# Overcoming the Challenges of Daylight Optical Tracking of LEOs

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**ABSTRACT**

Over the coming decade, the number of satellites in low Earth orbit (LEO) will experience unprecedented growth to a level unimaginable even a few years ago. SpaceX launches hundreds of Starlink satellites per month, and that is just the tip of the iceberg: Over 50,000 low Earth orbit (LEO) satellites are planned to launch in the next 10 years. Our current space domain awareness (SDA) infrastructure is aging and already stressed. While new systems like the Space Fence are coming online soon and commercial radar systems are growing, the number of objects in LEO is increasing far faster than the resources dedicated to monitoring them.

Small optical telescopes, such as those deployed worldwide by commercial firms, have proven to be a cost-effective augmentation to Department of Defense SDA systems for geostationary satellites. Because of observational geometry, LEO satellites are more challenging for optical telescopes. The satellites are only viewable for a few hours each day, just after dusk and just before dawn, and any particular satellite is only above the horizon of a given site for a few minutes per day – if ever – and may only be observable every few weeks. So, while each telescope is itself cost effective, the number of telescopes required to provide adequate twilight coverage of LEO undercuts that advantage.

That problem can be greatly reduced if LEO satellites can be observed during the day. Instead of an eighth of a day of usable time, the value increases to more than half. Moreover, if daylight LEO tracking systems can be produced with largely COTS-based components, then the cost effectiveness remains. We've shown that earthshine provides a natural light source to enable just that.

However, significant technical challenges remain. The most obvious revolve around measuring these objects against a very intense and changing background sky – a strong function of both angle above the horizon and distance from the Sun. Aerosols and cloud particles complicate this further. Daytime convection drives intense optical turbulence, blurring the images received during the day. And particulate matter in the atmosphere above the observing site appear as out-of-focus objects moving with the mean wind, sometimes looking like observing through a snowstorm, thus making for a complicated image processing problem.

Additionally, relatively few stars are bright enough to be visible in the daytime, only a few per square degree, rather than hundreds or thousands at night. That means that astrometric measurements must be made indirectly, relying on the stability of the telescope mount and optomechanical system. COTS-based mounts frequently have RMS-pointing repeatability in the 5-10 arcsecond range. It is unclear whether these values will hold for daytime observations when thermal changes will assuredly affect performance, as will a far different atmospheric refraction environment.

## 1. INTRODUCTION

For most optical telescopes, objects in LEO are only visible within a window of time approximately 90 minutes after sunset and before sunrise, when the observing site is dark, but the satellite is sunlit: so-called "terminator viewing conditions." During the remaining 21 hours per day, either the satellite is not illuminated by the Sun or the Sun is up at the observing site and the sky above it is very bright. This means that currently the only viable way of continuously tracking LEO objects is with large, expensive radar installations costing tens of millions of dollars for commercial systems and billions for Space Fence installations.

Daylight tracking of LEO objects with small, COTS-based optical systems with visible light sensors could change that, adding significant tracking and monitoring capabilities at a small fraction of the cost of other alternatives. This isn't a new idea – astronomers have been observing satellites in the daytime since the 1980s [1] – and realizing it will require substantial R&D effort, but it is an idea whose time has come. Several COTS-based technologies have matured enough in the last few years that they can be used together to enable effective daylight tracking of objects as cubesats.

In our previous work (Zimmer et al. 2020 [2]), we showed that Earthshine can be an effective illumination source for objects in LEO orbits. In visible wavelengths, the majority of that light comes from sunlight scattered off Earth's atmosphere, which makes the Earthshine signal very blue; see Figure 1. Of course, this same scattering mechanism also makes the background sky blue. The challenge then becomes determining where to cut off what light is included

