

# **Towards routine uncued surveillance of small objects at and near geostationary orbit with small telescopes**

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## **ABSTRACT**

There is considerable interest in the capability to discover and monitor small objects ( $d \sim 20\text{cm}$ ) in geosynchronous (GEO) and near-GEO orbital regimes using small, ground-based optical telescopes ( $D < 0.5\text{m}$ ). The threat of such objects is clear. Small telescopes have an unrivaled cost advantage and, under ideal lighting and sky conditions, have the capability of detecting faint objects. This combination of conditions, however, is relatively rare, making routine and persistent surveillance more challenging.

In a truly geostationary orbit, a small object is easy to detect because its apparent rate of motion is nearly zero for a ground-based observer, and signal accumulation occurs as it would for more traditional sidereal-tracked astronomical observations. In this regime, though, small objects are not expected to be in controlled or predictable orbits, thus a range of inclinations and eccentricities is possible. This results in a range of apparent angular rates and directions that must be surveilled. This firmly establishes this task as uncued or blind surveillance. Detections in this case are subject to what is commonly called “trailing loss,” where the signal from the object does not accumulate in a fixed detection element, resulting in far lower sensitivity than for a similar object optimally tracked.

We review some of the limits of detecting these objects under less than ideal observing conditions, subject further to the current limitations based on technological and operational realities. We demonstrate progress towards this goal using telescopes much smaller than normally considered viable for this task using novel detection and analysis techniques.

## **1. INTRODUCTION**

Over the last few years, J.T. McGraw and Associates, LLC (JTMA) has worked toward the development and optimization of surveillance throughput of small telescopes for optical space situational awareness (SSA) [1-4]. These efforts have focused principally on LEO and MEO, where large apparent angular rates of objects create faint streaks; but in more recent years, we have worked to extend this to GEO and near-GEO domains. Our techniques to date have focused primarily on achieving moderate (by astronomical standards) survey depth, in terms of limiting magnitude, but covering large areas of the sky, usually thousands of square degrees per hour. Depth vs. coverage are the two fundamental aspects of any astronomical survey and are linked by the physically conserved quantity “etendue” that can and must be traded off to effectively match a system to a mission.

A natural question emerges about how well these techniques can be applied to detecting faint objects over a much more restricted area. This tradeoff is not relevant to lower orbital regimes of LEO and MEO, because these objects do not dwell long enough within the field of view, even for systems with very large angular coverage. If detecting these objects were merely so simple as pointing inexpensive COTS telescopes, drives off, toward the GEO ring and staring, everyone would be doing that. Blanket the planet with small telescopes – problem solved. Clearly it is not so simple.

Where then does this concept fail? How can one use modern detection systems to circumvent some of these limitations and then correctly optimize system design and operation to maximum mission benefit? Where do those limits extend and what is the near-term potential for small telescope GEO surveillance?

## 2. COST EFFECTIVENESS OF SMALL TELESCOPES

The appeal of using small telescopes for routine surveillance of faint objects in and near GEO is unmistakable. The nature of the GEO regime necessitates observing systems spread over the world, because some objects will never rise over the local horizon. Practical considerations of ground-based optical SSA must account for diversity in sunlight conditions, complexity of weather, intricacies of geopolitics, and the availability of dark sky sites with good infrastructure.

The current budget environment does not appear favorable to wide-scale deployment of large telescopes with capabilities beyond that which currently exists. Small telescopes offer unrivaled cost advantage over larger systems in terms of cost per square meter of collecting area. Surveillance systems incorporating up to 0.35m (14”) diameter optics can be assembled almost entirely from COTS components, so the advantage of COTS comes both in terms of cost and availability. Cost is minimized for COTS components by robust commercial competition and the economics of scale. These systems are also far more readily available than larger systems, enabling rapid deployment on the scale of weeks, and they can be readily shipped around the world.

