SUN AND SOLAR SYSTEM

THE RESEARCH OF VARIATION OF THE PERIOD AND PRECESSION OF THE ROTATION AXIS OF EGS (AJISAI) SATELLITE BY USING PHOTOMETRIC MEASUREMENT

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ABSTRACT. The light curves of EGS Ajisai with temporal resolution of 20 ms referred to the time scale UTC (GPS) with an error of at most 0.1 ms were obtained. The observed flashes are produced when the mirrors which cover the spinning satellite's surface reflect off the sunlight. In previous paper the analysis of sequence of flashes allowed of reconstructing the arrangement and orientation of the mirrors, i.e. developing an opto-geometric model of the satellite (Korobeynikova et al., 2012), and to apply that model along with new photometric observations to determine the satellite's sidereal rotational period with an accuracy that was previously unachievable. A new technique for determination of the spin-axis orientation during each passage of the satellite over an observation site was developed. The secular slowdown of the satellite's spin rate (P_{sid} = 1.4858·EXP(0.000041099·T), where T is measured in days counted from the date of the satellite launch) and its variations correlating with the average duration of the satellite orbit out of the Earth's shadow were refined. New parameters of the spin-axis precession were estimated: the period P_{prec} = 116.44 days, α_{prec} = 18.0^h, δ_{prec} = 87.66°, the nutation angle θ = 1.78°.

1. Introduction

As noted in previous paper (Koshkin et al., 2010), the phase angle bisector position in the satellite-centric coordinate system determines which of those mirrors will reflect off the sunlight towards an observer. The mirrors in each ring should be considered in sets of three (Korobeynikova et al., 2012; Epishev et al., 2008) as all mirrors in each set are tilted at the same angle (which varies for different sets of three) to the central latitude of a certain ring. It was intended that while the Ajisai is spinning about its symmetry axis, any three mirrors with the same tilt can always reflect off sunlight towards an observer three times per rotation. If actual arrangement (orientation of the central normal) of the whole set of mirrors is available, it will enable the EGS spin period and orientation to be determined from photometric observations. As the spin axis of Ajisai is close to the celestial pole, the bisector declination in the equatorial coordinate system will be slightly different from the latitudes of the mirrors reflecting sunlight over a certain period of time.

2. Determination of the Ajisai spin-axis orientation

The time intervals between adjacent flashes over one rotation of the satellite allow to identify with confidence the corresponding set of three mirrors as well as to determine their satellite-centric latitude φ. When examining the differences of current declination of the bisector and latitudes of the reflecting mirrors, it can be seen that those differences at the instants of flashes for all three 'chains' merge with each other into a separate 'track' on the graph (see Fig. 1). Other 'chains' are figured by other tracks, which, as it was said above, overlap each other with time. Such geometric illustration reflects the fact that at a certain instant of time the plashes of sunlight on the satellite's surface moving in declination (δ), for instance, from south to north, reach the southern edge of a mirror (or to be more exact, of three mirrors), and respective flashes appear on the light curve up to the moment when the plashes have passed the northern edge of that mirror. It should be noted that if the Ajisai spin-axis orientation perfectly coincided with the celestial pole, then the differences (φ – δ) would be within the range ±Δ where value Δ is dependant on the angular dimensions of the mirror and the light source. The actual observed differences (φ – δ) also depend on the true spin-axis orientation in space. That enables to ascertain the current spin-axis orientation on the observation interval. For the true satellite spin pole, the differences (φ – β) where β – the bisector declination in the coordinate system related to the spin pole will be within the same range ±Δ. The flashes' amplitudes gradually change thereby defining the boundaries of 'chains'. Nevertheless, the beginning and the end of the chains are not strictly defined as a flash can be observed only upon reaching the corresponding phase of Ajisai's spinning; at that, the width of the plashes of sunlight, being continuously changed, could reach the edge of the mirror at the instant of time when it is out of sight of an observer.

