PHOTOMETRIC MONITORING OF NON-RESOLVED SPACE DEBRIS AND DATA-BASES OF OPTICAL LIGHT CURVES

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ABSTRACT

The population of space debris increased drastically during the last years. Collisions involving massive objects may produce large number of fragments leading to significantly growth of the space debris population. An effective remediation measure in order to stabilize the population in LEO, is therefore the removal of large, massive space debris. To remove these objects, not only precise orbits, but also more detailed information about their attitude states will be required. One important property of an object targeted for removal is its spin period and spin axis orientation. If we observe a rotating object, the observer sees different surface areas of the object which leads to changes in the measured intensity. Rotating objects will produce periodic brightness variations with frequencies which are related to the spin periods.

Photometric monitoring is the real tool for remote diagnostics of the satellite rotation around its center of mass. This information is also useful, for example, in case of contingency. Moreover, it is also important to take into account the orientation of non-spherical body (e.g. space debris) in the numerical integration of its motion when a close approach with the another spacecraft is predicted.

We introduce the two databases of light curves: the AIUB data base, which contains about a thousand light curves of LEO, MEO and high-altitude debris objects (including a few functional objects) obtained over more than seven years, and the data base of the Astronomical Observatory of Odessa University (Ukraine), which contains the results of more than 10 years of photometric monitoring of functioning satellites and large space debris objects in low Earth orbit. AIUB used its 1m ZIMLAT telescope for all light curves. For tracking low-orbit satellites, the Astronomical Observatory of Odessa used the KT-50 telescope, which has an alt-azimuth mount and allows tracking objects moving at a high angular velocity. The diameter of the KT-50 main mirror is 0.5 m, and the focal length is 3 m. The Odessa's Atlas of light curves includes almost 5,5 thousand light curves for ~500 correlated objects from a time period of 2005-2014.

The processing of light curves and the determination of the rotation period in the inertial frame is challenging. Extracted frequencies and reconstructed phases for some interesting targets, e.g. GLONASS satellites, for which also SLR data were available for confirmation, will be presented. The rotation of the Envisat satellite after its sudden failure will be analyzed. The deceleration of its rotation rate within 3 years is studied together with the attempt to determine the orientation of the rotation axis.

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 trough 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 sensors 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.

The Astronomical Observatory of I.I. Mechnikov Odessa National University has been monitoring the behavior of large space debris within the framework of the national program performed by the Ukrainian Network of Optical Facilities for Near-Earth Space Surveillance (UMOS).

2. THE ZIMMERWALD OBSERVATORY

AIUB's Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald consists of three main optical systems, the 1-m Zimmerwald Laser and Astrometry Telescope ZIMLAT (Figure 1), the 0.2-m Zimmerwald Small Aperture Robotic Telescope ZimSMART, 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/CMOS observations, 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 acquired (1).

Due to its wide field of view (FoV), which is 4.1° x 4.1°, 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 objects (2). 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 debris 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 are also performed. For this purpose the ZimSMART telescope is used because of its wide FoV.

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

3. LIGHT CURVES FROM ZIMMERWALD

3.1. Acquisition Methods

There are several different approaches how to acquire and construct a light curve of a space object. In the following 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. For the "classical" photometry the telescope is tracking the ephemeris of the object of interest in order to maximize the signal-to-noise ratio and a series of frames is acquired either with a CCD or a high-speed CMOS camera. Light curves with the ZIMLAT CCD camera are obtained by taking series of small sub-frames (200x200 pixels or 2.60' x 2.60') centered on the objects (the object is in fact tracked in a closed loop). 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 acquiring 500 sub-frames, a full frame with 2064x2048 pixels (26.6' x 26.6') is acquired for photometric calibration purposes, resulting in a gap of around 20s between every two series of 500 sub-frames. The intensity of the object is measured on the sub-frames by an automated real-time process and the results are screened for contamination by background stars or, e.g., over- or underexposures. The high-speed CMOS camera allows acquiring full frames with a frame rate of up to 100 frames per second. Closed loop tracking is not required in this case and the frames are processed off line.

An example of a single observation frame is given in Figure 2 were 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.