As a first approximation, we can assert that, all else being equal, the capability of a surveillance system for detecting faint objects scales proportionally to both the collecting area of the optics and the exposure time. The simplistic interpretation is that a telescope of half the diameter of some reference systems requires four times longer dwell time to achieve the same sensitivity.

Couple that with the well-explored [5 & 6] effect that the cost of telescope systems scales proportionally to aperture diameter to some power larger than two, and the result is that four telescopes each with half the diameter of some reference system will be lower cost – even more so when the small systems are based on COTS components. Thus, there is cost pressure toward a larger number of smaller optical systems, so long as those systems are adequate to the task of the measurements required. Therefore, there is an ongoing need to probe the real limits of small COTS-derived SSA systems.

## 3. GOOD NEWS/BAD NEWS FOR THESE SYSTEMS

The recent history of small optical systems for SSA has shown great strides towards detector-based performance.

- **QE is high:** Affordable detectors with high quantum efficiency (QE) are now widely available as COTS and stock parts. In the past, large format, backside-illuminated detectors were cost-prohibitive for small telescope systems. These CCD sensors were individually mechanically thinned, with the thinning process being both labor intensive and risky, resulting in low production yield. Newer CMOS processes now offer backside-illuminated performance with more scalable manufacturing processes [7]. See Fig. 1 for a comparison.
- **Read noise is down:** sCMOS and EMCCD technologies are pushing to ever lower effective read noise characteristics, now commonly in the  $< 2 e^-$  range, and soon approaching the tantalizing point of photon counting. Because read noise contributes in quadrature to the total noise variance, this advance cannot be emphasized enough for the task of faint object detection on small telescopes where smaller collecting areas cannot achieve the sky-noise limit as quickly as larger systems.
- **Frame rates are up:** Again, both EMCCD and sCMOS technologies achieve their low read noise at rapid frame rates compared to more traditional CCDs, which suffered from ever increasing read noise with pixel read rate. Twenty years ago, a typical astronomical grade CCD was one megapixel, read out at 50,000 pixels per second with  $7 e^-$  of read noise, resulting in frame rates of up to a few exposures per minute, all at a cost of a few hundred thousand dollars. Today, commodity EMCCDs and sCMOS read out far larger images in a fraction of a second - and at a fraction of the cost.

