

Detection, Tracking, and Characterization of Small, Faint Targets at GEO Distances using the Magdalena Ridge Observatory 2.4-meter Telescope

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ABSTRACT

As time progresses, satellites launched into the GEO region have gotten smaller, and smaller, making the ability to detect and track decimeter-sized targets at these distances increasingly difficult but important for determining operational status, revealing changes, identifying, and characterizing. Previously we demonstrated that by using the Magdalena Ridge Observatory's (MRO's) 2.4-meter telescope, we could detect debris and other objects in GEO at visible magnitudes as faint as $V \sim 20$ or fainter in single images, and were able to derive reliable and accurate astrometry. We also established that employing strategic shifting and summing of individual images based on the anticipated motion of the target allows for this magnitude limit to be extended somewhat. Initially, since objects in geostationary orbit typically move about 15 arc-seconds per second with respect to sidereal motion, we limited exposure times to half a second or less to avoid significant trailing and analyzed the photometric signatures using circular apertures. For this current work, we explore techniques using elliptical apertures and extend individual exposures to push our detection limits to $V \sim 21$ visible magnitude and fainter. We investigate the limitations in accuracy inherent in this approach and examine the relative practicalities of utilizing longer individual integration times versus the software shifting and summing of shorter exposures. We also explore the magnitude, and hence size, limitations that these techniques imply for the characterization of artificial objects when studying their temporal photometric and spectroscopic signatures.

1. INTRODUCTION

Satellites inhabiting the geosynchronous zone around Earth are important for basic applications (e.g., world-wide communication, weather monitoring) as well as for national security concerns (e.g., missile launch detection, etc.). As time progresses, satellites launched into the GEO region have gotten smaller, and smaller, making the ability to detect and track sub-meter to decimeter-sized targets at these distances increasingly difficult but important for determining operational status, revealing changes, identifying, and characterizing. In a previous work [1] we reported that the same techniques used 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 region. We demonstrated that by using the Magdalena Ridge Observatory's (MRO's) 2.4-meter telescope (see Fig. 1), we could detect debris and other objects in GEO at visible magnitudes as faint as $V \sim 20$ or fainter in single images, and we were able to derive reliable and accurate astrometry. We also established that employing strategic shifting and summing of individual images based on the anticipated motion of the target allows for this magnitude limit to be extended somewhat.

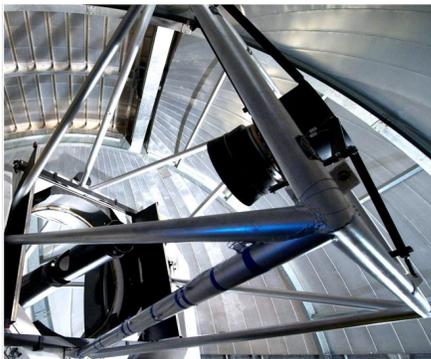


Fig. 1. The Magdalena Ridge Observatory 2.4-meter fast-tracking telescope located outside of Socorro, NM on Magdalena Ridge. The observatory performs target-of-opportunity scientific research focusing on asteroids and comets along with work in the area of space situational awareness.

Initially, since objects in geostationary orbit typically move about 15 arc-sec per second with respect to sidereal motion, we limited exposure times to half a second or less to avoid significant trailing and analyzed the photometric signatures using circular apertures. For this current work, we explore techniques using elliptical apertures and extend individual exposures to push our detection limits to $V \sim 21$ visible magnitude and fainter. We investigate the limitations in accuracy inherent in this approach and examine the relative practicalities of utilizing longer individual integration times versus the software shifting and summing of shorter exposures. We also explore the magnitude, and hence size, limitations that these techniques imply for the characterization of artificial objects when studying their temporal photometric and spectroscopic signatures. The MRO 2.4-meter telescope's large aperture and the site's environmental characteristics are ideal for the detection and characterization of small, natural objects in distant orbits, and we will demonstrate that the same can be accomplished for artificial targets.

1. BACKGROUND

The MRO 2.4-meter Telescope facility has had steady funding since 2007 to execute a comprehensive observational program to determine orbital and physical characterization information on objects in the near-Earth population (natural and artificial). The research is comprised of precision 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 2.4-meter telescope is fast-tracking, with slew rates of 10 degrees per second, and has a CCD camera and visible spectrometer mounted at all times. An observer can switch between both instruments within 26 seconds via a tertiary mirror, allowing for complete time-series photometric and spectroscopic data to be collected nearly simultaneously on any object on a given night. The program to study potential hazardous asteroids and comets has been highly synergistic with our efforts in space situational awareness (SSA), and we have leveraged and extended our NASA-based work to developing new approaches for acquiring data on faint satellites in orbit around the Earth at GEO altitudes.

