The long-term broadband photometric surveys of inactive AS-7000 and HS-601 box-wing geosynchronous satellites

M.A. Earl (a) and G.A. Wade (b)
(a) Royal Military College of Canada, Kingston ON, earl-m@castor2.ca
(b) Royal Military College of Canada

Abstract

Recent long-term broadband photometric observations of two AS-7000 (Lockheed Martin) and four HS-601 (Boeing) inactive box-wing geosynchronous satellites revealed that each had unique light curves that contained repeating characteristics over time, suggesting a spinning motion with periods between 2 and 30 minutes. Every satellite spin period varied with time, some cyclically and others secularly. A linear relationship between the spin period variation amplitude and the average spin period was proposed. A larger sampling of box-wing satellites, comprising five AS-7000 and five HS-601 satellites, provided additional broadband photometric light curves that verified these recent observations. Preliminary qualitative comparisons between the satellites' phase plot (folded light curve) characteristics were conducted. Full-period to half-period power spectrum ratio variations were compared to their corresponding spin period variations. Despite similar designs, each satellite's phase plot and spin period variation appeared to be unique in amplitude, shape and period. Strong correlations have been found between Telstar-401's full-period to half-period power spectrum ratios and its spin periods.

I Introduction

The geosynchronous (GEO) population consists of satellites orbiting at approximately 35,785 km in altitude with nearly circular orbits inclined at between 0° and 15° from the Earth's equatorial plane[1] [1]. Approximately 95% of all satellites are inactive [2]. A typical box-wing satellite has a central cube-shaped structure, flanked by two large-area solar panels and two communications dishes [3].

Papushev, et al. (2009) conducted photometric observations of inactive Russian Raduga, Gorizont and Ekran satellites from 1990 to 2004. They obtained high temporal resolution broadband optical light curves and observed large and periodic brightness variability, suggesting spinning motion and spin period variability over several years [4]. They observed spin periods between 0.3 minutes and 7.2 minutes. A single broadband light curve of Raduga 18, observed by Payne, et al. (2007), exhibited similar characteristics to those reported by Papushev, et al. but suggested a 30-minute period [5].

Binz, et al. (2014) observed a number of American box-wing satellites from January to May 2012. Some light curves exhibited more complex structures without a definitive period. Their results yielded apparent spin periods between 2.3 and 100 minutes. If estimated, their spin period variations were not reported [6].

Cognion (2014) obtained photometric observations of GOES[2]-8, 9, 10, 11 and 12 from December 2013 to August 2014 [7]. Cognion observed that each satellite's phase plot appeared different from the others, suggesting each satellite had a "very different rotational behaviour" [7]. Phase plots of GOES-8 and GOES-10 revealed coherent (repeating) patterns from cycle to cycle. Each satellite's spin period and spin period variability rate were observed to be significantly different. GOES-8's period was observed to increase from 16.83s to 75.66s over seven months. Ryan and Ryan (2015) measured GOES-8's spin period as

[1] The first three Sirius radio satellites could also be considered geosynchronous, despite orbit eccentricities of 0.27 and orbit inclinations of nearly 65° [1].

[2] Geostationary Operational Environmental Satellite

22.951±0.001s on April 24, 2014 [8] but they could not infer GOES-8's spin period from observations obtained on September 12, 2015. Cognion's observations of GOES-9, 11 and 12 revealed phase plots that changed significantly from cycle to cycle and reported an unsuccessful spin period determination of GOES-12. The GOES spin periods were estimated to be between several minutes and tens of minutes [7].

In the first survey, long-term broadband photometric (CCD[3]) observations of four inactive box-wing satellites, Solidaridad-1, Telstar-401, Echostar-2 and HGS[4]-1, were obtained from mid-June 2012 to late December 2013 [3]. Each satellite's light curves suggested rotational motion with unique spin periods compared with the other satellites. Spin periods ranged from 2.4 minutes (Telstar-401) to 30.8 minutes (HGS-1). Spin period variations of Telstar-401, Echostar-2 and HGS-1 appeared cyclical, while Solidaridad-1's spin period variation appeared secular [3]. When considering their amplitudes, shapes and apparent periods, the spin period variations were unique to each satellite. The variation cycle timescales were estimated to range from 280 days to at least 520 days. A linear regression fit relating the spin period variation amplitudes and the average apparent spin periods, is seen in [3] and in [9].

In the second survey, the four satellites, plus Paksat-1 and Intelsat-3R, were observed from January to October 2014. Intelsat-3R's and Paksat-1's light curves appeared noticeably different from those of the original four satellites. Intelsat-3R's spin period appeared to slowly and secularly increase over 500 days. Paksat-1's spin period variation appeared cyclical [9].

