Understanding the Oscillating Pattern in the Rotational Period Evolution of several GLONASS Satellites

Abdul Rachman[1,2]
Alessandro Vananti[1], Thomas Schildknecht[1]
[1]*Astronomical Institute University of Bern*
[2]*National Institute of Aeronautics and Space of Indonesia*

ABSTRACT

Previous studies have shown an oscillating pattern in the rotational period evolution of several decommissioned payloads in geosynchronous and medium Earth orbit. In the AIUB light curve database, 26 out of 70 GLONASS satellites show this pattern clearly. Most of them are GLONASS Block IIv satellites which have been considered debris for more than a decade. By inspecting a long evolution of the rotational period, a roughly annual pattern consisting of a series of peaks with triangular shape is revealed. The current study tries to understand this pattern by simulating the rotation rate of a satellite under different conditions. We have obtained preliminary results using a simple satellite model with cylinder shape for the bus and two rectangular plates as wings for the solar panels. Several simulations were run with various initial orientations of the satellites and of their rotation axis. We found that the roughly annual oscillating pattern is achievable only if the two solar panels are oriented differently. This result seems true whatever the initial orientation of the satellites and of the rotation axis are. There is evidence that the periodic behavior is caused by solar radiation pressure on the solar panel of the satellites by adding or subtracting angular momentum to the system periodically. For this type of satellite geometry, the asymmetry of the solar panels somehow plays a key role in understanding this behavior.

1. INTRODUCTION

Space debris continues to be a threat for the sustainability of future space activities. A remediation measure proposed since many years is to perform active debris removals (ADR). This can be done by nudging the large debris into a safer orbit or forcing it to reenter the atmosphere. To be successful, sufficient knowledge about the attitude (orientation) of the debris is mandatory. On the contrary with active satellites where their attitude can be acquired from the attitude determination and control system (ADCS), attitude of debris can only be obtained from observations. A long careful observation may reveal how the apparent spin rates of a debris will evolve with time.

Previous studies have shown that some inactive payloads exhibit an oscillating pattern in their spin period evolutions. Reference [1] studied several inactive satellites in geosynchronous orbit whose spin period vary cyclically especially in the case of Telstar-401 as shown in Fig. 1. Some inactive satellites in medium Earth orbit also display similar pattern [2, 3]. In fact, 26 out of 70 inactive GLONASS satellites in a light curve database which is maintained by the Astronomical Institute of University of Bern (AIUB) show this pattern clearly. All the cases show roughly an annual oscillation period but not all of them show consistent series of peaks with triangular shape similar to that in the 26 cases from AIUB database. The period evolution for these 26 satellites shows consistently linear segments with abrupt changes at the peaks which contribute to the triangular shape. The regular pattern in the evolutions allows estimating the period at a specific time once the associated segment is constructed using available data. Beside the oscillating pattern, secular trends also exist.

Most of the 26 GLONASS satellites which were mentioned before belong to the GLONASS Block IIv (or IIc) subtype. Together with Block I, IIa, and IIb they made up the first generation GLONASS navigation satellites (originally termed Uragan) which were operating from 1982 until 2008 [4]. They have a mass of roughly 1.4 ton (including propellant) and are made up of a cylindrical structure with a length of about 3.3 m and two solar panels with the total surface area of about 24 m^2 (see Fig. 2).

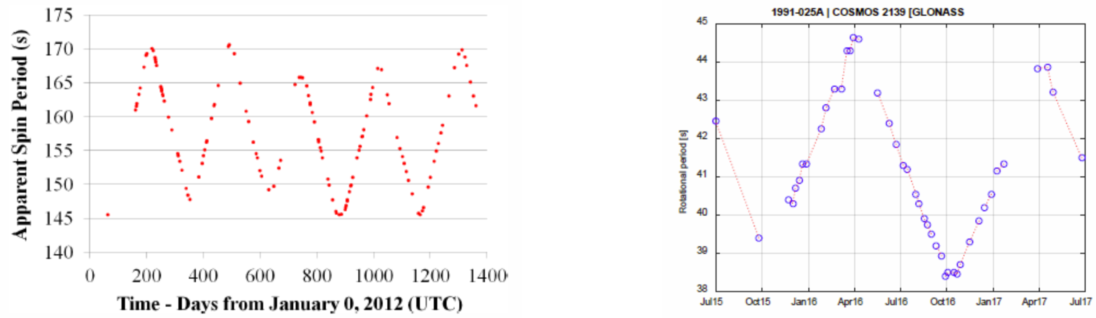

Fig. 1. Spin period evolution of Telstar-401 (left image) as taken from [1] and COSMOS 2139 (right image) as taken from [2].