For fast tumbling objects in MEO and LEO light curves may also be extracted from streaked images of the object. The wide-field ZimSMART telescope tracking in sidereal mode was used for this purpose. In this case relatively long exposure times were 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 Figure 3 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. This method is obviously not suitable for faint objects, where the object's intensity is redistributed over several dozens of pixels, which leads to low signal-to-noise ratio per pixel.

Figure 2: SWISSCUBE (2009-051B) CubeSat satellite captured by ZIMLAT telescope during the photometric campaign performed in June 2014.

Figure 3: SL-16 R/B (2000-006B) upper stage captured by ZimSMART telescope

3.2. 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 space data or limitations due to the frequency resolution. 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 analysis (5) 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 method (9) was chosen. Another strong method able to deal with unevenly spaced measurements in time series is the Lomb-Scargle periodogram (10). The reliability and strength of this method has been demonstrated and proven by several teams, e.g., for apparent period estimation from light curves (11) 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 used also a visual check of 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 comparing them between each other to find the best fit.

3.3. Example light curves

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 Figure 4. Plotted is the relative magnitude (vertical axis, internal uncalibrated magnitudes) versus time (horizontal axis).

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 Figure 5. 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.

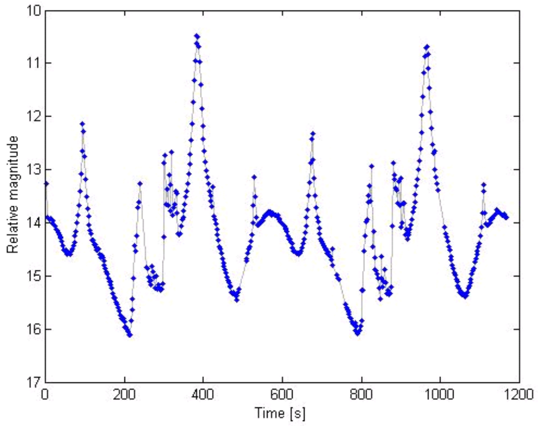

Figure 4: Light curve of PAKSAT (1996-006A) from 07.11.2014.

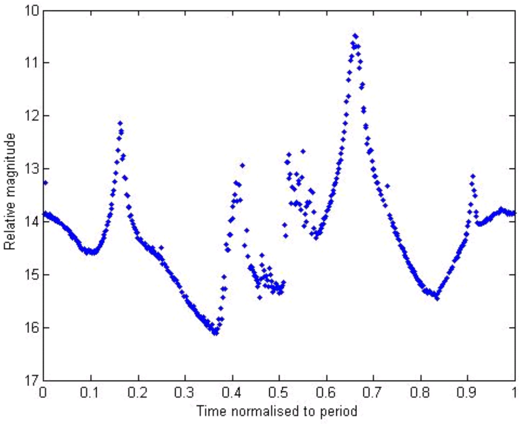

Figure 5: Reconstructed phase of PAKSAT (96006A) from light a curve acquired in 07.11.2014 with an extracted apparent period of 581 s.

An example of observations of a N1 rocket upper stage in LEO (1978-018B), is given in the following. It was observed with the ZIMLAT CCD, as well with the 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 Figure 6. The ZIMLAT CMOS observation was done on 10.02.2015 with a sampling interval of 0.014 s (Figure 7). 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 be seen in Figure 8.

Figure 9 shows a light curve from the decommissioned GLONASS COSMOS 1988 spacecraft (left) and the corresponding phase diagram (right). The reconstructed phase shows many details which cannot be identified in the original light curve. The latter clearly suffers from aliasing and undersampling. The period determined for this object was 9.26 s, being unexpectedly short for this large, massive object.

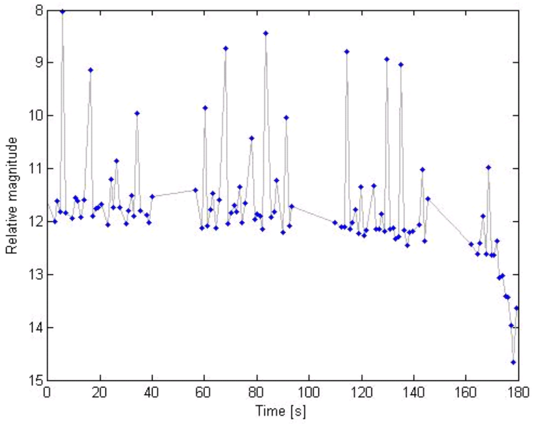

Figure 6: Light curve of 78018B from 06.06.2014, acquired with ZIMLAT CCD.

