Training the Next Generation in Space Situational Awareness Research

Damon Colpo
College of Optical Sciences, University of Arizona
Vishnu Reddy
Lunar and Planetary Laboratory, University of Arizona
Sameep Arora
Aerospace and Mechanical Engineering, University of Arizona
Scott Tucker
Starizona
Lindsie Jeffries
Biomechanical Engineering, University of Arizona
Doug May
Aerospace and Mechanical Engineering, University of Arizona
Ryan Bronson
College of Optical Sciences, University of Arizona
Evelyn Hunten
Electrical and Computer Engineering, University of Arizona

ABSTRACT

Traditional academic SSA research has relied on commercial off the shelf (COTS) systems for collecting metric and lightcurve data. COTS systems have several advantages over a custom built system including cost, easy integration, technical support and short deployment timescales. We at the University of Arizona took an alternative approach to develop a sensor system for space object characterization. Five engineering students designed and built two 0.6-meter F/4 electro-optical (EO) systems for collecting lightcurve and spectral data. All the design and fabrication work was carried out over the course of two semesters as part of their senior design project that is mandatory for the completion of their bachelors in engineering degree. The students designed over 200 individual parts using three-dimensional modeling software (SolidWorks), and conducted detailed optical design analysis using raytracing software (ZEMAX), with oversight and advice from faculty sponsor and Starizona, a local small business in Tucson. The components of the design were verified by test, analysis, inspection, or demonstration, per the process that the University of Arizona requires for each of its design projects. Methods to complete this project include mechanical FEA, optical testing methods (Foucault Knife Edge Test and Couder Mask Test), tests to verify the function of the thermometers, and a final pointing model test. A surprise outcome of our exercise is that 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 we were also able to reduce to the deployment times to those for a commercial system. Our experience shows that development of hardware and software for SSA research could be accomplished in an academic environment that would enable the training of the next generation with active support from local small businesses.

1. INTRODUCTION

Electro-optical systems have played a vital role in space surveillance. In recent years, Raven-class commercial off the shelf (COTS) systems have become integral part of both government and private space EO surveillance networks. At the University of Arizona, we developed two 0.6-meter F/4 systems as part of senior design project involving five undergraduate engineering students. The process of designing and constructing a large telescope has many steps and requires input from personnel of many different disciplines for the product to function correctly. Factors to consider for an automated telescope fall into three categories: considerations for the optical system, considerations for the mechanical system, and considerations for the electrical system. It is also very important to follow the engineering design process to ensure that the telescope design meets all the requirements as the design progresses. The Robotic Automated Pointing Telescope for Optical Reflectance Spectroscopy (RAPTORS) telescope is located at an observatory on top of the Lunar and Planetary Laboratory at the University of Arizona in Tucson. The project was performed to complete the senior capstone requirements for the engineering program and took a whole year to complete. The students completed the project in accordance with the engineering design process. Many preliminary designs of the mechanical, optical, and electrical systems were made, analyzed, and changed according to the requirements. After the design and machining process, the students constructed the telescope and got the chance to showcase it to the community at an Engineering Design Day put on by the College of Engineering at the University of Arizona. In addition to the design and construction of the telescope, the students are also involved in the upkeep of the telescope and the use of the telescope for gathering data.

2. TELESCOPE DESIGN

The telescope features a 24” (0.6-m) F/4 Newtonian truss tube design. There are three main subassemblies (Fig. 1): the upper cage that houses the secondary mirror (on the inside) and the camera module (on the outside), the middle cage that has the dovetail plate which is used to mount the telescope to the German equatorial mount, and the mirror cell which holds the primary mirror and houses the microcontroller for temperature and focus control. Carbon fiber truss tubes connect the sub-assemblies.

