Daylight imaging of LEO satellites using COTS hardware

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Abstract

This project investigates using commercially available, small aperture optical telescope systems to image Low Earth Orbit (LEO) satellites in daylight. A custom tracking system was developed to continuously track satellite passes. Several large satellites were imaged in daylight and tracked for the duration of the pass. The authors hope this project will prove that low cost optical observations of LEOs in daylight is feasible, opening the door to widespread usage of this method for enhanced SSA.

1. Introduction

Daylight imaging of satellites in LEO affords several unique advantages not present in traditional nighttime imaging. For many satellites, there are more passes over a ground observation site in daytime than twilight passes, when the observer must be in darkness and the object in sunlight. During most nighttime passes the satellite is in Earth's shadow and thus invisible to optical detection by reflected sunlight. For example, from February 19 to March 25, 2018, there were 129 passes of the Chinese space station Tiangong-1 over Ann Arbor, MI (Figure 1). 44% of these passes were unilluminated night passes, meaning they were not visible. Only 11% were illuminated night passes, which are detectable with conventional methods. 45% were in daylight, providing four times as many opportunities to observe.

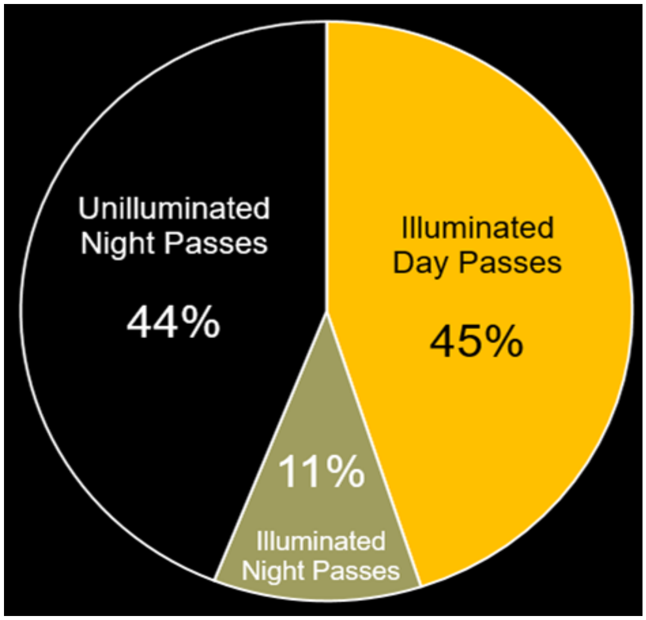


Figure 1. Tiangong-1 Pass Types Over a One Month Period

With more frequent observations, more accurate orbital elements can be obtained, and the orbital uncertainty can be reduced. There are many challenges to this type of observation, however. Principally, atmospheric scattering of sunlight produces a background sky many orders of magnitude brighter than at night, greatly reducing SNR and limiting observations to the brightest and largest satellites. Additionally, the astrometric value of observations is reduced for lack of background reference stars.

Daylight satellite observations date back to at least 1982, when MIT Lincoln Labs used a 0.8 m telescope and TV camera to observe satellites with a limiting magnitude of 8.3 [1]. Precise observation angles were produced and sent to the NORAD Space Defense Center. Currently, there is considerable interest in daytime observations of GEOs in the Short Wave Infrared (SWIR) regime. Nelson [2] experimented with infrared wavelengths for daytime observations at the Maui Space Surveillance Site. Up to a 7th magnitude star was visible in daytime with a 0.4 m system. Thomas and Cobb [3] modeled and measured daytime sky background radiance in the GEO belt as a function of wavelength. Measurements peaked at about 550 nm and showed a 40% radiance decrease at 630 nm with further decreases in the Near Infrared (NIR). Numerica [4] has developed an autonomous ≈0.4 m telescope system that observes GEO objects in daytime using a SWIR camera and advanced image processing algorithms. This capability is planned to be deployed worldwide to close the daytime observation gap.

Daytime observations in the LEO regime have been accomplished in at least two cases. Swindle et al. [5] observed the large satellite ENVISAT 2.5 hours after sunrise using a 3.65 m telescope. High resolution imagery was obtained by applying algorithms to correct for turbulent atmospheric layers. Event-based sensors, which are based on biological vision systems, transmit a signal when a significant change in light intensity is detected. Two of these sensors concurrently observed LEOs in daytime [6]. In this paper, we present our daytime LEO observations using small to medium aperture, conventional optical systems.

2. Senior Design Project

For a senior design class at the University of Michigan (UM), the authors investigated the feasibility of imaging satellites in daytime using an existing telescope and camera at UM. This research occurred from January to April of 2018.

