Optimizing Daylight Performance of Small Visible-NIR Optical Systems

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ABSTRACT

Low Earth orbit (LEO) is getting busy. As more and more satellites are launched, the demand for more and better data will grow. We've previously demonstrated how small optical systems can find, measure, and monitor LEO objects, even very small and faint ones. But the limitations of terminator viewing mean that maintaining custody of these objects with only these observations is not practical.

Other work presented at this conference in the last few years has shown the potential for daylight measurements of satellites. Much of that work has focused on short-wave infrared (SWIR) band methods. The far lower sky brightness in the SWIR regime has considerable benefits. However, the fundamental light source, the Sun, puts out dramatically more energy in the visible regime, and thus the advantages of SWIR are not unequivocal. And while SWIR systems can be made cost effective, visible and near-infrared telescopes and detectors are commercial products, benefiting from the full effects of production scale and availability.

We've presented extensively in the past on how to optimize twilight and nighttime SSA detection systems, but daylight operations pose a significantly different set of challenges. We start from a radiative transfer model (MODTRAN) of the daylight observing for LEO objects. We derive models for the signal and background levels that can be expected over a range of observing conditions. This becomes the basis of modeling throughput and detectivity as a function of different system configurations, and we make recommendations for various combinations of aperture size, focal length, pixel scale, exposure time, etc. We then compare this model to observational data obtained with a proof-of-concept system.

But detecting LEO objects in the daytime is only useful if those measurements can be calibrated to known astrometric reference stars. We discuss the challenges of doing so for a daylight system where the solar thermal load can appreciably change opto-mechanical alignment and make some recommendations for minimizing these effects.

1. INTRODUCTION

Space domain awareness (SDA), née space situational awareness (SSA), requires robust, persistent, and methodologically diverse data sources. All potential tools must be evaluated and those that prove effective must be exploited to the extent that they are practical, given the many conflicting constraints placed by budgets, geopolitics, and the environment. The products of these data sources – radar, optical telescopes both ground- and space-based, passive RF sensors, etc. – can then be fused into the clearest possible picture of the status of the space domain.

Nighttime optical observations of LEO objects are limited to terminator illumination conditions, where the satellite is directly illuminated by the Sun and the observing site is dark. This constrains observing windows to roughly 3 hours per day, and many objects are simply not observable from certain sites. Daylight observing opens up far more opportunities.

Daylight optical sensors face many challenges and must clear several hurdles to be proven effective. But these systems may well provide an additional new data source that leverages the illumination of near-Earth space by sunlight reflected off the Earth itself, called earthshine [1,2]. Daylight observations share some of the constraints that nighttime observations do, like weather – some places have statistically more time with clear sky – and geography – certain objects are unobservable from some locations both day and night. Other constraints work in favor of daylight observations, such as the effects of light pollution, which can drastically reduce the effectiveness of nighttime observations but is irrelevant in the day. This makes daylight observing sites near cities more viable than for nighttime systems and can make finding viable daylight observatory sites less of a challenge. But daytime atmospheric turbulence is dramatically stronger for just about any site one would reasonably consider. Most of the other constraints are more complex in their interplay.

To understand how all these factors combine to make optical daylight observations feasible for SDA/SSA applications, we first have to understand the underlying physics and geometry involved. These are complex for nighttime observing systems. Daylight observing adds several more parameters and lots of not terribly well-known variables. Take observing from Haleakala, a fine site for nighttime observing, but more complicated in the day: if clouds are above the observatory, that's bad; clouds below the observing site are good, because they have a high albedo increasing local earthshine; but no clouds at all, a good situation for nighttime, is less beneficial for daylight observing, because Haleakala is surrounded by ocean and open sea has a much lower reflectivity than clouds.

Where the target object is also matters. Earthshine can be very bright for objects in low Earth orbit (LEO) making them appear nearly as bright as during twilight observations. Objects in and near geostationary orbit (GEO) are not as well lit by earthshine, appearing hundreds of times fainter than their peak brightness at night because GEO objects are so much farther from the Earth that earthshine is weaker. For this reason, the work reported here focuses on daylight observations of LEO objects.

2. BACKGROUND INFORMATION

Observing stars and planets in the daytime has a long history, much of it incorrect – traceable as far back as Aristotle casually asserting that stars can be seen from the bottom of a well [3] – though others have correctly pointed out that stars and planets can be seen during the day with proper optics [4], but as more of a curiosity than used in practice. For SSA/SDA applications, the history is less sordid but still goes back decades.

In the 1980s, a group at Lincoln Labs site at White Sands tracked LEO and MEO objects with a 31″ telescope [5], pictured in Figure 1, with a vidicon sensor. They measured 18 satellites down to an impressive limiting magnitude of 8.3. They were also the first to report something they termed "angels," which they attributed to seeds and bugs, a familiar sight to those who have made similar measurements since.

