Please cite this paper as : J. Shaddix, J. Brannum, A. Ferris, A. Hariri, A. Larson, T. Mancini, and J. Aristoff, "Daytime GEO tracking with 'Aquila': approach and results froms a new ground-based SWIR small telescope system," in *Proceedings of the 2019 Advanced Maui Optical and Space Surveillance Technologies Conference*, (Wailea, HI), September 2019.

Daytime GEO Tracking with "Aquila": Approach and Results from a New Ground-Based SWIR Small Telescope System

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ABSTRACT

Numerica has developed a low-cost, ground-based optical daytime geosynchronous Earth orbit (GEO) satellite tracking capability that is being deployed to the Numerica Telescope Network (NTN). Numerica's daytime tracking system, "Aquila", will complement space-based and passive radio frequency (RF) sensors to help fill the daytime observation gap at GEO. This presentation will (i) discuss the advantages of shortwave infrared (SWIR) sensing during daytime diffuse skies; (ii) provide an overview of Numerica's Aquila daytime tracking solution; (iii) present initial results from the prototype Aquila system; and (iv) discuss its integration with the NTN.

1. INTRODUCTION

Space-based systems are relied upon internationally for the advancement of science, communication, defense, and our modern way of life. Protection of these systems requires persistent, timely, and accurate orbital updates on all nearby resident space objects (RSOs), whether those be controlled satellites or uncontrolled debris. RSOs in geosynchronous and geostationary orbits (GEO) may be especially difficult to detect given their near 36,000 km altitude. The US Space Surveillance Network, as well as current commercial telescope networks, primarily track GEO objects through ground-based optical sites. These systems are generally limited to nighttime operation due to the daytime sky background (or skylight). This background quickly saturates these sensors and reduces their detection potential due to the large increase in photon shot noise. While some exquisite ground-based systems have overcome these limitations, to date there are no low-cost options capable of global proliferation. Space-based sensors offer observing capability during daylight hours without terrestrial weather concerns, but are costly, may be limited to predictable observation patterns, and must deal with solar avoidance with limited baffle systems. Ground-based passive radio frequency (RF) systems may detect active GEO satellites throughout the day, but only when those satellites are actively transmitting. As such, many GEO objects spend the majority of daytime hours unobserved, allowing windows for undetected and potentially nefarious activity. In light of this challenge, Numerica has developed a low-cost, ground-based optical solution with demonstrated capability to produce observations on GEO objects in broad daylight. This capability can complement space-based and passive-RF solutions toward closing the daytime GEO observation gap. While this paper is focused on GEO observations, it is important to note that Aquila is capable of detecting RSOs in other orbital regimes.

The new daytime GEO satellite tracking system, "Aquila", senses in shortwave infrared (SWIR) as one way to mitigate the challenge of daytime imaging. SWIR provides two complementary benefits: (i) the diffuse sky spectral surface brightness is approximately two orders of magnitude lower in regions of SWIR than visible, and (ii) the spectral reflectance profile of many satellites markedly increases around 1.0 um wavelength (where visible sensors fall off). GEO objects are predominantly illuminated by direct sunlight at local night, but are also affected by earthshine reflection during the day. Even though both of these sources provide more incident light for satellite reflection in the visible than the SWIR, daytime sensing in SWIR may provide an order of magnitude improvement in signal-to-noise ratio. Likewise, the reduced background flux in the SWIR allows for longer integration times before sensor saturation. This paper will delve into more detail describing the efficiency of daytime sensing as a function of wavelength.

The optical train for Aquila maximizes SWIR throughput and minimizes the SWIR spot size for point-source targets. The telescope trades a small field-of-view in order to cut through the skylight surface brightness and improve detectability. Multiple filters are employed to maintain saturation control and provide SWIR

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target characterization potential. Even with this carefully chosen hardware, imaging techniques suitable for night observations are not sufficient during the day. Images must be acquired at high data rates and stacked effectively to reduce noise effects. For example, over 10GB of data is collected off the Aquila system per 1-minute observation. To address these and related challenges, Numerica has developed specialized image processing and observation reduction software. This paper will explain system design considerations, and show initial results.

2. DAYTIME SENSING OF SATELLITES

The Hunter's Moon waxed round in the night sky, and put to flight all the lesser stars.
—J.R.R. Tolkien, *The Two Towers*

Before discussing satellites, consider the stars. It is naturally apparent that the stars "take flight" when another light source comes near; be it the moon, city lights, or especially the sun. In the latter case of daytime skies, to the casual observer, the complete lack of visible stars may suggest that they have been somehow masked out. This is of course not true; they are still shining as bright onto the Earth as they do at night. The difference is simply a matter of contrast.

Consider taking a photograph of a landscape scene including the daytime sky: the signal from the stars are simply added on top of the bright sky background. However, three factors may prevent those stars from being detectable: saturation, quantization, and noise. Given that the sky is so bright, a photographer may choose to saturate (or wash out) the sky to properly expose for on the ground. Here either the photosites (physical sensor elements which produce pixels in an image) have either reached full-well condition (no more electrons can be collected before readout), or more likely the analog-to-digital converter (ADC) has reached a maximum digital output level. In either case, the additional signal of the stars is lost. On the other hand, the photographer may choose to take a shorter exposure time to retain detail in the sky. This exposure time would likely be measured in milliseconds, and, paired with a small aperture lens, star signals may simply be too low to register a single digital count coming off the ADC (quantization loss).

