Optical Studies of Space Debris at GEO - Survey and Follow-up with Two Telescopes

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ABSTRACT

For 14 nights in March 2007, we used two telescopes at the Cerro Tololo Inter-American Observatory (CTIO) in Chile to study the nature of space debris at Geosynchronous Earth Orbit (GEO).

In this project one telescope was dedicated to survey operations, while a second telescope was used for follow-up observations for orbits and colors. The goal was to obtain orbital and photometric information on every faint object found with the survey telescope. Thus we concentrate on objects fainter than R = 15th magnitude.

MODEST (Michigan Orbital DEbris Survey Telescope, the University of Michigan's 0.6/0.9-m Schmidt telescope at CTIO) was used in survey mode every night to scan a strip of sky 1.3-deg wide in declination by over 100 degrees long in hour angle. Five second exposures were obtained every 37.9 seconds, reaching a limiting R magnitude of 18.0 for a S/N of 10. With a field-of-view (fov) of 1.3-degrees, an average of eight detections are made of individual objects at GEO during a 5.2 minute time span.

A real-time processing pipeline detects objects and provides positions and magnitudes to the CTIO 0.9-m equipped with CCD imager with a fov of 0.22 degrees. Predictions of future rates and positions for the first recovery observation with the 0.9-m were made by fitting an assumed circular orbit (ACO) to the observed MODEST positions.

The recovery rate with the 0.9-m of objects found by MODEST was over 90%. The average time between the last detection on MODEST and acquisition on the 0.9-m was 17 minutes. The quickest hand-over was 4 minutes.

The 0.9-m was used to determine:

1. full six parameter orbits (including eccentricity). An initial orbit was determined based on observations during one night, and then refined with observations on subsequent nights. One challenge of studying these objects with periods close to 23h56m is that frequent observations are required to refine and update the orbit so the object can be recovered later.

2. magnitudes and colors in the standard astronomical BVRI system. Sequences of 10 observations in each filter were obtained to measure brightness variations.

In this paper we will summarize the results obtained and outline future work.

1. INTRODUCTION

Sine February, 2001, the University of Michigan's Curtis-Schmidt telescope has been used in an optical survey for space debris at geosynchronous Earth orbit (GEO) for NASA's Orbital Debris Program Office. The telescope is a classical Schmidt telescope with 0.61-m diameter corrector and 0.91-m diameter primary mirror located at Cerro Tololo Inter-American Observatory in Chile. Used for the debris program, the telescope is called MODEST (for Michigan Orbital DEbris Survey Telescope.

A brief summary of the facility and operation will be provided here. A full description has been presented at previous AMOS conferences [1,2].

A thinned, backside illuminated LN2 cooled SITe CCD is located at Newtonian focus. This CCD has a field of view (fov) of 1.3 by 1.3 degrees square with a pixel size of 2.318 arc-seconds. A broad R filter centered at 630 nm with a FWHM of 200 nm is used for all survey observations. Usual exposure time is 5 seconds, reaching a S/N of 10 at R = 18^{th} magnitude in the standard 5 second exposure time.

Each night the telescope tracks a fixed right ascension and declination just outside of the Earth's shadow cone at GEO. While the telescope tracks this point at the sidereal rate, the charge on the CCD is moved backwards to remove the effects of the Earth's rotation. Thus stars appear as streaks in the East-West direction, while geostationary objects appear as point sources, and other GEO objects appear as very short streaks. Four detections are required for a real object, and all detections are manually verified to guard against false detections.

The software on the system provides real-time data reduction, and is optimized for detecting objects with angular rates between -2.0 and 2.0 arc-seconds/second in hour angle (HA), and -5.0 to 5.0 arc-seconds/second in declination (DEC).

Each night the telescope scans a strip of sky over 100 degrees long at a fixed declination. The next night the telescope is offset by 1.2 degrees in declination but at the same right ascension. Thus a typical survey run will cover a region of sky 100 degrees long in HA by Nx1.2 degrees in declination, where N is the number of nights.

Each morning a summary report is produced, and times, magnitudes, and positions of all verified detections are sent to the Orbital Debris Program Office in Houston.

