SIMULTANEOUS MULTI-SITE PHOTOMETRY OF LEO SATELLITES FOR ROTATION CHARACTERIZATION

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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 cheapest way. 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 SOs based on simultaneous multi-site photometry with a high temporal resolution. The preconditions for the construction of a local photometric network capable of solving such a problem are estimated by the method of computer simulation. Synchronous observations of the unoperated spacecraft TOPEX/Poseidon were carried out. They were attended by the observatories of Odessa, Lviv and Uzhhorod universities, as well as the observation station of the State Space Agency of Ukraine in Zalistsi, Khmelnytskiy region, took part. Synchronous baseline photometric observations from 3 OS make it possible to calculate the time delays between the correlated fragments of the light curves and to determine quickly a direction of rotation, a satellite rotation axis orientation and angular velocity (a period) of rotation. 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 without specular flares in the light curves.

Keywords: LEO objects; photometry; attitude measurements.

1. INTRODUCTION

It becomes necessary to know the state of the Resident Space Objects' (RSO's) proper motion around the center of mass to solve many SSA problems. It makes it possible to increase the accuracy of orbits' determination and positions' propagation for spacecrafts (SCs) and space debris (SD) during the predicting dangerous approaches in the Near-Earth Space. It is a prerequisite for successful rendezvous planning during Active Debris Removal (ADR) operations.

However, many researchers note that determination of the rotation parameters of the RSO is a difficult task and often it has an ambiguous solution. Many such examples are presented, including on this conference. Photometric observations are traditionally used to obtain information about the rotation of the RSO relative to the center of mass: the period of rotation, the orientation of the rotation (spin) axis in Space-Fixed and in the Body-Fixed Coordinate System (CS), and (in some cases also) information about the geometric shape of the SO itself. The most useful technique is photometry with a high sampling rate (tens of hertz), since the technogenic shape of SC can consist of smooth surfaces, and SOs as a whole have a complex non-convex shape and often rotate rapidly. It leads (along with a rapid change of the phase angle and the spacecraft aspect angle due to orbital motion) to rapid changes in their brightness over a wide range of magnitudes. Rapid rotation around the center of mass leads to the observed periodic brightness variation of the SO (see, for example, [7] , [9]). Such brightness' change is characterized by the so-called "apparent" or more often discussed "average" period. The observed period of the SO's light curve can noticeably change during the time of the SC's pass over the observing site (OS). It is a result of a change in the sight's direction. Geometrically, it is expressed in the vector addition of the constant angular velocity of the SO's rotation around the center of mass and the variable angular velocity of the SO's apparent motion relative to the topocentric observer. For optical observations, it is necessary to consider not the relative motion of the SO and the observer, but the change in the direction of the phase angle bisector (PAB) [4], [5]. The measured change in the apparent period provides a key to determining the orientation of the SO's rotation axis in space. In the presence of all data about the shape and optical properties of the SC, the problem can be solved as a result of processing photometric observations

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for one pass of a Low Earth Orbit spacecraft (LEO SC) over the OS. However, the lack of the required data and the corresponding observational means did not allow (until recently) researchers to use widely this technique for the rapid determination of the rotation parameters of the RSO. A rare exception is the work [2], where the authors successfully applied the epoch method to determine the spin parameters of the rapidly rotating high-orbit satellite IMAGE. Usually, researchers limited themselves to measuring only the "apparent" (synodic) rotation period as a result of averaging (convolution) of the light curve in one way or another, since it is impossible to determine the "inertial" or "sidereal" rotation period separately from finding a solution for the SO's rotation axis orientation.

The LEO SO's observation time in one pass is determined by the geometry of its visibility from the OS and is limited to a few minutes. In this case, the phase angle (angle Sun-SO-observer) can usually vary in the range 20° ÷ 140°. It determines the amount of change in the PAB projection onto the plane perpendicular to the SC rotation axis. Exactly this value determines the change in the apparent period for the one SC's pass. If the rotation period of the LEO SO is up to several tens of seconds, then the observer will see several complete revolutions of the SO during one pass, and it can allow him to analyze the change in the apparent period in order to find a solution for the rotation axis orientation by the epoch method. Calculations show that the relative change of the apparent period is only a few percent in this case therefore, to measure it reliably, it is necessary to register the LEO SO's brightness with a sampling rate of 10-100 Hz. This is quite realistic for a set of modern equipment for photometric observations used by various researchers [1], [2].