But what if the photographer put down his small lens and instead used a large telescope? Indeed, the star signals could produce digital counts even at short exposure times, but the primary inhibitor remains: photon (or shot) noise. The number of photons from a light source collected by a sensor over an exposure period is not constant, but instead follows the Poisson distribution. Thus, in a single exposure, even for a flat background, each photosite collects a different amount of charge, producing noise in the resulting image. The signal-to-noise ratio (SNR) is the standard measure of signal contrast in the presence of noise, and is defined as the ratio of signal to the standard deviation of the noise. The standard deviation of shot noise is equal to the square root of the noise source's signal level (in photoelectrons, not counts). Thus, a bright daytime sky produces significant shot noise, hampering the visibility of stars, or of more pertinence, of satellites. But, the sky is blue – so what happens if we put a red filter in front of our camera? The analysis in this section will investigate how this natural SNR (independent of any sensor or optics) may be maximized through selection of spectral sensing bands.

The function for spectral SNR may be approximated as

$$SNR(\lambda) = \frac{S_t(\lambda)}{\sqrt{S_b(\lambda)}} \tag{1}$$

where $S_t(\lambda)$ is the background-subtracted target signal in electrons, $S_b(\lambda)$ is the background signal in electrons, and λ is the wavelength of light. This suitable approximation does not consider the effects of atmospheric turbulence or variability in the satellite's reflected signal (either at source or the target's own respective shot noise), both of which may be considered minor compared to the dominant background shot noise. Also bear in mind that camera noise sources and imperfections in image processing are not yet applied; this is simply the natural SNR available to a ground observer.

While useful on its own, Eq. 1 is dependent on knowledge of a given satellite's absolute signal level. This would be a function of solar angles, range, satellite attitude, satellite materials, and other factors. However, the question at hand is not: "What is the SNR of the satellite?", but rather: "How does my chosen spectral band affect my SNR?". Thus, we may consider normalizing the SNR equation by the SNR at a particular wavelength. A natural choice is 550 nm, the approximate center wavelength of the Johnson V magnitude system:

$$SNR_{relative}(\lambda) = \frac{SNR(\lambda)}{SNR_{550nm}} = \frac{S_t(\lambda)\sqrt{S_{b,550nm}}}{S_{t,550nm}\sqrt{S_b(\lambda)}} \tag{2}$$

Eq. 2 is now largely independent of target specifics beyond its relative spectral flux. Likewise, only the relative spectral flux of the background must be known. The sections below will explore these two spectral quantities.

2.1 Signal Spectral Profile

The spectral flux of a satellite incident on a ground observer is primarily a function of three quantities: source radiation, material reflectivity, and atmospheric transmission. Additional effects such as exo-atmospheric extinction are not considered significant for this analysis.

Electromagnetic radiation received by an observer from a target may have either been emitted by the target, or reflected by the target. This analysis will focus on reflected radiation, as blackbody emission at satellite temperatures are considered negligible compared to the reflected signals at the wavelengths being considered. For night observation, the dominant reflected source is our sun. For day observation, the dominant source is not as clear. Depending on the sun-target-observer (or solar phase) angle, and the physical geometry of the spacecraft, solar reflection may be rivaled by earthshine reflection (solar illumination of the Earth reflecting onto the satellite, then reflecting back to Earth). Clearly there are times when the geometry for earthshine is more advantageous, approaching a maximum around the satellite's local noon. Even night observation telescopes may be recognizing this effect at high phase angles.[1] In Fig. 1, the magnitude of several RSOs plateau at large phase angles, suggesting diffuse earthshine may be dominating the reflected signal. It should be noted that the relative spectral illumination of these sources differ as seen in Fig. 2. Molecular absorption reduces earthshine in various SWIR bands.[2] Satellite illumination may be considered an additive mixture of these two sources, and are thus bound by considering the individual cases of sole sunshine and sole earthshine. More detailed analysis of these sources have been performed in prior work.[3]

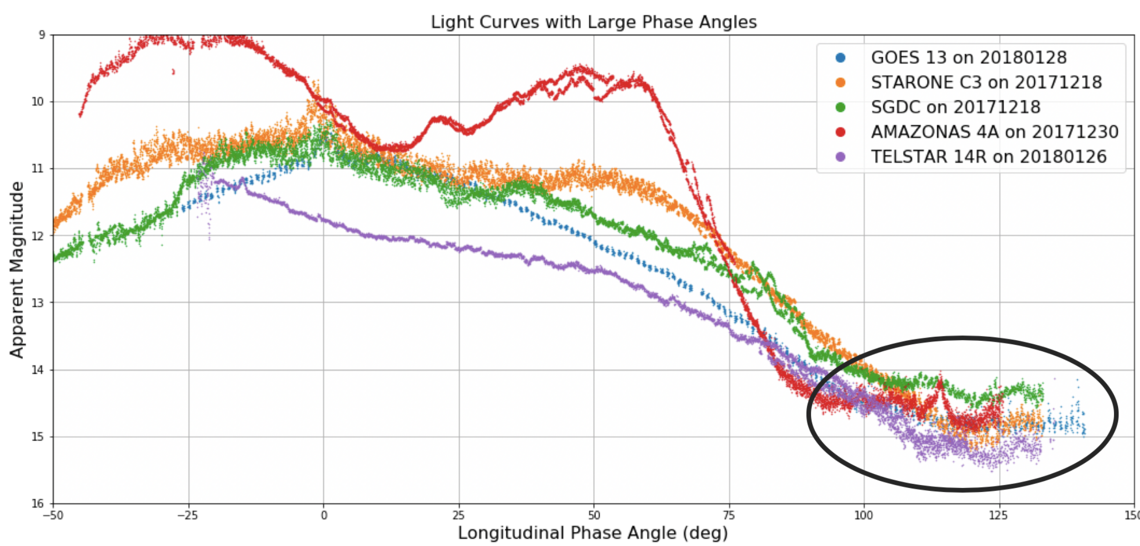

Figure 1. Photometric light curves of several satellites as detected by Numerica Telescope Network visible sensors. The plateau effect at large longitudinal phase angles (looking East near dawn) suggests earthshine is the dominant effect.

