DETERMINATION OF ATTITUDE AND ATTITUDE MOTION OF SPACE DEBRIS, USING LASER RANGING AND SINGLE-PHOTON LIGHT CURVE DATA

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ABSTRACT

The ESA project 'Debris Attitude Motion Measurements and Modeling' aims to determine spin parameters – like spin period, spin axis orientation, and their evolution during time – using laser ranging, passive optical methods, and radar.

This contribution will address the setup, operation and performance of the Satellite Laser Ranging (SLR) Station Graz, and how Graz data contributes to precise determination of attitude and attitude motion of debris targets, using both laser ranging to cooperative debris targets (usually defunct satellites with retro-reflectors) and single-photon light curve recording (also to uncooperative targets: debris without any retro-reflectors). The target sizes varies from small – e.g. cube sats – up to large targets like Envisat, in distances from a few 100 km (LEO) up to geostationary orbits (GEO), and with spin periods from a few seconds up to several 100 seconds.

1 INTRODUCTION

Since the first satellites were launched more than 50 years ago, the amount of space debris in orbit around Earth is constantly increasing, and poses a great threat to active satellites [1]–[4]. Due to the high velocity of several kilometers per second, even collisions with particles of a few millimeters size can lead to severe damage on satellites; parts with more than 1 cm size potentially can destroy satellites.

For accurate prediction of possible collisions, and for eventual scheduling of proper collision avoidance maneuvers, accurate predictions of the orbits for the next few days are necessary – and this requires also accurate knowledge of attitude and attitude motion.

SLR Graz (Fig. 1) has developed and applied several methods to determine attitude and attitude motion of cooperative (with retro-reflectors) and uncooperative (without retro-reflector) targets, and routinely collects such data of several tens of objects – in many cases simultaneously with our millimeter SLR activities.

Fig. 1: Observatory Lustbuehel, close to Graz

2 SLR GRAZ: HARDWARE SETUP

2.1 Telescope and Mount System

In 1983, the first version of Graz SLR station started to track satellites with a 10 Hz Nd:YAG laser; the only hardware surviving since that is our telescope and mount system: A 50 cm Cassegrain receive telescope, and parallel to it a 10 cm transmit telescope (Fig. 2). All other equipment – like computers, detectors, lasers, timing systems, cameras etc - has been replaced and updated continuously since then.

Fig. 2: Graz Laser Telescope, located at Observatory Lustbuehel, Austria

2.2 The kHz Laser System

In 2003, SLR Graz was the first laser station to implement a 2 kHz Nd:VAN laser system, which emits pulses with a pulse duration of 10 ps, and with a relatively low pulse energy of 400 µm (i.e. 0.8 W) @ 532 nm. This laser is our standard system for millimeter SLR to cooperative targets, actually used to measure distances to more than 150 target, and also to determine attitude and attitude motions of targets with retro-reflectors (usually defunct old satellites).

2.3 Space Debris Lasers in Graz

In 2012, SLR Graz implemented an additional laser with higher power, to range for the first time to non-cooperative targets, relying on diffuse reflection: A DPSS laser – on loan from DLR Stuttgart – with a 1 kHz repetition rate, 25 mJ and a few ns per pulse at 532 nm (25 W).

In 2013, this laser was replaced by another laser with 100 Hz / 200 mJ / few ns pulses also at 532 nm (20 W) – also on loan from SLR Stuttgart. With this laser, we tracked up to now several 100 different targets in LEO orbits, from < 1 m^2 up to > 19 m^2 RCS (Radar Cross Section), and in distances between < 500 km and up to about 3000 km (Fig. 3). This laser was also used for first successful tests of bi-static and multi-static SLR: While Graz SLR station was firing on non-cooperative debris targets, other SLR stations – Wettzell, Zimmerwald, Herstmonceux – could detect Graz photons, diffusely reflected from these targets: ONE debris laser thus produced distance data from 2 or more sites, resulting in significantly improved accuracy of orbit predictions for the next days [5, 6].

In March 2017, we have mounted a demo space debris laser system directly on our telescope; this laser delivers 80 mJ per 3-ns-pulse @ 532 nm, with a repetition rate of 200 Hz (i.e. 16 W). Due to the high laser beam quality, even with this reduced power we could demonstrate successful laser ranging to more than 30 different space debris targets (mainly old rocket bodies).

