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EVOLUTION OF THE ROTATION PARAMETERS OF THE ROCKET'S UPPER STAGE (SPACE OBJECT 1987-074G)

N. Koshkin [1], O. Kozhukhov [2], L. Shakun [1], O. Bryukhovetskyi [2], E. Korobeynikova [1], S. Melikyants [1], S. Strakhova [1], V. Dragomiretsky [1], A. Ryabov [1]

[1] Astronomical Observatory of Odesa I. I. Mechnikov National University, Odesa, Ukraine

[2] National Space Facilities Control and Test Center, Kyiv, Ukraine

ABSTRACT. Active space debris removal operations require a priori knowledge of the target objects' rotation parameters, i.e., information on their rotation speed and current orientation in space. This can be achieved through appropriate observations designed to determine these parameters. Recording and subsequent analysis of light curves is the most common method for monitoring space objects' rotation using optical means. This paper examines the results of long-term photometric observations of a large space debris object — the third stage of the SL-14 rocket (international COSPAR number 1987-074G, USSTRATCOM ID 18340). It shows how this resident space object's (RSO) rotation speed around its center of mass repeatedly changed between 2006 and 2025. To understand the cause of this behavior of RSO 18340, it is necessary to study the relationship between its different rotation speed states and the corresponding orientation of its rotation axis in inertial space. In paper, we consider the observed light curves of RSO 18340, recorded in 2024 at different observatories, analyze their structure and identify similar photometric patterns in different light curves. These photometric patterns are used to determine the spatial direction of the object's rotation axis in two short (1–3 days) time intervals in late February – early March 2024. As a result of this analysis of the light curves, four estimates of the average direction of the rotation axis and its evolution over a two-week interval were obtained. Using two light curves obtained during flybys over different observing points on February 27, 2024, we obtained the current direction of the rotation axis in the inertial coordinate system: RA = 10°, Decl. = -66°. And based on six light curves obtained on March 9, 10 and 11, 2024, the following average coordinates were determined: RA = 06°, Decl. = -39°. We estimate the internal error of these results to be ±(5–10)°. Based on these results, we hypothesize that there are no rapid shifts in the rotation axis of RSO 18340.

Keywords: space object; photometric observation; light curve; apparent period; photometric pattern; spin axis orientation.

АНОТАЦІЯ. Для операцій з активного видалення космічного брухту необхідне апріорне знання параметрів обертання цільових тіл, тобто інформація про швидкість їхнього обертання та поточну орієнтацію у просторі. Це може бути забезпечено відповідними спостереженнями, призначеними для визначення цих параметрів. Реєстрація та подальший аналіз кривих блиску є найпоширенішим методом моніторингу обертання космічних об'єктів оптичними засобами. У роботі розглянуті результати багаторічних фотометричних спостережень великого об'єкта космічного брухту – 3-го ступеня ракети SL-14 (міжнародний номер COSPAR 1987-074G, USSTRATCOM ID 18340). Показано, як протягом 2006–2025 рр. неодноразово змінювалася швидкість обертання навколо центру маси цього резидентного космічного об'єкта (КО). Для розуміння причини такої поведінки КО 18340 необхідно вивчити взаємозв'язок між різним станом швидкості його обертання та відповідною орієнтацією в інерційному просторі його осі обертання. У роботі для цього розглянуто спостережні криві блиску КО 18340, які отримані та зареєстровані в 2024 році на різних обсерваторіях, проаналізовано їх структуру та ідентифіковано схожі фотометричні патерни на різних кривих блиску. Ці фотометричні патерни потім були використані для визначення напрямку у просторі осі обертання даного об'єкта у двох коротких часових інтервалах (1–3 доби) наприкінці лютого – на початку березня 2024 року. В результаті цього аналізу кривих блиску отримано чотири оцінки середнього напряму осі обертання та її еволюцію на двотижневому інтервалі. Використання двох кривих блиску, отриманих у прольотах над різними пунктами спостереження 27 лютого 2024 року дозволило визначити поточний напрямок осі обертання в інерційній системі координат: RA = 10°, Decl. = -66°. А на основі шести кривих блиску, що отримано 9, 10 і 11 березня 2024 року визначені наступні середні координати: RA = 06°, Decl. = -39°. При цьому внутрішню помилку цих результатів ми оцінюємо як ±(5–10)°. На основі цих результатів зроблено припущення про відсутність швидких коливань осі обертання КО 18340.

Ключові слова: космічний об'єкт; фотометричні спостереження; крива блиску; видимий період; фотометричний патерн; орієнтація осі обертання.

1. Introduction

Orbital spacecraft play a vital role for modern civilization. However, as the number of objects in near-Earth space grows, so too do the undesirable consequences associated with possible and even inevitable collisions. The growing number of space debris is of exclusive concern. Space debris is artificial objects in orbit that perform no useful function (inoperative spacecraft, spent rockets, fragments of destroyed spacecraft, etc.). To protect operational spacecraft and the space environment as a whole, several measures have been proposed to reduce the risk of collisions—primarily, active debris removal (ADR).