The illumination incident on the satellite is reflected by materials on the spacecraft. These materials vary widely; including multi-layer insulation (MLI), various paints, and solar panels made from GaAs or Silicon. Many of these materials show strong spectral features.[4] As such, the signal spectral profile, and thus the relative SNR, will largely depend on the composition of the reflecting materials. Spectral characterization efforts of

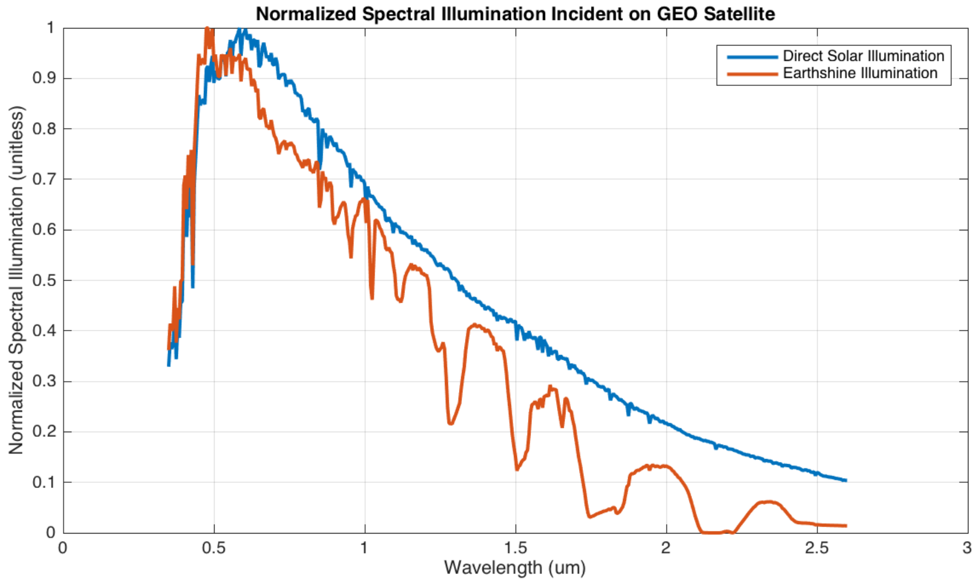

Figure 2. Relative spectral illumination of satellites by sunshine and earthshine‡. Earthshine features will vary by satellite nodal position and local time.

space objects have provided evidence that GEO satellites exhibit higher reflectivity in the near-infrared (NIR) to SWIR regime, particularly around 1.1 um.[5] The analysis in this section will use an averaged reflectance profile between SBS 2 and Galaxy 1R to represent a nominal GEO spacecraft.[5]

Finally, light reflected off of satellites must first make it through the atmosphere before reaching a ground observer. Atmospheric transmission is a well-analyzed field, and several tools exist to model this transmission. For this analysis, the European Southern Observatory (ESO) SkyCalc Tool§ was used to generate molecular absorption and ozone extinction information.[6] Rayleigh and aerosol extinction components were computed using altitude and aerosol optical depth (AOD) dependent models from the Harvard International Comet Quarterly.[7] These effects are shown combined in Fig. 3.

The combined normalized spectral flux for a ground observer of each satellite in both illumination conditions is shown in Fig. 4.

2.2 Noise Spectral Profile

At night, the sky background surface brightness varies widely by proximity to terrestrial light pollution, lunar phase, and lunar position relative to the observer line-of-sight (LOS). At a dark site on a new moon night, the atmosphere is still radiating a relatively small amount of light, called airglow, which has been measured to be brighter in the infrared than the visible.[8]

In opposition, during the day, light pollution and lunar conditions are insignificant compared to the diffuse skylight of the atmosphere. The shot noise produced from this skylight dominates the noise for a ground observer. Rayleigh scattering shifts the solar spectral flux toward blue, and attenuates toward the infrared. Daylight sky surface brightness has been modeled as a function of time of year, solar elevation, and viewing angles.[9] The background profile in this analysis is taken at vernal equinox around noon with a 45 degree viewing elevation. Both day and night background relative spectral surface brightness profiles are shown in Fig. 5.

‡Solar spectral radiation model courtesy American Society for Testing and Materials (ASTM) and National Renewable Energy Laboratory (NREL), https://rredc.nrel.gov/solar//spectra/am1.5/ASTMG173/ASTMG173.html. Earth reflectivity courtesy of The Astrophysical Journal.[2]

§http://www.eso.org/observing/etc/bin/gen/form?INS.MODE=swspectr+INS.NAME=SKYCALC

