Precision Tracking of Decimeter Targets at GEO Distances using the Magdalena Ridge Observatory 2.4-meter Telescope

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ABSTRACT

With the anticipated proliferation of cubesats reaching GEO in the coming years, the capability of detecting and tracking decimeter-sized targets at these distances will become increasingly important. We report here on efforts to develop this capability using the Magdalena Ridge Observatory (MRO) 2.4-meter telescope. Although the reported tests focus on small debris, these techniques will be equally applicable to active satellites. In this work, we present the results of the detection of decimeter-sized targets in single exposures using the MRO 2.4-meter. We then explore the extension to deeper magnitudes resulting from the utilization of synthetic tracking.

1. INTRODUCTION

Researchers at the Magdalena Ridge Observatory's (MRO) 2.4-meter telescope facility (see Fig. 1) have had an ongoing, comprehensive program to determine orbital and physical characterization information on objects in the near-Earth population (natural and artificial) for the past decade. The work includes astrometric follow-up and characterization of newly discovered asteroids and comets in the near-Earth region as well as the study and physical characterization of artificial satellites from the LEO to GEO zones. The effort in implementing both these tasks is highly synergistic: the same instrumentation and reduction/acquisition techniques are equally useful for observational studies of both natural and artificial targets. However, the focus of this work is to extend some of the more detailed approaches we have devised for acquiring data on near-Earth objects (NEOs) to faint satellites in orbit around the Earth at GEO altitudes.

MRO has leveraged a NASA-funded nightly astrometric follow-up program (for orbit refinement) to obtain physical data (primarily rotation rates and compositional determinations) on the most interesting, recently discovered periodic NEOs that come within a perihelion distance of 1.3 AU of Earth. This strategy allows one-of-a-kind, real-time access to the study of unique asteroids and comets before they leave the near-Earth vicinity. Fig. 2 illustrates two of the faintest and fastest moving asteroids we have studied to date, as well as one of the smallest asteroids (2016 CC_{136}, diameter ~5 meters).

Fig. 1. The Magdalena Ridge Observatory 2.4-meter fast-tracking telescope and support facility located outside of Socorro, NM on Magdalena Ridge. The observatory performs target-of-opportunity scientific research focusing on asteroids and comets along with work in the area of space situational awareness.

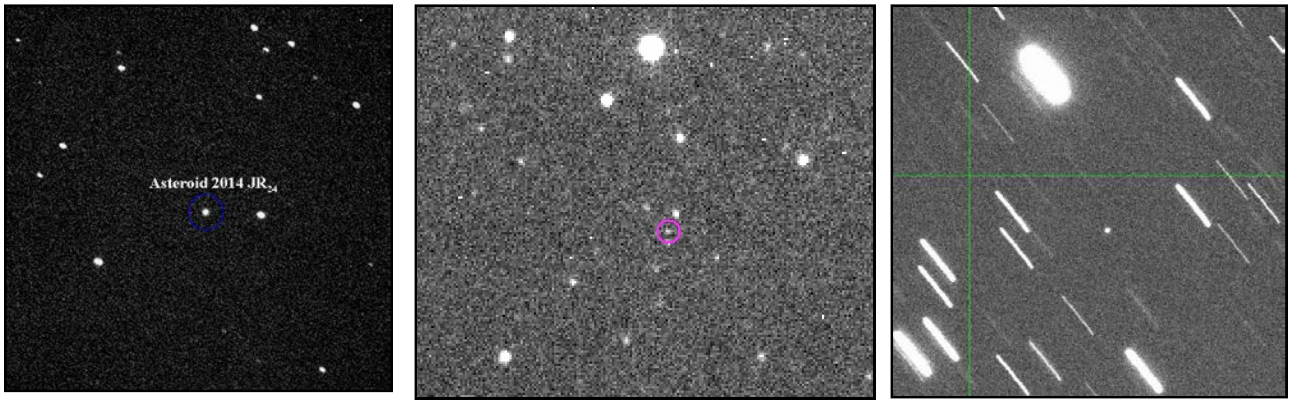

Fig. 2. Shown are images taken with the Magdalena Ridge Observatory 2.4-meter of Near-Earth asteroids 2014 JR_{24} (left) and 2012 XH (middle). 2014 JR_{24} was captured with a 0.5 sec exposure (at magnitude V~15.5) during its closest approach when moving ~300" per minute. Asteroid 2012 XH had a magnitude R=24.1, and was acquired in a single image with a 240 second exposure time. (Right) One of the smallest asteroids imaged, 2016 CC_{136}, (diameter ~5-6 meters), moving at ~100"/min.