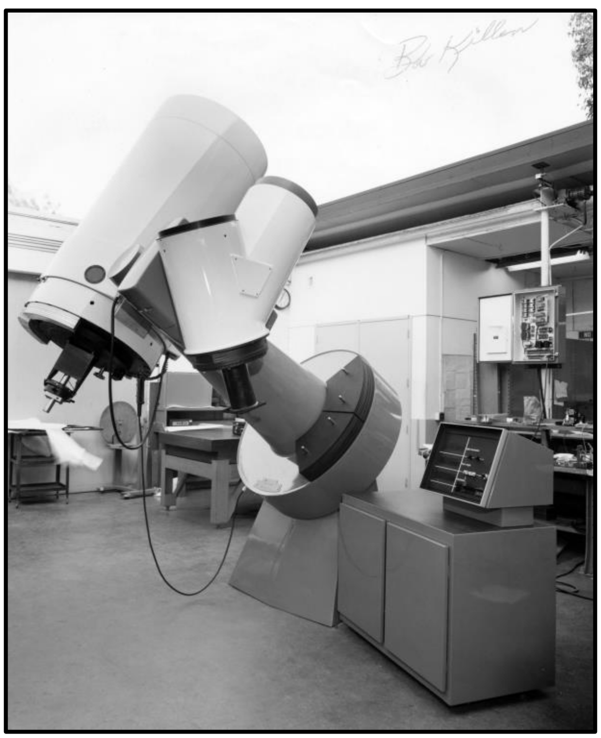

Figure 1 – The 31" telescope at White Sands used to test daylight observing in the 80s. This photo is from the Boller and Chivens archives.

Throughout the 2000s, there was an extensive effort on Maui by OceanIT using Raven-class and larger Air Force telescopes, observing in short wave infrared bands (SWIR) [6,7]. In recent years, there has been work reported by both AFRL and the University of Michigan [8] using small telescopes and CMOS cameras, focusing on R and I bands. Last year, Numerica [9] reported on a 16″ SWIR system they currently operate to detect GEOs in daylight. There are assuredly other efforts that have not been reported on in public spaces.

This is not intended to be a definitive history of daylight SDA efforts, but rather to show that interest has waxed and waned. And much like nighttime SDA systems, there are numerous outside factors that can influence how practical and cost effective these data sources can be. The proliferation of commercial off-the-shelf (COTS) telescopes, mounts and cameras, ostensibly targeted to the inexplicably well-resourced high-end amateur astronomy market, has allowed for an explosion of systems routinely performing SDA observations around the world in the last few years. It is not unreasonable to consider that the same could be true for daylight optical systems. The goal here is to try to identify the missing components and innovate new cost-effective solutions that add a heretofore untapped SDA data source.

There are some developments in recent years that can enable new capability. Foremost is the commercial availability of fast sCMOS sensors with high quantum efficiency (QE) and low read noise. At first glance, these features might not seem relevant to daylight observation. The combination of fast readout and low read noise means that one can obtain images rapidly without any readout deadtime. This is critical both night and day, because anytime a sensor isn't collecting light is a direct loss of system throughput. Speed is required so that the sensor does not saturate due to the intense daylight sky background. The noise from that background will likely dominate other noise sources from the detector, but unlike older CCD systems, the read noise of these newer sCMOS sensors does not increase with readout rate. High QE is also beneficial – the best way to improve signal-to-noise ratio (SNR) is to collect signal.

Fast readout of these sensors means lots of pixel data – many tens of GB per minute. Processing this volume of data to extract faint point sources from the imagery quickly is a teraflop-scale problem. Luckily, GPU technology just keeps getting more powerful, so "adding" hundreds of images per second on-site in real time is feasible.

Finally, the new generation of direct drive telescope mounts offers greatly improved stability and speed at a cost similar to classic gear drive mounts. Because there are only a very few stars measurable in daylight, the astrometric reductions frequently used for nighttime SDA observations cannot be applied. There simply are not enough measurable catalog stars to calibrate on the fly. Instead, the mechanical stability of the mount and telescope must be relied upon to bridge a nighttime pointing solution through the day. This is, of course, how measurements were made in the era before massive space-based astrometric catalogs and fancy starfield fitting software. We must go old school.

3. EARTHSHINE

The light that the Earth scatters and emits has been studied extensively both by atmospheric scientists, who are interested in the energy balance of the Earth, and astronomers seeking the observational signature of life bearing exoplanets. The most robust current measurements that can gather the spectral radiance data for the full disk of the Earth have been obtained from spacecraft. The current best values come from the EPOXI [10] mission, and a sample spectral radiance distribution is shown in Figure 2. One can see right away from these data that the spectrum of Earthshine is very blue. This makes sense because the spectrum of sunlight illuminating the Earth is also blue.

