

DETERMINATION OF THE RSO'S SPIN AXIS ORIENTATION USING PHOTOMETRY DATA

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ABSTRACT

Knowledge of the kinematic properties (angular velocity of rotation and spatial position of the rotation axis) of large space debris objects (failed satellites and rocket stages) is necessary to predict their orientation at any given time. This information may be important, for example, for the success of active debris removing (ADR) missions for these objects, or for improving the accuracy of predicting their orbital motion. The rotation state of resident space objects (RSO) is determined by various means, but it has usually been done using optical ground-based sensors by obtaining light curves, processing and analysing them.

It is quite difficult to determine the spatial orientation of the rotation axis of an RSO of unknown shape. The known methods for determining the orientation of the rotation axis are suitable only for a certain type of objects. Therefore, the development of new approaches to determining the orientation of the rotation axis, in particular, based on photometry, remains relevant.

In this report, we continue testing a new method for estimating the direction of the RSO's rotation axis in inertial frame, based on the structural analysis of the available set of light curves and the search for their similar fragments called "photometric patterns". The main advantage of this method is that its use does not require knowledge of the RSO's shape, but it has some limitations. This method is certainly applicable to stably, relatively fast rotating objects of complex shape that have smooth surfaces and, therefore, are capable of reflecting sunlight in a specular manner. As a result, the structure of the light curves of such RSOs can be expected to contain short-term brightness flares that form a unique photometric pattern. It can be argued that identical patterns are observed at the moments when the angle between the phase angle bisector (PAB) and the rotation

axis reaches the same values in different cases. The presence of such conditions allows one to determine the orientation of the rotation axis in the inertial coordinate system. However, in addition to the specular component, the light curves often have a significant diffuse component, which depends both on the phase angle and on the position of the rotation axis relative to the directions to the Sun and to the observer. This complicates the possibility of determining the moments when the PAB latitude relative to the unknown rotation axis reached identical values by the shape of the patterns. In this report we test the applicability limits of this method using synthetic and real light curves of the RSO observed from several sites on the Earth's surface as input data.

1 INTRODUCTION

Knowledge of kinematic properties (angular velocity of rotation and spatial position of the rotation axis) of large failed satellites and rocket bodies is necessary to predict their orientation at any given time. This information is of crucial importance, for example, for the success of active debris removal (ADR) missions for these objects, and for improving the accuracy of predicting the orbital motion of space objects (SO) in LEO. The rotation state of SOs is determined by various facilities, but historically it has been done using optical ground-based sensors (photometers) by obtaining light curves, processing them, and analyzing them. The period of proper rotation of a SO around its center of mass can be fairly easily estimated by measuring the period of brightness variations. However, determining the direction of the SO rotation axis in space much more difficult especially if the SO's shape is insufficiently known (as often happens). In most studies, the methods proposed for determining the orientation of the rotation axis of a SO are specific and suitable only for a certain type of object. The attempt to solve the general problem of the so-called

"inversion" of the light curve, as well as attempts to separate the contribution of the SO shape and the orientation of its rotation axis to the type of light curves, have not been successful even for fairly simple non-convex bodies. Nevertheless, one of the real ways to perform the inversion of light curves (to determine the orientation of the rotation axis and the shape of the SO) is precisely the ability to first estimate the current direction of the rotation axis in space. Therefore, the development of new approaches to determining the orientation of the rotation axis, in particular, based on photometry, remains relevant.

In this report, we use and test a new method for estimating the direction of the SO rotation axis in space. This method is based on the structural analysis of SO light curves and the search for similar fragments (we call them "photometric patterns") in observations obtained from one or several observatories simultaneously or over a short period of time [1]. The main advantage of this method is that its use does not require knowledge of the SO shape. In addition, this method does not require a very high frequency of brightness measurements and high accuracy of the timing of photometric observations, i.e., in fact, it does not put forward strict requirements for the quality of observations. Nevertheless, it also has its constraints. First of all, this method is certainly applicable to objects with complex shapes that have flat surfaces and, as a result, are capable of reflecting sunlight in a specular manner. In the structure of the light curves of such SOs, one can expect the presence of short-term brightness flares. If several such "specular" flares were observed in the light curve during one rotation of the SO, they can form a unique photometric pattern (in the sense of unique intervals between the specular flares). A similar pattern can also be observed in another light curve, for example, obtained at another observatory or during another passage of the given SO. In this case, it can be stated that the same patterns are observed when the angle between the phase angle bisector (PAB) and the rotation axis reaches equal values in both cases (See Fig. 1). However, in addition to the specular component, the light curves often have a significant diffuse component. It depends both on the magnitude of the phase angle and on the orientation of the phase angle plane (light scattering plane) relative to the rotation plane (angle θ in Fig. 1). We assume that within certain limits of variation of these two geometric factors, the structure and shape of diffuse-specular patterns will remain similar to themselves, provided that the latitude of PAB (β_i) is equal at the moments of observation of these patterns. This work is devoted to testing this assumption based on input data in the form of synthetic (simulated) light curves of the SO model observed from several points on the Earth's surface.

