SPACE OBJECTS BEHAVIORAL SCIENCES TELESCOPE

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Approved by:

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Mr. Gary Redford
College of Engineering
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Abstract

Traditional academic Space Situational Awareness (SSA) research has relied on Consumer Off the Shelf (COTS) systems for collecting metric and lightcurve data. Herein, we present an alternative approach to develop a sensor system for space object characterization. Two 0.6-meter F/4 electro-optical (EO) systems were developed for collecting lightcurve and spectral data. The optomechanical design includes over 200 individual parts and was modeled using SolidWorks. Optical design analysis was performed with raytracing software (ZEMAX). A combination of test, analysis, inspection, and demonstration procedures verified the components of the design. Methods to complete this project include finite element analysis of mechanical components, optical testing methods (Focault Knife Edge Test and Couder Mask Test), tests to verify the function of the thermometers, and a final pointing model test. The entire cost of the design and fabrication of these two EO systems was significantly lower than a COTS alternative. With careful planning and coordination, the deployment times were also reduced compared to a commercial system. This project shows that development of hardware and software for SSA research could be accomplished in an academic environment.
Team Members, Majors, and Contributions

Sameep Arora, Mechanical Engineering: Final Budget, Appendix III, System Design

Ryan Bronson, Optical Sciences and Engineering: System Design

Marco Colpo, Optical Sciences and Engineering: Acceptance Test Procedures

Evelyn Hunten, Electrical Engineering: System Requirements

Lindsie Jeffires, Biomedical Engineering: Scope, System Block Diagrams, Drawings, Lessons Learned, Models and Analyses, Appendix I

Scope

Scope of the document

This Final Report presents and defines the final concept for the optomechanical telescope assembly the team has designed. This document encompass the steps the team followed for the production, assembly, and testing for the final assembly. The introduction of this paper includes the original abstract for the project, any necessary background information the team used, the scope of the project itself, and the expected product that will be given to the customer, who is also described. Next the system will be defined and general information about the system presented including the system requirements, the results and changes from CDR, and concept of the system. Following sections will delve into the intricacies of the system involving a description of the design choices made and some of the evolution of the design. There will also be a detailed analysis of the subsystem, sub-assemblies, and the many interfaces. This section will also provide all analyses done to obtain the information for the design as well as methods of analysis performed on the design. A full development plan will then show what the team did in terms of production, fabrication, and assembly. There will also be a full review of the budget and suppliers, and of the requirements as they apply to the acceptance test plan. A summary of the management aspects of the project such as risk analysis and mitigation, the schedule and summary will then be presented. The document will conclude with an appendix containing references, detailed analyses, parts drawings, and the acceptance test plans.

Scope of Project

This satellite-tracking telescope system will be used primarily to image satellites in geostationary orbit. An imaging telescope will be used to find and follow the satellites. A user interface will connect the mount, telescope, and computer. ASCOM software will provide a database of pre-existing satellites for easier tracking capabilities. The team will fabricate two serrurier trusses used for 24 inch mirrors. Fabrication includes truss design (CAD), materials (carbon fiber, aluminum), as well as refurbishment of the pre-existing optical components.
Problem Statement
As low-earth orbit becomes increasingly congested with satellites and debris, the need to distinguish amongst various space assets becomes increasingly difficult. The aim of this project is to develop an optomechanical assembly that is equipped to image space objects. For this design team, the specific goal is to create two telescope optomechanical assemblies and interface the assemblies with a customer furnished commercial mount, camera, and filter wheel.

Project Goals
The design team is responsible for refurbishing the optical components of a preexisting telescope to create a new OTA that will be placed on either alt-alt or equatorial fork mount. With these components in mind, the primary technical challenge is to create an optomechanical assembly that can accommodate the existing optics. The new truss will have a universal interface, matching with any type of mount that will be used for this system. These trusses will be designed in Solidworks and sent to Starizona, a local business, for verification. The team will outsource manufacturing of two assemblies to the AME machine lab which will be mated with the customer furnished commercial mount. In order to develop a stable position for the telescope, the addition of weights as counterbalances will also be investigated. A final technical consideration that will be investigated is the positioning of the imaging scope.

