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

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ABSTRACT

With the power loss of ABRIXAS shortly after launch and consequent absence of telemetry, there was urgent need to determine ABRIXAS' spin rate and orientation to assess the possibility of re-establishing telemetry during periods of full-Sun orbits. We conducted optical and video observations of ABRIXAS passages, and later simulated the optical appearance of ABRIXAS based on a three-dimensional model of its reflectivity properties. Here we 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 discuss 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.

Key words: satellite failure, optical observations.

1. INTRODUCTION

ABRIXAS (A Broad Band Imaging X-ray All Sky Survey [1]), 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 working in the ~0.5–12 keV range. During a 3-year mission it was expected to scan the whole sky 6 times, and to discover ~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

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 Naturwissenschaften, FGAN) has measured several passages of ABRIXAS on 31 May, 8 June, and 11 June 1999. 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/groups/xray/abrixas/-abrixas_FGAN.html).

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 created in December 1994 [2]. SeeSat provides satellite observers with, e.g. up-to-date orbital elements of many satellites, reentry 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.

2. OPTICAL OBSERVATIONS

Optical observations of ABRIXAS were carried out using a visual photometric technique [3]. A number of observational opportunities were attempted between May 19, 1999 and January 1, 2000 from sites in Houston, Texas; Abiquiu, New Mexico; Mount Airey, Maryland and Zephyr, Ontario, Canada by one of the authors (P.D.M.).

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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° 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 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 3rd generation, low light level image intensifier using a 300mm objective lens and a CCD camera. Data was recorded on 8mm VHS video tape. Overall, we see quite dramatic variations of the reflected light intensity with amplitudes up to 4 magnitudes and as short as a few seconds.

3. 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 1) 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

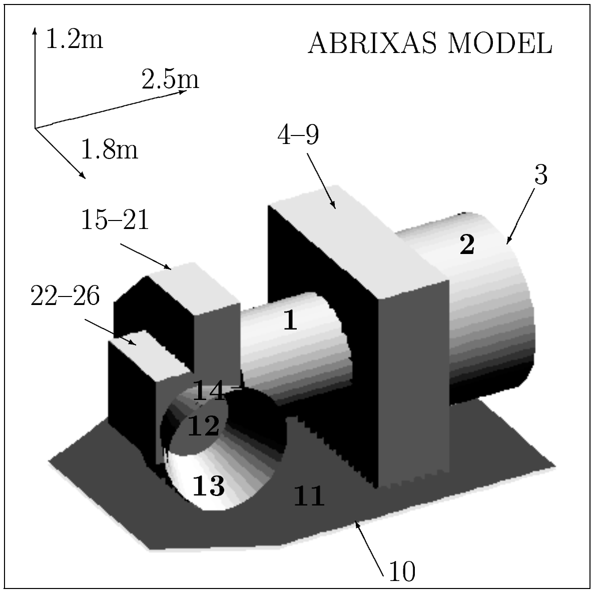

Figure 1. Sketch of the ABRIXAS satellite model used in our simulations, showing the 26 different faces included (see text for description). The satellite dimensions are indicated in the top left.

hidden from the observer. The total brightness of the plot is now proportional to the brightness of the satellite. We used a model of diffuse albedo with a glossy reflection. The surface brightness s of a piece was written in the form

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

where a is the overall albedo, r_{sun} and r_{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 1):

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

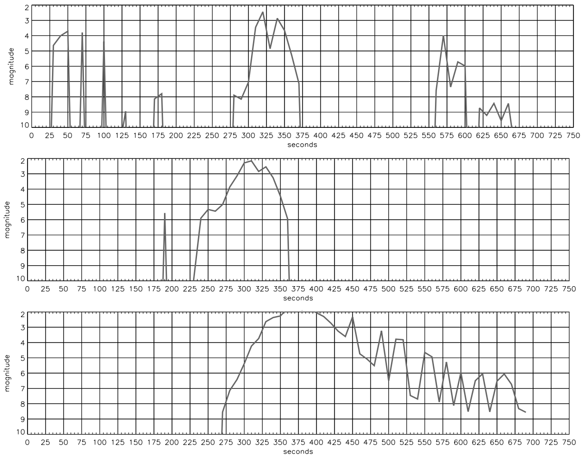

Figure 2. Simulated light curves of ABRIXAS for the full-Sun orbit period in early December 1999. Shown are plots for ABRIXAS' solar panel pointing towards the Sun, rotating at $P = 1000$ sec with phase $\Phi = 180°$ (top) or at $P = 3000$ sec with phase $\Phi = 0°$ (middle), and for ABRIXAS' solar panel pointing in anti-Sun direction and rotating at $P = 3000$ sec with phase $\Phi = 0°$ (bottom).

