Solar Array Thermal Snap and the Characteristics of Its Effect on UARS

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ABSTRACT

The single solar array on the Upper Atmosphere Research Satellite (UARS) is subjected to a thermal distortion when the spacecraft enters and exits the Earth's shadow. The distortion results in a torque that alters the spacecraft attitude. Due to the sudden nature of the attitude discontinuity, the effect has been termed "thermal snap." Thermal snap has also been experienced by Landsats 4 and 5.

Analyses by the spacecraft builder addressed the impact of the resultant torque on the onboard control system. This paper discusses the results of comparisons between the predicted effects of thermal snap on UARS and actual attitude solutions from UARS telemetry data. In addition, this paper describes the characteristics of the thermal snap on UARS in terms of maximum displacement, solar beta angle, and solar array drive angle. Comparisons are made between the actual times of thermal snaps and the predicted spacecraft sunrise and sunset times. The effects of the UARS thermal snap are summarized and a general comment is made relating possible effects of thermal snap on other satellites. Also, an analysis of UARS attitude solutions that span periods of thermal snap was performed to determine whether the gyro sampling time of 1/8 second is sufficient to properly model the resulting spacecraft attitude without compromising the accuracy requirements. The results of this analysis are discussed in this paper.

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1. INTRODUCTION

1.1 History and Motivation

It has been observed for some time that certain spacecraft entering or leaving the Earth's shadow experience attitude perturbations believed to result from a variety of thermal effects. Particularly large perturbations have been observed in spacecraft having flexible solar arrays. Flight data from Landsats 4 and 5, for example, showed large disturbances about the roll and yaw axes whenever the spacecraft entered or exited sunlight. Richmond [Reference 1] has postulated that these disturbances were caused by torques created by the flexing of the solar arrays. This effect has been termed "thermal snap" due to the sudden nature of the attitude disturbance. The possibility of such attitude disturbances during the UARS mission was a concern because the design of the solar array is similar to that of Landsat-4. Prelaunch analysis reports examined the control and stability implications of thermal snap. Jasper and Neste [Reference 2] and Freesland [Reference 3] developed models that reproduced Landsat-4 data to make predictions of UARS perturbations.

As predicted, attitude disturbances near spacecraft sunrise and sunset have been observed in UARS flight data. This paper examines the characteristics of these disturbances, discusses them in light of the predictions, and discusses the implications for UARS and other satellites.

2. DEFINITION OF SOLAR ARRAY THERMAL SNAP

2.1 Geometry

UARS is in a low Earth orbit with an inclination of approximately 57 degrees. The solar beta angle is the complement of the angle between the UARS orbit normal and the Earth-to-Sun vectors. Because of the precession of the UARS orbit and the relative motion of the Sun, the beta angle is constantly changing. The maximum beta angle is approximately 80 degrees.

The normal mission mode attitude reference frame for UARS is the orbital coordinate system (OCS). In the OCS, the spacecraft yaw axis is parallel to the Earth-to-spacecraft vector, and the pitch axis is parallel to the orbit normal vector. Therefore, UARS constantly pitches at the orbital rate.

UARS has a single solar array that is made up of six panels and is offset from the pitch axis by 17 degrees (Figure 1). The orientation of the solar array in the UARS body frame varies with spacecraft local time. At noon, the array is positioned at 270 degrees; at midnight it is at 90 degrees. The solar array drive angle at sunset and sunrise is near 180 or 0 degrees at low beta angles (depending on flying direction, which is explained below) and approaches 90 degrees for high beta angles. This is because the local times for sunset and sunrise become closer to midnight as the beta angle increases. The solar array is nominally driven around the pitch axis at the orbital rate in order to maximize the intensity of the Sun on the solar cells for power considerations. The intensity of the Sun on the array is primarily a function of the solar beta angle. Due to the offset from the pitch axis, the solar intensity on the array is maximum at the beta angle of 17 degrees.

Sunsets and sunrises as observed by UARS appear differently depending on the solar beta angle. At a low solar beta angle, the Sun appears to move perpendicularly to the limb of the Earth. At a high solar beta angle, the Sun appears to move along the limb. Therefore, the UARS solar array sees day/night transitions that decrease in speed and intensity as the beta angle increases.

