Attitude States of Space Debris determined from Optical Light Curve Observations

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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.

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. Acquiring such observations as well extracting attitude states from these measurements is challenging and requires sophisticated observations and processing techniques. The paper will introduce the corresponding techniques and methods used at the Astronomical Institute of the University of Bern (AIUB).

The 1-meter telescope ZIMLAT of the AIUB is used to collect light curves of LEO, MEO and GEO objects on a regular basis. Recently, Satellite Laser Ranging (SLR) observations of rotating LEO targets were acquired as well. We will present spin rates and their temporal evolution for a large set of decommissioned LEO, MEO and HEO spacecraft and upper stages, including more than 60 abandoned GLONASS satellites. These results were derived from more than 2000 light curves and several hundred SLR passes..

Key Words: Space Debris, Attitude State, Light Curves

1. Introduction

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. These techniques require precise knowledge of the attitude state and state changes of the target objects. In the former case, e.g. to devise methods to capture the target with 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.

The classical example where a prompt knowledge of the attitude state of a space object is required is the loss of contact with or the control of a spacecraft. Communication with the spacecraft is in most cases only possible during periods when the on-board antenna is oriented towards the Earth and the actual orientation is thus a crucial parameter when investigating the possible reasons for a loss of contact. Similarly the attitude motion may provide crucial information to determine possible causes and remediation measures in contingency situations.

Recently the determination of attitude states, and in particular rotation rates, of space objects became a topic of interest in the space debris community. This is to be seen in the context of the multitude of techniques which are currently proposed to remove space debris from orbit or to re-orbit them into disposal orbits. The majority of the techniques to remove large objects, which are driving the evolution of the space debris population on the long term, require capturing the target with a robotic arm, a net, a harpoon, or another mechanism. The attitude motion is in all these cases a critical parameter and the maximum tolerable target rotation rate is limited.

Another application where the attitude state of the object plays an import role is the orbit determination and orbit propagation as disturbing forces like air drag and solar radiation pressure depend on the attitude of the object. Precise predictions are required to prevent collisions between objects in space. If one of the potential collision partners in a predicted close conjunction is manoeuvrable, a collision avoidance manoeuvre may be performed. The efficiency of such manoeuvres is critically depending on the accuracy of the orbit prediction. New techniques are required if both objects are non-manoeuvrable. One proposed technique consists in nudging the objects by means of ground-based (or space-based) lasers. Again, the interaction of the laser beam with the target and thus the orbit change depends on the attitude motion of the object.

2. Observation Techniques

2.1. Passive optical observations

The temporal variation of the magnitude of an object, the so-called light curve, is a traditional technique to determine the attitude motion of space objects. Light curves are commonly used in the astronomical community to determine physical characteristics of minor planets, namely their rotation rate, spin axis direction, shape, and surface properties. An example of a light curve of a tumbling upper stage in GEO and the reconstructed phase are given in Fig. 1. All illustrations are from the “Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald” near Bern, Switzerland, an establishment of the Astronomical Institute of the University of Bern.

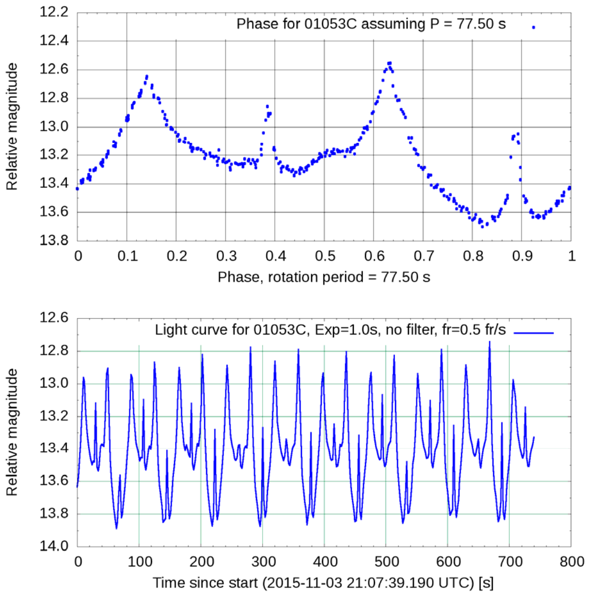

Fig. 1. Light curve (bottom) and reconstructed phase (top) of the GEO upper stage 2001-045D.