4. 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.
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
    - Φ = 0°, 15°, 30°, ... 345°
    - 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 3120 different start

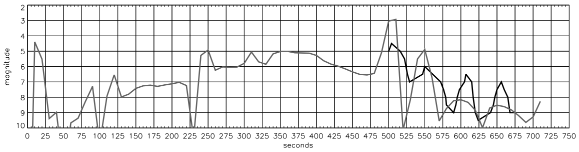

Figure 3. Comparison of the observed (thick line extending from 500–675 sec) and simulated (gray line) light curve for 10 June 1999.

We have simulated several selected passages over a reasonably wide range of the unknown input parameters, concentrating on the three passages in June, those of Sep. 14 and Nov. 1, and the four subsequent passages in December.

Some general considerations first: (1) In some light curves the satellite spin period manifests itself in a regular pattern of rapid brightening/fading. The recurrence time 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 1). For deriving the spin period using such light curves, primarily the portion near the horizon is 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 motion of the satellite, and the influence of the orientation of the satellite axis n is large. (3) Observations of a passage typically are short, $\lesssim$ 300 s. Therefore it is difficult to determine spin periods P which are of this order (or even longer) which applies to our 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 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 on the apparent altitude over the horizon.

Simulated light curves for the full-Sun orbit in December 1999 are shown in Figure 2. If the solar panel is oriented towards the Sun, 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 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 2). If, on the contrary, the solar panel is oriented away from the Sun (lower panel of Figure 2), the solar panel may block reflected light from the satellite towards the observer, and only a certain fraction of the orbit

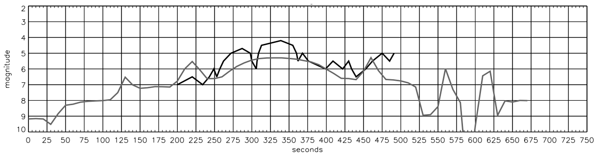

Figure 4. Comparison of the observed (thick line extending from 200–500 sec) and simulated (gray line) light curve for 14 September 1999.

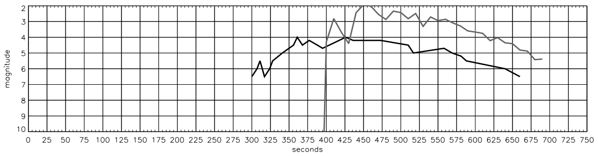

Figure 5. Comparison of the observed (thick line extending from 300–650 sec) and simulated (gray line) light curve for 22 December 1999.

5. RESULTS

Figures 3–5 show examples of simulations overplotted on the measured light curves: *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. *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. *22 December 1999*: It is 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. Despite having data from 4 days, it is difficult to determine the spin period, because for such long intervals (with respect to observational coverage) the light curve only marginally depends on the spin, but is a strong function of the orientation of the spin axis.

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. A linear damping with the rate as observed during the first two months after launch would predict a complete damping by early August 1999. Our interpretation of the optical light curves suggest that this may have happened only after September, but seemingly until December 1999.

The result on the orientation of the rotation axis is ambiguous. For most of the observations we can

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. Despite this knowledge, we cannot decide whether during the full-Sun period in December 1999 the solar panel was oriented towards the Sun or in anti-Sun direction.

6. CONCLUSIONS

Deriving the slow down of ABRIXAS' spin period could be achieved using the observed optical light curves of 17 passages. 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 different aspects are obtained with the satellite orientation being the same. Otherwise, the rapid change of orientation, in particular during early times after launch, cannot be properly mapped.

Overall, employing visual photometry can be a useful tool in learning 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 data in several such cases in the last few years. Using the programmes as developed here would allow to more accurately determine their fate.

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REFERENCES

Trümper J., Hasinger G., Staubert R., 1998, AN 319, 113

De Pontieu B., Clifford N., 2000, at URL www2.satellite.eu.org/sat/seesat/seesatindex.html