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## SIMULTANEOUS MULTI-SITE PHOTOMETRY OF LEO SATELLITES TO CHARACTERISE THEIR ROTATION STATES

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**ABSTRACT.** The photometry of space objects (SO) makes it possible to determine their state of rotation around the center of mass, orientation of the rotation axis and rotation speed in the most cost-effective manner. However, the methods for determining the attitude parameters from photometric data from a single observation site (OS) require long series of high-quality and high-frequency measurements. We propose a method for determining the orientation parameters of slowly rotating SO based on simultaneous multi-site photometry with a high temporal resolution. Preconditions for planning and building a local photometric network that can accomplish such a task have been tested via computer simulation. Synchronous observations of the unoperated spacecraft TOPEX/Poseidon were carried out. They were attended by the observatories of Odessa, Lvov and Uzhgorod universities, as well as the observation station of the State Space Agency of Ukraine in Zalistsi, Khmelnytsky region, took part. Synchronous network-based photometric observations from three OSs enable us to calculate time lags between correlated light-curve segments and promptly determine the direction of rotation, as well as the spatial orientation of a SO's spin axis and its angular spin rate. A local network of several distributed observation sites for synchronous monitoring of the rotation of various SO in LEO will make it possible to determine the rotation parameters of also slowly rotating objects that do not exhibit glints within their light curves.

**Key words:** space object (SO), rotation, attitude, photometry, synchronous observation.

**АНОТАЦІЯ.** Фотометрія космічних об'єктів (КО) дозволяє визначити їхній стан обертання навколо центру мас, орієнтацію осі обертання та швидкість обертання найбільш економічним способом. Однак методи визначення параметрів орієнтації на основі фотометричних даних з одного пункту спостереження (ПС) потребують довгих серій високоякісних та високочастотних вимірювань. В роботі запропоновано метод визначення параметрів орієнтації КО, що повільно обертаються, на основі одночасної багатопунктової

(мережевої) фотометрії з високою тимчасовою роздільною здатністю. Передумови для планування та побудови локальної фотометричної мережі, яка може виконати таке завдання, перевірені за допомогою комп'ютерного моделювання. Були проведені синхронні спостереження космічного корабля TOPEX/Poseidon, що вже не працює. У них взяли участь обсерваторії Одеського, Львівського та Ужгородського університетів, а також станція спостереження Державного космічного агентства України в м.Заліссі Хмельницької області. Синхронні мережеві фотометричні спостереження з трьох ПС дозволяють розрахувати затримки часу між корельованими сегментами кривих блиску та швидко визначити напрямок обертання, а також просторову орієнтацію осі обертання КО та кутову швидкість його обертання. Локальна мережа з кількох розподілених місць спостереження для синхронного моніторингу обертання різних низькоорбітальних КО дасть можливість визначити параметри обертання також об'єктів, що повільно обертаються та не мають періодичних спалахів у своїх кривих блиску.

**Ключові слова:** космічний об'єкт (КО), обертання, орієнтація, фотометрія, синхронні спостереження.

### 1. Introduction

Photometric observations of artificial satellites orbiting Earth are traditionally used as a source of information on the rotation about the centre of mass, spatial orientation and, finally, geometric shape of the observed object. Multi-hertz sample rate photometry is especially valuable as man-made SOs are commonly designed with smooth surfaces, they have non-convex overall shapes and can spin fast, etc. This results in periodic variations in the SO brightness amid rapidly changing phase and observation angles as the SO moves in its trajectory (see Fig. 1) (Kurosaki *et al.*, 2005; Koshkin *et al.*, 2018). Notably, such brightness variations are characterised by the so-called "apparent" period, that is, the observed period of the SO light curve which can vary significantly during a flyby of the SO over the ground OS as