This paper presents the initial results from the three box-wing photometric surveys conducted from early 2012 to early 2016. Phase plots and spin period variations of the 11 satellites shown in Table 1 will be discussed. Telstar-401's power spectrum ratios' (PSRs') relationships with the average spin period will be discussed. Specific attention is placed on the phase plot characteristics, the spin period variation amplitudes and cyclical periods (if observed) and the inferred relationships between PSRs and spin periods.

II Third Box-wing Photometric Survey

Additional broadband CCD observations of the box-wing satellites observed in the first and second surveys, except Intelsat-3R, were conducted from late-2014 to early 2016. Five box-wing satellites were added to the sample, totalling ten satellites (five AS-7000 and five HS-601), allowing comparison of broadband photometric light curves between similar designs and two manufacturers (Lockheed Martin and Boeing). The three additional AS-7000 satellites (Table 1) were chosen primarily because of their favorable access duration from the observation location. DirecTV-2 was suggested by Dr. Mark Skinner, who observed it in the thermal infra-red (IR) (8 to 13 μm) and the visible wavelengths [2] [10]. Solidaridad-2 was suggested by Dr. Jeremiah Salvatore nearly one year after the satellite was decommissioned and parked in the GEO graveyard orbit[5] [11]. This survey was conducted from the same location using the same equipment, observation procedure and observation criteria, as in [3] and [9].

Photometric analyses of raw images were performed using MATLAB software, designed and modified by Earl [12] [3] [9]. Prior to the third survey, a manual peak-to-peak method [12] [3] and a Lomb-Scargle[6] (L-S) (modified discrete Fourier transform) method [9] had been used to infer spin periods from the light curves. The "Cross-Residual Technique" (CRT) of spin period determination, described in [6], was used throughout the third survey.

[3] Charge-Coupled Device
[4] Hughes Global Services
[5] Solidaridad-2 had been decommissioned in December 2013 [11].
[6] Specifically, the MATLAB 'lombscargle.m' Lomb-Scargle analysis program, originally written by Dr. Brett Shoelson and modified by Earl in 2014. http://www.mathworks.com/matlabcentral/fileexchange/993-lombscargle-m/content/lombscargle.m. Last accessed on 04/03/16.

Table 1. *AS-7000 and HS-601 satellites surveyed from 2012 to 2016*

NORAD[7]	COSPAR[8]	COMMON NAME	DESIGN	OBSERVATIONS (mm/dd/yy)
22911	1993-073-A	Solidaridad-1	HS-601	06/16/12 to 09/23/15
22927	1993-077-A	Telstar-401	AS-7000	03/05/12 to 09/23/15
23192	1994-047-A	DirecTV-2 (DBS-2) (Nimiq-4i)	HS-601	11/14/14 to 01/08/16
23313	1994-065-A	Solidaridad-2	HS-601	11/14/14 to 11/04/15
23670	1995-049-A	Telstar-402R (Telstar-4)	AS-7000	07/16/13 to 10/12/15
23723	1995-064-A	AMOS-5i (Asiasat-2)	AS-7000	10/01/13 to 10/10/15
23764	1996-002-A	Intelsat-3R (PAS-3R)	HS-601HP[9]	02/16/13 to 10/13/14
23779	1996-006-A	Paksat-1 (Anatolia-1)	HS-601	10/11/13 to 10/12/15
24313	1996-055-A	Echostar-2	AS-7000	03/11/12 to 11/04/15
24846	1997-031-A	Intelsat-802	AS-7000	01/20/15 to 11/04/15
25126	1997-086-A	HGS-1 (Asiasat-3)	HS-601HP[10]	06/16/12 to 11/04/15

III Phase Plots

Phase plots, corresponding to every observation of all 11 satellites shown in Table 1, were extracted from the photometric data. Example AS-7000 phase plots are shown in Figs. 1(a) (Telstar-401), (b) (Telstar-402R), (c) (AMOS-5i) and (d) (Echostar-2). Example HS-601 phase plots are shown in Figs. 2(a) (Solidaridad-1), (b) (Solidaridad-2), (c) (DirecTV-2), (d) (HGS-1), (e) (Paksat-1 on July 10, 2014) and (f) (Paksat-1 on May 14, 2015). Each phase plot caption indicates, from left to right, the NORAD catalog number, the observation's beginning and ending times (UTC[11]) (hour:minute), the observation date (month-day-year), the estimated spin period and the satellite's average azimuth and elevation. The default broadband magnitude range is 17th (faintest) to 8th (brightest). If a satellite was brighter than 8th magnitude, the brightest integer magnitude is indicated.