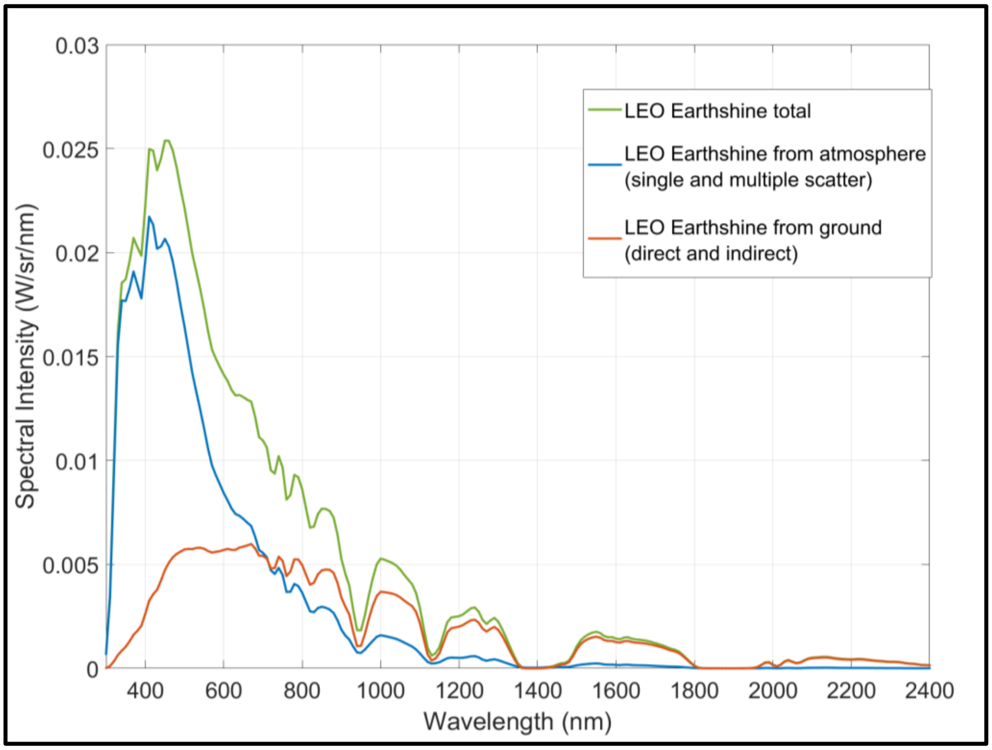


**Figure 1 – The combined earthshine illumination for the 1m diameter LEO object by source component (from Zimmer et al. 2020 [1]). Here we use spectral intensity to quantify the amount of incident earthshine reflected from the object to the observing site. Note that for wavelengths shorter/bluer than 700 nm, scatter from the atmosphere dominates.**

in the measurements, balancing the added signal with the added background noise (see Figure 2), and optimizing with a given optical system. In addition to this, most commercial CMOS sensors appropriate to this task are most sensitive to light in a range from 450 nm to 600 nm. Lastly, the transmission of the atmosphere is dominated by this same Rayleigh scattering mechanism, reducing the downwelling radiation from the object more in blue wavelengths. The combination of these effects is shown in Figure 3, where the signal-to-noise ratio (SNR) is shown versus the blue cutoff wavelength of the system. Even as more sky background was included, that background enters the SNR as the square root and the overall SNR increases because the signal is increasing as well. The primary challenge becomes handling that excess background.

Much of the prior work of observing satellites in the daytime has focused on using shortwave- (SWIR) and mid-infrared (MWIR) wavelengths [3-5]. The daytime sky is considerably darker in these regimes, but detectors and optics are much more expensive. Even commercial SWIR cameras cost more than 10 times that of similar sized optical sensors, and large sensors are non-existent. The market for SWIR and MWIR hardware is tiny in comparison to that of optical sensors. And large sensors are required to overcome the uncertainties in TLE predictive accuracy. For geostationary objects, though, this isn't an issue – the TLE errors are very small compared to the distance to the target.

Moreover, the illumination from earthshine is very small at GEO because of the two-way propagation, so it is not expected that optical observations will contribute significantly for this orbital regime in the daytime.

