

New Twin Tube Telescope for Photometry of LEO Objects

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ABSTRACT

Solving the problem of resident space objects (RSO) modeling, we encountered that photometry observations of RSO require high precision in the registration of flux and time. The available instruments in the Laboratory of Space Research did not meet these criteria. We present the result of creating a new device based on existing solutions under a limited budget. The main goal was to create a device that would be able to track LEO satellites with a lower altitude limit of ~700 km, capture light curves of RSO in two bands and short exposures, and cost less than 5k-7k euros in total, which is incredibly cheap for this segment of equipment.

The solution was achieved using the SkyWatcher AZ-EQ6 Pro mount and two tubes (F=1000 mm, D=200 mm), each equipped with a QHY-174M-GPS camera. After a year of operation with this device, we can present the observed results and describe both the positive and negative aspects of using the equipment. The obtained observations were used for modeling RSO objects with well-known shapes in the environment for 3D modeling, such as BLENDER and 3D MAX.

1. INTRODUCTION

Photometric observations of artificial Earth satellites play a crucial role in understanding their rotation, orientation, surface reflectivity, and operational status. These observations are performed using ground-based telescopes specifically configured to detect variations in the intensity of sunlight reflected from satellite surfaces. Telescopes used for this purpose combine moderate aperture optics, fast imaging sensors, and precise tracking systems capable of following objects in low and high Earth orbits. Typically, telescopes with apertures ranging from 0.2 to 1.5 meters are employed, with smaller instruments (0.3–0.5 m) being especially popular due to their affordability and sufficient photometric sensitivity. A wide field of view, often exceeding 1°, is essential for tracking fast-moving objects in low Earth orbit (LEO), while high-speed mounts allow for accurate tracking based on Two-Line Element (TLE) orbital data. To ensure the capture of fast brightness variations, most systems are equipped with CCD or CMOS detectors that offer high quantum efficiency (above 70%) and fast readout speeds [1, 2].

The capabilities of these systems extend beyond simple brightness monitoring. Photometric light curves can be used to infer the rotational state and surface properties of satellites, distinguish between active and non-functional objects, and even identify structural damage or configuration changes. In addition, photometry is increasingly employed in monitoring space debris, offering valuable insights into the population of non-cooperative objects orbiting Earth [1, 3].

The use of telescopes for photometric observation of artificial Earth satellites depends largely on the objectives and technical requirements of the study. For basic applications, such as tracking satellite rotation, monitoring brightness variations, detecting flares, or identifying gross structural changes, commercially available equipment is generally sufficient. This includes mid-range telescopes (with apertures ranging from 0.3 to 0.5 m), modern scientific-grade CCD/CMOS cameras, and commonly used tracking and processing software.

However, for more advanced and precision-demanding tasks, such as long-term monitoring of geostationary satellites, detecting small orbital debris, or conducting high-accuracy light curve studies, custom-built or highly specialized systems are required. These often include wide-field optical assemblies, robotic mounts with high tracking speeds, and integrated data acquisition and processing pipelines. Such systems are typically deployed in scientific observatories, defense monitoring networks, or national space agencies. Therefore, both commercial off-the-shelf solutions and custom-engineered systems are viable, depending on the complexity and scope of the mission objectives.

In this paper, we present the results of a commercial off-the-shelf solution that was made on the basis of the SkyWatcher AZ-EQ6 Pro mount and two Newton-type tubes equipped with QHY-174M-GPS cameras - “TwinPhot” telescope. The device was composed of two identical tubes, one tube with a B filter and the second with a V filter. Filters are placed right before the QHY camera without a filter wheel. The main parameters of the mount and CMOS cameras are presented in Table 1, photo of the telescope is in Fig. 1.

Table 1. Main parameters of the telescope.

Optics	Type	2 Newton tubes
	Aperture	200 mm
	Focal Length	1000 mm
Mount	Type	SkyWatcher AZ-EQ6 Pro with GOTO system (EQ/Alt-AZ Dual Mode)
	Slewing Speed	up to 4.2°/sec
	Driving Resolution	0.14 arc seconds
Camera	Type	2 x QHY-174M-GPS
	Chip	CMOS SONY IMX174
	Chip size	1920 x 1200 (11.25 mm x 7.03 mm)
	Pixel size	5.86 μm x 5.86 μm
	Pixel Scale	1.21 arcsec
	FoV	0.6 x 0.4 deg
	Max. Frame Rate	138FPS @ 1936 x 1216
	Shutter Type	Electric Global Shutter
	Time-Stamp Precision (GPS version)	1 microsecond of the GPS UTC clock

2. SYSTEM STANDARDISATION

To be able to compare the data obtained using different telescopes and instruments, photometric calibration is required — that is, converting instrumental magnitudes into a standard system. This study determines and presents the transformation coefficients for the Johnson-Cousin UBVRI system [4-6].

The transformation equations are defined as follows:

$$\begin{aligned} B_{inst} &= B_{std} + Z_B + K_B X + C_B(B - V)_{std}; \\ V_{inst} &= V_{std} + Z_V + K_V X + C_V(B - V)_{std}, \end{aligned}$$

where B_{inst} , V_{inst} are the instrumental magnitudes; B_{std} , V_{std} are the standard magnitudes; Z_B , Z_V are the zero points of the transformation equations; K_B , K_V are the first-order extinction coefficients; C_B , C_V are the color terms in the transformation equations; and X denotes the airmass.

