DERIVING THE SPIN RATE/ORIENTATION FROM THE QUIESCENT SPACECRAFT *ABRIXAS* USING OPTICAL OBSERVATIONS*

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ABSTRACT

With the loss of the battery system of ABRIXAS shortly after launch and consequent absence of telemetry, there was urgent need to determine ABRIXAS' spin rate and orientation in order to assess the possibility of re-establishing telemetry during periods of full-Sun orbits. We, therefore, conducted optical and video observations of ABRIXAS passages with a 1-second time resolution, and later simulated the optical appearance of ABRIXAS for several passages based on a three-dimensional model of the reflectivity properties of the 2.5m x 1.8m x 1.2m size-satellite. Here we present the results of the comparison of our grid of light curve models with the observations and show (i) how the spin rate of ABRIXAS slowed down between June and December 1999 and (ii) what information can be deduced on the temporal change of the orientation of the spin axis. We conclude with discussing the benefit of using ground based optical observation as a cost effective way to develop information about the orientation of a satellite when there is no telemetry.

INTRODUCTION

ABRIXAS[1] (A Broad Band Imaging X-ray All Sky Survey), a German small-satellite mission, was launched on April 28, 1999 and was designed to perform the first imaging all-sky survey above 2 keV. It consisted of seven 27-fold nested Wolter-I telescopes sharing one pn-CCD detector. This CCD detector is similar to the EPIC-pn camera on the European X-ray Multi-Mirror observatory XMM-Newton, and has an energy range between ~0.5–12 keV. During a three-year mission it was expected to scan the whole sky six times, and to discover at least 10 000 new hard X-ray sources, and substantially contribute to our understanding of obscured active galactic nuclei and the cosmic X-ray background.

After failure of the battery system of ABRIXAS shortly after launch, it became clear that the only chance for any period of continuous satellite operation was during the nearly one-week duration periods when ABRIXAS was in a full-Sun orbit. No telemetry had been received from the spacecraft; hence, the only way to determine spin rate/orientation would be from ground observations. In order to establish a telemetry connection to the satellite, its (single) solar panel has to point towards the Sun. Since there was no active control (but only orbital damping), the Sun pointing happens passively under specific orbit conditions which occur during the full-Sun periods. Another condition for communication with the 500 kg satellite is that the rotation of ABRIXAS must be slow enough so that one of its S-Band antennas would point to Earth during ground station passages and not interrupt any signal. ABRIXAS has a distribution of the moments of inertia such that its rotation will primarily be on the axis perpendicular to the solar panel. Hence, the concern was in rate and temporal evolution of ABRIXAS' spin and its orientation in space for the two full-Sun orbit periods in June/July and November/December 1999.

One option of acquiring this satellite attitude information is to use radar mapping. The Tracking and Imaging Radar (TIRA) of the Research Institute for High Frequency Physics and Radar Techniques (FHR) at the Research Society for Applied Natural Sciences (Forschungsgesellschaft für Angewandte

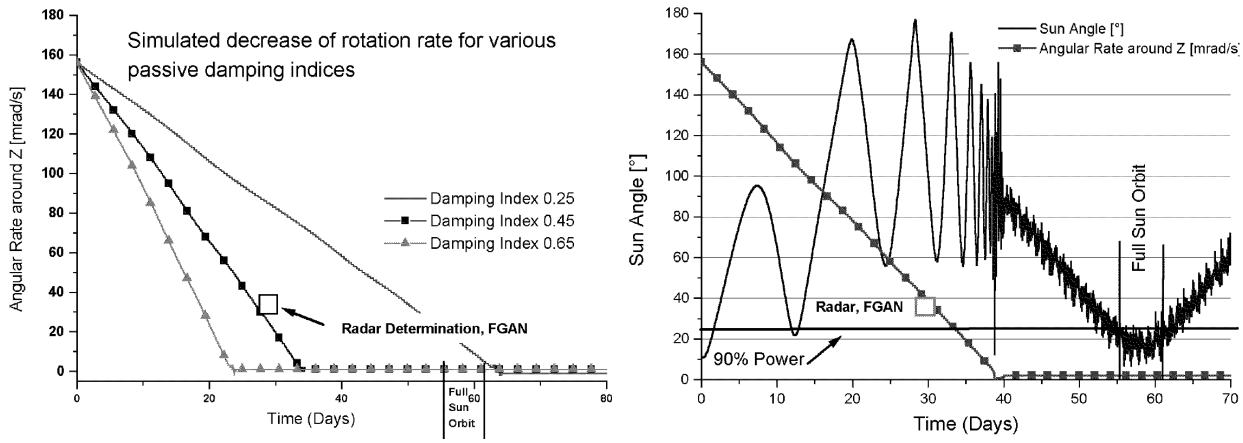

Figure 1: Predictions of the behaviour of the ABRIXAS satellite based on information until 30 days after launch. **Left:** Possible decline rates of the satellite's spin rate depending on different damping strengths. The FGAN measurement on May 31 was thought to constrain the damping strength. **Right:** With that damping strength the axis perpendicular to the solar panel should lock into (anti-)Sun-orientation after about 40 days, thus facing the solar panel towards the Sun during the full-Sun orbit period either in July 1999 or December 1999.

