

Recent developments in shadow imaging

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ABSTRACT

Shadow imaging is a technique to obtain highly resolved silhouettes of resident space objects (RSOs) which would otherwise be unattainable using conventional terrestrial based imaging approaches. This is done by post processing the measured irradiance pattern (shadow) cast onto the Earth as the RSO occults a star. The research presented here focuses on recent developments in shadow imaging of geosynchronous (GEO) satellites with near stationary orbits approximately 36,000 km from the Earth. A high fidelity shadow prediction tool is presented and verified using data collected taken by small aperture Raven class telescopes. The morphology of shadow densities on the Earth is shown in the context of the local galactic orientation over the course of a year, and is used to explore advantageous collection system location.

1. INTRODUCTION

Geosynchronous (GEO) satellites are essential for modern communication networks, weather forecasting, television broadcasts, and many defense/intelligence applications. Over the past half century, on the order of one thousand GEO satellites have been launched and placed into orbit. As this population grows over time, the available space for positioning these satellites will become increasingly scarce, and the need to observe the GEO belt will become commensurately more important. The largest terrestrial based optical telescopes are only capable of capturing imagery with resolvable features of several meters on GEO satellites. Shadow imaging of GEO satellites as they occult (or pass in front of) distant bright stars offers a means of recovering fine resolution silhouettes which contain information about satellite antennae and solar panel configuration, satellite pose, and the presence of other space objects in close proximity.

Shadow observation using a single collection aperture was first proposed in 1952 by Taylor [1], and a shadow of the asteroid Pallas was first successfully observed in 1978 [2]. Techniques have been developed to study distant objects in the Kuiper Belt and Oort Cloud using serendipitous observations of stellar occultations [3]. The idea of shadow imaging of GEO satellites using a linear array of small collection apertures coupled to high speed detectors was first proposed in 2005 by Burns, et al., [4]. It was shown that an iterative phase retrieval algorithm could be used to recover the satellite's silhouette. Shadow imaging of GEO satellites was examined in further detail in 2008 by Luu, et al., in which the collected light was split into spectral bins and image reconstruction performed separately on each bin [5]. The result was shown to improve the signal-to-noise (SNR) in the final silhouette by stacking the individual reconstructed silhouettes associated with each spectral bin. Work by Douglas in 2014 examined the image resolution limits of shadow imaging using a radiometric-based wave optics simulation approach by varying environmental, observational, and light collection parameters [6]. Recent work by Douglas, et al., has concentrated on examining various reconstruction algorithms based on the Fresnel integral approach and exploring the limits of resolution [7][8][9]. Paxman demonstrated a reconstruction algorithm using a binary image constraint on the recovered silhouette [10].

In shadow imaging it is important to calculate where to locate a terrestrial-based observer to capture the shadow as it traverses the earth in order to capture the occultation event. This is the problem of "being in the right place, at the right time." In [4], Burns, et al., proposed placing a shadow imaging system on a railroad track 10-20 km long orientated in a North/South direction such that the latitude could be varied. It was shown by analysis that the observed occultation probability increases significantly for this type of design. Development of a GEO satellite shadow prediction calculator is the focus of this paper, and relies on foundations well established in the literature. In

the following subsections, the methodology for prediction, the sources of errors, and results achieved to date are discussed.

2. SHADOW PREDICTION EXPERIMENTS

The methods used for predicting the shadow location on the earth from a stellar occultation are mainly geometric, although the earth atmosphere introduces randomness due to atmospheric refraction. The purpose behind the prediction also influences the details of the implementation, particularly the scale and accuracy required. In the following, an outline of the current methods is presented.

2.1 Shadow Location Prediction

Many of the details of the calculations have been disclosed in prior publications [7][8][9]. This section will review the main points and discuss their impacts on prediction accuracy.