Fig. 2. Illustration of one of the first generation of GLONASS satellites (taken from [4]).

This paper describes how the aforementioned rotation pattern of some of the inactive GLONASS satellites could be explained. This is done by simulating the rotation rate of a sample satellite under different conditions.

2. METHOD

The idea of the simulation is to be able to roughly replicate the pattern of spin rate evolution from one of the 26 GLONASS satellites that we obtain from the AIUB light curve database [5]. An iterative process was performed until we obtained a (roughly) similar pattern. We picked (rather arbitrarily) one satellite from the set of 26 satellites as the reference. The satellite is COSMOS 2140 (Cospar ID 1991-025B) which was launched on April 4, 1991 and retired on January 6, 1992. Apparent spin periods from the database are available from July 3, 2015. The data was obtained with the ZIMLAT telescope and a CCD camera with no color filter at AIUB's Observatory in Zimmerwald. Fig. 3 shows the spin period evolutions of the satellite. It is clear from the figure that beside the oscillating pattern, a secular decreasing trend also exists.

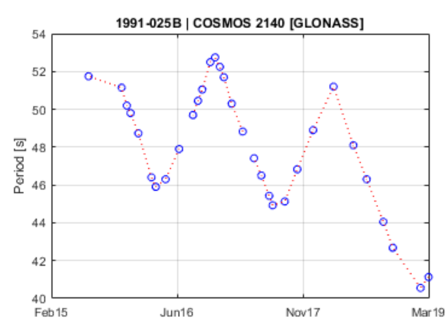

Fig. 3. Spin period evolution of COSMOS 2140 as obtained from AIUB light curve database.

In this study, several assumptions are necessary to be taken. First of all, we assumed that the object is a rigid body so that the distance between any two given points on it remains constant in time. We also assumed that there is no effects from attitude control system activation, tank sloshing, and specific impact or leakage events. Since simulations covering a period of several years were necessary, first simulations only considered solar radiation pressure (SRP) torque as the environmental torques to speed up the computation. This approach is reasonable since typically solar-pressure torques are the biggest environmental torques at medium orbit [6] and the satellite has relatively large solar panels.

Based on available data from [4] and [7], we created a simple model of the satellite structure. The model has cylinder shape for the bus and two rectangular plates as wings for the solar panels. Table 1 shows the basic physical properties of the model. Next, we created a 3D model using Blender, which is a free and open-source 3D computer graphics toolset. We assumed that the axis of solar panels run exactly through the center of the bus across the long axis as seen in Fig. 4. The 3D model shown in the figure is the basic model which means that both the solar panels are aligned to each other and they are orthogonal to the long axis of the body. The output of Blender is the surface geometry file (in `obj` format for this study) which was used in the subsequent process.

Table 1. Basic physical properties of the satellite model used in this study.

Mass	1415 kg
Bus length	4 m
Bus diameter	1.7 m
Solar panel length (one side)	4 m
Solar panel width (one side)	3 m
Solar panel depth	5 cm

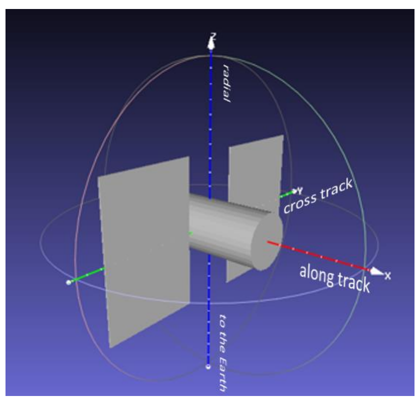

Fig. 4. The basic 3D model of COSMOS 2140 used in this study and its default orientation w.r.t the orbital frame.