Final Product
The team produced two Optomechanical Assemblies, one of which is mounted to the customer furnished mount, and the other will be used at the discretion of the sponsor. Other than the mount, the assemblies are identical and will also have customer furnished cameras, filter wheels, and focusers mounted on them.

Description of Customer
A former movie-maker, Dr. Vishnu Reddy is an assistant professor at the Lunar Planetary Lab whose research focuses on understanding the behavior of space objects (natural and artificial) using a range of Earth and space-based assets. To this end, he will use the assemblies to further the Space Object Science Initiative to utilize affordable telescopes to image objects in geostationary orbit.
System Requirements

<table>
<thead>
<tr>
<th></th>
<th>Functional</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>TSS image objects in geostationary orbit</td>
</tr>
<tr>
<td>1.2</td>
<td>TSS maintain structural integrity with regard to mechanical weight and bending</td>
</tr>
<tr>
<td>1.3</td>
<td>TSS maintain integrity with regard to thermal expansion</td>
</tr>
<tr>
<td>1.4</td>
<td>TSS interface and operate with customer furnished equipment</td>
</tr>
</tbody>
</table>

**TABLE 1: FUNCTIONAL REQUIREMENTS**

<table>
<thead>
<tr>
<th></th>
<th>Non-Functional Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1.0</td>
<td>Mechanical Requirements</td>
</tr>
<tr>
<td>2.1.1</td>
<td>TSS weight less than 220 lbs.</td>
</tr>
<tr>
<td>2.1.2</td>
<td>TSS operates within angular range of mount (62.5 degrees)</td>
</tr>
<tr>
<td>2.1.3</td>
<td>TSS maintain deformation of the mirrors of less than 125nm as caused by thermal effects</td>
</tr>
<tr>
<td>2.1.5</td>
<td>TSS shall attach to the Plane Wave Universal Mount</td>
</tr>
<tr>
<td>2.1.6</td>
<td>TSS have an attachment for the customer-furnished camera</td>
</tr>
<tr>
<td>2.1.7</td>
<td>TSS have an attachment for the customer-furnished focuser</td>
</tr>
<tr>
<td>2.1.8</td>
<td>TSS have an attachment for the customer-furnished filter wheel</td>
</tr>
<tr>
<td>2.1.9</td>
<td>TSS shall have an allowable bending of 0.0002324m</td>
</tr>
<tr>
<td>2.1.10</td>
<td>TSS have an attachment for the shroud to be tied to the telescope</td>
</tr>
<tr>
<td>2.2.0</td>
<td>Electrical</td>
</tr>
<tr>
<td>2.2.1</td>
<td>TSS have a temperature sensor in contact with the primary mirror</td>
</tr>
<tr>
<td>2.2.2</td>
<td>TSS have a ambient temperature sensor on the outside of the assembly</td>
</tr>
<tr>
<td>2.2.3</td>
<td>TSS compensate for temperature differentials by cooling the mirrors</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Optical Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3.1</td>
<td>TSS have a strehl ratio above 70% at final alignment</td>
</tr>
<tr>
<td>2.3.2</td>
<td>TSS maintain optics (i.e. mirrors, lenses) with optical surfaces at an RMS wavefront error below 1/12 wave</td>
</tr>
<tr>
<td>2.3.3</td>
<td>TSS have an image plane within a focuser range of 3 inches</td>
</tr>
<tr>
<td>2.3.4</td>
<td>TSS have a signal-to-noise ratio (SNR) above 5 per exposure</td>
</tr>
<tr>
<td>2.3.5</td>
<td>TSS have an exposure time of at least 3 seconds</td>
</tr>
</tbody>
</table>

**TABLE 2: NON-FUNCTIONAL REQUIREMENTS**
SYSTEM BLOCK DIAGRAMS

Please see Appendix I for a list provided to clarify the use of terms which will be frequently encountered in this report.

The optomechanical system is made of five subassemblies including: an upper optical assembly (UOA), an upper truss (UT), a middle cage (MC), a lower truss (LT), and a lower optical assembly (LOA). Within the system there are four interfaces: (1) UOA with the UT, (2) UT with MC, (3) MC with LT, (4) LT with LOA.

The UOA includes two aluminum rings, four aluminum dovetails, a spider, and a secondary mirror. The UOA includes attachments for the imaging equipment because it interfaces with the customer furnished imaging equipment which involves a camera, filter wheel, and focuser. Also, the UOA includes the sub assembly of the secondary mirror interfacing with the spider component. The function of the UOA is to support the secondary mirror and provide access to imaging equipment.

