Comparison of ENVISAT's attitude simulation and real optical and SLR observations in order to refine the satellite attitude model

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Abstract

The Astronomic Institute of the University of Bern (AIUB) in cooperation with other three partners is involved in an ESA study dedicated to the attitude determination of large spacecraft and upper stages. Two major goals are defined. First is the long term prediction of tumbling rates (e.g. 10 years) for selected targets for the future Active Debris Removal (ADR) missions. Second goal is the attitude state determination in case of contingencies, when a short response time is required between the observations themselves and the attitude determination.
One of the project consortium partners, Hypersonic Technology Goettingen (HTG), is developing a highly modular software tool ιOTA to perform short- (days) to long-term (years) propagations of the orbit and the attitude motion of spacecraft in space. Furthermore, ιOTA's post-processing modules will generate synthetic measurements, e.g. light curves, SLR residuals and Inverse Synthetic Aperture Radar (ISAR) images that can be compared with the real measurements.
In our work we will present the first attempt to compare real measurements with synthetic measurements in order to estimate the attitude state of tumbling satellite ENVISAT from observations performed by AIUB. We will shortly discuss the ESA project and ιOTA software tool. We will present AIUB's ENVISAT attitude state determined from the SLR ranges acquired by the Zimmerwald SLR station. This state was used as the initial conditions within the ιOTA software. Consequently the attitude of satellite was predicted by using ιOTA and compared with the real SLR residuals, as well with the high frame-rate light curves acquired by the Zimmerwald 1-m telescope.

Key words: ENVISAT, SLR, light curve, attitude modeling

1. INTRODUCTION

The population of space debris increased drastically during the last years. Catastrophic collisions involving massive objects produce large number of fragments leading to significant growth of the space debris population. An effective remediation measure in order to stabilize the population in Low Earth Orbit (LEO) is therefore the removal of large, massive space debris. Secondly, satellite malfunctions might lead to loss of contact with the spacecraft and an Waccurate attitude determination can help to identify the cause. Such scenarios are referred to as contingency cases.
Currently, the Astronomic Institute of the University of Bern (AIUB) in cooperation with three partners is involved in an ESA study Debris Attitude Motion Measurements and Modeling (ESA AO/1-7803/14/D/SR) dedicated to the attitude determination of large spacecraft and upper stages. One of the project consortium partners, Hypersonic Technology Goettingen (HTG), is developing a highly modular software tool ιOTA to perform short- (days) to long-term (years) propagations of the orbit and of the attitude motion of a spacecraft, taking into account all the relevant acting forces and torques [1]. Furthermore, ιOTA's post-processing modules will generate synthetic measurements, e.g. light curves, Satellite Laser Ranging (SLR) residuals and Inverse Synthetic Aperture Radar (ISAR) images that can be compared with the real measurements. The strength of the approach is the combination of various attitude measurement types to cancel out ambiguities of the individual methods and to combine this information with a dynamic model in order to establish attitude prediction. The validation of the attitude model will be done by comparison to real observations of targets with known attitude. For more about the ιOTA tool please refer to [1].

2. ENVISAT CASE

ENVISAT (ENVIronmental SATellite) (Cospar ID 2002-009A, NORAD 27386) is a former European Space Agency (ESA) mission dedicated to the Precise Orbit Determination (PDO) and radar altimeter instrument range bias calibration. Satellite was launched on the Sun-Synchronous Orbit (SSO) with mean altitude of about 800 km which corresponds to an orbital revolution of 100 minutes. In 8th of April 2012 the Agency lost contact with the satellite. Several different attempts have been performed in order to start communication with the spacecraft but all of them failed. Finally, one month later the Agency has declared for ENVISAT the end of mission. Currently, ENVISAT is one of the largest and heaviest objects in Low Earth Orbit (LEO) region, which is the highest dense region, and can pose a big treat in case of collision or break-up event.

For completeness we add that ENVISAT is a box-shaped satellite with one solar panel attached to it. The satellite shape can be seen in Fig 1. In the left panel is plotted satellite in real colors and in the right panel is plotted 3D model used within the ıOTA tool to generate synthetic measurements.

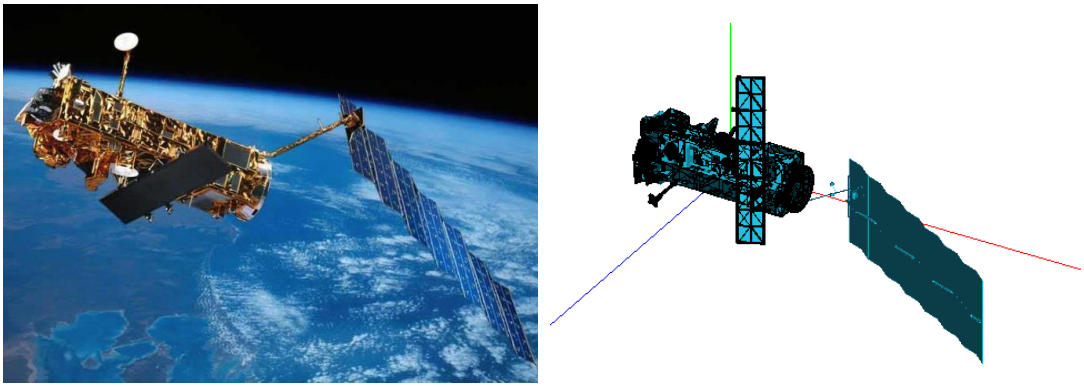


Fig. 1. ENVISAT satellite in real colors (left panel) and 3D model used in ıOTA tool to generate synthetic SLR and photometric measurements (right panel). Photo credit: ESA and HTG/ıOTA.