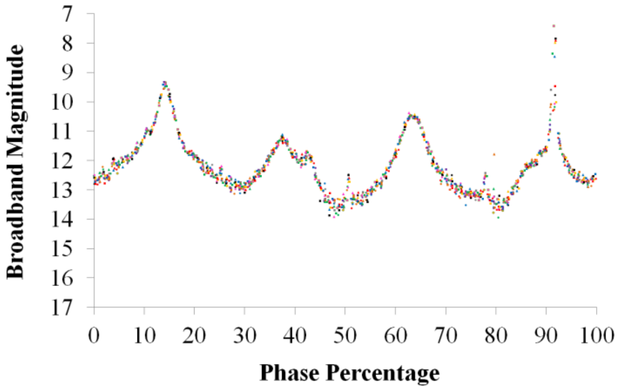
Telstar-401 and Telstar-402R had similar designs and both became inactive due to catastrophic malfunction [13] [14] but their phase plots (Figs. 1(a) and (b)) appeared to have different shapes and behaviors. This finding is similar to what Cognion had reported for the GOES satellites. Typically, Telstar-401's phase plots appeared coherent, meaning each plot cycle correlated well with previous and subsequent cycles, as in Fig. 1(a). Telstar-402R's phase plots appeared incoherent, meaning that each plot cycle showed significant differences with respect to the previous or subsequent cycles, as in Fig. 1(b).

A similarity between Telstar-401's, AMOS-5i's and Echostar-2's phase plots was noticed when comparing Figs. 1(a), (c) and (d). These phase plots have four dominant distributions, which suggest the four sides of the box-wing's cube structure. The two thin distributions suggest the two mirrored radiators[12] and not the solar panels, since each side of each solar panel has a different reflectivity and smoothness [15].

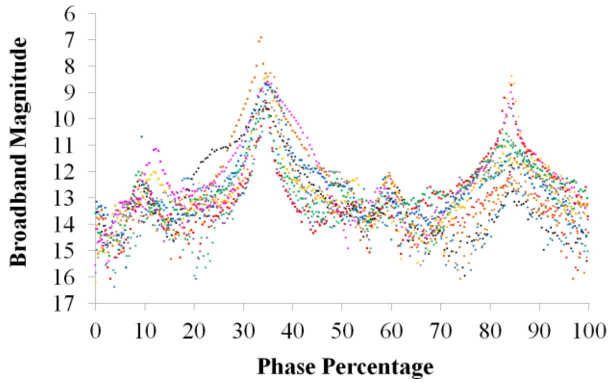
Echostar-2 also suffered a catastrophic failure [16] and its phase plots appeared to be coherent. AMOS-5i (Fig. 1(c)) and Intelsat-802 (not shown) were both retired [17] [18]; however, their phase plots appeared

[7] North American Aerospace Defense Command
[8] Committee on Space Research
[9] High power (HP) version of HS-601. Identical to the HS-601 design except for larger solar panels.
[10] Only one of HGS-1's two solar panels successfully deployed after launch.
[11] Coordinated Universal Time
[12] The radiators assist to dissipate heat away from the box-wing bus electrical components. All 11 satellites possess these radiators.

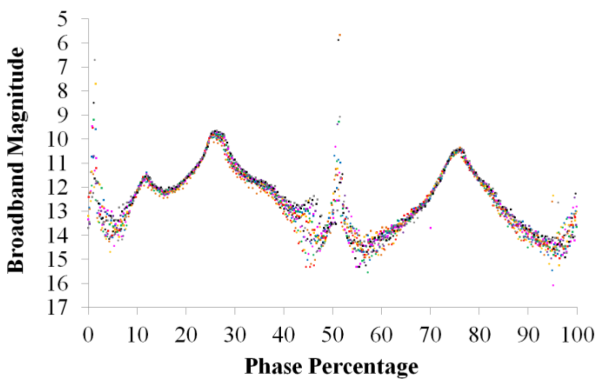
coherent. This suggests that the reason for inactivity will not contribute to an AS-7000 satellite's phase plot coherence.



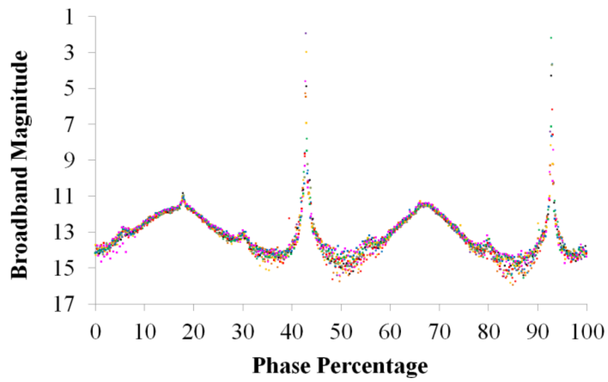
a) 22927; 05:10-06:11; 11-14-12; 153.4s; 220°; 29°



