

Exploring a new class of bright, ultra-fast, glints from resident space objects

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ABSTRACT

The recent discovery of sub-second, bright, optical flashes in the night sky by wide-field astronomical surveys has generated questions about sub-second flash origin. We discuss why the existing measurements indicate that most of the sub-second flashes are probably a previously unknown class of ultra-fast glints from Resident Space Objects (RSOs). The “point-like” nature of the flashes and their distribution on the sky suggests that the glinting surfaces are located at Geostationary (GEO) or higher altitudes. The ultra-short duration of the glints also suggests that many of the glinting RSOs belong to a poorly characterized population of spinning/tumbling space debris residing at altitudes where no natural removal mechanisms exist. As such, they pose a poorly defined risk to operational satellites.

We also discuss a new stereoscopic imaging system under development that is designed specifically to characterize the properties of sub-second glints and the altitude distribution of glint producing RSOs. This wide-field (4.5 sq-deg), stereoscopic imager employs high frame rate CMOS cameras that can efficiently detect sub-second flashes and derive the distance of the glinting object on an event-by-event basis. Located at high altitude observatory sites in Northern New Mexico, the 38-km separation of the imaging telescopes and the arc-second spatial resolution of the images enables glinting RSO distance measurements out to cislunar ranges. The system is being built to identify sub-second flash events in real time, estimate the flash distance, and rapidly follow-up with autonomous telescopes that have greater sensitivity. This will enable a search for a fainter Lambertian (diffuse) base component that can help distinguish satellite glints from debris generated glints. That, in turn, will enable a systematic exploration of the properties of the ultra-fast glint generating RSO population.

1. INTRODUCTION

We are now in an exciting era in Space Situational Awareness (SSA) and Astronomy where it is possible to persistently monitor large regions of the sky for fast, ephemeral, changes. Astronomical optical surveys such as the Zwicky Transient Facility [1] are now efficiently discovering new types of optical transients that last a minute or longer. But optical searches for sub-second transients have lagged the wide-field astronomical searches in the radio and gamma-ray bands that are detecting sub-second astrophysical transients. This is due to the long read-out times for conventional wide-field CCD (charge-coupled device) cameras, which make them inefficient for the detection of sub-second optical flashes in the night sky. Further, the alternate camera technology, optical photon counting sensors, is expensive and typically has a more constrained dynamic range that limits their utility for conducting wide-field SSA and astronomical surveys.

However, the landscape for high cadence, wide-field, optical sky monitoring is changing. Advances in CMOS (Complementary Metal Oxide Semiconductor) sensor technology—driven by intense competition in the consumer digital video/photography market—have now enabled the creation of affordable, large format, astronomical cameras that can collect at high frame rates (>1 Hz). Recently a wide-field astronomical search for sub-second optical flashes using this new CMOS camera technology was conducted using the, relatively small (55-cm), Weizmann Fast Astronomical Survey Telescope (W-FAST) in Israel [2]. The results were stunning. They discovered that sub-second optical flashes brighter than 11th magnitude occur at a rate of ~30-40 events/day/square degree. Sub-second optical flashes in the night sky are therefore brighter and more common than anyone had expected.

2. RSOS AS THE SOURCE OF SUB-SECOND OPTICAL FLASHES

While some of these sub-second flares could have an astrophysical origin, most of the sub-second optical flashes are likely glints of reflected sunlight from specular surfaces on RSOs. A robust prediction of this RSO glint hypothesis is that optical flashes should not be detected from locations where sunlight illumination is blocked—such as in the Earth’s shadow. For LEO residing RSOs, the earth shadow region is large and spans a circular patch of radius ~ 50 degrees centered on the solar antipode. For higher altitude RSOs the circular shadow region shrinks, reaching a radius of ~ 9 degrees for GEO residing RSOs. To test the glint hypothesis, Nir et al. [2] conducted an 8.2-hour search for sub-second flashes in the GEO shadow region. They did not detect any events from the GEO shadow region, yielding a 95% confidence event rate upper limit of $1.25 \text{ deg}^{-2} \text{ day}^{-1}$ for 11th magnitude or brighter sub-second flashes. This rate upper limit is more than an order of magnitude smaller than the detection rate measured outside the earth shadowed regions.