Shortly after the failure the International Laser Ranging Service (ILRS) reinitiated the SLR measurements to ENVISAT in order to improve its orbit. Since then the stations within the ILRS network are measuring it regular, including AIUB's Zimmerwald SLR station.

Photometric observations, as well SLR measurements revealed that ENVISAT is tumbling relatively fast, with rotational period between 2-3 minutes. Since 2013 there were several studies dedicated to the attitude determination for ENVISAT satellite. Several different techniques were applied were the most promising seems to be the analysis of the SLR measurements. The most extended and detailed work was performed by [2]. Authors in their work used SLR measurements acquired by high frequency laser. They estimated the direction of the spin axis and stated that it is stable within radial coordinate system (RCS).

Another team [3,4] used high frame rate video camera, 50 frames/s, to measure the specular reflections of the sun reflected from the ENVISAT surface. They calculated the apparent period by using the time difference between two consecutive specular flashes presumed to be from the same surface even the surface itself was unknown. By knowing the geometry of the pass, position of the observer and the position of the Sun they assumed an attitude state, spin axis direction, for which then they could calculate the inertial spin period. This way for each apparent spin period point they got an inertial spin period point. The basic assumption was that closer the assumed attitude state was to the reality then less spread was the set of the inertial spin period points. The best results were obtained for the case when the spin axis was parallel to the normal of the orbital plane and when satellite was rotating in the counter-clockwise (CCW) direction, direction opposite to the motion on the orbit. Even this approach seems to be correct their conclusion was partially condratictory to the results of [2] where authors state that the spin axis angle is slightly tilted comparing to the normal to the orbital plane.

Recently, AIUB developed a method to fit an SLR signal modulation in order to estimate ENVISAT attitude state. This method is based on the fitting the SLR residuals signal from one specific pass and to determine 6 unknown parameters which define the attitude state. First of these parameters is the inertial period. The rest 5 parameters are angles which define the exact spacecraft alignment in space and spin axis orientation in the inertial system. This method was applied to 31 ENVISAT passes acquired from Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald (hereafter Zimmerwald observatory) between July 2013 and October 2015. This analysis showed that ENVISAT spin axis is quit stable in the orbital reference frame and it is slightly tilted comparing to the

normal to the orbital plane. Due to the fact that this work is currently under preparation for a referee publication, we will not discuss here it in more detail. We will just mention that our results showed that rotation axis was rather stable in the orbital reference frame between years 2013-2015.

3. ZIMMERWALD OBSERVATIONS

One of the main instruments at AIUB's Zimmerwald observatory is 1-meter Zimmerwald Laser and Astrometry Telescope (ZIMLAT). ZIMLAT is used either for SLR to cooperative targets, targets equipped with SLR retroreflectors (RR/RRA), or for optical observations (astrometric positions and magnitudes) of artificial and natural objects in near-Earth space. During daytime the system operates in SLR mode only. During the night time the available observation time is shared between SLR and CCD/sCMOS [5,6] based on target priorities. The switching between the modes is done under computer control and needs less than half a minute. ZIMLAT telescope is shown in Fig. 2.

From CCD and CMOS cameras the extracted measurements are in form of the total intensity measured from pixels which contain the signal from the object. If this data are function of time we refer to such series as the light curve. The SLR measurements are quite different. From these one can obtain the residual variations which are caused by the rotation of the object around its center of mass. Then the relative movement of the Retro Reflector Array (RRA) around the center of mass toward the direction of laser beam can be measured from ground. These residuals can be in form of time, which is the light travel delay or in form of range residuals, difference between predicted and measured range to the RRA.

Fig. 2. ZIMLAT telescope during the day when only SLR observations are used (left panel) and a closer look at ZIMLAT telescope during the night when simultaneous SLR and CMOS observations are used (right panel). Photo credit: Silha and Bodenmann, 2016.

During a special observation campaign, which took place in the end of August 2016, simultaneous SLR and sCMOS observations have been performed. These observations took place during nights 2016-08-22 (1 pass), 2016-08-25 (2 passes) and 2016-08-27 (1 pass). The primary target was ENVISAT satellite. The geometries of all four ENVISAT passes in topocentric reference frame with the Zimmerwald observatory in the middle are plotted in Fig. 3. In all panels the East is facing up and the North is facing left. For all passes ENVISAT was flying from the South direction toward the North.

Summary for each pass is listed in Tab. 1. Listed are from left column AIUB's internal pass ID, date of observation, time of beginning of observations, duration of observations, direction in horizontal topocentric system, and maximum elevation of the pass. Except the pass EV25AU16T, all passes were in the West direction from the observatory.