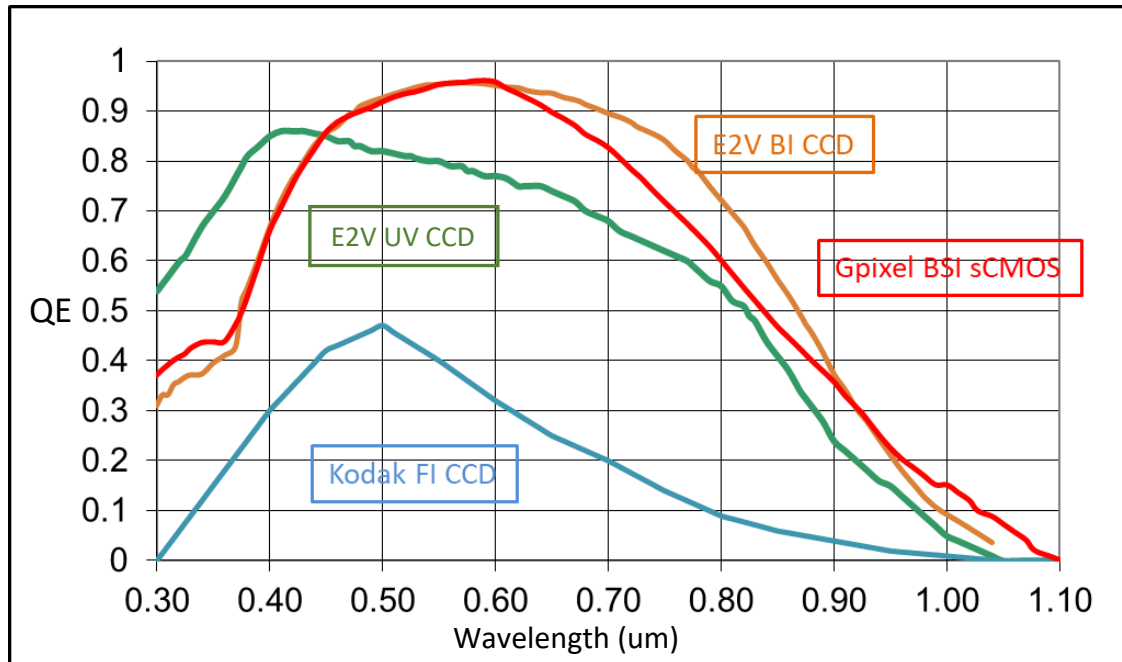


Fig. 1 – Sensor quantum efficiencies for various common devices are plotted versus wavelength. The lower blue curve was typical for sensors affordable on COTS SSA systems only a few years ago, whereas cameras with performance similar to the red curve are now available at costs feasible for small telescopes. The net gain in broadband sensitivity can easily exceed a factor of two.

- **Deadtime is all but gone:** sCMOS and interline-transfer EMCCDs can integrate and read out simultaneously with only a few microseconds of deadtime between frames. Coupled with the high frame rates described above, this leads to a significant increase in system throughput. This combination allows small telescopes to produce prodigious amounts of scientifically useful pixels.
- **Computation is cheap:** The deluge of available pixel data can be as much a curse as a blessing when useful measurements cannot be extracted from them in a timely manner. Fortunately, computer hardware continues to advance at a truly prodigious rate, making ever more advanced computational and image processing techniques both possible and affordable. This is key to the success of small telescopes for SSA. The affordability argument unravels if a supercomputer per telescope is required to process the resulting data.

The net result of these factors is that small telescopes are ever more capable and components that didn't used to scale well to smaller systems, such as detectors, now are affordable and plentiful. This moves the optimization problem closer to the ideal where all else is equal and area can be traded for observing time.

On the other hand, there are still a few less favorable factors.

- There's no magic left. The major limiting factors holding back small telescopes have been overcome. Near-miraculous advances in detector sensitivity can't ever make a detector with >100% QE, however. If you want a signal-to-noise ratio of 6, you must measure at least 36 photons.
- Optical manufacturing is a very mature business and, barring some as-of-yet elusive 3D printing for large, precision optical components, there is unlikely to be much change in cost of making big telescope systems. It is unlikely that wide-field telescopes larger than 0.5m will be COTS parts any time soon.
- Some gains could be made with better optical coatings applied to large optics. For small, optical bench-scale optics (~50mm), very high reflectivity broadband mirror coatings are now common. Hardly a miracle, but the gain from these coatings could add 10-20% more detected light if their application could be made

affordable on large mirror substrates, which also presumes these could be made to withstand observatory environments.

- Lastly, available detectors still limit the optimization space for small SSA systems. More and bigger commercial sensors are on the horizon, so this soon will move into the good news category.

#### 4. THE JTMA DETECTION SYSTEM

If the space for miraculous technological leaps has been explored, all that is left is to take the remaining imperfect components and combine them into the system most effective at achieve mission goals. To that end, JTMA has built and operates a 0.35m (14") optical system originally designed for uncued LEO surveillance and more recently adapted to MEO, HEO and GEO. The original intent was to cover large areas of the sky, and thus detector operation and data analysis was tailored to obtaining a large number of relatively short exposures and then quickly repointing.

The underlying telescope system, as shown in Figure 2, is largely unchanged from our previous work. The optical system is a Celestron C-14 fitted with a Hyperstar prime-focus corrector, which operates at  $f/1.9$  and delivers a  $1.88^\circ \times 1.88^\circ$  field of view onto the GPixel GSense400BSI sensor. The 11 $\mu$ m pixels subtend 3.32" and have a measured median read noise of 1.8 e-. The camera is thermoelectrically cooled to -10 C, which is sufficient to make the dark current for most pixels negligible, and the rest are readily masked. The sensor is housed in a Tucsen Dhyana 95 camera operated via USB 3.0, which is required for the high data rate, which can exceed 100 megapixels per second.