The point-like, sub-second, flashes discovered in the images from the W-FAST survey have typical durations of 0.1–0.3 second and often persist in multiple consecutive frames collected by the 25 Hz cadence CMOS camera. In principle, these bright flashes can also be detected in much slower cadence surveys. But detection is less efficient because the flash counts are diluted by the additional background counts collected during the longer exposure time. Furthermore, those single frame detections are subjected to significant populations of point-like, false positive, detections generated by cosmic ray hits in the camera sensor. Requiring detections in consecutive frames (or simultaneous frames collected at spatially separated locations) mitigates false positives from cosmic ray hits. Most optical time domain surveys therefore ignore transients that are only detected in a single frame. So, until now, the sub-second regime for optical transients has been little explored.

A slower cadence, wide-field, sky survey by the Evryscopes team, that was optimized for the detection of longer, sub-minute, optical transients has confirmed the existence of ultra-short flashes [3]. Using automated vetting software and visual inspection on their single-frame transient candidate pool, they were able to reject cosmic-ray generated false positives (~46% of the candidates) and establish a sample of more than two thousand flash candidates that are consistent with a real astrophysical transient. Using this sample—which is larger than the W-FAST flash sample—they found that the “prevalence of flashes decreases steadily with proximity to the shadow in the region covered for LEO objects, before falling in the solid angle covered for MEO and higher orbits.” [3] They concluded that most of the Evryscope ultra-short flash candidates were therefore likely generated by RSOs in middle- and high-Earth orbits.

The short durations of these ultra-fast glints are difficult to generate from a stabilized (non-spinning) RSO in a high-altitude orbit. The angular size of the Sun means that the narrowest glint beam pattern (generated by a flat mirror surface) is $\sim 1/2$ degree across. A glinting surface at GEO therefore generates a ground footprint of at least 330 km in diameter. If that glinting surface is on a stable GEO platform, the beam pattern takes about two minutes to sweep by the ground observer. So, the existence of large population of sub-second GEO-based glints that are nearly three orders of a magnitude shorter than the known class of bright GEO satellite glints [4] requires different conditions for glint generation.

Glints from stable LEO platforms do have shorter durations than stable GEO platforms because the reflection geometry changes much more rapidly. For example, figure 1 shows an image collected by the RQD2 persistent sky monitoring system [5], which captures a bright glint from a LEO satellite. In this case, the glint was generated by LANL’s Cibola Flight Experiment (CFE) satellite. CFE is a 3-axis stabilized LEO spacecraft that operates in a nearly circular orbit with altitude 560 km and an inclination of 35.4 degrees [6].

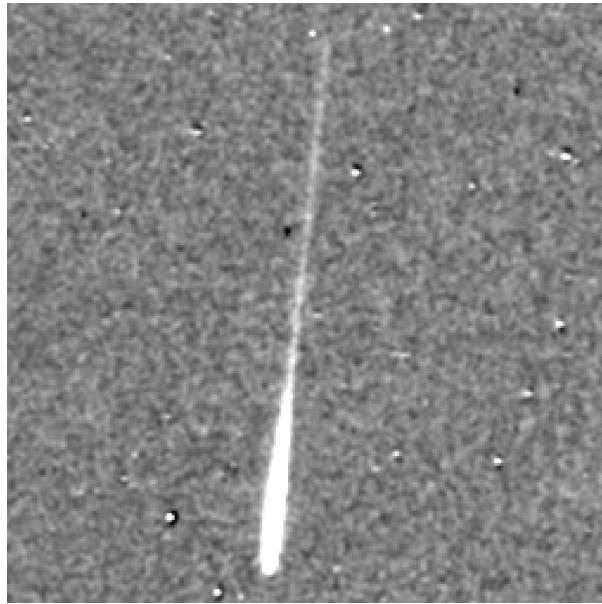


Figure 1. LEO satellites can generate unexpected bright glints. This glint from LANL's CFE satellite was captured during a 10 second exposure by the RQD2 sky monitoring system as the satellite moved through the field of view.

As a picture (figure 2) of the CFE spacecraft taken before launch indicates, there are multiple surfaces that could potentially generate the glint. Since LANL constructed and operates CFE, we know the geometry, composition of the surface panels, and the pose of the satellite when the glint shown in figure 1 was generated. Our forensic study of the generation of the glint concluded that it was generated by a specular glint from a piece of MLI (multi-layer insulation) thermal tape.