The details of the radiative transfer of earthshine are legion – too many to enumerate here. To guide our understanding of the problem, we turned to MODTRAN [11], which can capture many of the most important factors and has been thoroughly vetted over many decades. MODTRAN allows us to model all of the physical effects relevant to daylight LEO observations: scattering of light from the atmosphere and surface of the Earth to the satellite; the transmission losses from the satellite to the observing site; and the brightness of the sky looking from the site towards the object.

We use some simplifying assumptions: 1) the satellite is a 1m diameter Lambertian sphere with constant 18.5% reflectivity. 2) The surface of the Earth is a Lambertian scattering surface with albedo determined from NASA MODIS data products – open ocean albedo was taken to be 6% and assumed no clouds.

MODTRAN naturally provides a further breakdown in its reported spectral radiances that helps guide understanding of the relevant effects. The earthshine radiance illuminating the satellite is broken into four parts: direct ground scatter (which is sunlight that hits the surface of the Earth first and then scatters to the satellite); indirect ground scatter (light

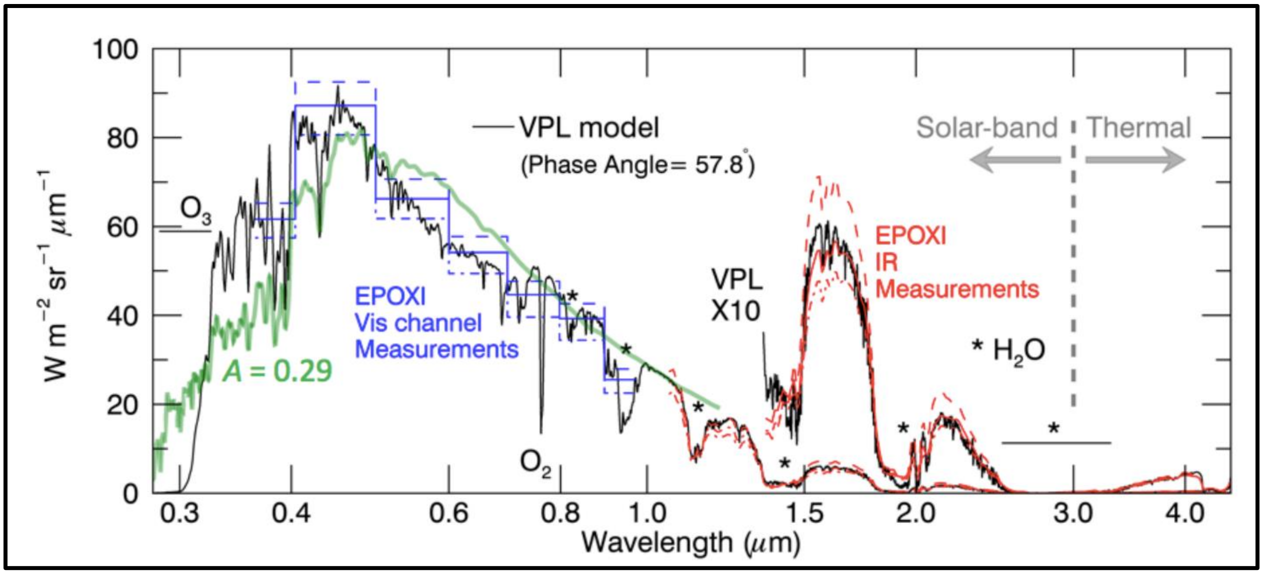

Figure 2 – These plots show earthshine measurements from the EPOXI mission [11] in blue, for the visible/NIR bands, and red for the SWIR spectrometer. Note that the upper traces from 1.4-2.5 um is scaled by 10x. For this case, the Sun-Earth-EPOXI phase angle was 57.8 degrees and these are a full-disk average.

that first has scattered off the atmosphere and then off the ground to the satellite); single scattering from the atmosphere to the satellite; and multiple scattering in the atmosphere and then to the satellite. Ground scattering dominates the earthshine in wavelengths longer than approximately 700 nm and the ground albedo variations matter more there; whereas in bluer light, the signature is predominantly that of Rayleigh scattering.

We model the Earth with a 0.1 x 0.1-degree facet grid in latitude and longitude. MODTRAN models are evaluated on a coarser grid, tailored to sample the changing illumination geometry, that is then interpolated onto the finer grid. Thus each facet that is both illuminated by the Sun and visible from the satellite gets a modeled spectral radiance. That radiance is then used to calculate the amount of earthshine from that facet that then scatters to the observer using a standard Lambertian sphere scattering functions, where the phase angle is set by the facet-satellite-observer angle. That light is then modified by the path through the atmosphere from satellite to observer, accounting for the range and