To determine the parameters mentioned above, we observed numerous Landolt standard stars [7] with a broad range of colors on photometric nights, spanning a wide range of airmass. Observations were carried out on three nights in 2025. All images were processed using standard photometric reduction procedures, after which the instrumental magnitudes and corresponding airmass values were obtained. Standard magnitudes and colors were adopted from [7], allowing all parameters to be derived through linear regression. The second-order extinction coefficients were found to be negligible and are therefore not considered in this paper.

Fig. 2 and 3 illustrate the relationship between the Landolt standard magnitudes and the calibrated magnitudes in the B, V bands adjusted using the transformation coefficients obtained from observations on Jun 30, 2025. The fitted lines have slopes very close to 1.0, indicating a high-quality calibration with no evident systematic errors.

All the calculated transformation coefficients for photometric nights are listed in Table 2. The observation dates are listed in the first column in Table 2. The filter names, zero points (Z), color terms C , and coefficient of correlation of Calibrated vs Catalog Magnitudes, are listed in the following table.

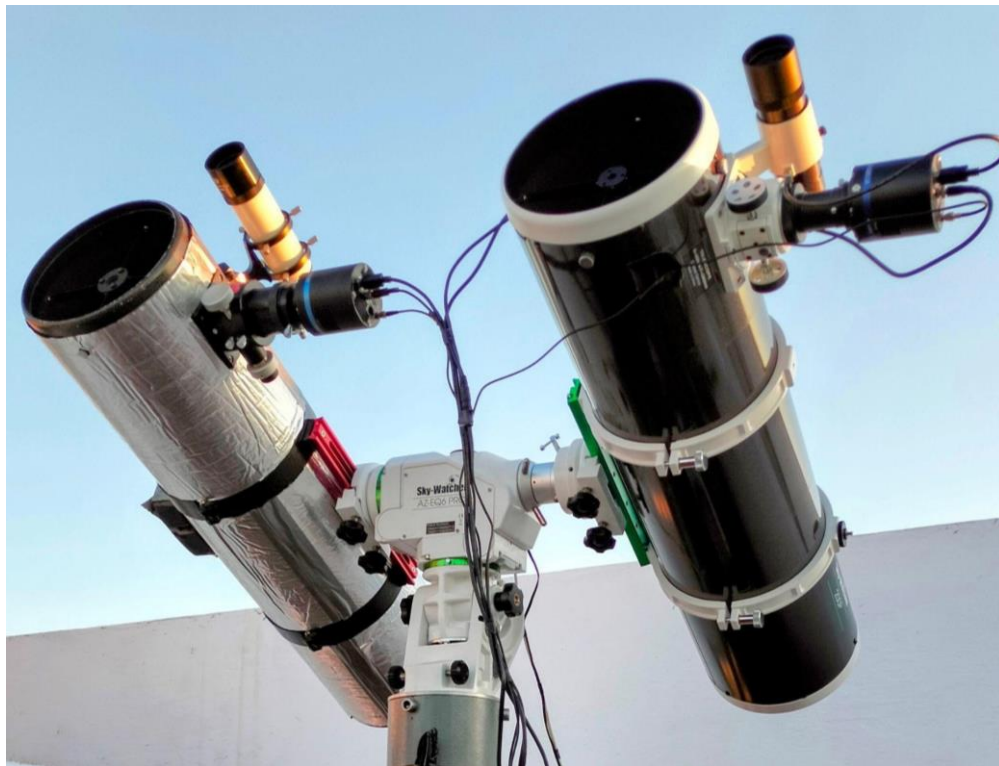


Fig. 1. Main view of the TwinPhot telescope

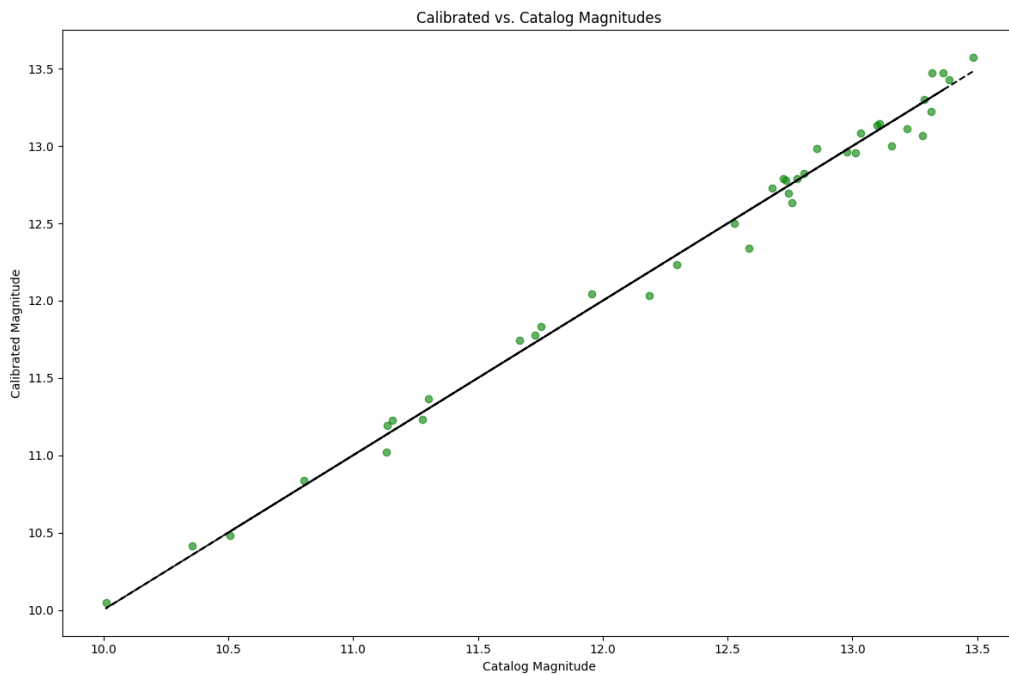


Fig 2. Relationship between the Landolt standard V magnitude and the shifted calibrated magnitude using transformation coefficients derived from observations taken on 2025 Jun 30

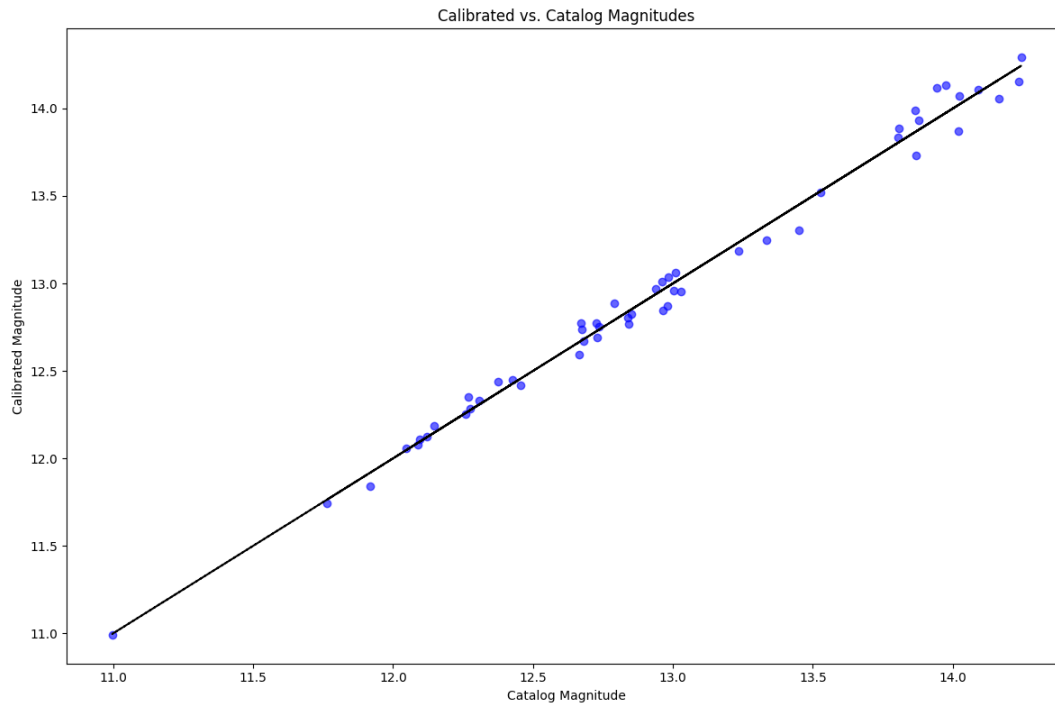


Fig. 3. Relationship between the Landolt standard B magnitude and the shifted calibrated magnitude using transformation coefficients derived from observations taken on 2025 Jun 30

Table 2. Calculated transformation coefficients for TwinPhot telescope

Date YYYY/MM/DD	Z	C	Correlation
B band			
2025/02/18	19.682 ± 0.0612	0.0529 ± 0.1060	0.9992
2025/06/30	20.257 ± 0.0150	0.0682 ± 0.0203	0.9966
2025/06/20	19.749 ± 0.0991	-0.0256 ± 0.0980	0.9858
Mean	19.896	0.0318	
V band			
2025/02/18	19.946 ± 0.0551	0.0423 ± 0.0760	0.9953
2025/06/20	19.963 ± 0.0239	-0.0394 ± 0.0249	0.9997
2025/06/30	20.034 ± 0.0232	0.0416 ± 0.0102	0.9980
Mean	19.981	0.0148	

For example, we show the RSO’s light curves obtained on this telescope in Figs 4 - 6.