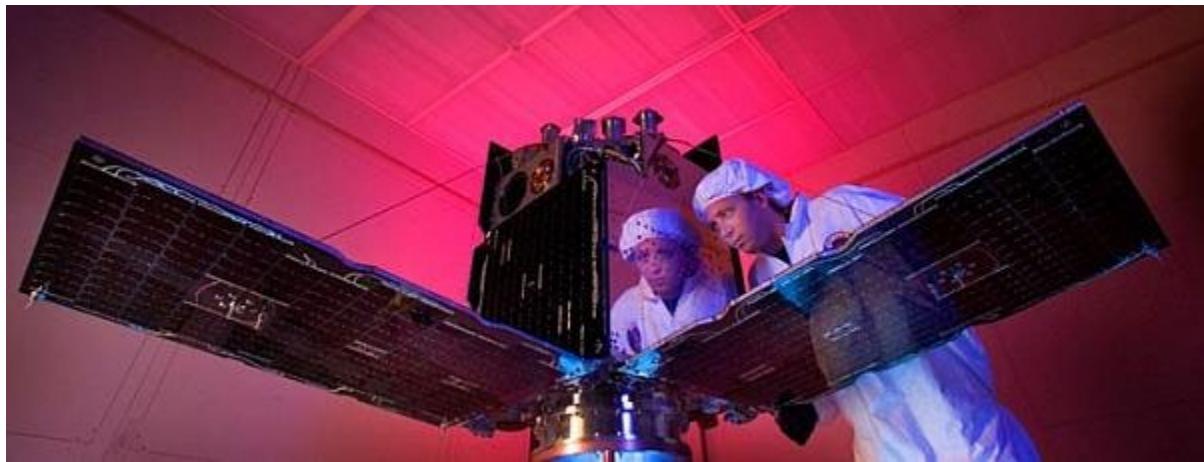


Figure 2 The Cibola Flight Experiment is a small, meter scale size, spacecraft that operates in a nearly circular, 560 km altitude, LEO orbit. The spacecraft is 3-axis stabilized and provides pointing stability within $\pm 0.5^\circ$ and pointing knowledge of 0.1° . This image of the spacecraft clearly shows that it has multiple surfaces that can generate glints.

The count profile (figure 3) extracted from the CFE glint detection image shows the glint intensity reaches a level of about a factor of $\sim 37x$ over the baseline brightness of the satellite bus. The duration of the glint was a few seconds — much shorter than a stabilized satellite can generate in a high-altitude orbit. However, the rapid angular motion of RSOs in the LEO orbital regime means that even glints as short as 0.2 seconds will appear as short streaks in the image sequences collected by W-FAST. Sub-second glints from LEO RSOs will only appear “point-like” in optical sky monitors with poor—several arcminutes or worse—spatial resolution.

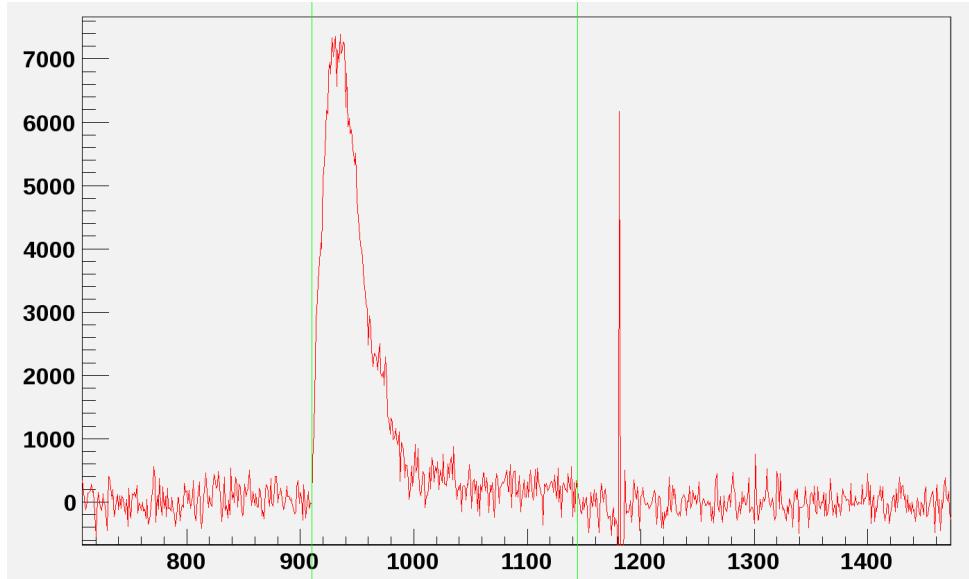


Figure 3. The counts/pixel length collected along the satellite track provides information about the light curve of the glint. The green vertical lines show the satellites position during shutter open and shutter close, 10 seconds later. Assuming constant angular velocity during this short interval, this LEO glint had a duration of a few seconds. The narrow spike near 1180 is an image subtraction artifact.

