DETERMINATION OF THE ROTATION PARAMETERS OF REFERENCE ARTIFICIAL SATELLITE AJISAI AND SYNCHRONIZATION OF THE PHOTOMETRIC CHANNELS

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ABSTRACT. The aim of the present study is to obtain the adjusted current coordinates of the rotation pole of artificial satellite Ajisai and the up-to-date sidereal period of its rotation. To do that, the light curves obtained in Odessa during 2009-2010 are considered. Using both the Ajisai pole's coordinates and the reduced null point of the hardware-based time scale, has made it possible to improve the timing of the observed flashes of its brightness. By the accurate timing of the simultaneous photometric observations of Ajisai satellite the photometric channels synchronization at the stations in Odessa and Eupatoria is accomplished. The further photometric observations of that satellite are necessary to construct a theory of its rotation about the centre of mass; that will allow of its using as a reference source of the time-calibrated optical signals for any ground-based observatories.

Introduction

Japanese experimental geodetic artificial satellite Ajisai was launched in 1986 to the almost circular orbit at altitude about 1500 km with the inclination of 50^0 to the equator. The satellite is manufactured from fiberglass strengthened plastic; it is of the spherical shape with the diameter of 2.15 m; 318 reflecting flat mirrors and 120 laser retro-reflectors are placed on its outer surface [1] (see Fig.1) The mirrors are made of an aluminium alloy and, when reflecting the sunlight by the rotating satellites, they emit short light pulses the duration of which is relative to the rotational velocity. Initially, they were intended to control the orientation and variation of the rotational velocity of the satellite under the influence of cosmic factors. The laser retro-reflectors consist of prisms that, being irradiated by the terraneous laser pulse, reflect the light signal accurately backwards to the radar telescope. That enables to determine the precise distance to the artificial satellite.

Both types of the reflectors are almost uniformly distributed by the designers on the surface of the spherical satellite. It was attained by the placement of the flat mirrors and retro-reflectors in 15 latitudinal rows (rings). The planes of the mirrors additionally inclined with different angles to the mean latitude of the given ring. As a result, the normals to the mirrors are rather evenly distributed in space (like the hedgehog's prickles) and, when the satellite is spinning around its axis, there are always some of them that can reflect the light towards the observer.

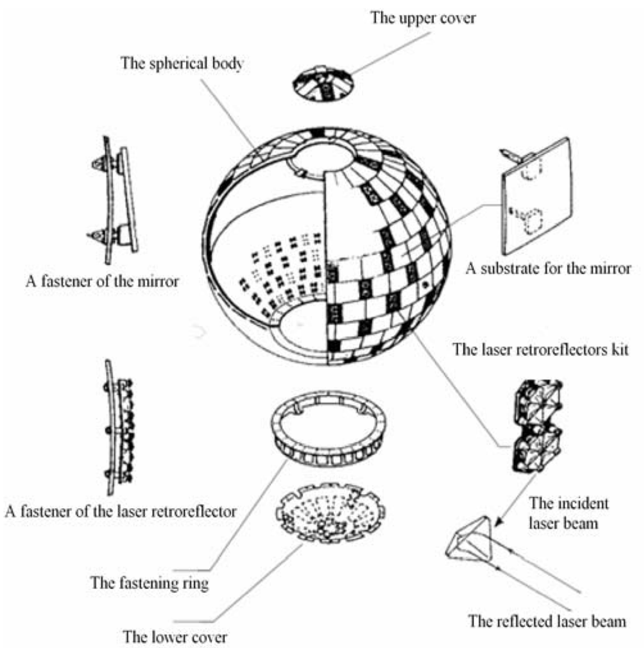

Figure 1. The design of Ajisai satellite [1].