However, it is known that many SOs quickly lose their angular velocity of rotation as a result of interaction with the Earth's magnetic field or under the action of other forces retarding rotation. It leads to the fact that the rotation period can exceed (and even significantly) the observation time of the LEO SO during one passage over the OS. The experience of observing a large number of nonoperational satellites and rocket stages shows that the light curves of such targets become non-periodic, and often they have very few "features" i.e. characteristic photometric "details" on the light curves. In this case, it is practically impossible even to estimate the period of its rotation by the method of photometry observations from one OS.

In [8], a method for determining the orientation parameters of slowly rotating SOs was proposed, based on simultaneous multi-site photometry with high temporal resolution, so in obtaining synchronous photometric observations. A feature of this method is its independence from the form of SO. Obviously, when the SO rotates, the luminous flux reflected by its surface also rotates in space. It can have a complex and rapidly transforming spatial structure of the brightness distribution. However, for closely spaced OSs of a local photometric network, under certain conditions, a similar sequence of brightness fluctuations of the SO should be observed, recorded with a certain time shift (offset). For example, if there is a quasi-specular reflection of sunlight by an arbitrary flat element of the SO's surface, then for closely spaced OSs, a flash on the light curve will be observed with one or another delay, depending on the direction and speed of the light spot along the Earth's surface. Fig. 1 shows a diagram of the location of three arbitrary OSs on the Earth's surface, marked with numbers 1, 2, 3. The circle represents a spot of light moving along the Earth's surface. It is the result of quasi-mirror reflection of light from a flat face on the surface of a rotating SO. The bold arrow shows the local direction of the spot movement. When the light spot passes over the photodetector of the OS, a flare of spacecraft brightness is recorded, and the maximum intensity of the flare will be observed when the angular distance of the OS from the center of the spot is minimal, i.e. when the spot diameter, perpendicular to the direction of its movement, intersects the OS. By measuring the time delays between the moments of the maximum flare intensity at each OS and knowing the distance between them, we can calculate the linear speed of the spot movement in a given place, and the angle between the direction of the speed and parallel. This technique is applicable both for rapidly rotating spacecraft and, it is especially important, for slowly rotating satellites, if their light curves contain a series of short "mirror" flares or other characteristic structures that make it possible to find mutually correlated fragments of light curves obtained on neighboring OSs. The method of synchronous photometric observations from more than one OS has already been discussed in the works of other researchers [1], [3], [10], [11]. However, no concrete results have yet been obtained to determine the rotation parameters of real SOs. Moreover, attention was not focused on the fact that it is actually the only way to determine the rotation parameters of "slow" SOs by photometric method. It is clear that the achievement of our goal is a reliable determination of the vector of the angular velocity of SO rotation and it depends on the adequacy of our model concept for the motion parameters of a spot of light on the Earth's surface to the real process of its displacement. For specular

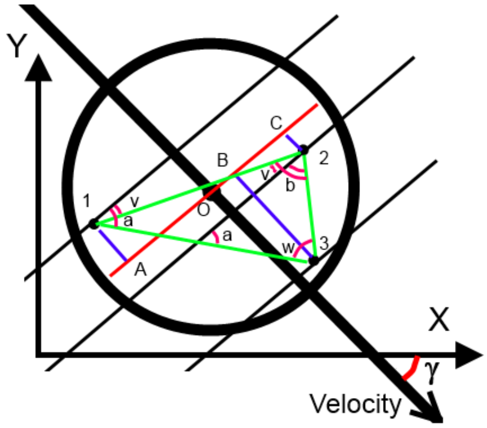

Figure 1. Scheme for calculating the direction of motion of a "spot of light", quasi-specular reflected from the flat surface of the SO, on the Earth's surface.

reflection of light from a flat surface, this model is the PAB offset.

