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ON THE DETERMINATION OF AJISAI'S SPIN PARAMETERS FROM GRAZ KHZ-SLR DATA

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Abstract

We determine the spin rate and spin direction of the spherical satellite AJISAI as well as its slow down between 2003/10 and 2005/06 using Graz full rate kHz satellite laser ranging (SLR) data.

Since October 2003, the SLR station Graz/Lustbuehel - as the first and only station worldwide - is capable of laser ranging to Earth orbiting satellites with a laser pulse repetition rate of 2 kHz. The high density of the kHz observations - compared to the regular 10 Hz systems - results in a very precise scanning of the distribution and orientation of the satellite's retro-reflector panels during its spinning motion. The frequencies resulting from spectral analysis methods allow to identify the arrangement of the involved laser retro reflector panels at any instant in time. Using this method, we calculated the spin rate with very high accuracy (RMS of 4.6×10^{-4} Hz), and determined a slow down of the spin rate of 0.0081 Hz/yr during the investigated period.

The main reason of this long term slow down is due to the interaction between the satellite's metallic parts and the Earth's magnetic field causing eddy currents. However, these mechanisms have not yet been modeled precisely. Furthermore, an approach was made to determine the attitude of AJISAI's spin axis at any instant in time.

Introduction

The structure of Japan's experimental geodetic satellite AJISAI (Fig. 1) is a hollow spherical body made of glass-fiber-reinforced plastics. The surface is covered with 318 reflecting mirrors and 120 laser retro reflectors (LRR) (Sasaki and Hashimoto, 1987). The solar reflectors which are made of an alloy of aluminum are designed to reflect sunlight visible as short flashes with a significant pulse length depending on the spin rate of the satellite.

Each of the LRR carries 12 corner cube reflectors which are built for satellite laser tracking only, i.e. to reflect the short laser pulses emitted by the ground station right the way back.

Both types of reflectors are almost uniformly distributed over the surface of the sphere with a diameter of 2.15 m. AJISAI was launched in 1986 into a 1500 km almost circular orbit with a 50° inclination and an initial spin rate of 40 rpm with the spin axis being almost parallel to the Earth's rotation axis.

Regular observations were made by a Japanese group for the determination of the spacecraft's spin rate. It is reported that the spin rate had decreased from 0.67 Hz after launch to 0.57 Hz in 1998, i.e. 12 years later.

Fig. 1: Experimental geodetic satellite AJISAI.

Another alternative approach to determine the spin motion was made by a spectral analysis of the full-rate (FR) data of the global satellite laser ranging network (Otsubo et al., 2000). The FR data represent the full amount of returns from the single shot measurements which are usually made at a 10 Hz firing rate. That study revealed a slowdown rate of AJISAI of 2.4×10^{-4} Hz/day from a one year analysis of SLR data obtained in 1998.

The present study focuses on the analysis of newly available kHz laser ranging data from the Graz SLR station. While most of the 40 laser stations worldwide are usually tracking with a 5 or 10 Hz repetition rate, an extensive technical upgrade was made at the Graz SLR system in 2003, which allows to routinely track satellites with a 2 kHz pulse repetition rate (Kirchner and Koidl, 2004). On the basis of spectral analysis methods of one and a half year Graz kHz SLR data we determined AJISAI's spin rate to be 0.506 Hz in July 2005 with a yearly slowdown rate of 7.75×10^{-3} Hz/yr (Kirchner at al, 2006).

AJISAI's LRR and ranging properties

The LRR panels of AJISAI are distributed in a very characteristic pattern arranged in 15 latitudinal rings. There are 5 rings with 12 LRR's, 4 rings with 9 LRR's, 2 rings with 6 LRR's, and 4 rings with 3 LRR's each which are positioned as indicated in Fig. 2. At the present level of accuracy of laser ranging measurements the main error sources are found on the one hand in the station's system noise and in inaccuracies of the present atmospheric delay models and on the other hand in the spread of retro-reflection due to multiple reflectors on the satellite. The latter does strictly speaking the centre-of-mass correction for spherical satellites not allow to be treated as a constant (Appleby, 1992).

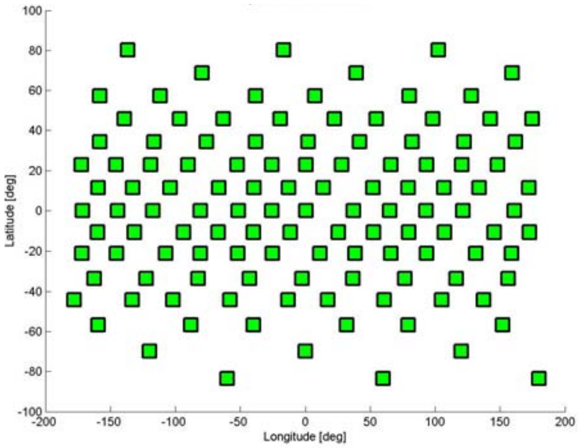

Fig. 2: Distribution of AJISAI's LRR panels.