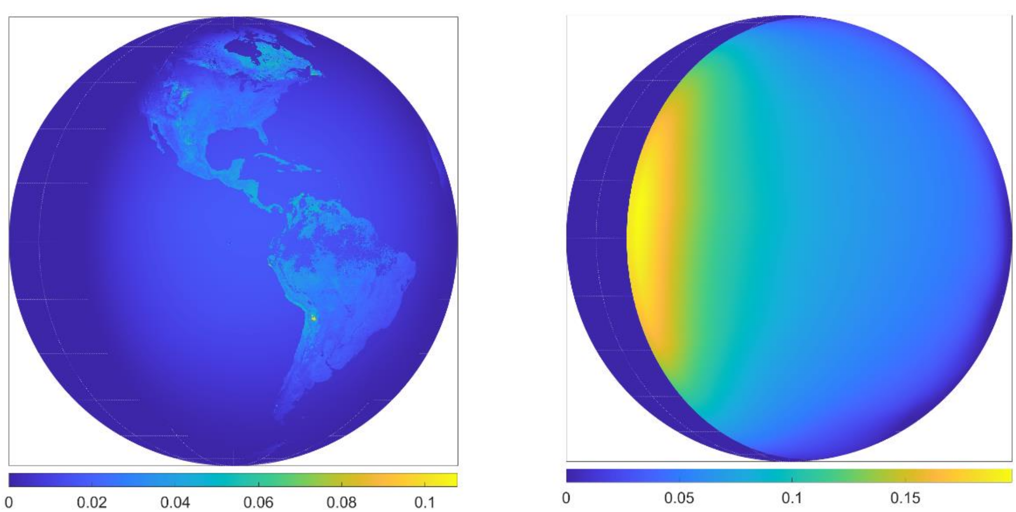

Figure 3 – Model earthshine radiance at 500nm is shown for ground reflected (left) and atmosphere reflected (right) , in W/m^2/sr/nm approximating the conditions for the EPOXI data shown in Figure 2. Averaged over the disk, the radiance is 92 W/m^2/sr/µm, which agrees with the upper bound of the errors on the EPOXI data and acceptable agreement given the approximations we used. This is very similar to the radiance pattern for a GEO satellite.

the atmospheric transmission. This model was able to replicate within expected errors the results from EPOXI above for the observation geometry, and those results are shown in Figure 3.

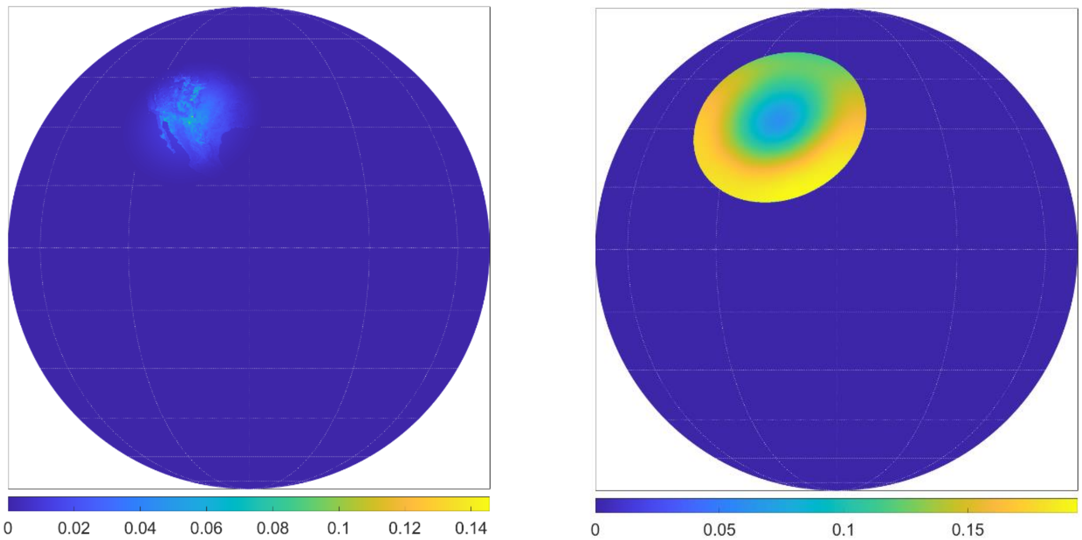

Figure 4 – Model earthshine radiance at 500nm is shown for a LEO satellite at 400km altitude in ground reflected (left) and atmosphere reflected (right) components, in W/m^2/sr/nm.

The earthshine model for a 400km altitude LEO object over northern New Mexico is shown in Figure 4. In this case it is easy to see what parts of the surface and atmosphere illuminate the object. The Sun in both this case and the case in Figure 3 is almost directly over the center point of the projection. The ground-reflected component is brightest below and towards Sun, as expected for a Lambertian sphere.