2. SIMULATION OF SYNCHRONOUS MULTI-SITE PHOTOMETRIC OBSERVATIONS

In the simulation experiment described below, we considered exactly the case of specular light reflection from a flat surface and carried out computer simulating of the conditions for obtaining synchronous photometric observations of SC for real OSs located on the territory of Ukraine. We calculated simulated light curves with a time resolution of 0.01 s for OS in Odessa, Nikolaev, Yevpatoria, Zalistsi, Khmelnytsky region, Lviv, and Derenivka (Uzhhorod National University), and calculated the time delays of the observed appearance of the brightness flare maximum at these sites.

The SC model consists of six identical symmetrically located polyhedrons rotated at a certain angle relative to each other and partially penetrating each other in order to reduce mutual shading (Fig. 2). The photometric properties of all flat faces of the model are the same and the reflection of light from them has a quasi-specular character, i.e. the indicatrix has a shape that is very elongated in the direction of specular reflection (the width of the indicatrix at half the intensity is ~ 2 degrees). The position of the rotation axis in the body of such model does not matter for this numerical experiment. We only assume that in all calculations the rotation axis orientation in the body of the model, and in the inertial CS, is fixed. A large number of model flat faces is necessary in order to the light curve of the rotating model has several almost randomly distributed in time light flares from different faces during the time interval less than one complete revolution for any orientation of the model rotation axis in space, as well as for different positions of the observer. As a basis for calculations, we took the real orbit of the Topex / Poseidon SC and its passage over several real OS of our local network that took place on August 2, 2020 at the interval of 20.52 - 20.69 hours UTC. The position of the source of parallel light rays (the Sun) is specified in the inertial equatorial CS by two angles: right ascension α = 133.16° and declination δ = 17.55°. We consider six OS, the coordinates of which are given by pairs of geographical coordinates (longitude, latitude) and altitude in the WGS-84 (Tab. 1).

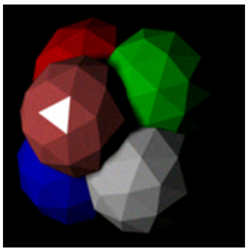

Figure 2. The optical-geometric model of the SC in the form of six polyhedrons partially penetrating each other (one of them shows a "mirror flare" of brightness from a flat face).

Table 1. Observation sites

Observation site	Additional ID	Location (WGS-84)
Odessa	Ods	Long: 30.75569°; Lat: 46.47775°; Altitude: 54 m
Lviv	Lvi	Long: 23.9544°; Lat: 49.9176°; Altitude: 360 m
Derenivka	-	Long: 22.4538°; Lat: 48.5636°; Altitude: 226 m
Zalistsi	Dun	Long: 26.7183°; Lat: 48.8483°; Altitude: 390 m
Nikolaev	Nik	Long: 31.9736°; Lat: 46.9711°; Altitude: 56 m
Yevpatoria	Evp	Long: 33.1640°; Lat: 45.2197°; Altitude: 47 m

At the same time, we have the following basic distances between different OSs: Odessa-Derenivka distance is 680 km, Odessa-Lviv distance is 640 km, Lviv-Derenivka distance is 185 km, Odessa-Zalistsi distance is 400 km, Lviv- Zalistsi distance is 235 km, Odessa-Nikolaev distance is 108 km, Dunaevtsy-Yevpatoria distance is 635 km, Odessa-Yevpatoria distance is 233 km, Nikolaev-Yevpatoria distance is 215 km. Thus, taking into account that the orbital altitude of this spacecraft is about 1.5 thousand km, the satellite-centered angular distance between the individual OS ranged from 3 to 30 degrees. Fig. 3 shows fragments of five simulated light curves obtained for the indicated OS (without Derenivka) on August 2, 2020 for 62.5 seconds at the beginning of the passage. In this case, the model, which rotates at a speed of 8 °/sec, managed to turn through an angle of 500° around the rotation axis, which has an orientation in the inertial equatorial CS: $\alpha_\Omega = 80°$ and $\delta_\Omega = 60°$. The X-axis is time (in hundredths of a second). The Y-axis represents the model's brightness in relative units.