the line-of-sight direction changes. Mathematically, it is expressed using vector addition of constant angular spin rate of the SO about its centre of mass and variable angular velocity of the phase-angle bisector (PAB), which depends on the SO orbital motion relative to a topocentric observer (Hall & Kervin, 2014). It is this condition that makes it possible, when solving the inverse photometric problem, to estimate the spatial orientation (in the inertial reference frame) of the SO spin-axis vector. Theoretically, the problem solution can result from processing of photometric observations during a single pass of the LEO SO over an OS. However, until recently, the described method for the real-time determination of rotation parameters of the SO could not be widely employed due to a lack of the required observing instruments and facilities. Therefore, researchers were often confined to only apparent (or synodic) rotation period measured from the light curve averaged out (or convoluted) in one way or another, since the “inertial” or sidereal rotation period could not be estimated separately from finding a solution to the SO spin-axis orientation.

The duration of the visibility of a LEO SO during its single pass is defined by the geometry of its visibility from the OS and is limited to several minutes. During this time span, a change in the phase angle (the angle Sun-SO-observer) can make up about  $90^\circ$  or slightly greater. A change in the “phase angle projection” onto the plane perpendicular to the satellite spin axis can be of the same order of value. It is the last value that determines the “apparent” period variation during a single pass. If the rotation period of a LEO SO is just several tens of seconds, an observer will see several complete revolutions made by the SO during each pass, which will allow the analysis of

the “apparent” period variation in order to find a solution to the SO spin-axis orientation. These estimates indicate that a relative change in the “apparent” period in the given example is just a few percentage points; hence, to measure it reliably, the LEO SO brightness must be recorded at a sample rate of at least 10-100 Hz. It is fairly feasible using a conventional set of instruments and equipment traditionally employed by different researchers to conduct photometric observations (Gasdia *et al.*, 2017; Hall *et al.*, 2006).

Meanwhile, it is known that many SOs experience a rapid decline in the angular spin rate resulting from their interaction with the Earth’s magnetic field. Consequently, the rotation period can exceed (and even significantly) the duration of viewing a LEO SO during its single pass (see Figure 2). Our experience of monitoring observations of a large number of satellites rendered inoperable, as well as upper-stages of rocket bodies, shows that the light curves of such targets become non-periodic and often do not have “features”. If that is the case, there is just a vague hope that the SO spin parameters can be inferred from single-site photometric data. In the present paper, we offer a problem-solving technique for such cases. This technique assumes creating local networks of multiple OSs and acquiring multi-site synchronous photometric observations of slowly rotating SOs. Methods of multi-site synchronous photometric observations have been already discussed in papers of other researchers (Hall *et al.*, 2007; Gasdia *et al.*, 2017; Schafer, 2017), though there has not been enough emphasis therein placed upon the fact that this is actually the only feasible way to estimate the spin parameters of “slow” SOs.

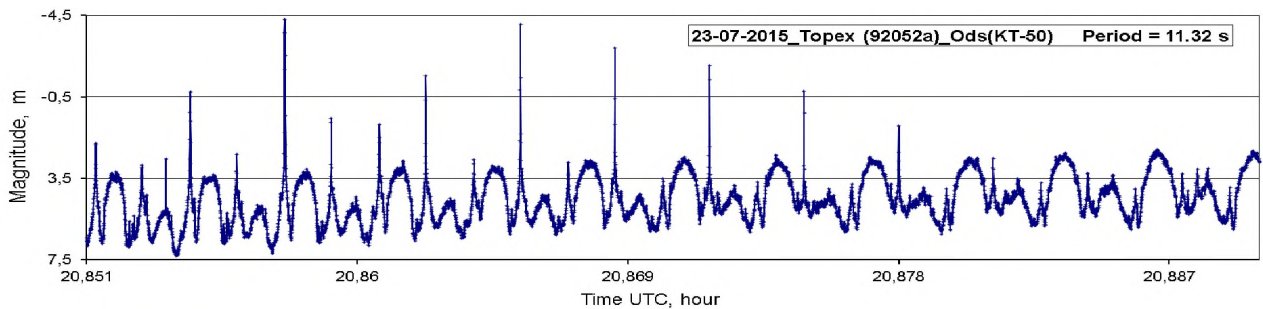


Figure 1: A light curve of the inactive Topex/Poseidon satellite (NORAD ID 22076;  $i = 66.039^\circ$ ,  $h = 1350$  km) obtained in Odessa with the KT-50 telescope on 23 July 2015. The length of the presented light-curve portion is 2.34 minutes (140 seconds). The apparent or synodic rotation period  $P_{syn} = 11.32$  sec. During the observing session, the phase angle changed by  $37^\circ$ .