b) 23670; 01:43-04:07; 10-29-13; 635s; 195°; 31°



c) 23723; 01:19-03:07; 05-07-14; 365.5s; 174°; 42°



d) 24313; 01:46-03:21; 09-12-12; 375.9s; 158°; 33°

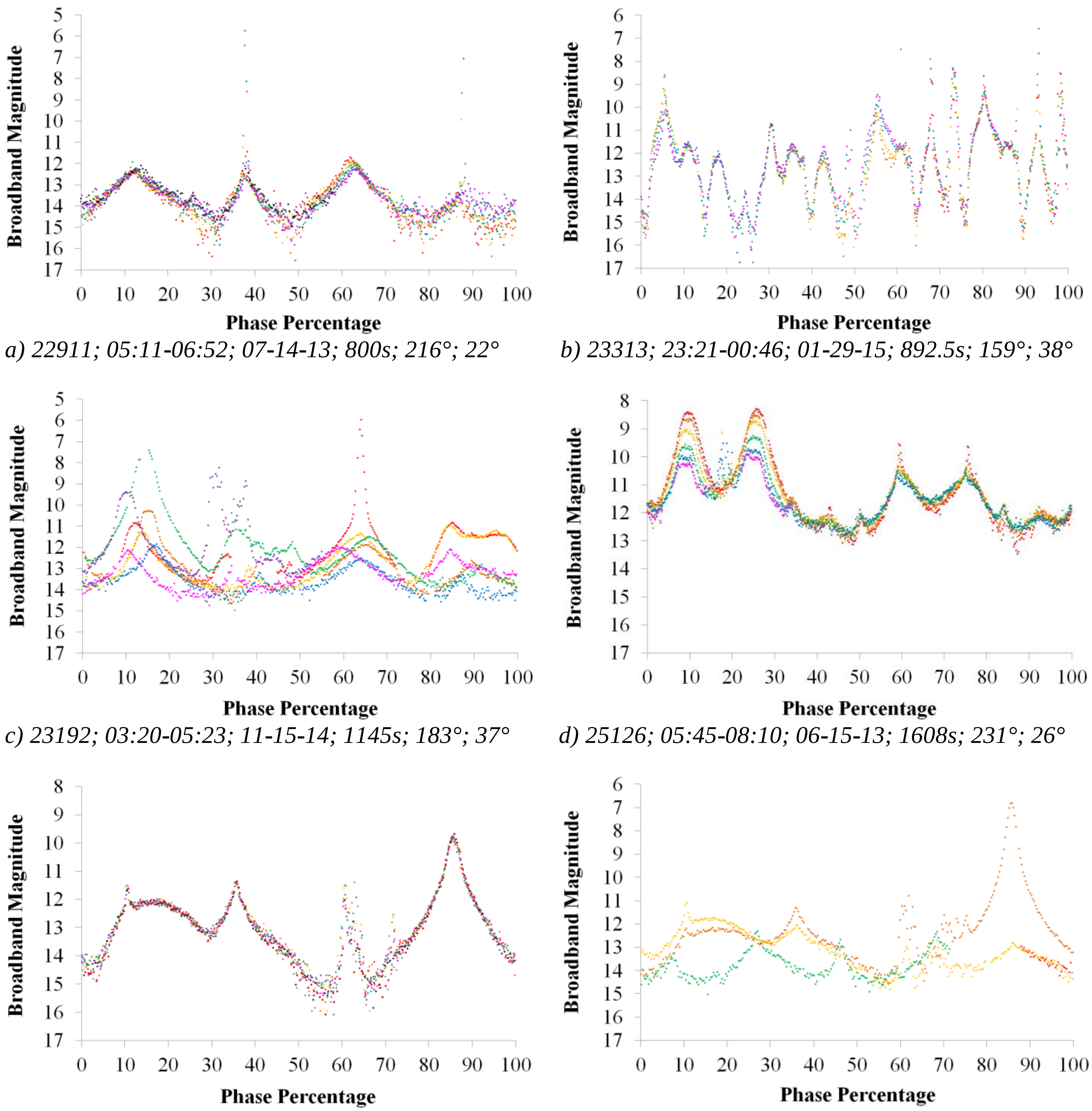
Fig. 1. *AS-7000 satellite phase plots*

Although Solidaridad-1 and 2 were identical in design [11], their phase plots, shown in Figs. 2(a) and (b), respectively, appear significantly different but consistently coherent. Solidaridad-1 suffered a catastrophic failure in August 2000 [19] and Solidaridad-2 was retired in December 2013 [11]. Solidaridad-1's phase plot also consists of four distributions, similar to those observed for Telstar-401, AMOS-5i and Echostar-2. This suggests that a single phase plot comparison cannot discriminate between the AS-7000 and the HS-601 designs. Solidaridad-2's phase plots appeared to feature at least 12 maxima per cycle. It is unclear how all of the satellite's sides could reflect sunlight to an Earth-bound observer in such a manner over one spin cycle.