Simulating of the rotation rate under different conditions was performed using iOTA (in Orbit Tumbling Analysis) [8]. It is a software to perform short- (days), medium- (months) and long-term (years) propagations of the orbit and attitude motion (six degrees-of-freedom) of spacecraft in Earth orbit. For our purpose, iOTA read the resulting surface geometry file (as mentioned in the previous paragraph) together with other input parameters like mass, center of mass, moments of inertia, radiation absorption factor (the difference to 1 is reflection), and diffuse reflection factor (the difference to 1 is specular reflection) of the satellite model. In this study, the center of mass and moments of inertia were calculated using another free and open-source software called Meshlab. We used the default value of absorption factor and diffuse reflection factor given by iOTA which are 0.7 and 0.6, respectively in the first iterations. This means 30% of the incident radiation is reflected and 40% of this reflection is reflected specularly.

We chose three parameters to define the conditions for the simulation. The first is the orientation of the solar panels with respect to the body frame; the second is the initial orientation of the satellite with respect to the orbital frame, and the third is the initial angular velocity vector of the rotation. Simulation time was varying from 3 minutes to 3 years. The shorter simulation time was set up to see the rotational dynamics in more detail. After getting the results from the first iterations (which only use SRP torque) we did the second iterations using also other relevant environmental forces available which are third body forces, Eddy current damping, and gravitational torque. Here we adjusted the orientation of the solar panels, the initial angular velocity (closer to the one from observations), the absorption factor and the diffuse reflection factor as necessary until we roughly replicated the pattern of the spin period evolution of COSMOS 2041.

In iOTA, the initial attitude state is specified using roll, pitch and yaw angles and the corresponding roll, pitch and yaw rates, either relative to the inertial frame or relative to the orbital frame. The latter is shown in Fig. 5. The rotations are performed in the following order w.r.t. the (non-rotated) reference axes: yaw – pitch – roll.

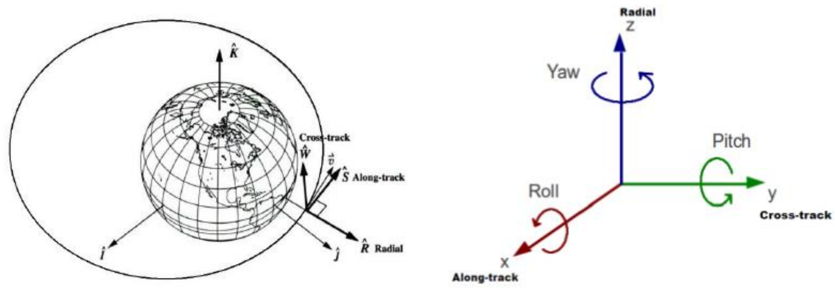

Fig. 5. Configuring initial state in iOTA [9].

Two-line element orbital data for the simulation which is needed by iOTA was obtained from the Space-Track website (www.space-track.org). State vectors were extracted from this data to obtain the positions and velocities of the satellite at the beginning of the simulations. COSMOS 2140 is moving in a circular medium Earth orbit with a radius around 19180 km from Earth's center and an inclination of 65.48°.

3. RESULTS AND DISCUSSION

After using different conditions we found that the orientation of solar panels w.r.t the body frame and the initial orientation of the satellite w.r.t the orbital frame as shown in Fig. 5 successfully produced an oscillating pattern with a period around one year. To be specific, the solar panels are orthogonal to each other and the group (both of the solar panels) is symmetric w.r.t the body (bus). Also we used initial angles of [0, 90, 0] which means that the model was rotated only around its pitch axis (y-axis in Fig. 5) by 90° and initial angular velocity of (0, 0, 6) which means that angular velocities were only applied around the yaw axis (z-axis in Fig. 5) by 6°/s. As a comparison to the default orientation before adding any rotation to the model, see Fig. 4. Fig. 6 shows the result of the simulation. Only SRP was used in this simulation.