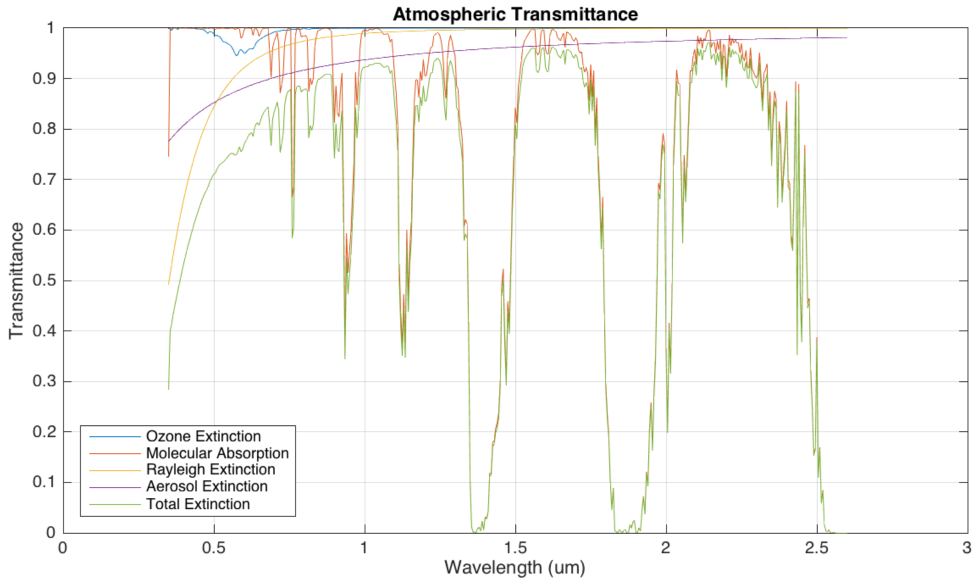

Figure 3. Representative atmospheric transmission split by component and total transmission

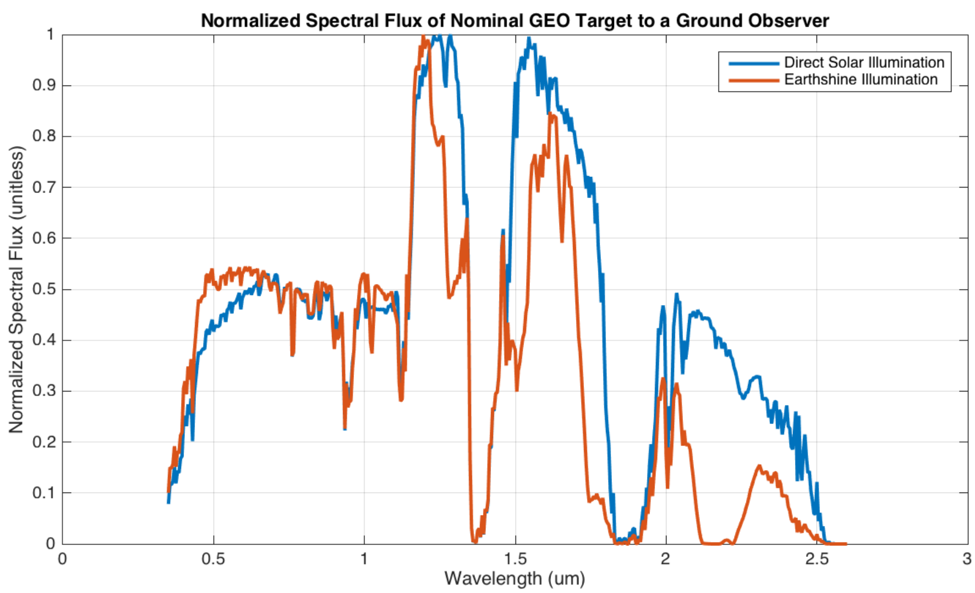

Figure 4. Normalized spectral flux for a ground observer of nominal GEO satellite under sunshine and earthshine conditions

2.3 Spectral Sensing Efficiency

The SNR relative to 550 nm (V band) for various conditions is displayed in Fig. 6. Here a 100nm passband has been applied to smooth sharp spectral features for readability. This may be considered a nominal "spectral sensing efficiency" for observing satellites similar to SDS 2 and Galaxy 1R by ground-based optical systems. During the day, spectral sensing efficiency significantly increases in the NIR and SWIR, reaching 10x or higher SNR levels versus visible throughout the H and K photometry bands. This effect is stronger with direct solar illumination compared to earthshine, but both follow the same trend. For comparison, Fig. 6 also shows the spectral sensing efficiency at night at a dark site, showing an SNR decrease toward the infrared as expected.

Given this analysis, Numerica pursued a SWIR (>1um) daytime satellite observation system. It is important

