67th International Astronautical Congress (IAC), Guadalajara, Mexico, 26-30 September 2016.

IAC-16-A6.1.4

# Light curve database of Astronomical Institute of the University of Bern

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## Abstract

Since 2007 the Astronomical Institute of the University of Bern (AIUB) is using its 1-meter telescope ZIMLAT situated at the Zimmerwald observatory, Switzerland to collect light curves of space debris objects including defunct spacecraft, upper stages and fragments. The last two and half years, 2014, 2015 and 2016, can be considered as the most productive for the Zimmerwald light curve acquisition. Several different photometric campaigns have been performed which were focused on Low Earth Orbit (LEO) targets suitable for future Active Debris Removal (ADR) missions, on regular monitoring of large defunct spacecraft in LEO and in the GLONASS constellation, and on new objects discovered during the Zimmerwald and ESA Geosynchronous Earth Orbit (GEO) surveys. From each light curve we extracted some information about the attitude motion. This information includes a general characterization of the attitude behaviour, like “stable” or “tumbling” state, and, if applicable, also the determination of the apparent spin period and the reconstruction of the phase.

Our paper will discuss the photometry observation techniques currently in use at the Zimmerwald observatory and the processing of the light curves with the aim to determine apparent spin periods and to reconstruct their phases. Spin rates for objects acquired with the ZIMLAT telescope during the last two years will be discussed and the morphology of their reconstructed phases will be briefly presented.

**Keywords:** space debris, light curves, period extraction, reconstructed phase

## 1. Introduction

Light curves are time series which usually contain information about the change of magnitude (or intensity) over time. Light curves are commonly used in the astronomical community to determine physical characteristics of minor planets, namely their rotation rate, spin axis direction, surface properties (e.g. albedo), shape, etc. Additionally they can be used to detect the presence of minor planets moons or multi-asteroid systems. In space debris domain, the light curves are the major source of information for the attitude state of uncontrolled objects. They are used to determine whether the objects are stable or tumbling. In case of tumbling behaviour, the apparent spin rates can be extracted. Light curves can be acquired for any type of object which is illuminated by the sun and is reflecting enough light to be visible from the ground instrument.

From the measured light curves the apparent rotational periods and their evolution can be estimated with reasonable accuracy for various types of objects, e.g., box-wing spacecraft, upper stages, fragmentation pieces, High-Area-To-Mass (HAMR) object, etc. These objects can be placed in different orbital regions, Low Earth Orbit (LEO) to Geosynchronous Earth Orbits (GEO). Several different photometric campaigns have been performed which were focused on LEO targets suitable for future Active Debris Removal (ADR) missions, on regular monitoring of large defunct spacecraft in LEO and in the GLONASS constellation, and on new objects discovered during the Zimmerwald and ESA Geosynchronous Earth Orbit (GEO) surveys.

In our work we will discuss the light curve acquisition on Zimmerald observatory, its construction and processing steps. We will summarize the results we got for last 2.5 years of data acquisition during which we obtained 1,278 light curves for more than 240 space debris objects which include defunct spacecraft, upper stages and fragmentation or unknown debris pieces.

## 2. ZIMLAT telescope

The Astronomical Institute of the University of Bern (AIUB) has wide experience with space debris research, including optical observations of space debris in order to investigate their attitude state through light curves and in order to determine and improve their orbits. The observation facility of the AIUB is located in Zimmerwald, 10 km south of Bern (Switzerland). Currently, there are several different instruments available at the Zimmerwald Observatory to acquire photometry of space debris objects, and there are several different established processing techniques used to extract apparent spin periods from light curves [1, 2].

One of the most productive systems is the 1-m Zimmerwald Laser and Astrometry Telescope (ZIMLAT). ZIMLAT allows perform photometric and atstrometric measurements to artificial and natural objects in near-Earth space. ZIMLAT is also a Satellite Laser Ranging (SLR) system which is used for the SLR to cooperative targets, targets equipped with retroreflectors. During daytime the system operates in SLR mode only. During night time the available observation time is shared between SLR and CCD based on target priorities. In some cases the astronomical and SLR measurements can be performed simultaneously.