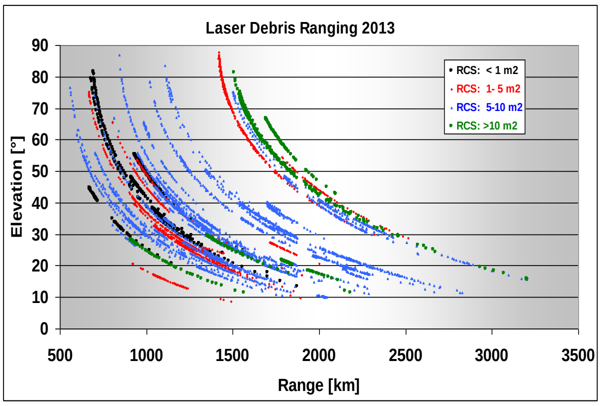

Fig. 3: A sample of measured debris target passes 2013; up to 3000 km distance, and down to low (10°) elevation

2.4 Single - Photon Light Curve Recording

In 2015, we installed a single-photon light curve (LC) recording system [7]; a single-photon avalanche detector (SPAD) detects sun photons diffusely reflected from targets in sunlight; these detections are counted in an FPGA within selectable time slots – usually 10 ms, giving a 100 Hz resolution. If the target changes its attitude, reflectivity also changes; this allows to record its spin; detailed analysis also allows to calculate spin parameters, e.g. spin axis orientation and its changes, spin direction etc. The detector uses the wavelengths between 600 to 900 nm; this is outside of our laser wavelengths (532 nm and 1064 nm), and thus allows operation to the selected target simultaneously with and independent of SLR operation.

For special tasks, it is also possible to record the *event time* of *each* detected photon; this results in extremely high resolution of the light curve; it is used for example for detailed analysis of the short (less than 10 ms) flashes of sunlight, reflected by mirrors on the satellite AJISAI.

3 RESULTS

3.1 kHz Laser: Attitude motion determination

Ranging with the kHz laser system to defunct, but cooperative targets allows easy determination of spin parameters (Fig. 4). Identifying returns from the 8 single retro-reflectors on the ENVISAT reflector pyramid, the spin parameters can be determined with even higher accuracy (Fig. 5). Such SLR measurements allow precise determination of spin evolution; e.g. the change of spin duration of ENVISAT is shown (Fig. 6) after its failure in 2012. Detailed analysis of the data allows determination of spin axis, and its change [9].

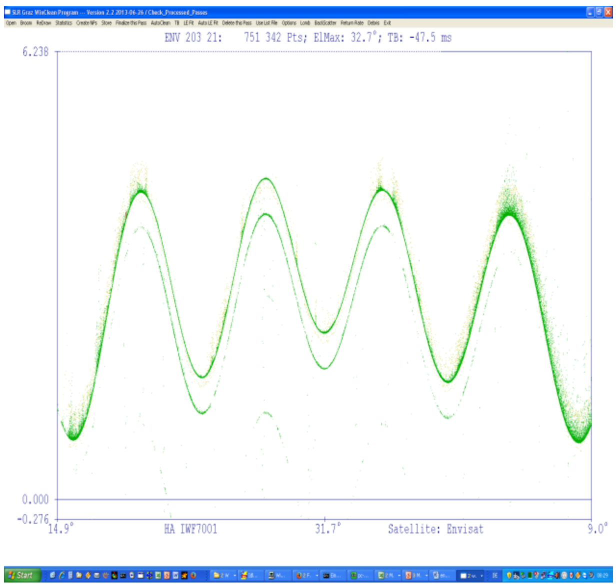

Fig. 4: kHz SLR to tumbling ENVISAT: Few meters variation of the residuals (O-C) show a spin duration of about 170 seconds (July 2015)