When launching into the orbit, Ajisai artificial satellite was spun with the velocity 40 revolutions per minute around the axis parallel to the Earth rotation axis. And the satellite rotation axis coincides with the symmetry axes of the rings at that. The regular observations of Japanese researchers showed that after the launch the spin velocity of the satellite monotonously decreased from 0.67 Hz (revolutions per second) at the launch to 0.57 Hz in 1988, i.e. 12 years later. According to the results of the high-frequency laser measurements [2], it was determined that the rotation axis in the Ajisai's body is deflected from the symmetry axis by 5.5°.

Objectives of the work

Our goal is to specify more precise the position of the rotation axis of artificial satellite Ajisai in space, and then to use it as the standard source of the optical pulses. When being observed, the satellite demonstrates numerous momentary flashes of brightness with the period of reiteration of the flashes series of about 2.02 sec (i.e. the rotational velocity was already 0.495 Hz in 2010). The light curve is regular during the time span of about several seconds only, and then it is rapidly transformed. It is explained by the fact that when the satellite is moving along the orbit, and a terrestrial observer is tracking it, the local area of the specular reflection is quickly moving on the spherical surface, and its latitude is also altered relative to the rotation axis inside the satellite's body. The set of mirrors reflecting the light towards the observer take turns at each spin of Ajisai at that. (The local area, for which the normals form a small angle with the phase angle bisector – of the order of the angular dimensions of the source of light – is called a "plash of sunlight" on the specular surface; the phase angle is the plane angle between the directions from the satellite towards the Sun and the observer).

Taking into account that the observer is located not in the centre of Earth and relative to that the angular velocity of the artificial satellite in the sky is very uneven, the visible rotation of the satellite turns to be also non constant. That is the result of the parallactic change of the direction towards the satellite and the composition of the angular velocities of the artificial satellite and its orbital movement. That unevenness is slightly contributed by the Earth's rotation along with the observer. When registering the periodicity of the reiteration of the flashes of brightness, the observer can measure only the synodic period of the rotation of Ajisai. The sidereal period of rotation (the period of spinning of the body relative to the inertial coordinate system) can be computed only if the precise orientation of the rotation axis of the satellite in space is known.

When observing the series of the momentary flashes of brightness, the inverse problem can be solved, i.e. it is possible to determine the true spatial orientation of the Ajisai rotation axis and the value of the sidereal period of its rotation.

The duration of the optical flash is determined by the angular dimensions of the light source; in the present case – the Sun; and it does not depend on the dimensions of the mirror. The smooth plane mirror of Ajisai, spinning with the period $P \approx 2$ sec, emits a flash with the minimum duration of $\Delta t = d/360^\circ \cdot P/2 \approx 0.0014$ sec, where d – the angular diameter of the Sun. But if the mirror is a bit rough (matt), then the brightness, shape and duration of the flare will depend on the width of the indicatrix of light reflection by such a "mirror" and on the minimum angle between the normal to it and the vector-bisectrix of the phase angle.

The determination of the polar orientation and the sidereal period of rotation

When considering the specular reflection of the light by the elements of the satellite surface, we will constantly use such terms as "the phase angle bisector" and "normal" to the reflecting area. In consequence of the satellite movement along the orbit, the direction "satellite-observer" is regularly altered, thus, as well as the vector-bisectrix of the phase angle. At the same time, as a result of the satellite rotation around the centre of mass, the normals to the plane mirrors form cones in space, and their traces on the celestial sphere describe concentric small circles. When at any moment the normal approaches to the phase angle bisector (or, vice versa) by the angle less than the width of the specular indicatrix of the plane mirror, then we will observe the "specular" increase of the artificial satellite brightness – a flash of brightness. Such picture is observed also when the specular reflection of the light by the conical or other developable surface of the satellite occurs.

