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Attitude State Evolution of Space Debris Determined from Optical Light Curve Observations

Abdul Rachman[a]*, Thomas Schildknecht[a], Jiri Silha[a], Jean-Noel Pittet[a], Alessandro Vananti[a]

[a] *Astronomical Institute University of Bern (AIUB), Switzerland, abdul.rachman@aiub.unibe.ch*
* Corresponding Author

Abstract

Space debris population increased drastically during the last years. One of the contributing factors is the incidental collisions involving massive objects which are predicted to be more pronounced in the future. The removal of large, massive space debris is considered necessary to stabilize the population. In this respect, not only precise orbits, but also more detailed information about their attitude states such as spin period and spin axis orientation is required. Non-resolving optical observations of the magnitude variations, so-called light curves, are a promising technique to determine the tumbling rates and the orientations of the actual objects' rotational axis, as well as their temporal changes. For this purpose, we use the 1-meter telescope ZIMLAT at the Astronomical Institute of the University of Bern (AIUB) to collect light curves of selected LEO, MEO and GEO objects on a regular basis. We have acquired more than 3,000 light curves from 512 objects in various types since January 2007. By analysing the light curve in the AIUB light curve database we could determine that most of the objects in the database were rotators (with known or unknown periods). They were located in all orbital regions unlike stable objects which were not found in high elliptical orbit. In addition, rotators, slow rotators (rotators but with unknown periods), and stable objects consist of all object types which include payloads, rocket bodies, and debris. Slow rotators and stable objects mostly located in low earth orbits while rotators mostly located in other orbital regions. Periods of rotation in the database ranged from less than 1 sec to nearly 900 sec. We identified three patterns in spin rate evolution of the rotating objects in the database which showed oscillating, increasing, or decreasing trends. There were 36 oscillating rotators, 10 increasing rotators, and 18 decreasing rotators. All the oscillating rotators were GLONASS satellites while increasing and decreasing rotators were distributed among payloads and rocket bodies in various orbital regions.

Keywords: space debris, optical observation, light curves, spin rate evolution

1. Introduction

Space debris population which threatens the sustainability of space activity keeps growing. This trend still prevails despite the existence of mitigation guidelines since 1995. The main reason for this is the substantial increase of breakup debris due to collisions between large objects. This type of debris contributes more than 53% of the current catalogued in-orbit Earth satellite population [1]. Even worst, it is predicted that the number of incidental collisions will be more pronounced in the future. This will happen after man-made satellite population density is high enough to trigger the collisional cascading event (the Kessler syndrome).

It is a common agreement that the mitigation measures should be accompanied by the so called Active Debris Removal (ADR) to stabilize the future population of space debris. This is conducted by nudging the large debris into a safer orbit or forcing it to prematurely reenter the atmosphere [2]. For the mission to be successful, sufficient knowledge about the attitude of the debris is mandatory. The information can be obtained using optical observations, satellite laser ranging (SLR), and other means.

By observing debris using optical telescope, we can measure its attitude by analysing the change of brightness over time. This variation which is represented in a so called light curve is obtained by using astronomical photometry. Compared with other methods, the light curve method has several advantages. First, generally it is the most cost effective method. Second, we can benefit from the long history of astronomical photometry in the study of natural objects especially asteroid. In fact, in the space debris domain, light curves are the major source of information to the attitude state of non-controlled objects [3]. Using light curves, we can determine whether the objects are stable or tumbling and measure the apparent periods (and thus the spin rates) as well as the orientations of the actual objects' rotational axis. Periodic observations can reveal the temporal changes. Light curves can also be used to validate other attitude determination techniques like radar or SLR measurements and forward modelling refinement [4].

In this paper we will present spin rates and their temporal evolution for a large set of selected decommissioned LEO, MEO, HEO, and GEO spacecraft and upper stages, including more than 60 abandoned GLONASS satellites. All of them are obtained from analysing light curves collected by the 1-meter telescope ZIMLAT at the Astronomical Institute University of Bern (AIUB). An overview of current status of the database is also presented in this paper.

2. Data and Methods

We used the light curve database collected using the CCD sensor of ZIMLAT telescope (Fig. 1) from January 2007 until June 2017. The database currently contains more than 3,000 light curves from 512 selected space objects which cover all orbital regions and different types of objects. The light curve itself is the variation of relative magnitude as a function of time with duration spans from 3 until 20 minutes and sampling interval of about twice the exposure time.