DirecTV-2's phase plot (Fig. 2(c)), appears incoherent in both amplitude and phase. This phenomenon was reported by Cognion and Ryan and Ryan when observing GOES-12 [7] and GOES-8 [8], respectively.

HGS-1's phase plots, (example in Fig. 2(d)), feature two pairs of distributions, one pair being two broad distributions and the other pair being tall spikes, each spaced by 16% of a cycle. The two pairs are separated by 50% of the spin cycle and suggest distinct satellite sides separated by 180°.

Paksat-1's phase plots closely resembled Fig. 2(e) from late 2013 to early 2015. When the satellite was observed after January 2015, its phase plot appeared incoherent (Fig. 2(f)). From October 2013 to January 2015, the satellite's estimated spin period increased from 259s to 1302s. GOES-8's spin period was increasing when Ryan and Ryan observed its incoherent phase plot in September 2015 [8]. These observations suggest that an increasing spin period could be related to an incoherent phase plot.



a) 22911; 05:11-06:52; 07-14-13; 800s; 216°; 22°

b) 23313; 23:21-00:46; 01-29-15; 892.5s; 159°; 38°

c) 23192; 03:20-05:23; 11-15-14; 1145s; 183°; 37°

d) 25126; 05:45-08:10; 06-15-13; 1608s; 231°; 26°

e) 23779; 04:36-05:44; 07-10-14; 441.6s; 125°; 20°

f) 23779; 01:33-02:16; 05-14-15; 913.0s; 160°; 40°

Fig. 2. *HS-601 satellite phase plots*

IV Spin Period Variations

Each satellite's spin period was inferred from its light curve by the peak-to-peak method (first survey), the peak-to-peak and L-S methods (second survey) and the peak-to-peak and CRT methods (third survey). Two example spin period variations are shown in Figs. 3(a) (Telstar-401) and (b) (Solidaridad-1).

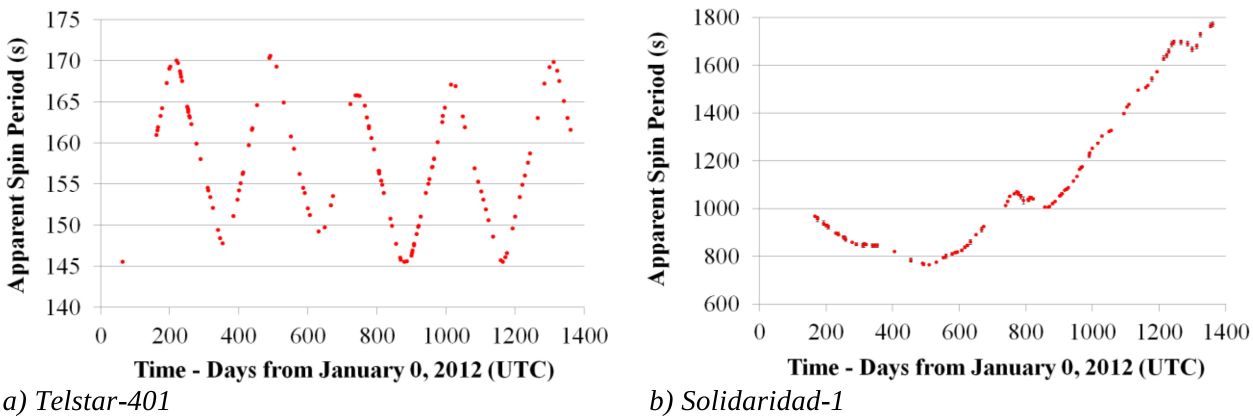


Fig. 3. *Satellite spin periods*

When considering shape, amplitude and time scale, each AS-7000 spin period variation appeared to be unique. Telstar-401's spin period (Fig. 3(a)), appears to cyclically vary. The variation amplitude decreased from 25s (2012) to 13s (2014), then increased to 25s (2016). The variation period decreased from 270s (2012) to 250s (2014) and then increased to nearly 300s (2015). The decrease (or increase) in variation amplitude appeared to coincide with the decrease (or increase) in the variation period. Telstar-402R's phase plots were incoherent; therefore its inferred periods might not represent its true spin periods.