Naturwissenschaften, FGAN) has measured several passages of ABRIXAS on 31 May, 8 June, and 11 June 1999. The TIRA system which is operated by the division Radar Techniques for Space Reconnaissance (RWA) consists of a narrow band tracking radar and a high resolution imaging radar supported by a large parabolic antenna with an aperture of 34m. The analysis of radar cross section signatures and series of highly resolved radar images with 25 cm resolution revealed that ABRIXAS was rotating with a period of approximately 180 seconds. It was assumed that the axis of rotation is perpendicular to the solar panel. (A sequence of six radar images is shown at URL http://www.aip.de/cgi-bin/w3-msql/groups/xray/abrixas/abrixas_FGAN.html).

Based on this observed spin period and the assumption that the ABRIXAS satellite initially (after loss of power and contact) was spinning rapidly, it was predicted that the spin rate could slow down within 30–40 days and then lock into a stable orientation (see Figure 1). This prediction was made under the additional assumption that there was no active attitude control anymore (which turned out to be wrong; see below), and that the main force of rotation damping is due to magnetic hysteresis effects. Apart from the gravitational gradient torque no further braking mechanisms were included in the simulation. As can be seen in the right panel of Figure 1, together with the spin damping the orientation of the main rotation axis (which is perpendicular to the solar panel and shown as the Sun angle distance) asymptotically approaches and finally, after about 30–40 days, locks into its gravitationally determined equilibrium orientation. From then on, the main rotation axis is mainly influenced by the gravity gradient torque, and thus follows a periodic curve which is defined by orbital influences. This curve exhibits minima (or maxima) of the Sun angle when the main rotation axis points towards the Sun, i.e. the Sun stands highest over (or under) the orbital plane (see e.g. Figure 9). During two ~1-week periods per year this coincides with the orbital plane being perpendicular to the Sun: then the satellite moves along the day-night border, and these are the so-called full-Sun orbits.

Another option of acquiring rotation and orientation information of ABRIXAS was from optical observations. Since these observations required high temporal resolution and sufficient accuracy, we did not attempt to do the observations by ourselves, but asked for help from SeeSat. SeeSat is the Internet mailing list for visual satellite observers[2] created in December 1994. SeeSat provides satellite observers with, e.g. up-to-date orbital elements of many satellites, re-entry predictions of decaying satellites, discussions about observing techniques, observation reports of exceptional sightings and much more. As a result of this request P.D.M. performed such observations.

In the subsequent sections we describe the optical observations of ABRIXAS, the model simulations of light curves, and the results derived from the detailed comparison of observations and models.

Table 1: Observation log

Date	Time (UT)	Elevation	Azimuth	Location
19 May 1999	02.25	54°	302°	Houston, Texas, USA
10 Jun 1999	09.16	55°	137°	Houston, Texas, USA
27 Jun 1999	03.30	29°	58°	Houston, Texas, USA
29 Jun 1999	10.25	31°	297°	Houston, Texas, USA
5 Jul 1999	02.23	44°	321°	Zephyr, Ontario, Canada
5 Jul 1999	04.04	67°	19°	Zephyr, Ontario, Canada
6 Jul 1999	04.08	46°	309°	Zephyr, Ontario, Canada
16 Jul 1999	03.00	30°	351°	Houston, Texas, USA
26 Aug 1999	10.50	27°	347°	Houston, Texas, USA
27 Aug 1999	10.53	30°	324°	Houston, Texas, USA
5 Sep 1999	02.53	20°	312°	Abiquiu, New Mexico, USA
14 Sep 1999	00.06	23°	340°	Mount Airey, Maryland, USA
1 Nov 1999	01.12	20°	316°	Houston, Texas, USA
22 Dec 1999	12.22	15°	337°	Houston, Texas, USA
23 Dec 1999	12.24	14°	324°	Houston, Texas, USA
24 Dec 1999	12.26	15°	313°	Houston, Texas, USA
25 Dec 1999	12.28	15°	300°	Houston, Texas, USA

OPTICAL OBSERVATIONS

Optical observations of ABRIXAS were carried out using a visual photometric technique[3]. Once the spacecraft instability situation was identified, a number of observational opportunities were attempted between May 19, 1999 and January 1, 2000 from sites in Houston, Texas; Abiquiu, New Mexico; and Zephyr, Ontario, Canada by one of the authors (P.D.M.). Table 1 gives an overview of the details.