We can see that in this fragment of passage in different OSs, the light curves of the model exhibit several flares of different intensities and the photometric signals are strongly correlated. This allows us to calculate the total time shift (delay) between the light curves obtained by different OSs. It was relative to Odessa: 1.14 seconds for Lviv, 0.75 seconds for Zalistsi, -0.11 seconds for Niko-

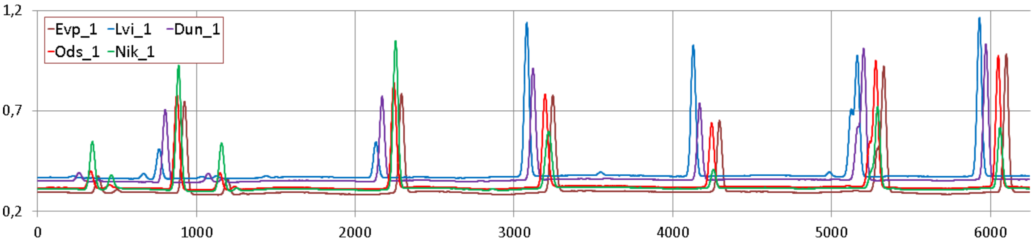

Figure 3. Fragments of five light curves of the SC model obtained in five different OSs, forming a local photometric network. The shown interval corresponds to 1.4 revolutions of the model around the center of mass ($\alpha_\Omega = 80°$ and $\delta_\Omega = 60°$).

laev and -0.49 seconds for Yevpatoria. The photometric or apparent period of rotation is not revealed in this fragment of the light curves (as well as on the full length of the light curves). It is explained by the fact that during one revolution even with a small change in the position of the PAB (more precisely, the latitude of the PAB in the SC's rotation axis-oriented CS) due to the orbital motion, the PAB is sufficiently move away from the corresponding normal to the flat face. Thus, there is no repeated flare of brightness from the same face, because the indicatrix of the specular reflection from the model faces is very narrow.

After shifting all light curves relative to one (the light curve, calculated for Odessa, was taken as reference) by the measured delay time, we obtained visual synchronization of the moments of light flares in different OSs (Fig. 4). The shifted light curves overlap rather well along the entire length of the fragment, demonstrating the synchronicity of the appearance of flares for different observers.

So, we have five OS spaced across the Earth's surface, where a series of details on the light curve (in this model case, mirror flares) were observed (with a slight time offset). In Fig. 5 in the equatorial SC-fixed CS shows the PAB coordinates for the indicated five OS and the same PAB positions in the rotation pole-oriented CS (for the moment UT = 20.54 hours). Right ascension (RA) and PAB longitude are adjusted to their averages for convenience. If the assumed position of the rotation pole corresponds to the real pole, then according to our model of the reflected light spot motion, the calculated longitudes of the PABs should form intervals between them in angular measure, which are proportional to the corresponding time shifts of the correlated parts of the light curves at these OS. In this case, the latitudes of PABs should lie in a rather narrow range of values (shown by dashed red lines). The proportionality coefficient in the obtained ratios is the inertial rotation period of the SC model.

Let's check the efficiency and sensitivity of this method for the rotation pole and inertial period determination. To do this, we use the calculated delays between the correlated parts of the light curves, and we will compare them with the calculated differences in longitudes PABs (in the tested trial pole-oriented CS). As a criterion for matching the test pole and the true one (specified in the simulation experiment), one can use the inverse variance of the obtained inertial period values for several independent sets of OS pairs. Fig. 6 shows the positions of the trial values of the rotation pole coordinates in the equatorial inertial CS, and Fig. 7 shows values of the characteristic parameter **Q** for this set of trial rotation pole's positions. We see that for the presented local field of values of the trial pole, the position of the maximum of the parameter **Q** is uniquely found as a characteristic of the found solution for the pole. It coincides with the true value with an uncertainty of $\sim 2°$ in both coordinates.

At the same time, the most suitable value of the inertial angular velocity of the model rotation was obtained equal to 7.9 ± 0.1 degrees per second.

3. SYNCHRONOUS OBSERVATIONS OF THE TOPEX/POSEIDON AND AJISAI SPACECRAFT BY THE NETWORK OF UKRAINIAN OBSERVATORIES

There are several astronomical observatories carry out photometric observations of satellites in Ukraine. Therefore, in order to test the possibility of obtaining synchronous basic (i.e., multi-site) photometric observations of such objects in August and September 2020, a joint campaign was carried out to observe the Topex / Poseidon and the Ajisai (EGS) SCs. The campaign was attended by the observatories of Odessa, Lviv and Uzhhorod (Derenivka)National Universities, as well as the observation station of the National Space Facilities Control and Tests Center of the State Space Agency of Ukraine in Zalistsi (Khmelnytskiy region). Synchronous observations of these SC were obtained during the periods of August 02-13 and September 21-30, 2020.