The studies of asteroids and artificial targets meet when the asteroid actually comes so close to the Earth, it passes through the geosynchronous satellite zone. A case in point is asteroid 2015 VY_{105}. This object made its close approach to the Earth on November 15, 2015. Data taken using the MRO 2.4-meter telescope showed that although 2015 VY_{105} would come within approximately 200 km of the *DirectTV 11* and *14* satellites, it would fortunately not impact either [1]. Figure 3 captures this asteroid in the same frame as another satellite (*TDRS 3*) on its incoming (not yet closest approach) trajectory. It was only 24 hours after discovery that this asteroid would make its closest approach to the Earth and pass through the GEO belt.

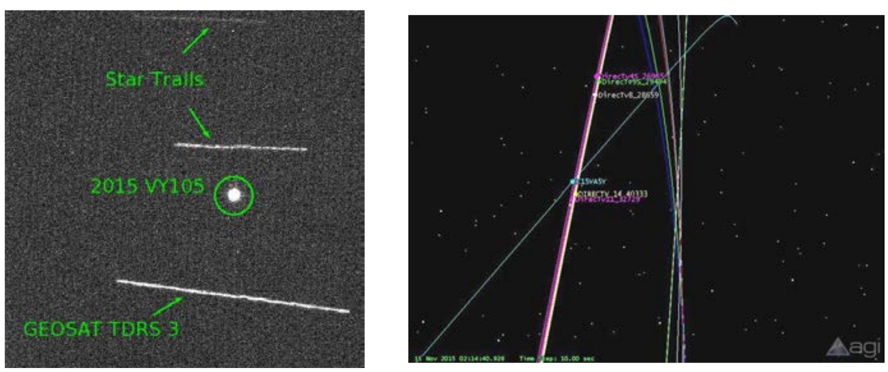

Fig. 3. (Left) Asteroid 2015 VY_{105} came within 0.1 Lunar distances (39, 494 km) of the Earth, and passed within the geosynchronous satellite belt. The image was taken using the MRO 2.4-meter telescope; the telescope is tracking on the asteroid such that stars appear trailed as does the satellite path. (Right) Orbit trajectory of 2015 VY_{105} (blue line) on November 15, 2015. Also shown are *DirectTV* satellites' paths in purple and white. (The image was generated using *AGI-STK 11* software.) The magnitude of the asteroid when the image was taken was V~18.5.

2. DETECTION AND ASTROMETRY OF GEO TARGETS

The purpose of this exercise was to examine the difficulty of folding in the acquisition of astrometric data on small *artificial* targets at GEO distances into the MRO 2.4-meter telescope operations paradigm. There are some differences with respect to imaging natural NEOs as opposed to satellites. Although they can move with respect to sidereal at rates up to thousands of are-seconds per minute, most NEO observations are taken when the objects is moving anywhere from typically a rate of one- to a few hundred arc-seconds per minute. These moderate speeds result in a detection limit for our facility of V~24 magnitude. Objects in or near geostationary orbit typically move much faster, approximately 900 arc-sec per min, or 15 arc-sec per second, with respect to sidereal motion.

Fig. 4 illustrates the detection of object the TITAN 3C Transtage debris object SSN #38692 at GEO in a single 3-second exposure image when the object had a visual magnitude of V~20.5; trailed streaks are background stars. The images as well as a radial profile of the object are shown as a quantitative confirmation of the detected signal. This demonstrates our capability to detect and keep custody of decimeter scale objects at GEO in extended exposures of 3-10 seconds. However, can we measure good astrometric positions on such targets?

