Determining and Modeling Space Debris Attitude States by Fusing Data from different Observation Techniques

T. Schildknecht(1), **J. Šilha**(1)

(1) *Astronomical Institute, University of Bern, Sidlerstr. 5, CH-3012 Bern, Switzerland, Email: thomas.schildknecht@aiub.unibe.ch*

ABSTRACT

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.

A reliable and prompt determination of the attitude and attitude motion of an inactive spacecraft is also required in contingency situations.

The paper will describe new techniques to determine space debris attitude states and to model their temporal evolution by combining heterogeneous observations from different ground-based observation techniques including synthetic aperture radar measurements, optical light curve observations, and cooperative laser ranging measurements. Results for a set of decommissioned or lost LEO, MEO and HEO spacecraft and upper stages will be presented.

1 INTRODUCTION

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 Figure 1. (If not noted otherwise, 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.)

Another passive optical technique to determine the attitude and the attitude motion is the acquisition of a series of resolved images of the target, so-called direct imaging. Ground-based observations suffer from atmospheric turbulence limiting the resolution of direct images. Large object in LEO, however, may be resolved by applying adaptive optics techniques or by "lucky-

Proc. 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017, published by the ESA Space Debris Office
Ed. T. Flohrer & F. Schmitz, (http://spacedebris2017.sdo.esoc.esa.int, June 2017)

imaging”. The latter consist in taking a large number of short exposures with integration times << 1s which in some lucky cases may “freeze” the turbulence.

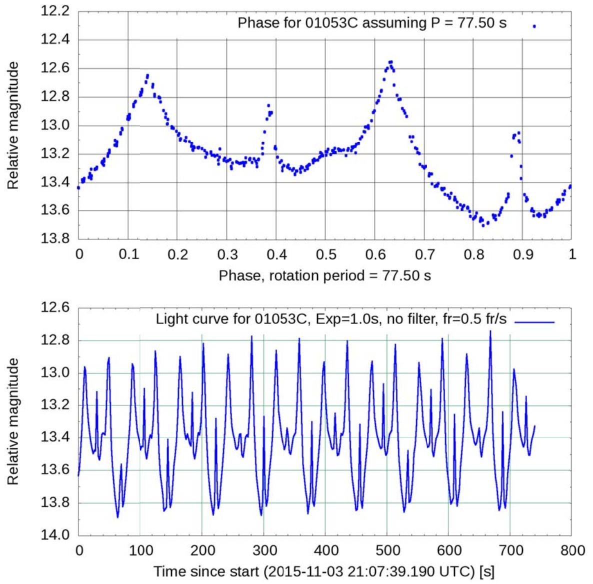

Figure 1. Light curve (bottom) and reconstructed phase (top) of the GEO upper stage 2001-045D.

2.2 Radar techniques

Similarly to the optical techniques, radar measurements of the temporal variation of the radar cross-section may be used to determine attitude states and in particular rotation rates of space objects. Two-dimensional images in the radar domain are obtained by applying inverse synthetic aperture radars (ISAR) techniques. This technique exploits the changing attitude of the object with respect to the radar [1]. Note that in order to reconstruct the image from the radar data the attitude motion of the objects has to be estimated from the same data. The generation of ISAR images and the determination of the object’s attitude are thus intimately related.

2.3 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 Figure 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.

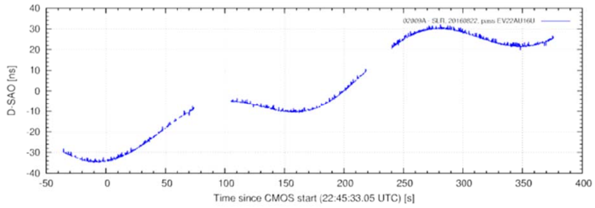

Figure 2. SLR range residuals in ns of a pass of the rotating ENVISAT spacecraft. The periodic signal reflects the attitude motion of the retroreflector around the centre of mass of the object.

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

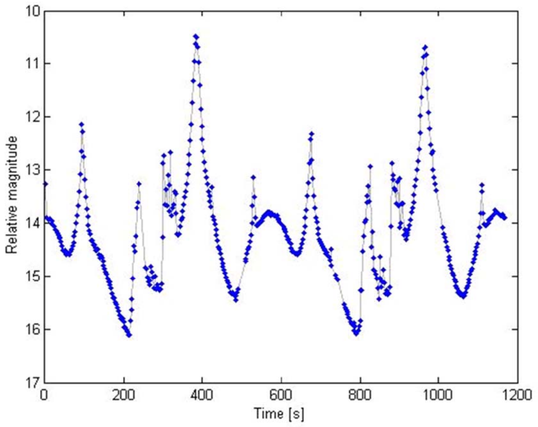

Figure 3. Light curve of PAKSAT (1996-006A) (7.11.2014).

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 (Figure 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 Figure 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 rater simple shape and a spin period of 5.31s.

