Photometric Studies of Rapidly Spinning Decommissioned GEO Satellites

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ABSTRACT

A satellite's general characteristics can be substantially influenced by changes in the space environment. Rapidly spinning decommissioned satellites provide an excellent opportunity to study the rotation-dependent physical processes that affect a resident space object's spin kinematics over time. Specifically, inactive satellites at or near geosynchronous Earth-orbit (GEO) provide easy targets for which high quality data can be collected and analyzed such that small differences can be detected under single-year or less timeframes.

Previous workers have shown that the rotational periods of defunct GEOs have been changing over time [1, 2, 3]. Further, the Yarkovsky-O'Keefe-Radzievskii-Paddak (YORP) effect, a phenomenon that has been well studied in the context of the changing the spin states of asteroids, has recently been suggested to be the cause of secular alterations in the rotational period of inactive satellites [4]. Researchers at the Magdalena Ridge Observatory (MRO) 2.4-meter telescope have been investigating the spins states of retired GEOs and other high altitude space debris since 2007 [5]. In this current work, the 2.4-meter telescope was used to track and observe the objects typically over a one- to two-hour duration, repeated several times over the course of months. When feasible, this was done for a target set on a yearly basis. Data is taken with a 1 second cadence, nominally in groups of three 600-second image sets. With the current equipment, the cadence of the image sequences is very precise while the start time is accurate only to the nearest second. Therefore, spin periods are determined individually using each image sequence. Repeatability of the period determination for each of these sequences is typically on the order of 0.01 seconds or better for objects where a single period is identified.

Rotation rates determined from the GEO light curves collected thus far have been found to range from ~3 sec to many tens of seconds. Based on these observed rotational characteristics, results will be discussed regarding both the long- and short-term spin-rate variations of selected targets. The objective of this project is to study a variety of satellites for rotational stability over time, and to discern how physical effects (such as YORP) might be dependent on the optical, thermal and geometrical parameters of the object.

1. INTRODUCTION

Several physical processes can affect the rotational motion of satellites in orbit around the Earth. Major factors in initiating change are solar radiation pressure and gravity-induced torques from the proximity of the Earth, Moon, and Sun. Since satellites can have geometric features with highly reflective surfaces, the magnitude of torques due to solar radiation pressure can be sizeable. Conversely, although the magnitudes of torques due to gravity may be smaller in comparison, the fact that they are constant and uncorrected means that they can contribute significantly to the rotational dynamics of the satellite. Another process that may affect geosynchronous satellites is the Yarkovsky effect [6]. This is a thermal radiation force that causes small bodies to undergo semimajor axis drift as a function of their size, orbit, and material properties. The basic principle is that these bodies absorb sunlight and then ultimately re-radiate the energy as heat, which then produces a small thrust. This recoil acceleration is much weaker than solar and planetary gravitational forces, but can have a definitive influence over time. The YORP [7] effect is a second-order variation on the Yarkovsky effect, and is a thermal torque produced by scattered sunlight that can increase or decrease a body's spin rate and modify its spin axis orientation. For natural objects like asteroids, the YORP effect has been studied extensively. The motivation for this current work is to study a subset of GEO satellites in order to potentially detect the YORP effect in man-made objects, as well as study how the other physical phenomena manifest themselves over time. Specifically, we see if changes in spin state can be detected over short (months) as well as longer (>>year) timescales.

The determination of a rotational period for a fast-spinning GEO satellite can be challenging. For this work we use MRO's fast-tracking 2.4-meter telescope (see Figure 1) located at 10,612 feet in New Mexico and operated by the New Mexico Institute of Mining and Technology (NMT). The seeing at Magdalena Ridge is excellent, typically sub-arcsecond, and consistent even at lower elevations (high-precision data has been collected at 5º elevation). The telescope is an altitude/azimuth design, with the ability to look 2º below horizontal, facilitating observations of low declination objects like rockets, space vehicles, or low elevation asteroids or comets. The telescope is capable of fast target acquisition (slew rates are 10º/sec) and non-sidereal tracking, and was designed to track resident space objects in low-Earth orbit. The telescope can accommodate up to 6 instruments mounted simultaneously, and is equipped with a tertiary mirror that can switch to a different instrument port in less than 26 seconds. This allows for astrometry, photometry, and spectroscopy to be collected on a target nearly simultaneously.