The rotation pole. When the artificial satellite is passing above the observation point, the phase angle bisector forms a certain variable angle $\rho \approx \pi/2 - \delta_B$ with the rotation axis of Ajisai as its rotation axis in space is close to the Pole. Therefore, the declination of bisector δ_B (in the equatorial coordinate system) defines the angle between the rotation axis and the bisector. And the flashes of the specular reflection are produced by those mirrors, which are mounted on the satellite close to the latitude of $\pi/2 - \rho$ at that. The quantity of the mirrors that are to produce the flashes of brightness per one rotation, the intervals and the brightness magnitude of those flashes depend on their distribution on that ring and on the actual positions of their normals. If the angle between the rotation axis and the bisector is to achieve the same value twice per passing of Ajisai, then, at those moments, the similar series of the flashes per that period are to be observed. On having assumed that the satellite rotation axis has not altered appreciably its position. That fact permits to determine the actual orientation of the Ajisai rotation axis in space by considering the corresponding pairs of segments of the light curve.

The course of changes of the declination of the phase angle bisector (in radians) are shown on the left of Fig. 2; two segments of the light curve close to moments t_1 and t_2, when the bisector declination took the identical values, are shown on the right of Fig. 2. The light curve was obtained 09.06.2010 in Odessa with telescope KT-50 with the time resolution of 0.02 sec [4]. The appearance of the two light curve segments in this case is different! However, the segment of the light curve *next* to the second one of the above mentioned pair (with the time lag of ~ +11 sec) almost duplicates the series of flashes on the first segment (see Fig. 3). That means that actually the light rotation pole does not coincide exactly with the celestial pole.

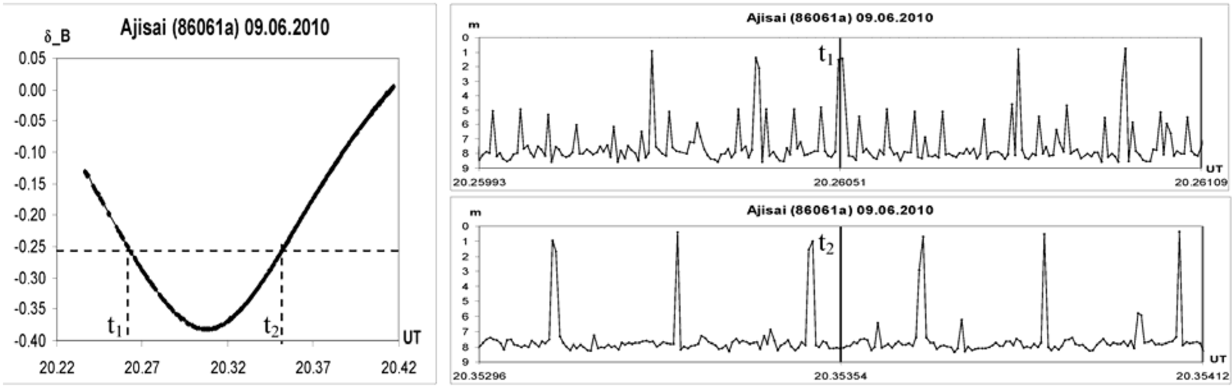

Figure 2. Changes of the declination of the phase angle bisector (on the left) and two segments of the Ajisai light curve close to moments t_1 and t_2 (on the right).

Let us name the pairs of mean time points close to which a series of flashes is repeated, and their associated bisector vectors as "conjugated". Two more pairs of segments of the light curve on 09.06.2010 where the series of flashes is also repeated in pairs are shown in Fig. 4 (a, b). It should be noticed that there are some gaps and other photometric defects on the light curve; that is why the repetition of the segment of the light curve within the interval of two revolutions is achieved only "in whole".

The difference of the values of the bisector actual declination during two "conjugated" moments defines the deflection of the Ajisai rotation axis from the Pole. The analysis of those observation data allows of making more precise the true position of the Ajisai rotation axis within the indicated time span.

Fig. 5 graphically demonstrates more precise definition of the rotation pole position using the positions of three pairs of the "conjugated" phase angle bisectors.