2.1 Tracking System

Observations were conducted at the University of Michigan's Angell Hall Observatory. This observatory is the University's student observatory and is primarily used for classes and public outreach due to its location in the center of campus and proximity to downtown Ann Arbor. The authors used the DFM 0.4 m Ritchey–Chrétien reflector in the observatory with a Canon T3i DSLR (Figure 2). The only modification made to the camera was removal of the infrared blocking filter to allow detection of longer wavelength light. No filters were used in the observations.

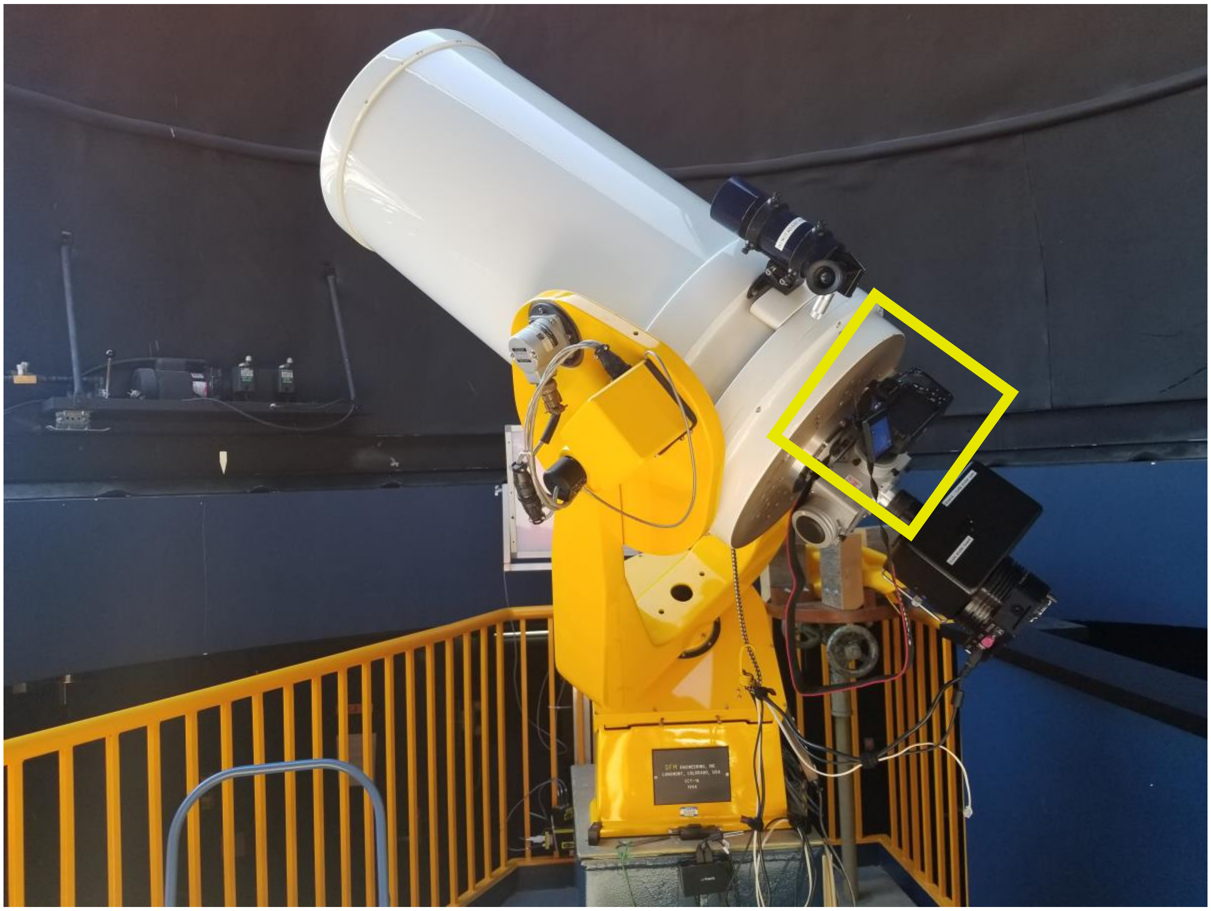


Figure 2. Telescope and Camera Setup for Senior Design Project

A simple point and stare method was used for observation. The coordinates of the pass were calculated beforehand and one position during the pass was chosen. The telescope was pointed to this spot and the camera recorded 1920x1080 video at 30 FPS for 60 seconds before and 60 seconds after the expected time of passage through the FOV, which was 0.39°x0.26°.

2.2 Observations

The primary object to view was the Chinese space station Tiangong-1, which reentered uncontrolled on April 2, 2018. The authors successfully observed Tiangong-1 at 11:28 AM local time approximately one week before its reentry (Table 1).

Name	Catalog #	Pass Start Time (UTC)	Max Visible Range (km)	Sun Elevation (deg)	RCS (m^2)
Tiangong-1	37820	3/25/2018 15:28	200	40.0	19.5

Table 1. Observation Summary

A composite image composed of the six frames in which Tiangong-1 is visible is seen in Figure 3.