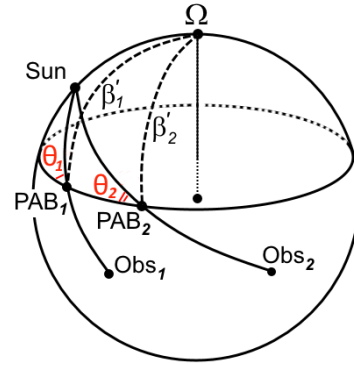


Figure 1. Satellite-centered arrangement of the main vectors determining the conditions of its illumination and visibility. The arc "Sun-Obs_i" determines the current phase angle. The arc "Ω-PAB_i" is equal to $\beta'_i = (\pi/2 - \beta_i)$, where β_i is the latitude of PAB relative to the pole of the rotation axis Ω. The angle θ_i determines the current position of the light scattering plane relative to the plane of SO rotation.

2 SPACE OBJECT MODEL AND SIMULATION OF LIGHT CURVES

In the method of photometric patterns [1], to find the orientation of the resident SO (RSO) rotation axis, it is necessary to obtain photometric observations from one or several sensors over a sufficiently short time interval (during this interval the sought orientation of the SO rotation axis can be considered unchanged) in a quantity sufficient to separate several types of patterns on the light curves, each detected at least twice.

In order to be sure to detect the same photometric pattern on different light curves of a given SO, it is necessary that the mutual configurations of the three vectors – the rotation axis and the satellite-centered directions to the Sun and to the observer – be identical. On the other hand, to reliably determine the direction of the rotation axis, we need the directions of the PAB vectors in inertial space for the same photometric pattern to be as different as possible. This contradiction can be overcome if similar patterns can be produced with slightly different configurations of the specified vectors. For example, this is always true for "specular" patterns, for which it is sufficient that only the angles between the rotation axis and the PAB vector coincide at the moments of appearance of identical patterns; the values of the phase angle and the angle θ may not coincide. And, as we will show below, this is also possible to a certain extent in the case of "diffuse-specular" patterns.

In practice, at present we still do not have a sufficient number of observations of any RSO obtained in the required geometry and within a short time interval, and this limits the possibility of making reliable estimates of the direction of the RSO rotation axis in the inertial coordinate system. However, it is possible to use

synthetic light curves of the RSO model obtained using animation and visualization programs for three-dimensional scenes such as Blender [2], 3D-Max [3], etc. In this work, we used the 3D-Max package [4, 5], which allows one to generate a fairly adequate geometric shape of the RSO model using the Max-script language, to assign the required diffuse and specular reflection coefficients of light to each elementary surface, as well as its color.

To generate synthetic light curves, we used a model whose shape is approximately similar to a spacecraft (SC) of the DMSP type [6]. For objects of this series, our photometric database [7-8] contains many observations and it can be noted that many of them often demonstrate periodicity of brightness variations, have a complex structure of light curves and the presence of a significant number of specular flares. Fig. 2 shows images of the DMSP 5D3 spacecraft and the model used to obtain synthetic light curves.

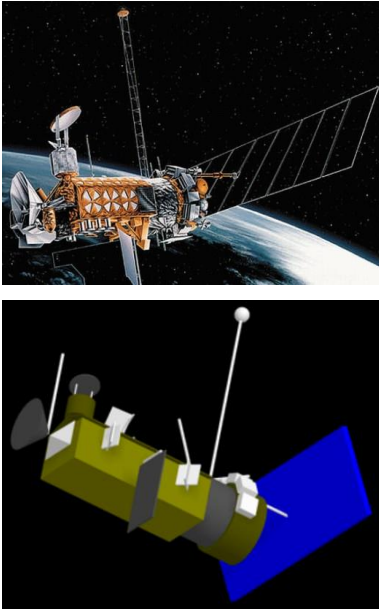


Figure 2. The spacecraft DMSP 5D3 (up) and model used to calculate the synthetic light curves (down).

