kHz SLR application on the attitude analysis of TechnoSat

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Abstract

TechnoSat is a 20 kg in-orbit technology demonstration satellite of Technische Universität Berlin, which was launched on July 14, 2017. TechnoSat carries fourteen commercial off-the-shelf 10 mm laser retroreflectors and has been tracked successfully by several ILRS stations. Within several experiments the feasibility and the credibility of attitude determination by using KHz SLR technique was demonstrated. By design, a maximum of 24 reflectors could have been mounted on 6 outer surfaces of TechnoSat. However, to achieve attitude and rate determination unique SLR signature was realised on each side. To this end, the optimal distribution of fourteen reflectors was simulated and tested on the ground. Estimated by Degnan's radar link equation, the expected detection probability of the implemented reflectors in a 600 km orbit and with a 45 degrees incidence angle is about two times of LAGEOS, which enables most of ILRS stations to get a reasonable amount of returns even in the worst case when only one reflector is visible to the station. In orbit, the attitude of TechnoSat varies between freely tumbling, nadir-, inertial-, or target-pointing according to the demands of different experiments. This in turn results in different scenarios for laser ranging. In this paper, we present our results in attitude analysis based on KHz SLR data from the laser ranging station in Graz, Austria and its comparison to records from the on-board attitude and rate measurements.

1. Introduction

In recent years, the interest in small spacecraft such as CubeSats has been rising continuously. Compact designs and commercial-off-the-shelf (COTS) components are enabling more affordable space activities for small countries, institutions or companies (Poghosyan and Golkar, 2017).

TechnoSat (COSPAR no. 2017-042E) is a technology demonstration satellite based on the TUBiX20 platform of Technische Universität Berlin. It was launched in July 2017 as the twelfth satellite of the university. The main objective of the mission is to demonstrate and verify newly developed satellite technologies and components in orbit (Barschke et al., 2016). First orbit results of the TechnoSat technology demonstration payloads can be found in (Barschke et al., 2018).

Among TechnoSat's seven technology payloads are fourteen laser retroreflectors that shall demonstrate the feasibility of laser ranging based on 10 mm COTS reflectors. Furthermore, attitude determination by using kHz SLR technique shall be demonstrated. All reflectors were evaluated individually by the German Research Centre for Geosciences (GFZ) Potsdam, Germany before being considered for orbit application (Grunwaldt et al., 2016). Estimated by Degnan's radar link equation (Degnan, 1993), the expected satellite laser ranging (SLR) detection probability of the implemented corner cube reflectors (CCRs) can be estimated. Assuming a 45° incidence angle at a 600 km orbit the return rate is twice the rate of LAGEOS, which enables most stations of the International Laser Ranging Service (ILRS) (Pearlman et al., 2002) to get a reasonable amount of returns.

In total, 24 corner cube reflectors could have been mounted on the six outer surfaces of the eight-edge prism satellite (four side faces, top face and bottom face). However, to achieve attitude and attitude rate determination a unique SLR signature of each side was required. A ground experiment has been used to confirm the optimal reflector pattern found through simulation. To this end geometry model of TechnoSat was placed on a small mountain about 32 km southwest of the satellite laser ranging station in Graz. The model simulated attitude motions while the distance to the satellite was measured with the 2 KHz SLR system.

In orbit, the attitude of TechnoSat varies from freely tumbling over (off-)nadir-pointing to target-pointing according to the demands of different tasks. This paper presents a comparison between simulations, ground measurements, and real SLR passes.

2. Reflector distribution

The octagonal prism structure of TechnoSat that is depicted in Figure 1 has dimensions of about 465 x 465 x 305 mm^3.

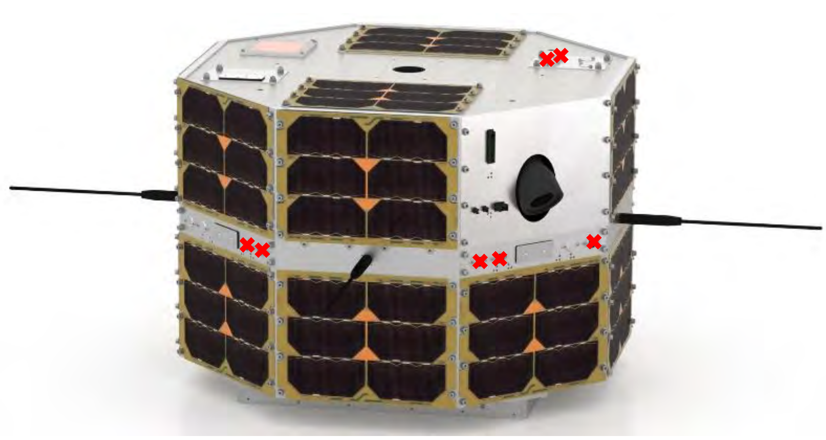

Figure 1: Rendering of TechnoSat with retroreflectors marked in red (Gordon et al., 2018)

The coordinates of the distribution with 14 CCRs realized for the TechnoSat mission based on a Cartesian coordinate system with the origin at the centre of geometry of the spacecraft are presented in Table 1.