## 3. Light curve acquisition and extraction

Light curves with the ZIMLAT CCD are obtained by taking series of small sub-frames (200x200 pixels or 2.60' x 2.60') centred on the objects. The exposure time can be chosen from 0.2s on upwards, and 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, resulting in a gap of around 20s between every two series of 500 sub-frames. The observation data is stored in the form of the original images. 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 star is present in the sub-frame or if the object is over- or underexposed. 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 file is the used for further analysis of the light curve. Examples of extracted light curves can be seen in Fig. 1.

## 4. Light curve processing and phase reconstruction

Extraction of the intensities and construction of the light curve is just the first step in our light curve processing scheme. 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)
- no or simple signal present in the data set most likely related to the phase/aspect angle change during the pass
- complex signal present in the data set indicating own rotation of the object
- clear or apparent periodic variation of signal over time

This classification does not characterize the objects according to their tumbling behaviour but simply just characterizes the light curve which is a function of the object's pass duration, hence altitude. As slow tumbler is characterized an object which rotation period is greater than the pass duration. E.g., an object which is on LEO and has own rotation period of 5 minutes, would be considered with our classification as a slow tumbler while an object with the same period but on GEO would be considered as tumbler.

Examples for the last three light curve types can be seen in Fig. 1. In the top panel is plotted light curve for LEO upper stage 2004-046B (CZ-2C R/B) acquired at 2016-06-22. Light curve showed a stable behaviour for given pass. In the middle panel is plotted a light curve of slow tumbling LEO satellite 2004-046B (ALOS) acquired at 2016-04-10. In the bottom panel plotted is light curve of a fast tumbling GEO upper stage 2001-045D (SL-12 R/B (2)) acquired at 2016-04-10.

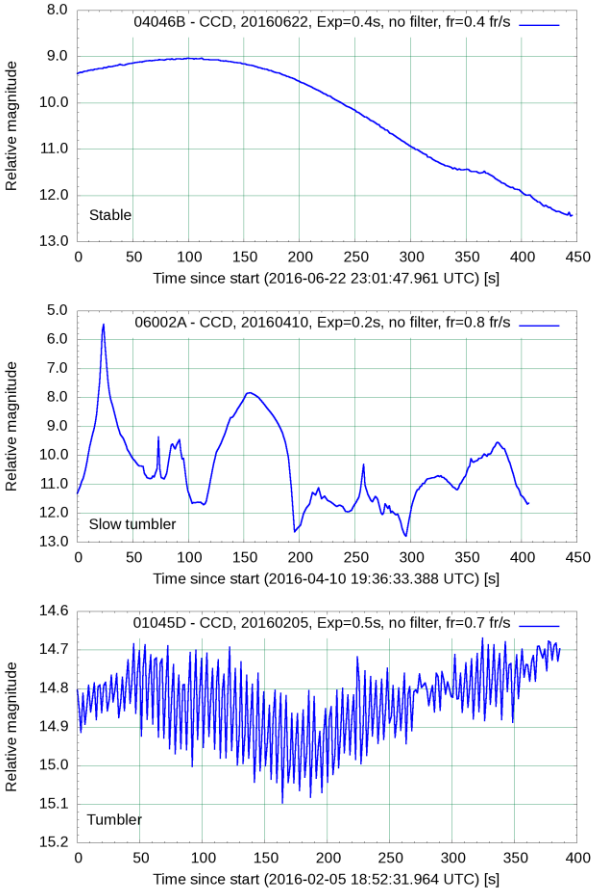
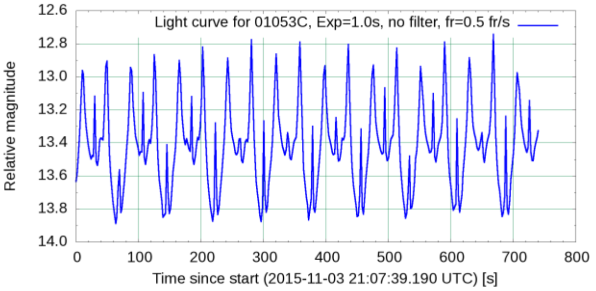


Fig. 1. Examples of light curves characterization. In the top panel is plotted an example of a stable object, in the middle panel of a slow tumbler and in the bottom panel of a tumbler.