To determine the rotation pole, it is necessary to find the pole of the small circle. It can be computed if there are at least *three* points, lying on that circle, available; or it is possible to use *two* points, lying on the small circle, and *two* more points, lying on the second small circle that is concentric to the first one. Let a point on the sphere is actually the unit vector r(x, y, z). Let us consider the pairs of differences of the corresponding coordinates and to introduce the following designations:

$$a_x \equiv \Delta y_1 \cdot \Delta z_2 - \Delta y_2 \cdot \Delta z_1,$$
$$a_y \equiv \Delta z_1 \cdot \Delta x_2 - \Delta z_2 \cdot \Delta x_1,$$
$$a_z \equiv \Delta x_1 \cdot \Delta y_2 - \Delta x_2 \cdot \Delta y_1,$$
$$D \equiv a_x^2 + a_y^2 + a_z^2,$$

where indexes 1 and 2 correspond to different independent pairs of points, lying on the same circle. Then the pole's direction cosines are equal to:

$$x = a_x/D,\ y = a_y/D,\ z = a_z/D.$$

The radius of the small circle ρ is determined from the equality: $\cos \rho_i = x \cdot x_i = y \cdot y_i = z \cdot z_i$.

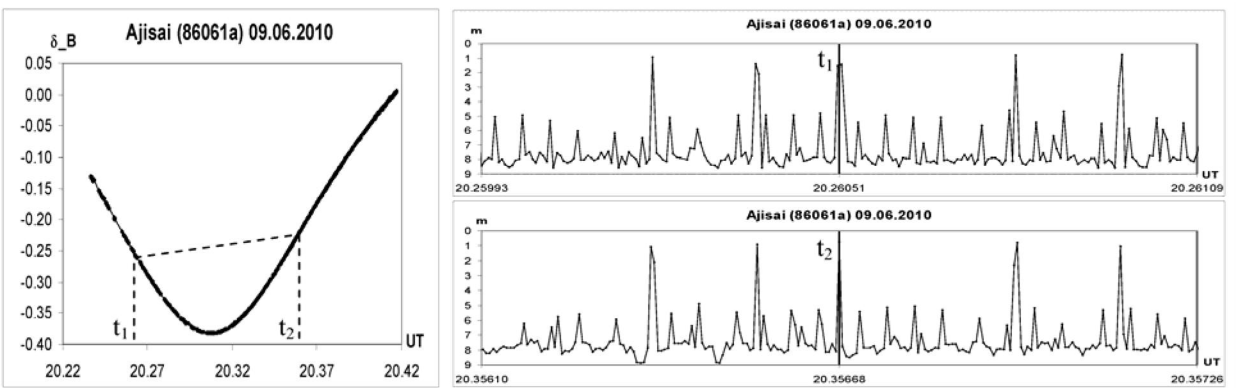

Figure 3. The same as in Fig. 2 but for another moment t_2.

