EXTENSIVE LIGHT CURVE DATABASE OF ASTRONOMICAL INSTITUTE OF THE UNIVERSITY OF BERN

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ABSTRACT

Our paper will discuss the photometry observation techniques currently in use by the Astronomical Institute of the University of Bern (AIUB) and at the Zimmerwald observatory. We present the processing of light curves with the aim to determine apparent spin periods of observed objects and to reconstruct their folded phase functions. We will summarize spin rates for 397 objects extracted from 1991 light curves which were acquired with the ZIMLAT telescope during the last ten years. More than dozen of defunct spacecraft showed a periodic change of the apparent spin rates over time. These cases will be briefly discussed.

1   INTRODUCTION

For more than ten years the Astronomical Institute of the University of Bern (AIUB) is using its 1-meter telescope ZIMLAT situated at the Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald (Switzerland) to collect photometric light curves of space debris. The last three years can be considered as the most productive for the Zimmerwald light curve acquisition leading to 3,000 observations for almost 500 objects in total to be stored in the AIUB's database.

Different photometric campaigns were focused on massive targets in Low Earth Orbit (LEO) which are candidates for future Active Debris Removal (ADR) missions, on regular monitoring of large defunct spacecraft in LEO, GEO, and in the GLONASS constellation, as well as on new objects discovered during the Zimmerwald and ESA GEO/GTO surveys. From almost each light curve we extracted limited information related to the attitude motion of the object. This information includes a general characterization of the attitude behaviour, like "stable" or "rotating" and, if applicable, we also determined the apparent rotation/spin period, its change over time and shape of the phase function (phase-folded light curve).

2   Zimmerwald observatory

AIUB's Zimmerwald Observatory consists of two main optical systems, the 1-m Zimmerwald Laser and Astrometry Telescope (ZIMLAT) (Fig. 1) and the 0.2-m Zimmerwald Small Aperture Robotic Telescope (ZimSMART.

ZIMLAT is used either for satellite laser ranging (SLR) or for optical observation (astrometry and photometry) of artificial and natural objects in near-Earth space. During daytime the system operates in SLR mode only. During night time the available observation time is shared between SLR and CCD/sCMOS based on target priorities. The switching between the modes is done under computer control. In addition, light curves and photometric observations can be acquired by ZIMLAT. The routine photometric measurements to be discussed in this paper are performed only with the ZIMLAT telescope.

3   Light curves acquisition and construction

3.1   Light curves acquisition with ZIMLAT telescope

For ZIMLAT there are two different tracking modes, the sidereal and the ephemerides (object) tracking mode. There are two different cameras placed in ZIMLAT focal length of 4-m which can be used to acquire images, Charged Coupled Device (CCD) camera SI1100 (referred to as ZIMLAT CCD), and the scientific Complementary Metal Oxide Semiconductor (sCMOS) camera (referred to as ZIMLAT CMOS) Andor Neo [1]. CMOS and CCD are two different sensor types used for digital photography.

Light curves with the ZIMLAT CCD are obtained by taking series of small sub-frames (200x200 pixels or 2.60' x 2.60') centered on the objects. The exposure time can be chosen from 0.2s on upwards and also filters can be used (e.g. B- and V-filter), depending on the brightness of the object. The sampling interval is about twice the exposure time. After 500 sub-frame images are acquired, an image with 2064x2048 pixels (26.6' x 26.6') is acquired for recalibration purposes. The observation data is stored in form of the original images and the intensity of the object is measured on the sub-frames in an automated real-time process. Some images are excluded, e.g. if a bright star contaminates the sub-frame or if the object is over- or underexposed, e.g. due to its own rotation. A text file

containing the measured intensities and epochs, as well as additional in information from the photometric reduction, is generated from the data of the remaining sub-frames. This output file is the further used for the light curve analysis.