**Fig. 2 – This 0.35m optical system is currently deployed at JTMA's R&D site just outside of Albuquerque, NM. The system is based upon a 14" Celestron SCT with a Hyperstar prime focus corrector.**

## 5. SOME COMPLICATIONS

There are a few complications involved with longer observations of objects that are nearly, but not exactly, geostationary. The effect of trailing loss on signal-to-noise is to dilute both the per-pixel signal-to-noise and the integrated signal to noise, factors which are well understood. A mismatch between the expected object rate used for measurement and the actual rate can lead to streaks. We've treated this in our previous work, but a quick rule of thumb for faint detection is that the per-pixel signal-to-noise is reduced by the length of the trail, and the streak-integrated signal-to-noise is reduced by the square root of the length. Thus, even short streaks hamper detection. Longer exposures trail more readily because the velocity mismatch has more time to grow the trail.

It is important to note that the target we are concerned with here, small objects in GEO, are most likely to be debris that is almost certainly not in a controlled orbit. Therefore, a wide range of velocities are possible. Other objects of this same optical signature in the GEO regime, but that can maneuver, are interesting as well, if for entirely different reasons. So, this issue must be addressed even for systems that stare to detect GEO rate objects. No object is exactly geostationary, and thus there is always a limit to integration time before an object trails.

In a case where a 15 arcsec/s rate is expected, a 1% rate difference accumulates into a one-pixel relative motion over ~20s. For our wide-field SSA system, this will still integrate effectively as a point source. Over a 60s exposure, the same 1% rate differential results in a three-pixel-long streak, dramatically reducing detectivity. One can use these examples to develop a precision track rate that maintains detectivity similar to normal point source detection assumed earlier. The minimum trailing loss is assured if the object moves less than one pixel in the integration time. In this way, longer integration times place ever tighter limits on target velocities to maintain optimum sensitivity.

Narrow-field systems with good seeing conditions will suffer worse trailing losses in such a case. This somewhat offsets the advantage these systems have in minimizing sky background contribution per pixel relative to the noise budget that is gained from a tight point-spread function.

If we determine that our small telescope needs 60s of exposure time to create a significant detection of a faint target under the assumed conditions, and our system has 3.32 arcsecond pixels, we can maintain maximum detectivity on objects in near-geostationary objects that are within +/- 0.05 arcseconds/s of the nominal GEO rate. This sets the resolution of a grid of potential object velocities that must be analyzed and shows how quickly this problem can become computationally daunting, even given the resources available.

## 6. OBSERVATIONAL SETUP

To test our deep imaging mode, we started with some of the fundamental limits of our optical and computational hardware. To maximize the individual signal-to-noise ratios of each frame, the exposure time is limited to the approximate crossing single-pixel crossing time of a geostationary object while in sidereal tracked mode. For this setup, we used 0.25s exposures to stay close to this criterion.

Our current computational resources use only a single NVidia Titan Xp GPU processor. This card has built in 12 GB of RAM, which limits the total number of pixels that can be analyzed simultaneously. There must be enough free memory for the input image, an output array and some left over for intermediate calculations. Roughly speaking, this means that the input image data needs to be less than ~1/3 of the total available RAM. This limits the amount of image data we can readily analyze to about 4 GB, or 1 gigapixel, using single-precision values. For our 2048 x 2048 detector, this is a stack of 256 exposures.

A full exploration the velocity space for uncued detection requires the testing of a dynamic range of possible object motion. We chose to target GOES-14 for our test because it is located near the 105 W GEO pinch point [8]. For this test, we are seeking a proof-of-concept verification rather than an exhaustive search, so we are intentionally choosing a location where debris is likely and its orbit inclination will be low.