Fig. 1. The Magdalena Ridge Observatory 2.4-meter fast-tracking telescope (right) and support facility (left) located outside of Socorro, NM on Magdalena Ridge. The observatory performs target-of-opportunity scientific research as well as work in the area of space situational awareness.

The near-Earth environment has presented many opportunities for the 2.4-meter facility researchers to contribute to monitoring and characterizing resident space objects. The areas of space situational awareness that we have had previous experience with include detection and/or tracking of man-made objects and the identification (and spectral characterization) of detected objects, as well as the determination and prediction of orbital status and spacecraft maneuvers. The 2.4-meter facility researchers have tracked hundreds of low-Earth orbiting objects (LEOs) since September 2007 for the Air Force and others. Figure 2 illustrates the various on-orbit fast-moving targets images taken with the 2.4-meter telescope early in its operational phase for tracking refinement purposes.

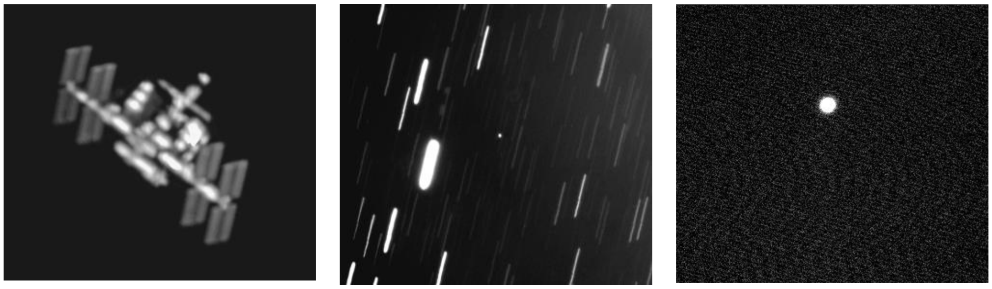

Fig. 2. A single, resolved image (left) of the International Space Station (ISS) taken with the 2.4-meter telescope on December 14, 2010. An unresolved image (middle) of GEO satellite 28659 (Direct TV-8) taken in 2012, and a tracked image (left) taken with the 2.4-meter telescope of newly generated space debris: the tool-bag lost by a shuttle astronaut while servicing the ISS on November 19, 2008.

In the following sections we describe a pilot project to establish a database using the 2.4-meter telescope to monitor spin rate changes in defunct GEO satellites in order to potentially reveal what mechanisms dominate their alteration (if any is detected) over time.

2. GEO SATELLITE TARGETS AND OBSERVATIONS

For this phase of our study of the dynamics of the spin states of inactive GEO satellites, we selected 3 target objects: GOES 8 (a weather satellite, decommissioned in 2004), and communication satellites BSAT 1A and Brazilsat B1. A sketch of GOES 8 is shown in Figure 3, along with an image of the satellite as it's tracked by the 2.4-meter telescope. GOES 8 is highly asymmetric, and is a good object to study physical effects such as YORP which would be enhanced by the geometric variation and surface reflectivity differences. The other 2 targets are symmetric (see Figure 4).

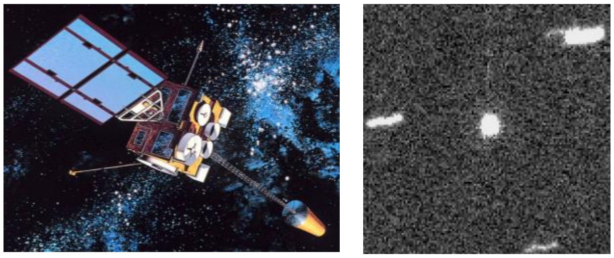

Fig. 3. (Left) Artist's drawing of NOAA weather satellite GOES 8 in orbit. (Right) Image of GOES 8 taken with the MRO 2.4-meter telescope on April 23, 2014. Background artifacts are star streaks as the telescope tracks the target object in the center.

Fig. 4. (Left) Artist's drawing of Japanese communications satellite BSAT 1A in orbit. (Right) Artist's drawing of communications satellite Brazilsat B1 in orbit (Boeing BSS).