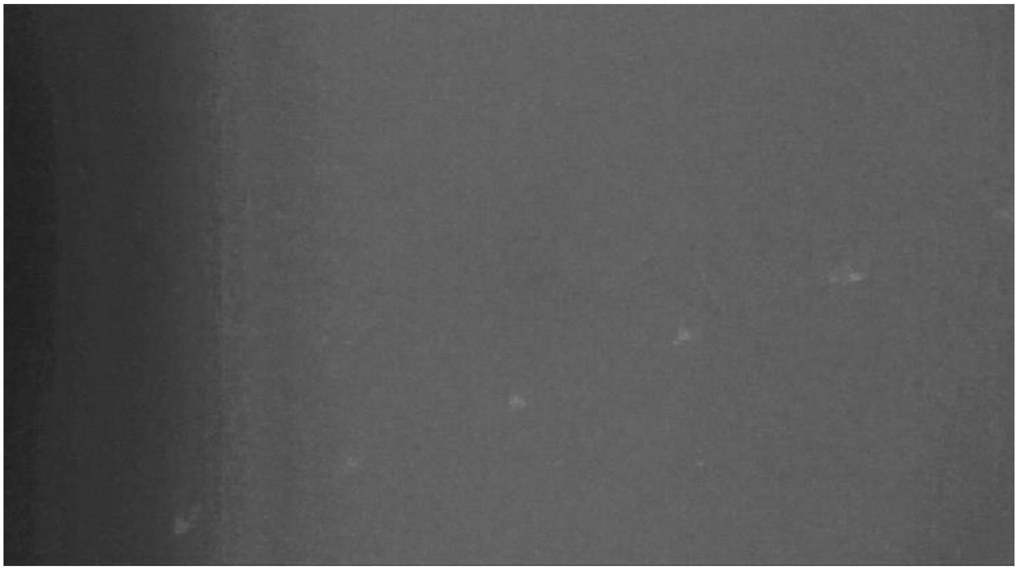


Figure 3. Tiangong-1 Composite Image

The authors measured the pixel distance between the object's position in each frame and converted it to angular distance. The spacecraft was almost overhead at the time of the observation and the range was known from the orbital propagation. Figure 4 shows the distance traveled in each frame in terms of pixels, arcseconds, and meters. The camera frame rate gave a nominal interval between frames of 0.033 s. This allowed the authors to get a rough estimate of the orbital speed of Tiangong-1 which was within 9% of the expected orbital velocity.

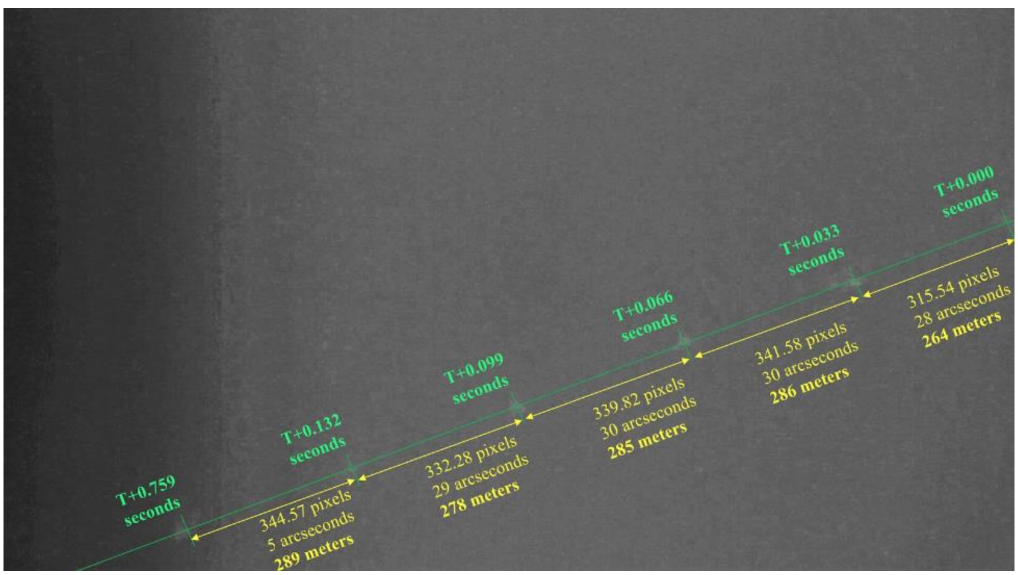


Figure 4. Tiangong-1 Composite Image with Position Information

3. Master's Research Project

As a follow on to the previous year's success, the authors conducted observations with the goal of imaging at a variety of ranges, elevations, and satellite sizes. Tracking software was developed and a new telescope and camera was used to improve the observation capability. This research took place from January to May of 2019.