The most likely explanation for the sub-second glints is that they are generated by spinning or tumbling high altitude RSOs. A single flat (mirror-like) surface attached to a spinning RSO will produce repeating sub-second glints with duration:

$$F_{duration} = \frac{P_{rot}\Theta_{sun}}{2\pi} = 0.042 \left(\frac{\text{Spin Rate}}{1 \text{ RPM}} \right)^{-1} \text{ seconds} \quad (1)$$

where Θ_{sun} = Solar angular radius and P_{rot} = RSO rotation period.

The typical sub-second flash durations of 0.1-0.3 seconds therefore require spinning angular velocities of $\sim 0.8\text{-}2$ deg/sec.

A single mirroring facet, spinning, high-altitude RSO would produce repeating, point-like, sub-second flashes that move on a trajectory determined by the RSO orbit motion and separated temporally by the duration of spin period. Nir et al. [2] found that many of the sub-second flares detected in the same monitoring field could be linked into groups with locations consistent with straight line trajectories. Further, while the grouped glints did not display the

strict flash periodicity expected for a simple spinning mirror, the flash locations in the group often moved at a rate expected for objects at GEO ranges. This suggests while many of the spinning progenitors are GEO RSOs, they also must have multiple glinting surfaces [7]. But it is important to emphasize that both the W-FAST and Evryscope surveys also found examples of ultra-short flashes that did not repeat. This suggests that some of the glint sources are not spinning, but tumbling RSOs; located at unknown high-altitude distances. The progenitors of sub-second flashes in the night sky therefore most likely belong to a poorly characterized population of spinning/tumbling space debris residing at altitudes where no natural removal mechanisms exist. As such, they pose a poorly quantified risk to operational satellites.

3.0 RANGING THE GLINTS WITH STEREOSCOPIC IMAGING

. At LANL, we pioneered real-time discrimination between astrophysical transients and foreground RSO (satellite) transients using stereoscopic ranging [8,9]. The ranging concept is simple and is illustrated in figure 4. Identical, but spatially separated, telescopes are synchronized to simultaneously image the same sky field. Requiring joint detection of a transient candidate by both telescopes allows one to reject false positives from cosmic ray hits and other image artifacts in a single exposure time interval. And the parallax shift observed in the stereoscopic image pair allows one to measure the range of the flash source.

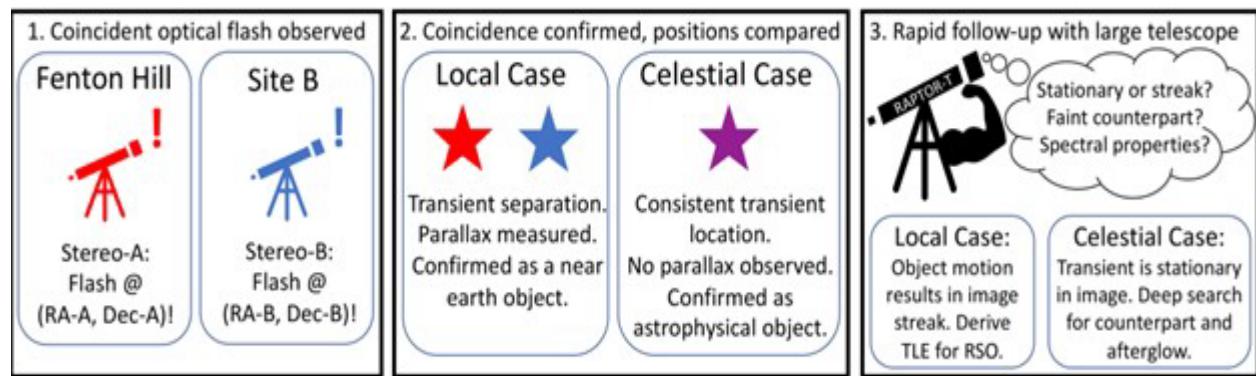


Figure 4 Using identical, autonomous, telescopes that view the same sky field from different locations, one can distinguish foreground RSO glints from astrophysical flashes on an event-by-event basis. This enables efficient distance and spatial distribution measurements of the poorly characterized sub-second glint population as well as the identification of astrophysical flashes in regions outside the earth's shadow. The cartoon inset outlines the process for discrimination between an astrophysical flash and a RSO glint and how, ultimately, we plan to conduct real-time follow-up based on the nature of the transient.

Distance between the telescope sites and spatial resolution of the images are key factors that determine the system's ranging capability. Our design goal was to establish a capability to range sub-second glints out to Cislunar distances. To meet that design goal, we have deployed telescopes, separated by 38 kilometers, that provide arcsecond spatial resolution. For flashes detected near the local sky meridian (i.e., no correction for projected baseline), figure 5 shows the parallax, range, and range uncertainty that telescope separation enables.