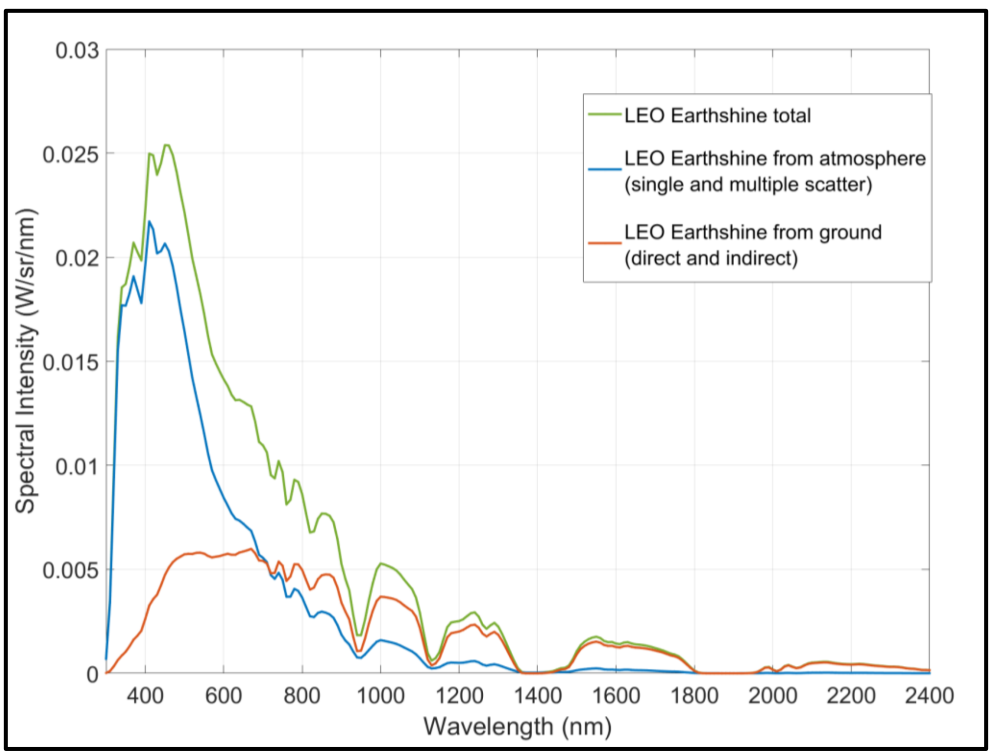

Figure 5 – The combined earthshine illumination for the 1m diameter LEO object by source component. Here we use spectral intensity to quantify the amount of incident earthshine reflected from the object to the observing site.

The component of earthshine from the atmosphere is more intense from oblique illumination angles, but each facet is farther away. However, there is more overall solid angle subtended. The net result is that when a LEO satellite is close to the Sun in the sky, and both are near the meridian, LEO objects are very bright in blue wavelengths. This combination, though, is also where the daytime sky is also brightest.

4. SKY BACKGROUND

Daytime sky brightness is many millions of times brighter than nighttime. Expressed in astronomical magnitudes, night sky surface brightness values typically range from 17 (near the full Moon) to 22 (very dark site) magnitudes per square arcsecond, whereas in the day this range is from 2 (near the Sun) to 5 (clear blue sky). This can vary a lot across the sky over time, depending on the composition of the atmosphere between the site and the object and around the site. Our MODTRAN model estimates the line of sight transmission and sky background for the observed object, such as shown in Figure 6.

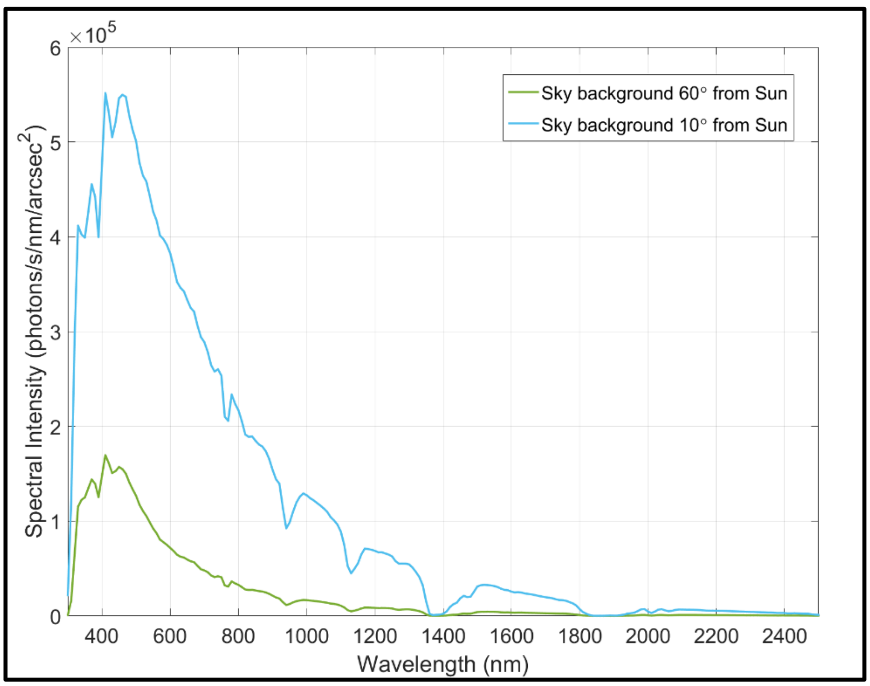

Figure 6 – Sky background modeled for 400km LEO object as received by a 14″ telescope when the Sun is near the meridian. The brightness for different angular separation from the Sun is shown with the green and blue lines. Even closer to the horizon, the sky brightens again and flattens spectrally due to aerosols.