3.1 Tracking System

The authors developed tracking software in MATLAB based on a program created by Tommaso Cardona, who tracked GEO and GPS satellites at Angell Hall Observatory as a Ph.D. student at Sapienza University in Rome. The software loads TLEs from Space-Track.org or custom TLEs from the user and then uses the SGP4 propagator to predict RA and Dec as a function of time.

Satellite passes are tracked at the satellite's angular rate in order to keep the object continuously in the FOV. The rates are calculated and sent over TCP/IP to the Telescope Control System (TCS) software which then sends the low-level commands to the equatorial mount. Both the TCS and mount are products of DFM Engineering. A proportional controller corrects the commanded rates in real time based on the error between the telescope and the satellite's expected position. The declination of satellite and telescope are seen in Fig. 5.

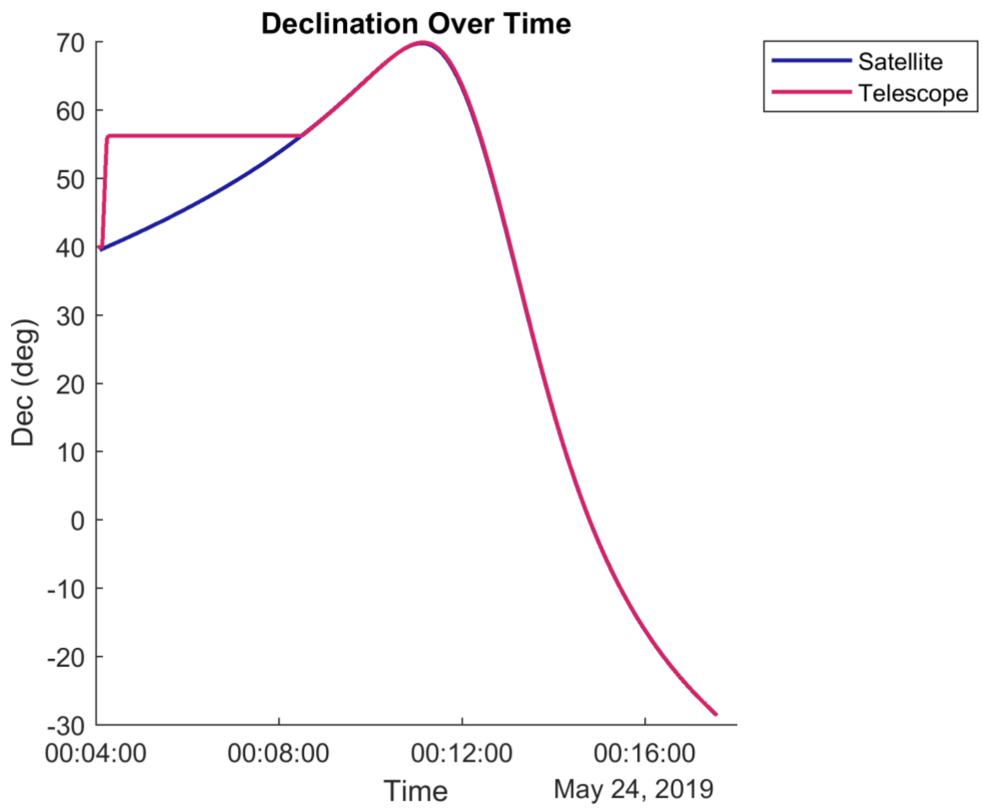


Fig 5. Tracking Performance in Declination

Average pointing error for all passes was about 0.25°. In this pass, the pointing error was 0.14° and reached a maximum as the satellite crossed the meridian and attained its highest angular speed (Fig. 6).