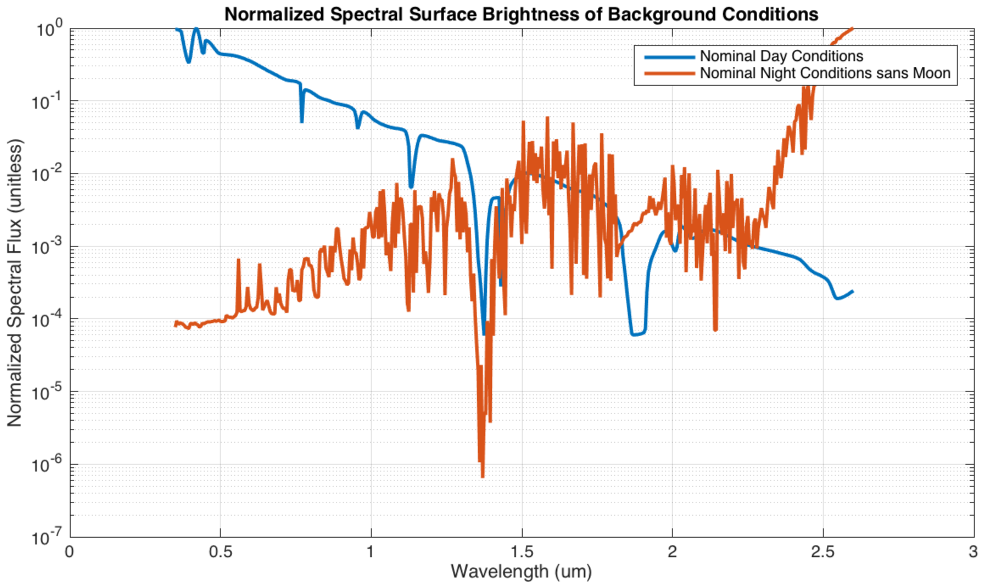

Figure 5. Nominal background conditions during day[9] and night[6] collections

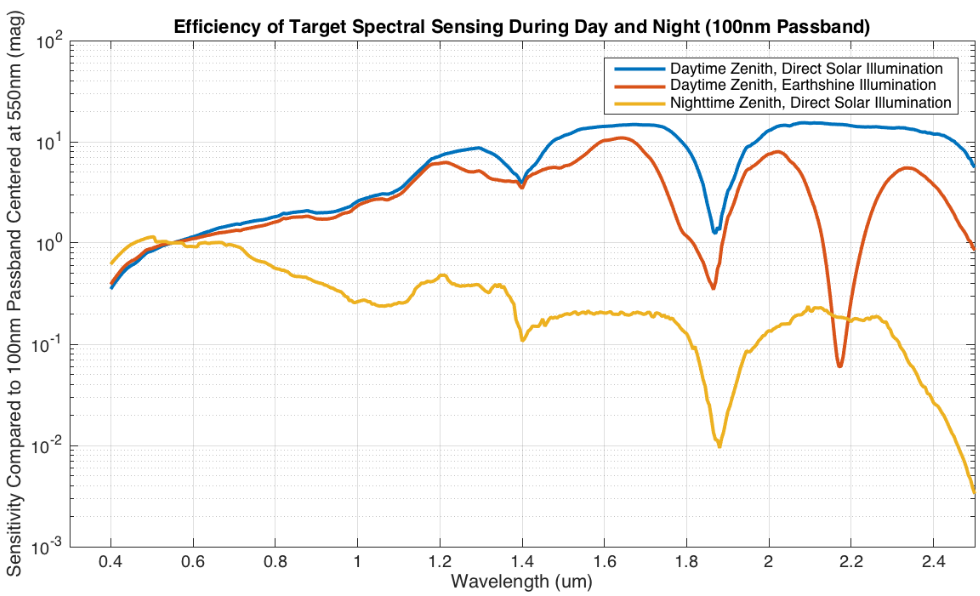

Figure 6. SNR of a 100nm passband centered at given wavelength as compared to centered at 550nm

to note that final SNR of an optical collection system is also dependent on optics and sensor system hardware, as well as image processing algorithms. In some cases, practical SWIR technology limitations may lend to visible/NIR sensors being more capable under certain circumstances. Full system analysis must be performed (and has been for Aquila) to trade these considerations.

3. ACQUISITION SYSTEM CONSIDERATIONS

The Lord of the eagles of the Misty Mountains had eyes that could look at the sun unblinking...
—J.R.R. Tolkien, *The Hobbit*

Numerica's daylight tracking system, "Aquila", latin for "eagle", is so named to signify its ability to see small objects from far away during the day. While not yet able to stare at the sun, Aquila is capable of GEO satellite acquisition in broad daylight. This capability requires attention to detail in optical design, and pushes sensor technology to their limits. This section will explore these considerations.

3.1 Building a SWIR System

Most commercial off-the-shelf (COTS) telescopes have been heavily optimized toward visible sensors (400–700nm). Common telescope designs include reflective (mirror) and refractive (lens) elements. Both element types include coatings that optimize transmission of light in a range of wavelengths, and, for refractive elements, reduce ghosting effects caused by internal reflections. Likewise, the materials used to develop refractive elements are chosen for a specific optical band, and may have low transmittance outside of the intended design. Furthermore, the amount that a refractive element bends a light ray is a function of its wavelength, which may lead to an effect called chromatic aberration. This aberration will cause the focal point of the system to vary by wavelength, blurring the point spread function (PSF) for broadband signals. Optical designers may mitigate these aberrations, but may focus correction in a wavelength regime (e.g. visible). Thus, simply putting a SWIR camera on the back of a COTS telescope may produce poor results.

Numerica has designed a low-cost, SWIR-specific telescope system. The prototype telescope has a 14-inch aperture, gold coated mirrors, and a custom-coated refractive package. The transmission of the optical train may be seen in Fig. 7, alongside a nominal COTS version suited for visible sensing. Note that transmission from 1.0-1.7 um is greatly improved. Likewise, the chromatic aberration of this system has been well controlled in the 1.0-1.7 um band. Larger apertures may be used to improve detectability at a higher price point.

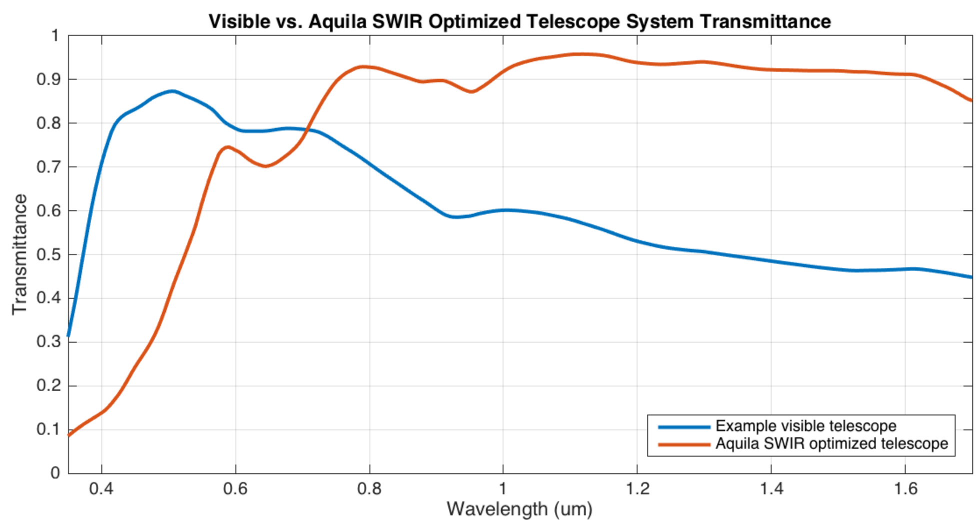

Figure 7. Transmittances of a typical visible telescope system and the SWIR-optimized telescope used for Aquila