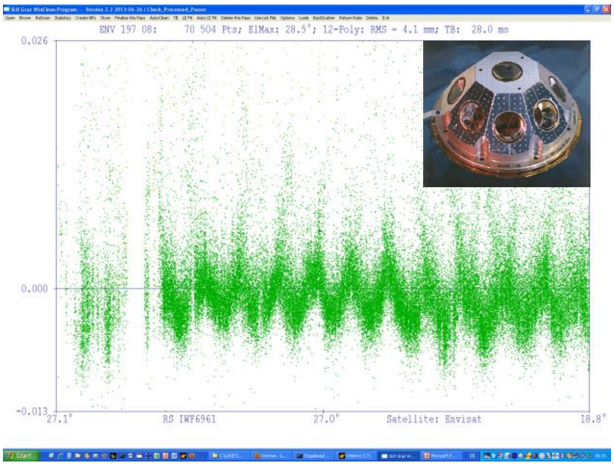

Fig. 5: Each of the 8 retros of the ENVISAT reflector unit slightly changes its distance from the SLR station, as ENVISAT is rotating; 8 'peaks' thus correspond to ONE full rotation of ENVISAT

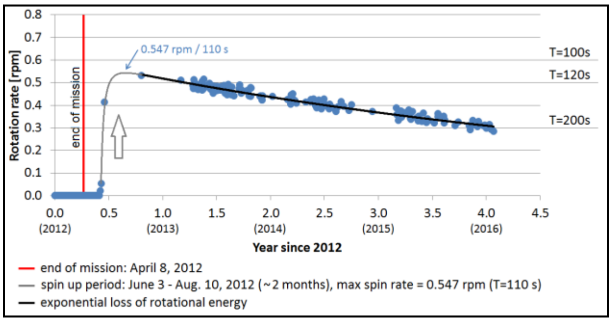

Fig 6: ENVISAT spin evolution [9]

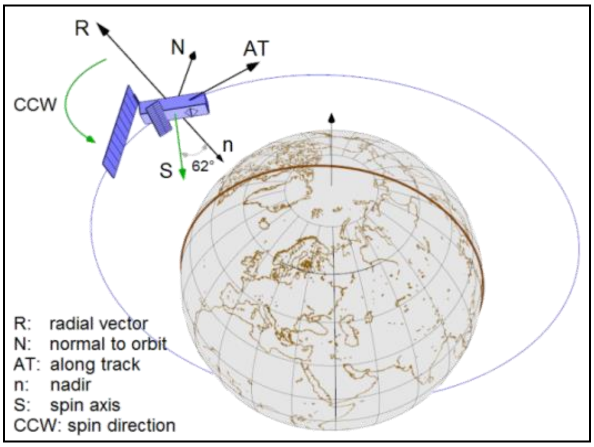

Fig. 7: Envisat attitude determination with SLR [9]

Topex/Poseidon is another defunct satellite, with a large ring of retro-reflectors; the satellite was switched off more than 10 years ago, and has started to spin (Fig. 8); this spin is accelerating since then, driven by solar radiation pressure [8], acting mainly on the solar panel. The defunct satellite has been measured by several ILRS laser stations in 2015 and 2016, allowing not only precise orbit determinations, but also accurate attitude and attitude motion parameters [9].

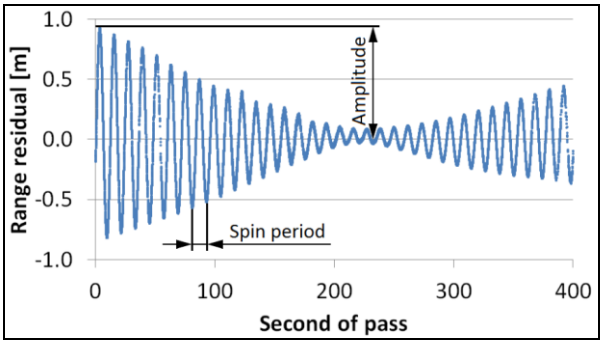

Fig. 8: Topex/Poseidon spin: Duration ≈ 11 secs [9]

ENVISAT and Topex are examples of satellites with a stabilized attitude; retro-reflectors are always visible, or at least during predictable pass configurations. However, other satellites 'show' their retro-reflectors only during a short part of their rotation (Fig. 9).