Such operations require a priori knowledge of the rotational parameters of the target bodies, that is, their rotational speed and current orientation in space. This can be ensured by appropriate observations designed to determine these parameters. In general, both for the mass removal of space debris from orbit and for accurately predicting its orbital motion, it is important to understand and consider the causes and mechanisms that cause changes in the rotation of space objects.

Light curve recording is the most common method for analyzing the rotation of space objects using optical means. They can be used to determine the rotation states of space debris, including the rotation period (Silha, 2018; Hall, 2014; Rachman, 2025) and the orientation of the rotation axis (Santoni, 2018; Zhao, 2020; Vananti, 2023; Kudak, 2024). Of interest is the study of the evolutionary of both the rotation period and the spatial orientation of the rotation axis of a space debris objects. Many authors have noted the cyclic nature of the rotation period variations in different studied space debris objects (See, for example, Earl, 2017; Rachman, 2025). The main goal of these studies was to extract apparent periods and explain the observed rotation accelerations and decelerations by modeling the torques acting on the space debris. For example, tilted solar panels with different orientations and different reflectivities for the front and back sides experience torques caused by the pressure of solar rays. For example, Ojakangas & Hill (2011), Albuja (2015), Benson & Scheeres (2017), it was shown that solar radiation pressure and the YORP effect can lead to complex, tumbling rotations of asymmetric satellites.

However, the causes of the acceleration and deceleration of the rotation of various inactive spacecraft and rocket bodies require further study. A better understanding of the relationship between different rotational speed states and the corresponding orientation of the satellite's spin axis is also needed.

2. Variations in the rotation period of RSO 18340

In this paper, we present the results of photometric observations and their analysis for a large space debris object, namely the 3rd stage of the SL-14 rocket body (R/B). This space debris object moves in a circular orbit at an altitude of approximately 1450 km above Earth with an inclination of 82.5°. The Astronomical Observatory of the Odesa I. I. Mechnikov National University has been take photometric monitoring of large space debris bodies in low orbits for many years (Koshkin, 2021). The first observations of RSO 18340 were obtained in September 2006. At the same time, the first estimates of the apparent rotation period of this space debris were made, which was approximately 135 seconds. However, observations obtained in May 2007 revealed that the period of its light curve decreased to approximately 68 seconds. This value was almost exactly half the duration of the period in the previous observation, and this gave some reason to consider it a harmonic of the main rotation period. It should be noted that the light curves of the RSO 18340 exhibits two significant oscillations with similar amplitudes per rotation, between which secondary maxima are sometimes observed, either as a separate increase in brightness or as a hump on the descending or ascending branch of the main oscillation. This fact provides a strong argument in favor of an acceleration of the rotation of RSO 18340 over the expired eight months. Observations in July 2008 showed that the brightness oscillation period of this RSO was approximately 58 seconds. Subsequent observations yielded the following estimates of its rotation period: on October 8, 2009 and September 10, 2010, it was approximately 50 seconds, while on April 26, 2010, it was approximately 72 seconds. Figure 1 shows the light curves of RSO 18340 that we recorded on these dates.

Subsequent, unfortunately also not always regular, photometric observations have shown that this object continues to experience significant variations in its rotation velocity around its center of mass. Figure 2 shows our obtained rotation period values for the period 2006–2022. We see mostly slow, possibly cyclical, variations in the apparent rotation period of RSO 18340, ranging from 30 to 158 seconds. The cycle length was likely approximately 2.5 years or more.

In 2020, an international campaign of photometric observations of rocket bodies (R/B) was launched, announced by the Inter-Agency Space Debris Coordination Committee (IADC). Its goal was to evaluate the potential of photometry to determine all possible rotation parameters of rocket bodies, given the availability of extensive data from various observatories. The observation program included eight R/Bs with orbital altitudes below 1000 km, i.e., located in the region of highest spatial density of space bodies. This region of altitude above Earth is primarily in need of active debris removal from orbit. However, RSO 18340 was also included in the observational program of this campaign, as it has an interesting history of rotational speed variations around its center of mass. The campaign lasted until mid-2022. Approximately 80 light curves of RSO 18340 were obtained, which were very unevenly distributed over time. Figure 3 shows the distribution of these observations, obtained at four observatories. As can be seen, there are intervals when a group of observations were obtained on close dates. However, overall, there are significant gaps between the observations, which significantly reduces their value for some types of analysis.