It was assumed that the model rotates stably around a fixed axis, rigidly connected to the body and this axis is perpendicular to the base and longitudinal axis of the satellite. In this case, we have a flat rotation of the model relative to one axis, which also maintains orientation in inertial space over short time intervals (about 1-2 days).

3 RESULTS OF LIGHT CURVE SIMULATIONS FOR DIFFERENT OBSERVATION SITES

Calculations of the synthetic light curves of the model were made for several observation sites located in different places in the northern and southern hemispheres (see Tab. 1).

Table 1. Coordinates of observation sites for which synthetic light curves have been calculated.

Site Name	Abbreviated Name	Geographical latitude, deg	Geographical longitude, deg
Odesa	Ods	46.5	30.7
Novosilky	Nov	50.6	30.6
Lviv	Lvi	49.9	24.0
New Zealand	NZel	-44.0	170.5
Northern Australia	NAus	-17.6	123.8
South Africa	SAfr	-32.4	20.7
Argentina	Arg	-45.6	-69.1

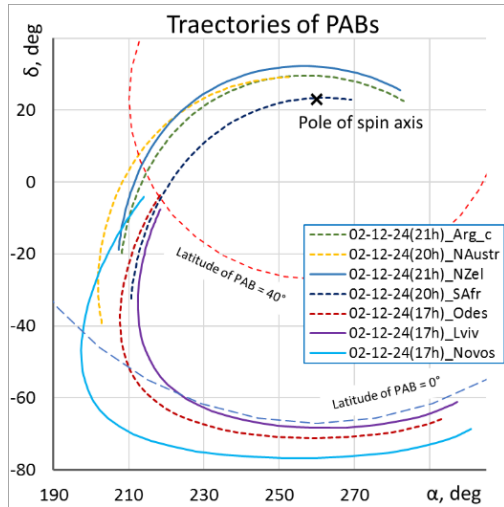
To calculate the visibility conditions of the model from different locations, the real orbit of SO with COSPAR ID 22154B ($i = 98.75$, $e = 0014$, $n = 14.17$) and typical observability conditions of the object were used. To calculate the light curves, the date of 02-Dec-2024 was selected, when visibility was realized from all seven observation sites. For this date, we considered only those SO passages for which the trajectories of the PAB vectors at least partially fall within the common region (see Fig. 3a) and, accordingly, the PAB latitudes can have a common range of change. For this purpose, in subsequent calculations of the light curves, the pole of the rotation axis of the model is taken in the direction determined by the equatorial coordinates ($\alpha_\Omega = 260^\circ$, $\delta_\Omega = +23^\circ$). The graphs of the change in the PAB latitude over time in the coordinate system associated with this rotation axis for all selected passages are shown in Fig. 3b). We see that the ranges of PAB latitude change overlap well in groups separately for northern and southern observation sites. For the chosen pole of rotation, these groups also partially overlap each other in the latitude range of about $+10^\circ \div +38^\circ$.

The inertial period of the model rotation is taken to be 18 sec, which with a discretization of 0.04 sec corresponds to 450 readings on the model's light curve. In different passes, up to 30 full rotations were observed while the object was in the visibility zone of the observation site.

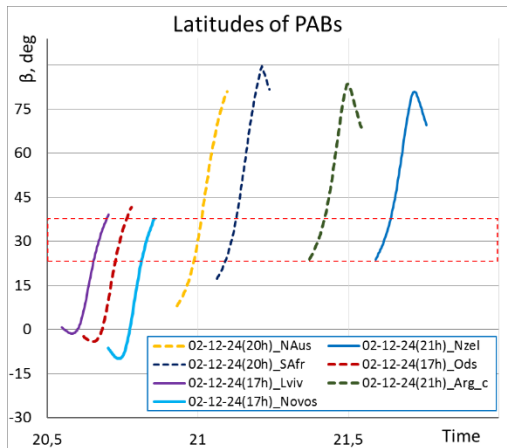
4 SELECTING SIMILAR PATTERNS

Let us now consider the obtained synthetic light curves of the model in order to compare them with each other and search for similar sections (patterns). For this purpose, one light curve was taken as a reference curve and it was divided into sections with a length equal to 1.5 rotation periods of the model. For each such fragment, sections similar in shape were searched for on all other light curves, and the two most similar ones were taken into consideration according to the adopted criterion. The sections were compared using the method proposed in [9]. In this case, for each pair of compared fragments, an indicator is generated that characterizes their difference

and allows only the most similar ones to be considered further.



a)



b)

Figure 3. a) – Trajectories of PAB vectors in seven passes of the SO model over different observation sites, for which synthetic light curves were calculated. The cross indicates the selected pole of the model's rotation axis, for which two latitude circles are shown. b) – Graphs of the change in latitude of PAB over time for these passages with the selected position of the pole of the rotation axis (graphs are arbitrarily shifted along the time axis).