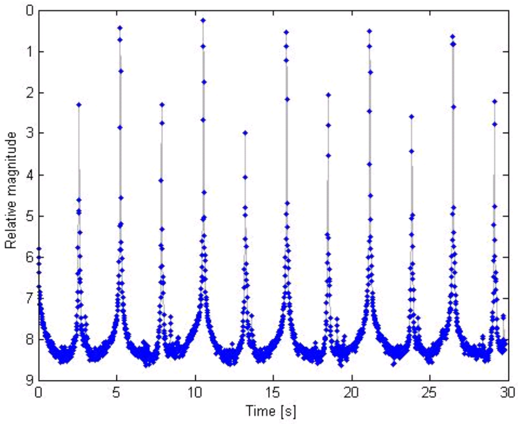

Figure 7: Light curve of 78018B from 10.02.2015, acquired with ZIMLAT CMOS at 67 frames per second.

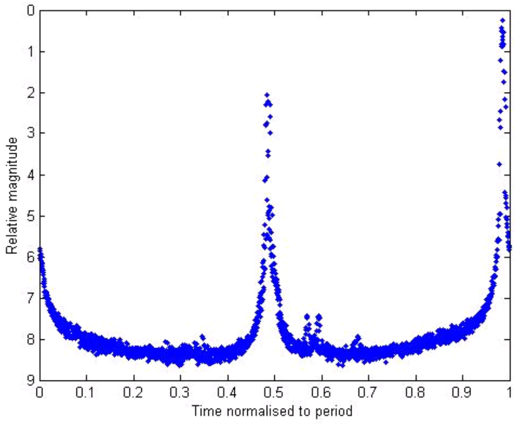

Figure 8 Reconstructed phase of 78018B obtained by the "phase reconstruction" method. The estimated apparent period equals to 5.31 s.

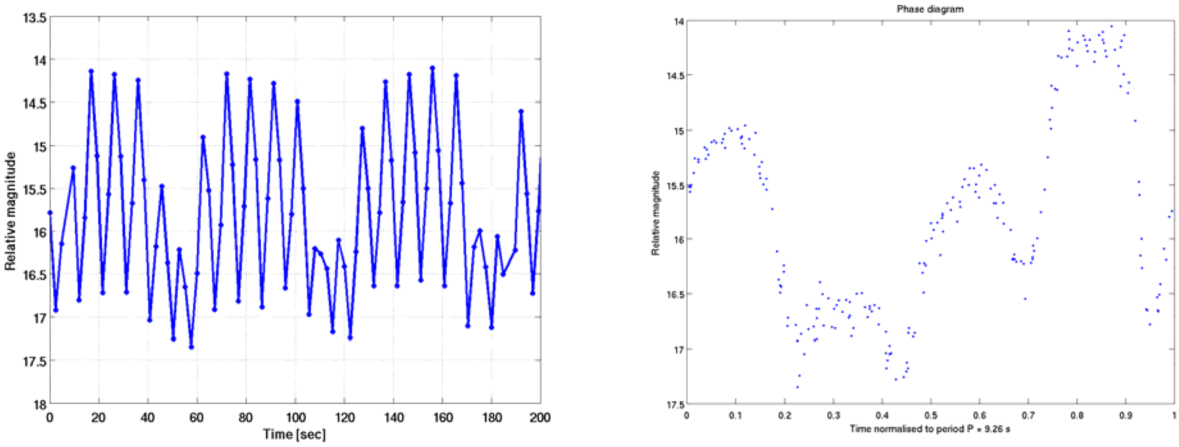

Figure 9: Example of a light curve from the decommissioned GLONASS COSMOS 1988 spacecraft (left) and the corresponding phase diagram (right). The light curve shows aliasing effects and is clearly undersampled.