Studying close-approaching, newly discovered asteroids has resulted in a wealth of information on their spin rates, shapes, and spectroscopically-derived compositions. For example, Fig. 2 illustrates data collected on one of the fastest moving and fastest spinning asteroids we have studied to date. Near-Earth Object (NEO) 2018 KW₁ is shown in a short-exposure astrometric image, a tracked image, and the resulting time-series photometric variation used for determining spin rate. 2018 KW₁ was moving 270"/min at its closest approach to the Earth, and rotating once every 10.8 seconds. Additional interesting faint asteroids are shown in Fig. 3., demonstrating our telescope's detection limits. An image of asteroid 2019 QD₂ taken in a one-second exposure was detected at magnitude $V \sim 20.8$. Excellent astrometry was also obtained for this object.

Also shown in Fig. 3 is a recent event that showcases the telescope's ability to acquire important information in a target-of-opportunity mode is data collected on object A/2017 U1 ('Oumuamua). On October 19, 2017, a rapidly moving object was detected and tagged for additional observations, initially as a comet. Follow-up observations by MRO's 2.4-meter telescope and other observers, coupled with subsequent analysis, verified the extrasolar hyperbolic trajectory of A/2017 U1. The 2.4-meter telescope researchers continued to acquire low-residual astrometry (helpful for determining the object's point of origin) through November 17, 2017, when A/2017 U1 (Fig. 3) had a visible magnitude as faint as 24.5. Because of its large aperture, the 2.4-meter telescope could accurately track the object for nearly a month after detection. This first discovery of an interstellar object helps shed light on the similarities of the solar system formation process around other stars.

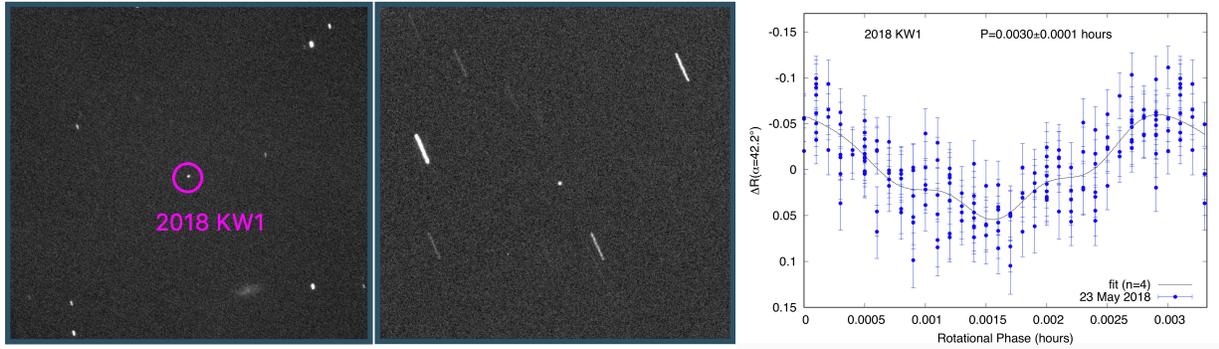


Fig. 2. Images taken with the Magdalena Ridge Observatory 2.4-meter of Near-Earth asteroids 2018 KW₁. On the (left) is a 0.5 second astrometric exposure of the V~17.5 NEO during closest approach when moving very fast at ~270” per minute. A (center) 5-minute photometric exposure is also shown, and the resulting lightcurve (right). The asteroid spin rate is 10.8 seconds.