Table 1: Coordinates of the fourteen CCRs on top (B1), bottom (B2), and on 4 out of the 8 side faces (A1 - A4) of TechnoSat with an accuracy of ± 0.5 mm

CCR no.	Position in x	Position in y	Position in z
A1-RA1	229.2	-70.0	0.0
A1-RA2	229.2	-45.0	0.0
A1-RA4	229.2	70.0	0.0
A2-RA2	45.0	229.2	0.0
A2-RA3	-45.0	229.2	0.0
A3-RA1	-229.2	70.0	0.0
A3-RA2	-229.2	45.0	0.0
A3-RA3	-229.2	-45.0	0.0
A3-RA4	-229.2	-70.0	0.0
A4-RA1	-70.0	-229.2	0.0
B1-RB1	44.2	161.6	153.0
B1-RB3	62.9	137.9	153.0
B2-RB2	-14.5	-47.5	-153.0
B2-RB3	18.0	-77.5	-153.0

3. Attitude determination simulation and ground experiment

For a first approach, it was assumed that TechnoSat always performs nadir-pointing. As shown in Figure 2 the incident angle α_{B2} between the normal of the satellites nadir phase (B2) and the laser beam direction from the ground station can be calculated as:

$$\alpha_{B2} = \sin^{-1}\left(\frac{R_E \times \sin(90^\circ + EL)}{R_E + H}\right) \quad (1)$$

where $R_E \approx 6378.1km$ is the radius of the Earth, EL the elevation angle and $H \approx 600km$ the orbit height of TechnoSat. For the COTS CCRs ($n \approx 1.44$, back coated) applied on TechnoSat, the effective optical cross-section breaks down when $\alpha_{B2} > 45^\circ$ (Degnan, 2012). Therefore the two CCRs on the satellites nadir phase are visible if $EL > 40^\circ$.

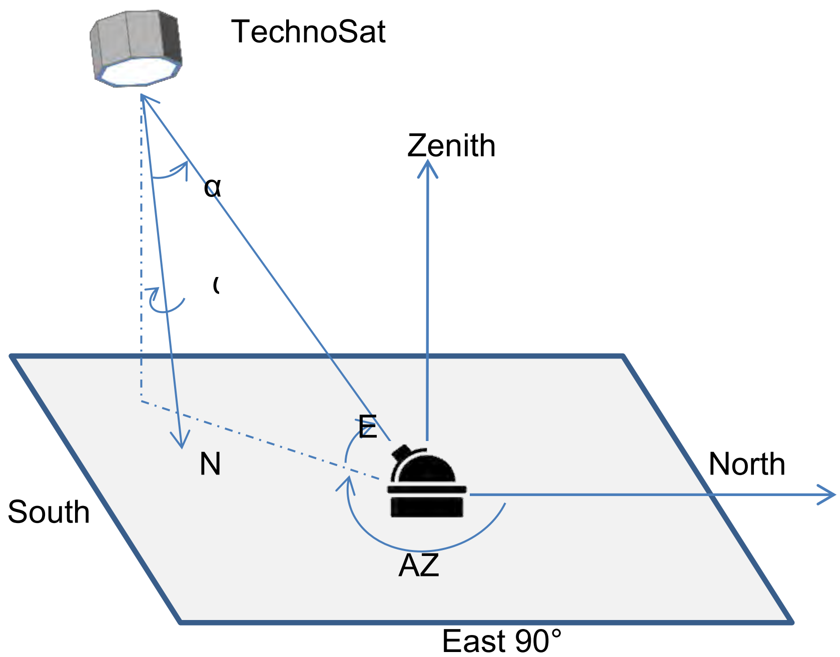

Figure 2: TechnoSat in attitude towards nadir-pointing and no spinning or tumbling