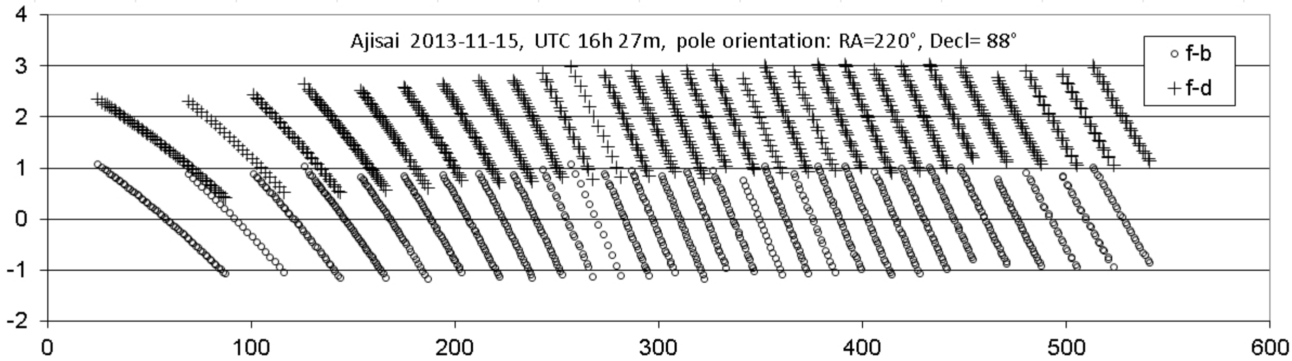

Figure 1: The time-dependent change in the differences between the mirrors' latitudes and bisector declination ($\varphi - \delta$) (marked with brown daggers) as well as the differences ($\varphi - \beta$) for the spin pole $\alpha_{pol} = 14.67^h$, $\delta_{pol} = 88.0°$, (marked with blue dots) during a passage of Ajisai on 15 November 2013. The X-axis represents the time in seconds since the measurements began; the differences in degrees are plotted in the Y-axis.

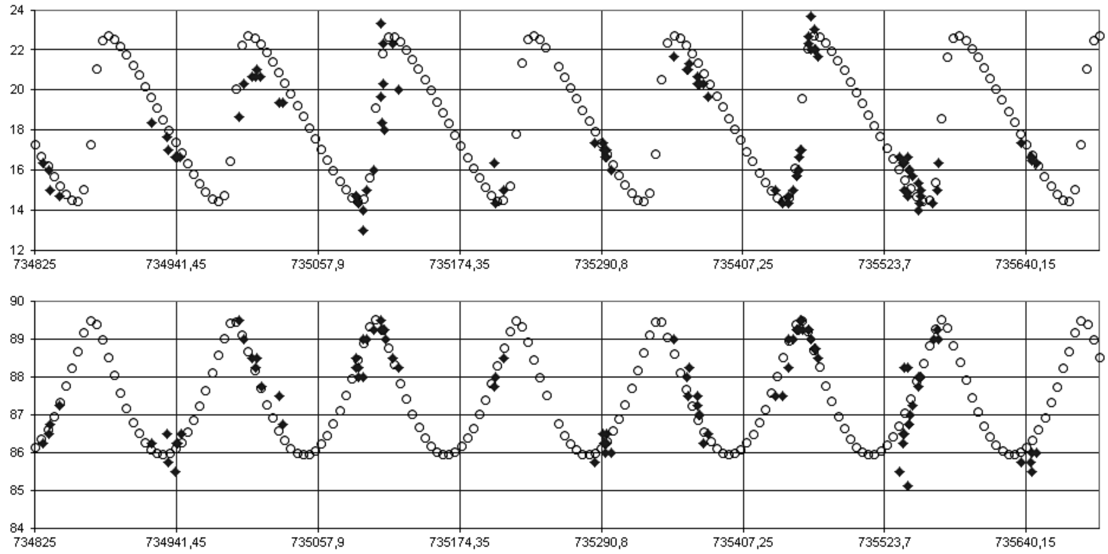

Figure 2: The Ajisai spin pole positions (indicated by solid circles), obtained from observations over the period of 2009-2014; the upper chart shows the right ascension of the pole (in hours); the lower chart represents the pole's inclination (in degrees). It also demonstrates the approximating trajectory of the spin-pole variations obtained with the following precession model: the pole is at the point $\alpha_{prec} = 18.0^h$, $\delta_{prec} = 87.66°$, the nutation angle is $\theta = 1.78°$ and nodal precession period is 116.44 days.