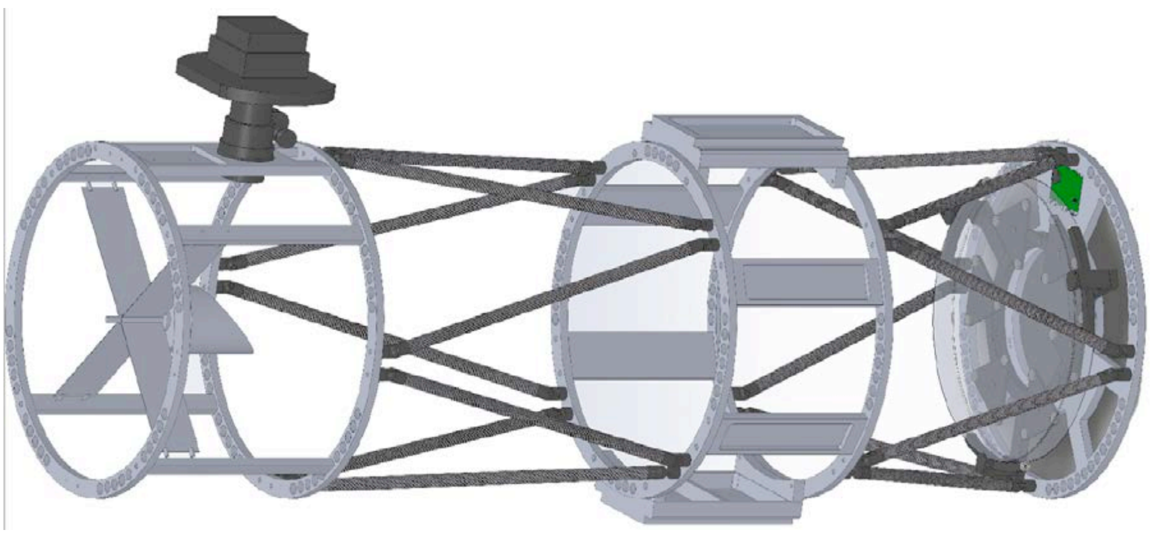


Figure 1: SolidWorks Model of the Final Design.

The core mechanical design of the telescope is the Serrurier Truss, with top, middle, and mirror cell assemblies, connected by carbon fiber tubes. The design allows for equal flexure about the mounting point, the dovetail plate on the middle cage on the opposite side of the camera module. This was critical for the design, as it minimized the total flexure of the system (and consequently the optical axes of each of the components) experienced, which had to be less than 0.2 mm relative to the mounting point in order to have acceptable image quality. Simulations of the flexure were done in SolidWorks in order to confirm the design met this requirement (Fig. 2).

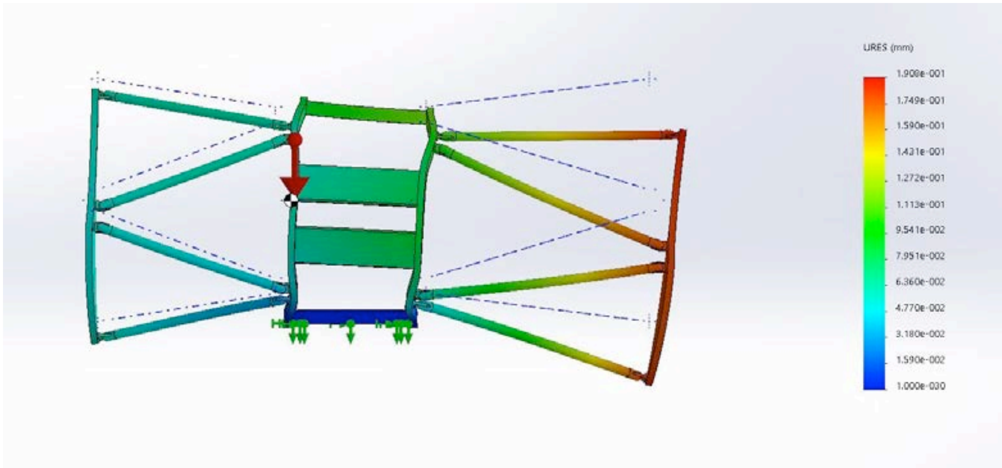


Figure 2: SolidWorks Model of the Bending in the Telescope. Maximum flexure is about 0.19 mm.

The weight of the telescope was a very important quantity to monitor as well, as the mount has a weight limit of 275 lbs. for which it can effectively point and track. The first iteration of the mechanical design was very sturdy and met the requirements for the bending, however, it weighed about 275 lbs., which would have put it right at the limit of the mount, making the system stability questionable. To remedy this, the design was changed so that each of the rings had holes cut out of them and their shape optimized, and this reduced the weight to a more appropriate 220 lbs.