Quantum efficiency (QE) describes a sensor's ability to convert incident photons into electrons, and is specified as a function of wavelength. While silicon-based semi-conductor materials are broadly used to make visible sensors, SWIR sensors may use various substrates such as InGaAs, HgCdTe, or IbSb. Each technology comes with specific advantages, and a variety of QE characteristics. Aquila focuses on InGaAs sensors with sensitivity upwards of 1.7um (hereby InGaAs 1.7) for three reasons: dark current, thermal emission sensitivity, and deployment cost. Dark current causes charge to build up on photosites in the absence of incident light. Just as day skylight produces shot noise, dark current likewise produces shot noise. The amount of dark current is primarily a function of sensor type and sensor temperature. For visible sensors, dark current is insignificant during daylight background conditions. For SWIR sensors, depending on cooling systems, the shot noise from dark current may rival or even exceed that of the daylight background. InGaAs 1.7 sensors are capable of maintaining dark current below 10 ke-/p/s (kilo-electrons per pixel per second) at sustainable sensor temperatures in outdoor environments using only thermoelectric coolers (TECs). Market research suggests alternatives sensitive to longer wavelengths (including those sensitive down to 2.5 um) required expensive cryogenic cooling systems to achieve these low dark currents. In order to reduce costs, maintanence, and manning burdens, Aquila has been designed for camera systems without cryogenic coolers. Limiting SWIR sensitivity to 1.7 um also prevents the need for cold stops and cooled optical elements, facilitating the proliferation of these systems.

Astronomy photometric systems have historically been geared around specific bands. The Johnson V (visual) band for instance, is the staple of the aptly named "visual" magnitude system. Today the sloan filters are popularized for color characterization using visible sensors. In the SWIR, atmospheric transmission windows have provided natural cutoffs for what has become known as J, H, and K bands. Star measurements in this spectral region, for instance the Two Micron All Sky Survey (2MASS), are conducted with a filter to select one of these bands.[10] SSA systems typically prioritize detection, and thus use a wide-open (clear) filter such that the spectral response of the system is primarily limited to the optics transmission and QE of the sensor. The QE curves for silicon-based visible sensors typically peak around 550 nm, but may vary significantly in the ultra-violet (UV) and near-infrared (NIR) spectra. Photometric measurements from these systems are not visual magnitudes, but rather "apparent" magnitudes according to each system's relative spectral response (RSR). Nonetheless, the lack of a specific color filter does increase SNR, and the same concept holds true for daytime SWIR sensing. Thus, instead of using a specific band such as J or H, Aquila uses a set of longpass filters. As a baseline, Aquila uses a 1 um longpass filter for maximizing SNR. Some InGaAs 1.7 sensors have QE starting around 1 um, in which case no filter is necessary. Additional longpass filters with longer cutoff wavelengths are used in conjunction with frame rate changes to prevent camera saturation. Finally, polarizers may be used to further reduce the background from skylight and potentially increase SNR. Selection of polarization angle is based on expected angle of skylight polarization at the point of observation, and is dynamically adjusted as part of the image acquisition strategy.

3.2 Image Acquisition

Image acquisition from a dark site at night is fairly straightforward. The exposure time is maximized to improve SNR under constraints of target/star motion limits and observation cadence. Multiple exposures may be stacked directly or through shift-and-stack (or track-before-detect) techniques. Regardless, unless the moon is nearby, background saturation is not a concern.

During the day, the opposite is true. Exposure time must be managed to produce a reasonable background level. ADC gain may be lowered to mitigate the problem, but at the cost of increased readout noise. From a design perspective, reducing the background signal may be done by either increasing the f-number of the telescope (ratio of focal length to aperture diameter), or choosing a sensor with smaller pixel size. Both options shrink the solid angle subtended by each photosite, cutting through the background at the cost of reduced field-of-view (FOV). As such, wide-FOV systems used for persistent night GEO observations are typically not feasible during the day. On the other hand, narrow-FOV systems may be limited by both diffraction and atmospheric seeing, both blurring the target signal and thus reducing SNR. Aquila pushes the edge of narrow-FOV systems before these limitations arise.

The trade between larger apertures and saturation will continue to keep exposure times short, thus frame stacking becomes necessary to maximize detectability. Ideally, the frame rate of the camera would match the exposure time such that the camera is continuously collecting. This ideal would represent running the camera at 100% duty cycle, where duty cycle is defined as the percentage of time spent integrating on the sensor. Under daytime conditions, this typically means running the sensor at frame rates of 100-500 Hz. Advancements in SWIR imaging has led to high speed cameras that enable such high frame rates. Readout noise generated through high-rate frame stacking is significant for night use, but still not significant during the day compared to the background shot noise. Thus, Aquila acquires and stacks frames at rates of 100 Hz or higher, depending on scene conditions. Stacking may last 60 seconds or longer for a single observation frame, reducing >10 GB of data per observation.