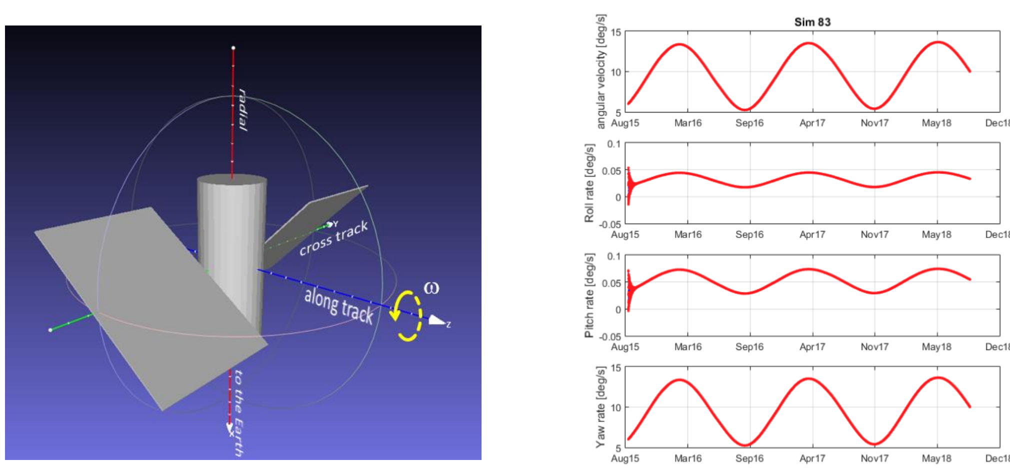

Fig. 5. The condition of solar panel solar panels w.r.t the body frame and the initial orientation of the satellite w.r.t the orbital frame which successfully produced an oscillating pattern with a period around one year (left image) and the result of the simulation (right image). On the left image, ω is the angular velocity.

By varying the angle between the two solar panels (or the canting angle) we found that this angle determined the amplitude of the oscillating pattern (Fig. 6). From this finding, we conclude that a roughly annual oscillating pattern is achievable only if the two solar panels oriented differently. We found that this conclusion seems true whatever the initial orientation of the satellites and of the rotation axis are as can be seen in Fig. 7.