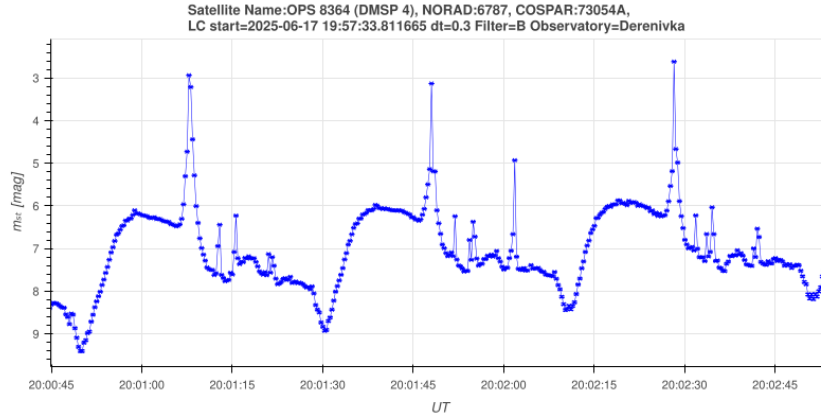


Fig. 4. Light curves of fast-rotating RSO objects

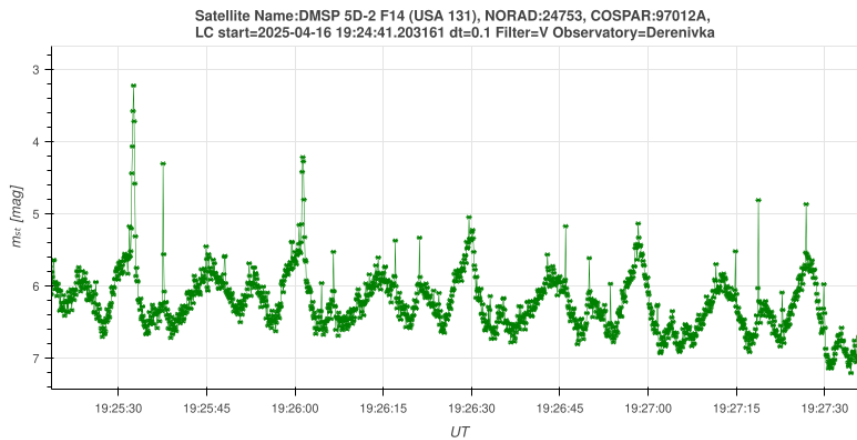


Fig. 5. Light curves of fast-rotating RSO objects

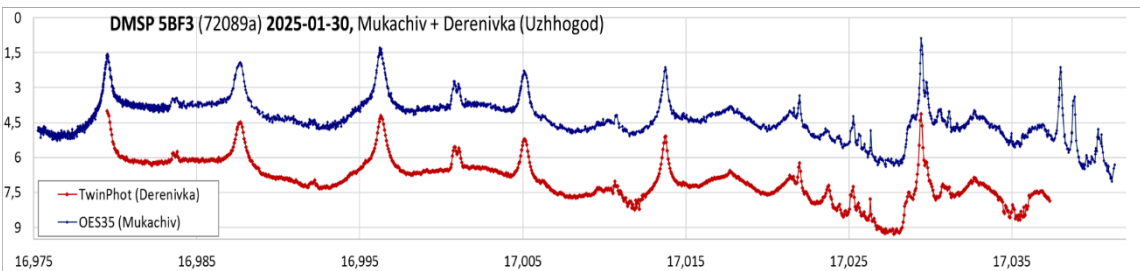


Fig. 6. Light curves of fast-rotating RSO objects obtained synchronously at two neighboring observatories - in Derenivka (TwinPhot) and in Mukachevo (OES35)

3. ANALYSIS OF PHOTOMETRIC OBSERVATIONS OF RSO BY THE UKRAINIAN NETWORK

One of the observational programs of the telescope network is the photometric monitoring of the spacecrafts of the OPS (DMSP) series. These spacecrafts 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 quite different. At the same time, according to photometric observations at the Astronomical Observatory of Odessa University, these spacecrafts show a cyclical variation in the rotation period over approximately one year. The shape of the light curves is usually complex, contains many specular flares and can be noticeably transformed during the spacecraft's flight over the observation station.

These spacecrafts are good candidates for the application of modern methods for determining the current orientation of the rotation axis in the inertial coordinate system using multi-point photometry data. For this, it is necessary to have a sufficiently dense series of light curves obtained over short time intervals, for example, over 1-3 days, from various observatories.

The results of such a campaign, conducted over agreed time intervals, are expected to yield estimates of the rotation axis direction and its evolution over time for several spacecraft of this series. This will allow a better understanding of the causes of the complex rotational behavior of such spacecraft, including the relationship between orientation change and rotation speed.

At present, five Ukrainian observatories have taken part in photometric observations of these spacecraft. The program has provisionally included 11 spacecrafts. During the first half of 2025, the telescopes of these observatories have obtained about 400 light curves of several OPS (DMSP) spacecrafts. Below are three fragments of light curves of different spacecrafts (Fig. 7).