The telescopes we are deploying in the stereoscopic system, when equipped with the high frame rate CMOS imagers we discuss in section 4.1, can detect sub-second flashes as faint as 9th to 10th magnitude depending on sky conditions at the two sites. If we assume the glinting surface is a simple flat reflecting surface, we can then estimate the minimum size and/or maximum range of detectable glint surfaces using equation 2 (see e.g. [10]):

$$m_{\text{flash}} = m_{\text{sun}} - 2.5 \log \left(\frac{A_{\text{obj}} L^2}{\pi \Delta_{\text{obj}}^2 \Theta_{\text{sun}}^2} \right) \quad (2)$$

or, in practical units

$$m_{\text{flash}} = 8.4 + 5.0 \log \left(\frac{\Delta_{\text{obj}}}{37,000 \text{ km}} \right) - 5.0 \log \left(\frac{L}{3 \text{ cm}} \right) - 2.5 \log(A_{\text{obj}})$$

where m_{sun} = sun's apparent magnitude; Θ_{sun} = Solar angular radius; Δ_{obj} = object range;

L = projected scale size of surface; A_{obj} = surface albedo

Our stereoscopic ranging system should be capable of detecting and ranging GEO glinting surfaces as small as 10 cm. Detecting and ranging glinting objects at cislunar distances will be limited to meter sized or larger glinting surfaces.

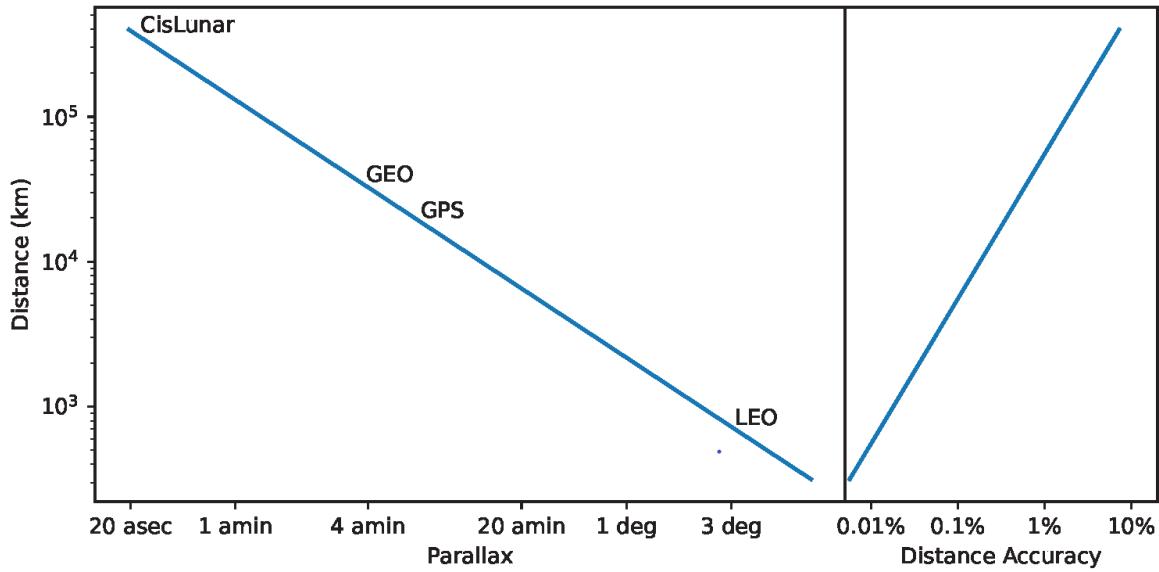


Figure 5. The distance and accuracy of the distance estimate for RSO sub-second flashes as a function of the measured parallax. This calculation assumes the telescopes are deployed with a 38-km separation and the viewing direction is near the meridian. Imagers with arc-second resolution would enable distance measurements for detected flashes out to the cislunar orbital regime.

4.0 CONSTRUCTING A STEREOSCOPIC RANGING SYSTEM FOR SUB-SECOND FLASHES

We have deployed two identical autonomous, wide-field, telescopes at dark, high-altitude, sites that are separated by 38 km (figure 6). One telescope is located near the Los Alamos Neutron Science Center (LANSCE) at an elevation of 7,320 ft in Los Alamos, New Mexico. The other telescope is located at the Fenton Hill Observatory site in the Jemez mountains at an elevation of 8,720 ft. Our baseline is almost due east-west; with an east-west length of 37.98 km and a north-south length of 1.33 km.