The structure of the UT and LT is a serrurier truss which maintains the alignment of the optical components by balancing the compression and tension about the center of gravity of the optomechanical system. Both the UT and LT include eight carbon fiber tubes, eight aluminum connectors, and aluminum rings. The function of the UT and LT are to support the system and to maintain alignment between the optical components.

The MC is made of an aluminum ring, two large aluminum dovetails with connectors, and four small aluminum dovetails. The MC interfaces with the customer furnished mount equipment which involves a mount and a pedestal. The function of the MC is to support the UT and UOA and to provide an attachment for the mount equipment.

The LOA includes the mirror cell and the primary mirror. The subassembly between the mirror cell and the primary mirror includes an interface between the primary mirror and mirror cell. The LOA has an interface for the temperature sensors and fans of the customer furnished equipment. The entire optomechanical system interfaces with the customer furnished shroud which protects the optomechanical system. The function of the LOA is to support the weight of all the other assemblies and to provide attachments for temperature sensors and fans to protect the primary mirror.
**Figure 1: Customer Furnished Equipment**

- **Assembly A: Imaging**
  1. Focuser
  2. Filter Wheel
  3. Camera

- **Assembly B: Sensors**
  1. Cooling Fans (4)
  2. Temperature Sensor
  3. Ambient Temp Sensor

- **Assembly C: Shroud**
  - Shroud Covering

- **Assembly D: Mount**
  1. Mount
  2. Pedestal
  3. Software

---

**Figure 2: Sub-Assemblies**

- **Sub Assembly A: Upper Optical Assembly (UOA)**
  1. Upper Ring
  2. Spider/Secondary Mirror
  3. Dovetails (4)

- **Sub Assembly B: Upper Truss**
  1. Ring 2
  2. Carbon Fiber Tubes (8)
  3. Connectors (8)
  4. Ring 3

- **Sub Assembly C: Middle Cage**
  1. Large Dovetails with connectors (2)
  2. Small Dovetails (4)
  3. Ring 4

- **Sub Assembly D: Lower Truss**
  1. Carbon Fiber Tubes (8)
  2. Connectors (8)
  3. Ring 5

- **Sub Assembly E: Lower Optical Assembly (LOA)**
  1. Primary Mirror
  2. Mirror Cell

---

**System: Optomechanical Assembly**

- **Assembly A**
  - Supports Sub-Sub Assembly A. Has attachments for camera, filter wheel, focuser (2.1.6-2.1.8)

- **Sub-Sub Assembly A: Secondary Mirror Interfaces with Spider**

- **Sub-Sub Assembly B: Primary Mirror Interfaces with Mirror Cell**

- **Sub-Sub Assembly C and D (10,12)**

- **Interface Sub B and Sub C (7,8,9)**

- **Interface Sub D and Sub E (13,15)**

- **Interface Sub A and Sub B (3,4)**

- **Interface Sub A and Sub B (3,4)**

- **Interface Sub A and Sub B (3,4)**

- **Interface Sub A and Sub B (3,4)**

- **Interface Sub A and Sub B (3,4)**

- **Interface Sub A and Sub B (3,4)**
**Figure 3: Optical Assembly Attachments**

**Customer Furnished Equipment**

**Assembly A: Imaging**
1. Focus
   2. Filter Wheel
2. Camera
3. 2.1.7 – attaches to Upper Optical Assembly
4. 2.1.8 – attaches to Upper Optical Assembly
5. Camera
6. 2.1.6 - attaches to Upper Optical Assembly