5. DETECTION AND MEASUREMENT

The interplay between the reflected earthshine signal getting brighter in blue wavelengths and the sky background getting brighter in blue wavelengths, but also atmospheric transmission falling toward blue wavelengths makes judging what bandpass through which to observe LEOs in the daytime non-trivial. Most previous work has focused on red and infrared bands. But from a detectivity standpoint, including wavelengths with more signal pays off as long as the background isn't growing at a much larger rate. Because the background comes in the signal-to-noise ratio (SNR) as the square root of the background photon count, even if there are 2 x 10^9 photons in the background during a measurement, an object signal of 2.7 x 10^5 photons in that same time yields an SNR of 6. For a 14" telescope, this is approximately 8^{th} magnitude.

For the LEO case, we show in Figure 7 a signal-to-noise calculation where a 14" telescope has its bandpass limited by a long pass filter and a back-illuminated sCMOS quantum efficiency curve. The wavelength where the filter cuts on is shown on the horizontal axis. Two representative scenarios are shown, both with the Sun near the meridian, but one with the object near zenith and one towards the horizon. Near the Sun, all the factors that make the earthshine brightest are working together. In both cases, the peak SNR is achieved in blue parts of the optical spectrum.

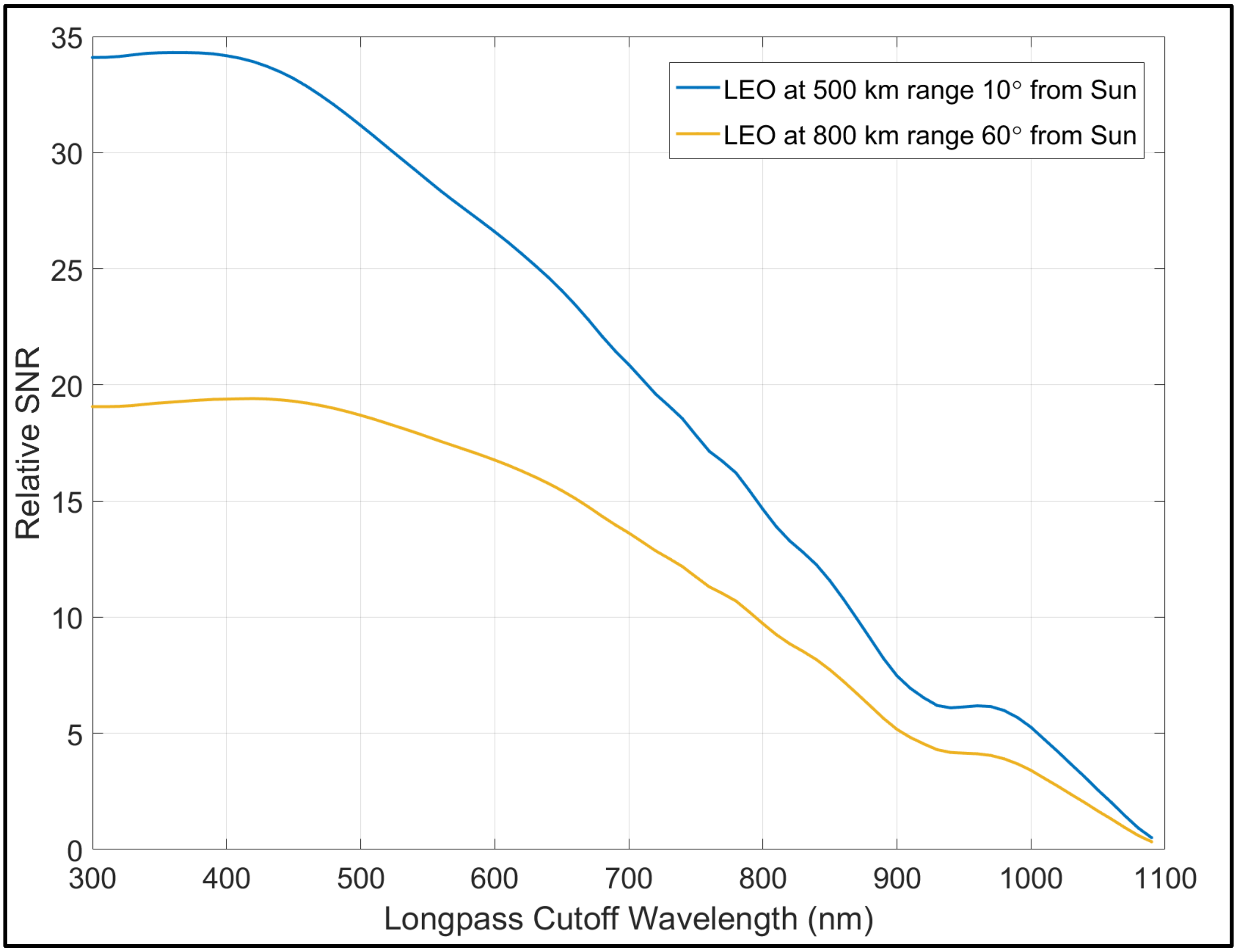

Figure 7 – Daytime SNR ratio for a 1m diameter LEO object at 400km altitude is shown for two observing geometries as a function of included bandpass. In each case, it is beneficial to include blue light.