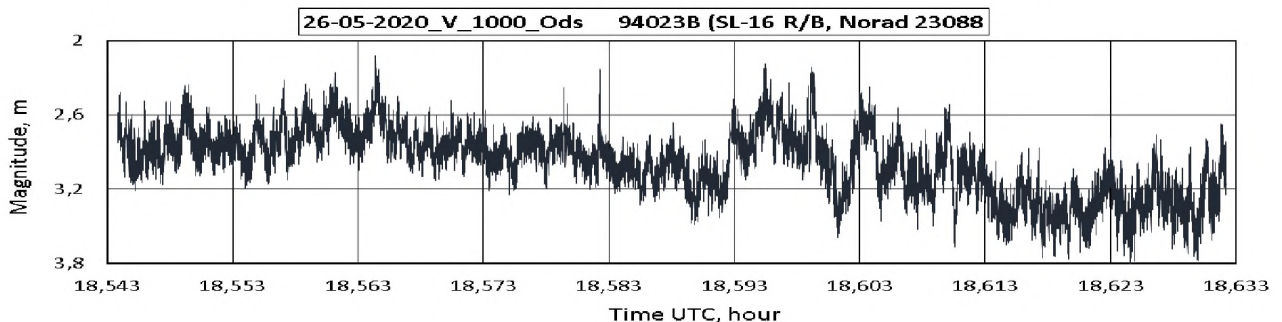


Figure 2: A light curve of the upper-stage SL-16 (NORAD ID 23088) obtained in Odessa with the KT-50 telescope on 26 May 2020 within the framework of the IADC (the Inter-Agency Space Debris Co-Ordination Committee) international campaign for the analysis of space debris (upper-stage rocket bodies) rotation. The length of the presented light-curve portion is 5.2 minutes (312 seconds).

## 2. Model computation to simulate multi-site synchronous photometric observations

We performed computer simulation of conditions for acquiring multi-site synchronous photometric observations of SOs. Our satellite model is a geometric representation of six identical, symmetrically located polyhedra, which are randomly oriented with respect to each other and partially penetrate each other's facets in order to minimize their mutual shading (Figure 3). Photometric properties of all flat facets of the model are identical; the reflection of light from each facet is quasi-specular, that is, the indicatrix is noticeably elongated in the direction of the specular reflection (the half-intensity indicatrix width is  $\sim 2$  degrees). The position of the spin axis related to the body of such a model does not matter; what is important is that the spin-axis orientation remains the same in all computations. Such a large number of flat facets integrated into the model is required to ensure that at varying spatial orientations of the model spin axis, as well as at different observer's locations, the light curve of the spinning model exhibits several almost randomly temporally-distributed glints given off of different facets over an interval shorter than the time required to complete a single revolution.



Figure 3: An optical-geometric satellite model represented as six polyhedra partially penetrating each other (a specular flash or glint given off a flat facet can be seen on one of the polyhedra).