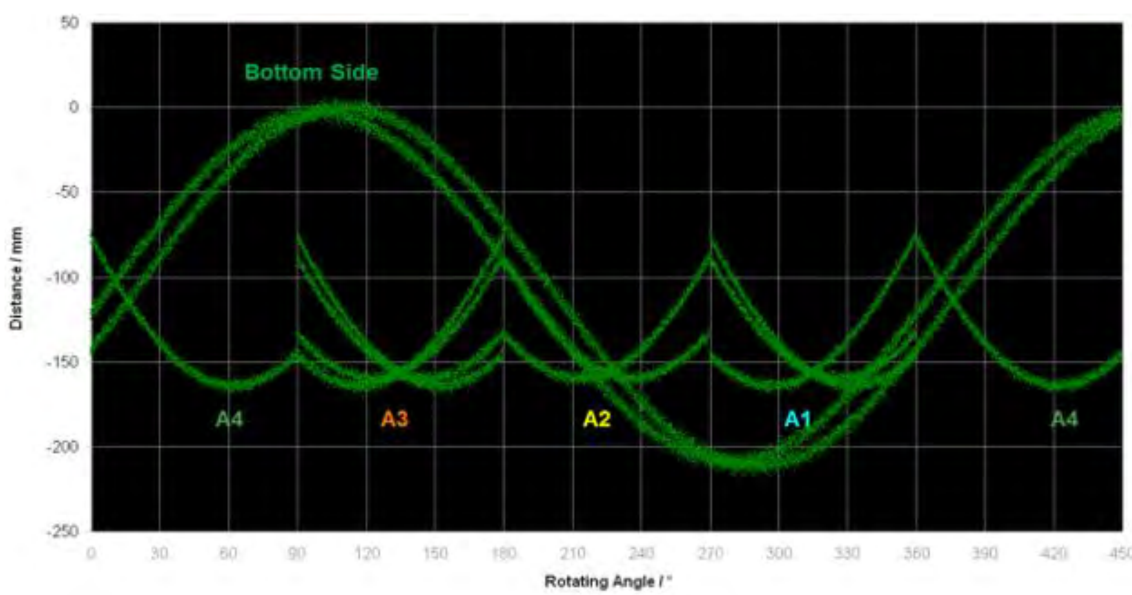

Figure 3: Calculation of the return signal with fixed elevation angle

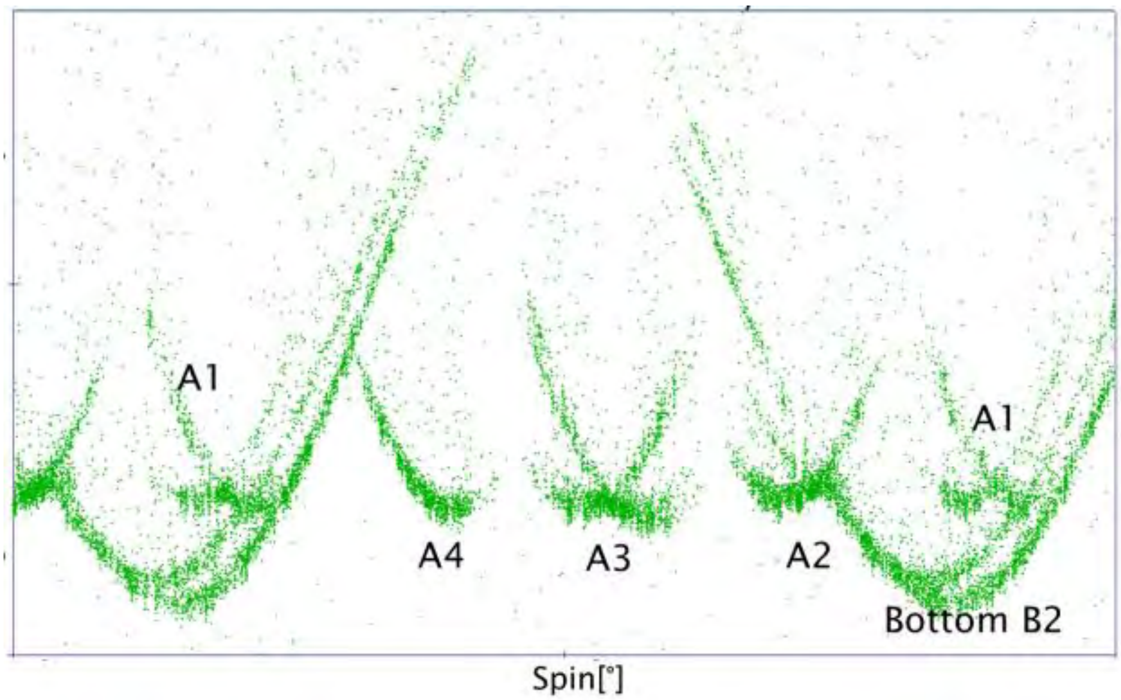

Figure 4: Return signal from ground experimentation for a fixed elevation angle

For a number of different CCR distributions the return signals have been calculated and tested in ground experiments (cf. section 1) to find the optimal solution that provides a unique pattern on each side of the satellite. Figure 3 depicts the result of a calculation which applies the selected distribution of CCRs and assumes that the TechnoSat satellite keeps a static elevation angle of 45° while spinning with a period of approximately 22.5 s. The variations in the distance to each visible CCR show unique patterns, thus a straightforward identification of each spacecraft side is possible. In Figure 4, the result of a ground experiment is shown that verifies the calculations above.

4. SLR measurements and attitude analysis

Since its launch in summer 2017, TechnoSat has been tracked by most ILRS stations. Figure 5 shows a typical SLR pass measured by the 2 kHz system in Granz on the 27^{th} of June, 2018. Here, the seven sections of the observed minus the computed (O-C) residuals (y axis) are marked with #1 to #7, which will provide an example of how the different faces are distinguished.

(1) The relatively large gap (~ 70 mm) between the patterns #1 and #2 as well as between the patterns #5 and #6, and #2 and #6 show that the same satellite faces are returning periodically. Thus, the spinning rate of TechnoSat can be estimated using the time between #2 and #5 which is approximately 139s.

(2) When analysing #2 in Figure 5 it can be seen that the pattern includes two laser return traces, where trace2 has a higher RMS and signal density than trace1. Therefore, it can be concluded that #2 is face A1 which hosts three CCRs.

(3) Both traces in pattern #4 (cf. Figure 7) show a similar RMS to trace2 in pattern #2, which indicates that those two traces are both originating from two CCRs, so that we can confirm that #4 is face A3.

(4) Considering the findings from above, it can be estimated that the returns #1/3/5 can only be the top or bottom faces, while the returns #2/4/6 are side faces. Since return #3 has an RMS close to the distance of two CCR on B2 and #3 has a larger RMS than #5, it is concluded that #3 is face B2 and #5 is B1. It can therefore be assumed, that TechnoSat was spinning in the sequential order of B2 → A1 → B1 → A3 → B2 → A1 → B1 during that pass (cf.Figure 7).