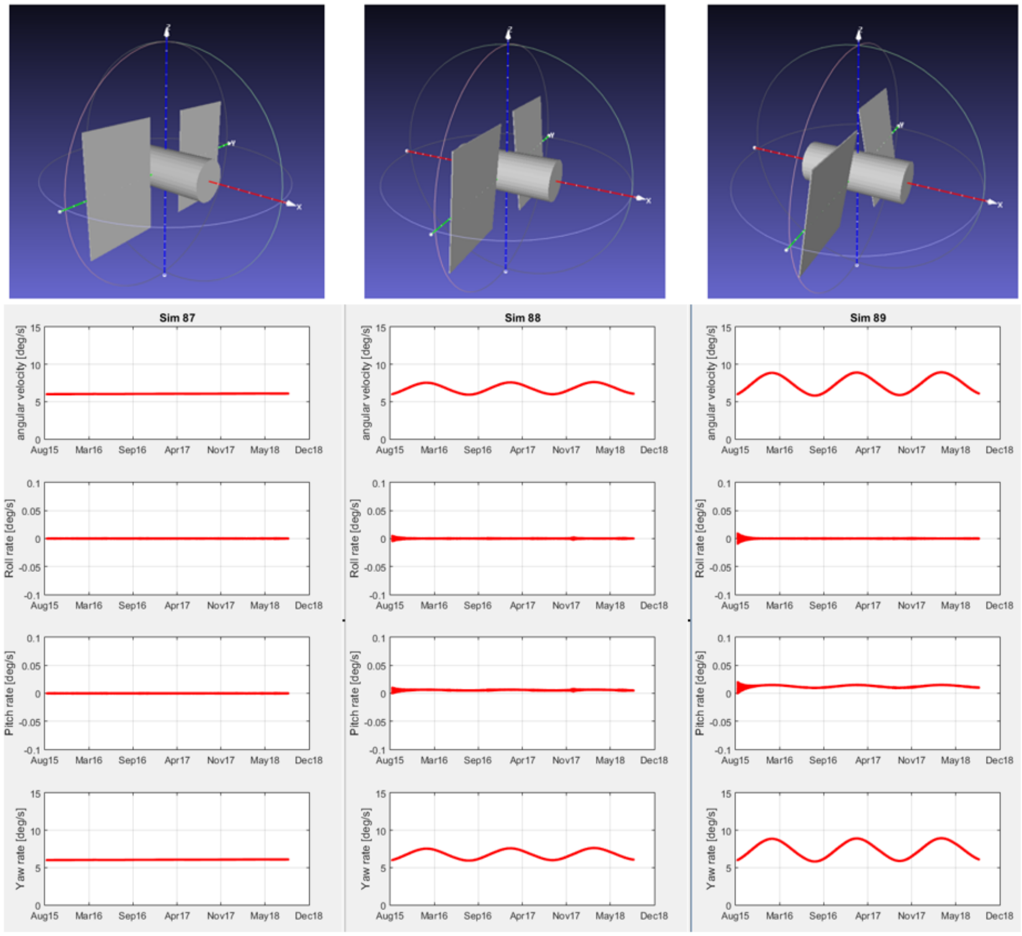

Fig. 6. The relation between canting angles and the amplitude of the oscillating spin rate evolution pattern: canting angle of 0° (left image), 10° (center image), and 20° (right image). All simulations were performed with only SRP, initial angle of [0, 90, 0] and initial angular velocity of (0, 0, 6).

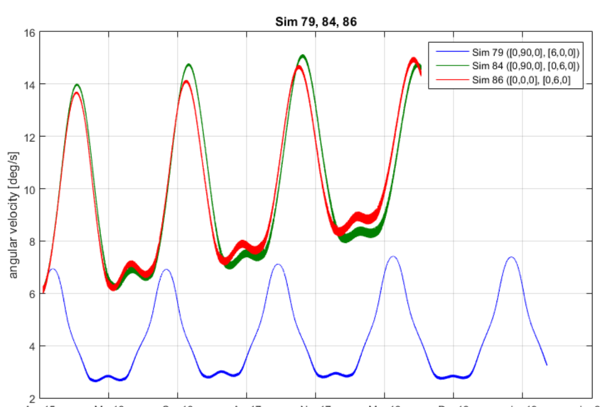

Fig. 7. Oscillating patterns of three simulations with different initial orientation of the satellites and of the rotation axes.

Fig. 8 shows that the only environmental force which is acting on the satellite that may be responsible for the oscillating pattern is the solar radiation pressure. We can see from the figure how the solar radiation pressure torque is amplified as the canting angle increases which is consistent with Fig. 6. Reference [10] also found the same behavior when analyzing the zig-zag pattern in ENVISAT long-term angular velocity simulation. They concluded that the periodic behavior is caused by solar radiation pressure on the solar array of the satellite. A plausible explanation is that when the solar array is illuminated in spin direction, the SRP torque increases the spin rate, adding angular momentum. Periodically, the orientation of the solar array w.r.t. the incoming radiation is flipping. This makes the angular acceleration from SRP to be directed in counter-spin direction for the following period; hence decreasing the rotation [10].