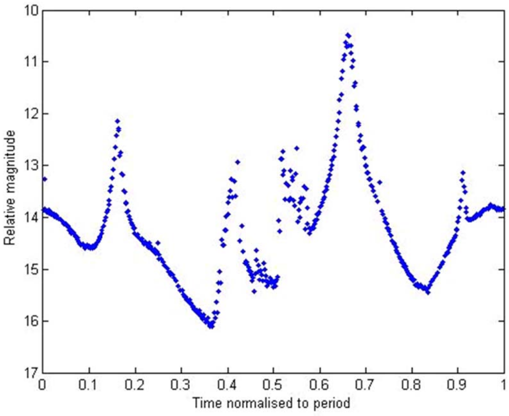

Figure 4. Reconstructed phase of PAKSAT (1996-006A) from a light curve acquired on 07.11.2014 with an extracted apparent period of 581s.

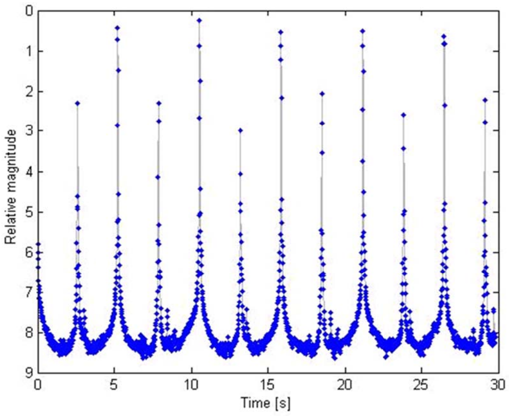

Figure 5. Light curve of 1978-018B from 10.02.2015, acquired with the ZIMLAT CMOS camera at 67 frames per second.

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 Figure 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.

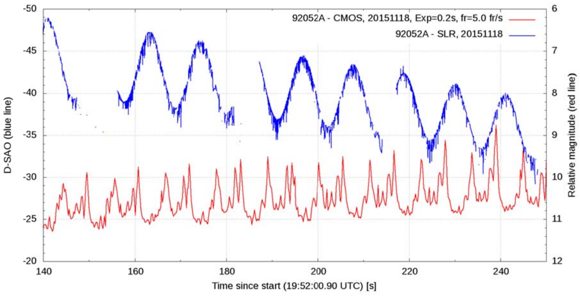

Figure 6. SLR range residuals (top) and high resolution light curve (bottom) of the decommissioned LEO satellite TOPEX (1992-052A) simultaneously acquired on 28.11.2015.

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. Figure 7 shows the synodic (blue) and the sidereal (red, green for clockwise and counterclockwise rotation) spin periods of Envisat as determined by these observations.

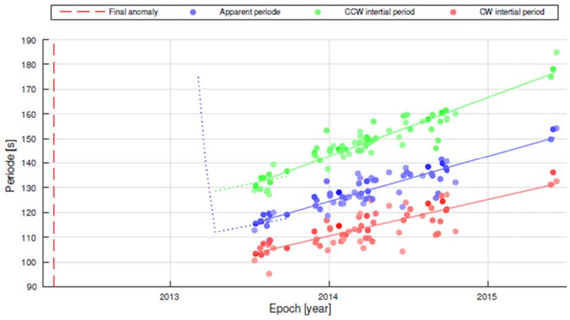

Figure 7. Evolution of the synodic (blue) and the sidereal (red, green for clockwise and counterclockwise rotation) spin periods of Envisat as determined from SLR observations from Zimmerwald.

Finally an ISAR image of Envisat acquired by the Tracking and Imaging Radar (TIRA) of the Fraunhofer FHR [3] is given in Figure 8. The generation of such images includes the determination of the instantaneous attitude motion (rotation axis and spin rate) of the object.

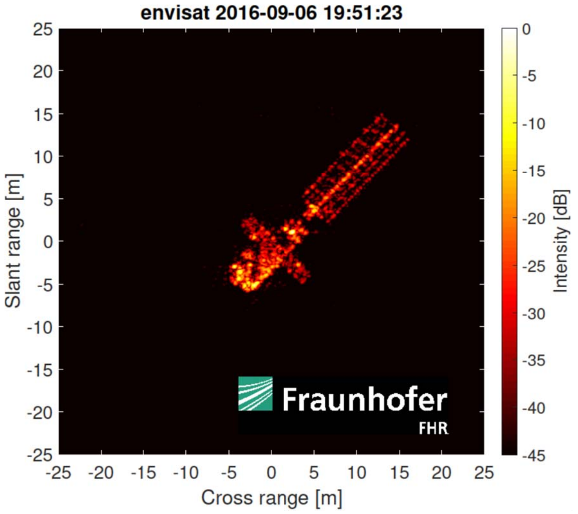

Figure 8. ISAR image of Envisat acquired by the Tracking and Imaging Radar (TIRA) of the Fraunhofer FHR, Germany (from [1]).