For this process to be most effective, look angles were computed from orbital element sets of ABRIXAS with an epoch of origin not older than one or two days prior to the observation date. Either 7x35 binoculars or a 15cm refracting telescope was employed to track the spacecraft during two possible visibility windows: 45 minutes to 2 hours past sunset, or 2 hours to 45 minutes before sunrise. A (typical) 5 degree field of view in the sky was pre-selected as early as possible in the pass, wherein reference stars of known magnitude were identified. As ABRIXAS would come into view, a tape recorder with fresh batteries was started to record a continuous stream of brightness estimates verbally called out during the pass. A typical pass lasted from two to six minutes depending upon local terrain masking and lighting conditions.

The brightness estimates were then reassembled based on the elapsed time from the start of the tape, and then a light curve was constructed with a time resolution of 1 sec. This resultant signature represented a trace of apparent visual magnitude without need to correct for slant range. The basis was to attempt to develop information on a tumble period (one complete spacecraft rotation), provided it could be determined. As ABRIXAS changed its rotational characteristics, the light curve changed correspondingly. Because the optical method is low resolution, it was never possible to see a physical shape to the satellite, but merely a moving dot which varied in brightness as sunlight reflected off the surface and was received by the observer's eye. As ABRIXAS' rotation was slowed, the challenge was to correlate known spacecraft features with peaks and valleys associated with the light curve by the modelers. If the tumble was rapid enough, one or more complete rotational cycles would be evident.

A video system was also used to record light variation from ABRIXAS in order to permanently document its character. The system is a low light level image intensified system using a 300mm objective lens, CCD camera and 3rd generation image intensifier. Data was recorded on 8mm VHS video tape. This medium was helpful in illustrating the changing signature as the spacecraft's light curve would change over time.

Overall, we see quite dramatic variations of the reflected light intensity with amplitudes up to 4 magnitudes and as short as a few seconds. All 17 observed light curves are presented in Figure 2 and give an overview of these variations.

Figure 2: All observed light curves of the ABRIXAS satellite (see Table 1) sorted by time (from top to bottom). The brightness scale is the same in all panels.

REFLECTIVITY MODEL OF ABRIXAS

The programme to determine the apparent magnitude of the ABRIXAS satellite uses an ordinary projection algorithm. A three-dimensional model of the reflectivity properties of the 2.5m x 1.8m x 1.2m-size ABRIXAS satellite has been developed which is based on a simplified geometric figure. The satellite is represented by some 26 faces (Figure 3) of different reflection characteristics (albedo and gloss). They are split into small pieces that are subject first to a projection with the sun as projection centre. The projected pieces are ordered in depth and marked if they are not seen from the projection centre. In the next step the unmarked pieces are projected with the observer as projection centre, their illumination and reflected light calculated, and then plotted after being sorted by depth in order to overdraw the pieces hidden from the observer. The total brightness of the plot is now proportional to the brightness of the satellite. The most difficult part was to model the gloss of the individual faces. We used a model of diffuse albedo with a glossy reflection. The surface brightness s of a piece was written in the form

$$s = a \cdot \frac{1}{r_{\rm sun}^2} \frac{1}{r_{\rm observer}^2} ((1-b) \cdot \cos\alpha + b \cdot \nu \exp[\mu \cos\gamma]),$$

where a is the overall albedo, $r_{\rm sun}$ and $r_{\rm observer}$ the distances (both varying only very slowly), b the gloss part, $\cos\alpha$ the direction cosine of the angle of incidence, $\cos\gamma$ the direction cosine of the angle of divergence between the line of sight and the direction of reflection, μ the percent of total light reflected in a specular manner, ν a corresponding normalization. The coefficients were estimated in a rough way and tried for fitting the light curves. We also note that the absolute values of the albedos of the different materials have not been measured prior to launch, so they are estimates with accuracy probably not better than 10%.

The model of the satellite consists of the following faces (see Figure 3):

1. the cylindric mantle of the main body,
2. the cylindric mantle of the front end of the telescope,
3. its circular front plate,

4.-9. six rectangular faces of the satellite bus,
10.-11. the front/back face of the solar panel,
12. the radiator bottom,
13.-14. the conical part of the radiator, inside and outside (with different albedo),
15.-21. seven faces of the focal plane instrument platform
22.-26. five faces of the camera head.