Fig. 1. ZIMLAT telescope at AIUB which is used to collect all the light curves for this study.

The light curve database not only contains the collection of light curves but also other related information such as their classifications and phase diagrams [5]. Four classifications are available: very low quality (only few measurement points are available), stable (the light curves only resemble the change in phase angles during the passes), slow rotator (complex signals present in the data set indicating objects' own rotations), and rotator (clear periodic variation of signals over time) [4]. In the case of a rotator, the apparent rotation period and phase diagram are also available. These are obtained through the period extraction process which begins with the estimation of the initial period and is finalized by using the phase reconstruction method [3].

The database is divided into four orbital groups and four object groups [5]. The first orbital group is the low earth orbit (LEO) which has a mean altitude below 2000 km from the earth's surface and a low eccentricity. The second is the medium earth orbit (MEO) which is located at around 20,000 km altitude and has a low eccentricity. This orbit is typically used by navigation satellites such as GLONASS and GPS constellation. The third is the high eccentric orbit (HEO) which has an eccentricity above 0.2. The last one is the geosynchronous earth orbit and other orbit which is any type of orbit not covered by any of the previous three groups (GEO/other).

The first object group is the *payload* (PL) which is usually a box-wing type of object with one or two solar panels attached to the main bus. The second is the rocket body (R/B) which typically has a cylindrical-like shape. The third is the debris which is either mission-related or fragmentation debris. The last one is the DIS group for objects discovered during ESA's GEO, GTO, and Molniya surveys. Origin of DIS, compared with the other groups, is unknown. Each type of objects exhibits different shapes of phase diagrams [5].

LEO objects are the biggest constituent of the database followed by GEO/other object then MEO and HEO objects as Fig. 2 shows. The figure also shows that most of the observed objects are rocket bodies followed by payloads, discovered objects, and debris. Indeed, most of the LEO objects are rocket bodies (82.4%) while most of MEO objects are payloads (93.3%), most of HEO objects are shared roughly equally by rocket bodies (40.0%) and discovered objects (45.7%), and most of GEO/other objects are discovered objects (63.2%).

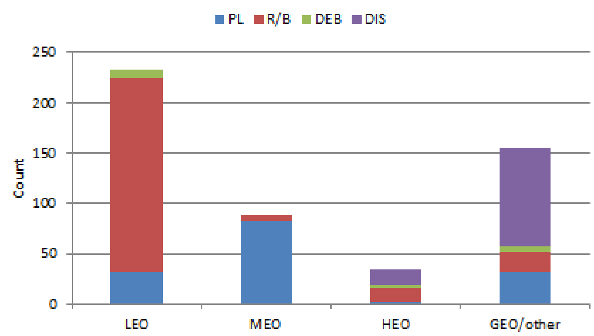

Fig. 2. AIUB light curve database consists of objects spread in all orbital regions and different types of objects which are payload (PL), rocket bodies (R/B), debris (DEB), and discovered objects (DIS).

To assess an object's attitude state evolution, we visually inspected its history of light curve processing results recorded in the database. Based on the assessment, we decided whether the object belongs to one of the four attitude groups: the rotator group (R), the slow rotator group (SR), the stable group (S), or the unknown group (U). An object which we found mostly as a rotator in its history is considered as rotator even though at some points we found it as a slow rotator or even a stable object. The slow rotator normally takes precedence over the stable which means that if the number of "slow rotating light curves" is the same as that of "stable light curves" for an object, then the object will be considered a slow rotator. Unknown attitude state evolution could be the result of three factors: 1) low quality data (not enough data available from observations); 2) light curves need further processing; 3) light curves are not yet processed.

For rotating objects, we took notes on their minimum and maximum spin rates as a function of object types and orbital regions. In addition, we also took notes on the value of spin rates for cases we considered interesting and important. Furthermore, we assessed whether there are specific patterns or trends in their attitude state evolutions. We then identified and grouped the objects according to their attitude trends.