**System: Optomechanical Assembly**

**Sub Assembly A: Upper Optical Assembly (UOA)**
1. Upper Ring
2. Spider/Secondary Mirror
3. Dovetails (4)

**Sub Assembly B: Upper Truss**
4. Ring 2
5. Carbon Fiber Tubes (8)
6. Connectors (8)
7. Ring 3

**Sub Assembly C: Middle Cage**
8. Large Dovetails with connectors (2)
9. Small Dovetails (4)
10. Ring 4

**Sub Assembly D: Lower Truss**
11. Carbon Fiber Tubes (8)
12. Connectors (8)
13. Ring 5

**Sub Assembly E: Lower Optical Assembly (LOA)**
14. Primary Mirror
15. Mirror Cell

---

**Figure 4: Electronics**

**Customer Furnished Equipment**

**Assembly B: Sensors**
1. Cooling Fans (4)
2. Temperature Sensor
3. Ambient Temp Sensor

**System: Optomechanical Assembly**

**Sub Assembly A: Upper Optical Assembly (UOA)**
1. Upper Ring
2. Spider/Secondary Mirror
3. Dovetails (4)

**Sub Assembly B: Upper Truss**
4. Ring 2
5. Carbon Fiber Tubes (8)
6. Connectors (8)
7. Ring 3

**Sub Assembly C: Middle Cage**
8. Large Dovetails with connectors (2)
9. Small Dovetails (4)
10. Ring 4

**Sub Assembly D: Lower Truss**
11. Carbon Fiber Tubes (8)
12. Connectors (8)
13. Ring 5

**Sub Assembly E: Lower Optical Assembly (LOA)**
14. Primary Mirror
15. Mirror Cell
**Figure 5: Shroud**

**Customer Furnished Equipment**

**Assembly C: Shroud**

- Shroud will protect the telescope.
- Shroud will interface with all assemblies.

**System: Optomechanical Assembly**

**Sub Assembly A: Upper Optical Assembly (UOA)**
1. Upper Ring
2. Spider/Secondary Mirror
3. Dovetails (4)

**Sub Assembly B: Upper Truss**
4. Ring 2
5. Carbon Fiber Tubes (8)
6. Connectors (8)
7. Ring 3

**Sub Assembly C: Middle Cage**
8. Large Dovetails with connectors (2)
9. Small Dovetails (4)
10. Ring 4

**Sub Assembly D: Lower Truss**
11. Carbon Fiber Tubes (8)
12. Connectors (8)
13. Ring 5

**Sub Assembly E: Lower Optical Assembly (LOA)**
14. Primary Mirror
15. Mirror Cell

**Figure 6: Mount**

**Customer Furnished Equipment**

**Assembly D: Mount**

- Universal Mount
- Plain Wave Universal Mount interfaces with Sub Assembly C (2.1.5)
- Software
  - Software locates space objects to be used in imaging. Software communicates with the mount. (1.1)
  - Pedestal
    - Interface with the universal mount to accommodate viewing in Lunar Planetarium

**System: Optomechanical Assembly**

**Sub Assembly A: Upper Optical Assembly (UOA)**
1. Upper Ring
2. Spider/Secondary Mirror
3. Dovetails (4)

**Sub Assembly B: Upper Truss**
4. Ring 2
5. Carbon Fiber Tubes (8)
6. Connectors (8)
7. Ring 3

**Sub Assembly C: Middle Cage**
8. Large Dovetails with connectors (2)
9. Small Dovetails (4)
10. Ring 4

**Sub Assembly D: Lower Truss**
11. Carbon Fiber Tubes (8)
12. Connectors (8)
13. Ring 5

**Sub Assembly E: Lower Optical Assembly (LOA)**
14. Primary Mirror
15. Mirror Cell
Drawings

This paper includes all SolidWorks drawings used for the final mechanical design. The final drawing presented was for the telescope design version 4.3. The model of the final design is presented along with FEA for the bending of the assembly. For the FEA analysis, the system was simplified so that SolidWorks could run without crashing. This was accomplished by making the upper optical assemblies and lower optical assemblies into single shapes. Reducing the number of parts allowed the model to run successfully in SolidWorks. The FEA was performed to determine the bending of the system was within the limit of 0.2mm. All SolidWorks drawings are in Appendix III.

Software Design

Not applicable.
Acceptance Test Procedures

Acceptance tests were performed to confirm that the mirrors had the correct figure, that the thermistors and fans functioned correctly, and that the telescope bending did not exceed the maximum allowable value.

To confirm the mirror figure was correct, the Foucault Knife Edge Test was performed with a Couder Mask placed on the mirror. The mirror was placed on a test stand and a knife edge rig was placed at the approximate center of curvature of the center zone of the mirror. The center of curvature of each zone was determined relative to the center zone of the mirror, and the data was processed to determine RMS wavefront error. The mirror would be deemed acceptable if it had an RMS wavefront Error of less than 1/12 wave.