The optical design follows the Newtonian design, where a parabolic primary mirror focuses light onto a flat secondary mirror, which diverts the light to the corrective optics and the camera module. The camera module features a FLI Proline 16803 camera with a 4k x 4k pixel array (pixel size 9 um x 9 um), a focuser with a translating range of 3"and space for corrective optics to be installed if necessary, and a filter wheel. The mirror that is used in the telescope is a 24" parabolic mirror that was salvaged from surplus. Thus, the optical design began with the 24" F/4 primary mirror and the optical tube assembly was built around it (Fig. 3). The focal length of the mirror is 96", and the camera plane is located about 18" from the optical axis of the primary mirror, so the primary-secondary distance had to be about 78". The secondary mirror had a minor axis diameter that was determined by the size of the ray bundle location of the intersection of the camera optical axis and primary mirror optical axis, which was calculated in the ZEMAX model to be about 5.5". The full field of view of the telescope had to be at least a degree, so the first ring of the upper cage of the telescope (as well as all the other rings) had to have an inner diameter of 26". The coma from the F/4 optical system was corrected with a Televue Paracorr Coma Corrector in the focuser.

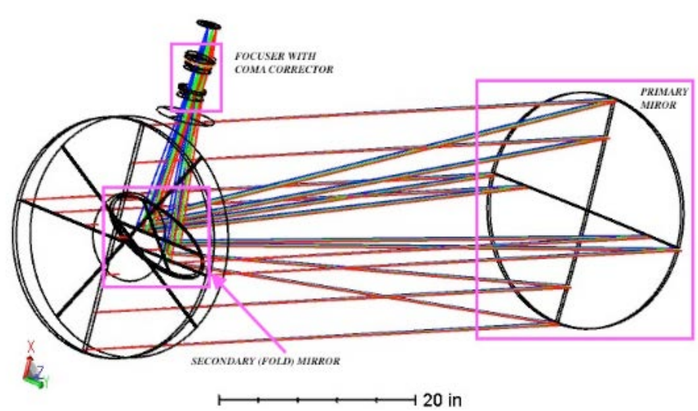


Figure 3: Optical Design Modeled in ZEMAX with Critical Components Labeled.

Part of the optical component of this project included testing the salvaged mirror. An acceptable RMS wavefront error value for this telescope was 1/12 of a wave, with a peak-to-peak error for no more than 1/4 of a wave. The Foucault Knife Edge Test was used to evaluate the mirror based on the deviation from the ideal parabolic shape that each mirror zone had. Our initial tests of the salvaged mirror showed a P/V error of 1/1.1 wave and an RMS of 1/5.7 wave (Fig. 4). We worked with a local small business, Starizona, to refigure the mirror to a final shape of 1/21.2 wave P/V and RMS of 1/68.2 wave (Fig. 5).

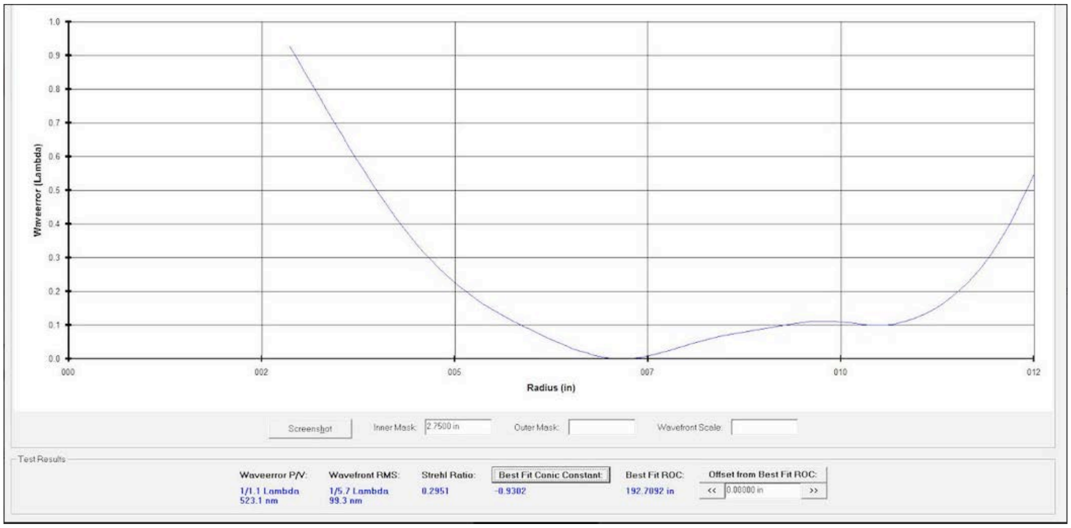


Figure 4: Surface Profile Measurement of Primary Mirror prior to being Refigured.