In Fig. 4, as an example, several such fragments (patterns) are shown, where a section of the reference light curve is shown in black, and two found similar sections of the compared curve are shown in color. For the reference and compared light curves, the point numbers corresponding to the beginning of the depicted fragments are indicated. In the first two panels, the curve

obtained for Odessa was taken as the reference light curve, and in the next three panels, the light curve obtained for Northern Australia was considered as the reference. We see that for different observation sites, very similar fragments are successfully found on the light curves obtained at different times.

Such an analysis and the method of comparing the light curves obtained from different observation sites allowed us to select fragments that are structurally similar to each other. For the 7 light curves under consideration, we were able to identify 92 photometric patterns that belong to 19 different types. From 2 to 7 patterns belong to one type. For the average moment of appearance of each pattern, the equatorial coordinates of the PAB vectors were calculated. We can also always calculate the values of the phase angle for these moments. In addition, in our simulating experiment, we know the orientation of the rotation axis and therefore can calculate the values of the angle θ , as well as the coordinates of the PAB vectors in the coordinate system associated with the rotation axis. But only the equatorial coordinates of the PAB vectors are used to calculate the orientation of the rotation axis.

The equatorial coordinates of the PAB vectors corresponding to the moments of registration of a particular pattern are shown in Fig. 5 (left). We see that the points – traces of the PAB vectors form groups that ideally should have the form of arcs of small circles, the common center of which is the pole of the rotation axis of the SC model (the pole specified in the calculations is indicated by a black cross “x”; the pole found by this method is indicated by a red “+” sign). Fig. 5 (right) shows the latitude values of the same PAB vectors, but in a coordinate system associated with the found rotation axis. Here, the points corresponding to one pattern are located on average at one latitude (with some scatter), corresponding to the location on the surface of the SC model of light-reflecting flat smooth faces and other surfaces that form this pattern. The magnitude of this scatter determines the error in the sought coordinates of the pole of the rotation axis and it is due to errors in determining the average moments of the patterns and the corresponding PAB vectors. Thus, based only on the average moments of registration of the selected similar patterns and the corresponding equatorial coordinates of the PAB vectors in different passes of the simulated satellite, we obtained a solution for the sought coordinates of the rotation pole using the method described in [1]. The pole of the rotation axis found by this method is located at the point with coordinates $(\alpha_{\Omega} = 274.2^{\circ}, \delta_{\Omega} = +26.7^{\circ})$, i.e. it is 15° away from the true one. Perhaps this solution can be improved by excluding from consideration, for example, those PABs that have a significant irregular spread in Fig. 5, on the left.