To determine that the electrical systems (the thermistors and fans) functioned correctly, a basic function tests were performed. First the system was shown to turn on and display correctly. Then, the fans were tested by turning them on and increasing and decreasing their speed. The system was wired to the control panel and a heat gun was used to apply a heat gradient between the thermistors. The system passed the test if the temperature readings matched the readings on a thermometer known to be correct.

The system bending will be tested using a laser triangulation test. With the telescope assembled and all components attached, a laser is placed in the same axial plane of the mirror on the lower cage. On the upper cage, a tab of cardstock is placed in the same axial plane as the secondary mirror, the laser turned on, and the location of the beam marked. The telescope is then mounted, and the same procedure is performed. The system will pass if the distance between the two incident beam positions on the cardstock is less than 0.02 mm.

Full descriptions of the acceptance test procedures are included in the acceptance test procedures section of the technical data package.
Models and Analysis

Modeling of the mechanical design was performed in SolidWorks. We performed an FEA on the telescope assembly in SolidWorks to determine the maximum bending. Zemax software was used to model the primary and secondary mirrors as well as the corrective optics to confirm mechanical positions of the elements. Modeling in Newt software was used for determining mirror cell dimensions and required number of support points. We also did FEA modeling on the primary mirror in SolidWorks to analyze deformations due to thermal effects and the mirror cell. The full analyses can be seen in Appendix II.

Multiple Foucault knife edge analyses were performed for each of the parabolic zones in the primary mirror to determine the surface quality of the mirror. MATLAB software was written to evaluate the amount of correction needed in each zone to meet RMS wavefront error and peak-to-valley wavefront error requirements.
System Design

Mechanical Design

The preliminary mechanical design of the Optical Tube Assembly included two main parts: the Upper Optical Assembly (UOA) and the Lower Optical Assembly (LOA), connected by the truss. The truss design was chosen to be a serrurier truss, specifically the serrurier truss based on the Hercules telescope model. The analysis of why this truss was chosen is summarized in the Table 1 below. The serrurier truss is beneficial because it maintains alignment between the optical components by balancing the compressive and tensile forces about the center of mass. The UOA consisted of a Kydex tube situated between two octagonal aluminum rings with an inner diameter of 13”, with a 4-arm mirror spider supporting the secondary mirror. This model weighed 220 pounds.

<table>
<thead>
<tr>
<th>3-Truss</th>
<th>4-Truss</th>
<th>Hercules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pro</td>
<td>Pro</td>
<td>Pro</td>
</tr>
<tr>
<td>Fewer materials</td>
<td>Symmetry</td>
<td>Symmetry</td>
</tr>
<tr>
<td>Reduced weight</td>
<td>Easier to calculate</td>
<td>Strength</td>
</tr>
<tr>
<td>Stability</td>
<td>Less deflection</td>
<td>center of mass in back</td>
</tr>
<tr>
<td>Con</td>
<td>Con</td>
<td>Con</td>
</tr>
<tr>
<td>Not symmetric</td>
<td>More materials</td>
<td>Complex to build</td>
</tr>
<tr>
<td>Harder to calculate</td>
<td>More weight</td>
<td>More materials</td>
</tr>
<tr>
<td>Deflections in UOA</td>
<td>Lacks strength of Hercules</td>
<td>More materials</td>
</tr>
</tbody>
</table>

**TABLE 3: TRUSS DESIGN STUDY**

Optical Design

The optical design features a Newtonian F/4 system, in which a concave, parabolic primary mirror focuses incident light, the light is diverted out of the optical tube by a flat secondary mirror, and an image forms after the corrective optics on the camera detector. The primary mirror has a diameter of 24” and a reported focal length of 96”, the secondary mirror has a minor axis of 5.5”. Note that the design assumes a 5.5” diameter obscuration and 0.15” thick spider arms.

The optical component of the system was designed around the salvaged primary mirror, which, even though it had a reported value of 96”, had to be measured by hand and had a true focal length of 96.75”. This parameter was highly important for the design as it was the main influence on the total length of the telescope as well as the location of the correction optics,
The corrective optics feature a coma corrector and focuser to primarily compensate for off-axis aberrations present in the system.