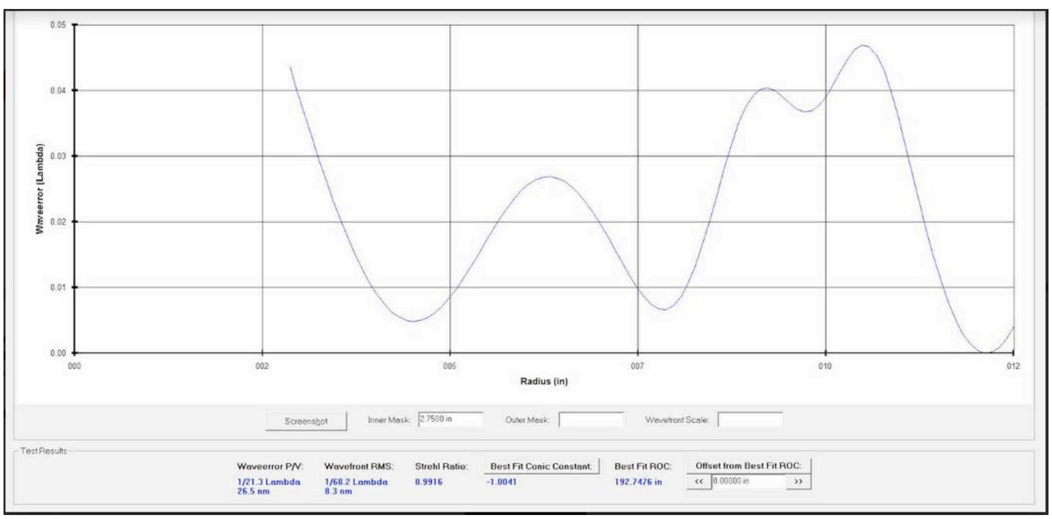
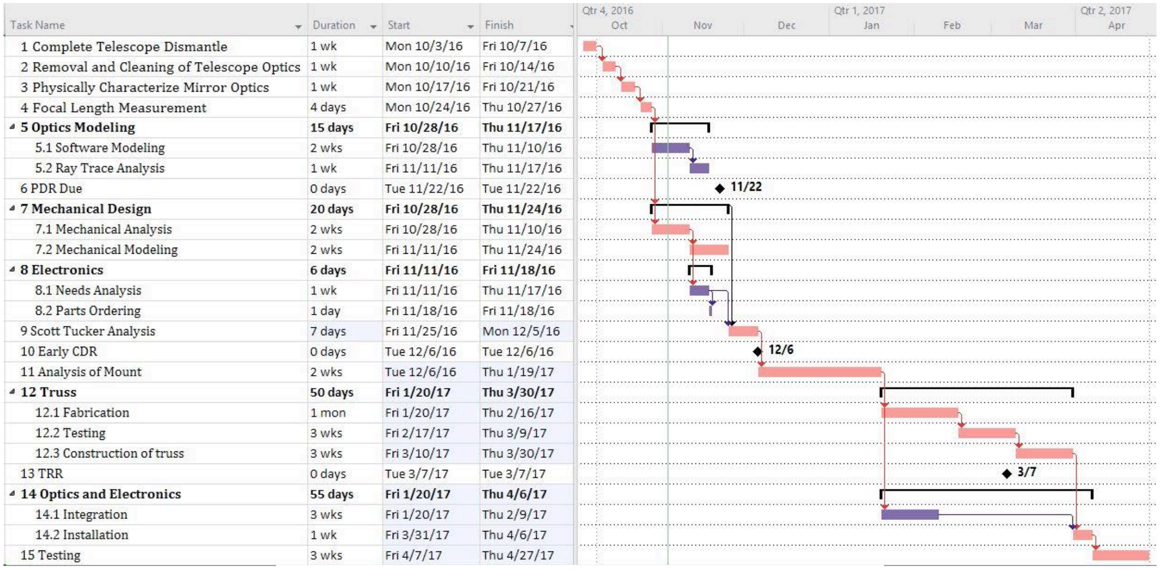


Figure 5: Surface Profile Measurement of Primary Mirror after being Refigured.