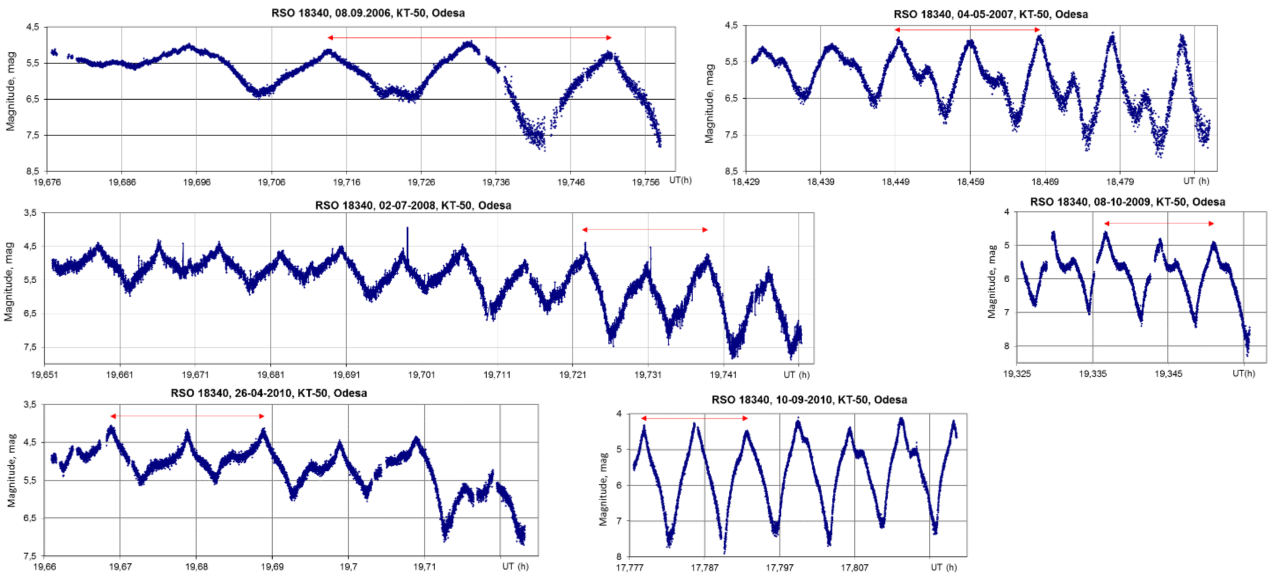

Figure 1: Examples of light curves for RSO 18340. The x-axis represents time in hours (the x-axis scale is maintained). The red line with arrows indicates the light curve period corresponding to the apparent rotation period of the RSO.

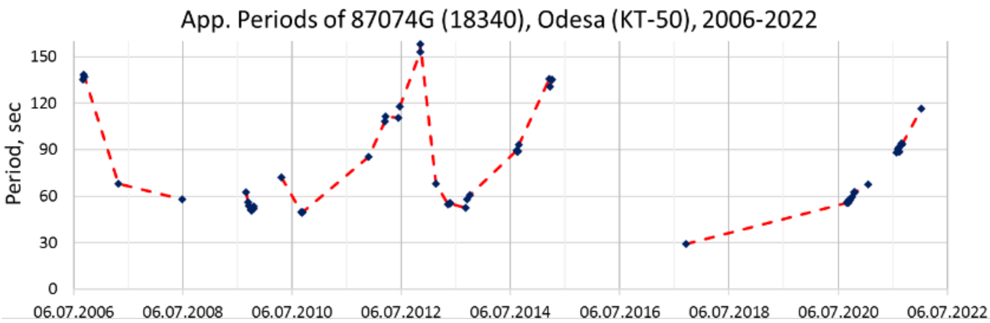

Figure 2: Variation in the apparent rotation period of RSO 18340 between 2006 and 2022. Odesa, KT-50 (Koshkin, 2021).

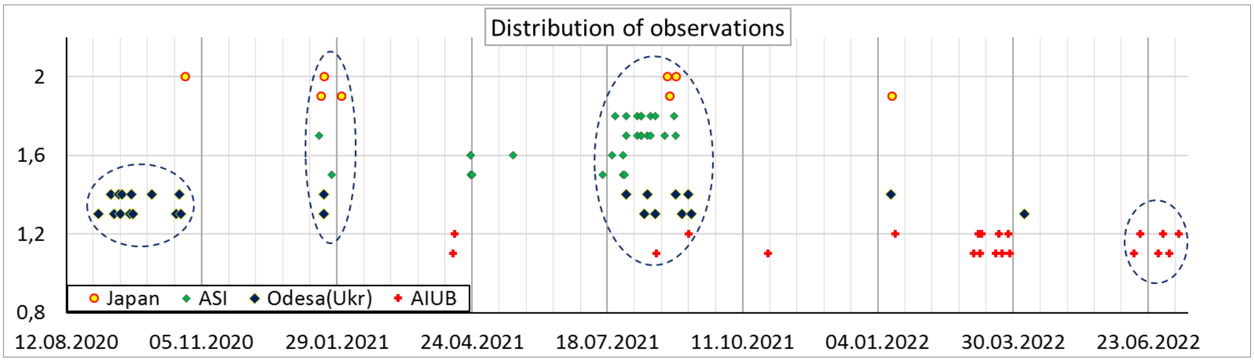

Figure 3: Time distribution of photometric observations of RSO 18340 obtained at four observatories during the IADC campaign in 2020–2022. The horizontal axis represents the observation date, and the vertical axis represents the arbitrary value (for clarity, to evenly distribute all points along the Y coordinate).