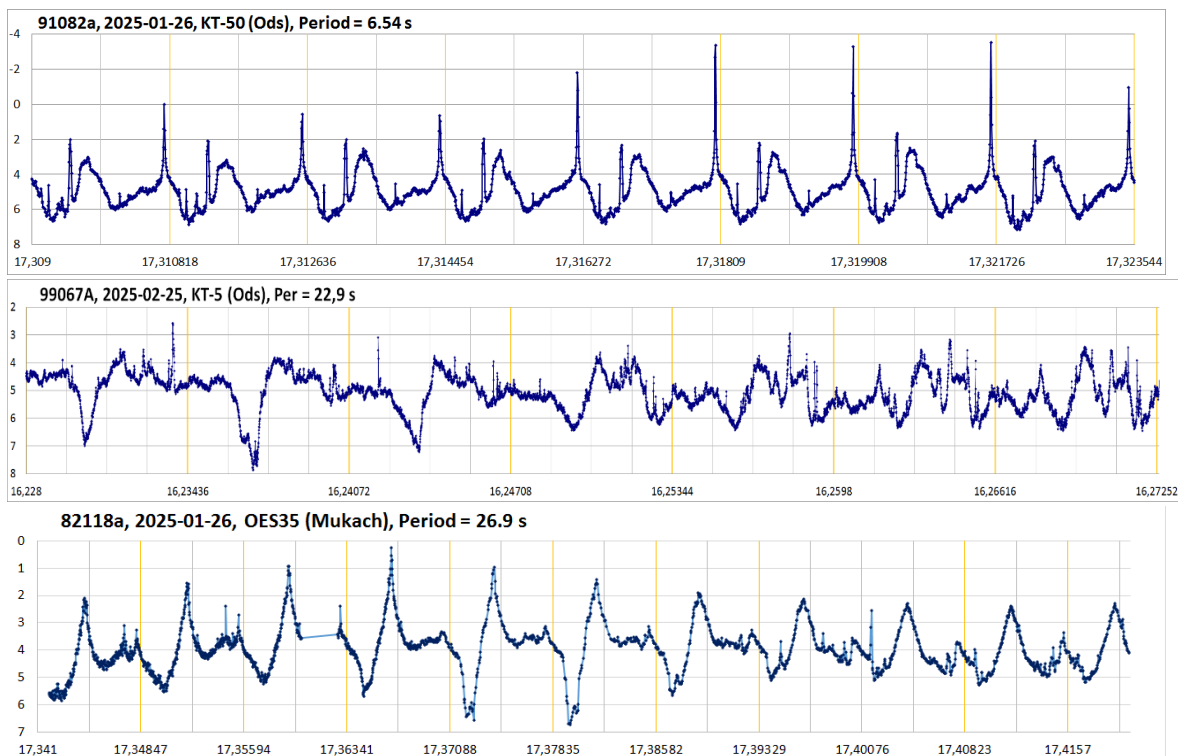


Fig. 7. Fragments of light curves of different RSOs of the OPS (DMSP) series

For the RSO 91082A (21798) in January-March 2025, the densest series of observations was obtained. Therefore, for the first time, we used observations of an RSO of this type to determine the spatial position of its rotation axis. For seven selected fairly short time intervals, different sections of the light curves were compared in order to identify sufficiently similar sections [8]. As an example, Fig. 8 below shows in black a section of the light curve of the RSO 91082A obtained on 11-02-2025 at the OES30 telescope in Novosilki (near Kyiv). Blue and yellow show two adjacent sections on the light curve of this RSO obtained on 09-02-2025 at the OES35 telescope in Mukachiv (near Uzhhorod).

It can be assumed that the very similar shape of the two fragments on different light curves is because at these two different moments in time, there were similar conditions of illumination and observation of this spacecraft. First of all, this concerns the angle between the satellite rotation axis and the phase angle bisector (PAB). After several dozen similar areas were discovered, we used the directions of the bisectors at the corresponding moments to determine some “average” direction of the spacecraft rotation axis for this time interval [8]. Fig. 9 shows seven such “average” directions of the rotation axis, related to the interval “January – early March 2025”.

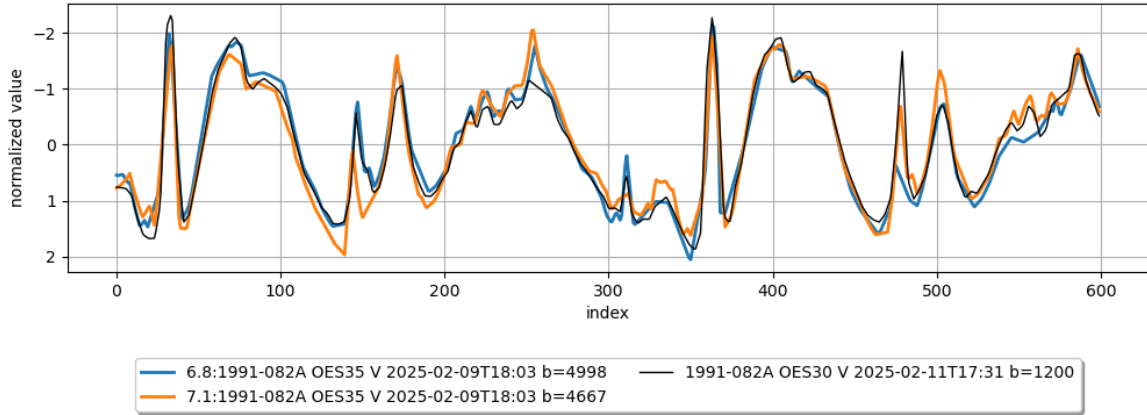


Fig. 8. Fragments of lightcurves RSO 91082A.

The following Fig. 10 shows the dependence of the coordinates of the rotation pole of the 91082A spacecraft on the date. The bottom panel shows the RA of the rotation axis in the orbital (i.e. slowly precessing) coordinate system. Here we see that relative to the plane of the orbit, the pole of the rotation axis does not have a systematic course as in the inertial coordinate system, but it has oscillations with a large amplitude ($\pm 25^\circ$).