Due to the primary mirror being parabolic, an offset of 3” in the plane of the secondary mirror is required for no vignetting to occur. Equivalently, an offset of 1.732” in both the direction towards the primary mirror and the direction perpendicular to that can be applied. In addition to the focal length, the surface quality of the primary mirror was tested and analyzed to ensure \( \frac{\lambda}{4} \) wave peak-to-valley and 1/12 wave RMS wavefront error requirements are met.

**Electrical Design**
The electrical components of the OTA are a Starizona-made printed circuit board (PCB) with switches, I/O ports, and an LCD. Connected to the PCB will be two thermistors (referred to as temperature sensors) that are connected to the primary mirror and the outside of the assembly to read ambient temperature. There are three fans on the inside of the assembly that will be triggered by the temperature to cool down the primary mirror. The temperature at which the fans will trigger can be determined by the user in the accompanying software. Below are diagrams of the PCB and wiring for the control panel. Some parts of the PCB will not be used such as heater connection, and the focuser connections.

![Control Panel PCB](image)

**Figure 8, 9: Control Panel PCB (Front, Left) (Back, Right)**
Final Design
This design represents a fully functional telescope. It is sturdy enough to meet the bending criteria of 0.2mm and has the correct dimensions for its housing in the LPL. The design has all the necessary interface attachments, and was designed so that stray light interference would be mitigated. The final weight is 220 pounds and the telescope is 7.5 feet long.
FIGURE 10: FINAL DESIGN
Acceptance Test Results

The team was able to design and fully assemble the OTA. Due to time constraints caused by vendor issues, the team was not able to fully perform the testing with the customer furnished pier and mount. The sponsor will perform these tests. The team is confident that the assembly will satisfy all tests because of the rigorous analyses performed and described in this document.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Test</th>
<th>ATDI</th>
<th>Satisfied</th>
<th>To Be Determined</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1.1 weigh system on scale</td>
<td></td>
<td>D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1.2 use FEA for mirror deformation due to thermal affects</td>
<td></td>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1.3 successful operation within mount angular range (62.5 degrees)</td>
<td></td>
<td>D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1.4 successful attachment of system to mount</td>
<td></td>
<td>I,D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1.5 successful attachment of system to camera</td>
<td></td>
<td>I,D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1.6 successful attachment of system to focuser</td>
<td></td>
<td>I,D</td>
<td></td>
<td></td>
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<td>2.1.7 use FEA to determine the bending of the system</td>
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<td>2.1.9 laser test for allowable bending</td>
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</tr>
<tr>
<td>2.1.9 bending test for carbon fiber truss</td>
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<tr>
<td>2.2.1 successful contact of temperature sensor with mirror</td>
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<td>I,D</td>
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<tr>
<td>2.2.2 successful contact of ambient temperature sensor with mount</td>
<td></td>
<td>I,D</td>
<td></td>
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<tr>
<td>2.2.3 heat test to confirm alert at temperature difference</td>
<td></td>
<td>T,J</td>
<td></td>
<td></td>
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<tr>
<td>2.3.1 pointing test to determine Strehl ratio</td>
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<tr>
<td>2.3.2 Foucault test to determine RMS wavefront error</td>
<td></td>
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<td>2.3.3 verify image appearance</td>
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<tr>
<td>2.3.4 calculate the signal-to-noise ratio of exposure time</td>
<td></td>
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<tr>
<td>2.3.6 calculation of 3 second exposure time</td>
<td></td>
<td>A</td>
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</table>

**Table 4: Requirements and Results**

Through the acceptance test process, the team was also able to verify that one of the mirrors that were tested had a figure that was far from acceptable (1.1 Waves RMS Wavefront Error). The original test results are depicted in the following diagram:
This mirror was sent off to a local expert to be refigured, and after refiguring, the mirror was retested and showed that it had an RMS Wavefront Error of less than 1/65 wave, thus meeting the requirement and passing the acceptance test. The figure below shows the test results:

**FIGURE 12: MIRROR SHAPE ANALYSIS AFTER REFIGURING**

Attached in Appendix IV are the full Acceptance Test Procedures and Results.
## Final Budget