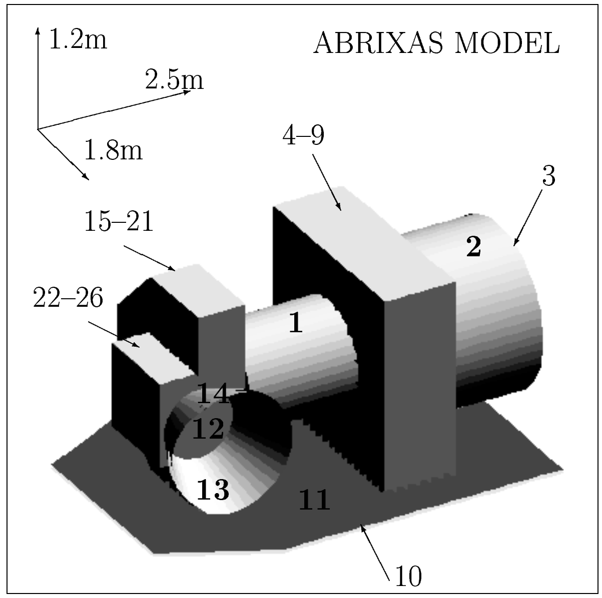

Figure 3: Sketch of the ABRIXAS satellite model used in our simulations, showing the 26 different faces included (see text for description). The satellite dimensions are indicated in the top left.

It is fortunate that the reflectivity varies drastically over the ABRIXAS surface. This is due to the very different surface materials: the (white) MLI (multi-layer insulation) foil which covers most of the satellite bus, the dark telescope lid, the radiator, and the solar panel.

Potential remaining problems in the model could be with details of the highly reflective areas such as the solar panel and the edges of the conical heat radiator. However, given the general success of the present model (see below) we have not tried to fine tune these geometric effects.

SIMULATIONS OF LIGHT CURVES

Given the above described model of the ABRIXAS satellite's surface reflectivity the input parameters for the simulation of a particular path of ABRIXAS over Earth can be divided into two classes:

1. Fixed parameters related to the overall lighting geometry: These include the geographical latitude of the observer, the azimuth of the highest satellite position, as well as the hour angle and declination of the Sun. For each particular path to be modelled these parameters have to be determined and then are valid just for this path, i.e. each path requires its own, unique parameter set.

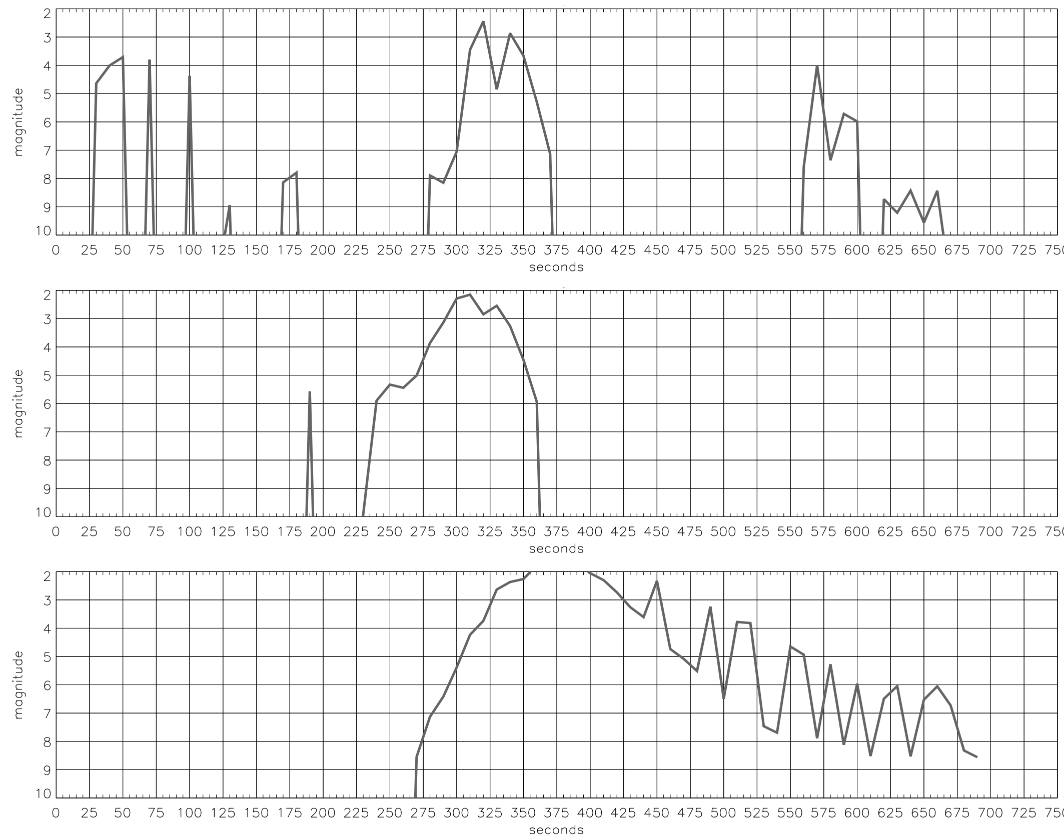

Figure 4: Simulated light curves of ABRIXAS for the full-Sun orbit period in early December 1999. Shown are plots for ABRIXAS' solar panel pointing towards the Sun, rotating at $P = 1000$ sec with phase $\Phi = 180°$ (top) or at $P = 3000$ sec with phase $\Phi = 0°$ (middle), and for ABRIXAS' solar panel pointing in anti-Sun direction and rotating at $P = 3000$ sec with phase $\Phi = 0°$ (bottom).