Figure 1. AIUB's 1-meter ZIMLAT telescope dedicated to the photometric and astrometric measurements

3.2 Light curve construction

To get astronomical magnitudes an additional step is necessary to convert the extracted intensities to the magnitudes. This is done for ZIMLAT CCD measurements by using the frame with reference stars which is acquired shortly before the whole photometry series is performed. For the purpose of period (or frequency) extraction from the data the conversion from intensities to magnitudes is not necessary. For that reason, we will not further focus on this step.

Example of a light curve can be seen in Fig. 2. Plotted is light curve of a fast rotating GEO upper stage 2001-045D (SL-12 R/B (2)) acquired at 2016-02-05 by ZIMLAT telescope.
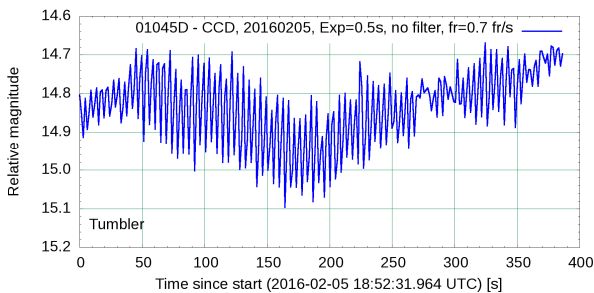

Figure 2. Light curve of GEO upper stage SL-12 2001-045D acquired by ZIMLAT telescope during night 2016-02-05

3.3 Light curve classification

The next step is to characterize the light curve by visually inspecting it. During this step the quality of the data set is judged which can be one of the following:

- very low quality (only few measurement points are available), light curve is discarded

- no or simple signal present in the data set most likely related to the phase/aspect angle change during the pass, object is considered as "stable"

- complex signal present in the data set indicating own rotation of the object, object is considered as "slow rotator"

- clear or apparent periodic variation of signal over time, object is considered as "rotator" and light curve is further processed for apparent rotation period extraction

3.4 Light curve processing, phase function reconstruction

Light curves are processed by applying two different methods depending on the type of the object [2]. First method is called the phase reconstruction which was developed by AIUB. During this method the data set is analysed with interval of testing rotation periods and each of the reconstructed phases for given testing period is evaluated. The testing period for which the reconstructed phase will get the highest evaluation parameter is considered as the solution or candidate solution. For the final confirmation, this value and the related reconstructed phase are visually inspected and if applicable, the value is also compared to the database data obtained for the same object in the past. Another method used by AIUB is the epoch folding [2]. This method also uses a test period interval. For each test period a so-called S-function is calculated. This method is more reliable for light curves of LEO objects. Its principle is described in [2] and in detail in [3]. For more about the light curve processing at AIUB refer to [4].

Examples of light curve and its reconstructed phase can be seen in Fig. 3 taken from [5]. Plotted is light curve for the GEO upper stage 2001-045D acquired at 2015-10-20 by ZIMLAT telescope. Light curve and for it reconstructed phase revealed rotation period of 4.49 s. The light curve showed secondary signal in the data set. This is not a real signal but a phenomenon caused by the aliasing due to the undersampled signal. This signal disappears once we reconstructed the phase function for the light curve.
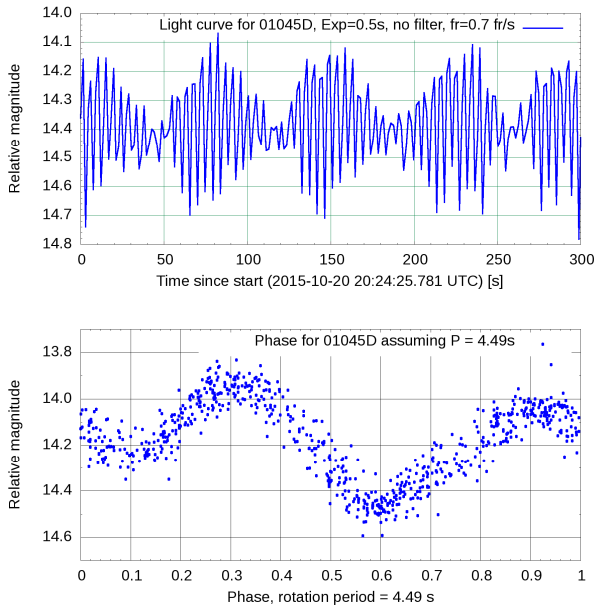
Figure 3. Light curve (upper panel) and reconstructed phase (lower panel) for GEO upper stage 2001-045D. The light curve clearly shows a secondary signal which is caused by the aliasing. This signal is not present anymore once the phase is reconstructed [5]