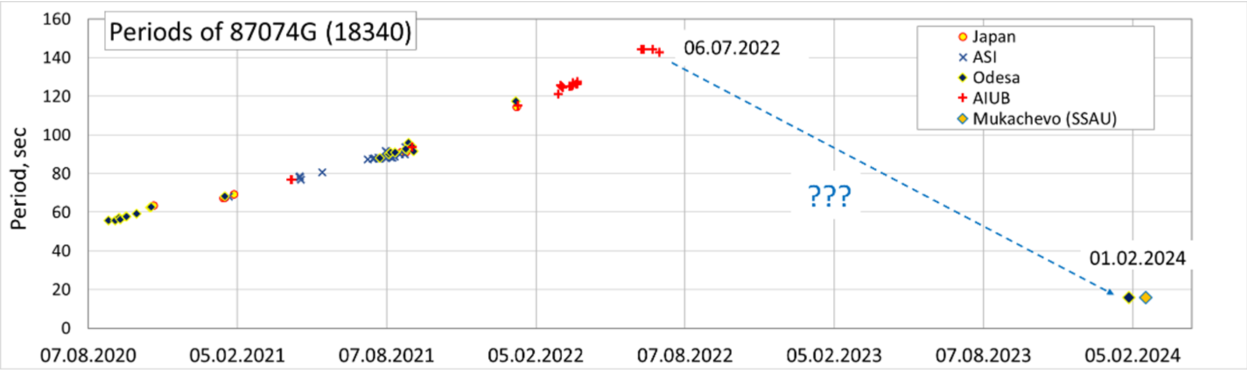

Figure 4: Trend in the apparent rotation period of RSO 18340. The data were obtained as a result of an international campaign organized by the IADC in 2020-2022.

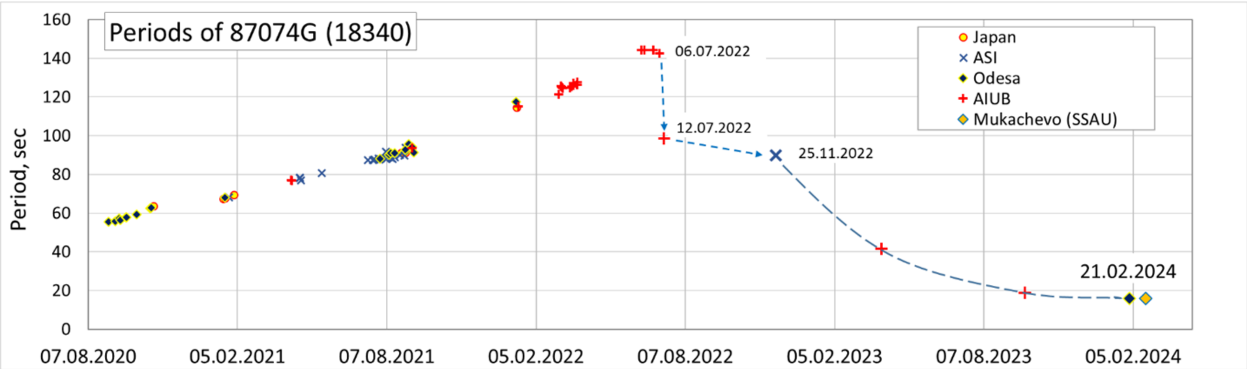

Figure 5: Variation in the apparent rotation period of RSO 18340. Data for the period 2020-2022 were obtained from the IADC. Period values after July 6, 2022, were provided by ASI and AIUB (see Kumar, 2025)

Nevertheless, these observations were analyzed for the possibility of estimating the apparent rotation period of RSO 18340. As a result, a nearly linear trend of increasing apparent rotation period of RSO 18340 from 55.6 seconds to 144.4 seconds was detected over the time period from September 2020 to early July 2022, with an average period increase rate of approximately 0.13 seconds/day. At this point, the campaign ended, and the operational exchange of observation data stopped. It seemed that RSO 18340's rotation had entered a state of stable, gradual deceleration, as is often observed in other space debris objects. However, on February 1, 2024, in Odesa, we obtained another light curve of this RSO, and unexpectedly found that the observed rotation period was 15.8 seconds. This represents a ninefold increase in the angular velocity (see Fig. 4).

At the same time, it was discovered that, after the end of the campaign, colleagues from Switzerland (AIUB) and Italy (ASI) also obtained sporadic observations of this RSO. Based on their data (Kumar, 2025), it was concluded that in the second week of July 2022, the rotation velocity of RSO 18340 rapidly increased (the period decreased to 98.6 sec) and possibly remained at almost the same level until the end of November 2022. After this, a period of slow rotational velocity increase was observed until the end of February 2024, as shown in Fig. 5. Let us pay attention to the fact that the acceleration of rotation of RSO 18340 (see Fig. 2) observed from 08.11.2012 to 20.02.2013 (the visible period decreased from 158 to 68 seconds) occurred in approximately 100 days, while the acceleration in 2022-2024 apparently continued for 1.5 years.