4. LIGHT CURVES OF ENVISAT FROM ODESSA

At the Astronomical Observatory of I.I. Mechnikov Odessa National University the telescope KT-50 with a high-speed alt-azimuth mount, a mirror of 50-cm diameter and television CCD camera Watec WAT 902H2 Sup has been used to acquire light curves (Figure 10). The telescope is operated in a tracking mode. 50 images of the satellite against the background stars are recorded per second. The telescope's field of view is ≈ 9'x12', and its limiting magnitude is up to 12m. The satellite brightness and positions are determined using all images, so several thousand measurements are recorded per each pass with a frequency of 50 Hz.

Figure 10: 0.5m aperture KT50 telescope of the Odessa National University.

When the ESA's Earth observation satellite EnviSat suddenly failed in April 2012, the determination of its attitude state by means of optical observations became of immediate interest. In May 2012 ESA was in addition asking the International Laser Ranging Service (ILRS) for support as the spacecraft is equipped with laser retroreflectors and range observations were regularly performed by ILRS before the contingency.

The Odessa Observatory performed photometric measurements of EnviSat without color filters. The response curve is determined by the integral transmission band of the optics and spectral sensitivity of the CCD-camera detector. The calibration of the photometric observations was carried out by means of observation of photometric standard stars. The atmospheric extinction was determined by measuring solar analogue stars and the photometric observations of the target object reduced accordingly. As the satellite reflects off the sunlight, the light curve appearance is defined by its rotation parameters. Generally, the period of the satellite's rotation around the center of mass can be determined if it is noticeably shorter than the total observation period and considerably longer (at least by an order of magnitude) than the time interval between adjacent measurements. When the satellite's rotation period is almost half of the length of the observation series during one satellite's pass or even greater, then the light curve no longer simply reflects the periodicity of the target rotation as the changing observation geometry (phase and aspect angles) results in a substantial change in the shape of the light-curve. Figure 11 shows the light curve of EnviSat obtained with the KT-50 in Odessa on July 9, 2013. The light curve was obtained during a 5.85 minute period when the phase angle increased from 22° to 134° over one pass (period of tracking). The structural analysis of the light curve shows a cyclic recurrence of brightness variations, and a period of 121.7 sec was estimated as the rough synodic rotation period of the satellite. Vertical solid lines mark this time interval. Meanwhile, a sequence of specular flashes, which are likely caused by reflection off one particular feature of the satellite surface, can be distinguished (they are labelled with numbers 1, 2 and 3 in the plot). It is also possible to recognize another sequence of (repeated) quasi-specular brightness peaks (which are labelled with number 4, 5 and 6 in the plot). The variation of the time interval between such flares during a pass depends on the changes in the object-observer geometry and can be used to estimate the orientation of the rotation axis of the object in an inertial frame. This is a prerequisite to transform the observed, so-called "synodic" period into the "sidereal" rotation period of the satellite as observed in an inertial reference frame.

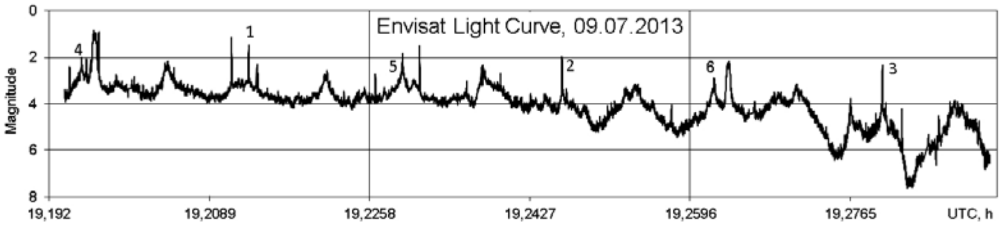

Figure 11: Light curve of EnviSat obtained with the KT-50 in Odessa on July 9, 2013. The synodic period is 121.7 sec (tagged by vertical lines).

Figure 12 shows the observed synodic (“dT”, open circles) and the determined sidereal (Psid+ conterclockwise, Psid- clockwise rotation) periods of the Envisat rotation from April 2013 to May 2015 (there is always an ambiguity between the clockwise and the counterclockwise rotation of the object which can only be solved by additional observations and modelling).