In connection with kHz laser tracking, i.e. with a very high repetition rate (2 kHz) and a very low energy per pulse (400 µJ) we assume, that we always range to the LRR closest to the ground station. The axial rotation of AJISAI and the well separated LRR generate a very characteristic pattern of distance variations.

An extensive simulation study was performed to associate the true measured ranges with the corresponding computed values. The example given in Fig. 3 shows both a simulated and a measured range pattern which make this issue very clear. The measured ranges (dots in the lower plot) correspond to the lowest values (i.e. nearest LRR) of the range simulation (solid line in the upper plot; each occurrence of a LRR appears as a parabola).

Spectral analysis of kHz SLR data

The raw full-rate ranging measurements have to be corrected for a number of effects (biases, atmospheric propagation, etc.) which is done in the frame of regular tracking. In order to analyze the ranging data a reference orbit and a low order polynomial are subtracted. This results to ranging residuals as shown in the upper plot of Fig. 4.

Even in good weather conditions SLR stations do not reach a 100% return rate and therefore the obtained full-rated measurements show gaps and non-equidistant firing epochs. This, in the strict sense, does not allow us to apply FFT methods for data analysis.

As an alternative to data interpolation and epoch time shifting we used the Lomb method which allows to handle non-uniformly spaced data.

We investigated a large number of passes which show many different frequencies resulting from the individual retro-rings as well as from combinations of simultaneously visible rings which show very significant occurrences of the LRR's.

There are some characteristic frequencies resulting from the individual single ring tracking periods. Each ring carries a specific known number of LRR's and yields a frequency which is a natural multiple of AJISAI's spin rate. These frequencies are 1.5, 3.1, 4.6 and 6.1 Hz corresponding to 3-, 6-, 9-, and 12-retro rings which are generated by the uniquely identifiable spin rate of about 0.505 Hz.

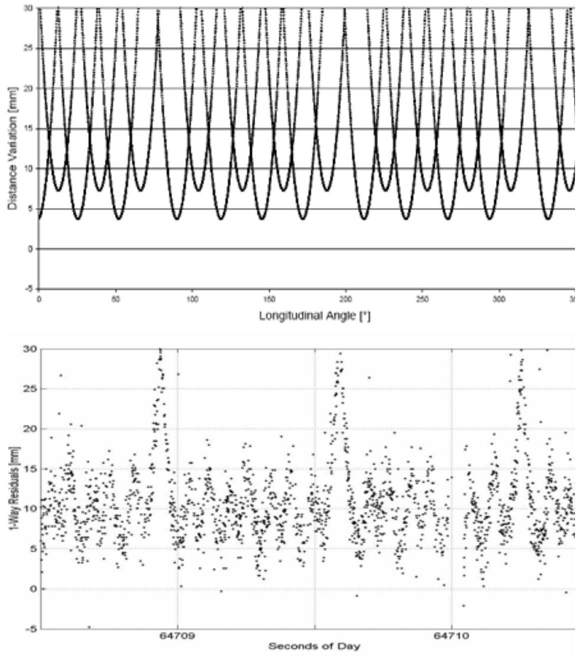

Fig. 3: Distance variation of AJISAI's LRR (top: simulation, bottom: measurements) when tracked with a laser beam incidence angle of 18.125 deg wrt. to the satellite's equator.

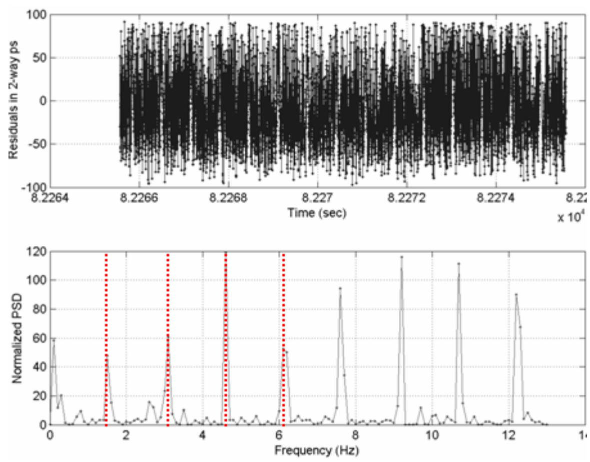

Fig. 4: Ten seconds (approx. 5 rotations) of full-rate ranging data (above) and the corresponding power spectrum (bottom).