2.1.1 *Satellite Position Calculations*

Given a point in time, or epoch, the positions of satellites of interest must be calculated. The starting point for this calculation is typically a Two Line Element (TLE) set, and the TLE data is used to predict the position of the satellite at a future epoch using the SGP4 theory. This work utilizes implementations of SGP4 propagation by Vallado [20] and Orekit 8.0 [19]. The accuracy of satellite state predictions based on TLE data has been the subject of prior study [15]. For GEO satellites, errors can be on the order of hundreds of meters or more at the TLE epoch. Based on straightforward geometric arguments, the along-track and cross-track errors in GEO satellite position will produce corresponding errors in the shadow locations.

The light time of the satellite, in this case defined as the time for star light occulted by the satellite to dim at the observer, is also of potential interest. For GEO satellites, this has been examined and affects the timing of the occultation event at the observer.

2.1.2 *Stellar Astrometrics*

The choice of catalog is important since not all contain the same levels of positional accuracy. The Tycho-2 catalog provides positions for approximately 2.6 million stars of 12th magnitude and brighter. These positions have errors in the range 50-100 milli arc seconds. The first data release from the Gaia mission, called the Tycho-Gaia Astrometric Solution (TGAS), includes an astrometric solution for all of the Tycho-2 stars as observed by Gaia (~2 million). This catalog has astrometric accuracy typically on the order of 200-300 micro arc seconds, and will become more complete and accurate as the Gaia mission proceeds. The next data release is scheduled for 2018. Both the Tycho-2 and TGAS catalogues have been used in this work.

In our work, the satellite positions are compared to stellar astrometric positions at the epoch of interest in either an inertial or terrestrial frame using the IAU Standards of Fundamental Astronomy software [18]. Corrections are made for the following effects:

- Space motion
- Annual parallax
- Light deflection
- Annual aberration
- Nutation, Precession, and Frame Bias
- Earth rotation
- Polar motion
- Diurnal parallax
- Diurnal aberration

The diurnal parallax is very small and can be neglected for this problem. The diurnal aberration can be large (2.7 arc seconds or more). However, for GEO satellites, it produces an along-track error that affects only the timing of the occultation event at the observer. More information on these subjects may be found in [16].

2.1.4 Earth Ellipsoid Intersection and Refraction Correction

An algorithm by Pucinelli [11] for locating the sensor boresight pointing is used in this work to solve for the location of the shadow to a first approximation (without refraction). The algorithm poses the problem as the solution to a quadratic equation and provides both the near and far intersections. Refraction due to the earth atmosphere causes the shadow to be displaced from this idealized location. There are several approaches one could choose to address this problem. Observations at low viewing elevations (< 20 degrees) pose difficulties for the shadow imaging approach. Above 20 degrees elevation, it is reasonable to pursue a one-step geometric solution for the shadow displacement along the observer’s azimuth direction. This correction provides a revised observer location based on a fixed height atmosphere. It is worth noting that the refraction is a random process. Dunn provides a useful study which includes an analysis of the statistical variation in the refraction [13].

2.2 Results and Discussion

In this section, we will summarize progress and results achieved thus far in developing the tools needed to characterize the distribution of shadows on the earth at small map scales, as well as predicting and capturing individual shadows at a particular site. Some example results are provided, including initial validation against imagery collected by a Raven small telescope system located at Kihei, Maui.

2.2.1 Raven Data Comparison

The Raven small telescope systems located on Maui and at other sites collect data on debris and satellites to facilitate orbit determination and the collection of “light curves.” As a routine matter, a large amount of imagery is collected over time. Our team was given access to a repository of Raven data produced by a Raven sensor located at Kihei, Maui. A data mining algorithm was applied to search through the astrometric results for imagery in which the observed space object was close to one of the stars in the field of view. Several observations of the Galaxy15 satellite were identified, and the astrometric information associated with one of these images was compared to past-prediction using the shadow prediction tool based on the TLE.