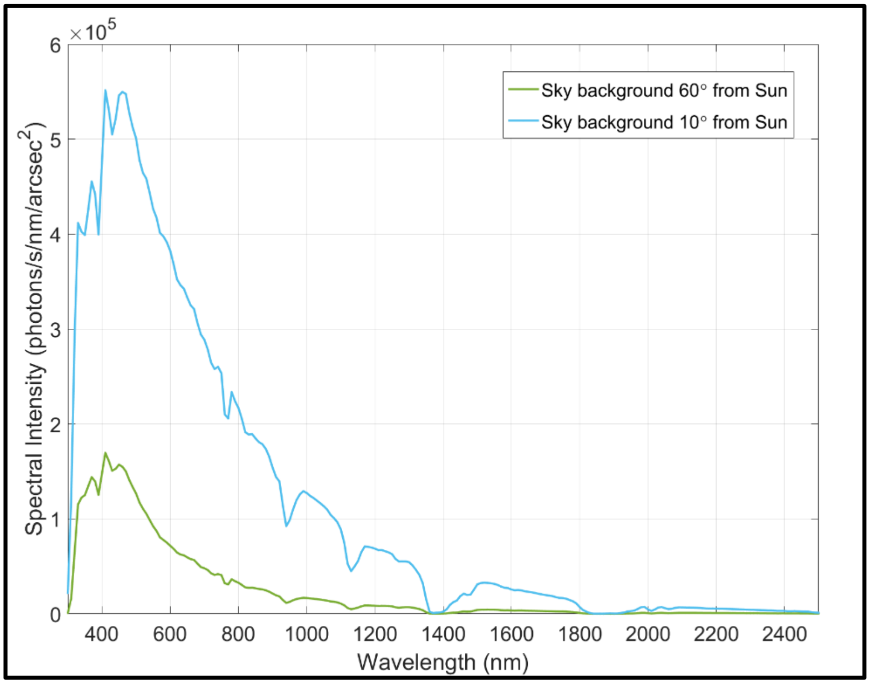


**Figure 2 – Sky background modeled for 400km LEO object as received by a 14″ telescope when the Sun is near the meridian. The brightness for different angular separation from the Sun is shown with the green and blue lines. Even closer to the horizon, the sky brightens again and flattens spectrally due to aerosols.**

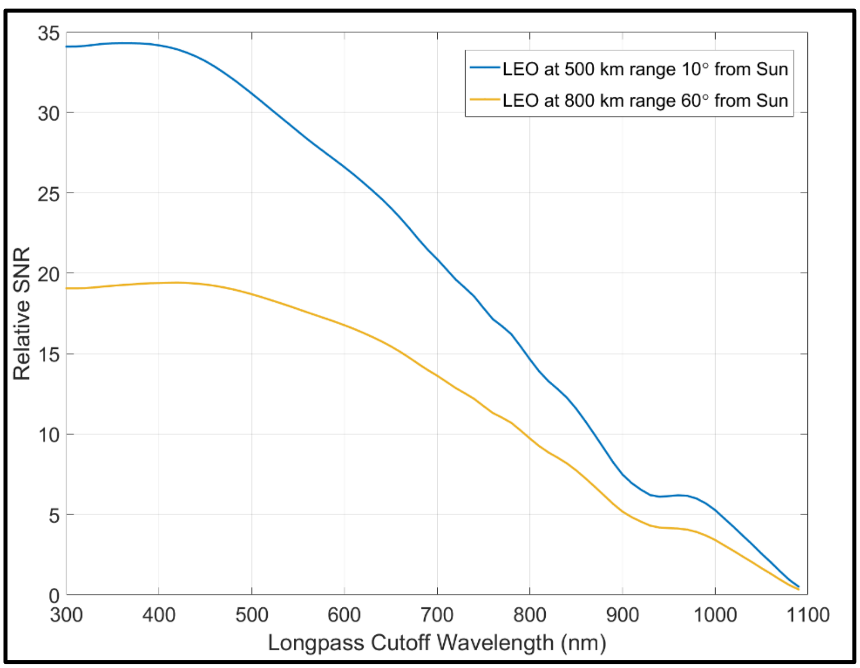


**Figure 3 – Daytime SNR ratio for a 1m diameter LEO object at 400km altitude is shown for two observing geometries as a function of included bandpass. In each case, it is beneficial to include blue light.**

Our early work identified some areas where we expected daylight observations of LEOs to be challenging beyond the task of detecting and measuring them against a very bright background. Other factors in observing during the day included scattered sunlight reflecting off the telescope structure and within the optics; the lack of astrometric reference stars co-observed with the LEO object means that the telescope and mount must be very stable throughout the day and night, even when exposed to the heating from direct sunlight; and the effects of daytime turbulence on the delivered image quality.