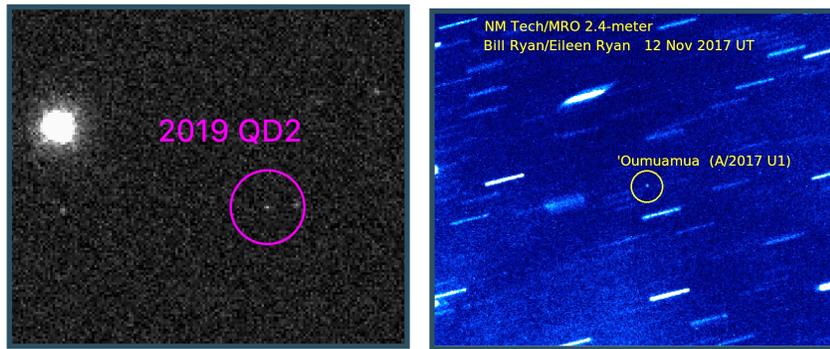


Fig. 3. (Left) Asteroid 2019 QD₂ was detected in a 1-second exposure at a magnitude V~20.8. (Right) Interstellar asteroid A/2017 U1 (‘Oumuamua) taken by the MRO 2.4-meter telescope via a stacked (36 minute) exposure when the asteroid was on its outbound trajectory (visible magnitude ~24.6). Astrometry was performed using three 12-minute stacks.

Our astrometric data analysis pipeline utilizing *SExtractor* [2], *SAO’s WCS Tools* [3], and *NOAO’s IRAF* [4] is described in [1]. *SExtractor* is used to identify the positions and magnitudes of stellar sources in the image and *WCS Tools* is used to match these sources with cataloged reference stars to calibrate the pixel-to-celestial coordinate transformation. Finally, *IRAF* is used to actually measure the positions and brightness of the targets in the calibrated images. The Windows-based GUI tool, *Astrometrica* [5] is used for verification when applicable.

In parallel with the asteroid work described above, researchers at MRO have also been involved in studying manmade objects in orbit around Earth since 2007. Reflectance Spectroscopy [6], [7], analysis of GEO debris spin rate diversity [8], [9], [10], and spin rate evolution of GEO objects [11] have been previous areas of analysis. However, detection of faint GEO targets has been a recent focus area of the facility’s SSA work and although the initial effort was the subject of [1], and we expand on that work in this current endeavor. The next sections discuss briefly our previous investigations, and detail techniques using elliptical point spread functions allowing us to extend individual exposures to drive our detection limits to V~21 visible magnitude while retaining astrometric accuracy.

2. DETECTION AND ASTROMETRY OF GEO TARGETS

Most NEO observations that we have obtained are of objects moving at a rate of less than one- to a few hundred arc-seconds per minute with respect to sidereal motion. These average speeds result in a detection limit for our facility of $V \sim 24$ magnitude for natural targets. However, 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. For larger sub-one meter scale, simply utilizing short exposures allows us to capture the target and determine positional information through accurate astrometry. Fig. 4 shows acquired images of two 50-centimeter sized GEO objects, SSN 43445 and SSN 43446 that were analyzed using our standard pipeline that employs circular apertures.

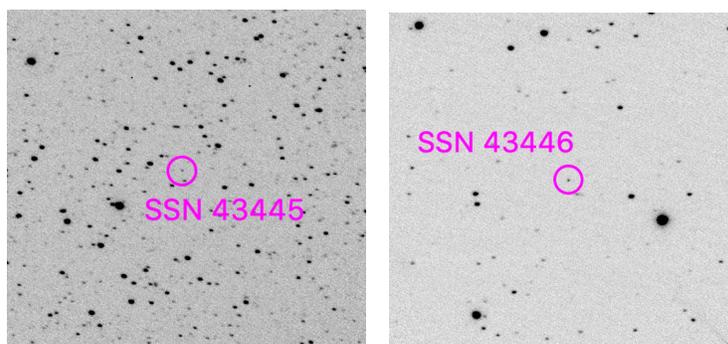


Fig. 4. Acquired 0.1 second exposures of 43445 ($V \sim 18.5$) and 43446 ($V \sim 17.4$) permit astrometry measured via the standard pipeline (circular apertures for reference stars). The two objects are ~ 50 cm in size.

To establish our capabilities for smaller targets, we utilized small debris to serve as surrogates for decimeter scale targets at or near GEO distances. Even larger debris targets can have large brightness variations as seen in Fig 5. Further, observing at larger solar phase angle can also provide sufficiently faint targets.