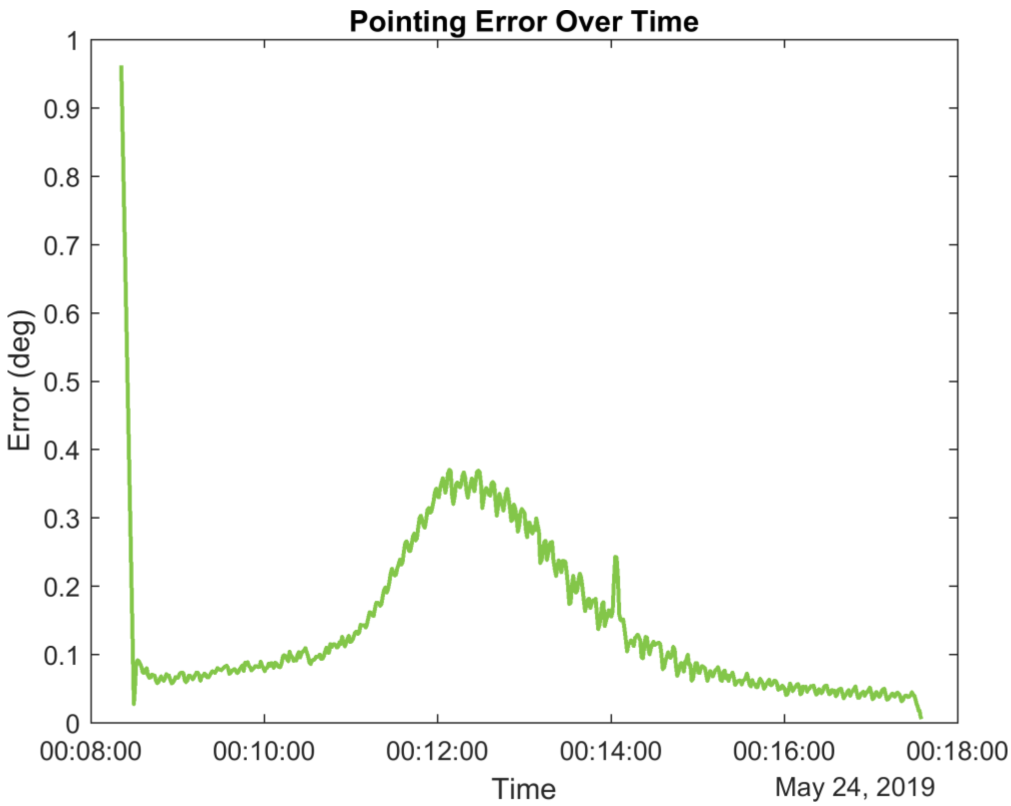
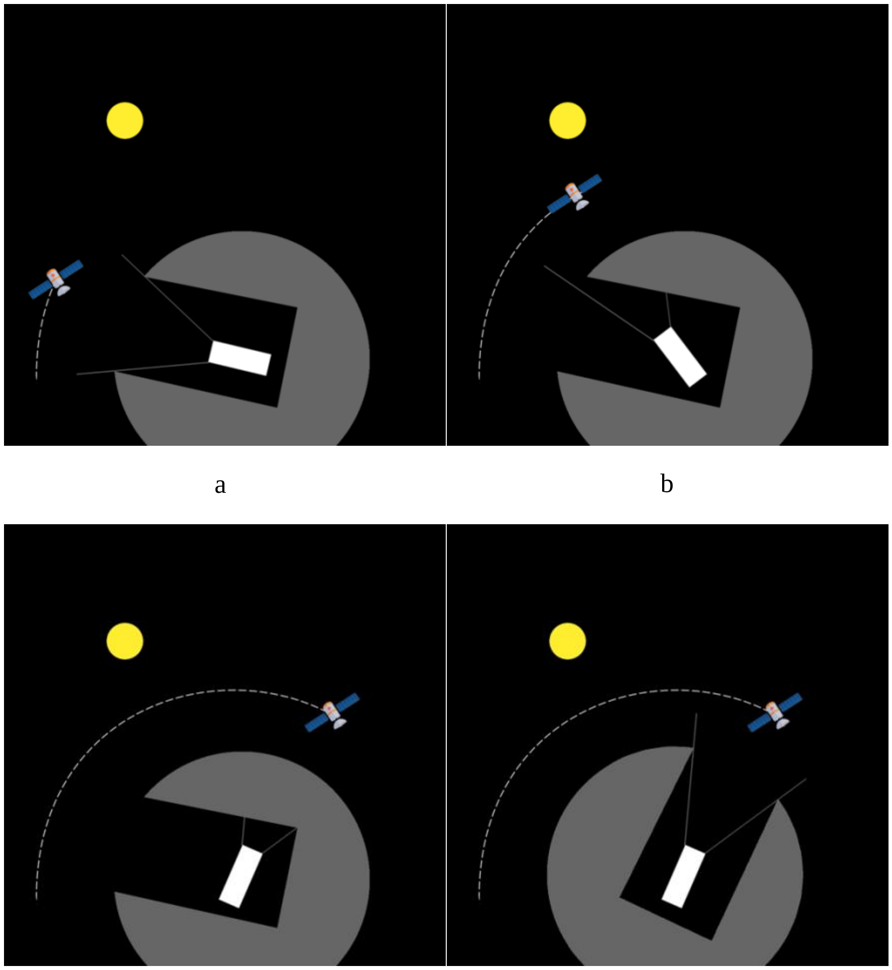


Fig 6. Telescope Pointing Error

A problem unique to daytime observations is sun avoidance. If the sun shines into the telescope, it could be focused on the focal plane and would destroy the camera. The tracking software calculates the sun position at every point in time. If the angular distance from the sun to the telescope is less than 40°, the autodome rotation feature is turned off and the dome stops. The telescope continues to track, but it is shielded from the sun by the dome. When the telescope leaves the sun avoidance region, autodome turns back on, and the dome catches up to where the telescope is. This sequence is illustrated in Figure 7.a-d.



a b

c d

Fig 7. Sun Avoidance Algorithm Sequence

Observations were conducted at the University of Michigan Angell Hall Observatory. The authors used the Takahashi FSQ-85EDX 85 mm aperture f/5.3 telescope and a ZWO ASI1600MM Pro camera. A Sloan r' filter with a central wavelength of 628 nm and a Full Width Half Max (FWHM) of 133 nm reduced background noise, which allowed satellites to be more easily detected with higher SNR [4]. The system FOV was 2.25°x1.70°. Image resolution was 4656x3520 pixels with image sampling of 1.74 arcsec/pixel. Images were captured in FITS format with SharpCap running on a Windows laptop. The control software was run with MATLAB on a second Windows laptop. Typical exposure time was 10 ms with an interval between images of 500 ms. The telescope setup is shown in Fig. 8.