## 2. CONSIDERATIONS FOR DAYLIGHT OPTICAL SYSTEMS

To further test and verify our daytime system model, and to demonstrate the potential of visible band imaging of LEOs in the daytime, we've constructed a prototype daylight optical system. We follow the optimization strategy we outlined in our earlier work [2]. Increased observing efficiency can be attained by opening the observing wavelength band further to blue wavelengths, so long as the consequent increase in the sky background doesn't overwhelm the detector. The sky background surface brightness can be spread over the detector to a greater or lesser degree by changing the focal length of the optical system. The field scale delivered to the detector scales as inverse of the focal length – a longer focal length spreads the imaged sky background over more pixels. The downside of this is that a longer focal length system will have a smaller field of view for a given sensor, so it can easily be the case that in mitigating the sky background, the FOV becomes too small to be useful. Position errors greater than 1 km are common with TLE-derived positions, which at 500 km range is almost 7 arcminutes. An optical system with a focal length that makes the chosen sensor subtend less than this will frequently miss the intended target.

The second balancing effort involves the rate at which the detector can be read without significant, or better yet any, time between frames. There are two major limiting mechanisms to how fast modern CMOS sensors can be read. The first bottle neck is within the sensor package itself. These sensors readout is highly parallel and sensor specific – attention to the sensor spec sheet is critical to managing this – but a rough approximation scales with the number of sensor lines read. Lower digitization bit depths are also possible on some sensors, which can increase the readout rates as well. Contrast this to subframe readout on CCDs, which typically scales like the area of pixels being read.

In addition to the sensor package read rate, the other major bottleneck is the communication bus from the camera to the controlling PC. In the case of USB3 communication, the theoretical bandwidth is 5 Gbps and a real-world value of 3 Gbps is more likely. This caps the read rate to 200 million 16-bit values or 400 million 8-bit values per second. Note that the pixel bit depth measured by the sensor package may not be the same as that transferred to the computing system. Larger bit depths can be truncated, and smaller ones padded to match align with 8-, 16-, or 24-bit values transferred over the USB3 (or other) bus.

Full well depth vs. pixel size is another part of the trade space, though there is only a limited amount of freedom. While there is some variation is charge capacity of CMOS pixels, for the most part it scales with the area of the pixel with some variation between pixel technology lines and newer sensors having generally better well depth per square micron. The downside of smaller pixels though is that for a given physical area, there are more of them to read, which increases the data rate.

## 3. THE PROTOTYPE SYSTEM

Our prototype original design was based around a 14" COTS optical system. However, the pandemic stressed the supply chains of many telescope and camera vendors, so the system we assembled is not quite what we expected a year ago. Still, the system performance exceeded our goals.

The prototype as deployed uses a 12.5" f/7 Planewave CDK telescope. The optical system uses a closed carbon fiber tube that minimizes both thermal expansion and scattered light, when compared to an open tube. A single filter changing slide is mounted immediately after the focus stage on the aft of the telescope tube: Positioning it as far away as practically possible from the sensor reduces the scattered light that reflects off the sensor, propagating back into the optical system and reflecting back again to the sensor from the back side of the filter. A motorized filter changer will eventually be incorporated, but in its initial assembly was found to be creating large, temperature dependent flexures, which significantly changed the pointing model in the daytime. We have a selection of long pass filters with cutoff wavelengths of 500, 550, 570, 685, and 725 nm. Pictures of the system as deployed are shown in Figures 4, 5, and 6. A 45-degree fold mirror shortens the overall system length and then passes the light to an optional Barlow optic, selectable from 2x to 4x focal length expansion, and then to the camera.