AMOS-5i's spin period variation appeared cyclical and suggested a nearly one year time scale and a 1025s amplitude, over forty times larger than Telstar-401's variation amplitude. From day 584 to 600 (since January 0, 2013), AMOS-5i's spin period variation rate appeared to be 10.5 $s \cdot day^{-1}$, while Telstar-401's highest rate is 0.2 $s \cdot day^{-1}$.

Echostar-2's spin period variation appeared cyclical. In 2012-13, Echostar-2's variation amplitude was at least 190s. In 2014-15, this amplitude decreased to 31s. The variation period also decreased in this time, from nearly one year in 2012-2013 to 270d in 2014-15. This phenomenon is similar to Telstar-401's spin period variation. Echostar-2's spin period variation rate appeared to decrease between days 132 and 192, days 340 and 397, days 454 and 510, days 1056 and 1137 and days 1193 and 1266.

Solidaridad-1's spin period (Fig. 3(b)), appears to increase secularly from day 510 to day 1400 (since January 0, 2012), with two exceptions near day 800 and near day 1275. The spin period also appears to have steadily and secularly decreased from day 165 to day 510, suggesting a greater than 3.3 years' cycle. Solidaridad-2's spin period appeared to be within the same order of magnitude observed for Solidaridad-1 and appeared to smoothly and secularly increase.

Paksat-1's spin period variation appeared cyclical with a complex structure. The variation time scale appeared to be greater than 200 days. The spin period variation rate between days 363 and 372 was 22.9 $s \cdot day^{-1}$. This occurred several weeks before Paksat-1's first incoherent phase plot (Fig. 2(f)) was observed.

HGS-1's spin period variation appeared cyclical. Between days 252 and 257 (since January 0, 2012) the spin period increased by 122s at a rate of 24.4 $s \cdot day^{-1}$. Despite the satellite's long spin period, its phase plots have appeared coherent. The variation time scale appeared to be 310 days in 2012-13, 330 days in 2014-15 and 362 days when comparing the two spin period minima on days 412 and 1137.

Figure 4 plots the spin period variation amplitude versus the average spin period. Green data points represent known spin period variation amplitudes and average spin periods. Red data points represent uncertain spin period amplitudes or uncertain average spin periods. Arrows indicate variation amplitudes that are larger than a plot indicates. Error bars show the range of variation amplitudes. The black trend line shows the relationship proposed in [9]. The proposed relationship in [9] does not fit most of the data in Fig. 4. The position of Solidaridad-1's data point has changed significantly since 2014 and now appears far above the proposed trend line. A significant discrepancy appears when comparing HGS-1's and DirecTV-2's data points, which could be due to HGS-1's un-deployed solar panel or DirecTV-2's incoherent phase plots.

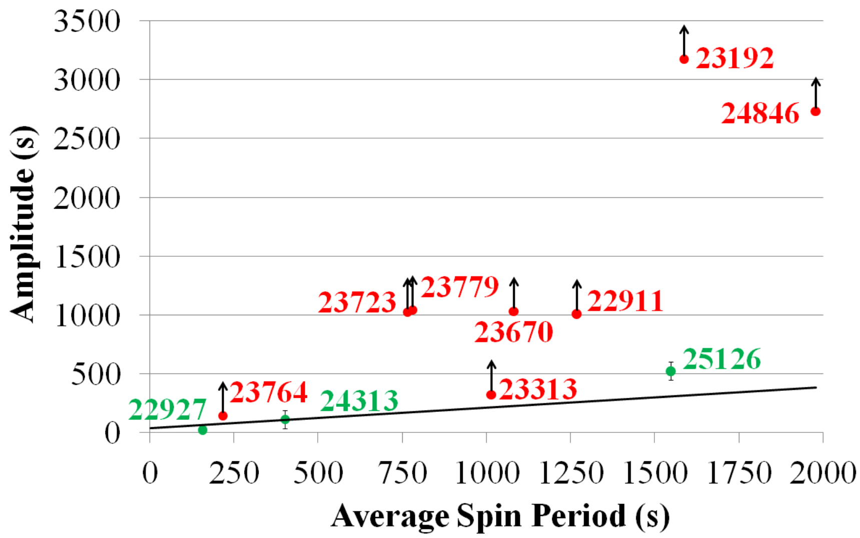


Fig. 4. *Spin period variation amplitude versus average spin period*

V Power Spectrum Ratios

L-S periodograms were extracted from the light curves of Telstar-401, Echostar-2, Solidaridad-1, Paksat-1 and HGS-1. Power spectrum maxima corresponding to 1, 2, 4 and 8 times the spin frequency (full, half, fourth and eighth spin periods, respectively) were extracted from each periodogram. A PSR is the ratio of one power spectrum maximum to another. All PSR combinations were compared to the spin period plots. The strongest correlations were found for Telstar-401 when comparing its full/half period PSRs (1:2 spin frequency ratios) with its spin periods, as in Fig. 5. Black circles depict the midpoint between maximum and minimum spin periods. Blue circles depict spin period curve locations corresponding to PSR maxima. Red circles depict PSR curve locations corresponding to spin period maxima or minima. Every Telstar-401 maximum and minimum spin period correlated to a PSR minimum (Fig. 5). Telstar-401's PSR maxima correlated with a point on the spin period curve between the midpoints (black circles) and the spin period extrema (maxima or minima). Telstar-401's spin period amplitude also appeared to vary with the maximum PSR magnitude (Fig. 5).