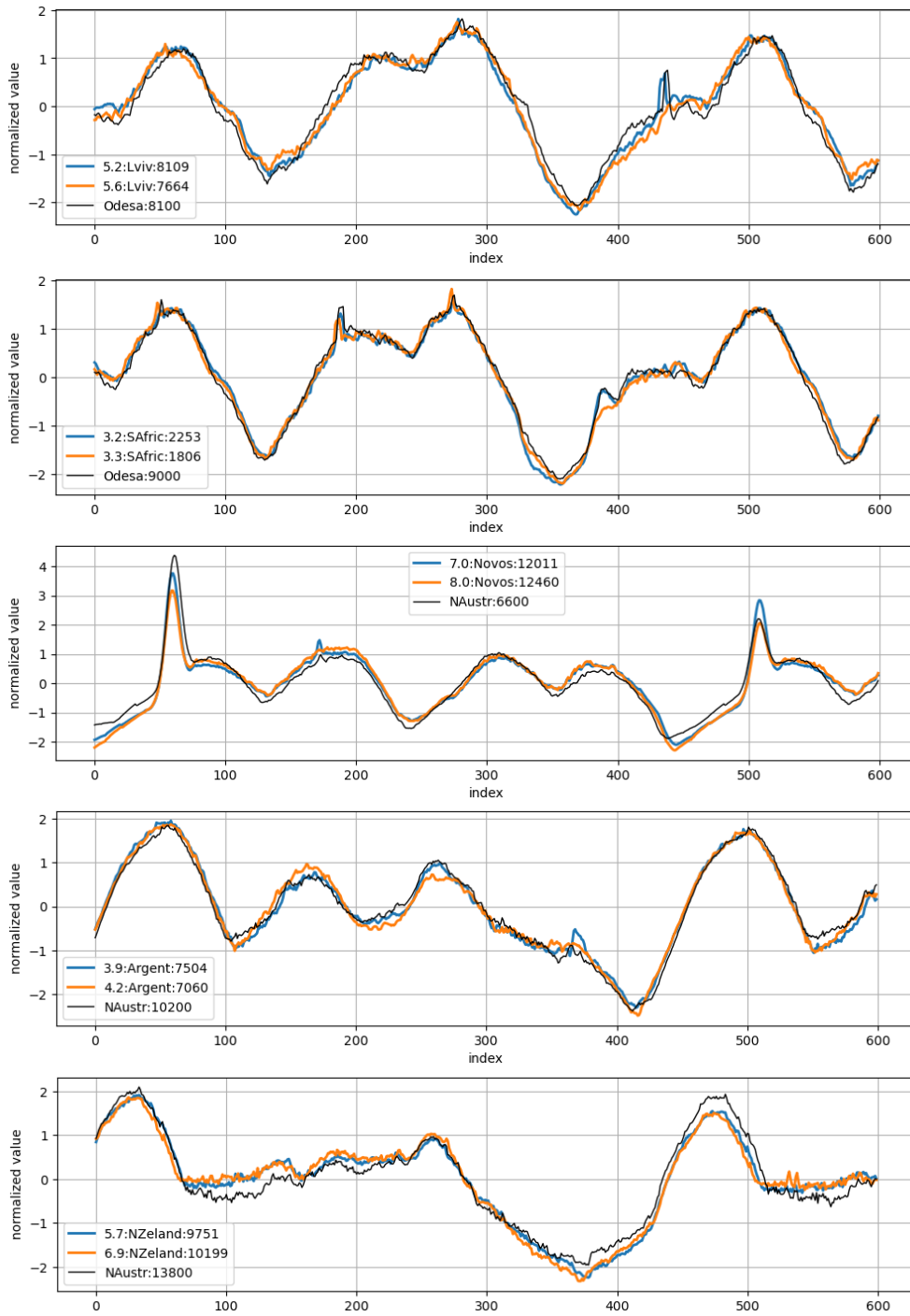


Figure 4. Fragments of the model's light curves showing similar patterns obtained from different observation sites. The black section shows the reference light curve, and the two most similar sections of the compared curve found are shown in color.

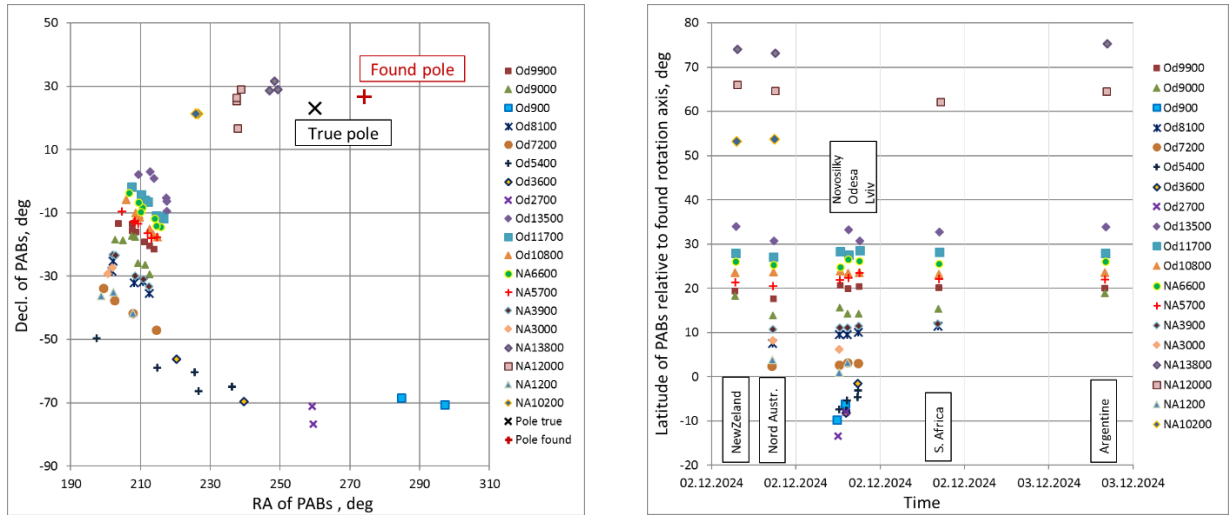


Figure 5. Left – Equatorial coordinates of the vectors of 92 PABs corresponding to the found similar patterns (the type is indicated in the legend). The a priori given (true) pole of the rotation axis and the one found by this method are shown by large crosses. Right – Distribution by latitude of these 92 PABs in the coordinate system associated with the found pole. The UTC time at the observation sites is plotted along the abscissa axis.

