

Optical Light Curve Observations to Determine Attitude States of Space Debris

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The currently proposed space debris remediation measures include the active removal of large objects and “just in time” collision avoidance by deviating the objects using, e.g., ground-based lasers. Both techniques require precise knowledge of the attitude state and state changes of the target objects. In the former case, to devise methods to grapple the target by a tug spacecraft, in the latter, to precisely propagate the orbits of potential collision partners as disturbing forces like air drag and solar radiation pressure depend on the attitude of the objects.

Non-resolving optical observations of the magnitude variations, so-called light curves, are a promising technique to determine rotation or tumbling rates and the orientations of the actual rotation axis of objects, as well as their temporal changes. The 1-meter telescope ZIMLAT of the Astronomical Institute of the University of Bern has been used to collect light curves of MEO and GEO objects for a considerable period of time. Recently, light curves of Low Earth Orbit (LEO) targets were acquired as well. We present different observation methods, including active tracking using a CCD subframe readout technique, and the use of a high-speed scientific CMOS camera. Technical challenges when tracking objects with poor orbit predictions, as well as different data reduction methods are addressed.

Results from a survey of abandoned rocket upper stages in LEO, examples of abandoned payloads and observations of high area-to-mass ratio debris will be presented. Eventually, first results of the analysis of these light curves are provided.

Key Words: Light curves, Space debris, sCMOS, Time series analysis

1. Introduction

The Astronomical Institute of 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, 10km South of Bern (Switzerland). From the light curves measured in the Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald, apparent rotational periods and their evolution are estimated for any type of objects (e.g., box-wing spacecraft, upper stages, fragmentation pieces, etc.) in different orbital regions. 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. These instruments, as well as the light curve processing techniques will be further discussed.

2. Zimmerwald Observatory

AIUB’s Zimmerwald Observatory consists of three main optical systems, the 1-m Zimmerwald Laser and Astrometry Telescope (ZIMLAT) (Fig. 1), the 0.2-m Zimmerwald Small Aperture Robotic Telescope (ZimSMART) (Fig. 2), and the 0.5-m experimental ZimSPACE telescope.

ZIMLAT is used either for satellite laser ranging (SLR) or for optical observation (astrometric positions and magnitudes) 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 and needs less than half a minute. In addition, light curves and photometric observations can be acquired¹⁾.

Due to its wide field of view (FoV), which is $4.1^\circ \times 4.1^\circ$, ZimSMART is best suited for sky surveys. The aim of these surveys is mainly to build-up and maintain a catalogue of artificial satellites and space debris objects²⁾. Although routine operations are performed, the system is kept in an experimental state to test new software and hardware, as well as new observation strategies.

Also the ZimSPACE telescope serves experimental purposes and is currently used only for follow-up observations to acquire astrometric positions of catalogued objects in order to improve their orbits.

Routine photometry measurements are currently mainly performed with ZIMLAT, but occasionally experimental photometric observations using a so-called “streak” approach (discussed further) are also performed. For this purpose the ZimSMART telescope is used because of its wide FoV.

3. Light curves acquisition and construction

There are several different approaches how to acquire and construct a light curve of a space object. In the following two sections we discuss two different methods for light curve acquisition, the “classical” photometry performed with ZIMLAT and the so-called “streak” photometry performed experimentally with ZimSMART.

3.1 Light curve acquisition on ZIMLAT

For ZIMLAT there are two different tracking modes: the sidereal and the ephemerides (object) tracking. Coordinates

and velocities are generated by the computer, in order to track the given ephemeris of the object. There are two different cameras placed in ZIMLAT focal length of 4-m which can be used to acquire images: the SI1100, which is a Charged Coupled Device (CCD) camera (referred to as ZIMLAT CCD), and the Andor Neo, a scientific Complementary Metal Oxide Semiconductor (sCMOS) camera (referred to as ZIMLAT CMOS)³⁾. CMOS and CCD are two different sensor types used for digital photography.



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



Fig. 2. AIUB's 0.18-meter ZimSMART telescope dedicated to the wide-field GEO surveys.

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 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 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 information from the photometric reduction, is generated from the data of the remaining sub-frames: This file is used for further analysis of the light curve.

In general, a different observation approach is chosen for objects, depending on their mean altitude. For example, a LEO (Low Earth Orbit) object is observed during its whole pass, while objects on higher orbits (e.g., Geosynchronous Transfer Orbit - GTO, Geosynchronous Earth Orbit - GEO, Medium Earth Orbit - MEO, etc.) are usually observed during time intervals with 20 min duration as maximum. Depending on the brightness of the object, a certain filter and appropriate exposure time is chosen. For large LEO spacecraft (e.g. ENVISAT, 2002-009A), the B-filter has to be chosen along with very short exposure time in order to avoid overexposing the pixels on the ZIMLAT CCD camera.