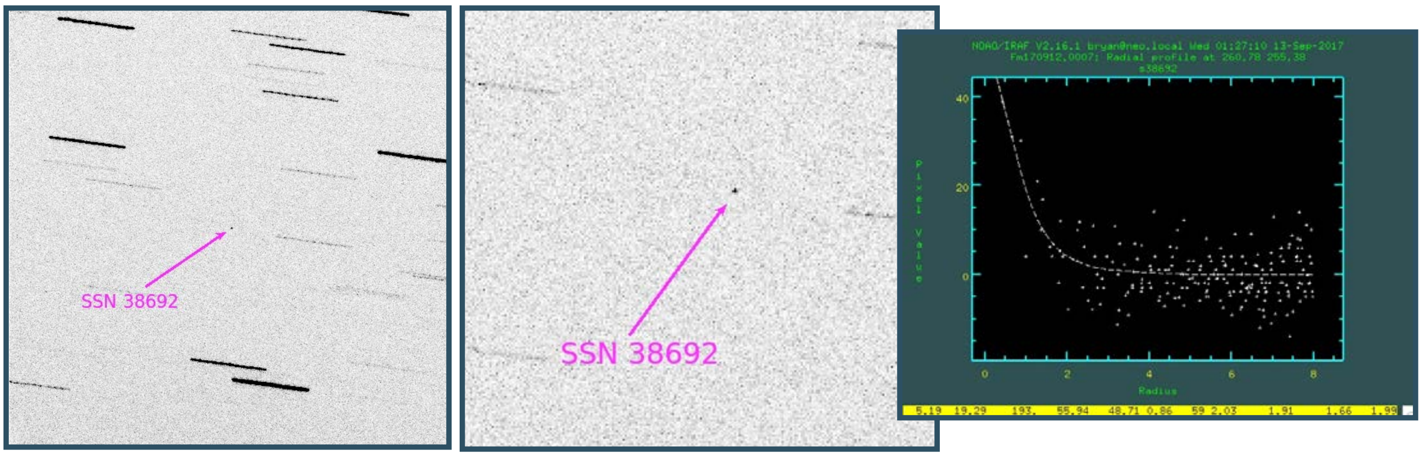

Fig. 4. Three-second images of 38692 (left) with enlargement (center) and profile plot of target signal (right). The solar phase was ~27°; magnitude was V~20.5.

Techniques do exist that make it possible to measure the center of the trailed reference stars. However, our experience has been that these can be error prone in less than perfect observing conditions. In particular, wind-shake of the telescope or variable seeing can cause the end points of these streaks to become ill defined, causing the midpoint determinations to become skewed. Therefore, we investigated the limitations that result from keeping exposure times at a half a second or less to avoid significant trailing of the field stars that are used as the metric fiducials. Using the MRO 2.4-meter, these exposure times permit detection to a visible magnitude of approximately V~20 or greater when tracking at or near the target rates such that the field stars appear nearly point sources for which a centroid can be accurately determined. Assuming an albedo of 0.2, this implies the detection of decimeter-scale targets.

Fig. 5 shows the same target as Fig 4 acquired using much shorter exposures (0.5 seconds) when the object has brightened to V~20.1. Since this is a marginal detection, we also show a sum of 4 such images to indicate the enhanced signal and also checked that object remained in the median image resulting from the same 4 frames (not shown). Convinced that the signal is real, we plot the profile to demonstrate that it is a measurable detection. In these images, the field stars are visibly elongated. However, reliable centroids can be determined utilizing elliptical apertures. For comparison, we also imaged SSN# 38692 with 0.2 second exposures a few hours later at a lower phase angle when it was much brighter at magnitude V~17.9 and SSN# 39688 at V~17.1 using only 0.1 second exposures. Fig. 6 shows example of these images where the targets demonstrate clear detections. At these exposure times, the background stars are only slightly elongated and sufficiently large circular apertures can be used for positional measurements.