2. Variable parameters related to the unknown behaviour of ABRIXAS: These include the spin period P, the phase angle Φ of the satellite relative to the Sun for a given point or time, and the orientation of the rotation axis n. We have parametrized these variables in the following way:
   - P = 250 s, 300 s, 500 s, 1000 s, 3000 s
   - $\Phi = 0°, 90°, 180°, 270°$
   - n = the 6 major axes [1,0,0], [–1,0,0], [0,1,0], [0,–1,0], [0,0,1], [0,0,–1]; 12 orientations of the axis in between the major axes, such as [1,1,0], [–1,1,0], [1,–1,0], [–1,–1,0] and so on for the other two planes; 8 diagonals [1,1,1], [–1,1,1], [1,–1,1], [1,1,–1], [–1,1,–1], [–1,–1,1], [1,–1,–1], [–1,–1,–1]; thus yielding a total of 26 orientations in three-dimensional X/Y/Z space.

   This leads to a grid of 520 different start parameters, and consequently computed light curves for each path considered.

We have *not* simulated the optical appearance of ABRIXAS for *all* of these 520 possibilities for *each* of the 17 observed paths, but for several selected passages over a reasonably wide range of the unknown input parameters. We have concentrated our efforts on the three passages in June, those of Sep. 14 and Nov. 1, and the four subsequent passages in December. For the early times, complete grids have been computed for the short periods (up to 500 s), while for the late times (December) mainly the long periods (≥ 500 s) have been covered.

Before describing some selected light curves in more detail, a few general considerations are worth mentioning. (1) In some of the light curves the satellite spin period manifests itself in a regular pattern of rapid brightening and fading. The time of recurrence most probably corresponds to 1/4 of the spin period due to the 4 edges of the satellite (see, e.g. faces 4–9 or 15–21 in Figure 3). For deriving the spin period using such light curves, primarily the portion near the horizon is particularly important, because the satellite has a relatively low "tumbling motion on the sky". (2) In contrast, portions of the light curves near the zenith are dominated by the tumbling mo-

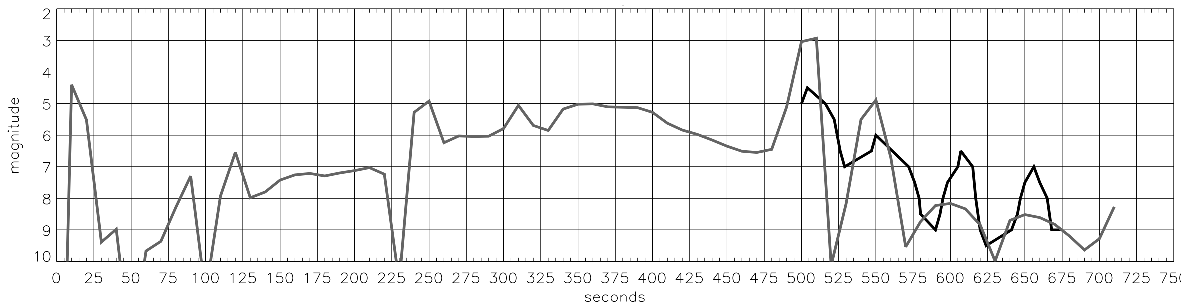

Figure 5: Comparison of the observed (thick line extending from 500–675 sec) and simulated (gray line) light curve for 10 June 1999.

tion of the satellite, and the influence of the orientation of the satellite axis n is large. (3) In general, observations of a passage are short (typically $\lesssim 300$ s), given the low altitude of the satellite orbit. Therefore it is difficult to determine spin periods P which are of the order of this duration (or even longer) which applies to our late time (December) light curves. In addition, any attempt to distinguish between "near-horizon" versus "near-zenith" portions of the orbit reduces the usable temporal coverage by about a factor of 2 and thus makes the situation even worse. (4) An additional effect is that an observer rarely can see the whole satellite pass since the satellite may not be illuminated by the Sun on all portions of its visible trajectory. This introduces an additional shortening of the passage time for which useful observations can be achieved. (5) Note that the phase Φ is indeed a real variable and does not just shift the light curve in time. Due to the changing projected speed relative to the observer the light curve is also stretched in a characteristic way depending primarily on the apparent altitude over the horizon.