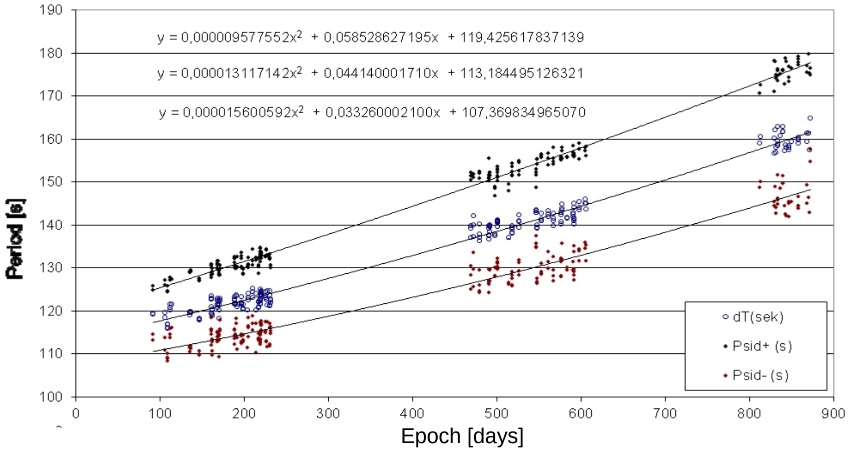

Figure 12: Changes in synodic (“dT”, open circles) and sidereal (Psid+ conterclockwise, Psid- clockwise rotation) periods of the Envisat rotation from April 2013 to May 2015.

AIUB independently determined spin rates for EnviSat from SLR observations performed at Zimmerwald. These range measurements refer to the retroreflector on EnviSat and reflect the motion of the latter around the center of mass of the spacecraft. Figure 13 shows the synodic (blue) and the sidereal (red, green for clockwise and counterclockwise rotation) spin periods of EnviSat as determined by these observations.

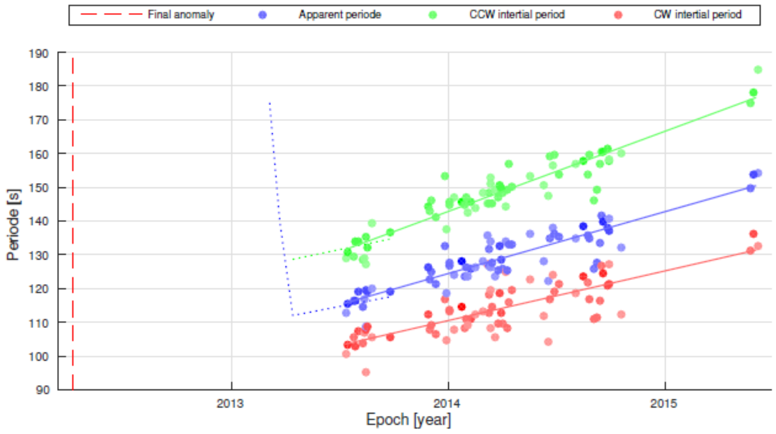

Figure 13: Evolution of the synodic (blue) and the sidereal (red, green for clockwise and counterclockwise rotation) spin periods of EnviSat as determined by AIUB from SLR observations from Zimmerwald.

5. SUMMARY

Photometric light curves proved to be an efficient tool to remotely determine the attitude states of space objects. Knowing the attitude states is of particular interest in cases of a contingency of an active spacecraft or for space debris objects which are potential targets of active removal missions. The Astronomical Institute of the University of Bern uses the sensors of its Swiss Optical Ground Station and Geodynamics Observatory in Zimmerwald to acquire light curves of artificial space objects including space debris in LEO, MEO and GEO orbits. Different methods for the actual acquisition of light curves, as well as the determination of attitude states from the latter have been developed.

At the Astronomical Observatory of I.I. Mechnikov Odessa National University the telescope 0.5m KT-50 telescope is used to acquire light curves of LEO objects with a sampling rate of 50Hz. We presented results of the particularly interesting object EnviSat where the spin period evolution was monitored over a time period of two years.

6. REFERENCES

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