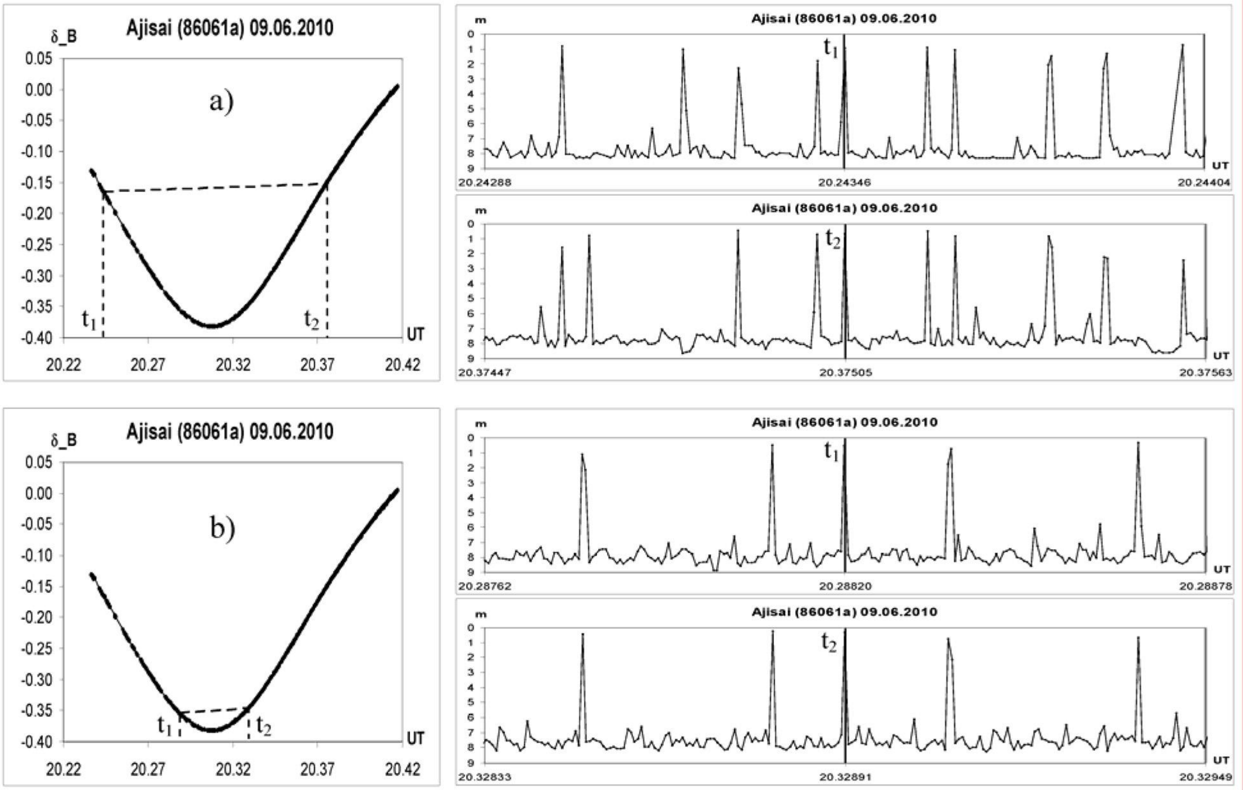

Figure 4. The same as in Fig. 2 but for two other pairs of moments t1 and t2 (their choice is shown on the links).

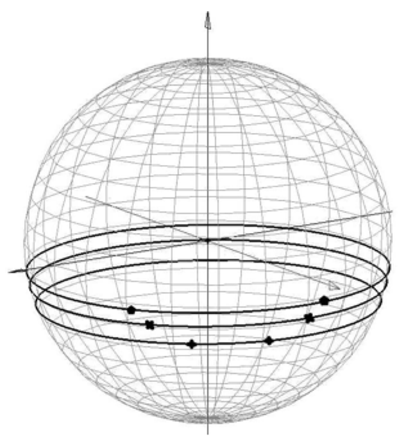

Figure 5. The positions of three pairs of the "conjugated" phase angle bisectors for the Ajisai passing above Odessa (on the base of observations on September 08, 2009).

The comparison of the segments of the Ajisai light curve, analogous to the above indicated, was made for three more dates – 08.09.2009, 16.09.2009 and 21.09.2009. The coordinates (the right ascension and the declination) of the bisectors for the data of artificial satellite Ajisai passings at the middle of intervals where the type of the light curve is repeated on the local segment, as well as the corresponding orientation of the rotation axis (α_{pole}, δ_{pole}) and the true polar distance of the reflecting normals (ρ_{pole}) are presented in Table 1.

The preliminary analysis of the obtained results permit to draw a conclusion on the slow precession of the Ajisai rotation axis near the celestial pole (the deviation is 1÷2°). With the data available, it is possible to assume the clockwise precession direction with the period of about one year.