Simulated light curves for the full-Sun orbit in December 1999 are shown in Figure 4 and demonstrate the expectation for the case when the major rotation axis indeed has aligned towards the Sun. If the solar panel is oriented towards the Sun, then it shadows nearly the full satellite from illumination, and most of the time no reflected light is visible. Only in rare cases along the satellite passage when Sun light hits a protruding piece of the satellite (such as the outer parts of the conical part of the radiator), a short-lived flash is observed. These flashes are hardly predictable since they depend on the very details of the satellite surface and orbit geometry (see top two panels of Figure 4). If, on the contrary, the solar panel is oriented away from the Sun (lower panel of Figure 4), the solar panel may block reflected light from the satellite towards the observer, and only for a certain fraction of the orbit light from one of the four sides perpendicular to the solar panel can be seen.

RESULTS

A quick check with Figure 2 shows that such a behaviour has not been observed, in particular not during the full-Sun orbit period early July 1999. For the other full-Sun orbit period, in early December 1999, the observations were conducted only about two weeks later. Since the period of the axis rotation is about 60 days, the satellite had already moved about 90° away from the (anti-)Sun alignment.

Figures 5–7 show examples of simulations overplotted on the measured light curves for 10 June, 14 September and 22 December 1999. We will discuss these cases in turn:

1. *10 June 1999*: Simulations with $P = 250$ s fit reasonably well, though the period actually may be somewhat shorter. This is consistent with the radar measurements mentioned in the Introduction which yielded about 180 s for June 8 and June 11, 1999. The absolute phase Φ cannot be accurately determined – values of 180° as well as 270° fit well.
2. *14 September 1999*: Simulations with $P = 250$ s and $P = 300$ s fit reasonably well, while those with $P \geq 500$ s produce light curves with too small amplitude. However, the dips in the light curve are difficult to reproduce. Such behaviour requires a satellite rotation axis orientation which leaves some reflecting area nearly always visible thus enhancing the mean brightness and allowing for dips due to lower reflectivity material passing along.
3. *22 December 1999*: It is quite obvious that the spin period P is larger than the duration of the observation, i.e. $P = 1000$ s or $P = 3000$ s are needed. Even though we have available a four-day sequence of observations, it seems difficult to actually determine the spin period. This is due to the fact that for such long intervals (with respect to observational coverage) the light curve

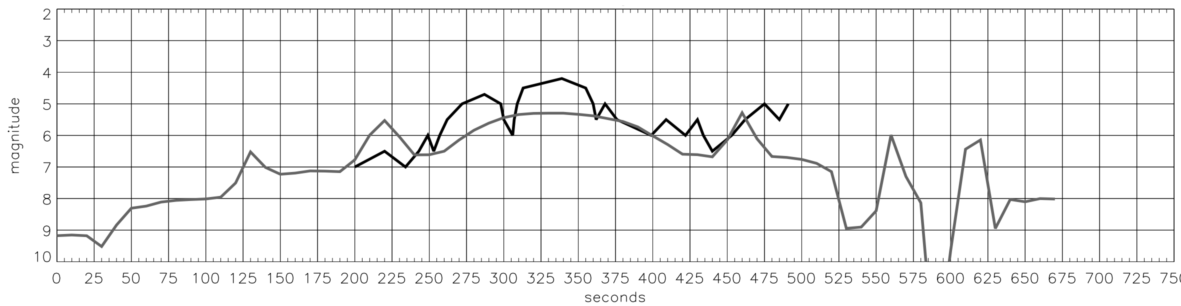

Figure 6: Comparison of the observed (thick line extending from 200–500 sec) and simulated (gray line) light curve for 14 September 1999.

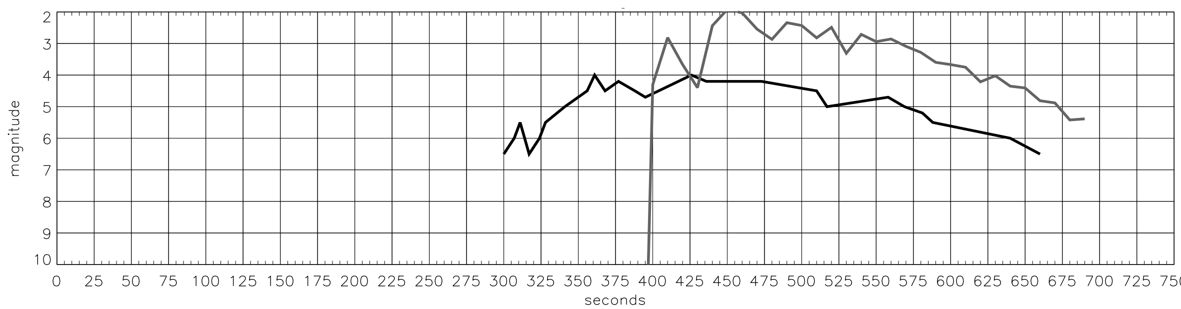

Figure 7: Comparison of the observed (thick line extending from 300–650 sec) and simulated (gray line) light curve for 22 December 1999.

only marginally depends on the spin, but is a strong function of the orientation of the spin axis.