The obtained results for the pole drift of the rotation axis need to be carefully checked. It is also necessary to obtain an estimate of the error's magnitude in determining the pole position. This work will be done in the future. However, the key condition for the success of such a study is coordinated quasi-synchronous observations in several observatories.

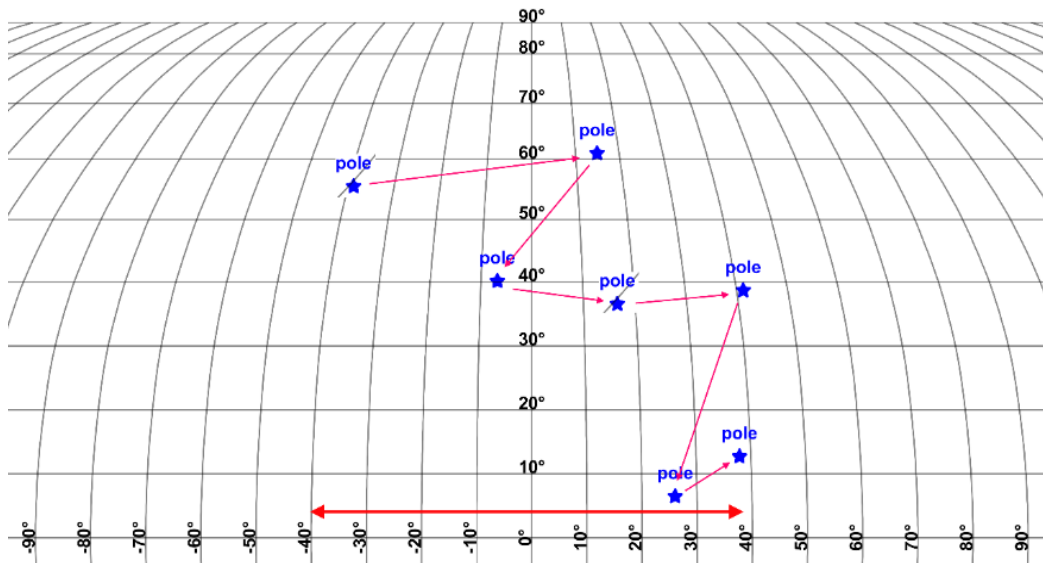


Fig. 9. Seven "average" directions of the rotation axis of RSO 91082A.

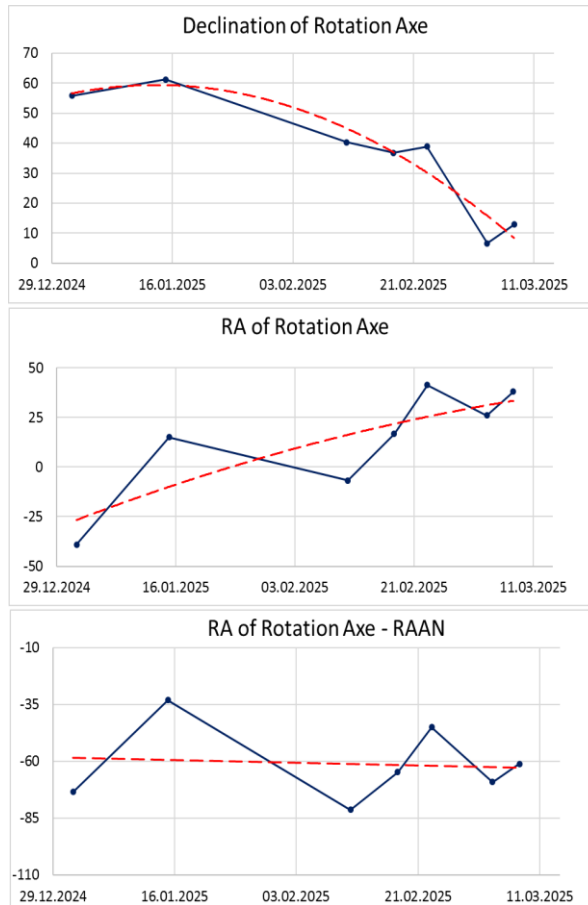


Fig. 10. Dependence of the coordinates of the rotation pole of the 91082A spacecraft.

4. 3D MODELING

4.1 Modelling RSO with Blender

A study was conducted to explore the possibility of using modern open-source software to model light curves. The Blender software was tested for generating synthetic light curves of a known form. The research results showed that using this method, it is possible to obtain a synthetic light curve of a satellite that will correspond with satisfactory accuracy to the real photometric curve of the satellite. The authors developed a light curve simulator based on Blender software and Python scripts, which uses a textured geometric model of the RSO, the parameters of its orbit, and the ground observation site. As a result, we generate a simulated light curve (apparent magnitude versus time) based on the reflection of sunlight from the object. The simulation results in such an environment are presented in Figs 11, 12 for the COSMOS 2528 satellite (NORAD 43657) [9].