The rotation period. When the position of the artificial satellite rotation pole in space is known, the possibility to compute the sidereal period of its rotation appears. As it was already mentioned above, only the synodic (observed) period, that depends on the direction and the angular velocity of the satellite's move, can be determined from the observations. As a result of that movement, the coordinates of the bisector of the phase angle change in the lapse of time according to some law. Let us to resolve the angular velocity of the bisector movement into two components – along the artificial satellite rotation axis and along the axis perpendicular to that one. Hence, the first component of the bisector angular velocity will be added to the angular velocity of its rotation. That allows of directly taking into account the movement of the artificial satellite along its orbit when the sidereal period of rotation is computed. The second component of the angular orbital movement, that equal to the rate of change of the angle between the rotation axis and the bisector, will determine the rate of transformation of the kind of the satellite light curve. For Ajisai such change cause the latitudinal shift of the "plash of sunlight" of the specular reflection and change of the mirrors reflecting the light towards the observer and contribute to the total light curve.

Table 1. The bisector positions for the pairs of the “conjugated” moments and the corresponding coordinates of the rotation axis of artificial satellite Ajisai (in degrees).

t_1	α_b	δ_b	t_2	α_b	δ_b	α_{pole}	δ_{pole}	ρ_{pole}
08.09.2009								
19.71249708	151.78	-13.35	19.81522774	191.71	-14.73	254.97	88.0	103.82
19.72628634	158.59	-15.64	19.79048817	185.07	-16.56	254.97	88.0	105.94
19.74561467	167.88	-17.53	19.76428741	176.30	-17.76	254.97	88.0	107.43
16.09.2009								
20.59230258	147.52	-30.68	20.62497658	166.53	-31.32	253.82	88.0	121.18
20.60111395	151.87	-31.45	20.61861935	162.53	-31.76	253.82	88.0	121.75
21.09.2009								
18.08324636	128.85	-31.43	18.15210336	167.80	-32.74	253.82	88.0	122.61
18.09675229	135.48	-34.13	18.13934789	159.93	-34.94	253.82	88.0	125.08
09.06.2010								
20.24345260	31.40	-9.43	20.37504481	96.58	-8.68	338.05	89.3	99.06
20.25279180	34.49	-11.92	20.36549450	93.73	-11.11			
20.26050600	37.39	-14.08	20.35668300	90.62	-13.40	338.05	89.3	103.79
20.26684650	40.08	-15.67	20.35003800	87.90	-15.12			
20.28819800	51.15	-20.27	20.32891000	77.08	-19.88	338.05	89.3	110.15

The synodic period between two specular flashes produced by the same mirror is $P_{syn} = (t_2\text{-}t_1)/2\pi\cdot n$. If the rotation pole is known, then the sidereal period P_{sid} can be determined by the formula: $P_{sid} = (t_2\text{-}t_1)/(\ 2\pi n \pm \Delta\alpha')$, where t_1 and t_2 – the recorded moments of the maximum brightness; n – the number of complete revolutions of the artificial satellite relative the fixed coordinate system during the time span t_2-t_1; $\Delta\alpha'$ – the angle between two projections of normal’s vectors on the plane perpendicular to the rotation axis.

If **r**(x, y, z) is a vector that defines the normal’ position in the equatorial coordinate system, and α_Ω, δ_Ω are coordinates of the rotation pole in that coordinate system, then the conversion of the normal’ vector to the coordinate system, related to the rotation axis, is carried out by multiplying by matrix $R = R_z(0) \cdot R_x(\pi/2 - \delta_\Omega) \cdot R_z(\alpha_\Omega + \pi/2)$. The index defines the axis, around which the rotation is made at the angle that is the argument. As a result we obtain the vector **r**'(x',y',z'), for which we find its “longitude” α' in this new coordinate system. The sign before Δα' determines the direction of rotation.

From the correlation of the observed course of the synodic period with satellite’s velocity variation by right ascension, the conclusion can be drawn that Ajisai has the reverse direction of rotation. Analysis of the six light curves obtained in Odessa on 21-23 September 2009 gives the value of the sidereal period error is equal to 0.0000003 sec. On the interval 21-22.09 – mean rotation period is equal to 2.1026397, and on the interval 22-23.09 – 2.1026461 sec.