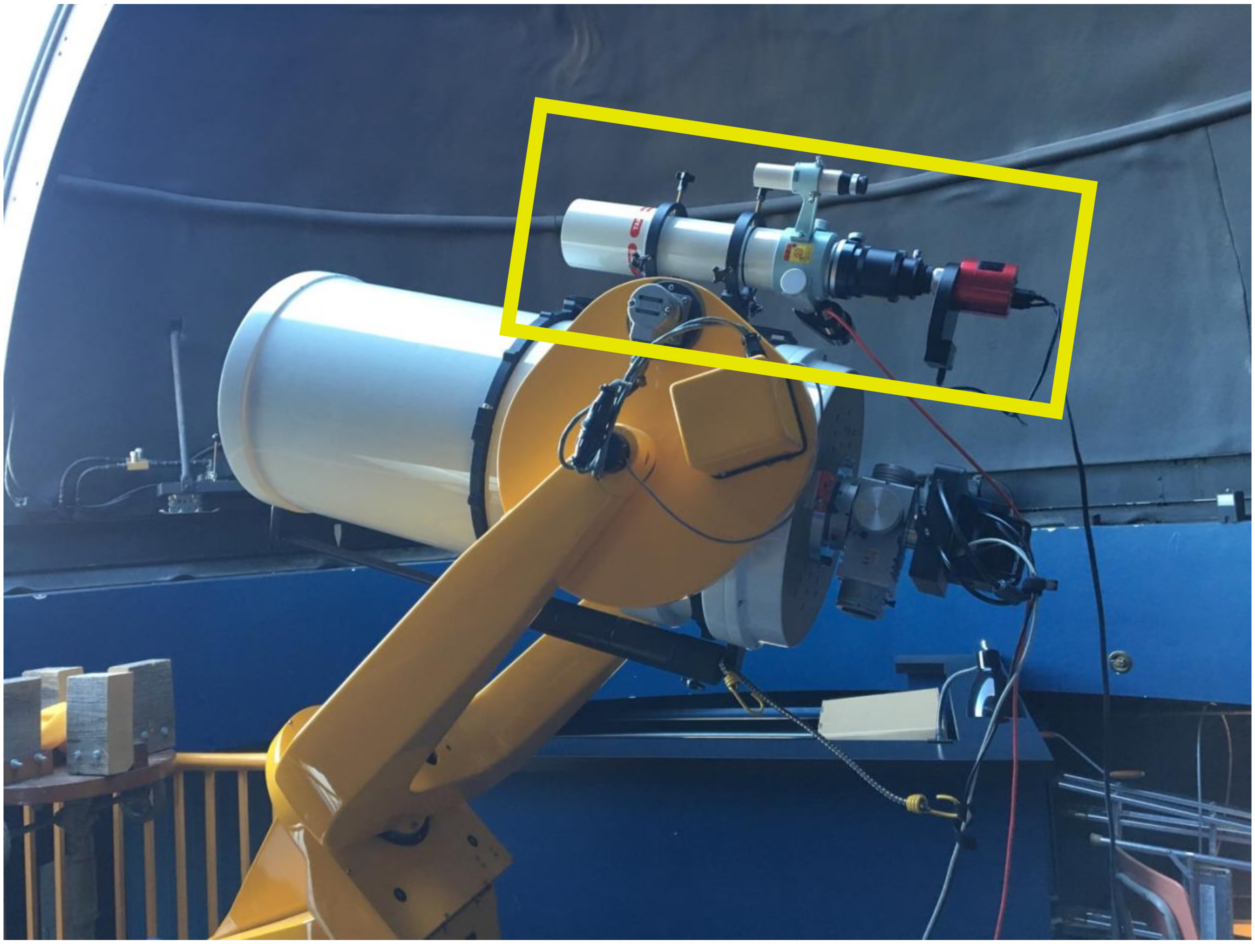


Fig 8. Telescope and Camera Setup for Master's Research Project with the Active System Indicated

3.2 Observations

Over only two observing sessions in May, the authors attempted to observe 8 passes in daylight and were successful for 7 of them. All objects were in LEO and were large with a median Radar Cross Section (RCS) of 6.2 m^2 (Table 2). All observations took place during daylight within 1 hour of sunset.