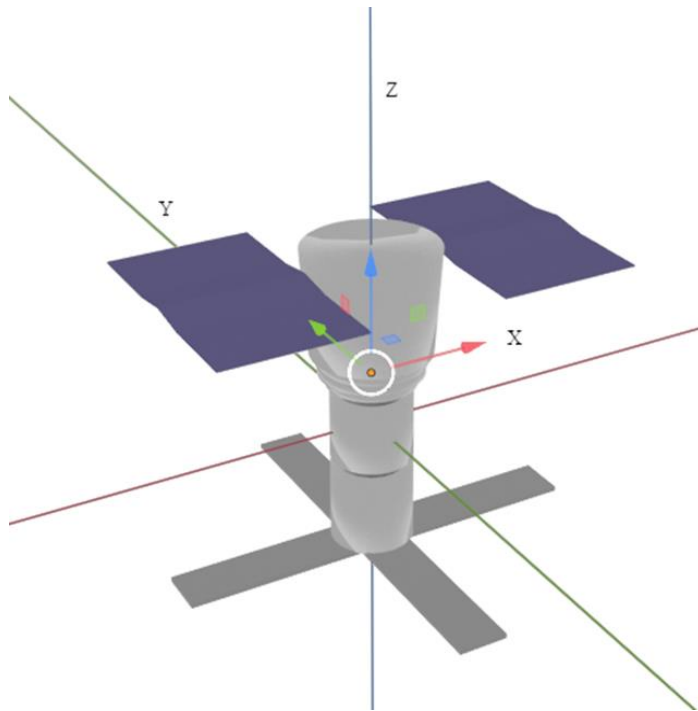


Fig. 11. 3D model of RSO COSMOS 2528 (NORAD:43657).

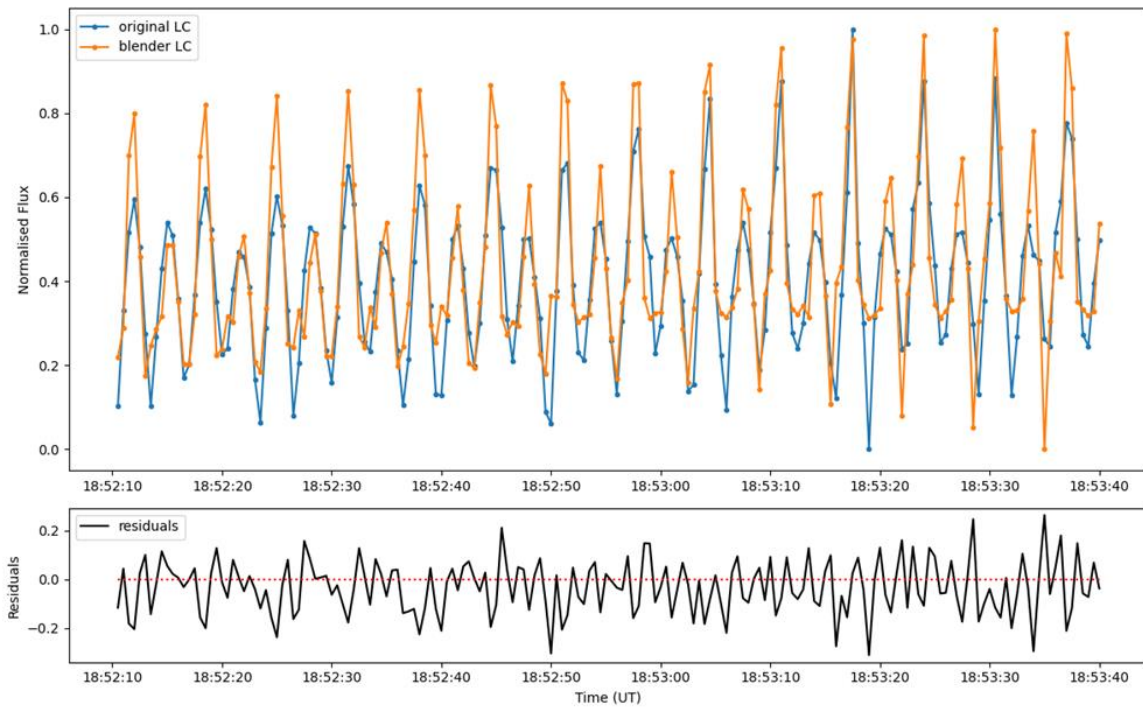


Fig. 12. Observed and synthetic light curves of the COSMOS 2528 satellite (NORAD 43657). The observation was made on August 18, 2022. The residuals between the two light curves are presented at the bottom of the figure

4.2 Modelling RSO with 3D Max

We have also accumulated experience using the 3D-Max package [10], which allows us to generate a fairly adequate geometric shape of the RSO model using the Max-script language, to set the required coefficients of diffuse and specular reflection of light for each elementary surface, as well as its color.

It is also important that in any simulator it is possible to set the correct ratio of the distances between the light source, the model and the radiation receiver in relation to the model dimensions. Since the observer always sees the RSO as a point source of light illuminated by the Sun's rays, all rays reflected towards the observer in a narrow solid angle (almost parallel to each other), for example, from all areas of a large flat surface of solar panels, should simultaneously hit the receiver. Otherwise, if the distance to the model is comparable to its dimensions, such a panel will be "visible" to the receiver in parts, i.e. "scanning" will be observed and a light flare, for example, from two strictly parallel solar panels located on both sides of the satellite body will look like a double one, which is not observed for real RSOs in orbit.