The position of a source of parallel light rays (the Sun) is specified in the inertial equatorial co-ordinate frame with two angles: the right ascension  $\alpha = 0^\circ$  and declination  $\delta = 0^\circ$ . Then, the directions for five observer's locations in the same co-ordinate system are specified with the following pairs of co-ordinates  $\alpha$  and  $\delta$ : ( $71^\circ, +01^\circ$ ); ( $73^\circ, -05^\circ$ ); ( $75^\circ, 00^\circ$ ); ( $76^\circ, +05^\circ$ ); ( $78^\circ, -03^\circ$ ). Thus, the phase angle during simulation of this model is about  $75^\circ$  while the satellite-centric angular distance between individual modelled observing sites varies from 3 to 10 degrees. Figure 4 shows all five light curves simulated for the given observer's locations and position of the Sun, upon rotating the model  $215^\circ$  around the spin axis, whose spatial orientation is specified with  $\alpha_\Omega = 40^\circ$  and  $\delta_\Omega = 75^\circ$ . The rotation phase in a degree (an analogue to time scale) is plotted on the X-axis against the light intensity (apparent brightness) of the model in relative units on the Y-axis. As is seen, at different observer's locations, from five to eight glints of varying intensity occur within each light curve of this model. Mutual positioning of individual glints, that is, the phase delay (or time lag) between individual flares, recurs for

some of adjacent pairs throughout different light curves. This enables us to calculate an overall phase shift between different light curves, that is, between different synchronous records (measurements) of brightness variations of one and the same spinning model.

In this computational experiment, the modelled satellite does not move along its orbit, that is, geometric conditions of its visibility, such as the phase angle, etc., remain unaltered. The entire simulated light curve can therefore be considered as a continuous curve with the same phase shift relative to any other light curve, taken as a "reference" one. Computing the observed phase differences between the simulated light curves (through calculating the cross-correlation function), followed by superimposing the light curves on each other with a phase shift corresponding to the resulting phase differences, yielded a pattern illustrated in Figure 5. The light curves, appearing as a series of sharp maxima, are superimposed on each other quite well throughout the entire length, demonstrating synchronous occurrence of glints as viewed by several observers (in different combinations of the observing locations). In a few cases, the phase of an individual glint within one of the light curves is shifted with respect to several other glints that are well-synchronised. It is associated with a random temporal (or phase) coincidence of glints produced when the light is reflected off some other flat facet in this complex model. Nevertheless, these synchronously occurring glints (flares) suffice to perform calculations of the phase difference (or time lag) between all simulated light curves.

An analysis of the observed time lags between "similar" events within the light curves (or correlated light-curve segments) recorded by three OSs enables us to compute a local direction in which a quasi-specularly reflected spot of light travels along the Earth's surface. In Figure 6, numbers denote locations of three ground-based observation sites; the circle marks a spot of light reflected off of a satellite's facet, and the thick black arrow points in the direction of the spot-of-light's motion. The Y-axis is directed towards the celestial pole while the X-axis is parallel to the equator. By measuring delays in time of the peak brightness occurrence as viewed from each OS, we can compute a direction of the spot-of-light's motion at each location, that is, the inclination of the small-circle arc along which the spot of light is moving at a given local network location (the angle  $\gamma$  in Figure 6), and also its angular velocity. Calculating the satellite's spin-axis orientation (co-ordinates of the rotation pole) requires estimating the inclination of the arc, along which the spot of light is moving, at least at two different positions.

A preliminary conclusion can be inferred from the simulation results. Specular flares from flat facets, which serve as excellent markers within the SO light curve, can only be observed quasi-synchronously from three or more OSs that form a local photometric network if a certain ratio between the distance to the satellite and distance between these OSs is maintained. The satellite-centric angular distance between OSs should not markedly exceed 0.2 radians. In such a case, it is quite feasible to acquire correlated light-curve segments from several adjacent OSs.

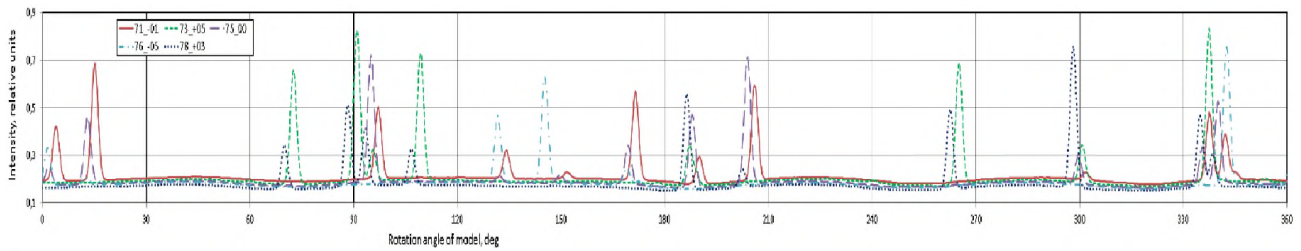


Figure 4: Superimposing five light curves of the satellite model simulated for five different modelled OSs forming a local photometric network.