The computation of an astrometric plate solution using the stars in the field of view is basic to the calibration of each Raven image. This is useful in our application for two purposes: (1) measuring the offset between the observed location of the satellite and that predicted using the SGP4 propagation algorithms; and (2) measuring the observed offset between the satellite and the nearby star to predict how close the shadow actually was to the site. The following table shows each of these data derived from the observation of the Galaxy15 satellite.

Table 1. Galaxy15 shadow track information for the Raven observation

Observation Date/Time	Star Catalog Data	TLE-Based Shadow Track Offset (meters)	Mensuration-Based Shadow Track Offset (meters)
2016.11.15 15:15:58.6687 UTC	Tycho-2 ID: 4789-1071-1 RA: 06:28:21.446 DEC: -3:27:39.80 VT: 8.5920	1437	1074

The right ascension and declination of the satellite as measured on the Raven focal plane was mapped to a ground location using the geometry of a line intersecting an ellipsoid of rotation. These calculations were done using both Vallado’s coordinate transformations and Orekit 8.0 to provide two independent approaches. The mensuration to determine the observed satellite position is subject to errors on the order of an arc second. Given that a state produced by TLE propagation is also on the order of a few hundred meters, this comparison can provide only a limited validation of the prediction tool. Figure 1 shows the results of plotting the predicted shadow track for this event using the TLE associated with the Raven collection. The red box surrounding the Remote Maui Experiment (RME) site is three kilometers per side, and provides an indication of scale. The red/blue line is the TLE-based shadow track prediction, while the yellow/green line is same track corrected for the error in the satellite position as measured on the Raven camera focal plane.



Figure 1. Shadow tracks in the vicinity of the Remote Maui Experiment (RME): (red/blue) track predicted from TLE-based prediction tool; (yellow/green) track corrected based on satellite-to-star offset mensuration using Raven system imagery.

2.2.2 Small Scale Shadow Density Morphology

The capability to map the density of shadows produced by one or more satellites at small scales is important to the sensor placement problem. In Figure 2, one can see an example of this for the TDRS11 GEO satellite. The surface of the earth is binned into 1 degree by 1 degree quadrangles to produce a histogram of shadow frequency on the earth surface. Maps are shown for two dates separated by ten days. The first thing to note is that the vertical cross-section through the longitude column containing the highest count shows that the distribution of shadows is skewed toward the northern hemisphere. Secondly, the two maps are highly correlated as can be seen in the difference plots. This tends to confirm the observation by Paxman that the shadow produced by a particular satellite/star combination will be present from night to night, subject to an offset on the order of a kilometer [10]. It seems safe to conclude that the morphology of these density maps will in general change slowly for GEO satellites. This will have important implications for operations.