Observatory	21798	7411	10033	13736	18123	23233	23533	24753	25991	26536	6275	7816
30.12.2024	Lviv	Lviv			Lviv							
02.01.2025	Ods	Ods		Ods+Ods	Ods+Ods					Ods		
05.01.2025	Nov											
08.01.2025	Ods			Ods	Ods		Ods		Ods		Ods	
09.01.2025	Ods	Ods		Ods	Ods		Ods		Ods+Ods		Ods	
13.01.2025	Muk											
14.01.2025	Ods	Ods		Ods	Ods		Ods		Ods	Ods		
15.01.2025	Ods	Ods		Ods	Ods				Ods	Ods		
19.01.2025	Nov											
20.01.2025	Lviv+Ods	Ods	Lviv	Ods	Lviv				Ods	Ods		
25.01.2025	Muk											
26.01.2025	Muk	Muk		Muk					Muk	Muk		
29.01.2025	Muk	Muk			Muk					Muk		
30.01.2025	Lviv+Uzh+Muk	Lviv+Muk							Muk	Lviv+Muk	Uzh+Muk	
01.02.2025	Uzh	Muk		Uzh								
02.02.2025	Nov											
03.02.2025	Uzh+Ods+Muk	Muk+Muk		Ods					Muk		Muk	
04.02.2025	Muk		Muk						Muk			
06.02.2025	Muk	Muk			Muk							
09.02.2025	Muk	Muk		Muk	Muk		Muk					
10.02.2025	Nov+Muk	Nov		Muk	Nov					Nov		
11.02.2025	Nov+Muk	Muk+Nov	Muk+Nov	Muk	Muk+Nov	Nov			Muk+Nov	Muk		
12.02.2025	Nov+Muk								Nov	Muk		Nov
13.02.2025	Nov	Nov		Nov				Nov				Nov
15.02.2025	Nov+Muk								Muk	Muk		
16.02.2025	Muk				Muk					Muk		
17.02.2025	Nov+Muk	Nov+Muk	Muk		Nov		Nov	Muk		Muk	Nov	Muk
18.02.2025	Nov+Muk+Uzh	Nov+Muk	Muk	Nov	Muk	Nov+Muk+Uzh	Nov		Muk		Nov	
19.02.2025	Muk	Muk			Muk					Muk		
20.02.2025	Muk		Muk									Muk
21.02.2025	Nov+Muk+Uzh	Nov		Nov			Muk	Uzh	Muk			
22.02.2025	Nov+Uzh	Nov+Muk										Nov+Uzh
23.02.2025	Nov					Nov				Nov		
24.02.2025	Nov+Ods	Nov+Ods	Ods		Ods	Ods		Ods	Ods	Ods		Nov+Ods
25.02.2025	Nov+Ods	Ods	Nov+Ods			Ods			Ods	Nov		
26.02.2025	Nov							Nov				
01.03.2025	Muk	Muk			Muk					Muk		
02.03.2025	Muk	Muk						Muk				
04.03.2025	Muk+Ods	Ods	Muk+Ods		Muk	Ods	Ods	Muk+Muk+Ods		Ods		Ods
05.03.2025	Muk	Muk						Muk	Muk			
06.03.2025	Nov+Muk+Ods	Nov+Muk			Ods	Nov+Muk	Nov+Ods	Ods	Ods			Muk+Ods
07.03.2025	Nov	Nov	Nov				Nov		Nov	Nov		
08.03.2025	Muk	Muk										Muk
09.03.2025	Nov+Muk	Nov								Nov		Nov
10.03.2025	Nov		Nov					Nov		Nov		
11.03.2025	Nov			Nov		Nov		Nov				Nov
12.03.2025	Nov		Nov						Nov			

Figure 6. List of SC and light curves obtained at different observation sites in 2025.