Ideally stacking of N frames would produce an SNR improvement equal to $\sqrt{N}$. In practice this is eventually limited by two factors: 1/F noise, and pixel response non-uniformity (PRNU). 1/F noise (or flicker noise), is named after its approximately inverse relationship to frequency, and is a noise effect inherent to electrical interfaces.[11] Frame stacking (temporal low-pass filtering) is not as effective on 1/F (temporally correlated) noise as white (temporally uncorrelated) noise. PRNU is the variability of each photosite's signal with respect to incident light. Standard practice from camera manufacturers is to apply a 2-point NUC (dark and gain terms) or 3-point NUC (dark, gain, and power terms) to correct for this noise source. Such practices have been found to be insufficient when attempting to reduce spatial noise down to stacked temporal noise limits. Numerica has developed a custom calibration routine to fit an arbitrary, continuous, monotonic function to each photosite using hundreds of measurements. This function is pre-computed in a laboratory environment using a uniform light source with variable luminosity.

3.3 Challenges in Practice

At night while tracking GEO objects, Numerica's SSA visible telescope systems will see tens to hundreds of stars as streaks in the FOV. These streaks may be centroided and used directly for astrometric calibration of any satellite targets within the scene. During the day, Aquila's intentionally narrow FOV and long exposure times (through stacking) combined with the higher background noise prevent this approach from being feasible. Most detection frames will not contain any stars, and those that do may have a star that streaks through the edge of the FOV, preventing their use in plate solving. Aquila approaches this problem through (i) a high-precision mount pointing model including camera orientation that provides approximately 10 arcsec 1-sigma astrometric error anywhere in its field-of-regard; and (ii) utilizing incidental star measurements with a Kalman filter to continuously update an independent pointing model localized to the current line-of-sight. A combination of these techniques may drive down astrometric error into single arcsecond range.

4. INITIAL RESULTS

The first Aquila prototype was assembled and tested at Numerica's headquarters in Fort Collins, Colorado. The test proved daytime GEO tracking potential through successfully detecting satellites from the Anik GEO cluster from before dawn into broad daylight. The image sequence in Fig. 8 below contains stills from this test. The solar elevations for these images are -6.5°, 3.5°, and 14.6°, respectively. The green circles represent detections from automated detection software.

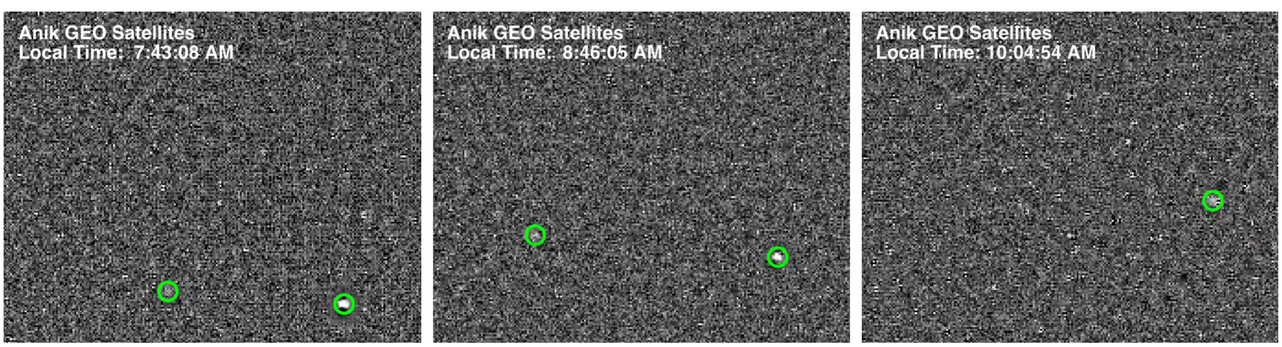

Figure 8. Sample Data on Anik Cluster: (a) two satellites detected approaching civil dawn (-6.5° solar elevation, (b) both satellites still being detected after sunrise (3.5° solar elevation), (c) full daylight conditions (14.6° solar elevation); in this example one GEO satellite is still bright enough for automated detection.

Numerica is now conducting GEO satellite detectability campaigns, with intention to catalog satellite SWIR photometric magnitude information.

5. TOWARD GLOBAL DEPLOYMENT

Over the past decade, Numerica has developed a comprehensive commercial SSA capability that includes a robust, low-latency tasking, collection, processing, exploitation, and dissemination (TCPED) pipeline and a global telescope network that together provide real-time, high-quality tracking information on thousands of satellites in GEO, HEO, MEO, and GTO, as depicted in Fig. 9a and described in Aristoff et al.[12] Further, our

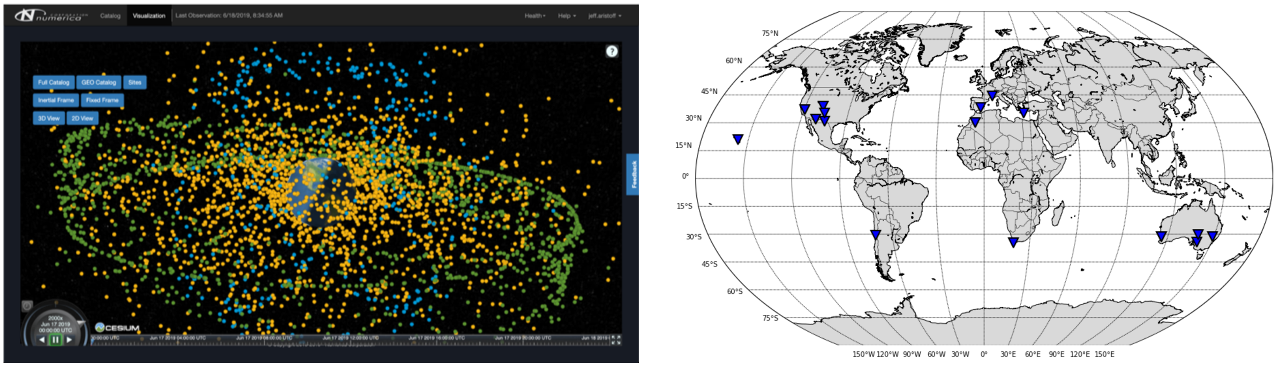

Figure 9. (a) Numerica space catalog visualization (b) Locations of operational NTN sites

best-of-breed uncorrelated track (UCT) processing software, MFAST, is deployed within the Numerica Telescope Network (NTN) and is used by the Air Force 18th Space Control Squadron (18 SPCS) on a daily basis due to its ability to rapidly generate candidate orbits from serendipitous optical and radar data collects. Numerica is currently demonstrating the utility of this commercial system for enhanced SSA; NTN data and information products are now available via the Unified Data Library (UDL) and via the NTN API/UI (see Fig. 10).