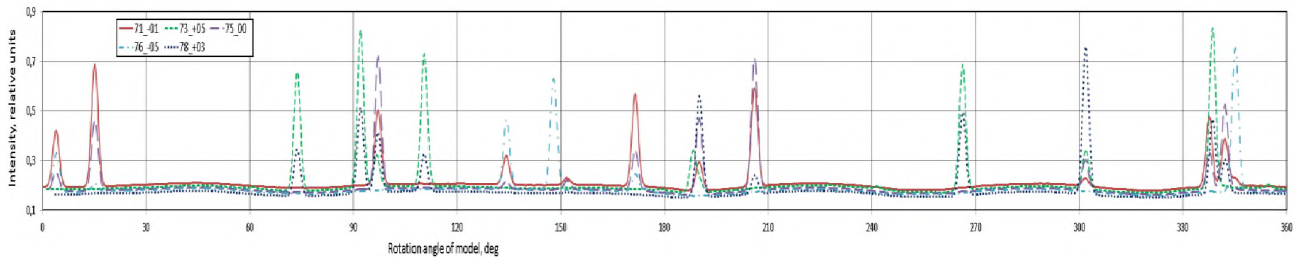


Figure 5: Superimposing five light curves of the satellite model simulated for five different modelled OSs, forming a local photometric network, after compensation for the actually observed phase shift between the light curves.

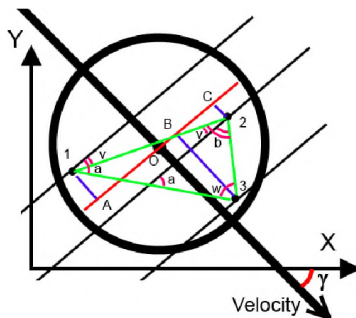


Figure 6: A pattern for calculating the direction, in which a “spot of light”, quasi-specularly reflected off of the satellite surface, travels along the Earth’s surface.

### 3. Synchronous observations of the Topex/Poseidon satellite by the Ukrainian network of observatories

There are several astronomical observatories in Ukraine that conduct photometric observations of artificial satellites and space debris. Taking that into consideration, in order to test the feasibility of obtaining synchronous network-based (that is, multi-site) photometric observations of such space objects, a campaign for observing inactive satellite Topex/Poseidon and the Experimental Geodetic Satellite Ajisai was carried out. Astronomical observatories of Odessa, Lviv and Uzhgorod universities, as well the observing station of the National Space Facilities Control and Test Centre of Ukraine in Zalistsi, participated in the campaign. Astronomical Observatory of Kharkiv University, located in Grakovo village, has also attempted to join the campaign, but failed so far. During the periods from 02 to 13 August and from 21 to 30 September 2020, synchronous observations of the afore-listed satellites were acquired from OSs that have the following co-ordinates: (Odessa:  $30.75569^\circ$  longitude,  $46.47775^\circ$  latitude, 54 m