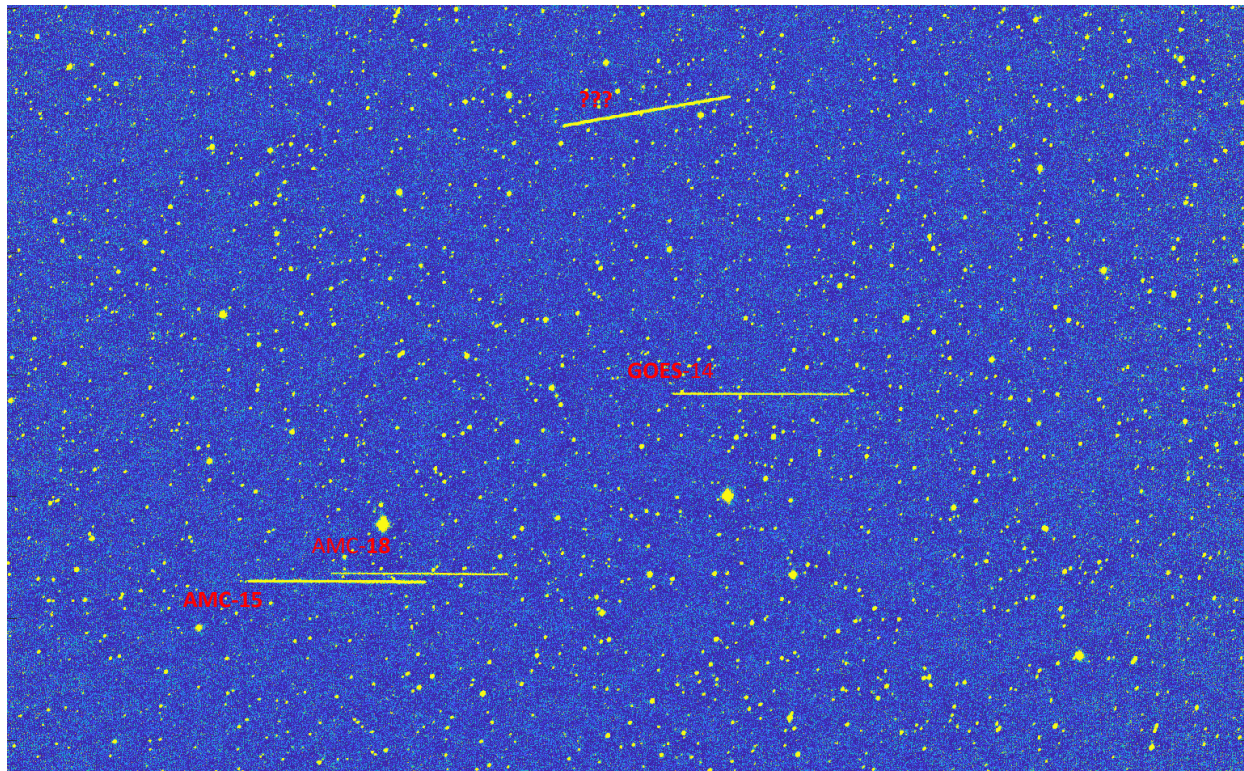
The image data used for these experiments were obtained on the night of September 1, 2017 under clear but bright skies (8 days after New Moon). The sky brightness near GOES-14 was approximately 19.3 magnitudes per square arcsecond, which is a fair approximation to the standard GEODSS sky brightness of 19.5 [9]. Moderately bright

skies offer a realistic test of real-world sensitivity, because although one might avoid the brightest of nights near Full Moon, a capability to detect faint objects needs to extend beyond the darkest possible skies.

Combining these limits, we end up with a net exposure time of 64s per stack. Under these conditions, we expect to be able to detect stars a bit fainter than 18<sup>th</sup> magnitude when the images are combined.