At the time of writing, the NTN spans 16 sites across 5 continents, as depicted in Fig. 9b. Sites within the United States are located in California, Arizona, Colorado, New Mexico, Texas, and Maui. Sites outside the United States are located in Chile, Morocco, Spain, France, South Africa, Crete, Western Australia, South Australia (two different sites), and New South Wales Australia. Together, this layout provides 100% coverage of all deep space orbital regimes, including GEO, with redundancy to both regional and seasonal weather. Additional sites are planned for the Middle East, Spain, Australia, and other locations within and outside the United States.

The NTN consists of multiple complementary telescope systems, each of which is comprised of several hundred carefully-selected COTS components together with components that have been designed and manufactured by Numerica, to provide a responsive, robust, and affordable commercial deep space tracking system. This includes (i) medium-aperture (0.3–0.4m) robotic telescopes providing precise astrometry and photometry, good detectability, and the ability to collect data on objects in all regimes of deep space, and (ii) robotic sensor arrays that exchange breadth for depth and collect continuous observations on all objects in GEO and near GEO. Like the medium-aperture telescopes, the sensor arrays provide high-quality astrometric and photometric observations, thus enabling object characterization and persistent (nightly) monitoring capabilities.

Soon, the NTN TCPED pipeline will ingest up to 24/7 observational data from the first Aquila-series telescope system in Colorado. Due to the relative low-cost nature of this solution, coupled with Numerica's proven track record in deploying and operating remote robotic telescopes all around the world, we hope to proliferate the Aquila technology worldwide in order to close the daytime ground-based optical coverage gap and provide up to 24/7 persistent space situational awareness at GEO and other orbital regimes.

6. CONCLUSIONS

Numerica is building the largest on-demand commercial deep space catalog to support space traffic management and space defense; data products are currently available via the Unified Data Library and through Numerica's API/UI. With the addition of daytime-capable telescopes and their integration into Numerica's existing worldwide telescope network, we are well-positioned to significantly improve the security of both commercial and government interests in space.

This paper detailed the challenges of SWIR sensing during daytime skies and provided an overview of Numerica's Aquila daytime tracking system. Initial results demonstrating the capability were presented, as were details regarding the existing Numerica Telescope Network and how it is being augmented with Aquila-produced data with the objective of closing the ground-based optical coverage gap at GEO.

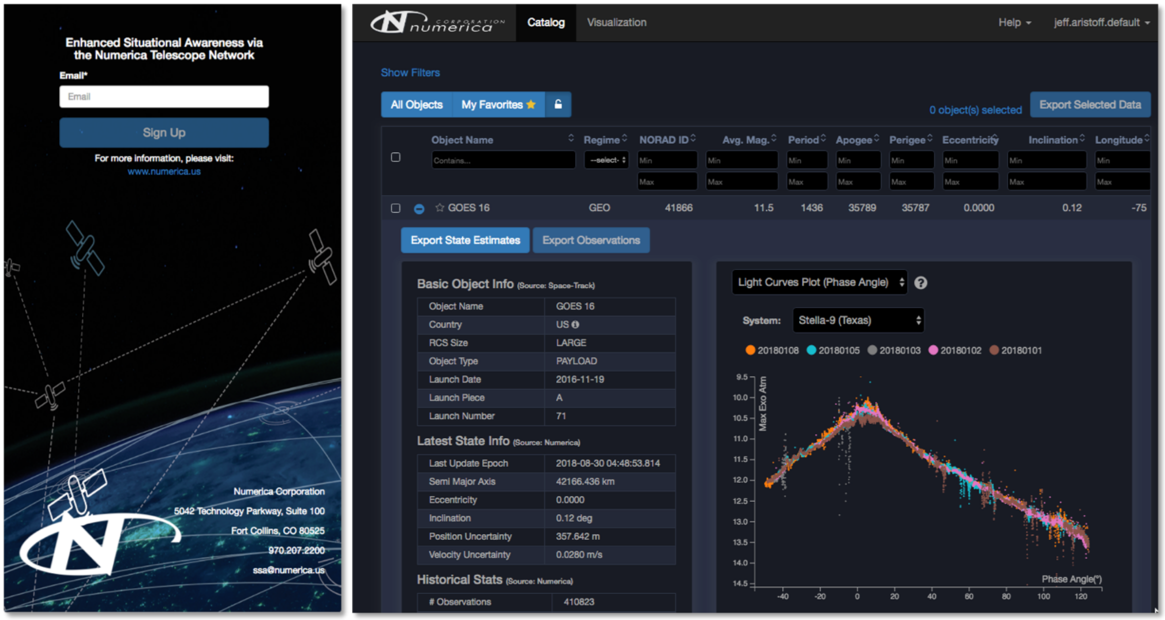

Figure 10. NTN user interface sign up page and catalog view showing several light curves

ACKNOWLEDGMENTS

We acknowledge financial support from Numerica's internal research and development program, and we thank Navraj Singh, Alec Stiller, Andrew Yee, and the Business Operations team at Numerica for their support in the development and testing of the first Aquila-series telescope system.

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