The changing beta angle also forces UARS to perform an attitude maneuver on approximately a monthly basis. The Sun must be kept in the hemisphere bounded by the X-Z plane and containing the solar array for instrument and power considerations. As the beta angle passes through 0 degrees, UARS performs a yaw

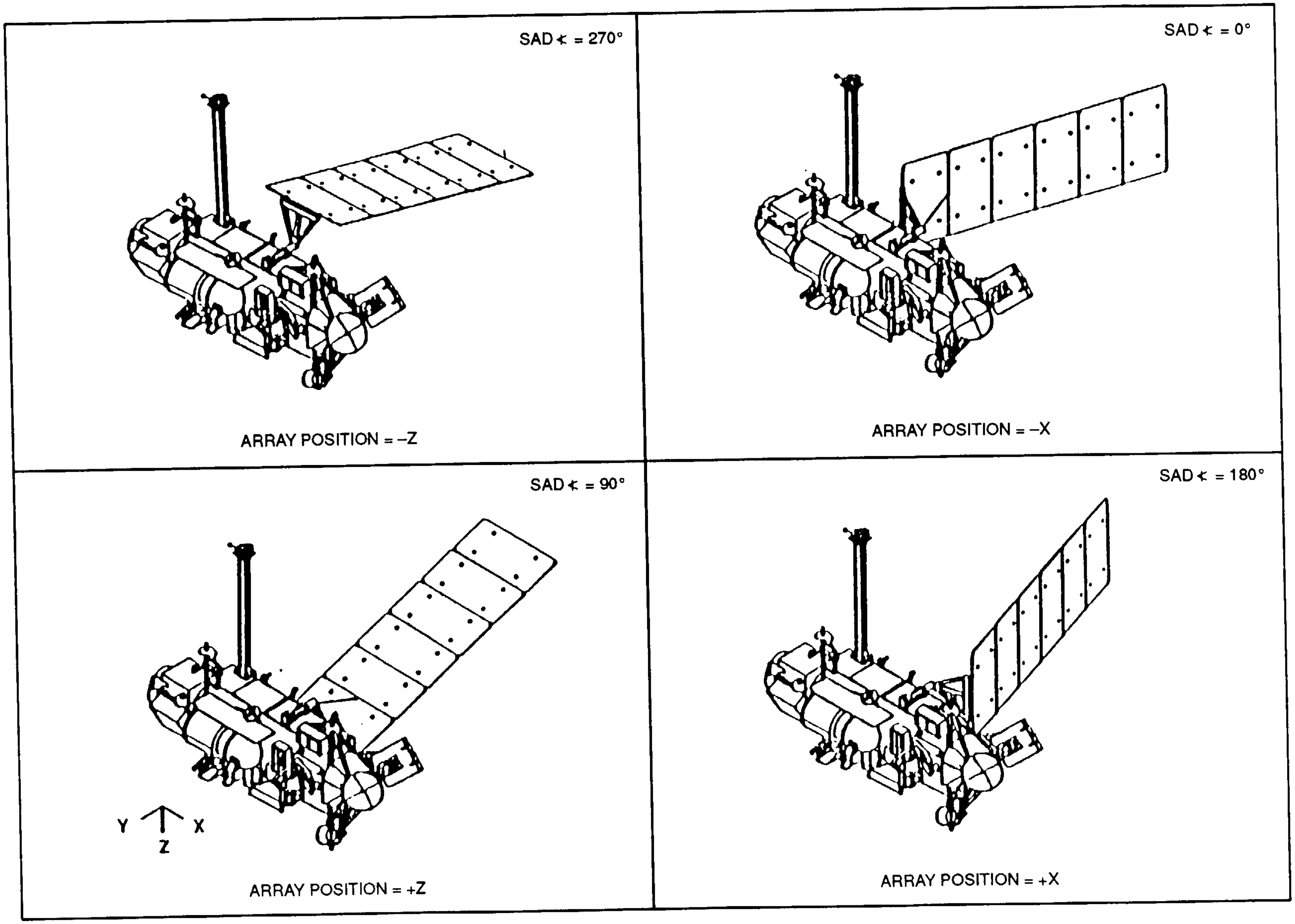


Figure 1. The UARS Observatory Solar Array Drive Positions

maneuver of 180 degrees about its Z-axis. UARS is said to be flying forward when its positive X-axis is aligned with its velocity vector; UARS is said to be flying backward when its negative X-axis is aligned with its velocity vector. The data used by the UARS attitude task in this study were obtained while the spacecraft was flying backward from December 5 to 20, 1991. However, a survey of the data for the spacecraft in the forward-flying mode indicates that the behavior is symmetric, as would be expected.