In addition to making and vetting the design, the process had to be well documented. This meant conducting a requirements revision, a preliminary design report, a critical design report, acceptance test procedures for individual systems in the telescope, and finally a final acceptance test for the system as a whole. This was to ensure that the telescope design was valid at each iteration of the design so that it would function properly at the end of the project. Below is a picture of the Gantt chart that was used for the project (Fig. 6).



Task Name	Duration	Start	Finish
1 Complete Telescope Dismantle	1 wk	Mon 10/3/16	Fri 10/7/16
2 Removal and Cleaning of Telescope Optics	1 wk	Mon 10/10/16	Fri 10/14/16
3 Physically Characterize Mirror Optics	1 wk	Mon 10/17/16	Fri 10/21/16
4 Focal Length Measurement	4 days	Mon 10/24/16	Thu 10/27/16
5 Optics Modeling	**15 days**	**Fri 10/28/16**	**Thu 11/17/16**
5.1 Software Modeling	2 wks	Fri 10/28/16	Thu 11/10/16
5.2 Ray Trace Analysis	1 wk	Fri 11/11/16	Thu 11/17/16
6 PDR Due	0 days	Tue 11/22/16	Tue 11/22/16
7 Mechanical Design	**20 days**	**Fri 10/28/16**	**Thu 11/24/16**
7.1 Mechanical Analysis	2 wks	Fri 10/28/16	Thu 11/10/16
7.2 Mechanical Modeling	2 wks	Fri 11/11/16	Thu 11/24/16
8 Electronics	**6 days**	**Fri 11/11/16**	**Fri 11/18/16**
8.1 Needs Analysis	1 wk	Fri 11/11/16	Thu 11/17/16
8.2 Parts Ordering	1 day	Fri 11/18/16	Fri 11/18/16
9 Scott Tucker Analysis	7 days	Fri 11/25/16	Mon 12/5/16
10 Early CDR	0 days	Tue 12/6/16	Tue 12/6/16
11 Analysis of Mount	2 wks	Tue 12/6/16	Thu 1/19/17
12 Truss	**50 days**	**Fri 1/20/17**	**Thu 3/30/17**
12.1 Fabrication	1 mon	Fri 1/20/17	Thu 2/16/17
12.2 Testing	3 wks	Fri 2/17/17	Thu 3/9/17
12.3 Construction of truss	3 wks	Fri 3/10/17	Thu 3/30/17
13 TRR	0 days	Tue 3/7/17	Tue 3/7/17
14 Optics and Electronics	**55 days**	**Fri 1/20/17**	**Thu 4/6/17**
14.1 Integration	3 wks	Fri 1/20/17	Thu 2/9/17
14.2 Installation	1 wk	Fri 3/31/17	Thu 4/6/17
15 Testing	3 wks	Fri 4/7/17	Thu 4/27/17

Figure 6: Gantt chart with the Deadlines for the Project.

3. TELESCOPE CONSTRUCTION

With the design finalized, the SolidWorks files for each of the telescope parts were sent off to the shop to be machined. The smaller parts that made up the mirror cell were machined at the Aerospace and Mechanical Engineering Machine Shop using standard sized CNC machines. The rings of the telescope were too large to be machined with conventional equipment, so they were sent to the machine shop at the University's Machining and Welding Center to be machined with a water jet (Fig. 7).