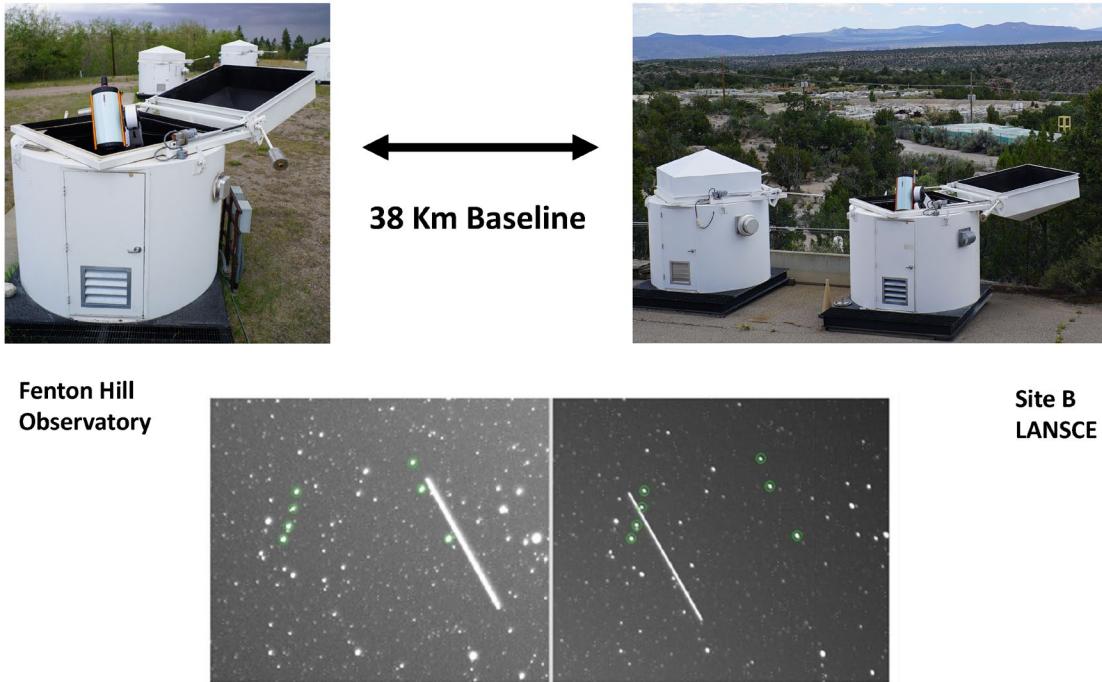


Figure 6. The stereoscopic imaging system employs two identical wide-field telescopes that are deployed at sites separated by 38 km. The two sky images of a LEO satellite were taken simultaneously during stereoscopic imaging experiments using that same 38 km baseline. To show the parallax shift of the satellite streak with respect to the background stars, we have circled (in green) a set of matching star patterns.

The telescopes are deployed in fully autonomous enclosures that are re-purposed from our first-generation RAPTOR stereoscopic ranging system [8]. They employ a suite of environmental sensors that halt operations under adverse conditions and close the enclosure hatch to protect the telescopes when environmental threats arise. For example, in the springtime, both observatory locations are often subject to high winds so, to avoid damage, wind velocities more than 30 mph force automatic system shutdowns. A Davis weather station provides measurements of wind velocity, direction, temperature, humidity, barometric pressure, and the dew point. Precipitation is sensed with a Vaisala DRD11A rain detector. Loss of power is another common threat, and each enclosure contains a back-up UPS power supply with sufficient capacity to close the enclosure hatch and secure the telescope whenever power is lost.

4.1 Fast-frame-rate CMOS cameras

While you can detect fast transients with slow frame rate cameras, the detectability of a given flash is decreased because the apparent magnitude of the flash is increased by the factor:

$$m_{\text{diluted flash}} = m_{\text{flash}} - 2.5 \log \left(\frac{F_{\text{duration}}}{T_{\text{exposure}}} \right) \quad (3)$$

where F_{duration} = Flash Duration and T_{exposure} = exposure time.

For efficient detection, one therefore wants to make the exposure times comparable to the expected flash durations. Efficient detection of the sub-second flashes discovered by W-FAST therefore requires cameras capable of running at frame rates higher than three frames per second.