Photometric measurements of the periodic light variation of these 3 targets were obtained at MRO using a an Andor iKon 936 CCD camera with a 2Kx2K EEV CCD42-40 array and 13.5 micron pixels thermoelectrically cooled to -85^{o}C. The images were taken through a Bessel VR filter, and exposure times were adjusted based on the satellite brightness. Typical realized seeing was on the order of one arc-second, and the CCD was binned 4x4 resulting in approximately 2 pixels per seeing width. This binning as well as windowing the read out portion of the chip down to 1/4 of the array size allowed for a sampling cadence between 1-2 Hz. The 2.4-meter telescope software utilized two-line element sets (TLE's) to track the GEO satellites as they moved against the sidereal motion of the sky such that the stars in the images appear as streaks in the right hand images of Figure 3. Observations were typically taken in 600 frame image stacks, although this number could be as high as 3000. The specific choice was dependent upon anticipated knowledge of the satellite's behavior, usually developed through test sequences or visual determinations through the acquisition telescope's video feed.

Photometry was extracted from the images and photon statistics determined using the IRAF *phot* task from which the sequential lightcurves were derived. Trial periods were identified using the IRAF *pdm* task. These were then tested and refined using custom python and IDL routines to 'fold' the data using these trial periods until a conclusive rotation period was identified. This allowed the lightcurves to be plotted as a function of rotational phase as shown in the following figures instead of the normal sequential time series format.

Figure 5 shows the resulting phased lightcurve for GOES 8 taken on April 24, 2014 and September 12, 2015. Figures 6 and 7 show the phased lightcurves for BSAT 1A and Brasilsat B1, respectively.

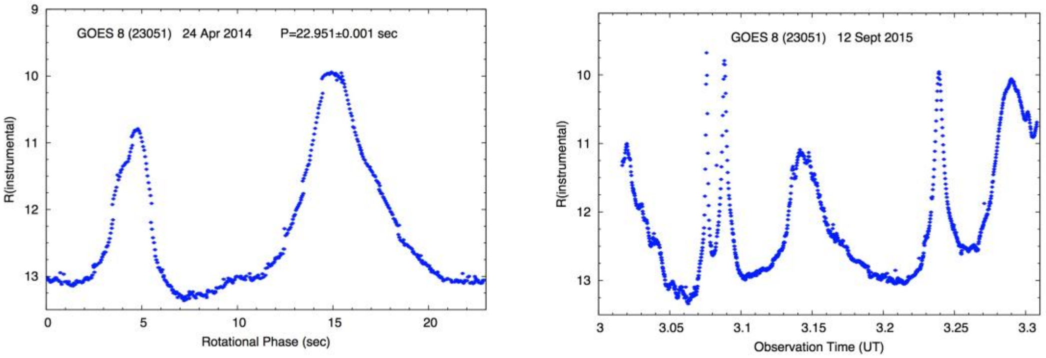

Fig. 5. (Left) Phased lighhtcurve for satellite GOES 8 taken in April 2014; the spin period was determined to be 22.95 seconds. (Right) GOES 8 lightcurve taken September 12, 2015; no discernably period detected.