altitude; Bryukhovichy:  $23.9544^\circ$ ,  $49.9176^\circ$ , 360 m; Uzhgorod:  $22.2986^\circ$ ,  $48.6334^\circ$ , 176 m; Derenevka:  $22.4538^\circ$ ,  $48.5636^\circ$ , 226 m; and Zalistsi:  $26.7183^\circ$ ,  $48.8483^\circ$ , 389.8 m). In so doing, the average distances between OSs were as follows: 680 km between Odessa and Uzhgorod; 640 km between Odessa and Lviv; 185 km between Lviv and Uzhgorod; 400 km between Odessa and Zalistsi; 320 km between Uzhgorod and Zalistsi, and 235 km between Lviv and Zalistsi. Given that the target satellites orbit at an altitude of about 1.5 thousand kilometres, each of the Odessa-Uzhgorod and Odessa-Lviv distances slightly exceeds the limiting/optimal estimated distance, which ensures a good correlation between quasi-specular flares within the light curves, while the distances between the other OSs are optimal. Figure 7 depicts portions of two light curves of the Topex/Poseidon satellite generated from synchronous observations in Odessa and Derenevka (an observing site of Uzhgorod National University) on 02 August 2020 at 20:32 (UTC), after performing a 0.25 sec time shift on one of the light curves.

The total length of the light curve acquired in Odessa is 10.1 minutes (with a short gap near zenith wherein the alt-azimuth mounted telescope KT-50 have got blind spot); the duration of the light curve obtained in Derenevka is 8.6 minutes (8.4 minutes of which correspond to synchronised guiding of the telescopes). During the first half of the pass, a very good similarity of the satellite light curves acquired at two sites distant from each other is observed over a long time span. During the second half of the pass, such a similarity is retained, though there is a marked contrast between the magnitudes of specular flares while the light curves differ in particulars. Figure 8 illustrates portions of two light curves of the Topex/Poseidon satellite acquired from simultaneous observations in Odessa and Lviv on 06 August 2020 at 20:05 (UTC), which have also been superimposed with regard to similar events through a 0.20 sec time-scale shift in one of them.

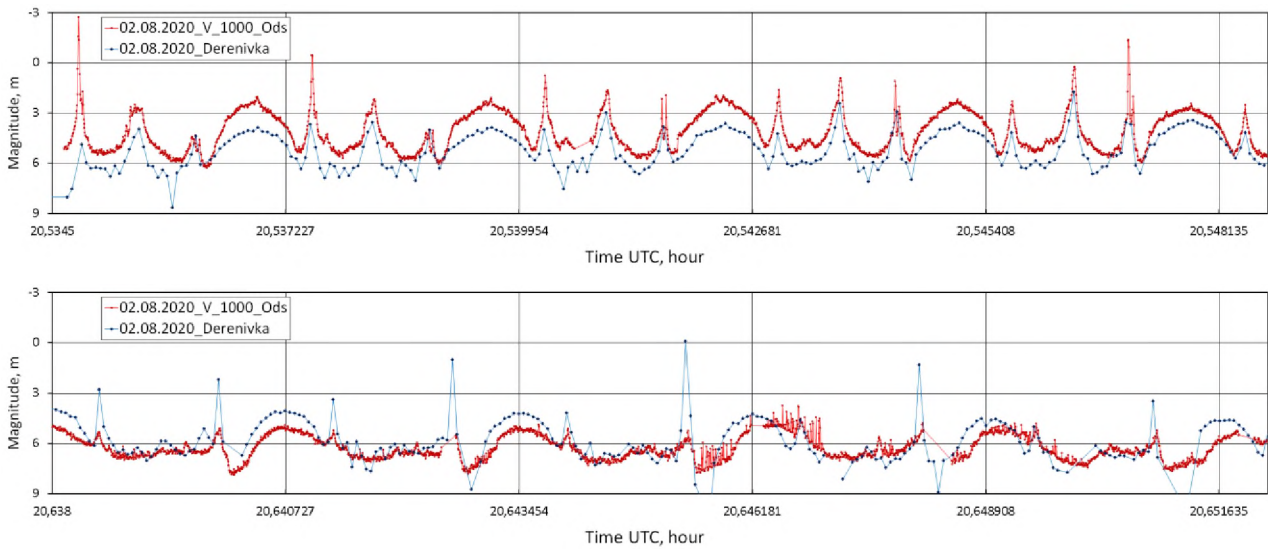


Figure 7: Portions of two light curves of the Topex/Poseidon satellite, synchronously observed in Odessa and Derenevka on 02 August 2020 at 20:32 (UTC), after performing a 0.25 sec time shift in one of the light curves.