We used synchronous brightness measurements of the geodetic satellite Ajisai to check the time synchronization offset at OS relative to each other. This could be done because the light curve of Ajisai contains numerous specific

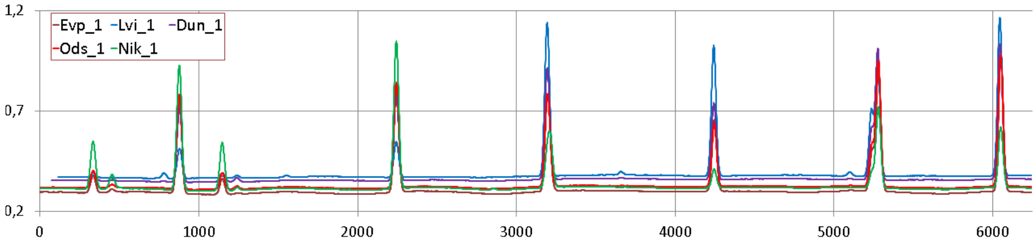

Figure 4. Shifted superposition of five light curves of the SC model obtained for five different OSs forming a local photometric network; the magnitude of the shift is determined by the best coincidence of all the flares' moments, i.e. compensates the actually observed phase difference between them.

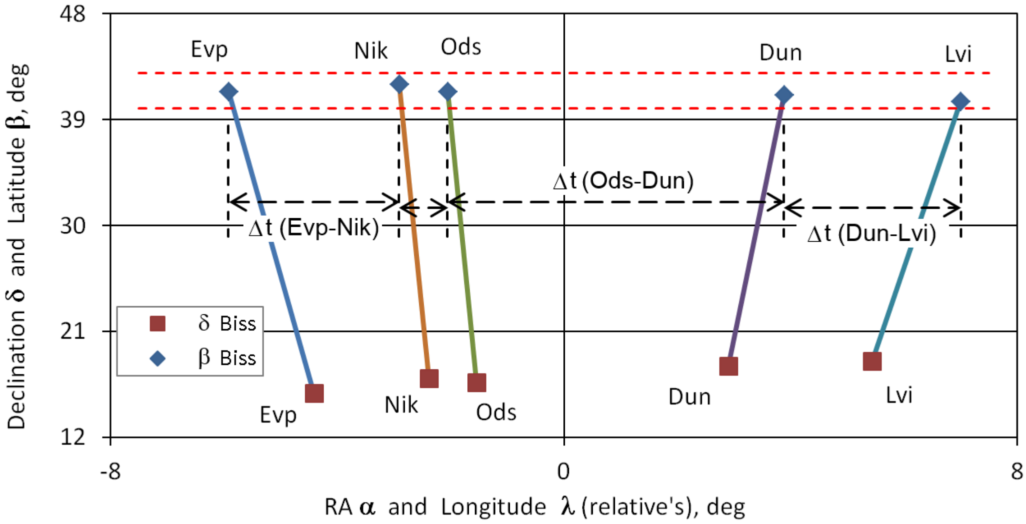

Figure 5. The equatorial coordinates of the PABs for five OSs and the same PAB positions in the rotation pole-oriented SC for the passage of the Topex SC on August 2, 2020, UT = 20.54 hours. The dashed lines mark the calculated differences in the PAB longitude values for the rotation pole:$\alpha_\Omega = 80°$ *and* $\delta_\Omega = 60°$*, which correspond to the obtained delays between the correlated regions on the light curves.*

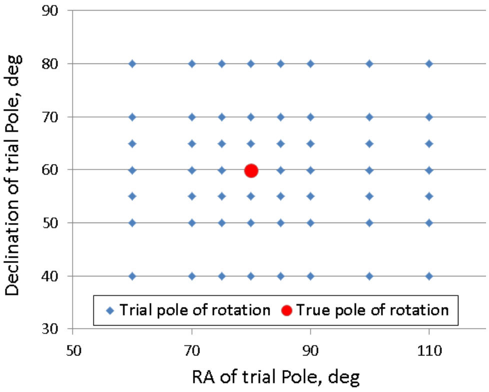

Figure 6. Distribution of trial rotation poles.