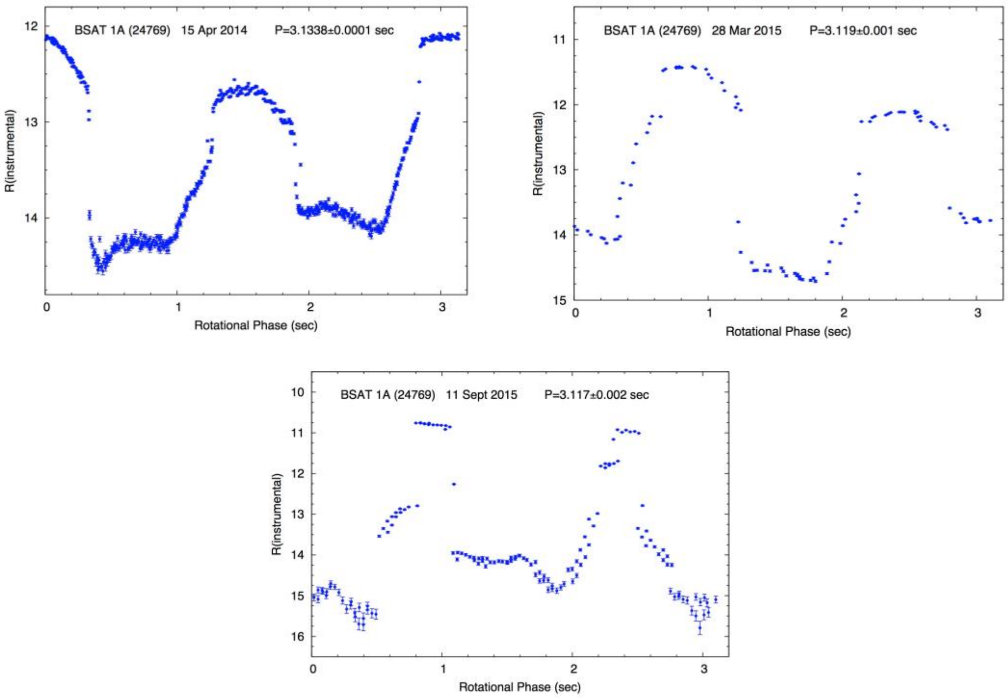

Fig. 6. Phased lighhtcurves for satellite BSAT 1A taken on April 15, 2014 (period is 3.134 seconds), on March 28, 2015 (period is 3.119), and again on September 11, 2015 (period is 3.117 seconds).

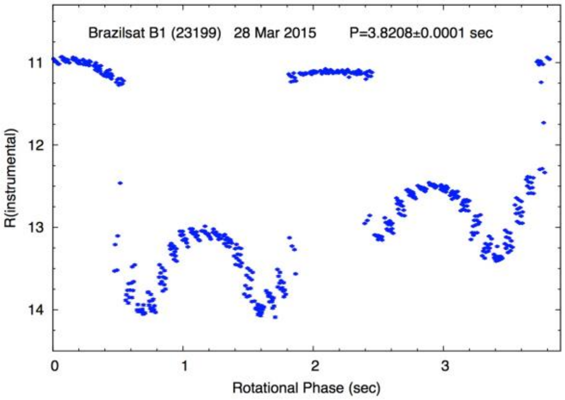

Fig. 7. Phased lighhtcurve for satellite Brazilsat B1. The spin period was determined to be 3.82 seconds.

3. RESULTS AND DISCUSSION

The preliminary results of this observing campaign are shown in Table 1. Also shown are the observations taken by [3] of satellite GOES 8 for comparison with our data.

Satellite	Date (UT)	Observer	Solar Phase Angle (º)	Period (sec)
GOES 8	2013-12-12	Cognion (2014)	32	16.83
GOES 8	2014-02-27	Cognion (2014)	30	16.48
GOES 8	2014-04-23	Ryan & Ryan (2015)	51	22.95
GOES 8	2014-07-25	Cognion (2014)	11	75.66
GOES 8	2015-09-12	Ryan & Ryan (2015)	29	*inconclusive*
BSAT 1A	2014-04-15	Ryan & Ryan (2015)	16	3.134
BSAT 1A	2015-03-28	Ryan & Ryan (2015)	42	3.119
BSAT 1A	2015-09-11	Ryan & Ryan (2015)	45	3.117
Brazilsat B1	2015-03-28	Ryan & Ryan (2015)	135	3.821

Table 1. Spin period and mid-observation solar phase angle data for satellites GOES 8, BSAT 1A, and Brazilsat B1.

Although some of the observations were taken at very high phase angle, the short periodicity observed in the lightcurves with respect to the rate of change in the phase angle bisector helps ensure that the observed rotation period is the sidereal period to within errors. However, this geometry did change in some cases enough during the course of an image stack to alter the shape of the lightcurve to a degree that is noticeable with respect to the photometric statistics. Therefore, many of the plots in the previous section for higher phase angle targets utilize only a subset of data from an image stack. However, the derived periods are still based on 50 or more rotation cycles.

All the inactive satellites observed in this study have very short rotation periods, on the order of 10's of seconds or less. GOES 8 has been inactive for years (since 2004) and has been previously observed [3]. Combining these past results with ours shows that its rotation period is slowing down rather dramatically. Our most recent observations indicate that either it evolved further into a complex rotational state or that it was simply observed from a non-ideal viewing angle that did not effectively highlight its rotational motion. Future observations from a different geometry will help resolve this. Data taken on BSAT 1A also shows that its period has definitively changed (to within the precision of the error bars) over an approximately 1 year time span although on a much less pronounced scale. Recently acquired data (September 2015) however indicates that it is essentially unchanged over a 6-month time span.

4. SUMMARY

It is clear from the observational data collected as part of this pilot study (as well as from previous work) that the rotational periods of inactive GEO satellites do vary over time. This is due do several physical processes acting on these bodies, and is likely a strong function of the satellite's shape characteristics and material properties. Therefore, different satellites can distinctly different rotational variations. Understanding the long-term behavior of these bodies can help reveal important knowledge about their rotational dynamics. This would have practical as well as scientific benefit, if in the future methods for safely removing defunct satellites are desired.

5. REFERENCES

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