Daylight Optical Measurements of LEO Satellites

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ABSTRACT

We present new measurements of satellites in low Earth orbit (LEO) from our prototype 0.3m daylight optical tracking system located in central New Mexico. Lessons learned from experiments over the last two years have led to significant improvements in system performance and a substantially larger field of view. The system reliably detects objects with radar cross sections smaller than 0.2 m2, including some medium-sized cubesats, and further work is expected to push the detection limit to substantially smaller objects sizes.

We've entered an era of unprecedented growth in the number of satellites launched into LEO, levels unimaginable even a few years ago. This growth rate far outstrips the growth in resources deployed to monitor and protect this investment and the collective resource that is near-Earth space. Our current space domain awareness (SDA) infrastructure is aging and already stressed. Radar is of course highly effective for monitoring LEO, but the costs of these systems and the ability to deploy them rapidly around the globe places real limits. COTS-based optical systems deployed widely can assist these radar systems in monitoring this ever-more-busy domain.

Operating at night, small optical telescopes around the world 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 - they are only viewable for a few hours each day, in twilight just after dusk and just before dawn. Any particular LEO satellite is only above the horizon of a given site for a few minutes per day and may only be observable in twilight very infrequently – not nearly enough to keep custody. So, while each telescope is itself cost effective, the number of telescopes required to provide adequate twilight coverage of LEO undercuts that advantage.

Passing over a daytime observing site, LEO satellites are illuminated both directly by the Sun and indirectly by earthshine, sunlight scattered off the Earth's surface and atmosphere. The combination of these two light sources makes objects in LEO appear bright by astronomical standards. The challenge of course is that the same scattering mechanisms make the sky background quite bright as well. The first main challenge in designing a daylight system is balancing the collection of the target signal while limiting the noise from the background. Because the daytime sky is so obviously blue, the first instinct would be to filter out bluer wavelengths, with for example a red or near infrared long-pass filter. However, both the direct solar spectrum and that of earthshine peak in the bluer part of the visible spectrum. Moreover, the most cost-effective sensors tend to have their peak quantum efficiency in the bluer spectral regions as well. Thus, signal-to-noise per unit time increases as the system includes more of the visible spectrum up to a point of diminished returns. Our daylight observing models show this point is typically between 550 and 600 nm, with field testing of those results underway.

To measure satellites against that bright background requires balancing the optical performance, most notably the focal ratio, with the sensor performance. Longer focal length optics spreads the background over more pixels but reduces the field of view. Commercial CMOS sensors have the critical combination of readout speed, quantum efficiency, and full-well depth so that the background doesn't saturate the pixels while also not losing light between exposures. This results in large images obtained at a high frame rate, so a significant data volume must be processed.

Fortunately, many of the developments of GPU-based processing for SDA observations over the last decade can be applied here as well, allowing faint satellites to be teased from a bright sky.

Turning these detections into metric observations remains challenging, because 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. Combined with a much smaller field of view, calibration of system pointing have to be done one star at a time. Astrometric measurements must be made indirectly, relying on the stability of the telescope mount and optomechanical system. COTS-based mounts typically have open loop rms pointing repeatability in the 5-10 arcsecond range. Those pointing models are made at night and are temperature dependent. This remains the primary obstacle to reducing daylight imagery to metric observations.

We present the progress we've made over the last year addressing these various technical challenges, report results from the system improvements, quantify their effects, and discuss plans for mitigating these issues.