4   AIUB's database

We present results obtained for light curves acquired by AIUB since year 2007 until 31st of June 2016 with ZIMLAT system. In total there have been acquired 1991 light curves for 429 individual objects. From these, 32 objects (7.5% from total observed objects) could not be processed, meaning that we were not able to confirm any period for them by using phase reconstruction even they were marked as "rotators". Therefore, there were in total 397 objects which were successfully processed by method mentioned in previous section.

4.1   Observed population

The largest population observed during last ten years were upper stages (or rocket bodies) which are marked as R/B in the public catalogue (www.space-track.org) and in this work. Upper stages are typical with their cylindrical-like shape and their phase functions have simpler shape which evokes sinusoidal function. It usually consists from two smooth maxima and two minima as shown in Fig. 3, lower panel. We observed in total 201 rocket bodies (50.6% from 397 objects). The spacecraft, which are marked as S/C in the public catalogue and in this work, are usually box-wing type of objects with one or two solar panels attached to the main bus. Their phase function usually shows four sharper maxima and minima. We observed in total 108 spacecraft (27.2%). We observed only few objects from group marked as debris (DEB) in the public catalogue. These were either mission-related or fragmentation

debris [6]. In total we acquired light curves for 17 (4.3%) debris objects. Last group we do recognize in this work are objects discovered during ESA's GEO, GTO [7], and Molniya surveys [8], as well during AIUB's GEO surveys [9]. We marked these objects as discoveries (DIS) within this work. In total there have been acquired light curves for 71 (17.9%) discoveries. For these objects we observed variety of shapes for the phase functions.

For simplicity we distinguish four groups of orbits. First is the Low Earth Orbit (LEO). This orbit is typical with its low mean altitude above the earth's surface (below 2000 km) and low eccentricities. We define the High Eccentric Orbit (HEO) which is any orbit with eccentricity above 0.2. The GLONASS orbit is defined as an orbit on which are placed the satellites of Global Navigation Satellite System (GLONASS) constellation. These orbits are with very low eccentricities, with about 11.25 hours orbital period and which are inclined to the equator with angle between 64° to 67°. The last type of orbit is Geosynchronous Earth Orbit (GEO) and other orbit, which is any type of orbit not covered by any of the previous three groups.

4.2   Rotation properties of observed objects

In Fig. 4 are plotted rotational properties of 397 objects as extracted from 1991 light curves acquired by ZIMLAT telescope during years 2007 to 30th of June 2016. Plotted are relative abundances for given population as a function of orbital type. We distinguish "stable objects", "slow rotators" and "rotators". For the last group we always also extracted apparent rotation period and phase function.

According to our results, the most stable population from attitude point of view are objects on LEO. For these we extracted apparent rotation period only for 4.4% objects which in principle means that the apparent rotation period was smaller than the passage duration (note: typical passage duration of LEO for Zimmerwald observatory is from 3-12 minutes). For LEO the majority of the observed population have been upper stages (50.6%). GEO and other population showed rotations for 89.2% of observed objects. This population consists from all four types of objects, S/C, R/B, DEB and DIS, where dominant have been DIS with representation of 52.9%. GLONASS population, consisting only from S/C, showed dominantly rotational properties, where for 74.2% we could extract the apparent rotation period. HEO population showed rotational properties with an extreme value of 400.9 °/s for the apparent angular velocity extracted for BREEZE-M R/B. Majority of the observed HEO objects have been R/B with representation of 66.7 %.
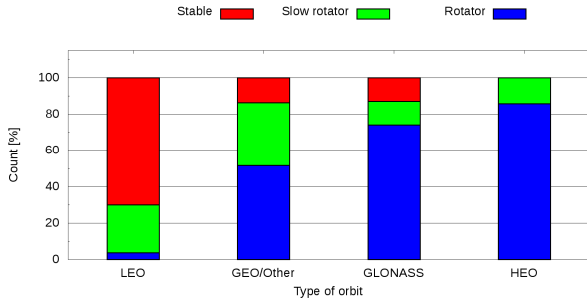
Figure 4. Relative counts as a function of orbital type and rotational properties for 397 individual objects as extracted from the 1991 light curves acquired by ZIMLAT telescope in years 2007 to 31th of June 2016