Once the light curve shows clear or apparent periodicity signal, it is further processed for the apparent spin period extraction and phase reconstruction. This is done by using two different methods depending on the type of the object [1]. 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 is considered as the solution. For the final confirmation, this value and the related reconstructed phase are visually inspected. Another method used by AIUB is the epoch folding [1]. This method also uses a test period interval. For each test period a so-called S-function is calculated. This method principle is described in [1] and in detail in [3].

For completeness, we will add that the phase reconstruction method is optimal for the cases when there is a sufficient observation duration comparing to the apparent period, e.g., light curve is covering 4-5 own rotations of the object. This is a usually case for high altitude objects, for which one can plan photometric series in order of 10s of minutes. This method also showed a large reliability for the extraction of periods shorter than the exposure time which makes it very powerful. On the other side, for LEO objects we don't usually have the appropriate observation window due to the short durations of the passes over the observatory site (e.g. from 3-9 minutes for LEO on ~850 km). If only 1.5 – 3 rotations are captured with sufficient number of measurement points (e.g. >100) epoch folding method might be applied. Additionally, comparing to the phase reconstruction this method is more robust toward the secondary signals present in the data sets, signals like the phase angle dependency or trends due to the unstable weather conditions.

Examples of light curves and their reconstructed phases can be seen in Fig. 2 and 3. Shown is light curve for satellite GLONASS 2380 (2001-053C) acquired at 2015-11-03. Light curve and then reconstructed phase showed that this target is rotating with 77.5 s rotation period. In Fig. 3 is plotted light curve for the GEO upper stage 2001-045D acquired at 2015-10-20. Light curve and for it reconstructed phase revealed rotation period of 4.49 s. In Fig.1 (bottom panel) is plotted light curve for the same target acquired four months later. For this date we extracted similar value for the rotation period equals to 4.53 s. In both light curves for 2001-045D there is present a 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 phases for both light curves.



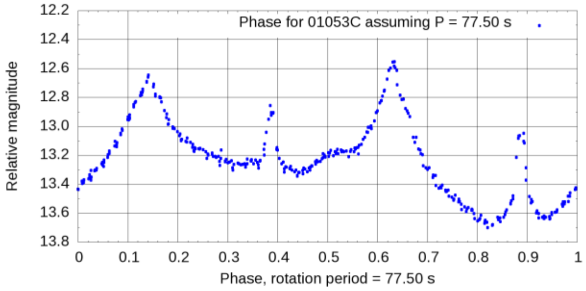


Fig. 2. Light curve (upper panel) and reconstructed phase (lower panel) for GLONASS satellite 2001-053C.

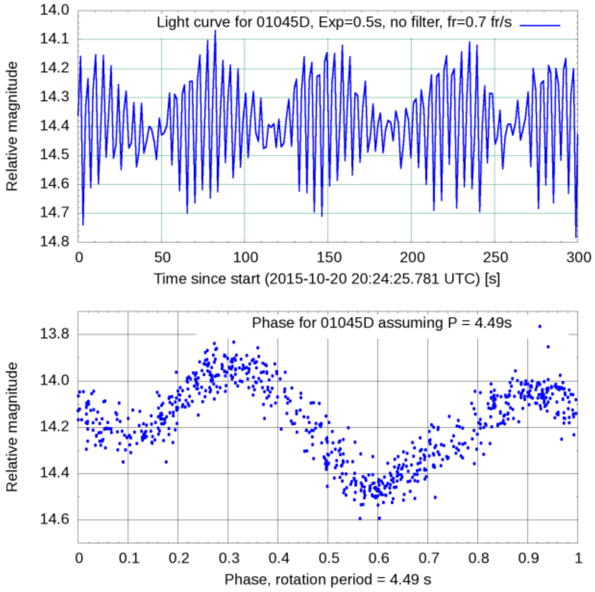


Fig. 3. Light curve (upper panel) and reconstructed phase (lower panel) for GEO upper stage 2001-045D. The light curve clearly shows a secondary signal which is caused by the aliasing. This signal is not present anymore once the phase is reconstructed.