## 7. SOME EARLY RESULTS

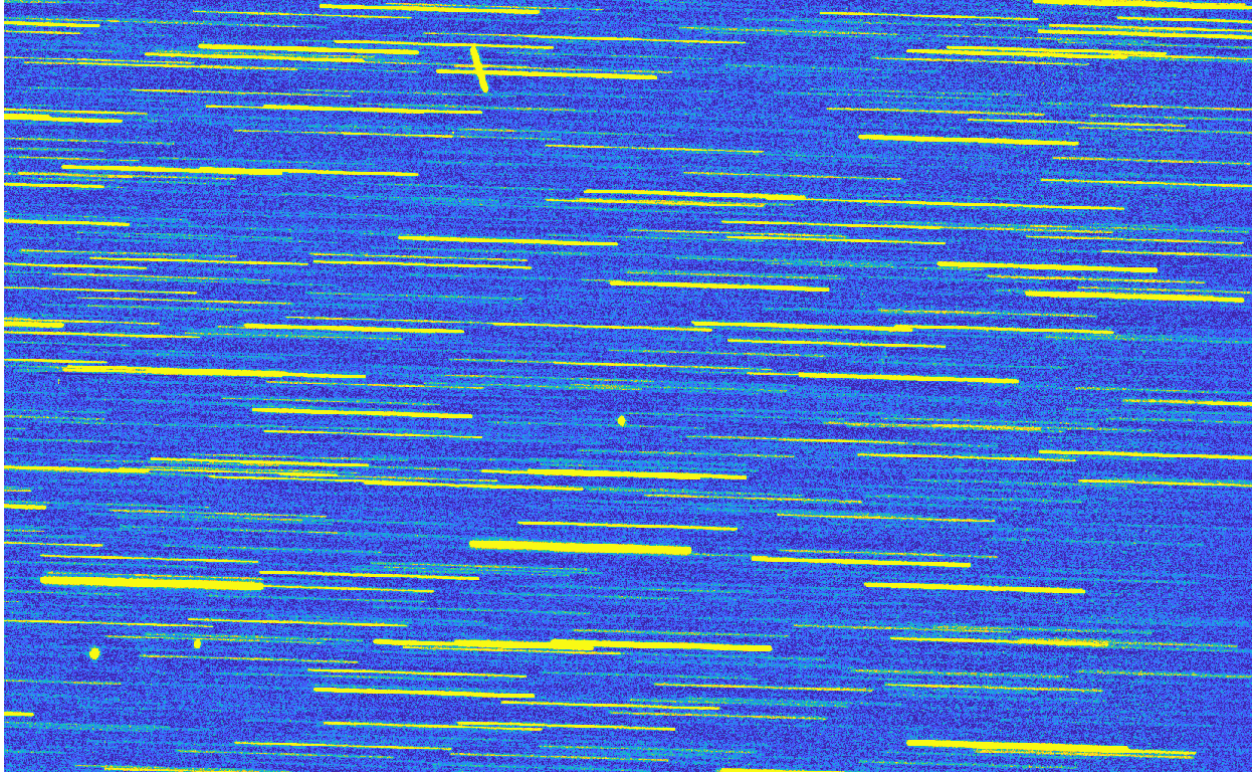
Figures 3 through 6 show some initial results of this analysis technique. All of these figures come from the same 256 frames, variously combined to detect different object rates. Figure 3 is a stack against the sidereal rate. Because these objects were tracked at the sidereal rate, the analysis rate here is zero. Stars appear as normal round point spread functions, and GEO and near-GEO objects streak.