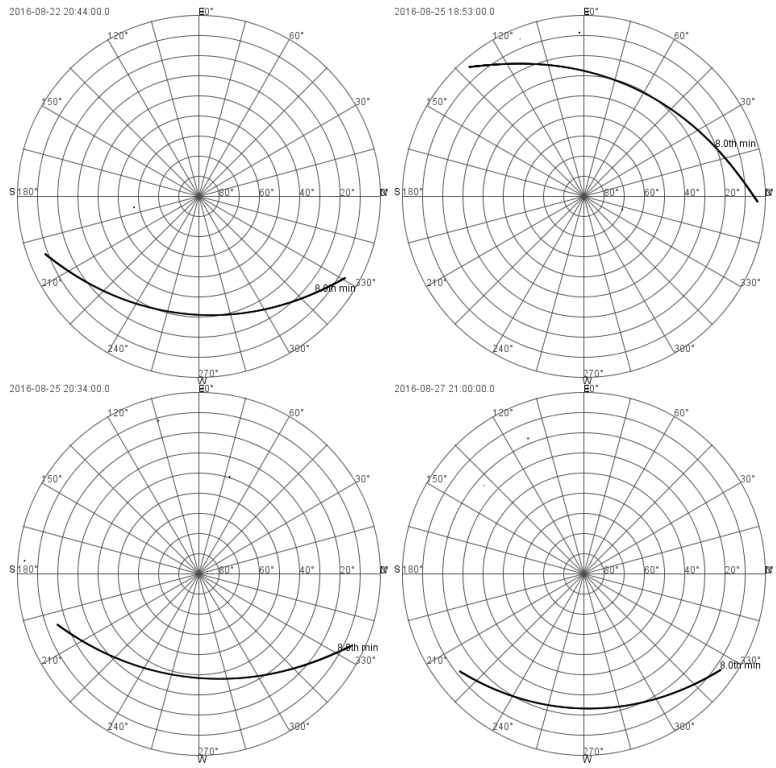


Fig. 3. Geometry of four ENVISAT passes for which simultaneous observations, SLR and CMOS, have been acquired by ZIMLAT system. Plotted is local horizontal system where the East is facing up, and the North is facing right.

Tab. 1. Summary of the ENVISAT passes for which simultaneous SLR and CMOS observation attempts have been performed.

Pass ID	Pass date	Start time [UTC]	Duration [min]	Direction	Object maximum elevation [deg]	Sun elevation [deg]
EV22AU16U	2016-08-22	20:45	10	West	32	-21
EV25AU16T	2016-08-25	18:57	8	East	31	-07
EV25AU16U	2016-08-25	20:33	10	West	39	-21
EV27AU16V	2016-08-27	21:01	9	West	23	-25

During the first night 2016-08-22 ENVISAT was observed during pass EV22AU16U simultaneously with SLR and CMOS camera. During these observations obtained were SLR residuals, which are differences between the planned and measured light travel duration (plotted as “Light travel delay”), as a function of time. With the CMOS camera obtained has been intensity variation as a function of time which was further used to construct the light curve. For intensity measurements used was exposure time of 0.05 s, Notch filter to filter the SLR laser signal and frame-rate 9 frames/s. Both data sets can be seen in Fig. 4. In the lower panel plotted is the light curve and in the upper panel plotted are measured raw SLR residuals. The starting time shown on both panels is the time when the CMOS acquisition started.

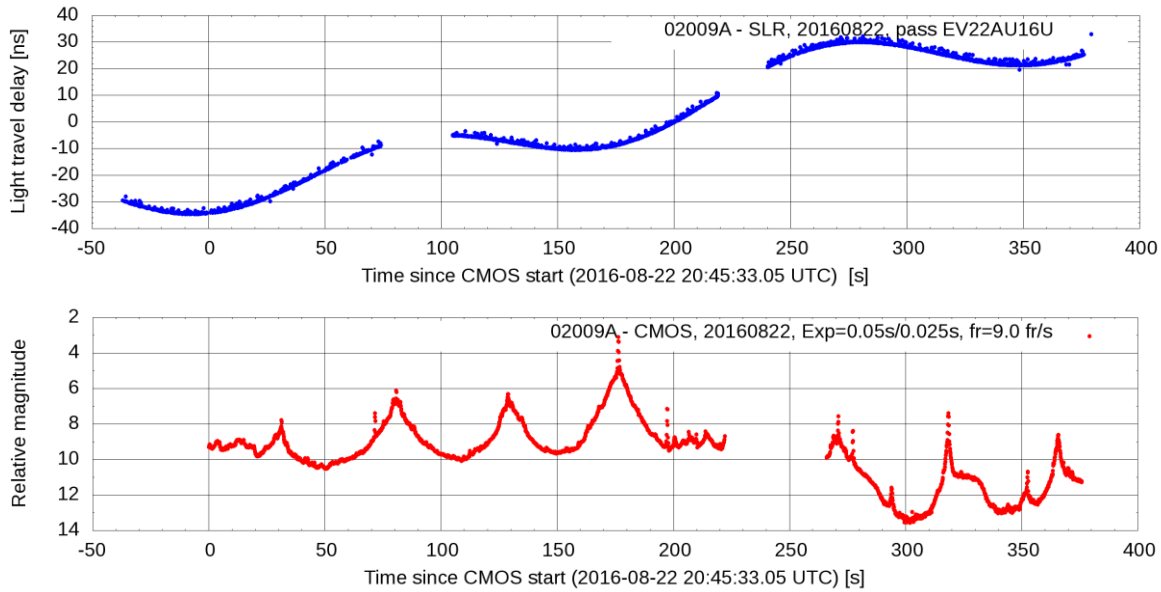


Fig. 4. SLR residuals (upper panel) and CMOS light curve (lower panel) acquired simultaneously by ZIMLAT system at 2016-08-22.