The results of the comparison of our grid of light curve models with the observations show that the spin rate of ABRIXAS possibly slowed down only slowly between June and September 1999, and rapidly thereafter until December 1999. Indeed, a linear damping with the rate as observed during the first two months after launch would predict a complete damping, and thus locking into the two rotations per orbital period value of 5760 sec, by early August 1999 (Figure 8). Our interpretation of the optical light curves suggest that this may have happened only after September, but seemingly until December 1999. We admit, however, that a misinterpretation of the few features could be possible and that the spin period in August actually is longer than 300 sec. A clarification of this issue requires a more dense grid of simulations.

The result on the orientation of the rotation axis is ambiguous. For most of the observations we can merely exclude certain orientations. Only for the four consecutive December 1999 observations we find reasonable consistency of the orientations. In particular, we find that $X = 0$ which means that the solar panel is neither oriented towards nor away from the Sun, but moved considerably apart. This is consistent with the above described shape of the light curve, the observation time being about two weeks after the full-Sun orbit and the consequent orientation 90° apart. Despite this knowledge, we cannot decide whether during the full-Sun period in early December 1999 the solar panel was oriented towards the Sun or in anti-Sun direction.

CONCLUSIONS

As has been shown, deriving the slow down of ABRIXAS' spin period could be achieved using the observed optical light curves of 17 passages. The spin rate derived from the August observation seems a bit short, but misinterpretation of the few features cannot be excluded. Overall, the damping of the rotation rate seems to be linear in time, suggesting a constant braking torque.

On the other hand, it turned out to be very difficult to determine the orientation of ABRIXAS' spin axis in space. In order to be able to derive this orientation, it seems necessary to obtain observations of satellite passages by several observers at different geographic locations on Earth. Also, these observations should be dense in time, e.g. at the same or at least subsequent satellite orbits, so that observations

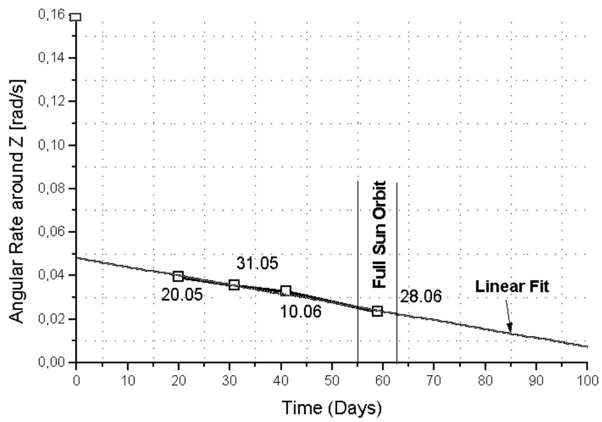

Figure 8: Linear fit of the spin rate decay through optical and FGAN measurements during the first two months after launch of ABRIXAS. The time axis is in days after launch, and the spin rate in radians per second. The open square at launch time at 0.16 rad/s was the early expectation of rapid satellite rotation (tumbling) after loss of contact. It is known that the solar panel was already perfectly pointing towards the Sun when power (and contact) was lost. Seemingly, the satellite occasionally must have been powered up again by the solar panels, leading to an active rotation damping as the immediate first action, thus reducing the spin rate during the sunny parts of the orbit. Our period of $P \approx 250$ sec in June 1999 corresponds to 0.025 rad/sec, and that of $P \approx 300$ sec in September 1999 (140 days after launch) to 0.021 rad/sec.