**Figure 4 (above) – The image above shows the prototype daylight system with its sunshield removed.**

**Figure 5 (right) – A view of the backend of the prototype system shows the filter slide, Barlow optics, and camera.**

**Figure 6 (below) – Prototype system is shown with sunshield in place.**


The camera currently in use is a ZWO ASI-183M Pro. This camera uses a Sony IMX183 backside-illuminated sensor with a 5496 x 3672 array of 2.4 µm pixels. The peak quantum efficiency is 84% at 525 nm and exceeds 70% from 450 nm to 625 nm. For daylight applications, the camera read noise is irrelevant compared to the noise from the sky background, so we run it at the lowest gain setting to maximize the well depth, which is 15000 $e^-$. The read rate of the sensor varies with the size of the frame that is read out and the bit depth of the pixels. We settled on a nominal operating mode using a subframe of 3672 x 3672 (13.4 Mpix) pixels at 8-bit digitization depth, which yields a consistent frame rate of 24 fps over the USB3 interface.

Even with the lower 8-bit pixel depth, the prototype generates a substantial data volume: 320 MB/s. Our initial analysis indicates that simple 8- or 16-deep frame stacking immediately upon readout will likely be sufficient to preserve the signal-to-noise, but we are also developing more intelligent stacking routines to assure this. For longer durations, careful coaddition is necessary due to field rotation induced by the alt-az mounting.

## 4. CALIBRATION MEASUREMENTS

We observed stars in the daytime for both astrometric and photometric reference using the 570nm long pass filter and no Barlow optics. This allowed us to use a 40 ms exposure time for most our observations, though in places close to the Sun and when thin cirrus or smoke was present, we had to lower this to 25 ms to avoid saturation. An example is shown in Figure 7. The star shown there is 18-Cam which has a GAIA DR3 catalog magnitude in the Rp band of 5.85.

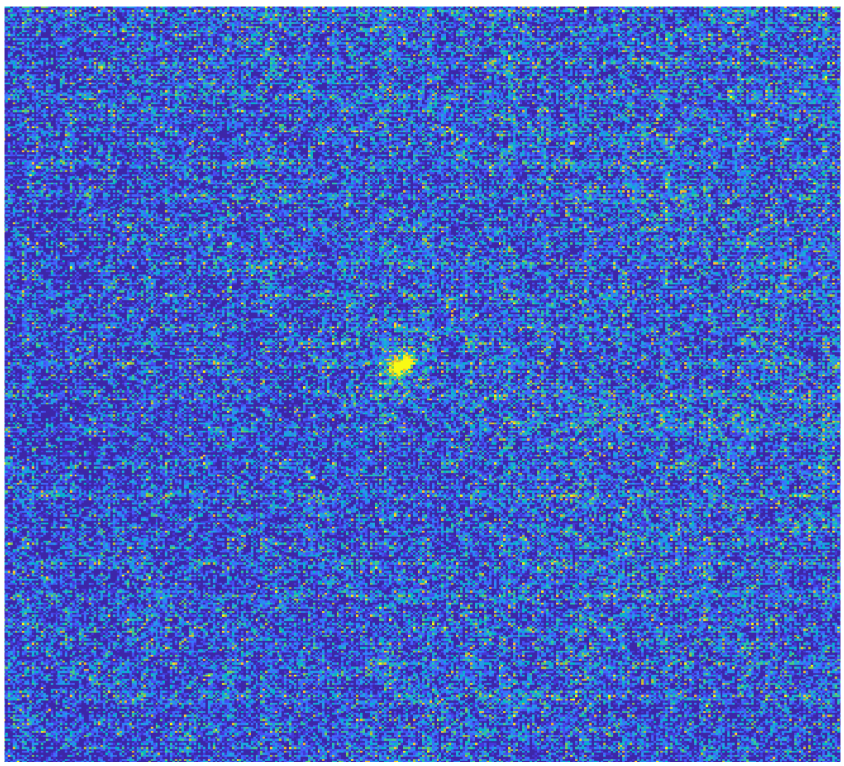

**Figure 7 -- The prototype easily detects stars down to GAIA Rp=6.5. This 10-frame co-added exposure of the star 18-Cam shows that at Rp=5.85, we achieve a SNR > 20 in 0.4 seconds total exposure.**

It is measured with SNR of 20.5 in a 10-frame stack with total exposure time of 400 ms and an average sky brightness of 3.58 magnitudes per square arcsecond. We used an ad hoc set of star observations to establish a rough flux calibration for our prototype, with GAIA Rp magnitudes in a range of 3 to 6.5. The 6σ limiting magnitude under these sky conditions was Rp = 7 for 400 ms total exposure time.

