracy. This includes environmental stability of the build area (temperature, vibration).
3. An assessment of stray light paths is a step to be included early in the concurrent optical / opto-mechanical design cycle.
4. A theodolite / fold mirror combination turned out to be a much easier and more stable platform to perform alignment tasks compared to a theodolite alone with height and translation capabilities.
5. Be mindful of backlash effects when using motorized actuators.
6. Theodolite operator control of the optical movements (via remote panel to the motion controller) provided immense time savings in aligning optics. This completely eliminated the “little more, little more, too much, little less” back and forth that often occurs when a theodolite operator instructs someone else to make the optical movements required to align.
7. Mounting theodolites directly to the optical table, rather than using a floor stand, had marked improvements in stability and alignment accuracy.
8. Photo documentation of the build process is an easy and effective way to record work done without excessive documentation rigor.

4.2 Path forward

Since the conclusion of work on this project, the alignment/assembly methodology presented has been used on 2 other flight programs with great success. The first program built a titanium structure with 2”-10” optics with an alignment setup as described in this paper. The second program is currently in progress and requires the alignment of small (0.25” diameter) lenses. For this second program, the alignment tooling was reconfigured. The new system (OMAR-II) uses DC servo linear stages for compactness. The theodolite was replaced with an Opticentric system from Trioptics USA. The Opticentric houses an autocollimator with a focusing lens mounted on a linear stage above an air bearing. This system allows accurate despace measurements to be made in addition to the decenter and tip/tilt alignment capability. The Opticentric software uses computer-based centroiding of the pips to eliminate "eyeball accuracy" error terms.

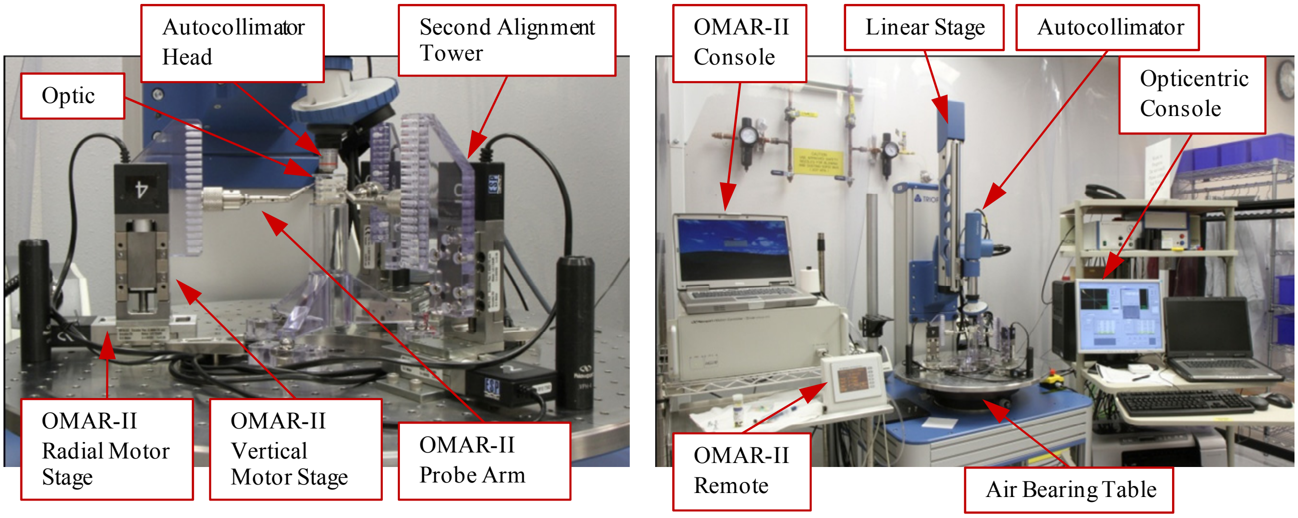

Figure 13. OMAR-II with Opticentric alignment station.

4.3 Conclusions

This project provided an opportunity to devise and develop a new concept in design and alignment methodology. This study shows that precision optical structures can be made without excessively costly hardware. Programs can see significant cost benefits by adopting this modular design strategy that involves co-development of the optical design, alignment plan, flight tooling and alignment tooling. This method is especially beneficial to programs where multiple flight units of the same design will be constructed. A testbed telescope was designed and constructed using this alignment methodology and was characterized for achievable alignment accuracy. This study stands as a good stepping stone to further development and improvements.

4.4 Sandia statement

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