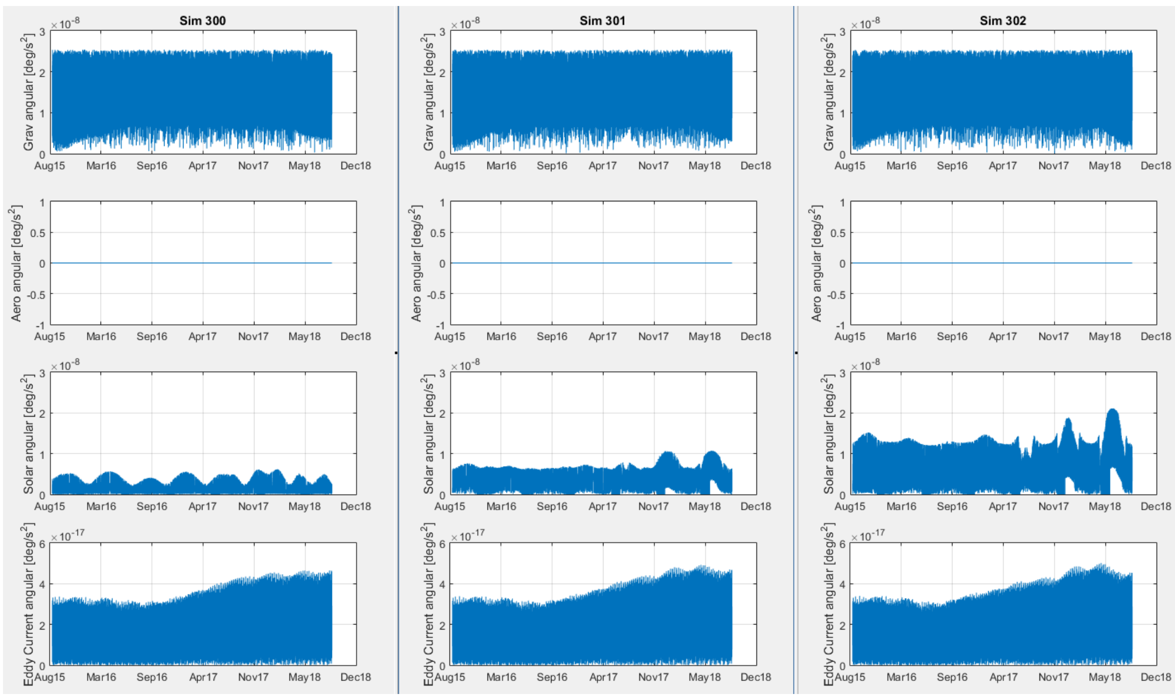

Fig. 8. COSMOS 2041 long-term environmental torques perturbations from three simulations: with canting angle of 0° (left image), 10° (center image), and 20° (right image). The effect of atmospheric drag is ignored in this simulation.

Later simulations revealed that we can get secular trends if we change the orientation of the group of solar panels w.r.t. the body. Here we defined an angle which we call base angle, which defines how far the group of solar panels inclines from the z-axis. It is considered positive if it is inclined toward the positive x-axis and negative if it is inclined toward the negative x-axis. Fig. 9 shows the secular trend for 45° base angle. We found that the small "bumps" between the peaks in the figure can be removed to some extent after using all relevant environmental forces.

Why secular trends? To answer this, we did a simple experiment by removing the bus (the cylinder) in the satellite 3D model but still using the same moments of inertia. Fig. 10 shows us that it greatly reduced the secular trend in the angular velocity. So, we assumed that the secular trends have something to do with self-shadowing of the bus and the solar panels. More investigations are needed to confirm this.

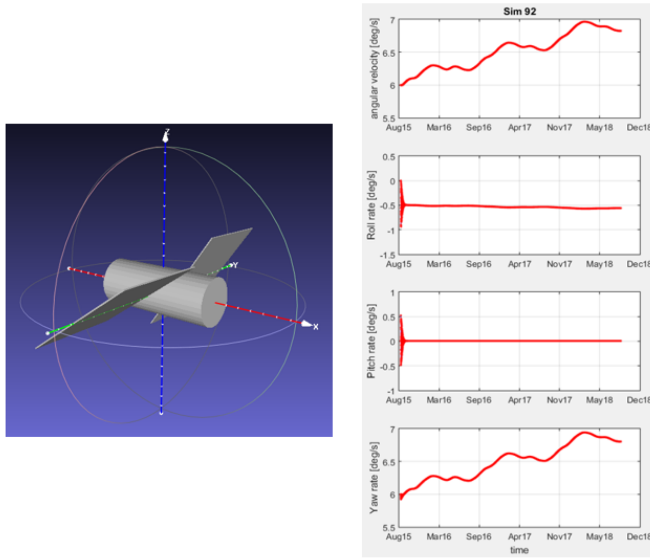

Fig. 9. The secular trend of the oscillating spin rate evolution pattern for 45° base angle with only SRP, initial angle of [0, 90, 0] and initial angular velocity of (0, 0, 6).