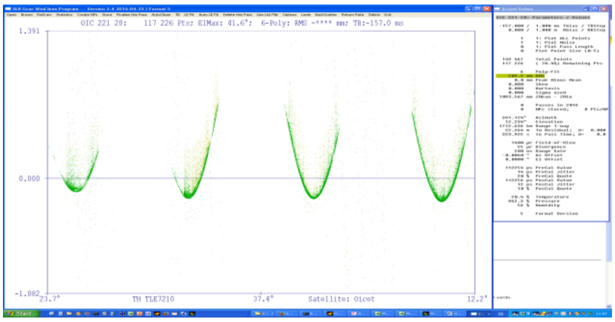

Fig. 9: OICETS: Spins with a period of ≈ 110 seconds

Another group of cooperative targets are defunct Glonass satellites – all of them are equipped with retro-reflector panels. Because of their relatively short life time, they are replaced frequently – leaving already a relatively large 'fleet' of defunct GLONASS satellites.

Due to their retro-reflector panels, these defunct satellites can be ranged easily with standard SLR equipment; Graz started these measurements in 2012; an example is given in Fig. 10: Glonass-41 residuals, indicating a spin period of about 8 seconds.

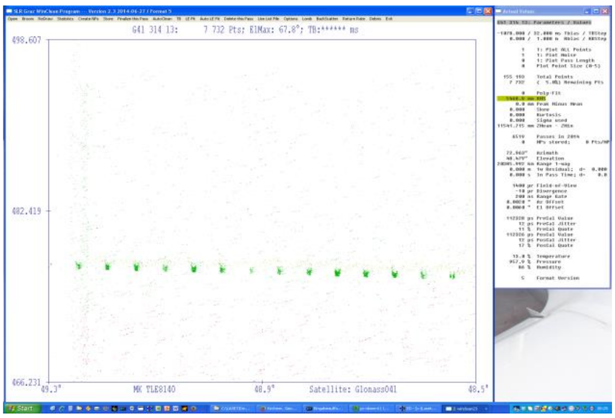

Fig. 10: Defunct Glonass-41: The residuals show a spin period of 8 seconds

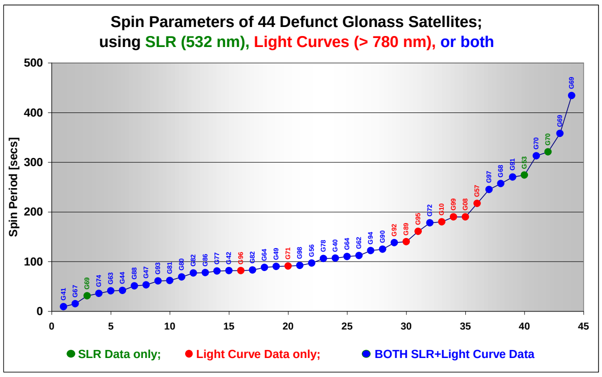

Fig. 11: Spin periods of > 40 defunct Glonass satellites

Fig. 11 shows the spin periods of more than 40 defunct Glonass satellites; some measured with the 2 kHz laser system, some with light curve recording, some with both. Spin periods range from 8 seconds (Glonass-41) up to more than 400 seconds.

3.2 Debris Laser: Attitude motion

Graz has measured several 100 passes of debris targets during the last 5 years, using different lasers, different detectors and various setups; but only in few passes we could see indications for attitude and / or attitude motions (Fig. 12); and only in very few of these it was possible to derive a rough estimation of spin period. Therefore, spin parameter determination of debris targets using a debris laser system is much less efficient than kHz SLR (to cooperative targets) or light curves (to cooperative AND non-cooperative targets).

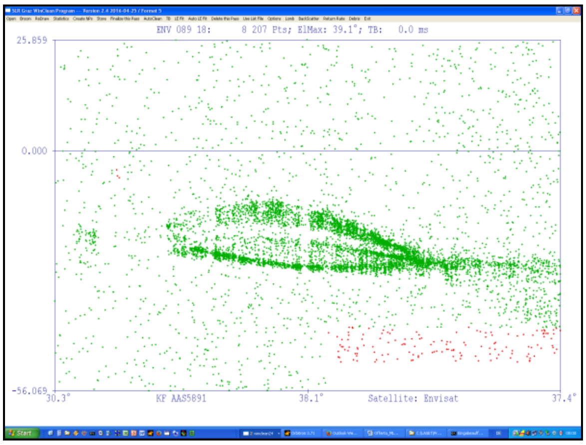

Fig. 12: ENVISAT measured with debris laser: Retros not visible – echoes from large body; difficult to extract accurate spin parameters (pass: 2017/day 089)

3.3 Single - Photon Light Curve Recording

This method results in relatively high resolution (Fig. 13): 10 ms resp. 100 Hz is our standard, but in principal almost unlimited resolution is possible, if event times of single photons are recorded. The method delivers much smaller data files, as compared to CCD imaging systems; and it is intrinsically single-photon sensitive. This allows to record spin data of targets up to GEO orbits even with our relatively small 50 cm telescope.