The most intense sky surface brightness that we successfully operated under was 2.67 magnitudes per square arcsecond, roughly 12 degrees from the Sun. Under those conditions, the 6σ limiting magnitude reduces to 6.5 for 400 ms of exposure time.

At present, the astrometric performance of the prototype is limited by thermal changes in the optomechanical system. We identified one major source, the filter wheel, and removed it. Still, we see 10-20 arcsecond drifts between daytime and nighttime pointing. The most recent tests lead us to believe it is in the optomechanics aft of the focuser stage. We are working to reinforce these and replace them with athermalized mechanical mounts.

## 5. FIRST LIGHT DATA

Our first test observations were of a Chinese communication satellite, RSW-02, launched on August 24, 2021 and believed to be an initial test payload for an upcoming large constellation. RSW-02 was detected with SNR in excess of 12 in each 40-ms frame with an estimated magnitude of 5.2. At the time of observation, RSW-02 was at a range between 1150 and 1180 km and between 59 and 55 degrees from the Sun. A sample image is shown in Figure 8.

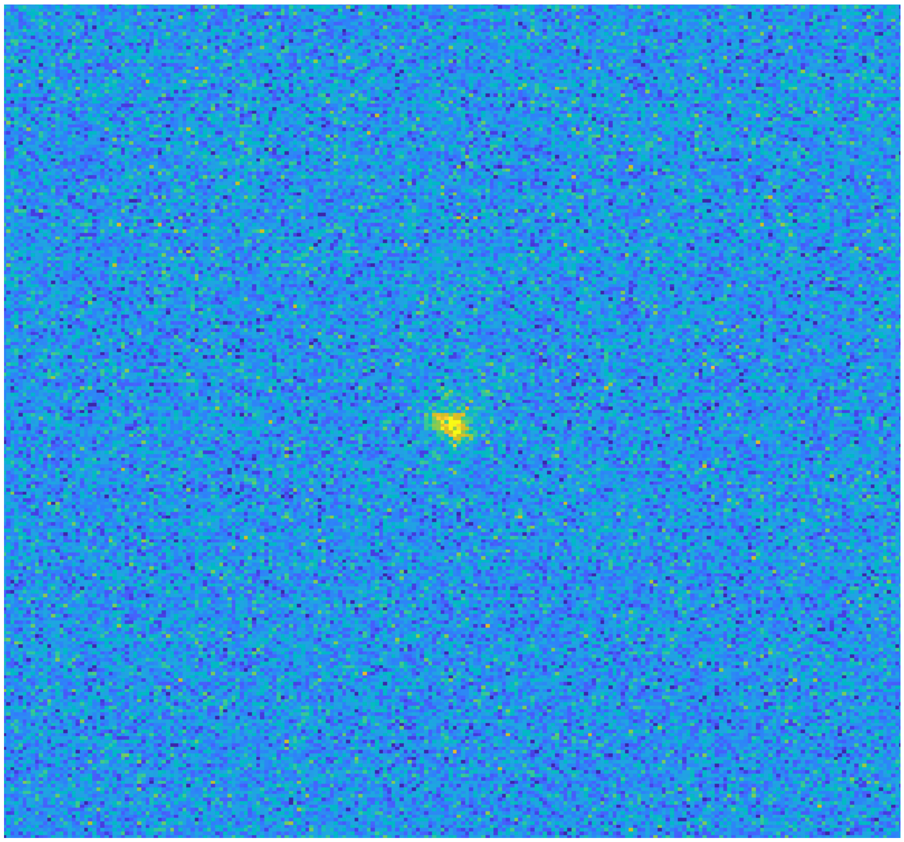

**Figure 8 – A sample daytime image of RSW-02, a recently launched LEO communications satellite.**

Over the course of the first few days of operation, we were able to obtain observations of a few dozen other LEO objects. Noteworthy examples are AJISAI, shown in Figure 9. AJISAI is a laser-ranging satellite covered with mirrors. Our observations of it showed it flickering and glinting, occasionally brighter than second magnitude. This pass brought AJISAI to within 18 degrees of the Sun.