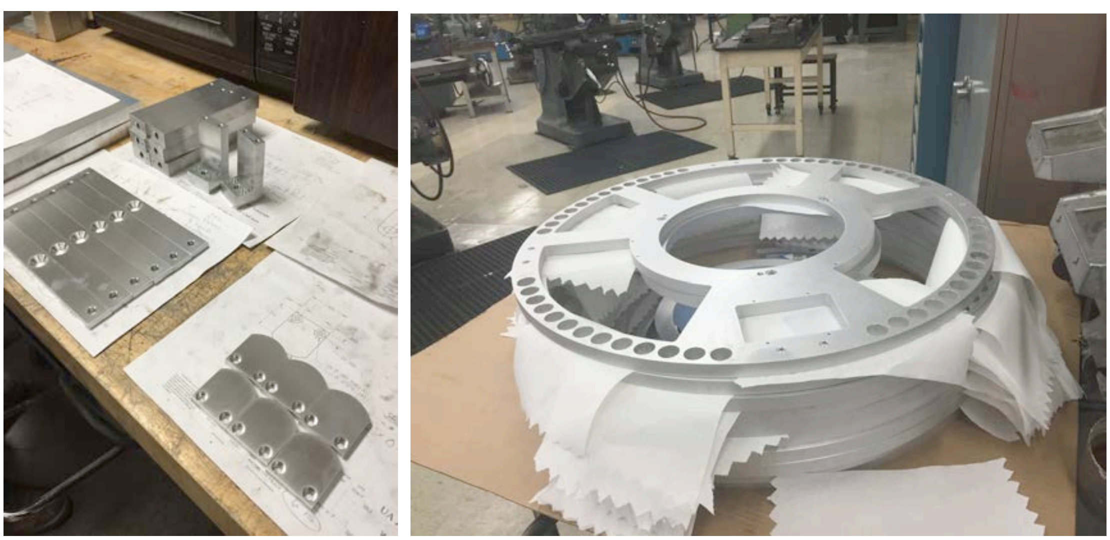


Figure 7: (Left) Mirror Cell was machined at the Aerospace and Mechanical Engineering Machine Shop. (Right) Telescope Rings that were machined at the Machining and Welding Center.

After machining was completed, the team had to perform a preliminary dry fit on the pieces, most notably the dovetail that had a large screw port for the focuser to seat into. The hole had very fine threads and a large diameter, so the potential for error was highest in that part of the design. The initial dry fit proved to be successful, and the parts were sent for anodizing. The parts were treated with a Type III Black Anodization, to harden the surface and reduce the potential for stray light in the system. The anodization added about one thousandth of an inch to each of the anodized surfaces, so the pieces had to be dry fit once again. This was taken into account by the team and the personnel at the machine shop, so the second dry fit was successful, and the pieces were ready to be put together.

After the parts were machined, the team assembled the telescope for the engineering design day. Though the telescope design was durable, the team was careful during the assembly process so as not to damage any of the components. Each subassembly was constructed first, and the upper and middle cages were connected with the truss. Before the mirror cell was connected to the upper cage, the mirror had to be placed in the cell such that it did not move when tilted. Care had to be taken when tightening the supporting collar and the tabs that come in contact with the mirror's edge so that the mirror would not be chipped (Fig. 8).

Figure 8: Fully assembled Optical Tube Assembly of the 24-inch F/4 RAPTORS telescope with the lead author of this paper as scale.

With construction complete, the team showcased the design at the Engineering Design Day fair and after which it was installed on top of the Lunar and Planetary Laboratory for regular operations.

4. DEPLOYMENT AND OPERATIONS

The telescope is currently located at an observatory on the roof of the Lunar and Planetary Laboratory (Fig. 9). The optical tube assembly was placed on a Planewave HR200 mount on a 5-foot Astro-Physics pier. This allows for the telescope to slew to an altitude of 35 degrees over the entire sky. An all-sky camera was placed on the roof of the observatory to monitor the sky above Tucson and a SkyAlert weather system was installed to monitor the weather, and these systems help determine when it was safe to use the telescope. Currently, the telescope remotely operated via remote desktop.

The telescope is controlled using Sidereal Technologies software to locate and track RSOs in space. A pointing model with 40 known stars was performed to accurately point the telescope. The FLI Proline 16803 camera has an 8-position 50 mm square filter wheel with a full compliment of Sloan photometric filters and three diffraction gratings with 30, 35 and 75 lines/mm resolution. The telescope takes images of these objects that can be used for astrometry, photometry, and spectroscopy. The telescope is part of the Space Situational Awareness initiative, and the data gathered will be used in an attempt to characterize space objects with their astrometric, photometric, and spectroscopic data. Dr. Tom Cooley of the Air Force Research Lab officially inaugurated the telescope on June 21, 2017.

Figure 9: Fully operational 24-inch F/4 RAPTORS telescope on top of the Lunar and Planetary Lab.