Corrections to the apparent spin rate

The spin rate of a satellite observed at any site on Earth is affected by its motion around its own axis as well as on its orbit around the Earth and by the Earth's rotation itself. Therefore the apparently measured rotation has to be corrected for these effects. A non-rotating spacecraft orbiting around the Earth is apparently observed as a body performing a once per revolution rotation around its own axis. For the following considerations an a-priori attitude of the spin axis parallel to the Earth's axis of rotation is assumed as this is the case with AJISAI.

Parallax Effect

Since the observer is located on the Earths surface rather than at the geocenter and the satellite orbit has a non-zero eccentricity, the relative position of the spacecraft with respect to the observer is affected by the parallax effect. This makes the observed rotation of the satellite appearing as a non-uniform rotation.

Synodic Period

A tracking system on Earth observes the spinning period of an orbiting satellite with a synodic rather than a sidereal period. The sidereal period corresponds to a 2π-rotation of the satellite around its own axis in an inertial reference frame. As the satellite during that time is moving on its orbit around the Earth in counter-clockwise direction it is apparently showing a slower spin.

Effect from Earth rotation

The ratio between synodic and sidereal period not only depends on the satellite's orbital motion around the Earth, but also on the Earth rotation itself.

For the estimation of the apparent satellite spin we assume a non-rotating satellite represented in an Earth-fixed topocentric reference system. Further, an arbitrary space fixed reference direction is defined to coincide with a particular phase, e.g. the zero-meridian of the spacecraft.

The corresponding longitude at which the laser beam hits the satellite is then computed from the azimuth and elevation angles for a given observation epoch. From a series of consecutive observation angles at an adequate resolution we compute the longitudinal rate of change and derive the corresponding apparent spin rates. Fig. 5 shows the corrections to the apparent spin rate of one AJISAI pass (pass-no. 01922).

Spin direction Both the computed and observed apparent spin rates always show an increase, i.e. a positive shift for the approaching arc of the satellite pass. From the fact, that the orbit of AJISAI is prograde (50 degrees inclination) and the apparent rise of the shift we conclude, that the satellite performs a retrograde rotation. In other words, AJISAI is spinning counter-clockwise.

Spin rate slow down

It was shown that each calculated frequency corresponds to a specific number of LRR panels on one ring. The ratio between the frequency and the number of panels of the corresponding ring gives the exact spin rate of AJISAI.

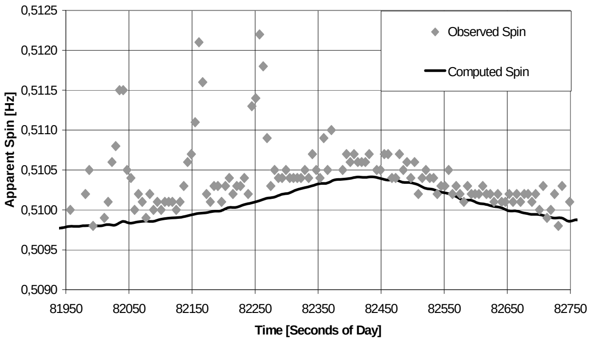

Fig. 5: Progression of the apparent spin (computed and observed) for one pass with the rising part being the approaching arc.

In order to perform a long-term analysis we selected a number of 195 passes between October 2003 and June 2005 which showed a rather good quality in terms of pass length and observation density. We concentrated on the 6-, 9-, and 12-retro rings only and after correction of all the previously discussed apparent effects the trend of the rotation rate becomes very clear (Fig. 6).

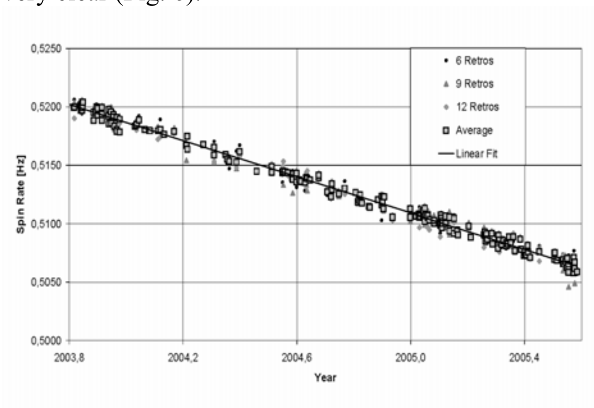

Fig. 6: Spin rate decrease from 195 selected passes between October 2003 and June 2005.