3. Results

Rotators and slow rotators in the database were located in all orbital groups as shown in Fig. 3. The same thing happened to stable objects except that we did not found them in HEO. In fact, rotators possessed the biggest portion in the database (32.6%) compared with other attitude groups. The number of slow rotators and stable objects were pretty much the same (around 24%) while the unknown group had the smallest portion (19.3%). The largest number of rotators was located in the GEO/other (73 out of 167 rotators) but the largest percentage was located in the MEO (70.8%).

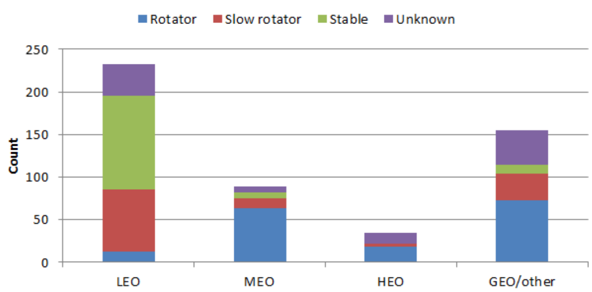

Fig. 3. Number of objects in the AIUB light curve database as a function of orbital type and attitude group.

Rotators, slow rotators, and stable objects consist of all object types as shown in Fig. 4. Among other attitude groups, rotators were mainly payloads while slow rotators and stable objects were mainly rocket bodies.

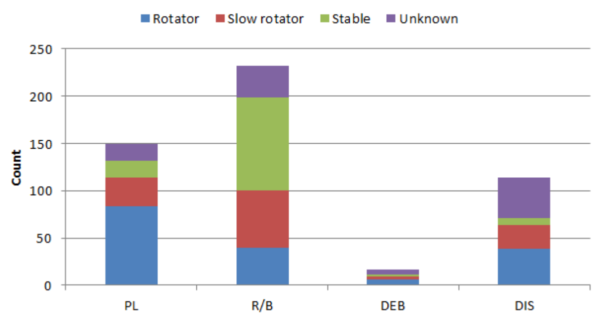

Fig. 4. Number of objects in the AIUB light curve database as a function of object type and attitude group.

Table 1 and Table 2 give the number of objects according to their object type and orbital type respectively. Out of 83 rotating payloads, 58 were located in MEO, 18 in GEO/other, and the rest (7) in LEO. Out of 60 slow rotating rocket bodies, 57 were located in LEO, 2 in GEO/other, and the rest (1) in HEO. All the 99 stable rocket bodies were located in LEO. Table 3 shows how the favoured attitude groups were distributed in the database.

Table 1. Number of objects as a function of object type and attitude state in the AIUB light curve database.

Object type	R	SR	S	U
PL	83	31	18	17
R/B	40	60	99	33
DEB	6	3	2	6
DIS	38	26	7	43

Table 2. Number of objects as a function of orbital type and attitude state in the AIUB light curve database.

Object type	R	SR	S	U
LEO	13	73	109	38
MEO	63	12	7	7
HEO	18	4	0	13
GEO/other	73	31	10	41

Table 3. Attitude state dominance as a function of object and orbital type in the AIUB light curve database.

Object type	LEO	MEO	HEO	GEO/other
PL	SR	R	U	R
R/B	S	R	R	R
DEB	U	-	R	R
DIS	-	-	U	R

Objects' periods vary from less than 1 sec to nearly 900 sec as can be seen in Table 4. We found that the fastest spin rate belonged to TITAN 3C TRANSTAGE DEB with period of 0.82 sec (spin rate equals 439 °/sec) while the slowest belonged to a discovered object E09287A with period of 850.50 sec (spin rate equals 0.423 °/sec). Both these objects were located in GEO/other. Minimum and maximum periods for each of the orbital groups are given in Table 5 until Table 8.

Table 4. Minimum and maximum periods of rotating objects in the AIUB light curve database as a function of object type (marked with their orbital region).

Object type	Min (sec)	Max (sec)
PL	1.55 (GEO)	740.00 (MEO)
R/B	0.88 (GEO)	260.37 (GEO)
DEB	0.82 (GEO)	174.43 (HEO)
DIS	1.22 (GEO)	850.50 (GEO)

Table 5. Minimum and maximum periods of rotating LEO objects in the AIUB light curve database as a function of object type.

Object type	Min (sec)	Max (sec)	Object count
PL	8.10	191.00	7
R/B	5.09	73.60	5
DEB	66.40	66.40	1
DIS	-	-	0

Table 6. Minimum and maximum periods of rotating MEO objects in the AIUB light curve database as a function of object type.