However, having examined numerous 'chains' during a satellite's passage over an observer, their boundary flashes can be definitely estimated in average that enables to determine the current position of the spin pole. Several tens of sets of three 'chains' (tracks on the graph "$\varphi - \delta$") can be observed with high-quality photometry during long-lasting well-observable passages. But when the observation conditions are unfavourable, the number of the observed chains is inadequate to definitely determine the spin pole position. The described technique of the spin-pole position determination implies that the spin axis in the satellite's solid almost coincides with its axis of symmetry (the mirrors' widths do not vary). It is possible that more thorough examination of the Ajisai light curve will allow of unravelling this and other thin effects in the satellite's spin-axis inclination variations.

Fig. 2 shows the results of our determination of the Ajisai spin-axis pole position on the time interval from November 2011 to February 2014. It also presents the approximating trajectory of the spin-pole inclination variations, which was obtained applying the following precession model: spin pole is at the point $\alpha_{prec} = 18.0^h$, $\delta_{prec} = 87.66°$, the nutation angle $\theta = 1.78°$ and period of 116.44 days (while the Ajisai nodal precession period is 117.1 days).

The Ajisai nodal precession period which was 116.44 according to our determinations is almost perfectly coincides with the period estimated by Kucharski D. et al. (Kucharski et al., 2010; Kucharski et al., 2013). The phase of the spin-pole inclination variations is also practically the same (within the accuracy of the phase estimations reported in the paper referenced above). However, the precession axis is noticeably shifted in right ascension comparing to the data by Kucharski. It may be an actual axis shift as the authors' analysis of different measurement intervals resulted in the following estimates of the precession pole mean position:

Kucharski, 2010	2003-2009	$\alpha_{prec} = 14.9^h$, $\delta_{prec} = 88.51°$
Kucharski, 2012	2003-2011	$\alpha_{prec} = 15.4^h$, $\delta_{prec} = 88.05°$
This study	2009-2014	$\alpha_{prec} = 18.0^h$, $\delta_{prec} = 87.66°$

For clarity, several dozen spin-axis pole positions on the sphere, which were obtained by us on different dates over the period from September 2009 to February 2014, are shown in Fig. 3. The spin-axis precession circular trajectory which approximates those data, as well as the circular trajectory according to the data by Kucharski et al. (Kucharski et al., 2010) obtained from the SLR observations in 2003-2011, is also plotted in the figure. It is obvious that our individual spin pole determinations can not be fitted by the precession pole from Kucharski et al.

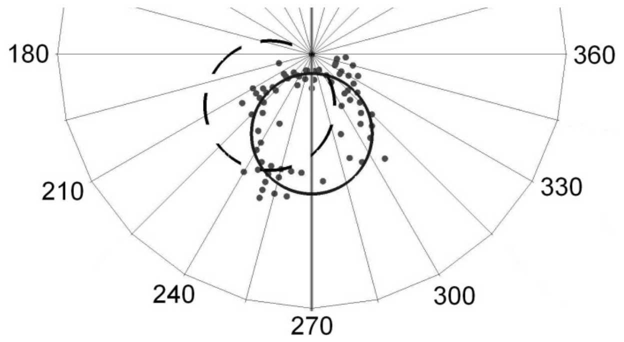

Figure 3: The spin-axis pole positions obtained on different dates over the period from September 2009 to February 2014, and the approximating circular trajectory of the spin-axis precession (indicated by the solid line). The dotted line indicates the spin-axis precession circular trajectory obtained by Kucharski et al. from the satellite laser range observations in 2003-2011.

3. Determination of the Ajisai spin period

The satellite's sidereal rotational period is determined based on the measurements of apparent (synodic) time intervals between individual flashes. Earlier, those measurements, being supplemented and checked at different passages of the satellite, were employed to develop a model for the mirrors' arrangement on the Ajisai's surface (Korobeynikova et al., 2012). And further, when determining the satellite's sidereal rotational period, the model is applied to compute the phase difference between any far off in time flashes from two different mirrors.

When the spin-pole orientation is not yet specified, we use the below-described quick-test which implies the neglect of the pole deviation from the celestial pole.