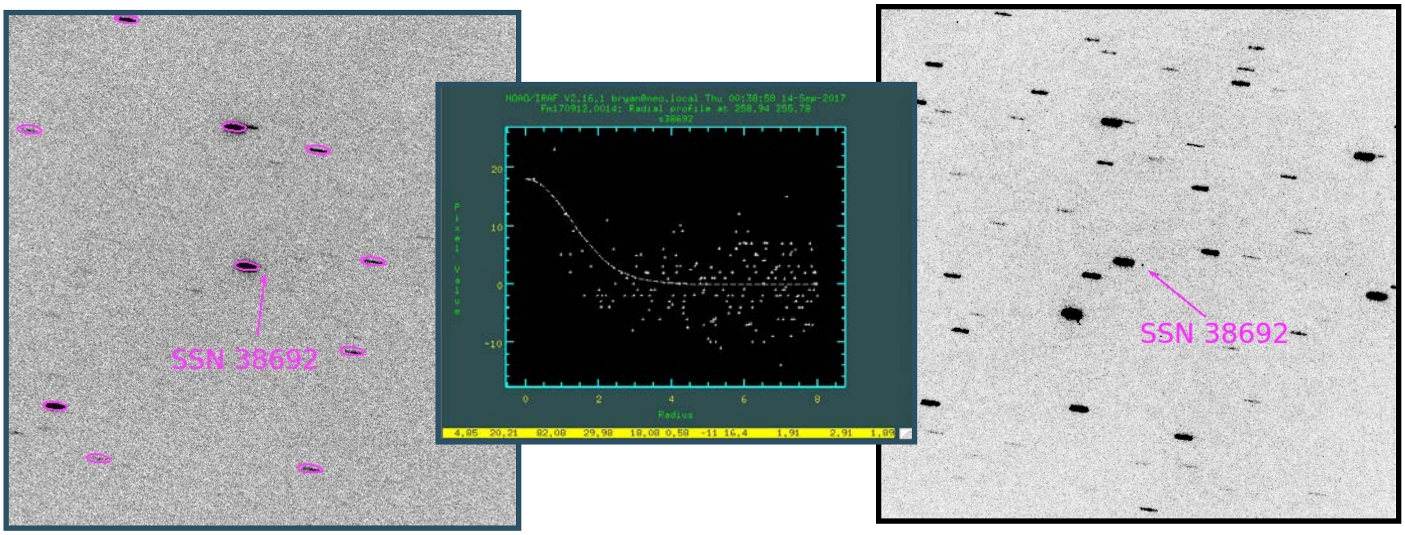

Fig 5. (Left) Shown is an image set appropriate for astrometry: a 0.5 sec image of SSN #38692 with radial profile (center) and a summed stack of 4 images (right).