2. BEYOND SURVEY

Much can be learned about the GEO environment from just survey observations alone. For example, Figure 1. below shows the observed angular rates of one year's sample. There is a very significant difference between the angular rate distribution of bright objects and that of faint objects. The bright objects tend to follow a locus which is what would be expected if the primary orbital perturbations are gravitational from Earth, Sun, and Moon. But the fainter objects have a much broader distribution in angular rate, which could be due to a range in the eccentricity distribution of the parent population. Such a eccentricity distribution has been found by the ESA Space Debris Telescope (ESA SDT) to be very broad, ranging up to e = 0.8 for faint GEO debris [3].

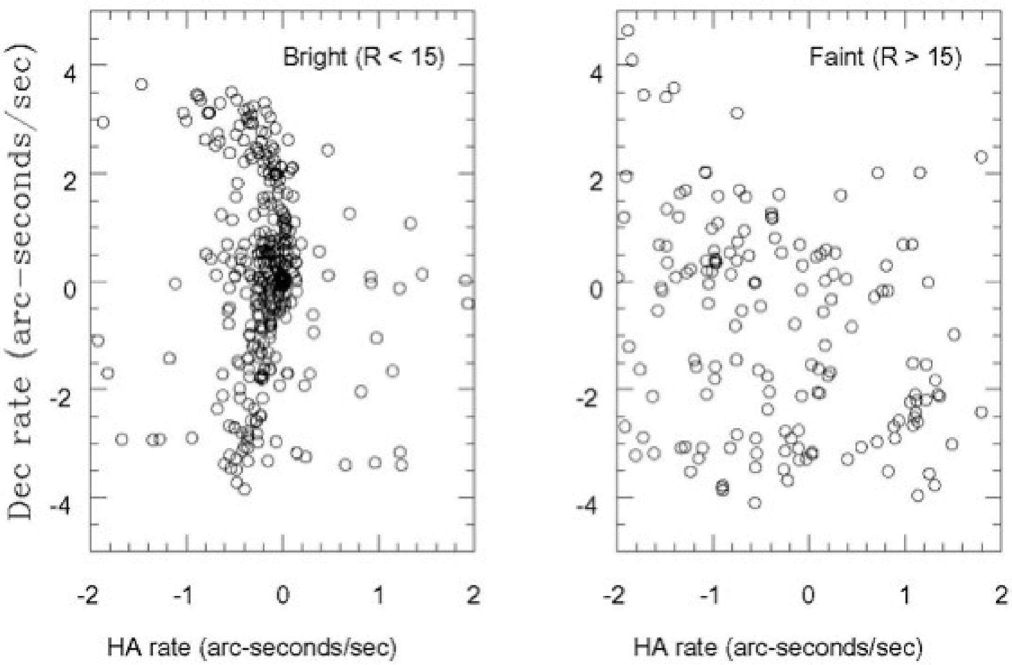

Fig 1. Observed angular rate distribution of one year of MODEST observing. Note difference between bright object (on left) and objects fainter than R = 15 on the right.

In the standard five minute observing window on each object, MODEST does not observe long enough to determine a full six parameter orbit. The orbital arc is simply not long enough (5 minutes out of an orbital period of 23h56m). In order to obtain a longer arc with just MODEST, though, we would have to stop survey mode in order to follow-up specific objects. This decreases the sky coverage of the survey and affects the completeness of the survey.

Therefore we turn to using a second telescope to do the follow-up observations. Our goal is to obtain follow-up positions, magnitudes, and colors of every faint object discovered by MODEST in survey mode.

Fortunately, at CTIO there are a number of other telescopes which could in principal be used for follow-up observations. In this paper we report on follow-up observations with the CTIO 0.9-m to obtain such a complete sample.

3. ORBIT DETERMINATION

In order to follow-up objects found by MODEST, we discovered that a straight linear extrapolation from 4-8 time-stamped positions in the 5 minute MODEST observing window was not good enough to reacquire the object more than a few minutes later with a small field-of-view telescope. Instead we solve for an Assumed Circular Orbit (ACO) based only on the MODEST survey observations. This orbit gives us predictions for the next several hours for reacquisition on the second telescope. Once we have reacquired the object, then a full six parameter orbit can be determined. In the following section we describe in detail how this is done.