To analyze the obtained observations, we used the 3D-Max package and a model whose shape roughly corresponds to the shape of a DMSP-type spacecraft¹. As mentioned above, many of them often demonstrate periodicity in brightness changes, have a complex structure of light curves and the presence of a significant number of specular highlights. Fig. 13 shows images of the spacecraft and model used to obtain synthetic light curves. Table 3 contains the optical parameters that we used to specify the optical properties of light reflection for different surfaces of this model.

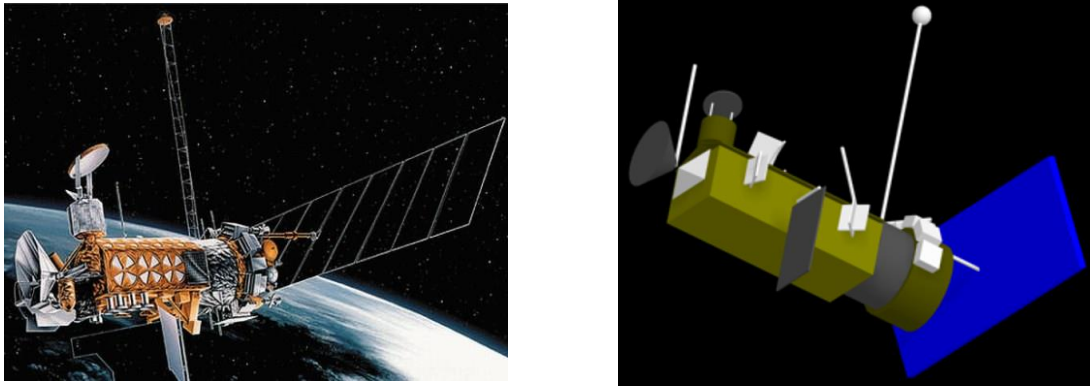


Fig. 13. The spacecraft DMSP 5D3 and model used to calculate the synthetic light curves in 3D-Max.

Table 3: Optical characteristics of the DMSP spacecraft model's individual parts specified in 3D-Max

Nomenclature	Color (RGB)	Diffuse Color	Specular Level	Glossiness
Main body of model	80, 80, 0	80, 80, 0	15	90
Small boxes, Small panels, Rods	150, 150, 150	150, 150, 150	990	100
Cylinder, cone, screen, disk	50, 50, 50	50, 50, 50	100	100
Solar Panel	0, 0, 170	0, 0, 170	10	60

5. RESULTS AND CONCLUSIONS

After the second year of observations, we obtained ~ 700 light curves of LEO RSO objects. The TwinPhot telescope was able to obtain light curves with an exposure time of 0.3-0.05 seconds, which is a good result for photometry of fast-rotating objects. Light curves of such fast-rotating objects are presented in Figs. 4-6.

The primary disadvantage of the system is the requirement to use two PCs, one for each QHY camera. Otherwise, in the case of one PC, it is not possible to achieve the desired short exposures (less than 0.1 sec) for the two cameras simultaneously. Having two monitors allows you to monitor the grabbing process in both channels in real-time and adjust the exposure, if necessary, which is also an advantage. Another disadvantage is the need to use USB 3.0 extension cables for QHY cameras, they should be of high quality.

¹ https://space.skyrocket.de/doc_sdat/dmsp-5d2.htm

Was also made an attempt to make astrometric measurements of RSO objects on more distant, geosynchronous orbits. The results were acceptable for use. If there were a sufficient number of stars on the frame, it was possible to resolve the frame and obtain an astrometric solution with Lemur software [11, 12].

Previously, in the paper [9], we tested photometry on the QHY-174M GPS camera to simulate the position of RSO objects with a known shape. This camera proved to be good, after which we decided to expand the system to two channels, B and V. In the future, we plan to conduct modeling attempts taking into account the color index. Attempts to simulate LCs with Blender and 3D MAX gave us good results.

The photometric monitoring of the OPS (DMSP) series spacecraft by the Ukrainian observational network has yielded significant insights into the rotational dynamics of these complex space objects. The comprehensive data set, which includes approximately 400 light curves, has enabled the calculation, in particular, of the rotation axis positions for the RSO 91082A over various observation intervals. The detection of cyclical variations in the rotation period and the oscillations in the rotation axis coordinates suggest intricate interactions between the spacecraft's orientation and its movement through space. These findings not only enhance our understanding of the rotational behavior of these satellites but also underscore the importance of coordinated, multi-site observational campaigns in advancing our knowledge of artificial satellites in densely populated orbits.

The successful application of modern photometric methods demonstrates the potential for further exploration of the rotational dynamics of other spacecraft within the OPS (DMSP) series and beyond. Future research will focus on refining the measurements of the rotation axis, estimating error magnitudes, and expanding the observational campaign to encompass a broader range of satellites. By continuing to leverage the capabilities of the Ukrainian network of observatories, researchers can better elucidate the complex influences that shape the behavior of these artificial objects, ultimately contributing to more effective management and operational strategies for satellites in low-Earth orbit.

6. REFERENCES

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