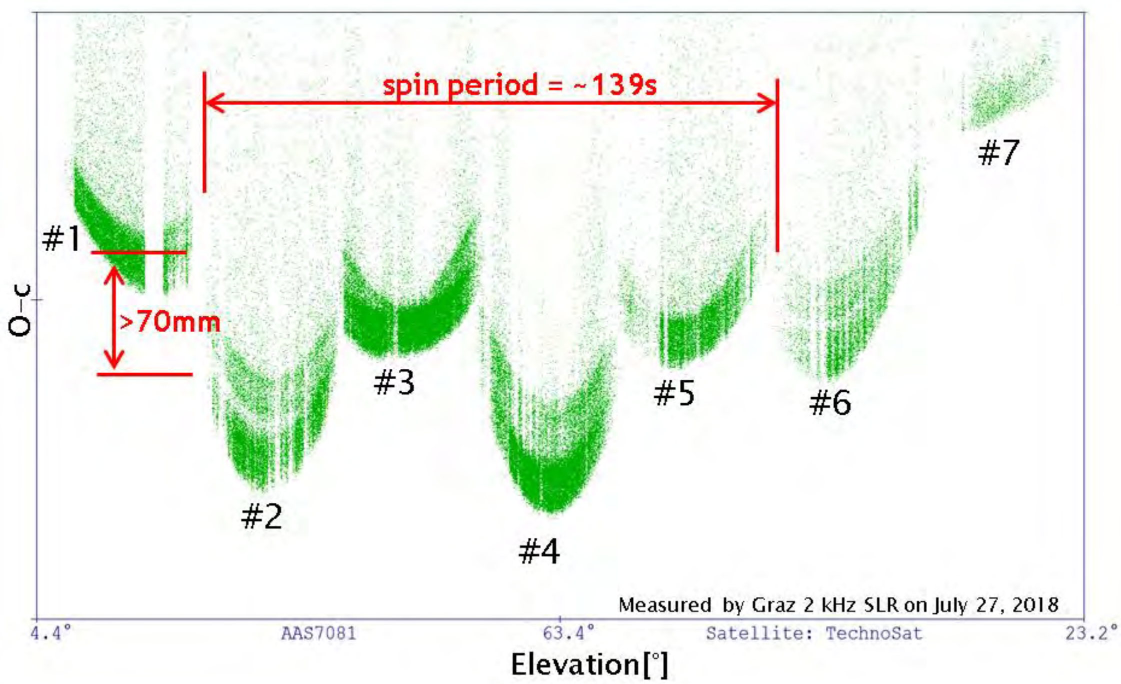

Figure 5: Seven faces of TechnoSat tracked by the 2 kHz laser ranging system in Graz while spinning with a period of approximately 139s

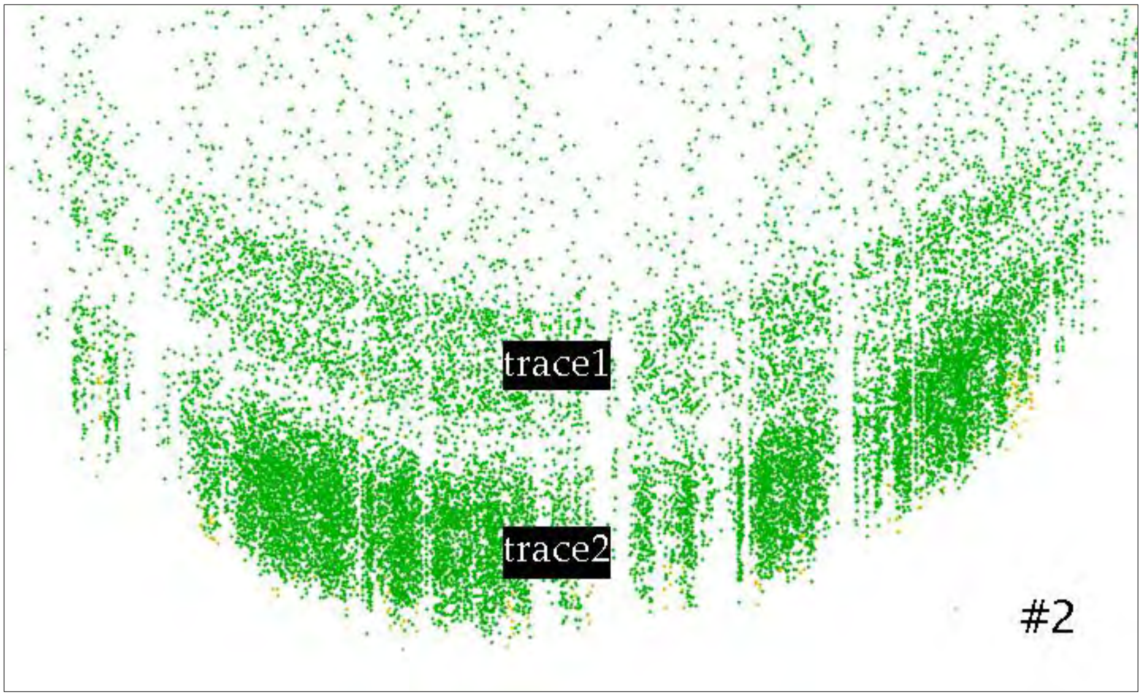

Figure 6: Two traces of laser returns, where the RMS and signal density of trace1 are less than of trace2