4 FUSING THE DATA

Attitude states can in most cases not be directly derived from the raw observations. Direct inversion of light curves to obtain attitude states and object shapes is, e.g., impossible in the general case. In the first place, light curves allow determining the apparent spin rate of an object. If the shape of the object is known and simple, e.g. a simple cylinder, there are ways to determine the rotation rate and the spin axis orientation, provided that light curves were acquired with a wide range of viewing geometries [4]. Another approach is to use forward modelling trying to fit the observed light curve with simulated data by adjusting the attitude and attitude motion in the model [5]. Obviously the shape and the details of the surface reflection properties, i.e. the bidirectional reflectance distribution functions (BRDF) need to be known. For most space objects the latter are not known and simplifying assumption are necessary.

SLR observations of cooperative objects are somewhat simpler to handle, as the position of the retroreflector in the body-fixed system is usually well known. Analysing the observation geometries where SLR observations were successful, i.e. where the retroreflector array was “visible” from the station, constrains the possible attitudes. Applying some additional assumptions on the spin axis in the body-fixed frame then allows determining the spin axis orientation in the inertial frame [6].

The generation of radar images require a shape model of the object (and some further assumptions) in order to determine the spin axis orientation and the spin rate from the same data.

All above-mentioned methods to determine the attitude state fail, if the space object is in a complicated tumbling motion. This is in particular the case for the construction of ISAR images. On the other hand, indication of a complicated attitude motion is usually clearly seen in light curves. It is thus obvious that fusion of the different data types would be beneficial to fully exploit the complementary information in the different observables. Ideally one would set up a parameter estimation problem in order to estimate the attitude state (in the body-fixed and the inertial frame) directly from the fused data. However, given the many model uncertainties for the individual techniques and a particular space object (e.g. unknown surface BRDFs or unknown radar scattering properties), this approach might be too ambitious to start with. In order to learn more about how to model the observations of individual objects, forward modelling is required in a first step. E.g. the ESA In-Orbit Tumbling Analysis (iOTA) simulation tool [5] may be used to determine an attitude state which best fits a particular light curve, to propagate this attitude state to the epoch of another light curve and to perform a comparison which allows then a refinement of the model. Similarly, the attitude state determined by passive optical observations can be used to simulate SLR observations of the same object, or vice versa [7]. The same state could also be propagated to the epoch of ISAR measurements of the same object and used as input data to facilitate the image generation. Eventually the model and the attitude state may be iteratively improved using forward modelling and comparison with all measurement types.

5 SUMMARY

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.

Currently three major techniques are used to determine attitude states of space debris objects: Passive optical light curves, satellite laser ranging, and direct optical or radar imaging. In general all these techniques are not able to provide attitude states directly from the observation without making some more or less justified assumptions. A fusion of the data from the different techniques is thus required. First attempts are currently undertaken by using forward modelling simulation tools.

6 ACKNOWLEDGEMENTS

We would like to thank all the observers and staff at the observatories which spent so much effort to acquire the data. Part of the data presented was acquired in the context of the ESA project “Debris Attitude Motion Measurements and Modeling” 4000112447/14/D/SR.

7 REFERENCES

1. Silha, J., T. Schildknecht, J.-N. Pittet, G. Kirchner, M. Steindorfer, D. Kucharski, D. Cerutti-Maori, J. Rosebrock, S. Sommer, L. Leushacke, P. Kärräng, R. Kanzler, H. Krag, *Debris Attitude Motion Measurements and Modelling by Combining Different Observation Techniques*, Proceedings of this conference.
2. Kirchner, G., Koidl, F., Friederich, F., Buske, I., Völker, U., & Riede, W., Laser measurements to space debris from Graz SLR station. Advances in Space Research, 51(1), 21-24, 2013.
3. D. Mehrholz. (1996). Ein Verfolgungs- und Abbildungsradarsystem zur Beobachtung von Weltraumobjekten, *Frequenz*, 50:138–146, July 1996. doi:10.1515/FREQ.1996.50.7-8.138.
4. Santoni, F., E. Cordelli, and F. Piergentili, Determination of Disposed-Upper-Stage Attitude Motion by Ground-Based Optical Observations, JSR, Vol. 50, No. 3, May–June 2013.
5. Kanzler, R., Schildknecht, T., Lips, T., Fritsche, B., Silha, J., Krag, H., *Space Debris Attitude Simulation - ιOTA (In-Orbit Tumbling Analysis)*, Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, held in Wailea, Maui, Hawaii, September 15-18, 2014.
6. Kucharski, D., Kirchner, G., Koidl, F., Cunbo Fan, Carman, R., Moore, C., Dmytrotsa, A., Ploner, M., Bianco, G., Medvedskij, M., Makeyev, A., Appleby, G., Suzuki, M., Torre, J.-M., Zhang Zhongping, Grunwaldt, L., Qu Feng, *Attitude and Spin Period of Space Debris Envisat Measured by Satellite Laser Ranging IEEE transactions on geoscience and remote sensing*, 12, 7651-7657, 2014.
7. Silha, J., Schildknecht, T., Pittet, J.-N., Bodenmann, D., Kanzler, R., Karrang, P., Krag, H., *Comparison of ENVISAT’s attitude simulation and real optical and SLR observations in order to refine the satellite attitude model,* Proceedings of AMOS Conference, Maui, Hawaii, 2016, (AIUB).