Our other noteworthy examples are observations of Starlink constellation members. Our measurements of these objects far exceeded our expectations: They are bright in the daytime too! Figures 10 and 11 show sample observations. The measured brightness of the Starlink satellites varied most often between magnitude 3.5 and 4, but some were as bright as magnitude 2.6. We don't have enough information yet to ascertain exactly why they are so bright, but they are in considerably lower altitude orbits than the other objects we observed. Their shape and orientation are well enough known and there are so many available to observe at any given time that we hope in the future we will be able to model and predict their daylight optical signature in detail.

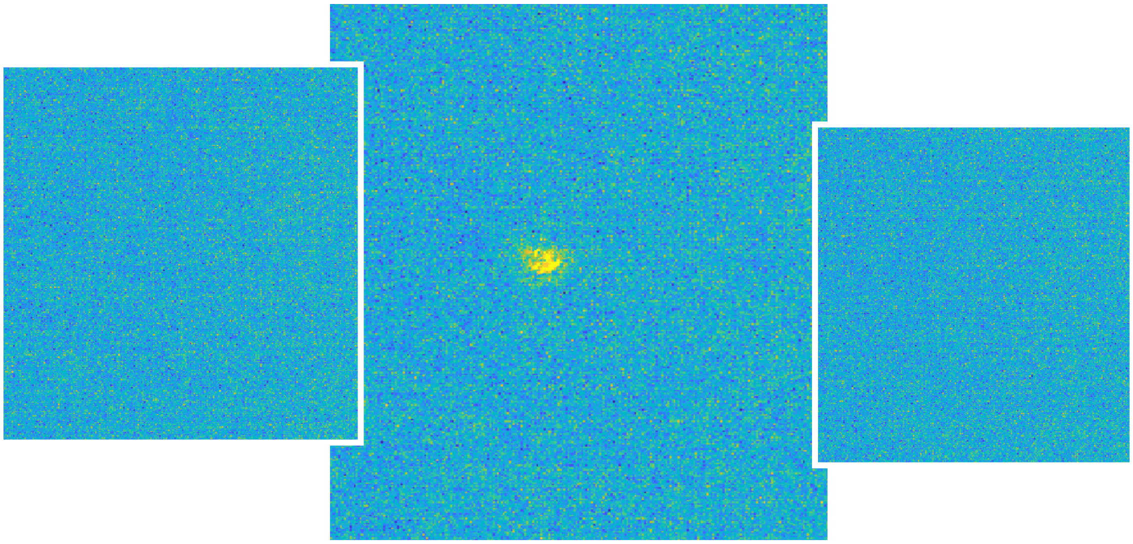

**Figure 9 – These three images are adjacent 40 ms exposures taken of the AJISAI laser ranging satellite. In the middle frame, it is glinting at magnitude 2.9 and is not detectable in the adjacent frames. The sky noise limit in those frames puts an upper limit on AJISAI's brightness there at magnitude 6.4.**