As a result, the cooperative observing campaign for photometry of RSO 18340 was restart from late February 2024. It involved primarily two observing stations of the National Space Facilities Control and Test Center of Ukraine in Novosilki and Mukachevo, as well as the Astronomical Observatories of Odesa, Uzhgorod, and Lviv Universities. Some observations were also provided by the UK Space Agency (UKSA, Herstmonceux) and the Italian Space Agency (ASI, Scudo), and the Swiss company s2a systems subsequently joined the observations. Ultimately, it was established that, since the end of February 2024, the apparent rotation period of RSO 18340 has been increasing monotonically, initially slowly at a rate of approximately 0.02 sec/day, then more rapidly at a rate of approximately 0.05 sec/day (Fig. 6). However, the rate of period increase never reached the level observed in 2020–2022, remaining, on average, three times slower.

We observed another nonlinear change in the apparent rotation period of RSO 18340 beginning on June 22, 2025, when it decreased by 0.3 seconds over approximately three weeks and then continued to increase at a rate of approximately 0.072 seconds/day for several months (see Fig. 7).

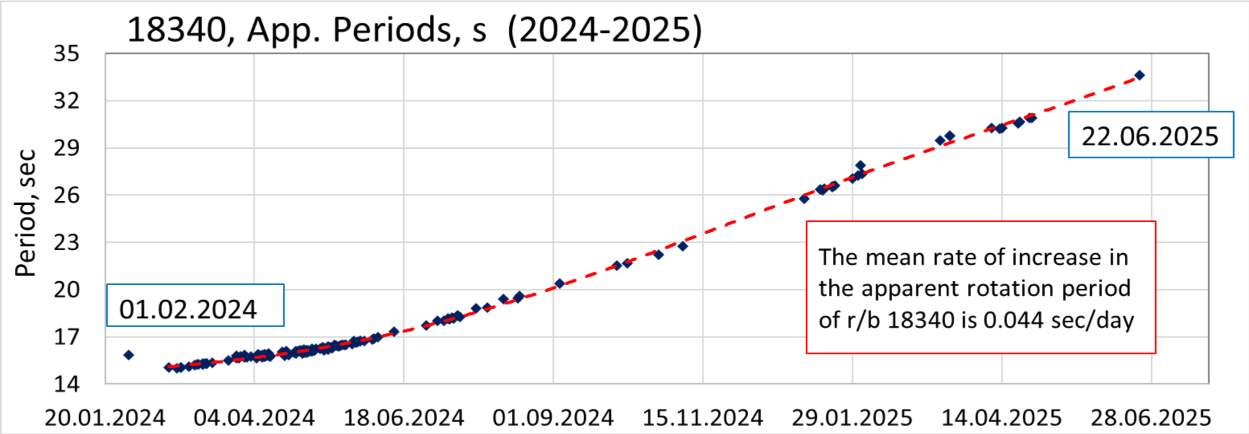

Figure 6: Change in the apparent rotation period of RSO 18340 from February 1, 2024 to Juny 22, 2025.

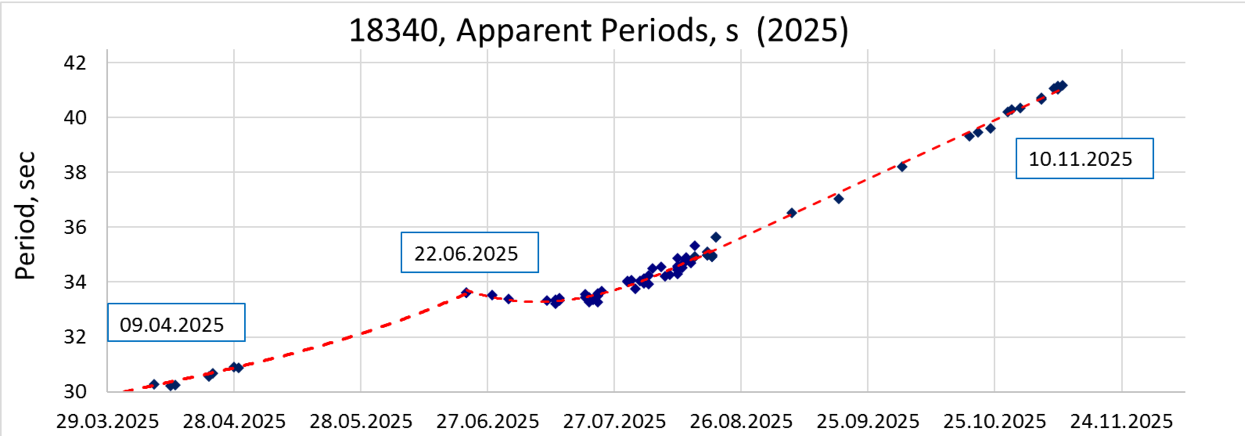

Figure 7: Variation in the apparent rotation period of RSO 18340 between April 9, 2025 and November 10, 2025.