5. FIRST RESULTS

The telescope has thus far been successful in collecting astrometric and photometric data of objects in geostationary orbit. Below is an example data of the Anik cluster taken with Sloan r band.

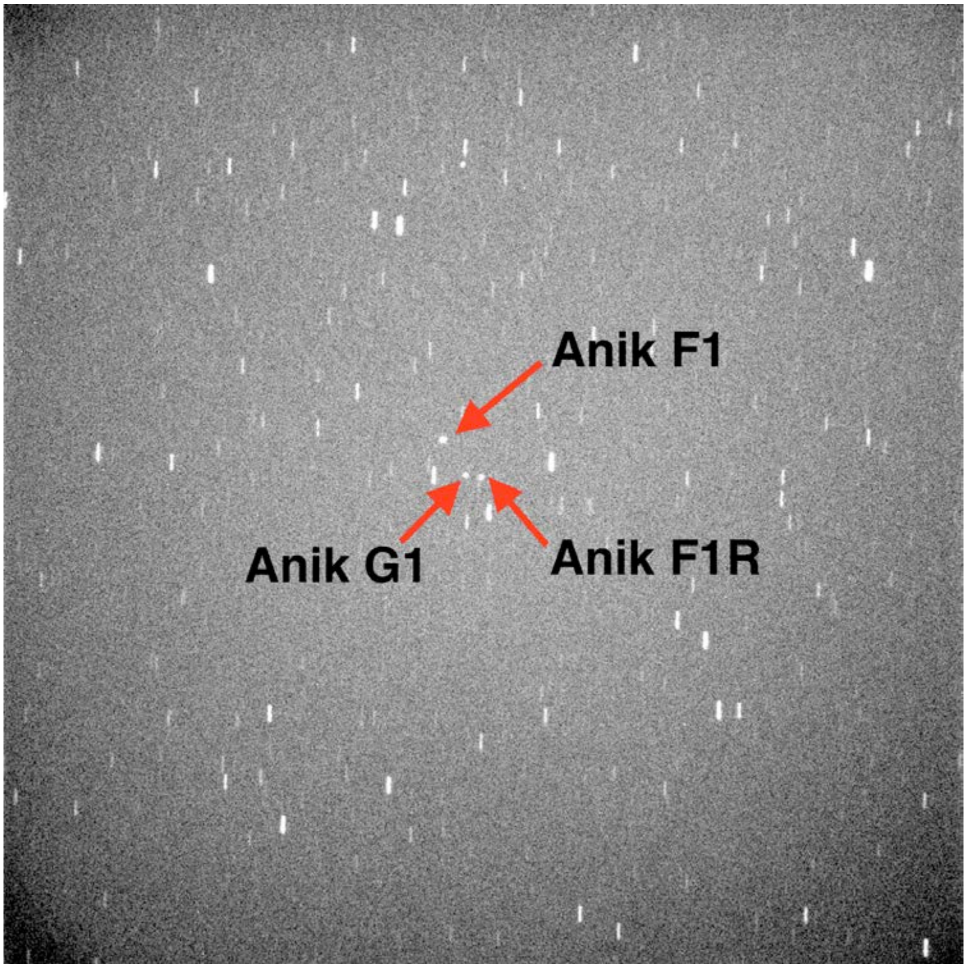


Figure 10: Sloan r' band image of Anik cluster from the 24-inch F/4 RAPTORS telescope. The exposure time is 3 seconds and the field of view is 45 x 45 arc minutes and the image is binned 2x (1.32"/pixel)

6. SUMMARY

Five engineering students designed and constructed two 24" F/4 Newtonian telescopes for tracking RSOs to complete their capstone requirement for the engineering degree at the University of Arizona. Over the course of the 2016-2017, the team created, edited, and presented designs of each of the systems within the telescope. When the final design had been approved, the team sent the drawings of the parts to be machined, the mirror to be refigured, and assembled the electrical components. The team constructed the telescopes and showcased them at Engineering Design Day put on by the College of Engineering at the University of Arizona. After the showcase, the students operationalized one of the telescopes in the observatory at the Lunar and Planetary Laboratory. Today, the telescope is used for gathering astrometric, photometric, and spectroscopic data on RSOs in Earth orbit.

7. ACKNOWLEDGEMENT

We to thank University of Arizona's office of Research, Discovery and Innovation for support our project.