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. However, for the frequency extraction procedure, where we are interested in the extraction of apparent spin rates, the conversion from intensities to magnitudes is not necessary. For that reason, we will not further focus on this step.

Special observations with the Andor Neo sCMOS-camera are also possible with ZIMLAT. For our work, the following differences between the cameras and processing of the data are relevant: The ZIMLAT CMOS camera is able to take images equally spaced in time, without any gaps and with high a sampling frequency of the order of tens of Hz (sampling frequency > 10 Hz). However, the ZIMLAT CMOS camera requires a trained observer, which means that currently only few people are able to operate it. Also, the processing of the CMOS images is currently done manually and but some automation is planned in near future. As mentioned above, light curves taken with the ZIMLAT CCD may contain regular gaps of several seconds in the measured data due to technical constrains. The intensity measurements taken with the ZIMLAT CCD camera are not as equally spaced as for ZIMLAT CMOS and the sampling frequency is usually one frame per few seconds (sampling frequency < 1 Hz). However, the huge advantage of ZIMLAT CCD is that its operating, as well as the image processing are automated and therefore light curves with this camera can be regularly acquired by any night observer.

An example of a single observation frame is given in Fig. 3 where we show SWISSCUBE (2009-051B), a CubeSat type of satellite, in a full frame (26.6' x 26.6') observed during the photometric campaign performed in summer 2014. The object appears in the figure as bright point in the middle of the frame (marked by red circle) with stars appearing as very long streaks. This observation was acquired with the ZIMLAT CCD with a 0.5s exposure time and with no filter.



Fig. 3. SWISSCUBE (2009-051B) CubeSat satellite captured by ZIMLAT telescope during the photometric campaign performed in June 2014.

3.2 Streak acquisition on ZimSMART

In the previous case, where ZIMLAT telescope was used for photometry, the basic idea behind light curve acquisition is to track the object and then to build a light curve from a series of points, where every point is extracted from acquired image in given time. However, this is not the only approach to investigate the tumbling/stable behavior of space objects. With the ZimSMART telescope we used experimentally several times an approach, where not several but only one frame per object was taken using the sidereal tracking mode. In this case a relatively long exposure time was used (few minutes for MEO, few seconds for LEO), which led to a situation that object would appear on the frame as a streak. By assuming that the object is moving linearly in the frame during the exposure time (an assumption which is usually justified), the intensity of the streak along its length can be measured (across the streak) and epochs defined by the starting epoch and exposure time can be assigned to given extracted intensity points.

As an example, we show in Fig. 4 an observation of the SL-16 R/B (2000-006B), an upper stage situated in LEO observed with ZimSMART in April 2015. The object appears in the figure as bright streak in the middle of the frame, with stars appearing as points. The observation was performed with ZimSMART using 3.0s exposure time and with no filter.

Here it is necessary to mention, that the ZimSMART “streak” photometry approach has several disadvantages compared to the ZIMLAT “classical” photometry approach. The assumption, that the object moves linearly on the frame is not always the case, the object can change slightly its apparent angular velocity during the exposure (e.g. MEO object in the culmination point). This would cause that the extracted observation epochs might not be precisely defined. This method is also not suitable for faint objects, where the object’s intensity is redistributed between several dozens of pixels, which leads to low signal-to-noise ratio (SNR) per pixel.



Fig. 4. SL-16 R/B (2000-006B) upper stage captured by ZimSMART telescope during the “streak” photometric campaign performed in 2015.

Additionally, for LEO objects, whose apparent angular velocities are relatively high, the “streak” method allows acquiring only light curve of a few seconds, before the object would leave the FoV. However, despite these disadvantages, a huge advantage of “streak” method is the minimized use of telescope time and of data storage. For fast spinning objects (spin rate < 1 s), the high sampling achieved with this method is very beneficial and can lead to a light curve resolution of tenths of seconds no matter what kind of sensor or shutter was used for the observation.

4. Apparent Spin Rate Extraction Methods

In general, there are several approaches how to extract frequencies from time series, in our case from light curves. The most popular is Fourier analysis and with it related Fast Fourier Transformation. In astronomy and in space debris area, some other methods were or are used in order to avoid the drawbacks of the Fourier based methods, such as necessity for equally spaced data or limitations due to the frequency resolution.⁴⁾

After a detailed literature review about time series analysis, it was decided to test six different methods in order to extract the apparent spin rate from obtained light curves. The first three implemented methods were the Fast Fourier Transformation (FFT), the Periodogram analysis⁵⁾ and Welch's method.⁶⁾ These three approaches to detect periods from light curves were chosen as a starting point, despite their mentioned limitations. Further, FFT is commonly used by space debris community to extract frequencies from light curves^{7,8)}. For that reason it is good to also use this method in order to compare directly results with other authors. The Periodogram analysis and Welch's method were chosen to cross-check results from FFT.