## 5. Light curve applications

Light curves have several applications. Except identifying whether or not the object is tumbling they can also help us to determine or at least refine the estimated attitude for investigated object and predict its evolution.

For demonstration purposes we plotted in Fig. 4 reconstructed phases of an upper stage measured during one night at four different times under different geometry conditions (phase angle and aspect angle). As can be seen from Fig. 4 the viewing geometry and rotation properties (rotation axis direction) influenced the shape of the phase. Such information, like the magnitude difference between the maxima and minima for given viewing geometry, can be further used for the spin axis orientation estimation [4].

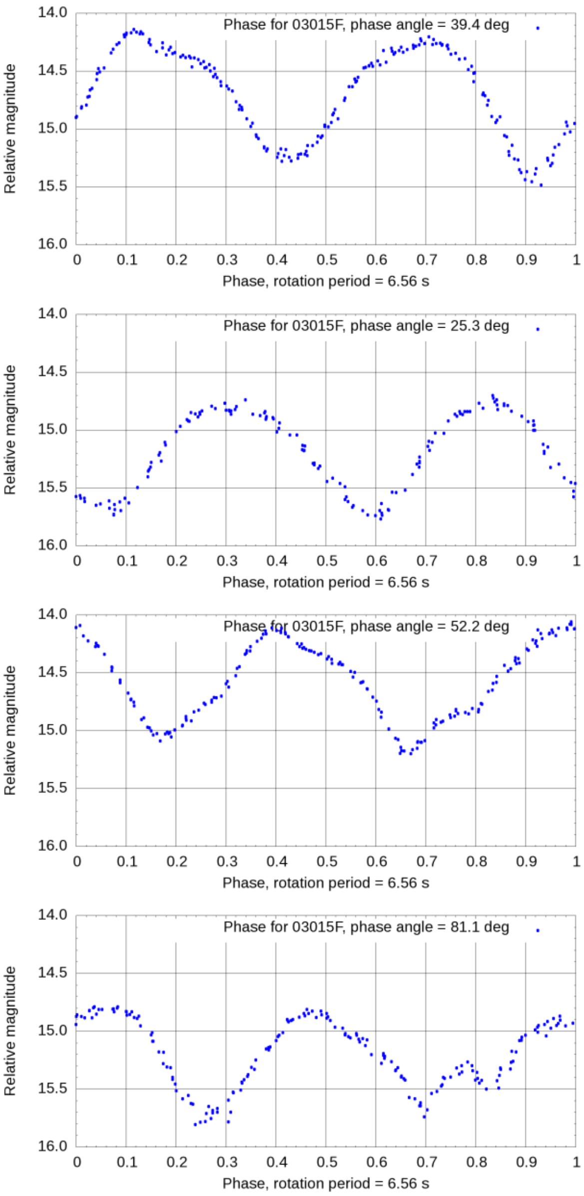


Fig. 4. Reconstructed phases for upper stage 03015F. Objects was observed under four different phase angles, 39.4° (upper panel), 25.3° (second panel from top), 52.2° (second panel from bottom) and 81.1° (botom panel).

Another application for light curves is monitoring of the apparent angular velocity change over time. Such an example is plotted in Fig. 5 for GLONASS 2277 (94021C). From figure is visible that the satellite rotation accelerated toward the end of the year 2015 from 3.3 s to maximum value of 5.4 s. From that moment the satellite started to decelerate its rotation.