During the second night 2016-08-25 there have been two passes of ENVISAT when we tried to acquire CMOS and SLR simultaneously. The first early pass was EV25AU16T at 18:57 UTC. During this pass we were not able to get the SLR return signal. However, we could acquire intensity measurements by using CMOS camera, exposure time of 0.005 s, Notch filter and frame-rate of 5 frames/s. The obtained light curve is plotted in Fig. 5.

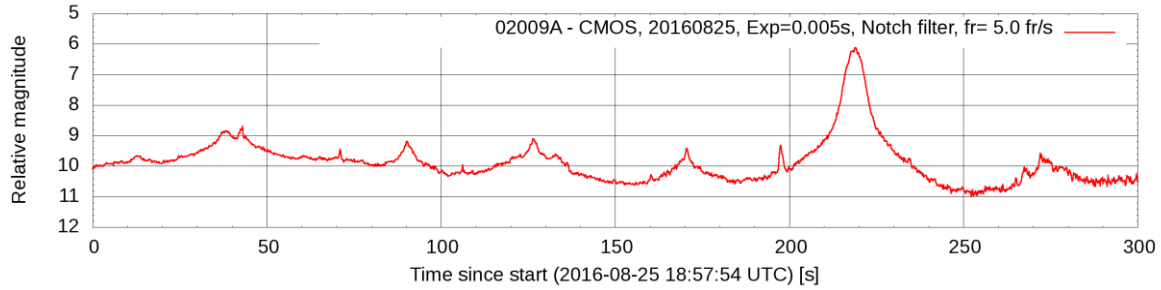
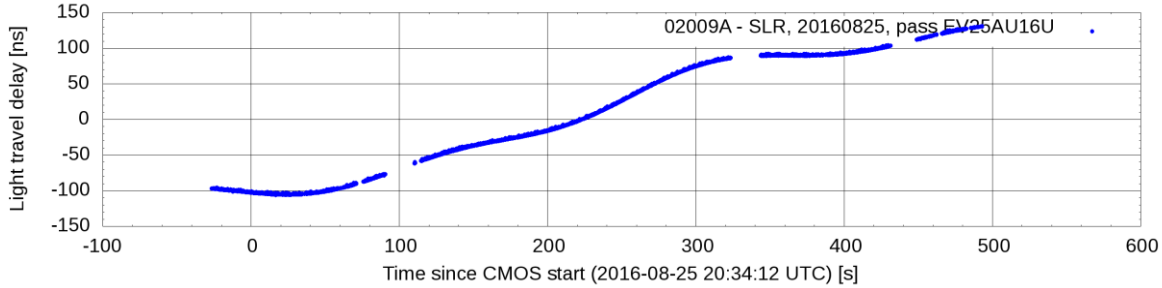


Fig. 5. CMOS light curve acquired simultaneously with SLR by ZIMLAT system at 2016-08-25, starting at 18:57 UTC.

Simultaneous observations have been successful for the later second pass of that night EV25AU16U at 20:34 UTC. During this pass we obtained SLR residuals, as well photometric measurements. For the photometry measurements we used exposure time of 0.005 s, Notch filter and frame-rate of 3.8 frames/s. The obtained light curve and raw SLR residuals are plotted in Fig. 6.



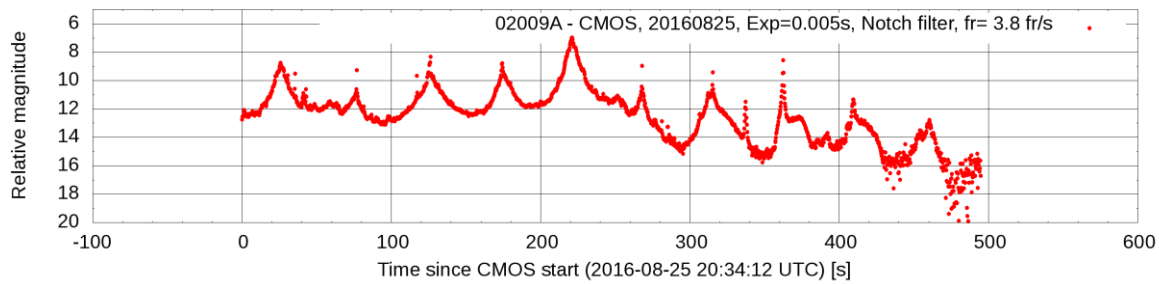


Fig.6. SLR residuals (upper panel) and CMOS light curve (lower panel) acquired simultaneously by ZIMLAT system at 2016-08-25, starting at 20:34 UTC.

For the last pass EV27AU16V simultaneous observations have been successful and we obtained SLR residuals and also the intensity measurements. For the photometry measurements we used exposure time of 0.05 s, Notch filter and frame-rate of 7.5 frames/s. The obtained light curve and raw SLR residuals are plotted in Fig. 7.