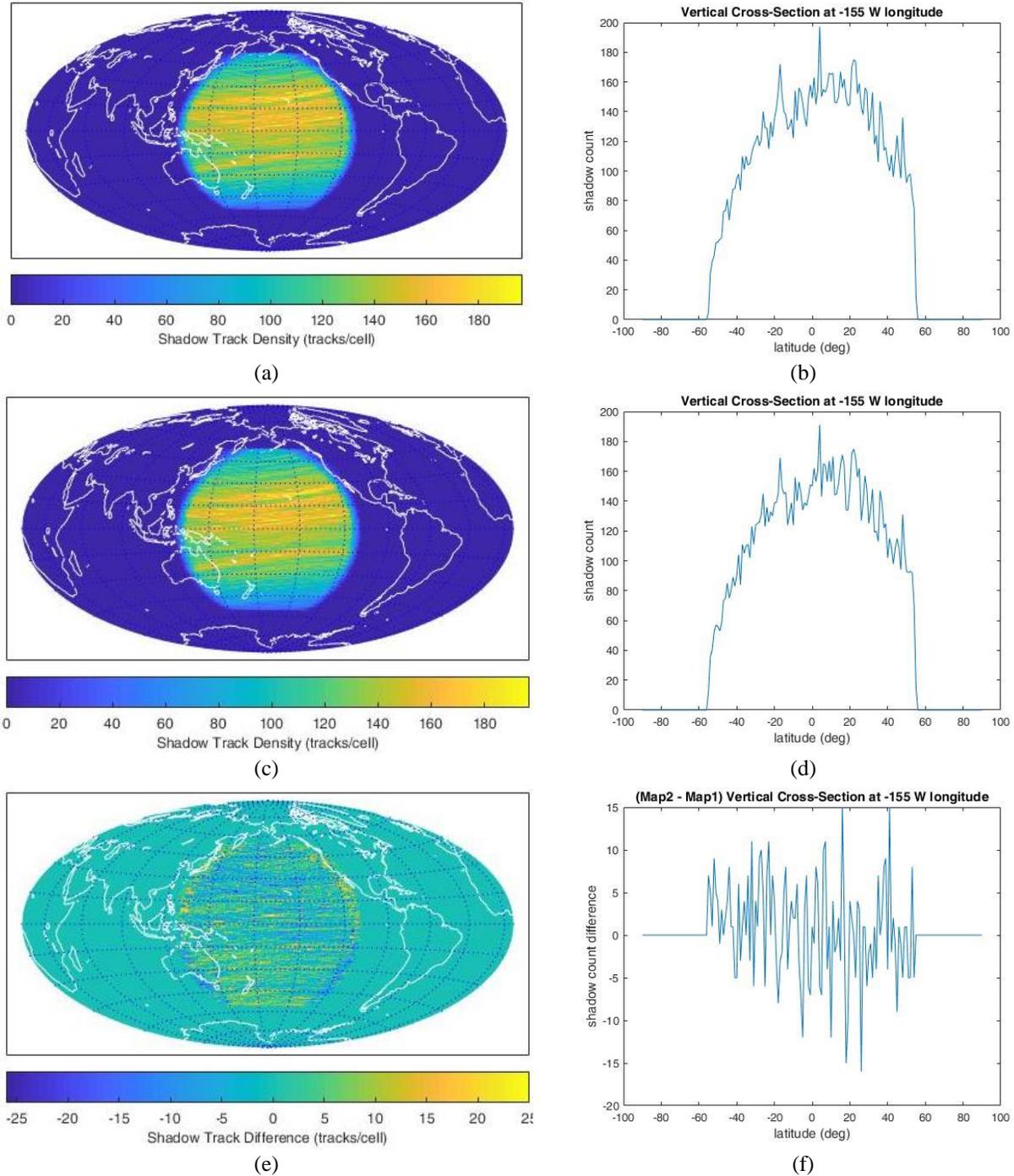


Figure 2. Small-scale shadow histogram plots for the TDRS11 GEO satellite: (a) 12/31/2014 – 1/1/2015; (b) vertical cross-section of (a); (c) 1/9/2015 – 1/10/2015; (d) vertical cross-section for (c); (e) difference (c)-(a); and (f) vertical cross-section of (e).

2.2.3 Galactic Plane Influence

Corresponding to the small-scale maps, it is valuable to note the rate at which the occultations occur during the night. This is shown in Figure 3. The occultations are also displayed so as to illustrate the increase that accrues by including dimmer stars. The lower half of the figure shows the portion of the Celestial Sphere behind the satellite as

viewed from the Geocenter through a transparent Earth. The peak value of the curve corresponds to when the satellite is in front of the Galactic Plane. The presence of this plane will have important implications for scheduling observations as the probability of obtaining an occultation can more than double during these times.