We employ QHY 600M-Pro CMOS monochrome cameras in our stereoscopic glint ranging system. This camera employs an electronic shutter that provides full frame readout speeds of 4 frames second for the full 16-bit native A/D converter and up to 9 frames per second in 14-bit mode. The camera utilizes a full-frame (36 mm x 24 mm) Sony IMX 455, back-illuminated, CMOS chip as the sensor. This 60 Megapixel monochrome chip has 3.76-micron square pixels that reach > 80% quantum efficiency near the peak at a wavelength of 525 nm. The well depth of the pixels is 51K electrons and the read noise is 1 (high gain mode) to 3.7 electrons (low gain mode). The cameras also employ a dual stage, thermoelectric, cooler and achieves a dark current of 0.002 electrons/pixel/sec at -20 C.

To achieve the high frame rates needed for sub-second flash detection, the camera requires a special PCIE frame grabber card that enables an optical 2x10 gigabit fiber port connection for data transfer to the acquisition computer. Our data acquisition computers were constructed by Titanus Technologies and have an Intel core i7 3.6 GHz processor with 8 cores and 64 GB of 3600MHz DDR4 memory. These machines have a 4U rack mounted chassis and are deployed in the telescope enclosures. Precision timing for the frames is provided by a GPS timing unit that is built by QHY for the QHY 600M-Pro camera.

4.2 Optical Tube Assemblies (OTAs)

The telescopes at both sites employ a 36-cm Rowe-Ackermann Schmidt Astrograph (RASA) optical tube assembly (OTA) that is manufactured by Celestron corporation (see figure 7). To optimize efficiency, our flash survey requires an OTA with an effective aperture larger than ~30 cm and the largest field-of-view (FOV) possible. Using extra-low dispersion glass in a 4-element lens group, the RASA design provides a fast, f/2.2, focal ratio and enables sharp imaging (spot size < 6.3-micron RMS) across a large 60 mm diameter image circle with modest vignetting (~17% at edges). Focus control is provided by an automated focuser designed and manufactured specifically for the RASA OTA by Starlight Instruments. An unconventional aspect of the RASA design is that the image plane is opposite the primary mirror—requiring mounting of the camera at the front end of the telescope. The QHY 600 Pro camera body is a slim, 90mm diameter, 170mm long cylinder that is specifically designed to minimize incident light blockage when mounted on a RASA OTA. Deployed on the RASA 36-cm OTA, it provides a 4.54 sq-degree FOV (2.61-degree x 1.74 degree) with a single pixel IFOV of 0.98 arc second.



Figure 7. A RASA 36-cm optical tube assembly deployed on a PlaneWave L-500 mount at our Fenton Hill observatory site. These COTS components and the rapid advances in high frame rate CMOS camera technology are now making wide field searches for sub-second optical flashes in the night sky practical.

4.3 Fast-Slewing Telescope Mounts

The RASA OTAs are mounted on L-500 direct drive mounts from PlaneWave Instruments. The direct drive motors and on-axis encoders of the L-500 mount enable rapid slewing at speeds of 50 deg/sec and tracking of even fast-moving Low Earth Orbit (LEO) satellites. The mounts can carry payloads of up to 200 lbs. With an OTA weight of 75 lbs. and camera/cabling of 5 lbs., we are operating well within the load capability of the L-500 mount. Both mounts are deployed in the enclosures on rigid steel piers topped with wedges that allow the mounts to operate as equatorial mounts.

4.5 Glint Recognition: Edge Sensing with a Particle Accelerator Style Approach to Data Management

Two of the so-called “V’s” of big data, velocity and volume, pose significant challenges to our wide-field surveys for sub-second optical flashes. The software pipeline, illustrated in Figure 8, plays an essential role in the discovery and follow-up of sub-second optical flashes. This pipeline starts by consuming images as they are acquired to generate transient candidate locations. When a pair of candidates are received with consistent timing, it is probable that a sub-second optical flash was detected. The coincidence will then generate an alert for immediate follow-up observations at the location of the suspected flash. It also queries the pair of sites for the data from the image stacks containing the transient, collecting the “postage stamp” of data local to the transient from both telescopes. This data is then collected into a nightly report of sub-second flashes, to review by eye. This immediate data reduction and reporting allows us to assess survey and instrument performance daily.

Much of the required image analysis is on hand as part of our existing real-time pipeline, but that pipeline takes seconds to process images, while also containing precision photometric and astrometric analysis components not required for our application. We are therefore adapting our existing transient identification code and plan to boost performance by tuning to our very specific high-frame-rate application. For example, we are exploring the use of pre-computed analysis products based on pointing, and segmenting images into sub-frames allowing for trivial parallelization of the analysis. The goal is to develop an ultra-fast pipeline that performs image differencing across image sequences to derive possible transients and their location. An instance of this high-speed pipeline will run at each observing site. We expect that running this pipeline in real-time at the image acquisition rate (using stacks of 10 images, running at 8 Hz: process 9.6 GB per second) may require the use of GPUs (Graphics Processing Units).