Let us consider four successive instants of flashes, which appear during one rotation of the satellite at the beginning of its passing above the observation site. The time interval between the fourth and first instants gives a preliminary estimate of the sidereal period P_1. By dividing three time intervals by that sidereal period we will determine approximate differences in longitudes of three reflecting mirrors. Based on those differences in longitudes, we can easily identify three corresponding mirrors in the model and hence to get to know their longitudes and common latitude on the satellite's surface.

Then, we can perform the similar identification of the mirrors for four successive flashes at the end of the satellite's passage. After that, we select two flashes from the examined eight ones (one of the selected flashes is in the beginning of the satellite's passage, and another one is at the end of it), for which the respective mirrors' longitudes minimally differ from each other. Let us divide the time interval between those flashes by the estimated sidereal period P_1 mentioned above to find the number of complete revolutions N between the given instants, which is the nearest integer. Thereby, it is possible to determine the sidereal period as the mean value of several estimates resulted from the following formula:

$$P_{sid} = (t_{fin} - t_{beg})/[N - (\alpha_{fin} - \alpha_{beg}) + (A_{fin} - A_{beg})] ,$$

where t_{beg} and t_{fin} – any pair of instants in the beginning and at the end of the satellite's passage; α_{fin}, α_{beg}, A_{fin} and A_{beg} – corresponding bisector right ascensions and mirrors' longitudes in the satellite's model expressed in fractions of rotation. The signs placed in front of corrections to the integer value of a number of rotations depend on the sense of the satellite's spinning; they enabled to find out that Ajisai is spinning in a clockwise direction (in the opposite direction to that of the Earth's rotation). The error in the period determination is caused by the errors in the obtained instants of flashes (<0.02 sec) and to the far smaller extent by the errors in the satellite's model and in the substitution the bisector right ascension for the bisector longitude in the coordinate system related to the satellite's spin axis. In our results, values N vary in the range from 50 to 320. Thus, the period's errors tend to be less than 0.0002 sec.

When the Ajisai spin-axis orientation is determined as it is described above, it is possible to ascertain the sidereal period for all available measurements of the instants of flashes:

$$P_{sid} = (t_i - t_1)/[N_i - (\lambda_i - \lambda_1) + (A_i - A_1)],$$

where t_1 and t_i – the first and all successive instants of Ajisai flashes during one passage; λ_1 , λ_i , A_1 and A_i – corresponding bisector longitudes in the coordinate frame related to the spin axis at the *i*-th instant of time and mirrors' longitudes in the satellite's model; N_i – the number of complete revolutions of the satellite over the interval $(t_i - t_1)$.

Thereby found values of the Ajisai sidereal rotational period are in good agreement with the most precise data by other authors (Kirchner et al., 2007; Vovchyk, 2003; Korobeynikova et al., 2012) – the duration of one rotation exponentially increases with time, i.e. the satellite slows down. Moreover, there is a well noticeable variation of the spin deceleration rate relative to the background of the secular slowing down of the satellite's spinning.

On the time interval 2009-2013, the increase in period can be approximately calculated by the linear formula (to visualize of the deceleration rate):

$$P_{sid} = 1.3596901371 + 0.0000879961\cdot(t - 12\text{-}08\text{-}1986),$$

where t – the observation date counted from the date of the satellite launch on 12 August, 1986. However, to make the calculation more accurate for that time interval, the formula of the Ajisai deceleration looks as follows:

$$P_{sid} = 1.485802163871\cdot EXP(0.015011430489\cdot(t - 12\text{-}08\text{-}1986))$$

where 1.4858 – the initial spin period of the satellite just after launching obtained according to our data.