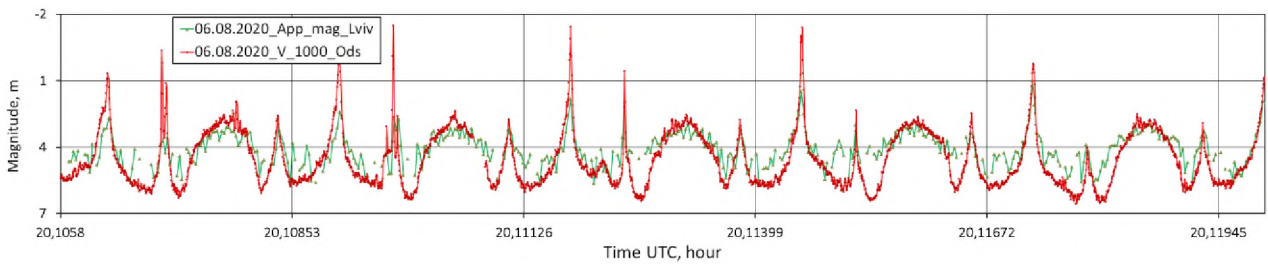


Figure 8: Portions of two light curves of the Topex/Poseidon satellite, synchronously observed in Odessa and Lviv on 06 August 2020 at 20:05 (UTC), after a 0.20 sec time-scale shift in one of the light curves.

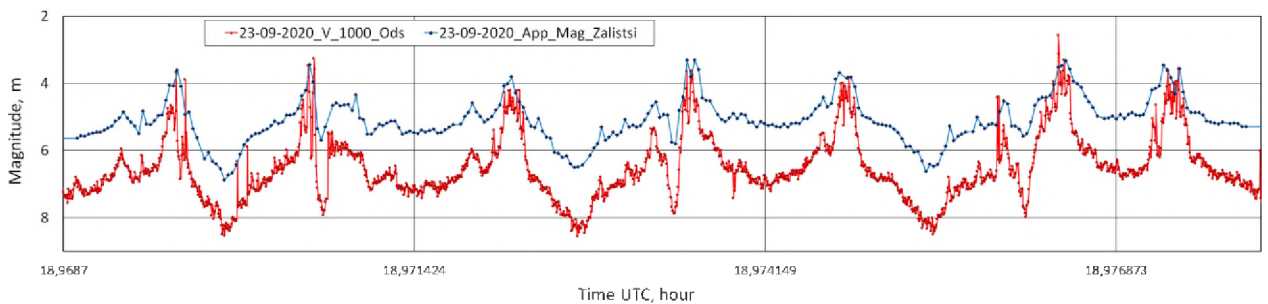


Figure 9: Portions of two light curves of the Topex/Poseidon satellite, synchronously observed in Odessa and Zalistski on 23 September 2020 at 18:58 (UTC).

Despite a considerably higher noise and lower rate of brightness measurements as compared to the photometric data from the KT-50 telescope, the light curve obtained in Lviv is similar, in principle, to that acquired in Odessa. Four major increases in brightness with a distinctive wide “diffuse” maximum and three quasi-specular maxima in between such increases are observed over a single revolution of the satellite. The Topex/Poseidon light curve exhibits such behaviour till the end of this pass.

During another pass, a portion of which is shown in Figure 9, the Topex/Poseidon light curve behaves differently: there are only two major increases in brightness associated with complex quasi-specular reflection of light during that pass of the satellite.

Notably, the interval between adjacent maxima changes rapidly from one revolution to the next, which is usually the case when the light is reflected off of a smooth conical surface. Synodic rotation period is characterised by intervals between minima of the satellite brightness. The light curves presented in Figure 9 were obtained synchronously in Odessa and Zalistski on 23 September 2020 at 18:58 (UTC), but to obtain visual similarity in terms of the shape of the light curves, the time-scale of the Zalistski observations was shifted additionally by four synodic periods. At the end of this pass, both light curves have a typical appearance with four major increases in brightness with a wide “diffuse” maximum and three quasi-specular flashes in between them (same as in Figure 7).