5 OPS/DMSP SERIES SPACECRAFT PHOTOMETRY CAMPAIGN (21798 AND OTHERS)

In order to apply the described method for determining the rotation axis direction to the light curves of real SC, it is necessary to have a several series of brightness measurements obtained over few days. In this case, one can hope that the SC rotation axis has not shifted significantly in the inertial coordinate system and the found similar patterns can be used to search for a single solution. For this purpose, we conducted two observation campaigns of several inactive SC of the OPS (DMSP) series. These SC have generally similar shapes, large sizes and are located in a densely populated altitude region in sun-synchronous orbits. Many of them rotate around the center of mass, but their rotation periods are very different. The shape of the light curves of these SC is usually complex, contains many specular brightness flares and quickly transforms during the spacecraft's flight over the observation site.

The first campaign took place from February 8 to March 3, 2023. Observatories located in Ukraine (Odesa, Novosilky near Kyiv, Mukachevo, Uzhhorod) and Slovakia (Modra Observatory) participated in it. In the second campaign, which runs from December 2024 to March 2025, two sensors of the NSFCTC (Novosilky and Mukachevo) and university observatories of Odesa, Lviv and Uzhhorod took part. The list of SC and the light curves obtained at different observatories is given in Fig. 6.

The largest number of light curves were obtained for the SC 21798 (91082A, DMSP 5D-2). Over the past few years, the rotation period of this SC has decreased significantly (see Fig. 7), and this acceleration of rotation has a seasonal character.

Fig. 8 shows the light curve of the SC 21798 (a fragment including 5 revolutions), obtained in Odesa on January 15, 2025. We see that during one revolution of the spacecraft, at least 9-10 short-term increases in brightness (flares) of varying intensity and amplitude appear on this fragment of the light curve.

Direct comparison of light curves obtained at observatories with different equipment is complicated by



Figure 8. A fragment of the light curve of SC 21798 (91082A, DMSP 5D-2 F11), obtained on 15-01-2025 in Odesa on the KT-50 telescope in tracking mode. The apparent rotation period is 6.91 sec (it is marked with vertical lines on the light curve).

the fact that they have different intervals between measurements. Therefore, comparison of light curves in order to find similar fragments is preceded by operations of data series approximation, noise smoothing and digitization with the same step. Fig. 9 shows an example of the results of searching for similar fragments in two light curves of SC 21798 obtained in Odesa on March 4, 2025 (interval between measurements is 0.02 sec) and in Mukachevo (OES35 telescope) on March 2, 2025 (average interval between measurements is 0.1 sec). The curve obtained in Odesa was chosen as the reference light curve. In the first panel we see a fragment of the reference light curve (black), which starts from the 1200th point, and two fragments of the second curve (colored), which start from the 254th and 578th points (neighboring spacecraft rotation cycles). The similarity of the two fragments can be considered good, since both the low-frequency and high-frequency components have the same brightness variation pattern. The latter is represented by several short-term increases in the spacecraft brightness in both fragments (taking into account the significant difference in the actual measurement frequency). A similar picture is observed in the three subsequent sections of the compared light curves, which on the reference curve start from the 6000th, 10800th, and 14400th points, respectively. Thus, for this case, the search for similar fragments can be considered successful.

We continue to process the accumulated photometric data for several selected RSOs using the method described above to obtain the current orientation of the rotation axis over short time intervals.

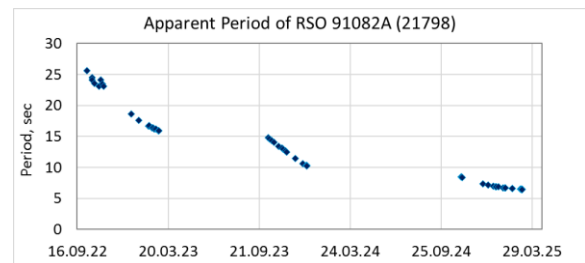


Figure 7. Change in the apparent rotation period of the SC 21798 (91082A) in 2022-2025.