<table>
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<tr>
<th>ITEM</th>
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<th>AMOUNT</th>
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<td>5</td>
<td>Astro-Physics 10&quot;x62&quot; Portable Pier</td>
<td>STARIZONA</td>
<td>5744397</td>
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<td>6</td>
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<td>Astrosystems 3.1&quot; Secondary Mirror, Astrosystems 3.1&quot; Secondary Holder, Astrosystems Spider for 8&quot; Telescope, Feathertouch SIPS 2&quot; Focuser, Feathertouch Custom Curved Base, Celestron 8&quot; f/5 Newtonian OTA, AP Pier to Planewave Mount Custom Plate - TBD, Losmandy DUP14 Dovetail Plate, 1 Custom Machining Mods to 8&quot; OTA, MicroTouch Direct Drive Motor - 3&quot; FT</td>
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**Lessons Learned**

It was very helpful to stay in frequent contact with the sponsor as the sponsor’s vision for the project changed. For example, originally we were expected to make a telescope assembly for imaging and spectroscopy, but that changing to being an imaging telescope. Much of the system design also depended on customer furnished equipment such as the weight limit of a mount. We were not sure of type of mount our sponsor would purchase for much of the first semester and kept in contact so that our design would be as up to date as possible. We stayed in contact with our sponsor by using email, texting, and setting up meetings. A challenge we ran into in our project was that one of our vendors delivered the wrong parts and then delaying the shipment of our correct parts. We ordered early in the second semester so we had some cushion time for error and were able to get the parts in mid-April. However, it was stressful and could have been catastrophic for the project. The company we ordered from was less well known so we would recommend ordering early on from more established, reputable companies. Finally, we found it very helpful to start machining early before the machine shop became overwhelmed with other team’s orders. As we had over 200 parts we had to be very diligent in checking on the machining progress to make sure that all parts were completed; we found this to be easiest using the AME shop on campus.

**References**


Appendix I

The following list is provided to clarify the use of terms which will be frequently encountered in this report.

Truss - Basic structure that will be used to support telescope structure. The system includes an upper truss and a lower truss. Each truss is made of 8 carbon fiber tubes. See Block Diagrams.

Optomechanical - A structure involving optical and mechanical components. The entire telescope system is itself an optomechanical system. The interfaces between the spider and secondary mirror and the mirror cell and primary mirror can be considered sub optomechanical systems. See Block Diagrams.

Geostationary orbit - orbit that follows the rotation of the earth. The telescope will image objects in this orbit.

LPL - Lunar Planetarium; the department on the University of Arizona campus where the telescope will be housed and will operate.

FEA - Finite Element Analysis. Used in SolidWorks to analyze telescope structure. See Appendix Drawings.

Primary mirror - The mirror which comes into first contact with light and which reflects the light to the secondary mirror and imaging equipment. See Block Diagrams.

Secondary mirror - The mirror which redirects the light into the imaging assembly off into the side. This prevents the imaging assembly from inhibiting the path of light. See Block Diagrams.

Mount - The structure which supports the weight of the telescope assembly. It includes software for tracking objects in space and attachments for electrical components and power. The mount used is a Planewave HR200. The mount is customer furnished equipment. See Block Diagrams.

Pedestal - The structure which will support the mount to allow clearance of the telescope above the roof in the LPL. The pedestal is customer furnished equipment.

Spider - The mechanical structure which holds the secondary mirror. See Block Diagrams.

Imaging - Customer furnished equipment used to generate images. Includes camera, filter wheel, focuser. See Block Diagrams.
Mirror Cell - Structure which holds the primary mirror. Made of Aluminum 6061. See Block Diagrams.

Shroud - covering which will protect the telescope. Customer furnished equipment.

Clevis Connectors - used to connect truss components to rings of telescope system. Made of 6061 Aluminum. See Block Diagrams.

Optical assembly - structure which includes optical components; for this project that includes the primary and the secondary mirror. See Block Diagrams.