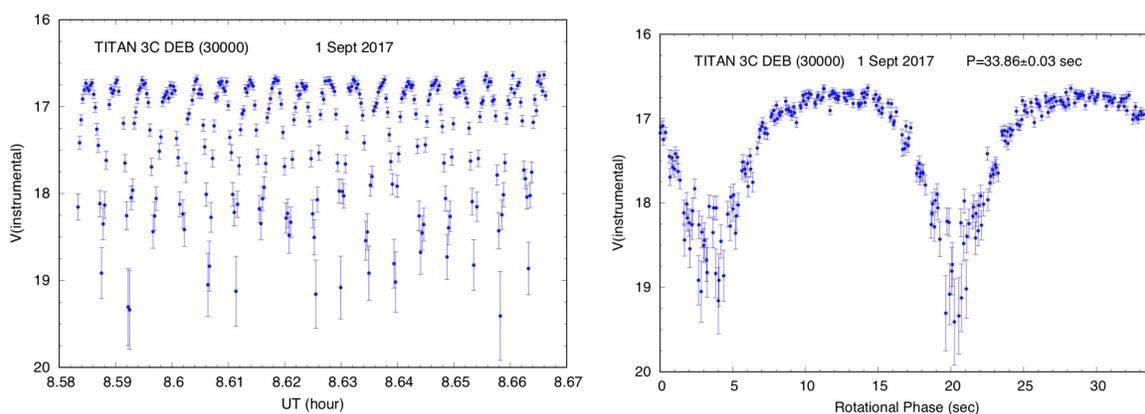


Fig. 5. Sequential (left) and composite (right) lightcurves for 5 minutes of time-series photometry of Titan 3C DEB (3000). From [1].

Fig. 6 illustrates the detection of TITAN 3C Transtage debris object SSN #38692 at GEO in a single 3-second exposure image when the object had a visual magnitude of $V \sim 20.5$ (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 establishes our capability to detect and keep custody of decimeter scale objects at GEO in extended exposures of 3-10 seconds.



Fig. 6. Three-second images of 38692 (left) with enlargement (center) and profile plot of target signal (right). The solar phase angle was $\sim 27^\circ$; the magnitude was $V \sim 20.5$. From [1].

With the MRO 2.4-meter telescope, we showed that these exposure times permit detection to a visible magnitude of approximately $V \sim 20$ or greater. Thus, assuming an albedo of 0.2, this implies that we have successfully detected decimeter-scale targets. However, we must still establish that we can acquire accurate astrometry on these targets. Two methods to achieve this are described in the next section.

3. ASTROMETRY OF FAST MOVING TARGETS

There are two possible approaches to determining accurate astrometry when tracking on targets that are moving rapidly with respect to the background reference stars. One is to take many frames limiting the exposure times of each such that the reference stars are minimally trailed and can still be measured as near point sources. Then strategically shift each image based on the anticipated motion of the target and co-add the images such that the target signal accumulates at the same location. Utilizing this so called ‘synthetic tracking’ technique was investigated in [1] and is summarized below. The second method is to endeavor to identify the centers of trailed images of reference stars in longer exposures. This method is also demonstrated below.

The process of simply co-adding frames can be utilized 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 technique involves finding World Coordinate System (WCS) fit for each individual image by our standard pipeline. Then, using a trial rate and direction of motion, we calculate the offset in degrees from reference position at mid-observation time and apply this offset to the WCS terms for image center (CRVAL1 and CRVAL2). Finally, the images are summed using *SWarp* [12] or a similar WCS-aware co-adding technique.

An example of this strategy is shown in Fig. 8 where we have images with weaker signal and the target is hidden in the noise as shown in the upper left. Two such images then are shifted based on a trial rate and direction and then co-added, resulting in the stronger signal as seen in the upper right. The bottom two images are an expanded view of the center of the summed image and a profile plot of the target signal.