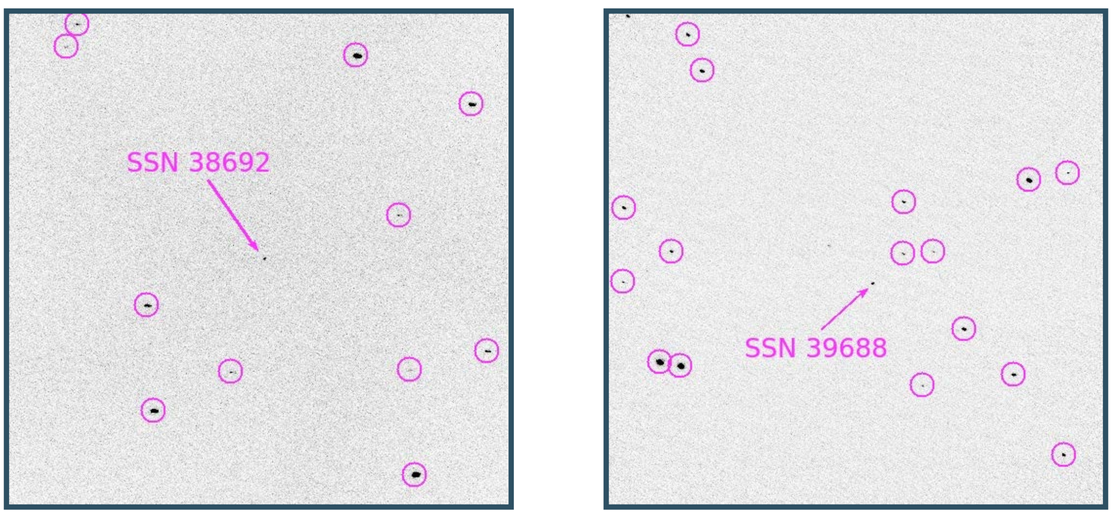

Fig. 6. Shown above is a 0.2 second exposure of object SSN #38692 at V~17.9 (left), and 0.1 sec exposure of SSN #39688 at V~17.1 (right).

To determine the astrometric positions of the targets, an analysis pipeline utilizing *SExtractor* [2], *SAO's WCS Tools* [3], and *NOAO's IRAF* [4] is used. *SExtractor* is used to extract the positions and magnitudes of the fields stars and *WCS Tools* is used to match these sources with reference stars to calibrate the pixel-to-celestial coordinate transformation. The photometric calibration is also done with respect to these same reference stars. Finally, *IRAF* is used to actually measure the positions and brightness of the targets in the calibrated images. There exists a Windows-based GUI tool, *Astrometrica* [5], and this software is very reliable when circular apertures can be used. Therefore, this tool is used for verification when applicable.

The open source *Project Pluto* library [6] is used to determine orbits from these observations and evaluate residuals of the astrometric data. Ephemeris data for the targets can then be generated and converted into a format that can be input directly into the telescope control system. This capability allowed us to perform quick sanity-check experiments. Astrometric data for SSN #38692 from 2017-09-11 and 12 were used to determine geocentric orbit resulting with mean residuals of 0.69 arc-sec. This orbit was then employed to generate an ephemeris of the target for 2017-09-13. In Fig. 7, we show that this pointing information based solely on the previous nights' astrometry resulted in the target being very close to the center of the field. This process proved that the astrometric techniques we were using were a success.

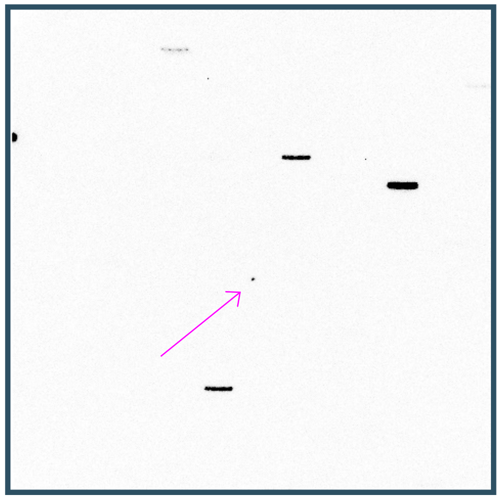

Fig. 7. Shown above is object SSN #38692. The satellite was observed on 2017-09-13 based on a generated orbit and not TLE (two-line element) data, validating the reduction techniques being used in our astrometric pipeline.

3. SYNTHETIC TRACKING

In Figure 5, we demonstrated the increase in target signal realized when co-adding frames. This was done by simply summing four 0.5 second exposures without any alignment corrections. This approach can work in cases where the target trajectory is well defined and we can rely on the telescope to accurately track the object. However, in general, we will not necessarily know the trajectory to sufficient precision to rely on the target residing on the same pixel position in each image. Therefore, we utilize a method that has come to be known as 'synthetic tracking', but has gone by the names 'shift and co-add', 'track and stack', and others over the years. There are many variations, but the end result is to strategically shift the position of each image such that the target is placed at the same pixel location in the summed image. This may be accomplished manually by guessing trial target motions, or systematically searching over the parameter space of likely motions.