Similar, albeit weaker, correlations were found for Echostar-2. Some maximum or minimum spin periods nearly correlated to PSR maxima. Some PSR maxima appeared to correlate with the beginning and ending points where the spin period variation rate decreases (between the spin period maximum and minimum). Some PSR maxima did not appear to correlate with any significant spin period variation characteristic. Echostar-2's maximum PSRs appeared to vary with the maximum PSR magnitude, similar to the behavior observed for Telstar-401.

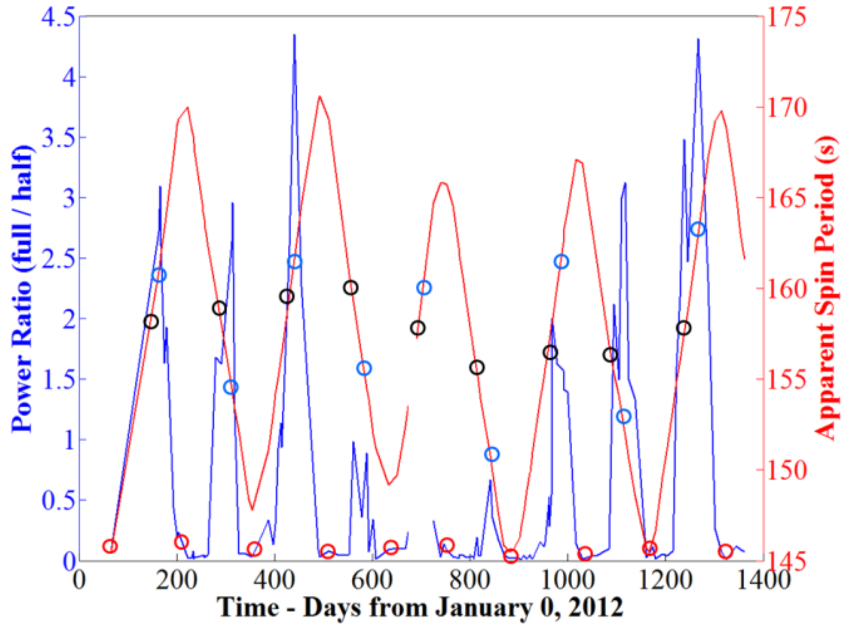


Fig. 5. *Telstar-401's full/half period PSR versus spin period*

VI Conclusions and Future Work

Each of the 11 satellites' phase plots appeared to be unique. Amongst the AS-7000 or the HS-601 satellite groups, there were few similarities between the respective phase plots. Qualitatively, there were insufficient phase plot characteristics that could discriminate the AS-7000 from the HS-601 designs.

Spin period variations of Telstar-401, AMOS-5i, Echostar-2, Paksat-1 and HGS-1 appeared cyclical. Spin period variations of Intelsat-802, Solidaridad-1, Solidaridad-2, Intelsat-3R and DirecTV-2 appeared secular. The linear trend line originally proposed in [9] relating the spin period variation amplitude to the average spin period could not adequately model the supplementary survey data.

Strong correlations were found between the full/half period PSR maxima and the spin periods of Telstar-401. Telstar-401's PSR minima appeared to temporally correlate with spin period maxima and minima. Telstar-401's PSR maxima appeared to temporally correlate between the spin period extrema and the midpoint between spin period maxima and minima. Some of Echostar-2's PSR maxima appeared to temporally correlate with the spin period maxima and minima. Telstar-401's and Echostar-2's PSR maxima appeared to vary with the spin period variation amplitude.

Phase plots, spin period variations and periodograms of all satellites described in this paper will be used to test solar radiation pressure (SRP) dynamics models. Additional observations of the 11 satellites and a larger inactive box-wing GEO sample are required to understand each of their complex dynamics.

References

[1] JFCC SPACE/J3 - Space Track - https://www.space-track.org (accessed 03/25/16).

[2] Skinner, M., Russell, R., Kelecy, T., Gregory, S., Rudy, R., Kim, D., and Crawford, K., "Observations in the thermal IR and visible of a retired satellite in the graveyard orbit, and comparisons to active satellites in GEO," *Acta Astronautica*, Vol. 105, August 2014, pp. 1–10, doi:10.1016/j.actaastro.2014.08.016.