The synchronization of the photometric observations

Relating various measurements to the world time scale is done nowadays by receiving and registering second-long impulses in the UTC scale from the specialized satellite grouping, for instance, GPS satellites. This binding of the local time storage system to the UTC scale can be performed with sufficiently high accuracy of 10^{-4}-10^{-6} sec. However, any equipment for measurement registration introduces “hardware delay” which is difficult to measure inside an observation complex when the outer time-calibrated signal is not available. While carrying out photometry using CCD receivers (e.g. television CCD cameras), the moments (intervals, to be exact) of matrix exposition by the light of a signal source are, as a rule, separated in time from the image registration in the computer. Relating the image to the UTC scale is performed at the registration stage, so there occurs some uncertainty as to the “hardware delay” value, as well as the question: which instant of time does the obtained image refer to?

Artificial satellite Ajisai can be a convenient source of the optical signals to synchronize the photometric observations, obtained at the separated points, as far its pole position and rotational velocity are known with rather high accuracy. The availability of an independent and globally accessible source of calibrated optical impulses makes it possible either to determine the “hardware delay” value itself in timing of photometric measurements, or to find the “hardware delay” difference of two observation stations.

Figure 6 demonstrates two fragments of the light curves of artificial satellite Ajisai obtained simultaneously (!) in Odessa and Eupatoria, that are referred to the “conjugated” time spans when the bisectors of the corresponding phase angle had the same declination in the coordinate system related to the rotation axis of the satellite. In that case, both Odessa and Eupatoria observers watched the brightness flashes produced by the same mirrors of Ajisai. That is confirmed by the similar shape of the recorded light curves during that time span.

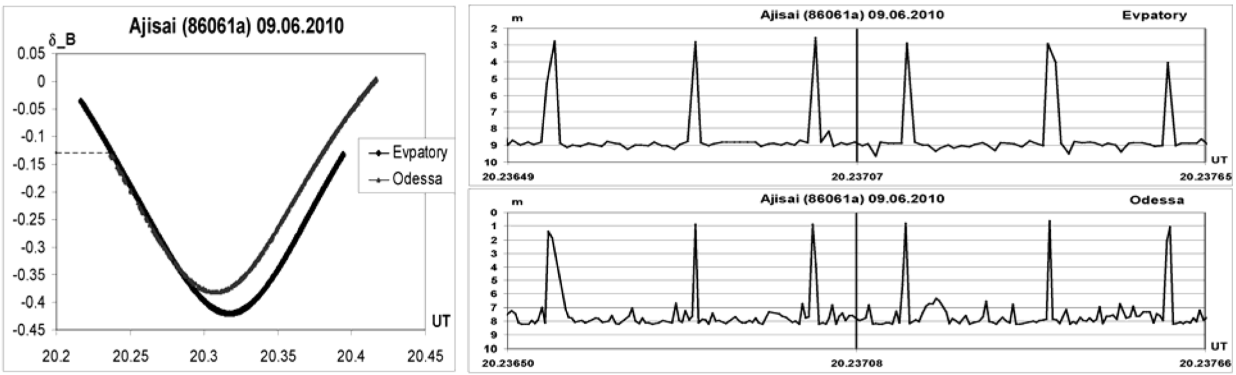

Figure 6. The synchronous change of declination of the phase angle bisector for two observation points (on the left) and the Ajisai light curves segments close to the "conjugated" moments $t_1 \approx t_2$.

However, between the moments of the corresponding flashes, recorded at different observation points, there should exist a delay equaled to the difference of the longitudes of the points in the coordinate system related to the current rotation axis of the satellite. Such a delay is easily computed and taken into account. The residual difference between the fixed flash moments at two observation points represents the "hardware delay" difference of time registration in making photometric observations. It allows the two systems of time registration to be synchronized. The necessity of such synchronization is extremely important when the basic photometric observations are conducted with the goal to jointly process those data to obtain the rotation parameters of any other artificial satellite (for instance, in case of emergency).

The error of determining this synchronizing correction is equal to the sum of uncertainty values of an optical event's time registration moments at two observation stations. This uncertainty is conditioned by finite time of image exposition: we don't know when exactly the flash of brightness within the exposition interval occurred.