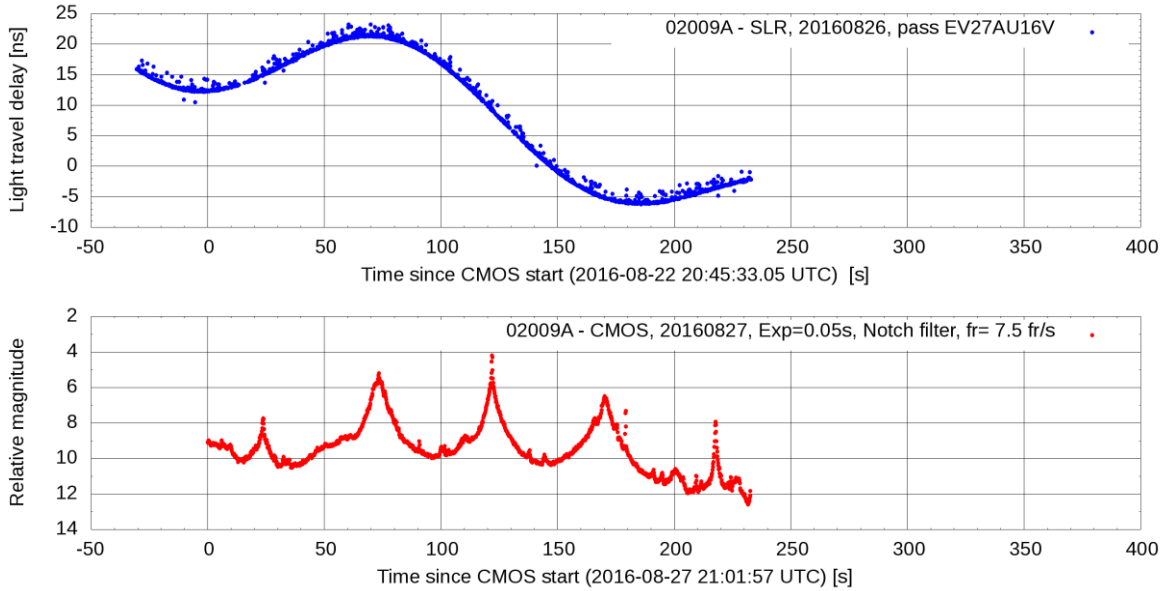


Fig. 7. SLR residuals (upper panel) and CMOS light curve (lower panel) acquired simultaneously by ZIMLAT system at 2016-08-27.

4. COMPARISON OF REAL AND SYNTHETIC MEASUREMENTS

Next step was to compare the ENVISAT's real and synthetic measurements. To run the ιOTA simulation we had to provide the inputs to the tool. The osculating elements of the satellite have been calculated by using Two Line Elements (TLE) and SGP4 propagation model [7]. The inertial period of the spacecraft has been extracted by using AIUB's method of SLR signal pre-processing. We determined that ENVISAT had apparent spin period equals to 179.2 s while the inertial spin period, assuming rotation axis to be aligned with normal to the orbital plane, was 215.4 s assuming CCW rotation. This corresponds to angular velocity of 1.671 deg/s. Comparing these values to last years [4,3,2], ENVISAT is continuing decelerating its rotation following the behavior from previous years. During the pre-processing we also de-trended the signal by removing the along-track trend caused by the un-accurate orbit predictions. The necessary information such as the RRA position, as well the last known position of center of mass, has been retrieved from [8].

It was also necessary to make some assumptions before we launched the ιOTA simulations. Assumptions were that the spacecraft angular velocity is 1.671 deg/s and the spacecraft is rotating around the principal axis of inertia, which is aligned with the direction of the ENVISAT RRA pointing. Additionally, we assumed that the satellite rotation

axis is relatively stable in the orbital reference frame and for the investigated pass we could assume it is even quasi-stable in the inertial reference frame.
Last parameters which were missing were the initial alignment of the spacecraft and its spin axis in space by using the system of three different angles defined in Local-Vertical/Local-Horizontal (LVLH) reference frame, namely α, β and γ. These angles had to be determined with ιOTA by using iterative procedure.
We used ιOTA tool to generate SLR residuals and then we compared them to the real residuals. During simulations all the forces have been deactivated except the gravitational torque. Once we got the best match we found the desired system of angles α, β and γ for given pass. When we applied the iterative method to the first pass EV22AU16U, we assumed two different spin rotation directions, clockwise (CW) and counter-clockwise (CCW) comparing to the orbital motion. For the CCW solution we got the best match for combination α = 230°, β = 345° and γ = 110°. For the CW solution we got the best match for combination α = 123°, β = 214° and γ = 295°.
Comparison of real and synthetic SLR residuals for CCW and CW solutions can be seen in Fig. 8. The synthetic light curve generated by ιOTA for given pass and CCW and CW solutions can be seen in Fig. 9. In the upper panel is plotted the real light curve, in the middle panel the synthetic light curve for CCW solution and in the lower panel is the light curve for CW solution. For better visibility all three light curves are plotted in the relative intensity units and not in the magnitudes. During the light curve generation by ιOTA we assumed only diffuse reflection of the sun light from the satellite surface toward observer.