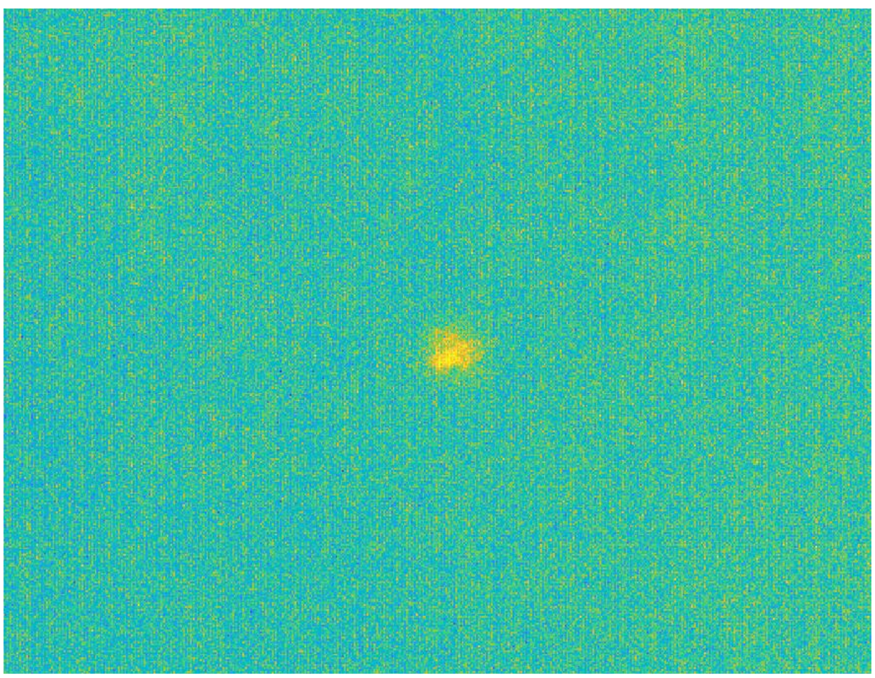

**Figure 10 -- Starlink-1008 with apparent mag. 3.8 detected at 30σ in a single 26 ms exposure with the 570 long-pass filter, at 10:40am local, 80º from the Sun, and background 3.5 mag/"2.**

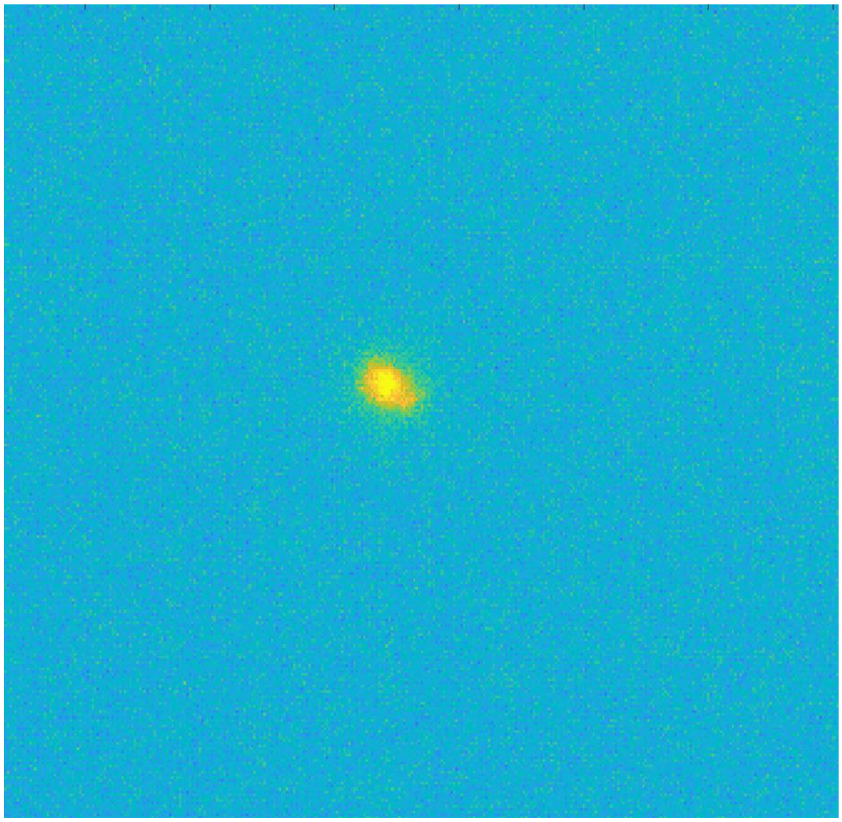

**Figure 11 – Starlink-1642 imaged near zenith, 50° from the Sun. We detect it at 60σ with apparent magnitude 2.6 on a sky background of 2.9 mag/”2. They are bright in the daytime too.**

## 6. ONGOING WORK

We are now equipped with a daylight observing model and a prototype daylight observing system that can help verify that model. The first light data from this system is very encouraging. Our near-term goal of measuring Starlink satellites was readily achieved. We’ll continue to improve the optomechanical performance of this system so that detections can become operational SDA data.

We will focus significant effort on the automation of the system so that the data acquisition and analysis process is less user intensive, and the calibration observations need to be incorporated seamlessly with the mount model to provide accurate astrometric data.

The long-term goal of measuring cubesats is within reach, but will require R&D on the image processing and analysis. These initial observations show that visible band daylight observations of LEO satellites are a viable and affordable method for providing SDA data.

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