Object type	Min (sec)	Max (sec)	Object count
PL	7.82	740.00	58
R/B	1.52	64.70	5
DEB	-	-	0
DIS	-	-	-

Table 7. Minimum and maximum periods of rotating HEO objects in the AIUB light curve database as a function of object type.

Object type	Min (sec)	Max (sec)	Object count
PL	-	-	0
R/B	0.86	209.28	12
DEB	89.20	174.43	2
DIS	5.20	721.89	4

Table 8. Minimum and maximum periods of rotating GEO/other objects in the AIUB light curve database as a function of object type.

Object type	Min (sec)	Max (sec)	Object count
PL	1.55	607.40	18
R/B	0.88	260.37	18
DEB	0.82	12.95	3
DIS	1.22	850.50	34

We found three patterns in attitude state evolution of the rotating objects: oscillating, increasing, and decreasing. Therefore we created the three relevant groups and the other rotating objects (with unknown trends) were classified as common rotators. In the selection, we ignored seven objects (6 payloads and 1 rocket body) which we found switched from rotators to slow rotators. These peculiar objects were located in various orbital regions.

Inside the database, there were 36 oscillating rotators, 10 increasing rotators, and 18 decreasing rotators. The oscillating rotators were found only in MEO payloads while other groups showed no such preferences as Fig. 5 and Fig. 6 show. All the oscillating rotators were 36 of GLONASS satellites. Comparatively, increasing rotators were 4 payloads and 6 rocket bodies while decreasing rotators were 9 payloads, 3 rocket bodies, and 6 discovered objects. The increasing and decreasing rotators were located in various orbital regions.

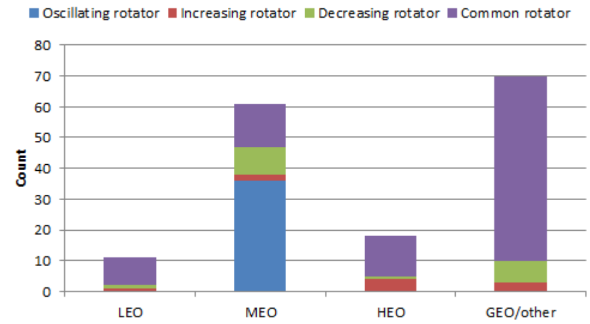

Fig. 5. Number of rotating objects in the AIUB light curve database as a function of orbital type and attitude trend.

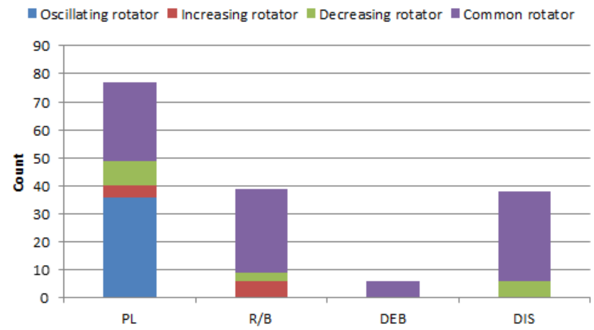

Fig. 6. Number of rotating objects in the AIUB light curve database as a function of object type and attitude trend.

All the oscillating rotators appeared to display a similar pattern with linear segments and abrupt changes as shown in Fig. 7. The rate of the increasing and decreasing rotators also appeared to change somewhat linearly as can be seen in Fig. 8 and Fig. 9.

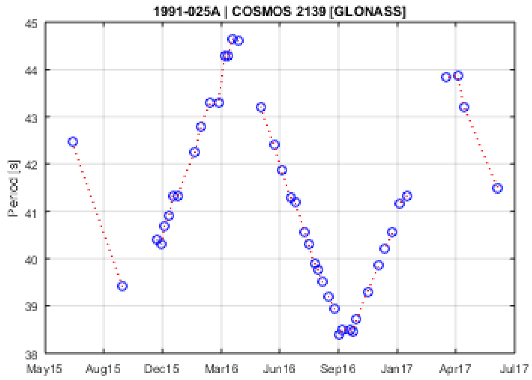

Fig. 7. Attitude state evolution of one of the oscillating rotators in the AIUB light curve database.