Our implementation of this strategy is to perform the image sum after aligning images based on the *World Coordinate* (WCS) information associated with each images. The WCS information provides the transformation between pixel and celestial coordinates that is found by using field stars with cataloged known positions as reference stars as described in the previous section. In particular, the *SWarp* [7] software package will align images according to celestial coordinates and then sum them. Therefore, our procedure is to find the WCS solution for each image, calculate the offset from a reference position for every image based on a trial rate and direction of motion, then apply these offsets to the WCS terms for the image center (*CRVAL1* and *CRVAL2*) in each image. Then we simply sum using *SWarp* or other WCS-aware co-adding technique. An example of the result of this strategy is shown in Fig. 8 where four images with weaker signal shown in the upper image are shifted based on a trial rate and direction and then co-added, resulting in the stronger signal in the lower figure. As can be seen by examining the profile plots, the trial rate and direction were almost perfect in that the stellar width in the single images and the sum were almost exactly the same.

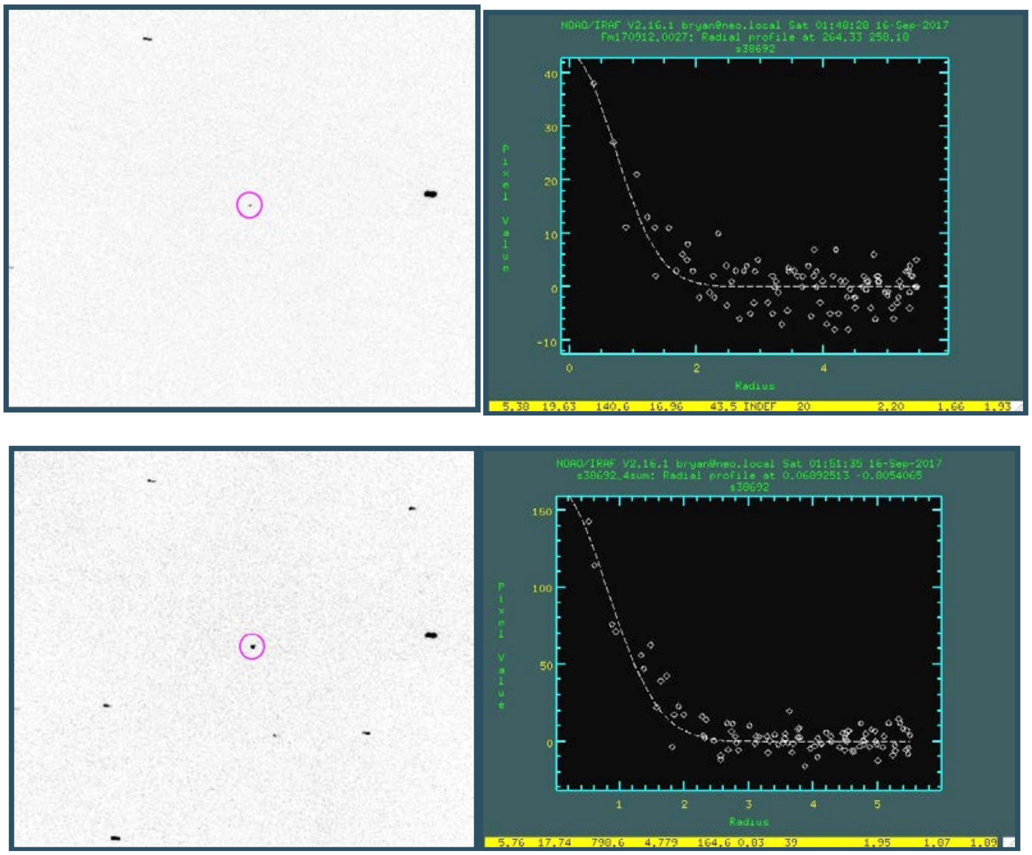

Fig. 8. (Top) The center of a single 0.2 sec image of the SSN #38692 field (left) with a radial plot of the detected object shown when it was of magnitude V~18.5 (right). (Bottom) Sum of 4 images (right) co-added after accounting for the motion of 888.3 arc-sec/minute @84.00°.