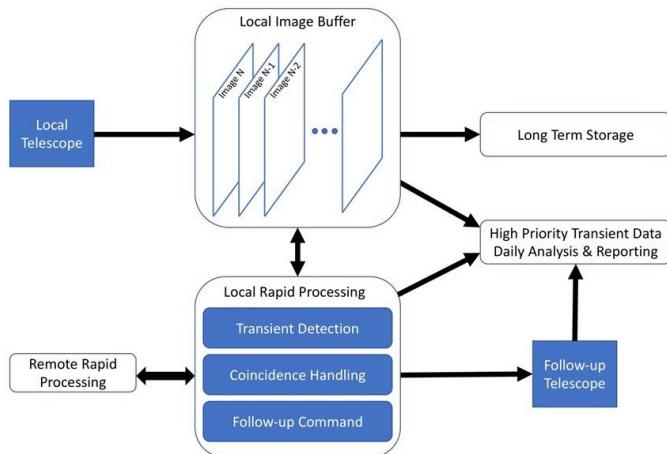


Figure 8. The processing segments and information flow between the optical ranging telescopes and the follow-up telescope.

We are also developing software to provide crude, but real-time, orbit estimation using our range measurements of RSO generated flashes. The point-like nature of the sub-second flashes from RSOs means that the traditional streak-based angles only approach to orbit estimation will not work. We are therefore developing a new approach to orbit estimation that employs the parallax range information from the joint detection and, whenever possible, grouping of detected flashes along a straight trajectory. The ability to estimate the orbit of the glinting RSOs will enable real time follow-up on the sub-second flashes to search for a fainter RSO counterpart.

5.0 FOLLOW-UP AND FLASH COLORS

For rapid follow-up observations of glint generating RSOs, we plan to bring our RAPTOR-T(technicolor) telescope at the Fenton Hill Observatory site back on-line. RAPTOR-T is an array composed of four OTAs that are co-aligned and co-located on a single rapidly slewing mount (see figure 9). The four COTS tube assemblies are 0.41-meter f/5 telescopes (with commandable filter wheels) that together yield an effective aperture for RAPTOR-T of 0.82-meter. Each telescope employs a CCD camera with a 1Kx1K Marconi back-illuminated chip, and all four cameras are synchronized to perform simultaneous multi-color or monochrome imaging. The array can be operated in: (1) unfiltered monochrome mode where the images can be co-added to achieve maximum sensitivity or (2) multicolor mode where each optical tube images the same field, but through a different ($g'r'i'z'$) Sloan filter.



Figure 9. The RAPTOR-T telescope will be used to conduct rapid follow-up observations of sub-second flash progenitors. The four co-aligned 0.41-m telescopes tubes can be used in a monochrome mode where unfiltered images are co-added to make the most sensitive observations or in multi-color mode to make simultaneous $g'r'i'z'$ Sloan color measurements.

The colors of the sub-second flashes are currently unknown. During the initial survey, we will be operating both telescopes in the stereoscopic pair without filters. However, as our studies progress, we will be installing a r' band Sloan filter on the LANSCE RASA telescope and a g' band Sloan filter on the RASA telescope at Fenton Hill. This will allow us to explore the colors of the sub-second flash population with the goal of obtaining a better understanding of the glinting surfaces.

6.0 CONCLUSIONS AND FUTURE WORK

The sub-second optical flashes recently discovered by astronomical sky surveys are likely a previously unknown class of ultra-fast glints from high-altitude RSOs. The salient evidence that drives that conclusion is statistical--the sub-second flash rate drops by more than an order of magnitude in the directions covered by earth shadow at GEO orbit altitudes. Generation of the 0.1-0.3 second duration, “point-like”, flashes at high-altitudes requires glinting surfaces on RSOs that are rapidly spinning or tumbling to produce instantaneous angular velocities of~ 0.8-2.0 deg/sec. To explore the properties and determine the distances of the glinting RSOs on an event-by-event basis, we have developed a stereoscopic imaging system optimized to efficiently detect sub-second flashes. The 38-kilometer separation of the telescopes coupled with the sensitivity and resolution of the collected images will enable the detection and ranging of glinting surfaces as small as 3-10 cm at GEO distances and glinting meter-scale surfaces out to cislunar distances. We will use this capability to characterize this poorly understood population of ultra-fast glint generating RSOs that seem to reside at distances where no natural removal mechanisms exist. This will allow us to better quantify the risk that they pose to operational satellites.

7.0 REFERENCES

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