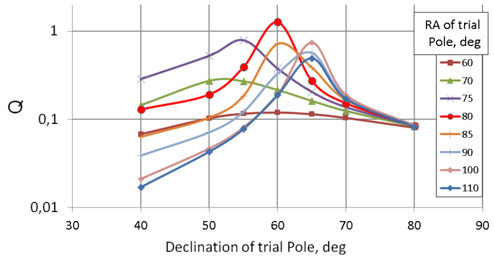

Figure 7. The values of the **Q** *parameter for a set of trial positions of the rotation pole. The found solution corresponds to the maximum value of* **Q***, which coincides with the true pole with an accuracy of* $\sim 2°$*in both coordinates.*

sequences of very short flares (about 0.01 seconds in duration). The previously constructed model of the location of all mirrors on the Ajisai's surface and the theory of its rotation and precession [6] allows one to calculate the exact time delay the onset of each flare of its brightness in neighboring OSs with an error not exceeding the time interval between nearby measurements of its brightness. An uncalculated delay at the instant of the onset of the same flare in the light curves obtained at two OSs will indicate the corresponding error of the zero point of the time scale in one of the compared OSs.

Let us consider the results of synchronous photometry for the Topex / Poseidon SC. Its orientation is not known to us and it was subject to determination based on the results of the observation campaign. Fig. 8 shows fragments of two SC light curves obtained in Odessa and Derenivka on August 2, 2020 at 20 hours 32 minutes UTC, after one of them was shifted along the time axis by 0.25 seconds. The total duration of the light curve obtained in Odessa is 10.1 minutes (with a small break at the zenith, where the KT-50 alt-azimuth telescope has a "dead zone"). The duration of the light curve obtained in Derenivka is 8.6 minutes (of which 8.4 minutes are synchronous tracking by two OS). In the first half of the passage over a long-time interval, a very good similarity of the light curves of this SC, obtained from two different OS, is observed. In the second half of the passage, this similarity is also preserved, but the brightness of the specular light flares differs significantly, and the light curves do not coincide in detail. The observed synodic rotation period is approximately 9.8172 sec. Fig. 9 shows fragments of two light curves for the Topex / Poseidon SC obtained in Odessa and Lviv on August 6, 2020 at 20:05 UTC, after aligning such details by shifting the time scale of one of them by 0.20 seconds. Despite the significantly higher noise and lower brightness measurement frequency compared to the data of the KT-50 telescope (Odessa), the light curve obtained in Lviv is similar in its main details to light curve obtained in Odessa. During one revolution of the satellite, there are four main increases in brightness with one characteristic broad "diffuse" maximum and three quasi-specular flares, the positions of which vary slightly relative to each other. The Topex/Poseidon SC's light curve had such character until the end of this passage. The observed synodic rotation period is approximately 9.828 seconds.

However, in another passage, synchronously observed in Odessa and in Zalistsi on September 23, 2020 at 18 hours 58 minutes UTC, a fragment of which is shown in Fig. 10, the light curve for the Topex SC demonstrates a different character. Only two main increases in brightness are observed during one revolution of the satellite, maybe due to quasi-specular reflection of light from the spacecraft surface. Moreover, the interval between adjacent peaks changes very rapidly from revolution to revolution. It usually occurs when light is reflected from a smooth conical surface. In this case, the synodic rotation period is more clearly determined by the intervals between the brightness minimums of the satellite. It should be noted that the light curve obtained in Zalistsi is additionally shifted by 4 synodic periods to visually match its shape. At the end of this passage, both light curves had the usual form: four main light enhancements with a characteristic broad "diffuse" maximum. The observed synodic rotation period was approximately 9.8075 seconds.

4. CONCLUSION

As a result of the campaign, we can say that a Ukrainian local photometric network can obtain synchronous well-correlated light curves of spacecraft, including LEO. From general considerations, it is clear that the lower the orbit is above the Earth's surface, the more difficult it is to obtain correlated portions of the light curves by different OS, because the satellite-centric angular distance between them is greater. On the other hand, the higher the spacecraft's orbit or the greater the speed of its rotation, the greater the linear speed of reflected light spot's (reflected by SC) motion on the surface of the Earth. It makes it easier to detect and measure the offset between the correlated fragments of the light curves with the availability of high-frequency observations of the spacecraft brightness and the possibility of reliable precision time-tagging when recording the light curves.