This is promising for daylight LEO observing. However, there is the issue of how to manage these intense light levels. Billions of photons per second would overwhelm most nighttime observing systems in a very short time – milliseconds.

6. OPTIMIZING FOR DAYTIME

One of the most challenging aspects of optimizing nighttime SDA systems is the difficulty and cost of creating large optics with a fast (small) focal ratio, in particular below f/2. For a fixed focal length, which sets the image scale and field of view (FOV) for a given detector, moving to a faster focal ratio increases the collecting area and therefore SNR. At some point that cost curve increases so dramatically that it is more cost effective to build multiple, smaller telescopes.

For daytime systems, the challenge is to manage the large amount of incoming background light without losing any of the signal. For a given pixel size, the background intensity is set by the focal ratio. Additionally, the pixel full-well depth, which determines how many photoelectrons can be stored without saturation, of most commercially available sCMOS sensors roughly scales with the area of the pixel. The key then is to find a sensor that can be read out fast enough that there is no dead time between exposures, thus avoiding that light loss while not saturating in that time.

For instance, we'll consider a sCMOS sensor with 6.5 μm pixels, a minimum no-dead-time exposure time of 14 ms, and a full well depth of 55,000 e^- on the 14″ telescope analyzed above: With its QE response and under the bright sky shown in Figure 6, the sky background will contribute 9.4 x 10^7 photons per second per square arcsecond; if we have a goal of having that sky contribute no more than ~1/3 of the full well in the 14 ms exposure time, the signal from 1 square arcsecond needs to be spread over at least 64 pixels. This could be achieved by using a telescope with a focal length of 10.8 m, which for a 14″ telescope is f/31. This is a very slow optical system, and the 2048 x 2048 sensor on it has a tiny FOV: 256 x 256 arcseconds.

Luckily, unlike the cost and complexity of making faster optical systems, making slow optical systems is not as challenging. In fact, f/31 is close to the f/33 achievable with a COTS 14" f/11 telescope with a 3x focal expander. Given the wide variety of COTS telescopes available, these sorts of combinations of sensor and optics are numerous.

Almost all of the commercially available cameras we've analyzed in this way yield similar results. This is not too surprising because the well depth and pixel area are correlated, and the frame rate, which sets the non-overlapped exposure time, is correlated with the size of the detector array. Other limits involve the data rate of pixel data over USB3 or other communication channels. Some cameras increase their readout rate by digitizing the signal into fewer bits, sometimes as low as 8 bits per pixel. Uncertainty from the finite digitization levels can become significant at these coarse-grained quantization levels.

Nothing comes without a trade-off though: The errors typically encountered when observing LEO satellites based on TLE predictions are often much larger than 256 arcseconds. So there remains work to be done to find the right combination of optics and detector.

7. PROOF OF CONCEPT TELESCOPE

We performed some initial testing of our results using an 80mm f/28 refractor. We operated both with no filter and with two different long-pass filters with 680 nm and 740 nm cut-on wavelength. We were able to detect more than a dozen LEO objects, including several rocket bodies, all of which are quite large with radar cross sections > 10 m^2. While the varying lighting and cloud conditions made direct quantitative comparison difficult, it was clear that operating with no filter achieved similar SNR in far shorter exposure times, typically 25 ms with the long-pass filters and 10 ms with no filter. Unfortunately, with this system we were not able to change the filter during a satellite pass, so the direct comparison is not available. However, these results were promising enough that we are pursuing a larger prototype optical system.

A sample image from this system is shown in Figure 8. This shows a 10 ms exposure using no filter of a SL-16 R/B at a range of 866 km and 25 degrees from the Sun, roughly 90 minutes before local noon. The SNR of the object in this frame is about 20 but varies drastically during the pass. Note that the streaks seen in this image are not the normal background stars one sees in nighttime observations, but sunlit material aloft in the atmosphere: what the observers at White Sands [5] called "angels." This debris, probably seeds and bugs, is clearly in the near field given that it is out of focus. It is nearly always apparent, though the density of the debris can be a few to hundreds per frame. These objects complicate the image processing and analysis, though they can be readily removed.