Name	Catalog #	Pass Start Time (UTC)	Max Visible Range (km)	Sun Elevation (deg)	RCS (m^2)
SL-3 RB	13068	5/15/2019 00:21	570	4.6	5.4
CZ-4B RB	29507	5/23/2019 23:38	1276	14.1	4.4
Genesis I	29252	5/23/2019 23:54	1291	10.8	6.2
SL-16 RB	25407	5/24/2019 00:11	1989	8.1	12.0
ISS	25544	5/24/2019 00:26	1179	5.3	401.8
SL-3 RB	13154	5/24/2019 00:39	1189	2.7	5.8
CZ-2D RB	28738	5/24/2019 00:55	1423	0.5	12.9

Table 2. Observation Summary

The SL-16 RB pass is shown in Fig. 9 as 20 unaligned images stacked together. This is one of the bright passes and is visible just to the right of center.

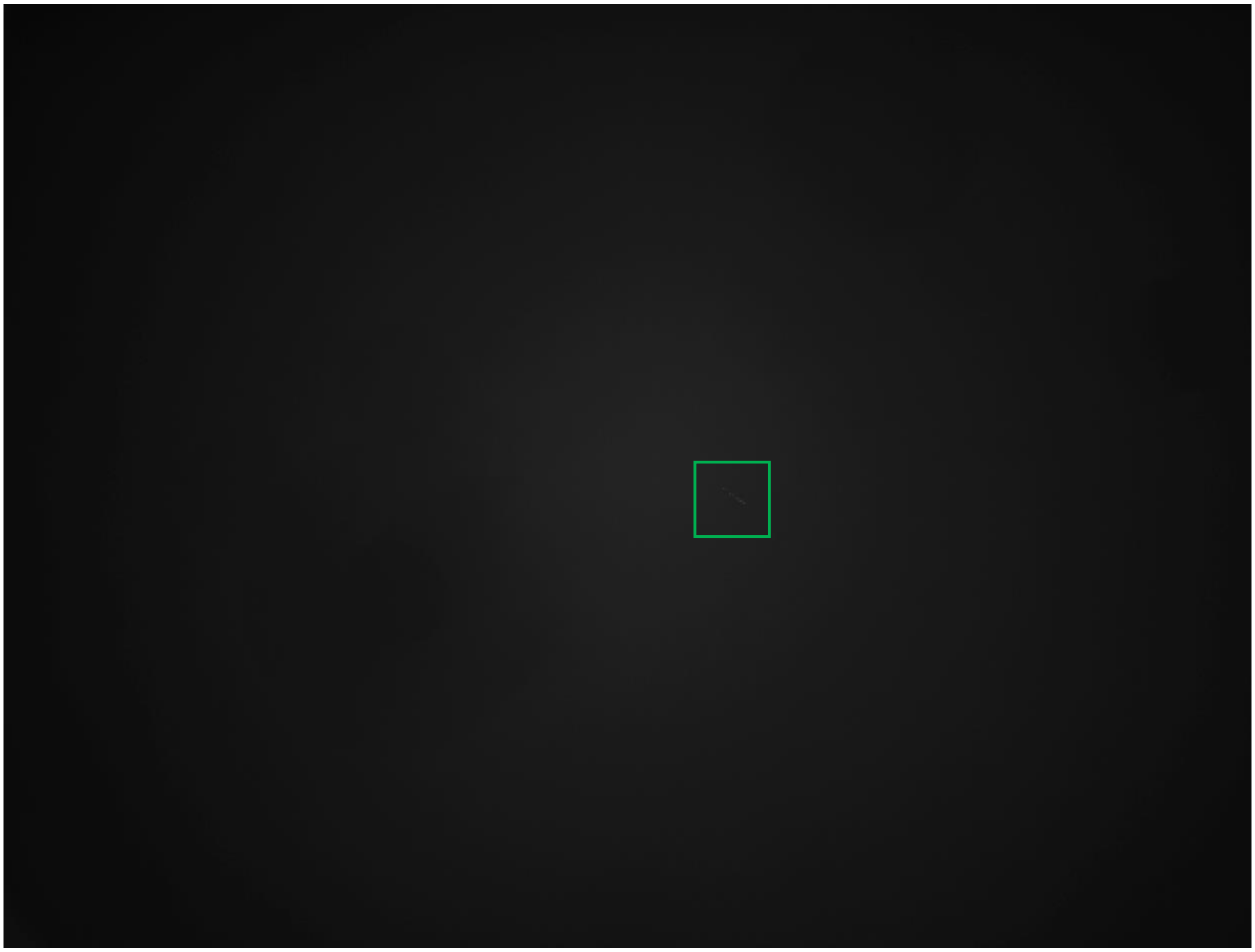


Fig 9. SL-16 RB Pass

A zoomed in view shows the detail (Fig. 10).