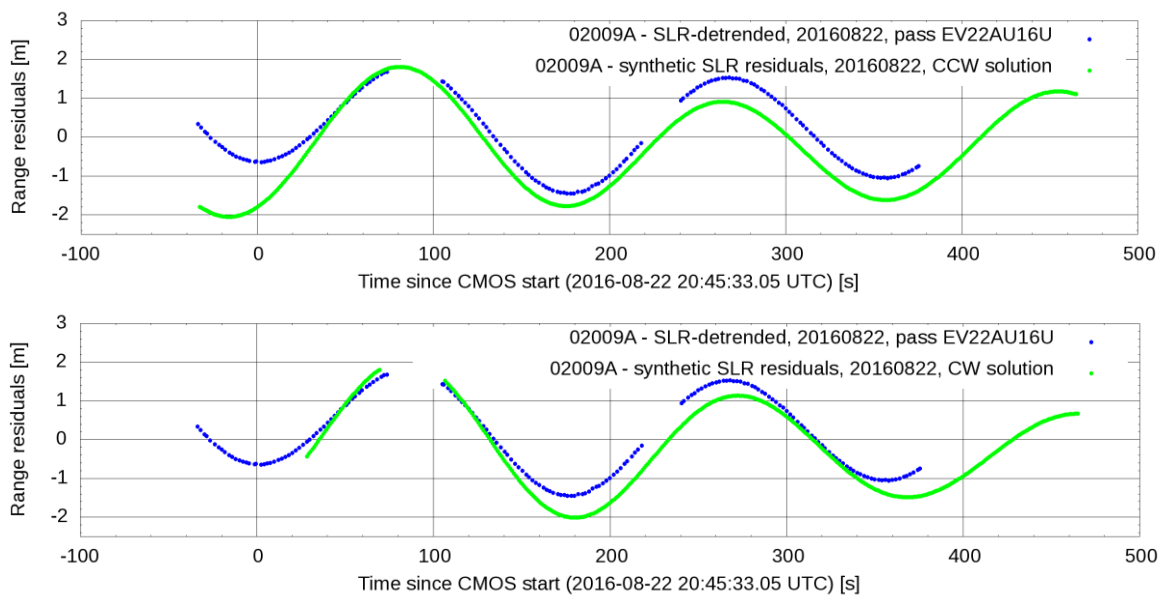


Fig. 8. Comparison of real SLR residuals (blue, de-trended signal) and synthetic SLR residuals (green) for the pass EV22AU16U. In upper panel are plotted results for CCW solution and in the lower panel for CW solution.

We performed similar analysis as for the first pass also for the third pass EV25AU16U and we assumed again two different spin rotation directions, CW and CCW. For the CCW solution we got the best match for combination α = 60°, β = 340° and γ = 20°. For the CW solution we got the best match for combination α = 55°, β = 340° and γ = 20°.
Comparison of real and synthetic SLR residuals for CCW and CW solutions for EV25AU16U can be seen in Fig. 10. The synthetic light curve generated by ιOTA for given pass and CCW and CW solutions can be seen in Fig. 11. In the upper panel is plotted the real light curve, in the middle panel the synthetic light curve for CCW solution and in the lower panel is the light curve for CW solution. For better visibility all three light curves are plotted in the relative intensity units and not in the magnitudes.