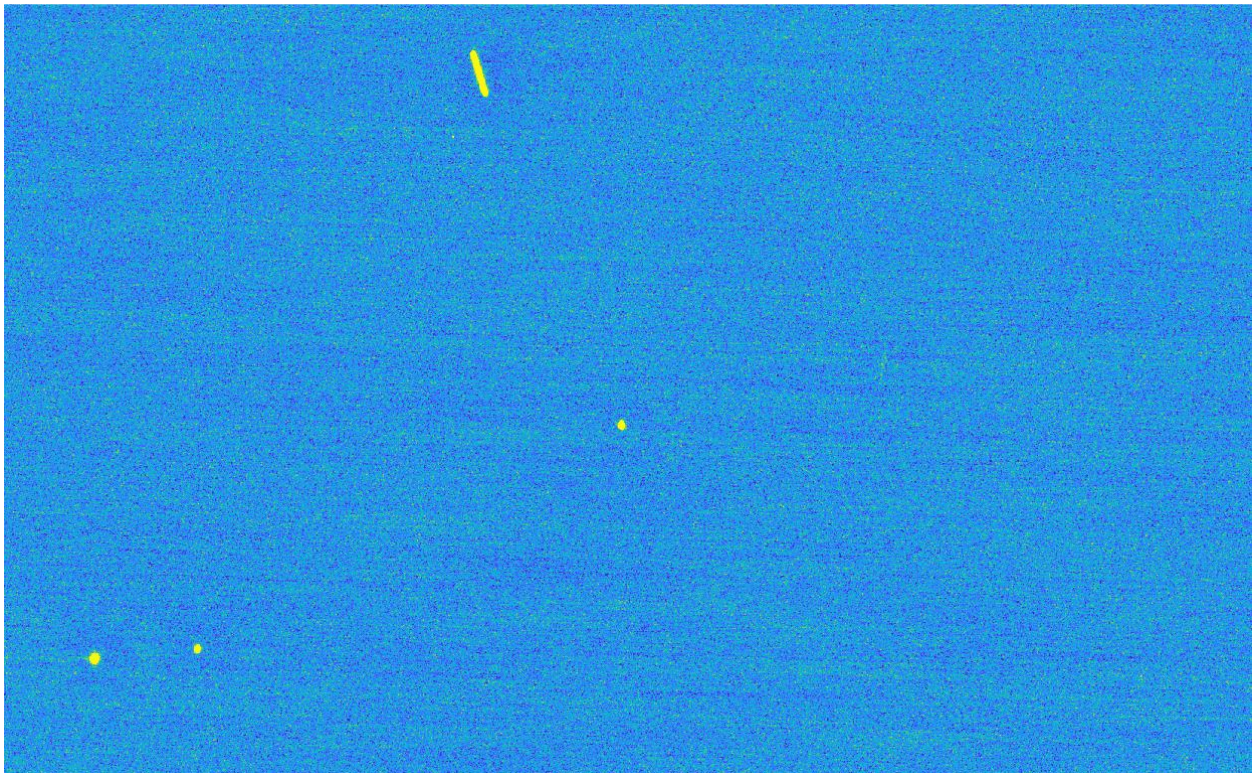
**Fig. 3 – Sidereal rate stack of images showing a moderate density star field, three easily identified geostationary objects and one bright near-geostationary object. The unidentified object is not in the public catalog but is bright enough that sophisticated analysis is not needed to detect it.**

Figure 4 is the same data but stacked again the geostationary rate. The geostationary objects now integrate into point sources, and stars form streaks. The near-geostationary object demonstrates how the relative motions add, but still can have appreciable differential angular velocity. Moreover, the streaked stars make a complex background upon which to detect objects.

In Figure 5, we've applied our proprietary star rejection algorithm to simplify the detection process. This shows the tremendous advantage of tacking short individual exposures. While there is a per-pixel noise cost in doing so, careful optimization can minimize this effect.