[3] Earl, M. and Wade, G., “Observations of the Spin-Period Variations of Inactive Box-Wing Geosynchronous Satellites,” *Journal of Spacecraft and Rockets*, Vol. 52, 2015, pp. 968–977, doi:10.2514/1.A33077.

[4] Papushev, P., Karavaev, Yu., and Mishina, M., “Investigations of the evolution of optical characteristics and dynamics of proper rotation of uncontrolled geostationary artificial satellites,” *Advances in Space Research*, Vol. 43, February 2009, pp. 1416–1422, doi:10.1016/j.asr.2009.02.007.

[5] Payne, T., Gregory, S., Tombasco, J., Luu, K., and Durr, L., “Satellite Monitoring, Change Detection, and Characterization Using Non-Resolved Electro-Optical Data From a Small Aperture Telescope,” *Proceedings of the 2007 Advanced Maui Optical and Space Surveillance (AMOS) Technologies Conference*, edited by S. Ryan, Maui Economic Development Board, September 2007.

[6] Binz, C., Davis, M., Kelm, B., and Moore, C., “Optical Survey of the Tumble Rates of Retired GEO Satellites,” *Proceedings of the 2014 Advanced Maui Optical and Space Surveillance (AMOS) Technologies Conference*, edited by S. Ryan, Maui Economic Development Board, September 2014.

[7] Cognion, R., “Rotation rates of inactive satellites near geosynchronous earth orbit,” *Proceedings of the 2014 Advanced Maui Optical and Space Surveillance (AMOS) Technologies Conference*, edited by S. Ryan, Maui Economic Development Board, September 2014.

[8] Ryan, W. and Ryan, E., “Photometric Studies of Rapidly Spinning Decommissioned GEO Satellites,” *Proceedings of the 2015 Advanced Maui Optical and Space Surveillance (AMOS) Technologies Conference*, edited by S. Ryan, Maui Economic Development Board, September 2015.

[9] Earl, M. and Wade, G., “Observation and Analysis of the Apparent Spin Period Variations of Inactive Box-wing Geosynchronous Resident Space Objects,” *Proceedings of the 65th International Astronautical Congress, Toronto, Canada*, International Aeronautical Federation, October 2014.

[10] Skinner, M., Russell, R., Kelecy, T., Gregory, S., Rudy, R., and Kim, D., “Comparison of thermal IR and visible signatures of graveyard orbit objects,” *Proceedings of the 66th International Astronautical Congress, Jerusalem, Israel*, International Astronautical Federation, 2015.

[11] Personal telephone correspondence with Dr. Jeremiah Salvatore, retired Boeing senior research fellow: October 23, 2014.

[12] Earl, M., *Observation and Analysis of the Spin Period Variations of Inactive Box-wing Telecommunications Satellites in Geosynchronous Orbit*, MSc thesis, Royal Military College of Canada (RMCC), May 2013, http://www.castor2.ca/08_Papers/earl_thesis.pdf, accessed 03/27/16.

[13] Carlowicz, M. and Lopez, R., *Storms from the Sun: The Emerging Science of Space Weather*, Joseph Henry Press, 2002.

[14] Encyclopedia Astronautica - Telstar - http://www.astronautix.com/project/telstar.htm (accessed 04/01/16).

[15] List, M., Bremer, S., Rievers, B., and Selig, H., “Modelling of Solar Radiation Pressure Effects: Parameter Analysis for the MICROSCOPE Mission,” *International Journal of Aerospace Engineering*, Vol. 2015, October 2015, pp. 6, doi:10.1155/2015/928206.

[16] Bergin, C., “Sea Launch lofts EchoStar 11 - EchoStar 2 dies on orbit,” https://www.nasaspaceflight.com, July 2008, accessed 04/01/16.

[17] Min, J. et al., “Branching Out - Reaching New Heights,” Tech. rep., Asia Satellite Telecommunications Holdings Limited, August 2012, http://www.asiasat.com/sites/default/files/ir_2012.pdf, accessed 04/01/16.

[18] Intelsat, “Form 10-K: Annual Report Pursuant to Section 13 or 15(d) of the Securities Exchange Act Report,” Tech. rep., United States Securities and Exchange Commission, December 2012, http://www.intelsat.com/wpcontent/uploads/2013/02/Q4-2012-Intelsat-Form10K.pdf, accessed 04/01/16.

[19] Jeffery, M., “SATMEX’s Solidaridad 1 Satellite Lost,” http://www.loral.com/inthenews/itn2/000830.html, August 2000, accessed 04/01/16.