However, the mentioned three methods are all based on the Fast Fourier Transformation and therefore they need as an input equally spaced data in time, which is not always possible to obtain in real observation series. To be able to process also unevenly spaced measurements, the Epoch folding method⁹⁾ was chosen. Another strong method able to deal with

unevenly spaced measurements in time series is the Lomb-Scargle periodogram¹⁰. The reliability and strength of this method has been demonstrated and proven by several teams, e.g., for apparent period estimation from light curves¹¹ or for apparent period estimation from SLR (Satellite Laser Ranging) range measurements to cooperative targets (objects equipped with retro-reflectors)¹². Additionally, for the final confirmation for the extracted apparent period being present in the data, we developed also a visual method called the phase reconstruction. As the name already implies, this method is based on reconstructing the phase by separating the light curve into equally long parts defined by the investigated apparent period and then visually comparing them between each other to find the best fit. Once all these equally long parts achieve to have very similar shape, the correct apparent period is found. Due to the fact, that the intensity measurements taken by ZIMLAT are not necessarily equally spaced in time and since the FFT, Periodogram analysis and Welch's method need equally spaced intensity measurements, the light curve data were linearly interpolated. In the following sections we present and discuss a few example cases of light curves acquired by ZIMLAT and of the apparent spin rates extracted from them by using the mentioned time series analysis methods.

As the first example we present observations of PAKSAT 1 (1996-006A), a GEO spacecraft which is not attitude stabilized. Its light curve from 07.11.2014 can be seen in Fig. 5. Plotted is the relative magnitude (vertical axis, internal not calibrated magnitude) versus time (horizontal axis).

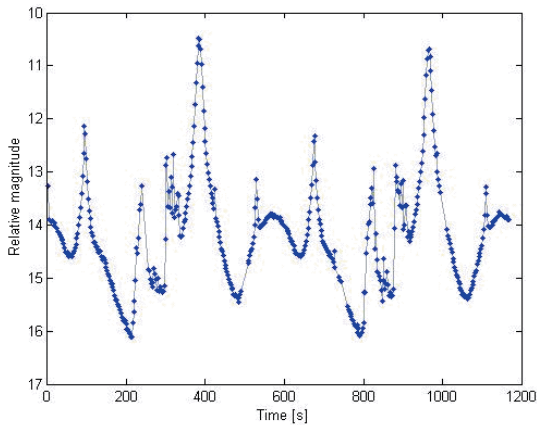


Fig. 5. Light curve of PAKSAT (1996-006A) from 07.11.2014. Already by eye, it is visible from Fig. 5 that not even two whole phases (periods) are present in plotted light curve. For this case, the Fast Fourier Transformation, Periodogram analysis and Welch's method showed no conclusive periods in their power spectra. The Epoch Folding detected a period of 585 s and Lomb-Scargle periodogram showed many periods, where the period with the highest power was 519.3 s. Finally, the phase reconstruction was performed, where the investigation started with a period of 550 s, visible by eye in the light curve. The best phase was found for a period of

581 s, which is a value close to the one obtained by Epoch folding. The reconstructed phase for PAKSAT 1 is plotted in Fig. 6. For this object its reconstructed phase is rather complex, with one dominant peak and with several smaller peaks and structures. Such a complex phase has been already seen in several cases, mostly for box-wing type of spacecraft like defunct GEO or GLONASS satellites.

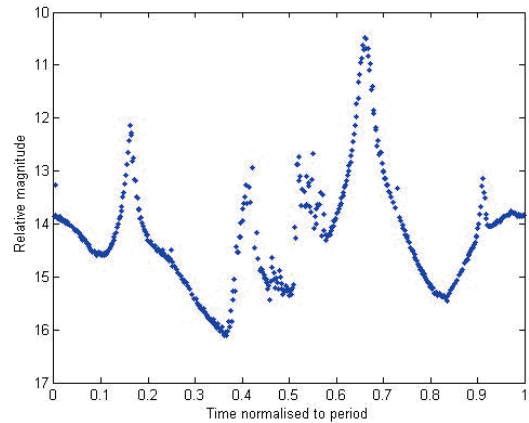


Fig. 6. Reconstructed phase of PAKSAT (96006A) from light curve acquired in 07.11.2014 with extracted apparent a period of 581 s.