2.2. Satellite laser ranging

For space objects equipped with retroreflectors, so-called cooperative targets, Satellite Laser Ranging (SLR) is a well-established technique, provided that precise orbit predictions are available and that the retroreflectors are always pointing towards the Earth. If a cooperative target starts rotating or tumbling, it may be still possible to obtain classical range measurements during the periods where the retroreflector is visible by the observer. These measurements will then reveal the motion of the retroreflector around the center of mass of the spacecraft. An example is given in Fig. 2 which shows SLR range residuals in ns of a pass of the rotating ENVISAT spacecraft. The periodic signal reflects the attitude motion of the retroreflector around the centre of mass of the object.

If the target is non-cooperative, i.e. not carrying retroreflectors, laser ranging becomes challenging. Nevertheless, recent experimental studies showed that laser tracking of non-cooperative large objects is possible [2]. The ranges for these targets are two orders of magnitude less accurate than for cooperative targets, as the photons may be reflected by any surface part of the object (the so-called target depth is of the order of the size of the object). Under favorable circumstances and for large objects it is possible to derive spin rates from such observations.

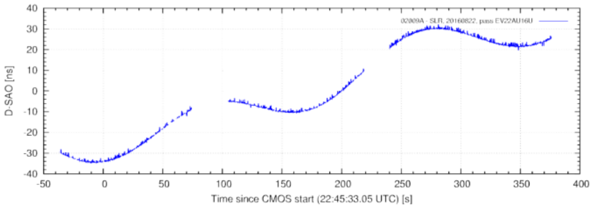

Fig. 2. SLR range residuals in ns of a pass of the rotating ENVISAT spacecraft. The periodic signal reflects the attitude motion of the retroreflector around the centre of mass of the object.

3. Results from observations

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

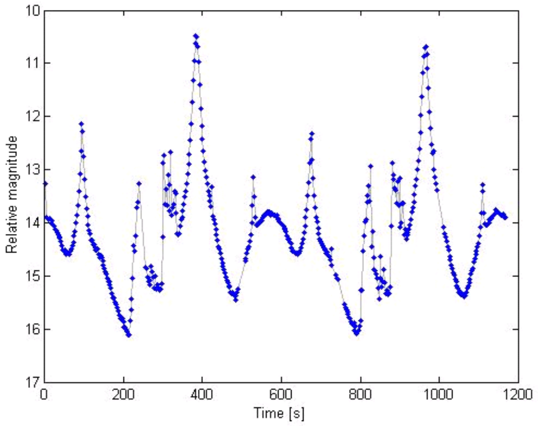

Fig. 3. Light curve of PAKSAT (1996-006A) (7.11.2014).

A phase reconstruction was performed, starting with a period of 550s, manually derived from the light curve. The best phase was found for a period of 581s (Fig. 4). This example shows a rather complex phase function due to the complex shape of the object. An example of observations of a N1 rocket upper stage in LEO (1978-018B), is given in Fig. 5. This highly resolved light curve from the ZIMLAT CMOS camera acquired at the Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald shows a fast rotating object with a rather simple shape and a spin period of 5.31s

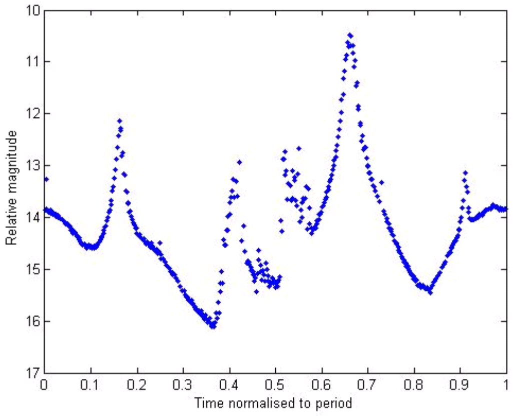

Fig. 4. Reconstructed phase of PAKSAT (1996-006A) from a light curve acquired on 07.11.2014 with an extracted apparent period of 581s.