The analysis of the obtained synchronous brightness measurements of the Topex/Poseidon SC should have made it possible to determine the instantaneous parameters of the SC rotation: the inertial rotation period and the orientation of the rotation axis in space. At the moment, this task has not been solved and a similar campaign should be continued in the future. The problem lies in the low frequency of measurements obtained at the participating observatories, which reduces the accuracy of calculating the time delays between the correlated portions of the spacecraft light curves. Also, a low signal-to-noise ratio in SC brightness measurements is a factor that reduces the accuracy of the obtained estimates of these delays (offsets), and a reliable solution for the rotation parameters cannot be obtained without them.

The carried-out simulation experiment gives reason to hope for the effective performance of this method of simultaneous multi-site photometric observations for the quick determination of the SC rotation parameters, including slowly rotating ones. In this case, the method is completely independent of the SO form. In the future, apparently, it will be expedient to organize photometric networks according to a hierarchical principle, for example, with several local networks spaced at a distance greater than the distance between OSs of separate networks.

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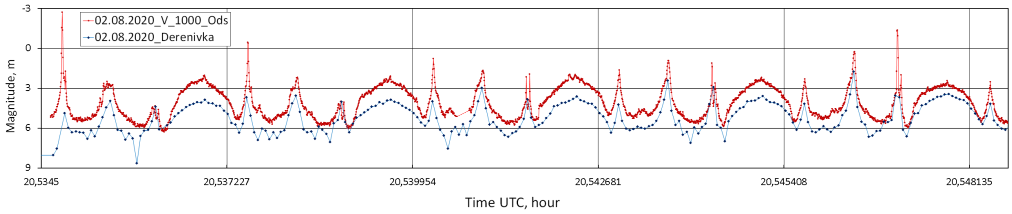

Figure 8. Two fragments of the light curves for the Topex / Poseidon SC, synchronously observed in Odessa and Derenivka on August 2, 2020 at 20h 32m (UTC) after the time scale of one of them was shifted by 0.25 seconds.

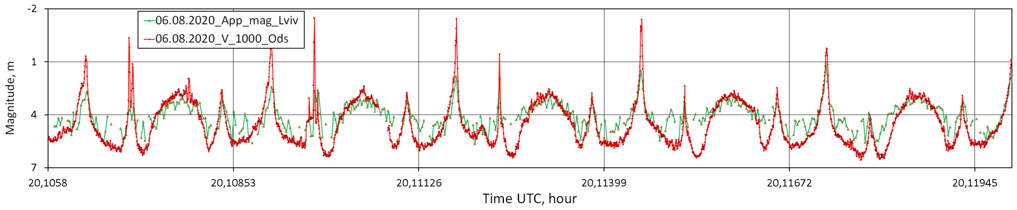

Figure 9. Fragments of two light curves for the Topex / Poseidon SC, synchronously observed in Odessa and Lviv on August 6, 2020 at 20:05 pm (UTC) after the time scale of one of them was shifted by 0.20 seconds.

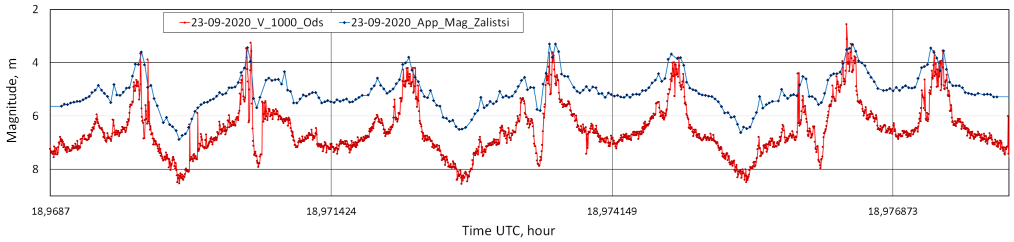

Figure 10. Fragments of two light curves for the Topex / Poseidon SC, synchronously observed in Odessa and in Zalistsi on September 23, 2020 at 18:58 UTC.

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