An example of observations of a LEO object, namely N-1 R/B (1978-018B), a rocket upper stage, is given in the following. It was observed with ZIMLAT CCD, as well with ZIMLAT CMOS camera. The ZIMLAT CCD measurements were taken on 17.02.2014, 16.03.2014 and 06.06.2014. The sampling interval was around 1 s. 1.2 s or 1.1 s. The light curve from 06.06.2014 can be seen in Fig. 7. The ZIMLAT CMOS observation was done on 10.02.2015 and has a sampling interval of 0.01 s and it can be seen in Fig. 8. For the measurements taken with the ZIMLAT CCD, the resulting extracted period from phase reconstruction was 11.4 s, 10.25 s and 10.3 s, for 17.02.2014, 16.03.2014 and 06.06.2014, respectively. However, for the highly resolved light curve from the ZIMLAT CMOS camera, the best phase reconstruction was found for a period of 5.31 s. The reconstructed phase from CMOS data can be seen in Fig. 9.

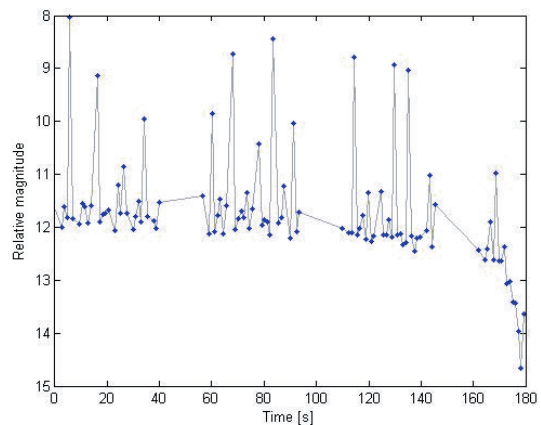


Fig. 7. Light curve of 78018B from 06.06.2014, acquired with ZIMLAT CCD.

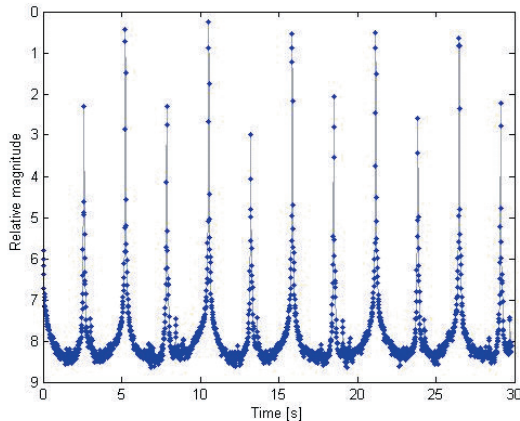


Fig. 8 Light curve of 78018B from 10.02.2015, acquired with ZIMLAT CMOS.

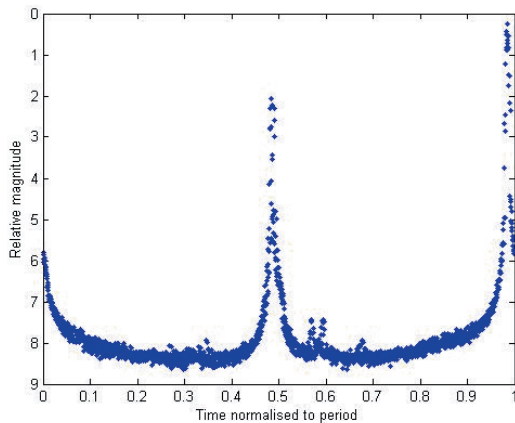


Fig. 9 Reconstructed phase of 78018B obtained during the “phase reconstruction” method. Determined apparent period equals to 5.31 s.

5. Conclusion

AIUB is currently operating three different optical systems situated in Zimmerwald Observatory (Switzerland) in order to perform photometry and astrometry to space debris objects. The ZIMLAT telescope with 1-m aperture is used for a routine light curve acquisition by using two different cameras, an SI1100 CCD and Andor Neo sCMOS camera, allowing high resolution light curves in order of 100s frames per second. For the CCD light curves observations, a fully automated pipeline including the automated active object tracking and image acquisition, and the image processing and extraction of object intensities, is available. For the sCMOS camera currently this has to be done manually and the automation of the system is planned in near future.

This paper is briefly discussing also the so-called “streak” photometry performed with ZimSMART telescope, a 0.2-m aperture optical system with a wide FoV ($4.1^\circ \times 4.1^\circ$). This

type of photometry can be applied for a “first look” approach to get initial information about the objects current attitude state, “stable/tumbling”. Besides that, this method allows acquiring high resolution light curves for fast tumbling targets by using any type of camera irrespective of the camera’s framerate capabilities.

Finally, we discussed different time series analysis methods which are currently used at AIUB for the extraction of apparent periods from acquired light curves. Except the Fourier based methods, like FFT, Periodogram and Welch’s method, AIUB is currently using also Epoch folding, Lomb-Scargle periodogram and its own phase reconstruction method in order to reliably determine the apparent spin rates for space objects. Several cases are demonstrated in the paper and their light curves, as well their reconstructed phases are given.

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