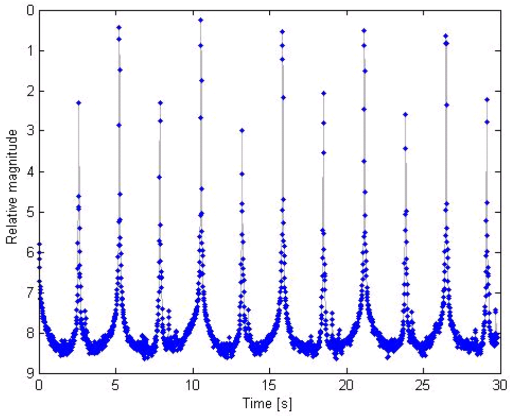

Fig. 5. Light curve of 1978-018B from 10.02.2015, acquired with the ZIMLAT CMOS camera at 67 frames per second.

An example of simultaneously acquired SLR range residuals and a high resolution light curve of the decommissioned LEO satellite TOPEX (1992-052A) is given in Fig. 6. The spin period at this epoch was about 12s which is very short given that the spacecraft was switched off in January 2006. After almost 10 years an initial attitude motion is expected to be damped completely.

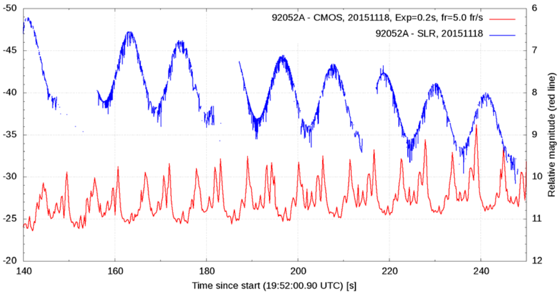

Fig. 6. SLR range residuals (top) and high resolution light curve (bottom) of the decommissioned LEO satellite TOPEX (1992-052A) simultaneously acquired on 28.11.2015.

Spin rates for the non-operational Envisat spacecraft were derived 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. Fig. 7 shows the synodic (blue) and the sidereal (red, green for clockwise and counterclockwise rotation) spin periods of Envisat as determined by these observations.

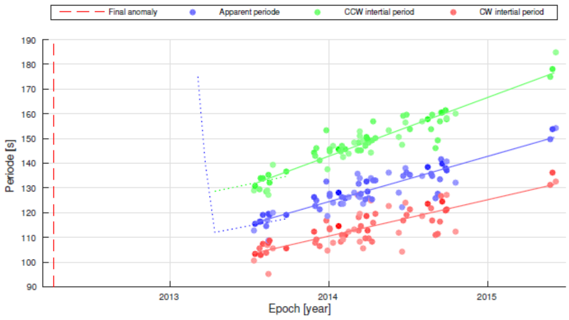

Fig. 7. Evolution of the synodic (blue) and the sidereal (red, green for clockwise and counterclockwise rotation) spin periods of Envisat as determined from SLR observations from Zimmerwald.