The spin rate decrease of AJISAI naturally follows an exponential function. However, from the relatively short time interval of our analysis we computed a linear trend of 0.00774974 Hz/yr with a standard deviation of 0.000403 Hz.

Thus we can give a sufficiently accurate rule of thumb of AJISAI's spin rate (ω_A) for the upcoming years:

$$\omega_A\ [Hz] = -0.0077\ t_Y + 16.0491,$$

where t_Y is the pass time given in absolute calendar years.

Eddy currents

By the motion of the spinning satellite along its Earth orbit the metallic solar reflectors are moved through a

spatially varying magnetic field. This induces Eddy currents which start to circulate through the metal and in turn generate a magnetic field, which counteracts with the Earth's magnetic field and thus decelerate the satellite's spin motion. On the one hand this breaking action depends on the number (318 pieces) and specific material of the reflectors (alloy of aluminum) and its base, respectively, as well as on its size (approx. 350 cm^2) and relative velocity (Fig. 7). On the other hand also the direction and strength of the magnetic field is a crucial factor since the effect reaches its maximum, when the Earth's magnetic field vectors are perpendicular to the plates. Thus, the deceleration effect is directly proportional to the latitude of the orbital position.
Some issues have already been considered at the spacecraft design stage in order to reduce the decrease in the spin rate. Materials of low conductivity were used and parts were made small and thin where good conductivity materials had to be used (Sasaki and Hashimoto, 1987).

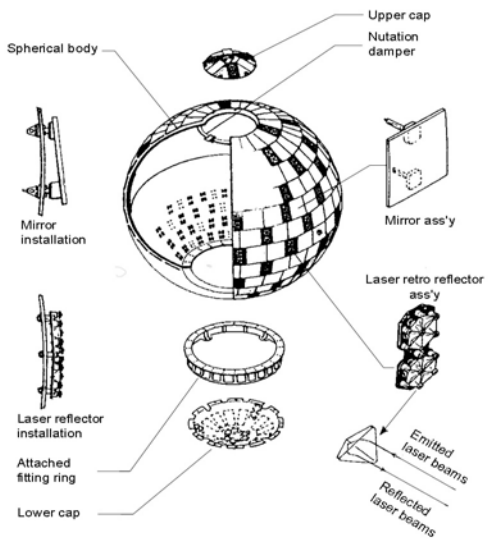

Fig. 7: System elements and construction of AJISAI (from Sasaki and Hashimoto, 1987).

Spin axis attitude

From previous studies dealing with spectral analysis of 10 Hz laser ranging data it was not possible to gain any information about the spin axis orientation. On the basis of 2 kHz single photon measurements to spherical satellites this situation changes and we may assume to know the exact distance between the laser station and the closest LRR at any instant which allows a precise CoM-correction.
From spectral analyses of the laser returns we can also derive the exact instant in time at which the laser beam points perpendicular to any row of LRR's. The precise knowledge of the construction and dimension of AJISAI allows to compute one point on the spin axis corresponding to the latitude of the observed LRR-row.
Both, this point and the center of mass define one possible direction of the spin axis, but with a degree of freedom. The entirety of all possible directions of the rotation axis describes a cone with its apex in the CoM and its base describing a circle on the satellites spherical surface (Fig. 8). From the observations of different rings the resulting circles intersect in one common point, which uniquely represents the actual position of spin axis.

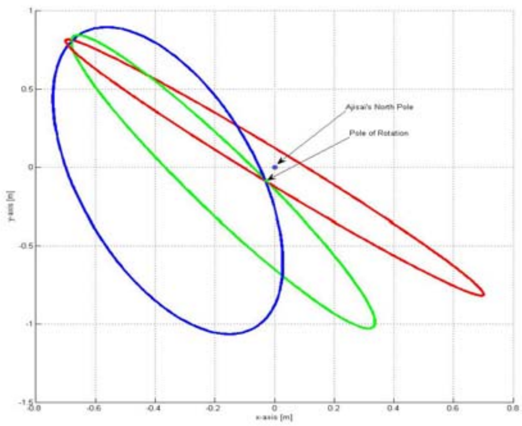

Fig. 8: Unique determination of the instantaneous attitude of AJISAI's spin axis from the observation of different LRR rings (pass-no. 01922).

Conclusion

KHz SLR is a powerful technique, not only for ranging to Earth orbiting satellites with mm-precision, but also for the precise determination of spin parameters of rotating spherical spacecraft.
The tremendous accuracy reveals tiny variations of the measured distances to individual retro-reflectors and is thus applicable for the determination of the attitude of many spacecraft.

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