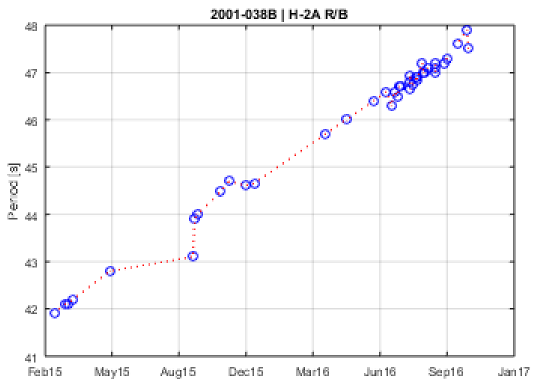

Fig. 8. Attitude state evolution of one of the increasing rotators in the AIUB light curve database.

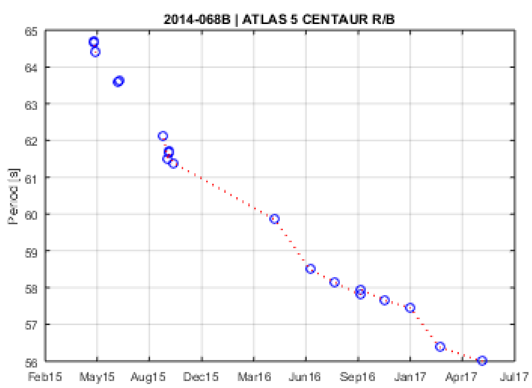

Fig. 9. Attitude state evolution of one of the decreasing rotators in the AIUB light curve database.

4. Discussion

There are two major differences between current study and our previous studies [4, 5] in describing the AIUB light curve database. First, current study concerns more on the whole history of objects' attitude state evolutions. This somewhat affected the number of identified rotators, slow rotators, and stable objects. Second, current study includes the entire objects in the database not only the ones which possess high quality data or which have been analysed in any way. This will only significantly increase the size of the unknown group (which was not reported in the previous studies) and not the other critical groups. Therefore we assume that it will not substantially alter the consistency of our studies' results.

One should be careful in reading the database regarding with the selection effects. For example, while it is true that slow rotators and stable objects were found mainly in rocket bodies, most of rocket bodies which were found in orbital regions other than LEO were rotators. This was due to significantly higher number of rocket bodies observed in LEO than in other orbital regions and the crucial fact that most of LEO rocket bodies are stable objects. Another example is related with the period determination of very slow rotating objects. The highest period in the database could be much larger than 850.50 sec which was reported in this study since the maximum time for AIUB photometric observation series are 20 minutes (1,200 sec). Everything rotating slower than that (or 80% of that) will not be marked as rotator but as slow rotator.

5. Conclusions

AIUB light curve database currently consists of more than 3,000 light curves from 512 selected space objects which cover all orbital regions and different types of objects. LEO objects are the biggest constituent of the database followed by GEO/other object then MEO and HEO objects. Most of the observed objects are rocket bodies followed by payloads, discovered objects, and debris. By visually inspecting the history of light curve processing results of all objects recorded in the database, we could determine that rotators and slow rotators in the database were located in all orbital groups. The same thing happened to stable objects except that we did not found them in HEO. In fact, rotators possessed the biggest portion in the database (32.6%) compared with other attitude groups.

We found that periods of all objects in the database ranged from less than 1 sec to nearly 900 sec. The fastest spin rate belonged to TITAN 3C TRANSTAGE DEB with period of 0.82 sec (spin rate equals 439 °/sec) while the slowest belonged to a discovered object E09287A with period of 850.50 sec (spin rate equals 0.423 °/sec). Both of this objects were located in GEO/other.

We also found three patterns in attitude state evolution of the rotating objects: oscillating, increasing, and decreasing. There were 36 oscillating rotators, 10 increasing rotators, and 18 decreasing rotators. The oscillating rotators were found only in MEO payloads while other groups showed no such preferences. All the oscillating rotators were 36 of GLONASS satellites. Comparatively, increasing rotators were 4 payloads and 6 rocket bodies while decreasing rotators were 9 payloads, 3 rocket bodies, and 6 discovered objects. The increasing and decreasing rotators were located in various orbital regions.

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