This unstable change in the rotation speed of RSO 18340 raises questions about its possible cause. In (Kumar, 2025), the authors considered the possible cause to be the loss of residual fuel due to a mechanical failure of one of the R/B engine's nozzle valves during its spin-up period from July 2022 to February 2024. Such a cause cannot be ruled out, but given the entire history of its rotation period variations, its effect must be very complex and repetitive.

3. Orientation of the Rotation Axis of RSO 18340

A comprehensive study of the nature of its rotation around the center of mass could be the solution to the problem of the complex, possibly cyclical, variations in the rotation period of RSO 18340. On the one hand, the slow deceleration of its rotation observed in recent years occurs at varying rates. This could support a change in the nature of its rotation and the position of its rotation axis within the body. On the other hand, the shape of its light curves generally appears to be consistent across seasons over many years.

An attempt was made at the Sapienza University of Rome (Kumar, 2025) to determine the rotation parameters of RSO 18340 by comparing the observed and synthetic light curves, using a physical and digital model (physical simulation + “digital twin”). By fitting model light curves to the observed one, they obtained a complex motion, including rapid nutation and precession of the rotation axis of R/B 18340.

We attempted to test an alternative hypothesis, which assumes a planar rotation of the RSO around a single axis within the body and a slow precession of the rotation axis in space. We used our previously proposed method for determining the spatial orientation of the rotation axis of an arbitrary-shaped RSO (Koshkin, 2024a and Koshkin, 2024b). To do this, we examined 13 light curves of RSO 18340 obtained from several observatories between February 27 and March 11, 2024 (10 light curves from the National Space Center, 1 from Lviv University, and 2 from Herstmonceux). Through expert comparison, we identified 17 fragments (patterns) in these light curves that are similar to each other and distinct from the others. For the time of each pattern observation, the position of the phase angle bisector (PAB) vector was calculated. By grouping these data, the average position of the rotation axis in the inertial coordinate system was determined for each 1-2-day time interval (Fig. 8). We see a significant drift of the rotation axis in declination, while right ascension changed little. At the same time, the results based on observations over a single night show a scatter of approximately ±3° relative to the solution based on a two-day observation interval, i.e., the averaged solution. This allows us to estimate the internal error of the individual pole solution as no more than ±(5-10)°. In the orbital coordinate system, the rotation axis is offset from the ascending node by an average of 122-127 degrees in right ascension.

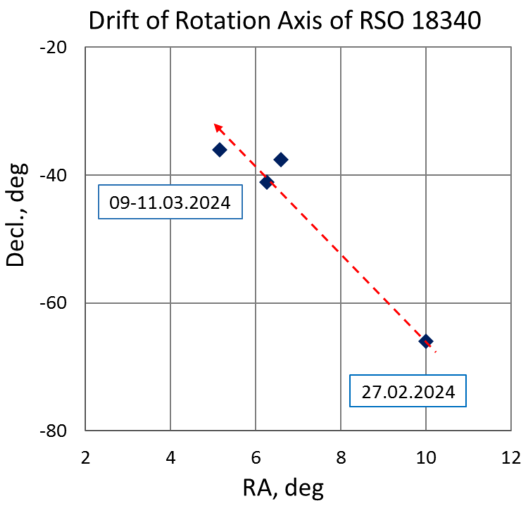

Figure 8: The position of the rotation axis of RSO 18340 in the inertial coordinate system for four dates, calculated by selecting similar photometric patterns in light curves obtained at different observatories over short time intervals (1-3 days).

In addition to searching for the optimal position of the rotation axis in space, this method allows us to simultaneously determine of the latitude of each photometric pattern in the coordinate system associated with rotation axis in the satellite body. This latitude is determined by the current latitude of the PAB vector in the inertial coordinate system. In this sense, we use the term "latitude of the photometric pattern." The determined correspondence between the photometric pattern and latitude should remain constant for all satellite passes as long as the rotation axis maintains its position within the body (although it shifts in space).

In Figure 9, fragments of the observed light curves (patterns) are superimposed on the PAB latitude plots for RSO 18340 at the exact times and latitudes calculated for the determined rotation axis position in space. We see the close equality of the latitudes of the similar patterns across different transits and for different observation sites, confirming the correctness of the determined rotation axis position in the corresponding time interval.

4. Discussion and future work

It appears that our estimates of the spatial position of RSO 18340's rotation axis may indicate a slow shift over an interval of approximately two weeks (February 27 – March 11, 2024), i.e., the absence of rapid, significant oscillations. However, this conclusion remains insufficiently substantiated. Although we (together with colleagues) obtained numerous light curves for RSO 18340 in 2024 and 2025, we have not yet been able to determine the rotation axis orientation and its evolution over significant timescales. This is because the technical challenge of creating a pipeline for comparing many light curves and identifying unique patterns across the entire dataset remains unresolved. The light curves of RSO 18340 often exhibit very similar patterns over several rotations, making clustering them difficult.