4. Rotation properties of observed objects

Fig. 8 shows the rotational properties of 397 objects as extracted from 1991 light curves acquired by ZIMLAT telescope during years 2007 to 30 2016. Shown 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 point of view the attitude is LEO population. For this we extracted apparent rotation periods only for 4.4% of the objects which in principle means that the apparent rotation period was smaller than the pass duration (note: typical pass duration of LEO objects for Zimmerwald observatory is from 3-12 minutes). For LEO the majority of the observed objects were upper stages (50.6%). GEO and other population showed rotations for 89.2% of observed objects. This population consists of all four types of objects, spacecraft (S/C), rocket bodies (R/B), fragments (DEB) and objects discovered by our own surveys (DIS), where DIS were dominating with 52.9%. The GLONASS population, consisting only of 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 for the apparent angular velocity extracted for BREEZE-M R/B. The majority of the observed HEO objects have been R/B with representation of 66.7 %

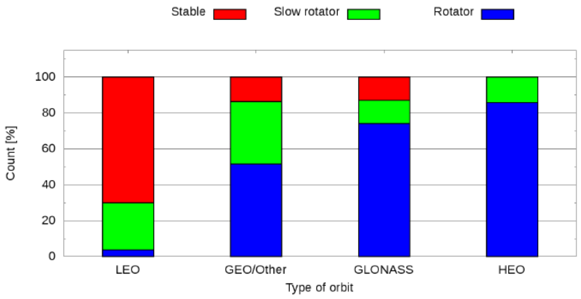

Fig. 8. Relative counts as a function of orbital type and rotational properties for 397 individual objects as extracted from the 1991 light curves acquired by ZIMLAT telescope in years 2007 to 31th of June 2016.

An example of the distribution of the extracted apparent angular rates for GLONASS objects can be seen in Fig. 9. This population reached apparent angular rates from 1.1°/s to 42.2°/s. Additionally we observed changes of the rotation periods 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 behavior can be seen in Fig. 10. One year evolution of the apparent angular velocity for GLONASS satellite 1994-021C from light curves acquired by ZIMLAT telescope between years 2015 and 2016.

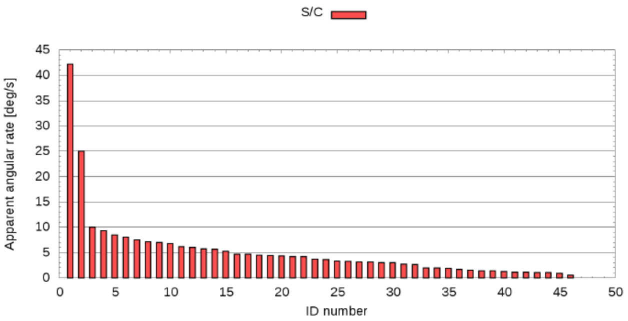

Fig. 9. Apparent angular rates of spacecraft (S/C) on GLONASS orbits as extracted from ZIMLAT light curves.

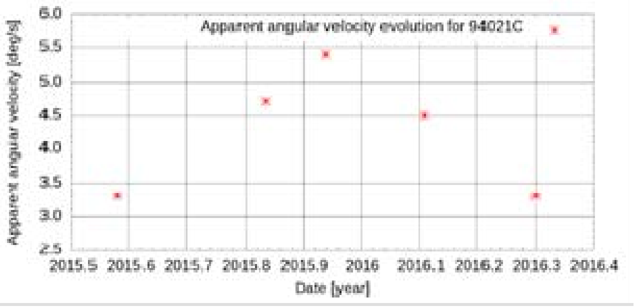

Fig. 10. One year evolution of the apparent angular velocity for GLONASS satellite 1994-021C from light curves acquired by ZIMLAT telescope between years 2015 and 2016.

5. Conclusion

The determination of attitude states (attitude and attitude motion) of space objects is particularly important in contingency cases. Furthermore, all future active debris removal concepts will require precise a priori knowledge of the attitude state. Similarly, orbit determination and orbit propagation depend on this knowledge, as disturbing forces like air drag and solar radiation pressure depend on the attitude of the object. This will become a crucial component in a future high precision space debris orbit catalogue used to prevent collisions.

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 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).

AIUB's photometric program is monitoring 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 analysis at AIUB

6. Acknowledgements

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