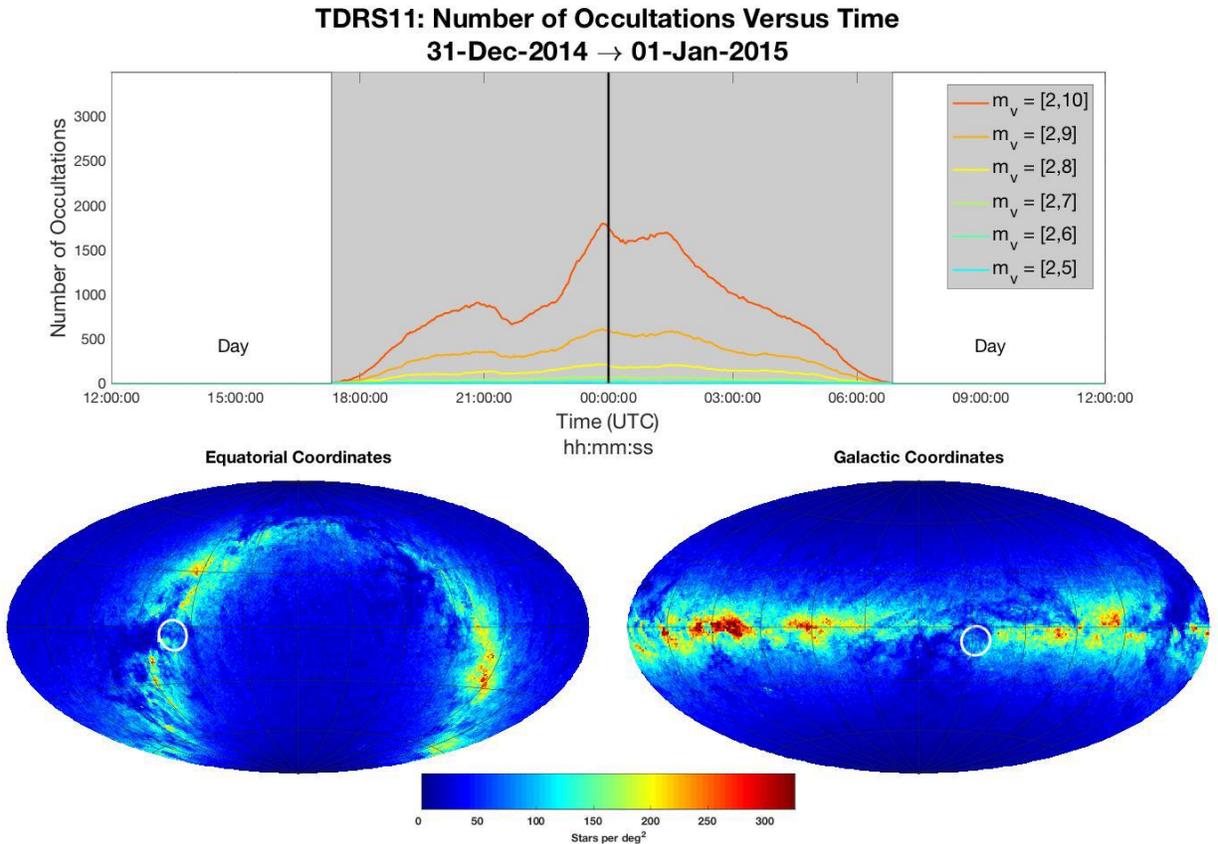


Figure 3. Galactic plane influence on shadow track density: (upper) histogram of occultations binned in time; (lower) geocentric satellite location on the Celestial Sphere near the histogram peak.

3. CONCLUDING REMARKS

The foregoing has reported on progress that our group has made in developing the tools needed to characterize the solution space for the solving the optimization problem of sensor placement and for understanding the intricacies of predicting and capturing individual occultation events. Future will include the following: (1) determining optimal sensor locations by thoroughly characterizing the shadow map morphology affecting the solution space; (2) extending the large-scale prediction capability to include computing the shadow location using Digital Elevation Maps (DEM); and (3) seeking additional opportunities to work with real data and to collect successfully an actual GEO satellite occultation event in real time.

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