The successful solution to the problem of determining the rotation axis orientation of RSO 18340 using the pattern method in the two-week interval discussed above in February–March 2024 was facilitated by the fact that the PAB trajectory during these RSO transits apparently approached the direction of the current rotation axis. This was manifested in a significant change in the amplitude of brightness variations during the considered RSO transits—from 0.5 to 3 magnitudes on average (see Fig. 10). This resulted in an increased diversity of observed pattern types and a significant distribution by latitude in the coordinate system related with the current rotation axis.

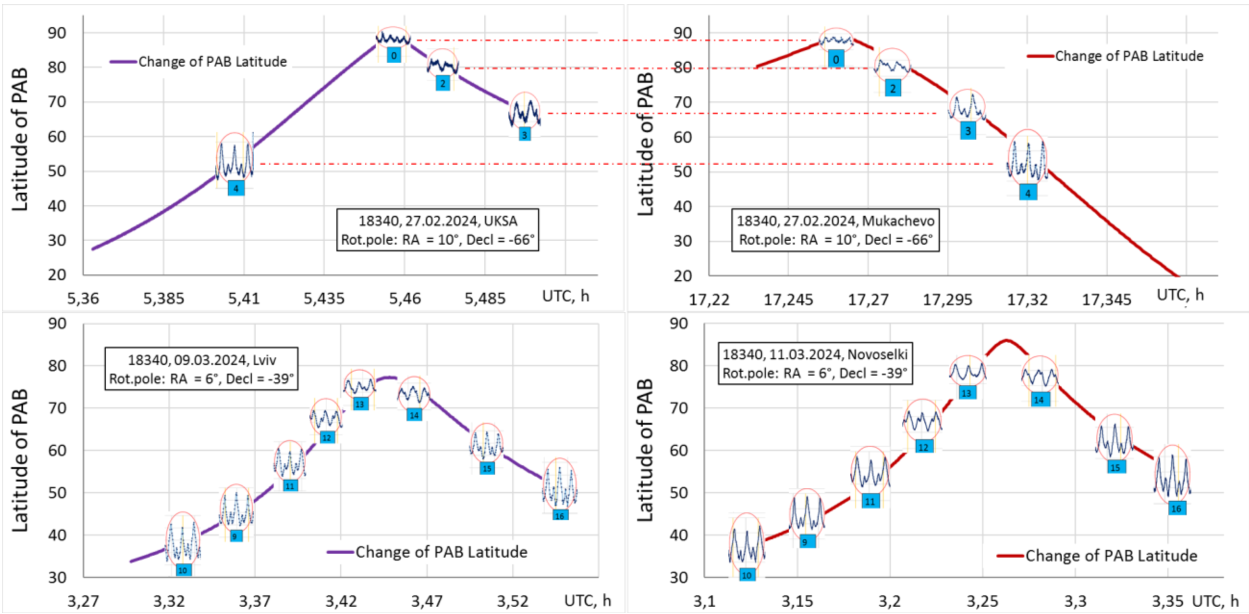

Figure 9: Graphs of the PAB latitude variation during different transits of RSO 18340 for different observing sites. The used by us patterns at the corresponding times and at the latitude calculated for the current rotation axis position are also shown. The top panel shows observations on February 27, 2024, obtained at Herstmonceux and Mukachevo. The bottom panel shows observations obtained on March 9 in Lviv and on March 11, 2024, at Novosilky.

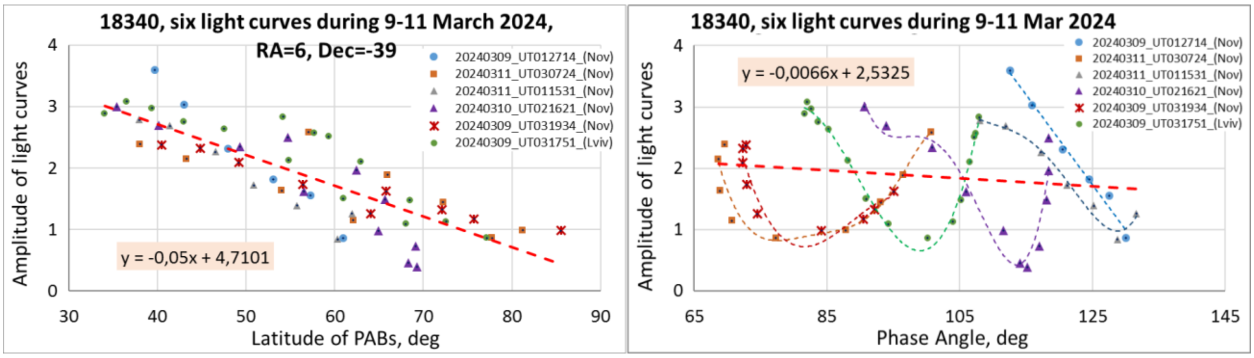

Figure 10: Dependence of the amplitude of the light curves of RSO 18340 on the latitude PAB for the adopted direction of the rotation axis RA = 6°, Decl = -39°, common for six passages in the interval of March 09 – 11, 2024 (left); Dependence of the same amplitude values of the light curves of RSO 18340 on the phase angle (right).