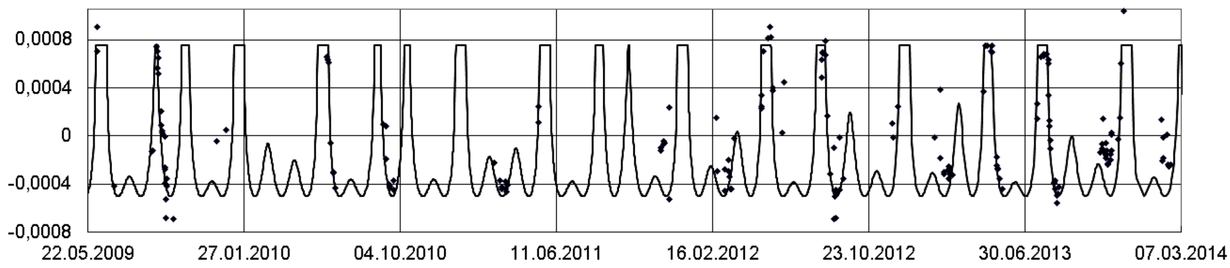

Figure 4: The Ajisai spin deceleration rate variations calculated from observations – the remainder after subtracting the exponential approximation (of the point). The solid-line curve is the renormed graph, which illustrates a part of the satellite's orbit out of the Earth's shadow (it occurs in the minimum of 0.7 and the maximum of 1.0).

Therefore, the Ajisai axial spin period, for instance, in 2013 was about 2.23 sec and it has been increasing on average by 0.00009 sec per day.

However, it is known that there are some non-periodic variations of the Ajisai spin deceleration rate (Kucharski et al., 2009), and that is completely borne out by our measurements. The variations of the Ajisai spin deceleration rate – the remainder after subtracting the exponential fit – are shown in Fig. 4 (of the filled point). The solid-line curve in the figure demonstrates the graph, renormed for the same range, which illustrates a part of the satellite's orbit out of the Earth's shadow (for Ajisai it occurs in the minimum of 0.7 and the maximum of 1.0).

It can be calculated rather easy by simple formulae for the circular orbit of Ajisai. If α is an angle between the normal to the orbit and the direction towards the Sun, then the illuminated part of the orbit is calculated as follows:

$$(\pi/2 + \arccos((R_E^2 - a^2\cdot\cos^2\alpha)^{0.5}/a\cdot\sin\alpha))/\pi,$$

where a – the semi-major axis of the satellite; R_E – the Earth's radius.

This graph demonstrated a noticeable correlation between the period of the satellite's illumination by the Sun and its deceleration rate (increase in the satellite's spin period) (Kucharski et al., 2010). Kucharski et al. suggested that such correlation can be caused by the Yarkovsky effect. However, it is known that for spherically symmetrical bodies there is no additional torque due to the YORP-effect on the rotating body. This observation fact provides a area for theoretical generalisation and interpretation of the obtained data.

4. Conclusions

A new technique for determination of the spin-axis orientation during each passage of the satellite over an observation site was developed. The secular slowdown of the satellite's spin rate ($P_{sid} = 1.4858\cdot EXP(0.000041099\cdot T)$ where T is measured in days counted from the date of the satellite launch) and its variations correlating with the average duration of the satellite orbit out of the Earth's shadow were borne out (Kucharski et al., 2009). New parameters of the spin-axis precession were estimated: the period P_{prec} = 116.44 days, $\alpha_{prec} = 18.0^h$, $\delta_{prec} = 87.66°$, the nutation angle $\theta = 1.78°$ and maximum value of $\delta_{pol} = 89.5°$ is achieved on 7.78 August 2013.

Regular photometric observations of the satellite are expected to clear up the physical nature of the discovered specific features of its rotation, enable to calculate the precise ephemeris of its position in space and use this space object for communications between widely distant observation sites.

The described technique of the photometric observations and their processing aimed to determine the Ajisai rotation parameters enable to directly identify any mirror on the satellite's surface which produced a recorded flash. That considerably simplifies, first of all, the procedure of the spin period determination. The error in determination of the period δP linearly decreases with increasing number of rotations N on the interval of measurements ΔT between two flashes.

$$P \pm \delta P = \Delta T/(N \pm dN) \pm 2\cdot\delta T/(N \pm dN),$$

where δT – the error in measurement of the instant of flash.

The application of the model for the mirrors' arrangement opens the way to ascertain dN and determine the spin period with high accuracy not only during one passage of the satellite, but also to proportionally increase the accuracy of period determination by calculating it on the interval of either two successive passages (with the spin period formal error is $\delta P \sim 0.00001$ sec) or a 24 hours-period ($\delta P \sim 0.000001$ sec). As the characteristic time of the change in the period variation rate equals to several days, this method allows of studying minute particulars of those variations.

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