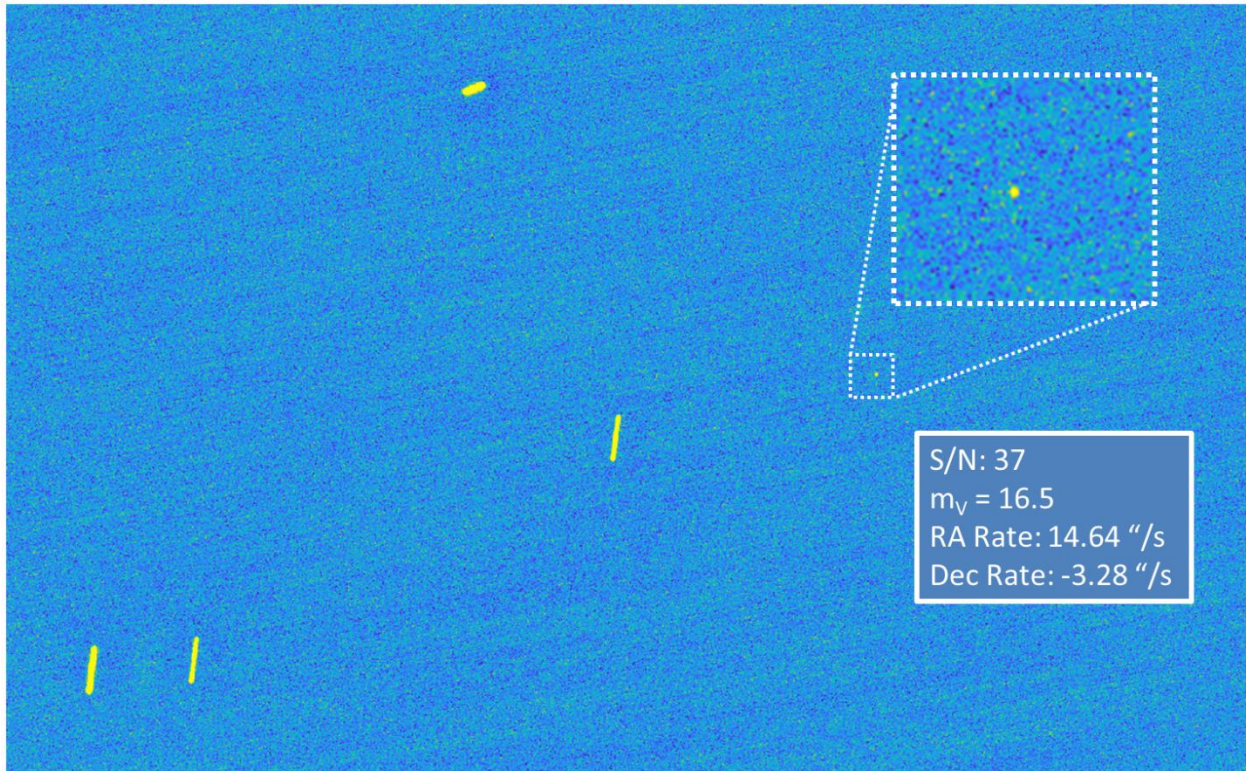


**Fig. 4 – Geostationary rate stack of images showing the streaked star field and the same three easily identified geostationary objects and one bright near-geostationary object.**



**Fig. 5 – Geostationary rate stack of images with stars rejected.**

The full analysis of this image stack revealed another near-geostationary object, shown in Figure 6. The astute eye might have noticed the faint streak in Figure 5. This object is not all that faint at  $m_v=16.5$  but would still be challenging for most traditional techniques. Its presence is confirmed in adjacent image stacks.



**Fig. 6 – Near-geostationary rate stack of images with stars rejected showing an object moving a bit more than 3 arcseconds per second with respect to GEO.**

## 8. ONGOING EXPERIMENTS

We are encouraged by these results, and they show the extreme of what large-scale image stacking can produce. The sensitivity limits of the demonstrated mode are  $m_v < 18$ , and that level can be maintained for a search rate of 180 square degrees per hour. Uncued detections for near-geostationary objects should hold for objects moving up to 22 arcseconds per second, or 7 arcseconds per second with respect to GEO.

Although it is currently outside of our computational capacity, very large stacks of images can be analyzed in this manner allowing for very deep surveys, though at a proportionally survey rate. Luckily computing power is the one component of a small telescope based SSA system that has almost boundless room to grow.

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