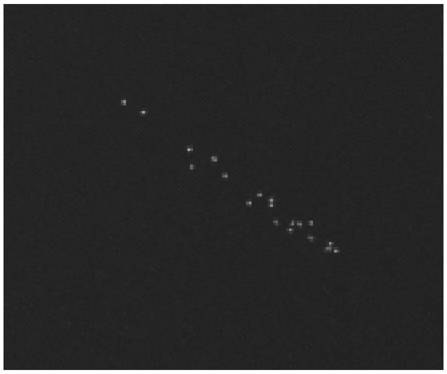


Fig 10. SL-16 RB Pass Detail

Genesis I was a faint pass, but when zoomed in, was still clearly visible (Fig. 11).

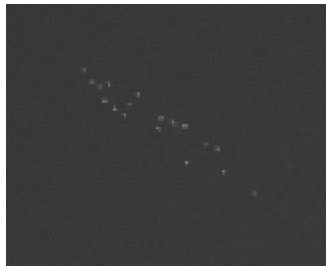
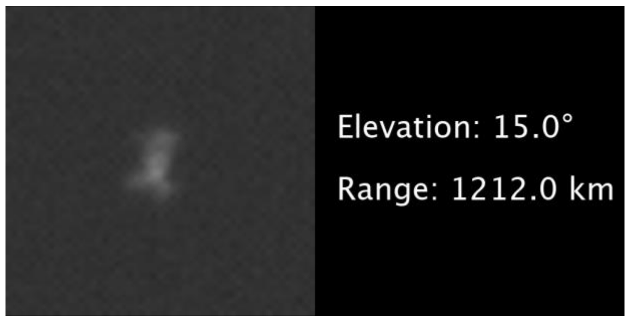
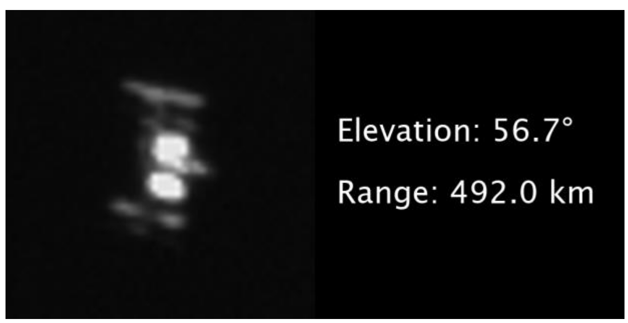


Fig 11. Genesis I Pass Detail

The ISS pass was by far the most detailed pass the authors have captured. It was tracked for about 5 minutes and viewed in real time on the laptop screen. Images from the start of the pass (Fig. 12.a), closest approach (Fig. 12.b), and end of pass (Fig. 12.c) show the change in size, clarity, and orientation over the pass. The FOV was 87x87 arcseconds.



a



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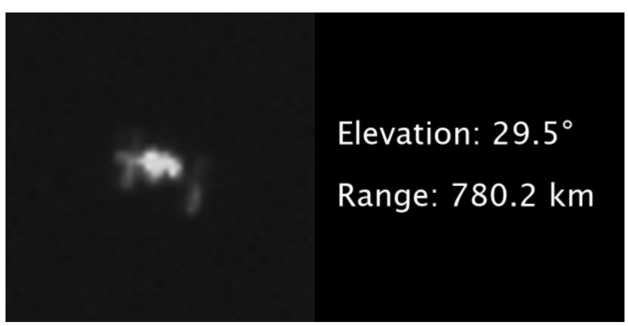

c

Fig 12. ISS Pass Detail

To obtain the most accurate satellite observation angles, stars must be visible to identify exactly where the satellite is on the celestial sphere. During the daytime passes, no stars were visible passing through the FOV. However, passes shortly after sunset did have visible stars. One pass starting 2 minutes after sunset had 1 visible star. A second pass 22 minutes after sunset had 10 visible stars go through. Better filtering or a larger telescope may allow a sufficient number of stars to be seen in daylight for angle determination. The alternative is to utilize accurate telescope position encoders and an accurate clock to record exactly when and where each image was captured.

4. Summary

Observation of satellites in daylight is feasible with low cost telescopes and cameras. The authors hope to expand the observational envelope to include different times of day and smaller objects. Other areas of interest include observations with a larger telescope, quantification of satellite brightness, and a brightness model as a function of range, sun elevation, and other parameters. A major problem still to be solved is astrometry, given the low number of visible stars in the FOV. The authors hope future work will be done that could lead to a worldwide network of low-cost, autonomous, daylight observatories that will enhance SSA capabilities.

5. Acknowledgements

The assistance of Jack Underwood with the Angell Hall observations is gratefully acknowledged. The Takahashi telescope and ZWO CMOS camera were purchased through an award from the MCubed program at the University of Michigan.

6. References

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