The MODEST debris finder code produces a set of four to eight positions over a short-arc from which we need to determine an orbit solution. Fitting a set of angles-only observations has been a long-standing problem in astrodynamics since the early days of astronomy. Historically, orbits are defined by six-dimensional Kepler elements (there are several ways to represent these elements – all equivalent – but a typical set consists of the semi-major axis, eccentricity, inclination, ascending node, argument of perigee, and true anomaly, all at a given epoch). However, "moving around" in this six-dimensional space to optimize a solution presents a number of difficulties. Kepler elements have singularities in their derivatives, and even specialized "non-singular" elements have potential problems. There is a way of representing a state vector of an orbit that is non-singular, however, and that is by using Cartesian coordinates. There is a one-to-one correspondence between a six-dimensional Cartesian state vector (3 dimensions of position, 3 of velocity) and a set of Kepler elements, so any set of Cartesian state vectors can be easily converted into conventional Kepler elements, and *vice versa*.

Our orbit fit program [4] uses an all-purpose multidimensional optimization routine known as a simplex method taken from Numerical Recipes [5]. While not always the most efficient method, it is robust enough to use with any data configuration. For a set of short-arc observations, an epoch time is chosen (such as the epoch of the first observation). Different six-dimensional Cartesian vectors are tested by transforming each into Kepler orbits, propagating them to each observation time in the set of observations, and computing the differences between the predicted and observed look angle vectors. One obvious way to measure this difference is to take the arc cosine of the vector dot product of the two normalized look vectors. However, if the angle between the vectors is small, the dot-product is very close to 1.0, and can lead to round off problems. Instead, we use the vector difference between the two normal vectors. This gives an excellent approximation of the angle between the two vectors if they are sufficiently close and can be transformed into a positional error on the sky in arc seconds. The optimization routine "experiments" with various Cartesian coordinate configurations until the sum of the squares of the positional errors (DVEC) is minimized. DVEC is used as a measure of the accuracy of the fit in arcseconds. The orbit solution with the lowest DVEC is used for propagation.

Because the observation arcs are so short, there are in general a variety of different orbits (of varying eccentricity) that give relatively good fits to the data, making it difficult to determine a single optimal orbit with no constraints on the solution. Therefore, the current configuration of the software penalizes solutions by how far their eccentricities differ from zero. This penalty is added to the positional error described above, resulting in an optimized solution equivalent to the best-fit circular orbit to the data set. We define this best-fit circular orbit as the assumed circular orbit (ACO) solution because the software has severely penalized any solution where eccentricity is greater than zero Similarly, we define the eccentric orbit solution as one where the software penalties have been removed and the eccentricity has been allowed to vary. Our orbit code can fit a set of observations with either an ACO or full 6-parameter solution by simply setting a flag in the code.

MODEST survey observations are initially fit with an ACO solution which provides positions and rates for follow-up on the 0.9m telescope. After acquiring the target and additional 0.9m positions the full 6-parameter or eccentric orbit solution is turned on. Then the entire observational dataset is used to calculate an eccentric orbit solution and predictions are made for new follow-up positions and rates for either telescope. The solution with the minimum DVEC is used for the predictions.

4. RESULTS

Our first experiments in two telescope survey and follow-up were done in March 2007, using MODEST in survey mode and the CTIO 0.9-m in follow-up mode. 11 out of 14 nights were clear and photometric. The first 6 nights were used for engineering and checkout, and the last 8 nights we were fully operational with both telescopes.

The primary challenge with the CTIO 0.9-m is the relatively small field-of-view (fov): only 0.2 degrees compared with 1.3 degrees for MODEST. Thus follow-up observations will be frequent in order to avoid losing the object.

In our 8 night operational run, we had a success rate of over 80% in handing off detections from the MODEST survey to the CTIO 0.9-m. Our average time between an object exiting the MODEST field of view, and reacquisition on the 0.9-m was 17 minutes. Our quickest handoff was 4 minutes.

This was made possible by real-time data reduction and orbit determination pipelines on both telescopes.

As a check on functioning of the entire system, one bright object (SSN 19688 – ASTR1a, 88109B) was found in the MODEST survey, and followed up for 8 additional nights. The MODEST survey data was used to cold-start the orbit – no additional information was used from any outside source. After 9 nights, the comparison with published data from Space-Track.org was excellent.

Our best sample consists of 32 objects found and chased for the 8 operational nights. Four objects were followed for 6 nights, and multiple objects were followed for 3 or more nights.

Figure 2 below is perhaps the best summary of our results.