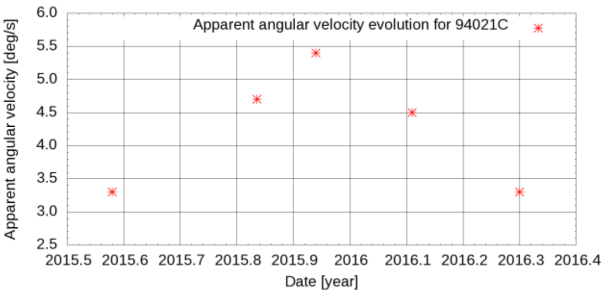


Fig. 5. One year evolution of the apparent angular velocity for satellite 94021C extracted from light curves.

Light curves can be used also for validation of other attitude determination techniques like radar measurements, Satellite Laser Ranging (SLR) measurements [5] or forward modelling refinement, when synthetic data are generated and then compared to the measurements [6].

## 6. Results of the light curve database processing

Since January 2014 till the end of June 2016 in total 1,278 light curves were acquired by the ZIMLAT telescope. Namely, 308 light curves were acquired in year 2014, 626 in 2015 and 344 in 2016 (to 30th of June 2016). All these light curves, which belong to 245 different objects, were processed by using two methods discussed in previous section.

For the majority of the objects, namely 110 (44.9%), a “stable” attitude or very slow attitude motion was observed. For these only phase angle related changes of the relative magnitude over time could be observed.

For 42 objects (17.1%) we observed slow tumbling behavior. These were the objects for which we observed complex brightness variation patterns but the length of time series was not sufficient to cover an entire rotation period. This was often the case for LEO targets which have relatively short passage times.

Finally, there have been 93 (38.0%) objects which could be reliably categorized as tumbling. For these we reconstructed the phase and extracted the apparent spin period. In the case that the objects were observed several times we extracted also the evolution of their apparent angular rates over time.

When we summarize the results by using the mean altitude of the observed object we will get values listed in Table 1 and in Fig. 6. Within this paper, the LEO orbits are orbits with mean altitude above the Earth surface below > 2,000 km. The GEO orbits are all orbits with mean altitude between 34,000 – 36,200 km with inclination below 20°. Every other orbit was marked as MEO (Mean Earth Orbit), $\text{MEO}_{circ}$ if the eccentricity was $e < 0.1$ or $\text{MEO}_{ecc}$ if $e \geq 0.1$.

Table 1. Number of stable objects, slow tumblers and tumblers as a function of orbit

| | Stable* | Slow tumblers | Tumblers | Total |
|---|---|---|---|---|
| LEO | 96 | 31 | 7 | 134 |
| MEO$_{circ}$ | 9 | 8 | 52 | 69 |
| MEO$_{ecc}$ | 0 | 1 | 11 | 12 |
| GEO | 5 | 2 | 23 | 30 |

* Concluded during the visual inspection of the light curve. Object could be rotating but the observation period was too short to confirm such behaviour.

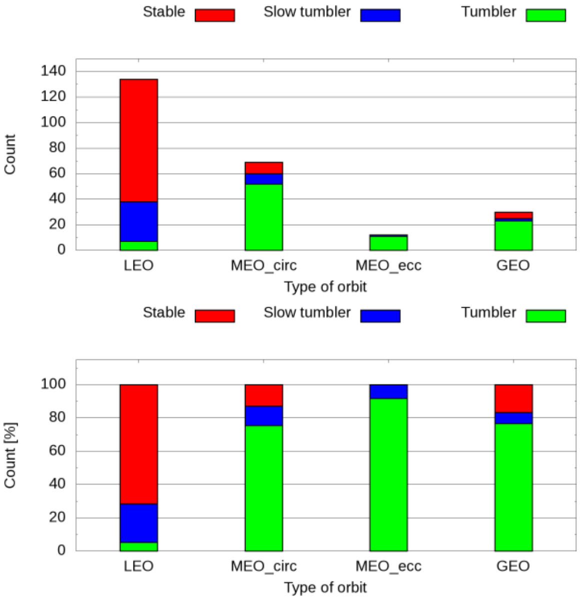


Fig. 6. Total count (upper panel) and relative count (lower panel) as a function of orbital type.