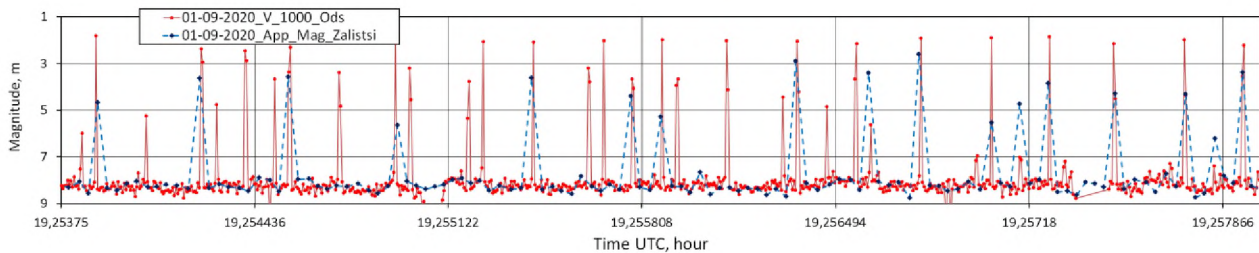


Figure 10: Portions of two light curves of the Ajisai satellite, synchronously observed in Odessa and Zalistski on 01 September 2020 at 19:15 (UTC).

Synchronous brightness measurements of the geodetic satellite Ajisai were only employed to verify the time-scale displacement (shift) at OSs relative to each other and with respect to Coordinated Universal Time (UTC). It is a feasible procedure as the Ajisai light curve exhibits numerous glints with an ultra-short duration of about 0.01 seconds (Koshkin *et al.*, 2017), and the developed model of this satellite and its rotation makes it possible to calculate precisely a time lag in the occurrence of each glint as observed from different OSs within similar error. An off-nominal delay in the occurrence of the glint at two OSs will indicate a respective error at the zero-point of the time scale at one of the OSs.

Portions of two light curves of the Ajisai satellite, acquired synchronously in Odessa and Zalistski, are plotted in Figure 10 (for the sake of convenience, one of the light curves is already shifted along the time scale by the computed time lag). As can be seen, a large number of glints occur synchronously, which suggests that there is no noticeable systematic error at the zero-point of the time scale at two OSs. Some glints are missing within the Ajisai light curve obtained in Zalistski due to insufficient sample rate of brightness measurements at this OS.

The analysis of synchronous measurements of the Topex/Poseidon satellite brightness acquired by the network of observatories is still ongoing. The main challenge is a low sampling frequency of measurements taken at some observatories, which impairs the accuracy of calculating phase and time delays between correlated segments of the satellite light curves. A low signal-to-noise ratio of the brightness measurements for this satellite is also a factor that contributes to reduced accuracy of the resulting estimates of time lags.

#### 4. Conclusions

It is well known that photometry of SO enables the estimation of their spin-axis orientations and spin rates in the most cost-effective manner; however, methods of determinate the spin-axis orientation from photometric data obtained at a single OS require long high-quality time-series of observations.

This paper introduces a new technique for estimating orientation parameters of slowly spinning SOs that relies on simultaneous multi-site photometry with high temporal resolution. Preconditions for effective planning and building a local photometric network of OSs have been

tested via computer simulation. Synchronous photometric observations from three OSs enable us to calculate time lags (phase delays) between correlated light-curve segments and almost instantly solve the problem of the determination of the direction of the SO rotation and its angular spin rate. Repeated measurement of these parameters by this local network or second independent measurements allows the estimation of the spatial orientation of the SO spin axis.

Monitoring the rotation of different SO in LEO requires a distributed local network comprising from five to nine OSs (photometric sensors). Such a local network will allow solving this problem in general, and in particular, it will make it feasible to estimate orientation of slowly rotating SOs that do not produce specular flares with respective peculiarities in their light curves.

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