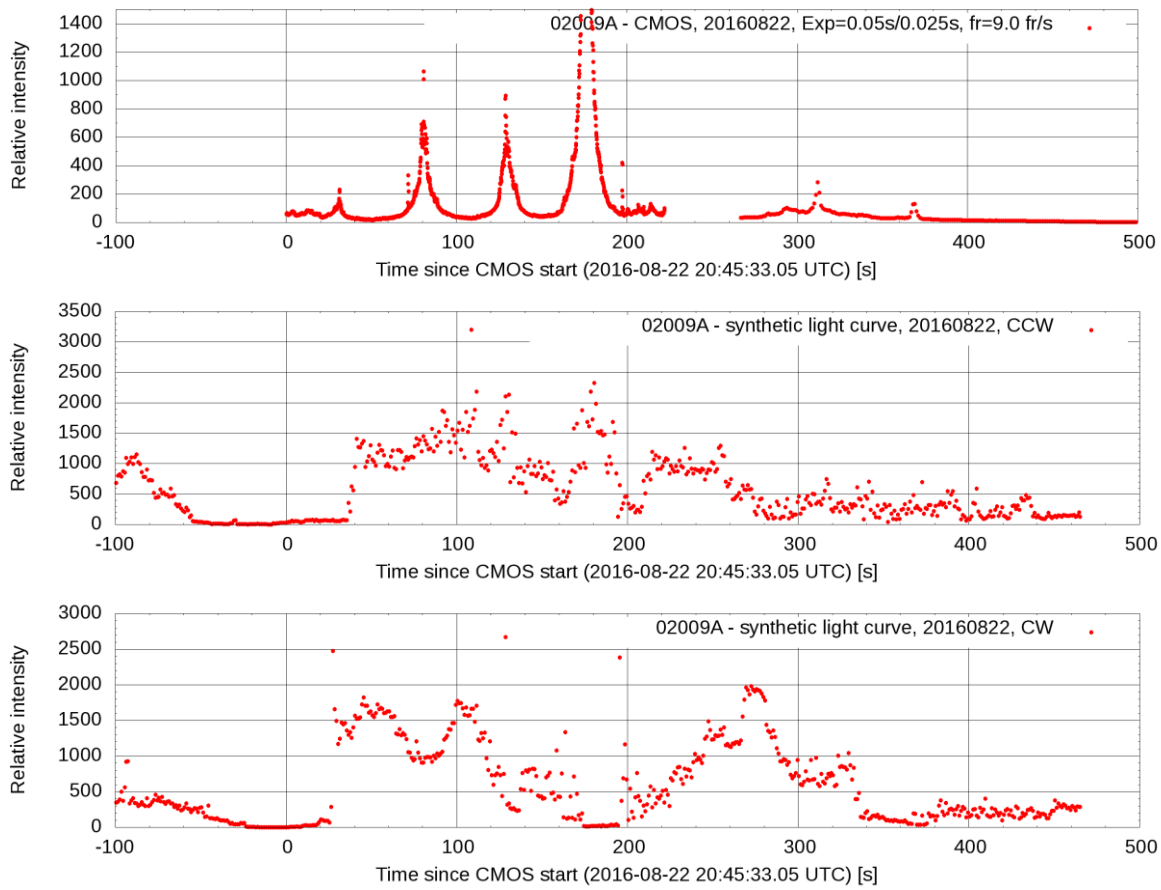


Fig. 9. Comparison of real light curve (upper panel) and synthetic light curves, CCW solution (middle panel) and CW solution (lower panel), for the pass EV22AU16U.

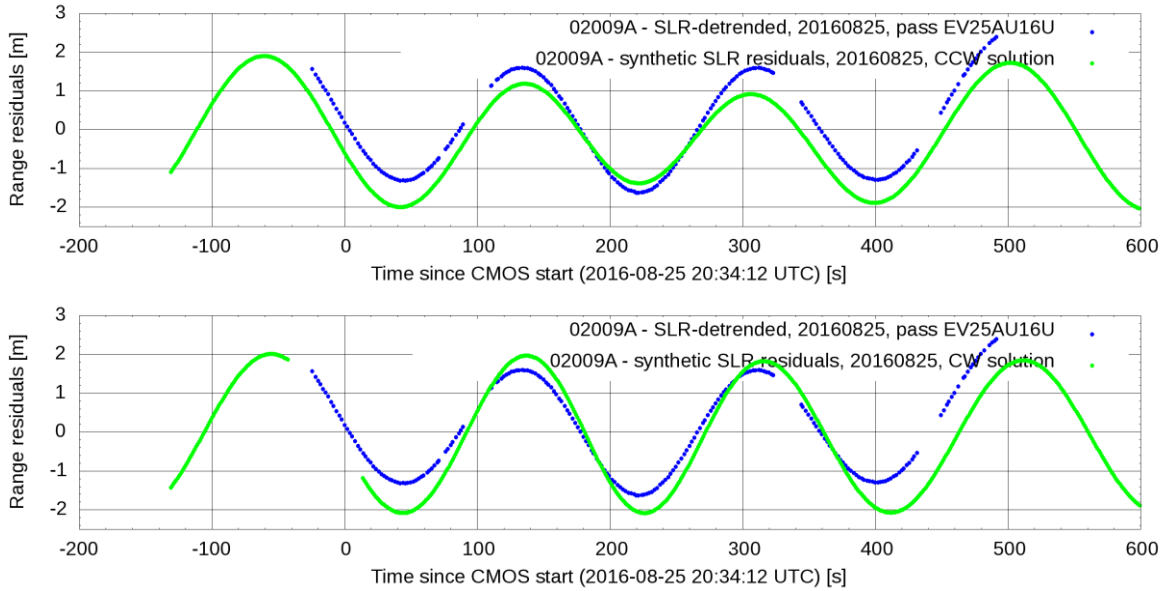


Fig. 10. Comparison of real SLR residuals (blue, de-trended signal) and synthetic SLR residuals (green) for the pass EV25AU16U. In upper panel are plotted results for CCW solution and in the lower panel for CW solution.