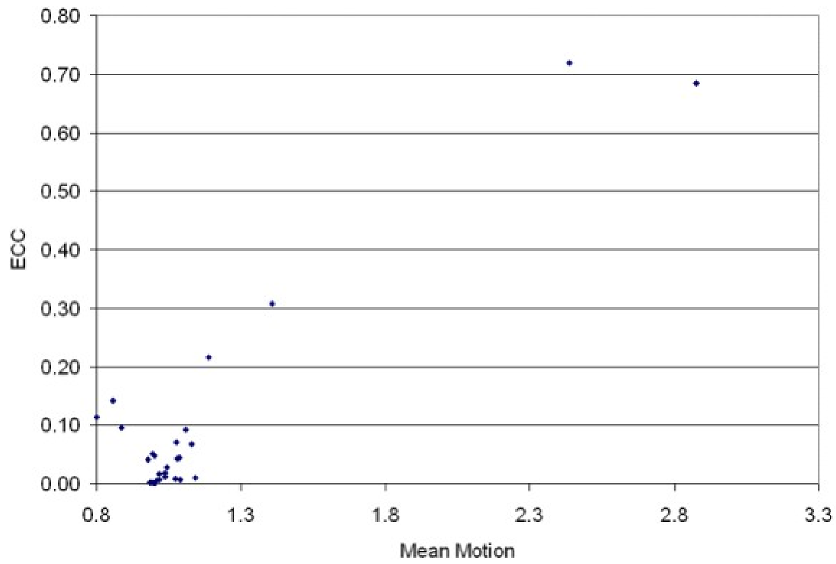

Figure 2. Plot of mean motion versus eccentricity for the 32 objects in our final sample.

In this plot several things should be evident:

1. There is a wide range of eccentricity, with values up to e = 0.72.
2. The two objects at the upper right are probably objects in GEO Transfer Orbit (GTO).
3. One of the objects at mean motion = 1.0 and eccentricity = 0.0 is the bright object discussed above.
4. Three of the objects have mean motions less than 0.9.

5. CONCLUSIONS AND FUTURE WORK

On the basis of this initial work with two telescope survey and follow-up, we can conclude that an angular rate selected sample is not a pure sample of objects at GEO. There are a number of objects that are GTO, and others that are above GEO.

A second conclusion is that for a faint sample, the majority are on eccentric orbits and not circular, as are the bright objects. This is not too surprising given the results from Schildknecht et al.[3], on faint GEO debris. Note that his selection effect is different from the MODEST sample.

We plan to continue this work in the future. Two weeks of simultaneous observing with MODEST and the CTIO 0.9-m are scheduled and funded for November 2007. Another two weeks are funded for March 2008. Telescope time is available but not yet scheduled.

6. REFERENCES

1. Seitzer, P., et al., A Survey for Space Debris in Geosynchronous Orbit., *Proceedings of AMOS 2001 Technical Conference*, Maui, Hawaii, 2001.
2. Seitzer, P., et al., Results from the NASA/Michigan GEO Debris Survey, *Proceedings of AMOS 2004 Technical Conference Proceedings*, Maui, Hawaii, pp. 213-214, 2005.

3. Schildknecht, T., et al., Optical Observations of Space Debris in High-Altitude Orbits, *Proceedings of the Fourth European Conference on Space Debris*, ESA SP-587, Darmstadt, Germany, pp. 113 - 118, 2005.
4. Barker E., et al., Comparison of Orbital Parameters for GEO Debris Predicted by LEGEND and Observed by MODEST: Can Sources of Orbital Debris be Identified?, *Proceedings of AMOS 2006 Technical Conference Proceedings*, Maui, Hawaii, pp. 596-604, 2006.
5. *Numerical Recipes in Fortran 77 The Art of Scientific Computing*, 2^{nd} Edition, Vol. 1, Cambridge University Press, p. 403, 1992.
6. Barker, E., et al. Analysis of Working Assumptions in the Determination of Populations and Size Distributions of Orbital Debris from Optical Measurements, *Proceedings of the 2004 AMOS Technical Conference*, Wailea, Maui, HI, pp. 225-235, 2004.
7. Mulrooney, M. and M. J. Matney, Derivation and Application of a Global Albedo yielding an Optical Brightness To Physical Size Transformation Free of Systematic Errors, *Proceedings of the 2007 AMOS Technical Conference*, Wailea, Maui, HI, this conference , September 12-15, 2007.