Serrurier Truss - type of truss structure which maintains alignment between optical components by balancing tensile and compressive forces. This truss structure is used for this telescope.
Appendix II – Analyses

Serrurier Truss Analysis and FEA of Optomechanical Assembly

The purpose of this analysis section is to provide structural analysis on the complete telescope assembly and determine the amount of deflection at various telescope orientations with respect to gravity. Large optical assemblies, like the 24 inch primary mirror, often require truss supports to preclude the system weight, volume and cost. The serrurier truss design is a center supported truss with equal and parallel end deflections. The equations below allow for the maximum allowable deflection to be calculated as well as the equal, parallel deflections at the end rings to be achieved, thus preserving system collimation.

\[
\left( \frac{W_1}{E_1 A_1} \right) \left( \frac{4 (L_1)^2}{b^2} + 1 \right)^{\frac{3}{2}} = \left( \frac{W_2}{E_2 A_2} \right) \left( \frac{4 (L_2)^2}{b^2} + 1 \right)^{\frac{3}{2}}
\]

Where:
- \( W_1, W_2 \) : End ring loads
- \( L_1, L_2 \) : Distance from end rings to support
- \( E_1, E_2 \) : Truss member elastic modulus
- \( A_1, A_2 \) : Truss member cross sections
- \( b \) : End ring diameter
$$\delta_{(\text{max})} = \left( \frac{Wb}{4EA} \right) \left( \frac{4L^2}{b^2} + 1 \right)^{\frac{3}{2}}$$
The amount of allowable deflection of the UOA relative to the LOA is 0.2324 mm. The simulations present a maximum deflection of the LOA relative to the system’s center of gravity of 1.92 mm.

Primary Mirror Self-Weight Deflection

The purpose of this analysis section is to provide a means of estimating the amount of surface displacement on the 24 inch primary mirror due to the kinematic constraints of the mirror cell. Note that the calculation and simulations assume a three point support model as this was done to simplify calculations as well as boundary constraints and processing time of the simulations.

The volume of the mirror ‘V’ is given by the effective area multiplied by the thickness ‘h’, where ‘R’ is defined as the mirror radius. The total weight of the mirror is determined by its material density multiplied by the volume of the mirror. Note that the material density of Zerodur is roughly 2.5 g/cm³. The calculations are given below:

\[ V = \pi R^2 h \]
\[ V = \pi (0.305 \text{ m})^2 (0.0483 \text{ m}) \]
\[ V = 0.01412 \text{ m}^3 \]

\[ W = \rho V \]
\[ W = (2.53 \text{ g/cm}^3)(0.01412 \text{ m}^3) \]
\[ W = 35,712.25 \text{ g} \]
\[ W = 78.73 \text{ lbs} \]

With the mirror positioned on its back, the optimal locations for the three support points are equally spaced along a circle at 64.5% of the mirror diameter (64.5 mm). For small cylinder mirrors self-weight deflection is determined by the mirror material (specific stiffness), diameter, thickness, support condition, and position of the gravity vector.

The below expression describes the maximum or peak-to-peak deflection of the mirror surface, accurate to roughly 5% of true surface deflection. The variables include: deflection constant
‘C₀’, elastic modulus ‘E’, direction of gravity vector, material Poisson ratio. Note that for a three point support at 64.5% diameter, the deflection constant is roughly 0.316.

\[ \delta_{\text{max}}(C_0, \theta) = C_0 \left( \frac{\rho}{E} \right) \left( \frac{R}{h} \right)^2 R^2 (1 - \nu)^2 \cos(\theta) \]

\[ \delta_{\text{max}}(0.316, 0) = C_0 \left( \frac{\rho}{E} \right) \left( \frac{R}{h} \right)^2 R^2 (1 - \nu)^2 \cos(\theta) \]

\[ \delta_{\text{max}}(0.316, 0) = (0.316) \left( \frac{2.53 \text{ g/cm}^3}{91 \text{ GPa}} \right) \left( \frac{0.305 \text{ m}}{0.0483 \text{ m}} \right)^2 (0.305 \text{ m})^2 (1 - (0.24))^2 (1) \]

\[ \delta_{\text{max}}(0.316, 0) = 18.82 \mu m \]

The Solidworks analysis was done such that the mirror was kinematically constrained at three optimal points, allowing for minimal self-weight deflection. The post-processing determined low orders of magnitude in the surface and RMS surface irregularity maps after removing bias, tilt, and power. Ultimately the geometry of how the mirror is constrained, including type and positioning of constraints, limits the performance of the mirror. The self-weight deflection of the mirror is within \(1/30\)th of a wave RMS.

Transverse direction:
\[ \delta_{\text{max}}(0.316, 0) = 18.82 \mu m \]

Lateral direction:
\[ \delta_{\text{max}}(0.316, 0) = 2.83 \mu m \]