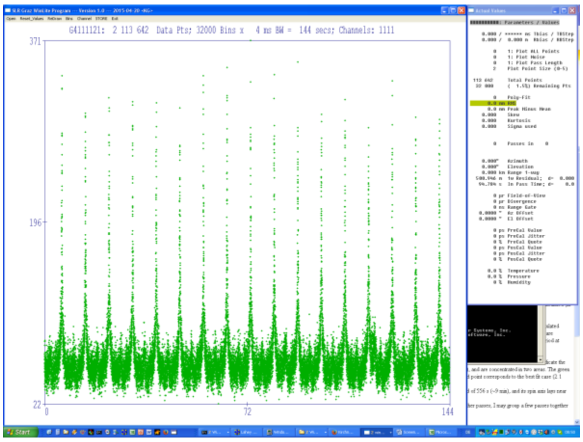

Fig. 13: Single Photon Light Curve of defunct Glonass-41; all 4 sides of the 'box' are visible; spin period 8.4 s

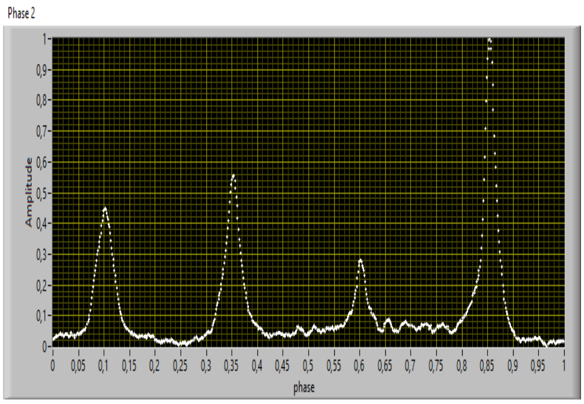

Fig. 14: PDM / Phase Dispersion Minimization: Clear averaged full rotation; all 4 sides of this 'box-wing' satellite are clearly identified

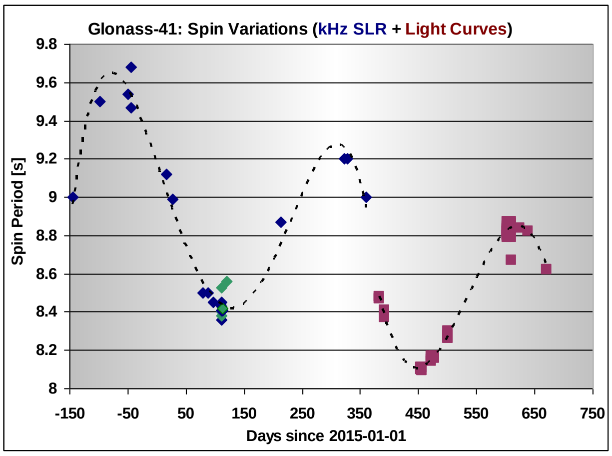

Fig 15: Defunct Glonass41: Spin duration derived from ***kHz SLR*** *AND* ***Light Curves****: Spin is accelerating, and shows clear yearly variations.*

The only disadvantage: The targets have to be in sunlight, and the station needs to be in darkness – for LEOs, this restricts light curve recordings roughly to the 2 hours of the terminator period.

Usually, the spin period is derived using the Phase Dispersion Minimization (PDM); all phases of every full rotation are averaged and plotted; this results in very clear images of a full phase of one rotation, giving accurate spin duration values (Fig. 14).

Observing these defunct Glonass satellites over several years shows in some cases a slow change in spin rate (increasing or decreasing), and /or also variations of spin rate within certain periods; e.g. yearly variations of Glonass-41 spin rate, Fig. 15). This research is still on-going.

4 REFERENCES

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