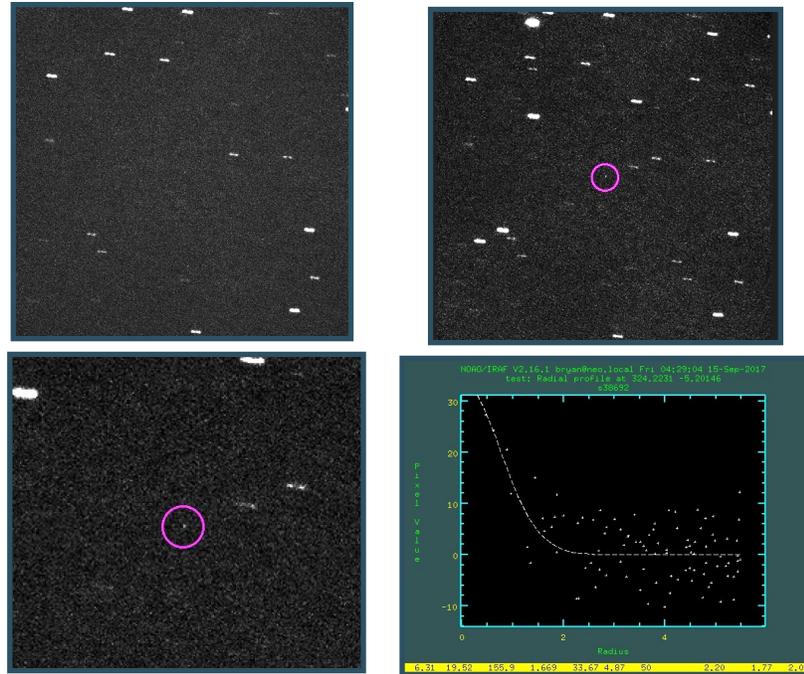


Fig. 7. (Top left) Single 0.5 sec image of 38692 field and pair of images co-added (top right). Expanded view of co-added images of 38692 (bottom left). (Bottom right) Profile of the target signal after accounting for a motion of 908.0 arc-sec/minute at 82.40°. From [1].

The second technique involves using longer exposure images where the target signal is clearly detected as in Fig 6 and Fig 8 below. This technique necessarily requires prior knowledge of the targets motion and was used previously at the MRO 2.4-meter telescope only to search for targets before utilizing shorter exposures and synthetic tracking for the actual astrometric measurements. In these cases, the reference stars form extended trails and can no longer be measured using circular apertures. Therefore, the reference star images in Fig 8 were modeled using the IRAF *fitpsf* task as elliptical Gaussians to determine their centers. These reference stars positions were then used to determine the astrometric fit. The result was the astrometric measurement of a V~21 target to order ~0.5 arc-sec precision.

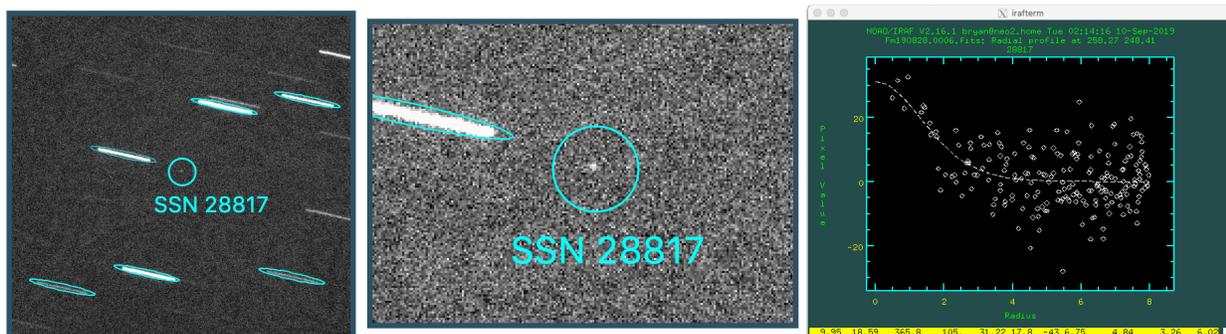


Fig. 8. Two second exposure of V~21 target 28817. Radial profile of signal at right. Reference stars were modeled using IRAF *fitpsf* with elliptical Gaussians resulting in plate solutions with <0.5" rms.

4. SUMMARY

Through the efforts reported on in this paper, we have established that the capability of using the MRO 2.4-meter telescope exists to detect and reliably measure astrometrically magnitude $V \sim 20 - 21$ (decimeter scale) targets at GEO distances. This was demonstrated utilizing two techniques – single extended exposures and synthetic tracking using many shorter exposures. Single, longer exposures have the advantage of only being digitized once, minimizing the read noise in the process. However, this technique requires prior knowledge of the target's motion, which would not always be available. Synthetic tracking does not require such prior knowledge of the target's movement and many trial tracks can be employed until the correct one is identified. It does, however, suffer from accumulated read noise from the many exposures, although this is becoming less of an issue with newer cameras. In summary, having both techniques available allows us to be confident of the ability to track the faint targets that will be populating regions near GEO distances in the future.

5. REFERENCES

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6. ACKNOWLEDGEMENTS

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