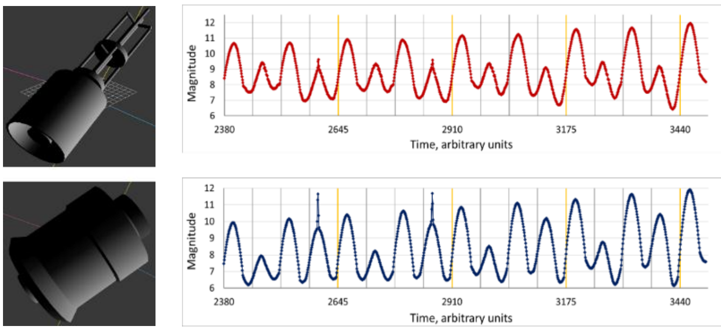

Figure 11: Computer model of RSO 18340 in two variants of its shape (left) and fragments of the corresponding synthetic light curves (right).

Figure 10 (left) shows the local amplitude of brightness variations in six different transits of RSO 18340 during the interval March 9–11, 2024. The X-axis plots the PAB latitude at the corresponding mean times. We see a good correlation between the amplitude and latitude of the PAB for the mean direction of the rotation axis (RA = 6°, Decl. = -39°). This confirms the expected dependence of the amplitude on the PAB latitude for an elongated body. This also indirectly confirms the agreement between the position obtained in our analysis and the actual position of the rotation axis of RSO 18340 during this time interval. The noticeable spread in the amplitude values can be partially explained by the influence of other observing conditions during different RSO transits — the phase angle and the orientation of the light scattering plane (relative to the rotation plane). The right panel of Figure 10 shows the dependence of the same amplitude values on the phase angle. This dependence, while expected, is generally almost an order of magnitude less significant than the amplitude dependence on PAB latitude (slopes of 0.0066 and 0.05 magnitudes per degree of phase angle and per degree of PAB latitude, respectively). Moreover, this graph significantly reveals a different amplitude dependence, distinct from the phase dependence, for each individual transit (highlighted by color and thin dashed lines).

Considering that for man-made space objects, even in the absence of specular flares, the amplitude of brightness variations is quite large (in this case, reaching 3m), and the phase dependence of the amplitude is significantly less significant than its dependence on the PAB latitude, this can in some cases serve as a rough method for finding the current position of the rotation axis in space. This requires several light curves obtained over a short time interval (e.g., over the course of a day and preferably from different observation sites), demonstrating significant amplitude variations. In this case, an attempt can be made to find the minimum scatter of observed local amplitude values for all light curves in each latitude interval of the PAB (in the coordinate system associated with the trial axis) by enumerating trial rotation axis directions. The spatial direction of the trial rotation axis in this case will likely be close to the actual direction.

To test the solution to the inverse problem of determining the satellite's rotation axis orientation based on photometric data, we also plan to use its digital optical-geometric model. The modeling was done in 3ds Max software. Figure 11 on the left shows a computer digital model of RSO 18340 in two variants of its shape (based on data from different sources), and the panel on the right shows the corresponding synthetic light curves. The model rotates around an axis almost perpendicular to its longitudinal axis, and in space, the rotation axis has coordinates: RA = 10°, Decl. = -66°. The calculation of the synthetic light curve was made for the passage of RSO 18340 over the observation point Mukachevo on 02/27/2024 at 17h15m UTC.

Comparison of the synthetic light curves of the RSO 18340 model with numerous observed curves should provide additional support for a conclusion regarding the rotation pattern of this SL-14 rocket's third stage and the possible cause of its repeated spin accelerations. Furthermore, we propose an international observational campaign to photometry other similar space objects, as a cluster (approximately 20 RSOs) of identical SL-14 rocket stages orbits in very similar orbits.

5. Conclusion

In this paper, we consider the results of long-term photometric monitoring of a large space debris object—the 3rd stage of the SL-14 rocket (RSO 18340). It is shown how the rotation velocity around the center of mass of this object repeatedly changed during 2006–2025. To better understand the reason for this behavior of RSO 18340, the structure of its light curves is considered, and the identified similar photometric patterns are used to determine the direction of the rotation axis of this object in inertial frame. As a result of this analysis of the light curves of RSO 18340, estimates are made of the average direction of the rotation axis during two short (1–3 days) time intervals in late February – early March 2024. Based on two light curves obtained during the flybys of RSO 18340 over Mukachevo and Herstmonceux on February 27, 2024, the following coordinates of the rotation axis in the inertial coordinate system were found: RA = 10°, Decl. = -66°. Based on six light curves obtained on March 9, 10, and 11, 2024, at different observation locations, the average coordinates of the rotation axis were found to be RA = 06°, Decl. = -39°. We estimate the internal error of these results to be ±(5-10)°.

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