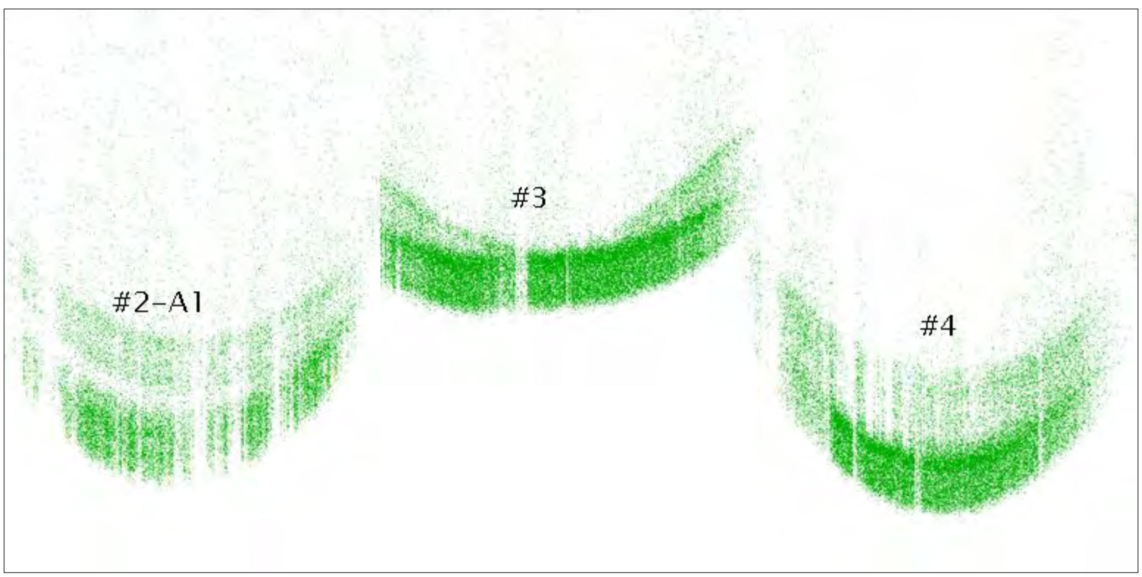

Figure 7: presents similar RMS as **Figure 6**

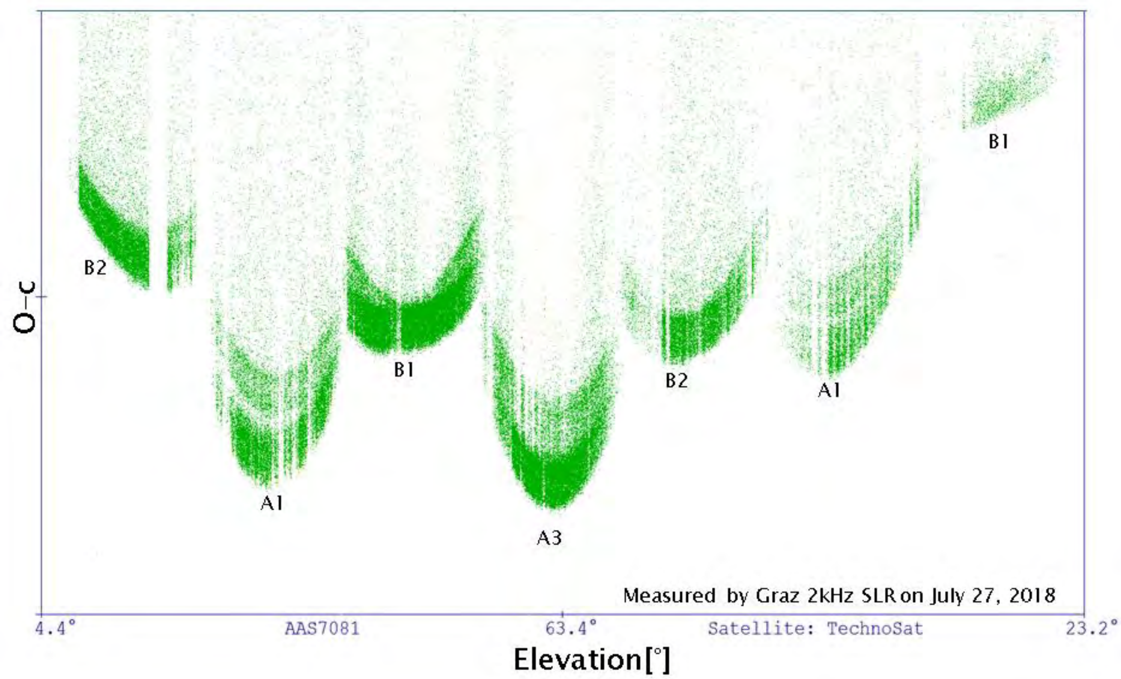

Figure 8: TechnoSat spin in the sequential order of B2 → A1 → B1 → A3→ B 2 → A1 → B1

Conclusions

The work presented in this paper shows that the commercial off-the-shelf (COTS) corner cube reflectors (CCRs) with a diameter of 10 mm applied on the TechnoSat technology demonstration mission of Technische Universität Berlin are fully adequate for satellite laser-ranging in low Earth orbit (LEO) to achieve position and orbit determination (POD). Most laser ranging stations of the International Laser Ranging Service (ILRS) were able to get returns from TechnoSat. Furthermore, adjusting the distribution of the CCRs enables the analysis of attitude and attitude variation even after the end of the satellites lifetime down to short before the re-entry into the atmosphere (Kirchner et al., 2013).

Acknowledgements

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