While for LEO population we see mostly stable behaviour, for the MEO and GEO population the tumbling behaviour is dominant for the observed objects. Here is necessary to mention that these results have to be taken with cautions, specially the Fig. 6 (lower panel). There is a strong selection effect present in the data. For all mentioned orbital regimes we observed different types of objects and we covered only small part of the entire population. For example, for LEO the majority of observed and processed objects were cylindrical upper stages (114 in total), which could be future possible ADR targets. These showed quite a stable behaviour. While for MEO we observed mostly box-wing defunct GLONASS satellites (62 in total) which are placed on near-circular orbits. Defunct GLONASS showed in most cases a tumbling behaviour. These groups of objects clearly dominate the values presented in Table 1 and in Fig. 6. For both groups different physical mechanisms affect the attitude states due to the different altitudes regimes (LEO vs circular MEO) and shapes (cylindrical vs box-wing).

## 7. Conclusions

In our work the light curve acquisition program at The Astronomical Institute of the University of Bern (AIUB) was presented. The main instrument for the measurements is AIUB's ZIMLAT telescope installed in the Zimmerwald observatory. We briefly discussed the light curve extraction and construction. The methods used for the light curve processing to extract the apparent spin periods and to reconstruct phases have been discussed, as well. These methods are the epoch folding, which is most suitable for LEO light curves with presence of strong trends, and the AIUB's own phase reconstruction method for higher quality light curves.

In total we processed 1,278 light curves for 245 different objects. We distinguished tree types of behaviour for these objects. Stable, if no signal variation was observed during the light curve acquisition sequence. Slow tumbler, if a complex pattern(s) was (were) present in the light curve but did not repeat in the data set anymore. Tumbler, in case that light curve showed apparent or clear periodic signal which was further processed. In summary 110 objects showed stable type of behaviour. We counted 42 slow tumblers and we extracted apparent periods for 93 tumblers. For these we also reconstructed phase diagram.

The AIUB's light curve database currently contains 2,162 light curves acquired since 2007, including the already processed and in here presented 1,278 data sets. The future goal is to finish the processing of the whole database, the rest of 884 light curves acquired for additional 240 objects. In that case the statistical sample will be 485 space debris objects. We will monitor the already observed objects, we will routinely continue processing light curves which are acquired on daily basis and we will investigate the apparent angular velocity evolution for all the objects we discovered tumblers we discovered so far.

## Acknowledgements

We would like to thank all the night observers at Zimmerwald observatory for the acquisition of the light curves in the last 2.5 years. We would like to also thank to the Zimmerwald observatory technical staff for their support during the last years.

## References

[1] Linder E., Silha J., Schildknecht T., Hager M., Extraction of Spin Periods of Space Debris from Optical Light Curves, IAC-15.A6.1.2, 66th International Astronautical Congress, Jerusalem, Israel, 2015, 12 – 16 October.

[2] Silha J., Linder E., Hager M., Schildknecht T.,

Optical Light Curve Observations to Determine Attitude States of Space Debris, Proceedings of 30th International Symposium on Space Technology and Science, Kobe-Hyogo, Japan, 2015.

[3] Larsson S., Parameter Estimation in Epoch Folding Analysis, Astronomy and Astrophysics, 1996, Supplement series 117, 197-201.

[4] Santoni F., Cordelli E., Piergentili F., Determination of Disposed-Upper-Stage Attitude Motion by Ground-Based Optical Observations, Determination of Disposed-Upper-Stage Attitude Motion by Ground-Based Optical Observations, 10.2514/1.A32372.

[5] Schildknecht, T., Linder, E., Silha, J., Koshkin, N., Korobeinikova, E., Melikiants, S., Shakun, L., Strakhov, S., Photometric Monitoring of Non-Resolved Space Debris Databases of Optical Light Curves, Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, held in Wailea, Maui, Hawaii, September 15-18, 2014.

[6] Kanzler, R., Schildknecht, T., Lips, T., Fritsche, B., Silha, J., Krag, H., Space Debris Attitude Simulation - IOTA (In-Orbit Tumbling Analysis), Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, held in Wailea, Maui, Hawaii, September 15-18, 2014.