An example of the distribution of the extracted apparent angular rates for GLONASS objects can be seen in Fig. 5. This population reached apparent angular rates between interval from 1.1 °/s to 42.2 °/s. Additionally, we observed change of rotation over time for all observed spacecraft, where for eight cases we observed acceleration and deceleration of the apparent angular velocity over time. An example for GLONASS satellite 1994-021C for which we observed this type of behaviour can be seen in Fig 6.
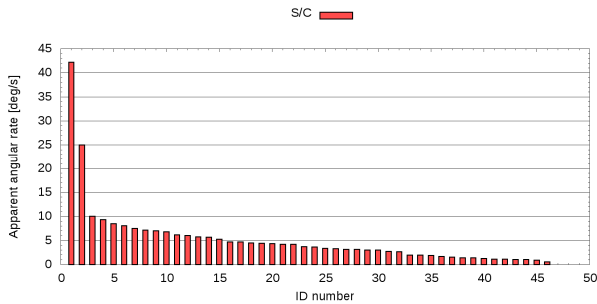

Figure 5. Apparent angular rates of spacecraft (S/C) on GLONASS orbits as extracted from ZIMLAT light curves
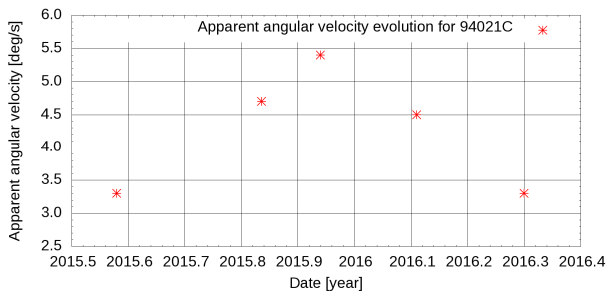

Figure 6. One year evolution of the apparent angular velocity for GLONASS satellite 1994-021C extracted from light curve acquired by ZIMLAT telescope between years 2015 and 2016 [5]

For more information about the rotational properties extracted from the AIUB's light curve database can be found in [4].

5 CONCLUSIONS

The Astronomical Institute of the University of Bern (AIUB) monitored for more than 10 years, from 2007 to 30th of June 2016, rotational properties of 397 space debris objects including defunct spacecraft, upper stages and fragments. This information was extracted from light curves of these objects acquired with AIUB's 1-meter telescope ZIMLAT situated at the Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald (Switzerland). In our work we presented the AIUB's photometric program, light curve acquisition and its processing in order to extract apparent rotation periods from light curves.

Last but not least we presented statistical results of rotation properties of space debris as a function of orbital type (LEO, GEO, HEO, GLONASS) and object type (S/C, R/B, DEB, DIS). In total we acquired 1991 light curves for 397 individual objects. For some objects we acquired light curves repeatedly to monitor change of their attitude states over time.

From July to December 2016 the AIUB's database has extended rapidly, by about 50 %, reaching 2911 light curves (to 31st of December 2016) for almost 500 objects. These data are already processed and the statistics will be published in near future.

AIUB's photometric program, which is fully complete, helps to monitor and collect data for space debris population. We use it to monitor space debris rotational properties and their changes over time. The extracted results such as apparent angular velocities and phase functions will be used for further scientific processing to be performed at AIUB.

6 REFERENCES

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