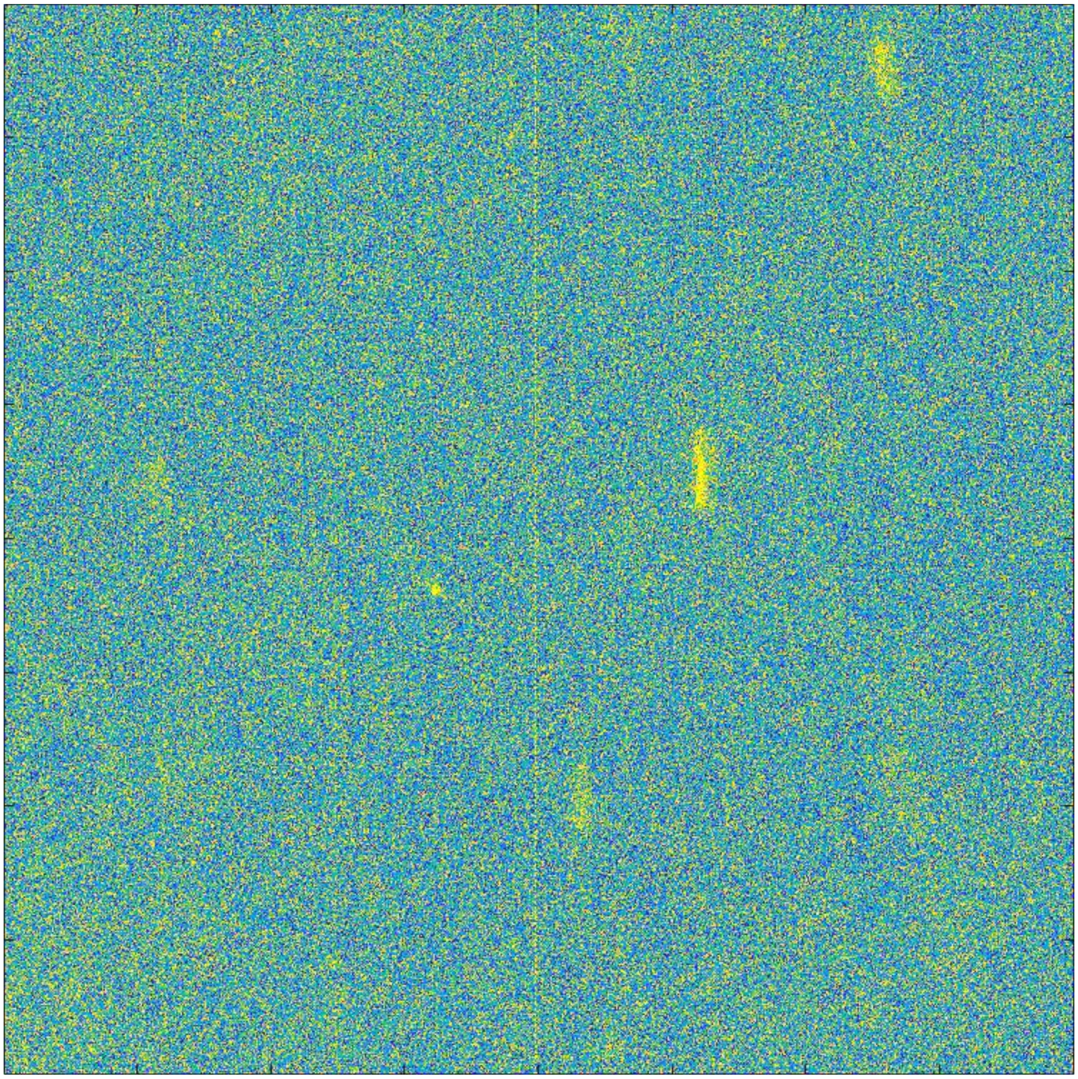

Figure 8 – This image shows SNR ~20 detection of an SL-16 R/B taken with our 80mm proof-of-concept daylight telescope. The long, out-of-focus streaks are sunlit debris floating with the wind.

8. ONGOING WORK

We have only just started modeling, exploring, and experimenting within the design space of daylight optical SDA observation systems. We've outlined how earthshine provides substantial signal in visible wavelength, generating levels that can dominate over the noise from very high daytime sky levels. Optical systems can be tailored to accommodate these high background levels, but many other factors remain to be analyzed.

Observing the sky near the Sun adds some additional complication. Scattered sunlight in the optical system and within the observatory will add to the background levels. Direct sunlight on the telescope and mount heats the structures, changing their mechanical response, which can change the pointing performance. Daytime atmospheric turbulence is considerably more intense than at night and dilutes the signal from the satellite over more pixels. These factors alone are difficult to assess via modeling, and real optical systems will have even more issues.

Our next step is to deploy a 14″ optical system optimized to address the issues we've identified here and use the data it generates to improve our models and subsequent analysis. We anticipate that such a system will be able to measure objects of 1m characteristic size and smaller. How much further these observations can be pushed, and whether they will ultimately be cost effective, remains an open R&D question.

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