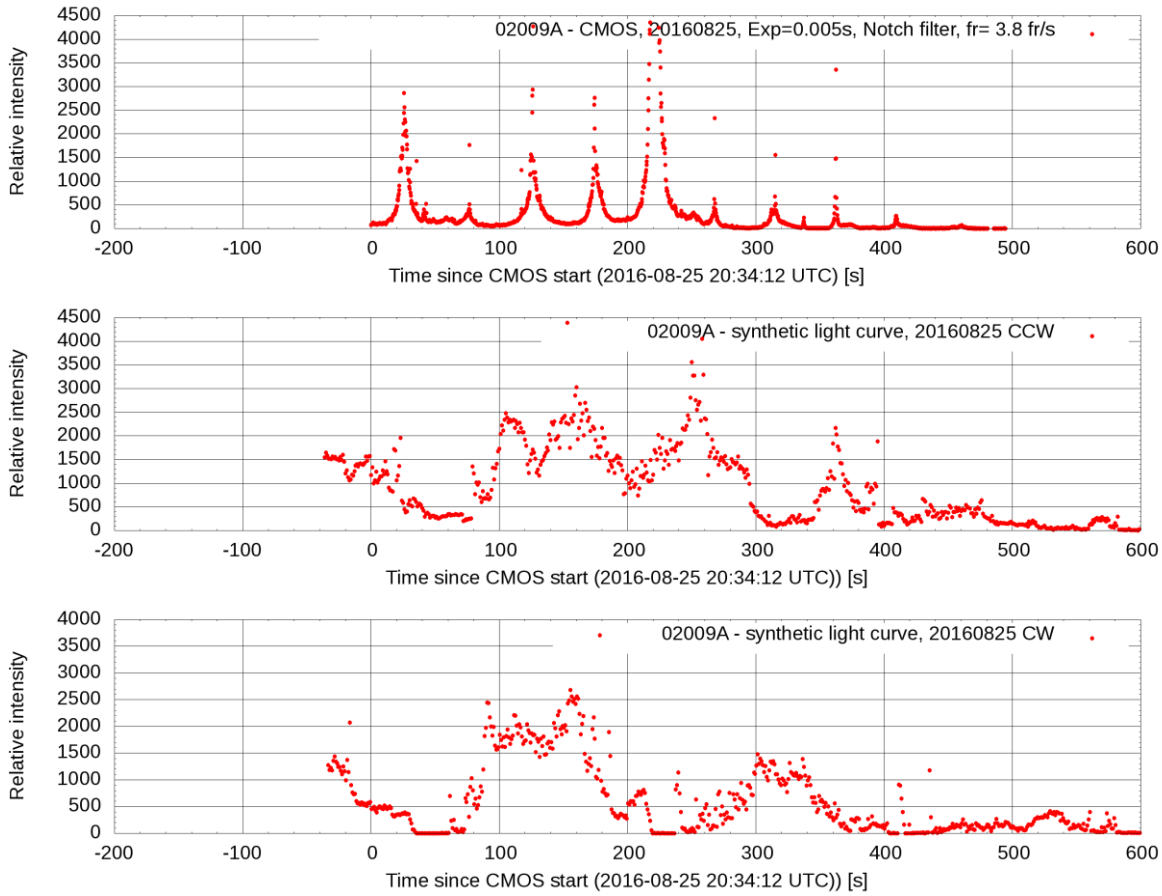


Fig. 11. Comparison of real light curve (upper panel) and synthetic light curves, CCW solution (middle panel) and CW solution (lower panel), for the pass EV25AU16U.

5. DISCUSION

The comparison between SLR residuals for CCW and CW solutions is rather un-conclusive. It is obvious that we have two good solutions for each of two analyzed passes. When we look closer to the SLR residuals for both passes we can notice that the position of extrema (minima and maxima) for real residuals are slightly shifted from peak to peak for the CW case, while for the CCW they stay aligned. This indicates that the apparent period for CCW case and real SLR residuals are in better agreement than for CW case. Additionally, by looking at the synthetic light curves, one can see that the peaks are shifted for the CW case comparing to the real light curve peaks. This is not the case for the light curves of CCW case which showed quite good match with the real light curve peaks, specially for pass EV22AU16U. Even we can not conclude with absolute certainty that the CCW case is the right one, according to our first analysis by using ıOTA tool this seems to be the case.

For completeness we mention again that in reality the satellite is spinning in CCW direction and its spin axis is slightly tilted comparing to the normal to the orbital pane. If this is the case it also means that RRA is visible only on one side of the orbit. If the observer's position during the pass is in the "blind" spot, there won't be any returns for SLR measurements. This is actually what we had observed during the night 2016-08-25 during first pass EV25AU16UT when the satellite was passing on the East side from the observatory.

6. SUMMARY AND CONCLUSIONS

In our work we presented first results of synthetic data generation by using the ıOTA tool, a tool to predict an attitude state of a non-active space objects, such as defunct satellites or upper stages. One of the tool's functionalities is the synthetic data generation for light curves, SLR residuals and radar ISAR images. This tool is currently still under development within an ESA study. Study contains several consortia members, where the

Hypersonic Technology Goettingen (HTG) is responsible for the tool development and AIUB is responsible for the tool functionalities testing.

Herein we presented an unique set of data acquired for ENVISAT satellite, a tumbling defunct LEO satellite, during three different observation nights, namely 2016-08-22, 2016-08-25 and 2016-08-27. During these nights ENVISAT was observed with AIUB's ZIMLAT telescope, the main optical instrument at the AIUB's Zimmerwald observatory. Thanks to the simultaneous mode when the SLR and light curve data are acquired simultaneously we acquired two types of data at the same moment.

We generated synthetic data for the ENVISAT passes EV22AU16U and EV25AU16U by using satellite's TLE and SGP4 model. Assumed was a spin axis orientation aligned with the principal axis of inertia. We extracted from the acquired SLR data ENVISAT's inertial period. This was done by using the AIUB's SLR pre-processing methods. In our simulations we assumed two different rotation directions comparing to the orbital motion, the clockwise CW and counter-clockwise CCW rotation. By using all the inputs we iteratively generated synthetic SLR measurements with ιOTA tool and we compared these measurements to the real SLR residuals we acquired during the nights 2016-08-22 and 2016-08-25 further pre-processed by AIUB's methods.

Finally, we obtained two different solutions for the initial attitude state a priori to the observations, one for CCW case and one for CW case. By comparing these solutions it seems that the results for CCW case are in much better agreement with real measurements than for CW case. The apparent spin period for synthetic SLR residuals seem to be in a very good match with the real observed apparent period and the synthetic light curve for CCW case shows peaks at similar positions in time that the real light curve.

ιOTA tool is currently still under development. Our first look on its synthetic data generation, when we used a very unique set of data of simultaneously acquired SLR and photometric measurements, showed a strong promise for our approach of combining different measurement techniques. This method will get even stronger once the synthetic measurements modules are optimized and included will be also Inverse Synthetic Aperture Radar imaging. Successful development and full testing of the method are our next primary aims.

7. REFERENCES

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