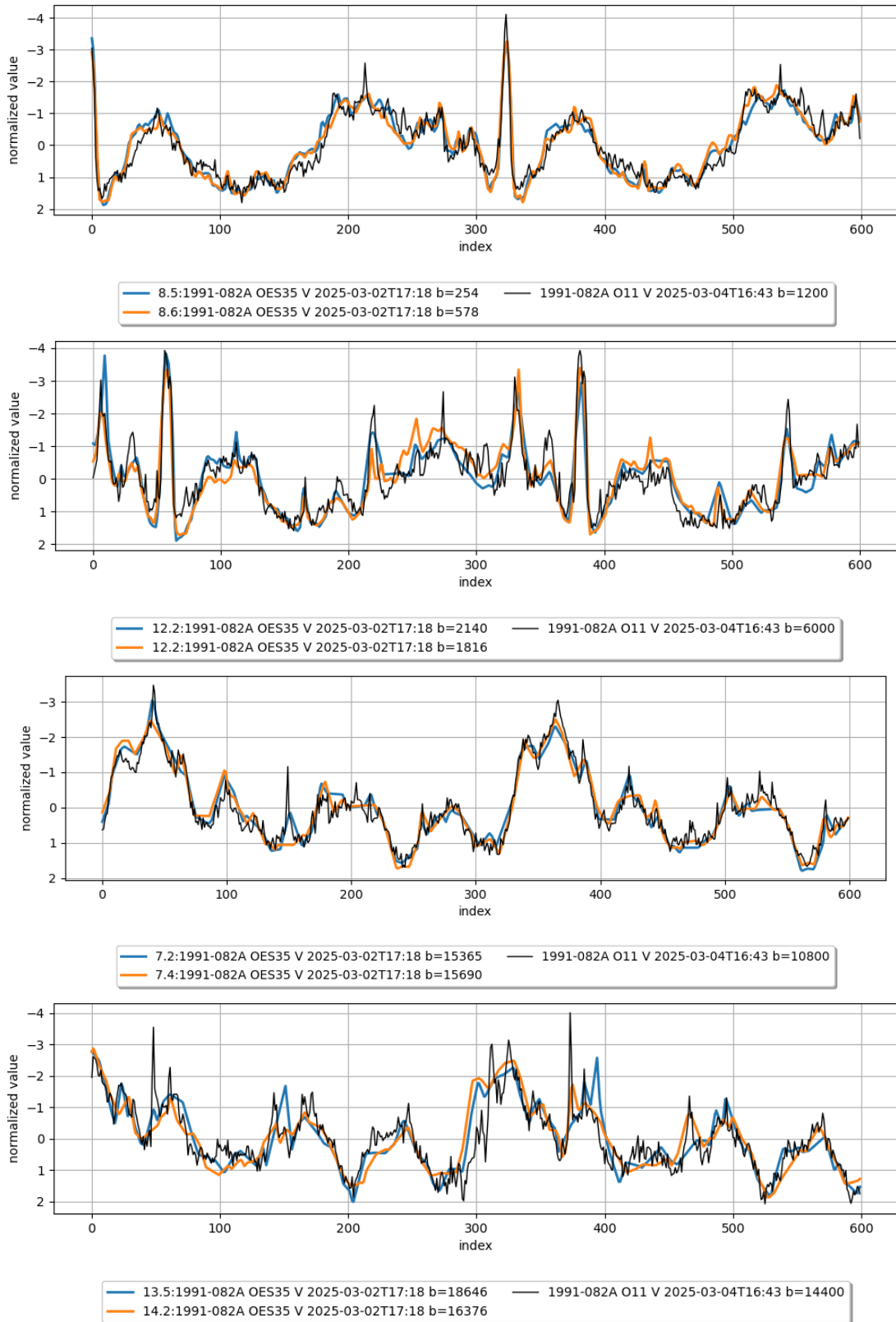


Figure 9. Four fragments of light curves obtained on 04-03-2025 in Odessa and on 02-03-2025 in Mukachevo, demonstrating similar patterns.

6 CONCLUSION

The method proposed in [1] for determining the direction in space of the rotation axis of a complex-shaped RSO rotating fairly quickly relative to the time of flight over the observation site was verified using synthetic photometric data of the SO model. In addition to the diffuse component, the light curves of the model used also contain a significant number of short-term “specular” brightness flares. Over a time interval of about 14 hours, a set of seven light curves was obtained for seven observation sites located both in the northern hemisphere (within Ukraine) and in the southern hemisphere (widely distributed in longitude). For all calculations of these synthetic light curves, it was assumed that the model rotates about one axis, fixed both in the body and unchanging in space. 92 sections with a duration of about one SO rotation were identified on the light curves, and based on their similarity, they were classified into 19 groups. For the average moments of their appearance on the light curves, the coordinates of the PAB were calculated, which were used to determine the direction (pole) of the model's rotation axis. Comparison of the found direction of the rotation axis with that specified when calculating the light curves of the model shows a discrepancy of about 15 degrees. Thus, this numerical experiment shows that diffuse-specular patterns similar in structure are successfully detected, which allows them to be used to determine the pole of rapidly rotating RSOs. Similar fragments are also successfully found on the light curves of the SC 21798 obtained as a result of a campaign by several observatories, so it can be expected that the accumulation of data will allow determining the orientation of the rotation axis of this SC on short time intervals.

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