Clearly, this technique can allow for more robust centroiding measurements in low signal-to-noise data, resulting in more precise astrometry for the target. However, this technique becomes even more valuable when the target is hidden in the noise of the single images. The image in the upper left of Fig. 9 is one of a pair of 0.5-sec images of SSN #38692 where the target was not visible. However, when shifting the images assuming a motion of 908.0 arc-sec per min at a position angle of 82.4° and then coadding, the object becomes visible. This result is shown in the upper right image of Fig. 9. The bottom two images are an expanded view of the center of the summed image and a profile plot of the target signal.

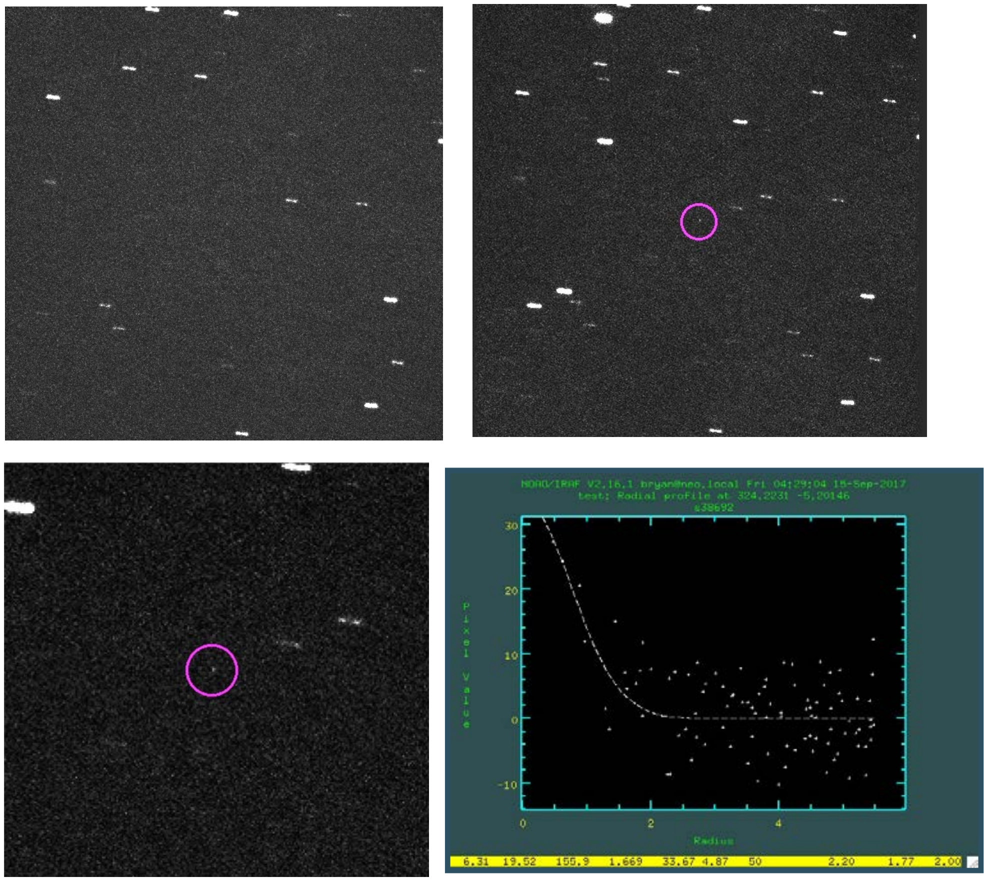

Fig. 9. Single 0.5 sec image of 38692 field (left). Pair of images (center) co-added with expanded view. Profile of target (right) after accounting or motion of 908.0 arc-sec/minute @82.40°.

4. SUMMARY

The same techniques for detection and characterization of natural objects such as asteroids and comets can be successfully applied to decimeter scale artificial targets in the geosynchronous satellite zone. In this paper, we have shown that using the MRO 2.4-meter telescope we can detect debris and other objects in GEO at magnitudes as faint as V~20 or fainter in single images for which reliable astrometry can be derived. We also demonstrated that employing strategic shifting of individual images based on anticipated motion of the target allows for this magnitude limit to be extended. Therefore, future development on this topic will explore the limitations of this synthetic tracking technique.

5. REFERENCES

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6. ACKNOWLEDGEMENTS

This research is funded in part through NASA's NEOO program.