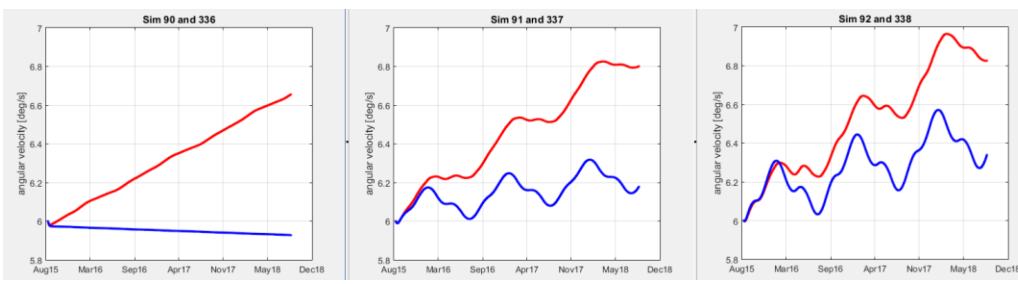

Fig. 10. Comparison of angular velocity of the model with bus (red line) and no bus (blue line) for 45° base angle and three canting angles: 0° (left image), 10° (center image), and 20° (right image).

In the second series of simulations, we tried to set up some simulations that will roughly replicate the observations. Here we used all relevant environmental forces which can remove (to some extent) the small "bumps" between peaks as we see in Fig. 9 and Fig. 10. We found that the best set up was with a base angle of 40°, canting angle of 70°, initial angle of [0, 90, 0], initial angular velocity of (0, 0, 7.5), absorption factor of 0.4, and diffuse reflection factor of 0.6. The result is shown in Fig. 11.

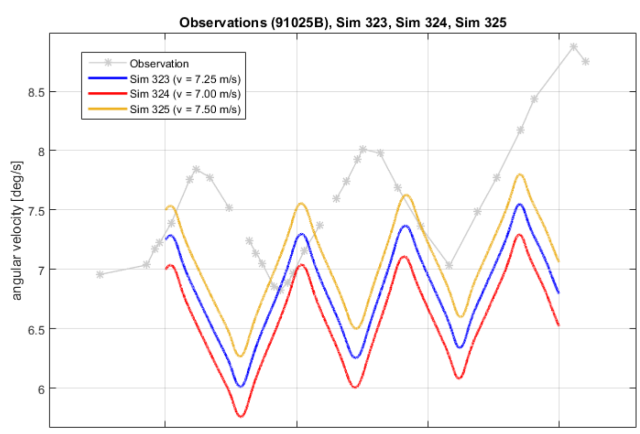

Fig. 11. Comparison between results of the simulations and observations for COSMOS 2041.

4. CONCLUSION

Several studies have shown an oscillating pattern in the rotational period evolution of several inactive payloads in geosynchronous and medium Earth orbit. In the AIUB light curve database, the long-term evolution of the rotational period of several inactive GLONASS satellites shows a roughly annual pattern consisting of a series positive and negative peaks with triangular shape. In addition, secular trends also exist. This study aimed at understanding the pattern by simulating the rotation rate of one of the satellites under different conditions. The chosen satellite is COSMOS 2041 which was launched on April 4, 1991 and retired on January 6, 1992. Several simulations were run using a simple satellite model with cylinder shape for the bus and two rectangular plates as wings for the solar panels. Various initial orientations of the satellites in the inertial system and of the solar panels in the body-fixed system were tested.

We found that the roughly annual oscillating pattern is achievable only if both the solar panels oriented differently. This seems true whatever the initial orientation of the satellites and of the rotation axis are. Also, we found an indication that the periodic behavior is caused by solar radiation pressure on the solar array of the satellite. In addition, other results of simulations inspired us to assume that the secular trends may be caused by self-shadowing of the bus and the solar panels. More investigations are needed to confirm this. Finally, we found a configuration and initial angular velocity allowing to roughly replicate the pattern of the spin rate evolution of COSMOS 2041.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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