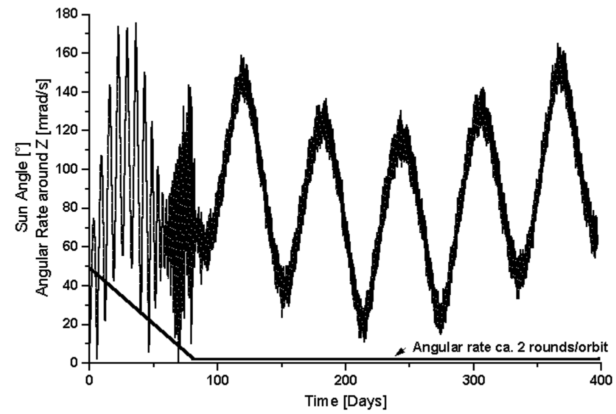

Figure 9: Possible pattern of the spin axis orientation deduced from the linear fit of the data obtained during the first two months after launch (see Figure 8). Clearly visible is the ~60 day period of the spin axis movement.

at different aspects are obtained with the satellite orientation being the same. Otherwise, the rapid change of orientation, in particular during early times after launch (see the wild oscillations in the right panel of Figure 1), cannot be properly mapped.

Overall, we find that in the case of ABRIXAS, employing visual photometry can be a useful tool in attempting to learn more about the rotation rate of a tumbling satellite whose exact rotation (stability) is unknown. Apart from these results directly related to the ABRIXAS satellite, our effort of optical observations and light curve simulations has some more broader implications. In the absence of telemetry, this is not the first time when such information could be of benefit. There are examples of satellite failures that occur on a regular basis as more and more spacecraft are being built and technology is focusing on smaller, lower cost satellites. P.D.M. has gathered optical characteristics data in several cases in the last few years where satellite failures have occurred.

The Japanese ADEOS satellite experienced a solar array problem in June, 1997 which resulted in loss of power, hence telemetry loss as well. P.D.M. was asked to make observations to determine if the satellite was tumbling out of control or seemed to be in a stable orientation. Observations were conducted soon after the event occurred and were reported to the proper agency which showed an irregular light pattern. This was clear evidence of instability.

About 3 years ago, FAISAT-2v (1997-52B) experienced a problem. Here minimal telemetry was available and ground controllers had no success in commanding to the satellite. Within less than a day of launch an onboard beacon remained silent. Therefore it was not possible to know with certainty whether or not a gravity gradient stabilization boom that was supposed to be deployed to control the rotation rate had actually deployed. The satellite operators issued a call for ground observers to attempt to view the vehicle to see if it was giving off flashes of sunlight at certain times or was reflecting light in a regular or irregular manner. In this way, some information might be gleaned as to if the satellite had lost power completely and become unstable.

The following year (August 1998) the Japanese Engineering Test Satellite (ETS) VII experienced a problem releasing a small subsatellite which was supposed to stationkeep and then be retrieved by a robot arm on the parent satellite. Communications with the subsatellite were lost and the Japanese space agency NASDA needed to know whether the subsatellite was stable enough for retrieval. P.D.M. again made observations which were fed back to NASDA that indicated that both spacecraft appeared to be stable (or rotating at a rate slower than the local pass time would allow to be determined). The subsatellite was later successfully retrieved. It turns out that both the target and chaser vehicle were indeed stable.

In 1999 the Iridium satellite constellation was being gradually constructed with multiple satellites launched on expendable rockets from the US, China and Russia. A discovery was made by P.D.M. that brilliant flashes from the spacecraft were recurring in the same part of the sky on successive days. This was especially noticeable when 5 satellites deployed on orbit were in close proximity as they passed over Houston, Texas on one predawn pass. As they crossed the same small area in the sky one after the other, each satellite gave off a unique specular flash. This region of reflection was clearly related to the angle between sun-earth-satellite. It was later determined after investigation with representatives from Motorola, the satellite builder, that the mirror-like Multi-Mission Antennas (MMA) were the source. Other satellite watchers determined a method to calculating local visibility time of these flashes, some of which were so bright they could be observed in daylight hours. In order for the Iridium satellites to function properly, each of the three MMA's located on every spacecraft would have to be oriented with precision so that telephone signals could be relayed from the ground to the satellite and to other satellites in the system to effect the purpose of Iridium which was to allow for worldwide satellite communications from every place on the planet. Unlike other systems, this was the first truly functional global satellite communication system. Now, if a satellite's attitude became anomalous, the forecasted flashes would not occur or occurred with a different brightness than predicted. This would be a signal that something was possibly wrong with the satellite's status. In succeeding months 14 of these satellite's were oberved to be either tumbling rapidly, rotating slowly or otherwise, and were not matching the predicted flash profiles. Thus it was possible for ground observers to know with relative certainty that a satellite had failed or was in temporary trouble. Even in the absence of telemetry, as was the case with the first few Iridium satellite failures, it was easy to make this determination without the need for sophisticated and costly monitoring techniques.

In July 2000, a report was issued that Japan's Advanced Satellite for Cosmology and Astrophysics (also known as ASTRO-D) was spinning out of control. Soon after this announcement P.D.M. observed that its light variation showed that its reflection was exhibiting a gradual, if not slowly varying, pattern suggesting instability. As this paper was being developed more observational work is in progress.

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COVER

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