The uncertainty of the measurement registration time moment is of the order $T_{exp}/2$. Thus, it is possible to synchronize time scales by the photometric method with the same accuracy as the observations themselves are obtained. Changing to shorter expositions in satellite's photometry is only possible in applying high-speed CCD cameras.

The hardware delay. The technology of observation of an artificial satellite with the panoramic receivers, such as a CCD camera, enables to record its picture against the starry sky background. The artificial satellite coordinates relative to the stars and the brightness of all images in the frame, including the satellite, are measured simultaneously at that. Such simultaneous measurement of the coordinates and brightness of the artificial satellite results in the unified time binding of the proper hardware time scale to the UTC scale. The advantage of that technique is that the corrections of the null point of the time scale can be found by the comparing of the obtained momentary coordinates of the artificial satellite with the coordinate-time measurements, received by different high-precision observational networks. One such high-precision network can be the International Laser Ranging Service (ILRS) [4], which everyday publishes in the Internet forecasts of the positions of the reference geodesic artificial satellites on the basis of the modern high-precision theories of perturbed motion. Using the "normal" coordinates of artificial satellite Ajisai in the International Terrestrial Reference System (ITRS) on the basis of the ILRS ephemerides, I.Kara [5] has converted them to the precision ephemerides of that artificial satellite for the observation point in Odessa in the stars catalogue system for epoch J2000,0. The comparison of the ephemerides of a number of reference artificial satellites with the actual measurements of their coordinates in the same system demonstrated the presence of the "hardware delay" and the necessity to correct the null point of the time scale by about –0.011 sec.

Despite the correction value is great, it is rather expected as the CCD camera operates in the "interlaced mode" and the exposing of the next half-frame takes place during the transmission and recording the previous one [3]. The discrepancies of the measured coordinates of artificial satellite Ajisai relative to the ILRS ephemerides before and after correcting the null point of the time scale are shown in Fig. 7.

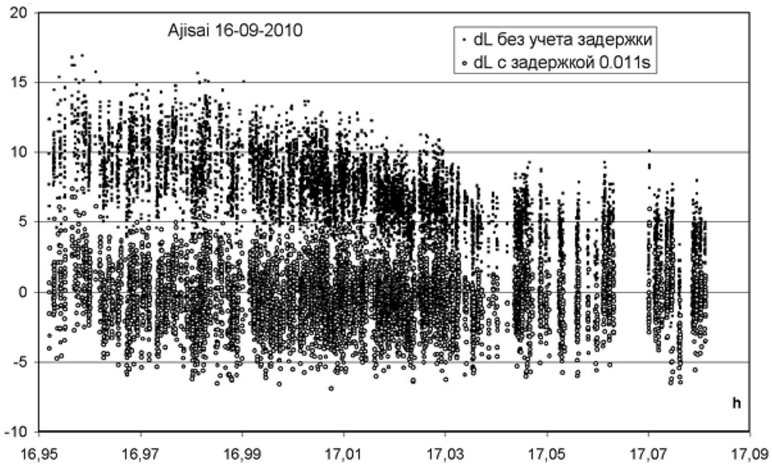

Figure 7. The discrepancies dL (in arc seconds) along the visible trajectory of the artificial satellite between the observed and computed with the ILRS ephemerides positions [4, 5].

Conclusion

As a result of obtaining the adjusted current coordinates of the rotation pole of artificial satellite Ajisai together with the reduction of the null point of the hardware-based time scale and application of the present value of the sidereal rotation period, timing of the observed light flashes of this satellite has been improved. That allowed of realizing the synchronization of the photometric channels at the stations in Odessa and Eupatoria by carrying out the simultaneous photometric observations of the reference artificial satellite Ajisay. The further photometric observations of that satellite will enable to construct a theory of its rotation around the centre of mass and to use it as a reference source of the time-calibrated optical signals by any ground-based observatory.

References

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