2.2 Mechanics of Thermal Snap

The single solar array on UARS is about 30 feet long and is made up of six panels of equal size. Each panel is constructed mainly of aluminum facesheet and aluminum honeycomb. Jasper and Neste and Zimbelman, et al. [Reference 4], have described the bending of the solar array in terms of time derivatives of the thermal gradient across the panels. When the spacecraft enters sunlight, the hot side of the panel heats up faster than the cold side, causing the panel to bend away from the sun. When the spacecraft exits sunlight, the hot side cools down more rapidly than the cold side and the array bends back again. This bending creates torques about the spacecraft axes. Conserving angular momentum, the spacecraft responds with a rapid change of attitude (Figure 2). The duration of sunrise and sunset and solar intensity, as seen by the spacecraft, depends on the solar beta angle, as discussed in the previous section. This in turn will affect the magnitude and timing of the thermal snap because the temperature gradients will differ. Plots of temperature gradients versus time presented by Jasper and Neste indicate that the disturbance should occur at the penumbral entrance for both sunset and sunrise (where the temperature gradient across the array changes most rapidly).

3. ANALYSIS RESULTS AND DISCUSSION

3.1 Discussion of Predicted Effects of Thermal Snap on UARS

Freesland has presented several estimates of the magnitude of UARS attitude disturbances. Early predictions concentrated on the effects at a solar beta angle of 18 degrees because the total torque on the spacecraft should be maximum there. It was also felt that the effects at sunrise and sunset would be very similar, so while the numbers cited here are for sunrise, it is not clear that the thermal modeling was sophisticated enough to draw any distinction that may exist between sunrise and sunset. Two sets of numbers from Reference 3 are given in Table 1 as Cases 1 and 2. The primary distinction between them is in the mass properties used. Note that Case 2 shows increased disturbances for the reduced mass properties.

A more recent estimate is included as Case 3 [Reference 5]. Case 3 is compared in Reference 5 to flight data in which the spacecraft is entering sunset at a beta angle of 35 degrees. It is assumed here that the estimate was produced under these conditions.

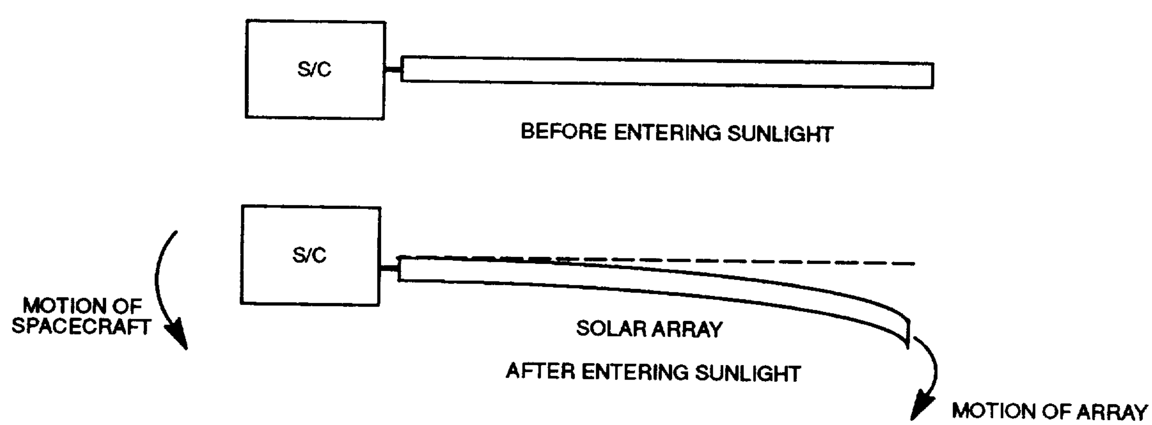


Figure 2. Bending of Solar Array

Table 1. Predictions of Attitude Disturbances (arcseconds)

Case	Disturbance		Mass Properties (FT-LB-sec^2)						
	Yaw	Roll	Ixx	Iyy	Izz	Ixy	Ixz	Iyz	
1	144	197	13200	34500	38200	–3610	–920	1360	Baseline
2	155	221	11808	31910	35449	–3344	–847	1443	
3	150	250	13400	35209	39974	–4366	–1089	1751	Beginning of Mission
			12632	31519	35623	–3236	–909	1696	End of Mission

Finally, predicted end-of-mission mass properties are included for reference. Note that the principal moments of inertia for the end-of-mission mass properties lie between those for Cases 1 and 2.

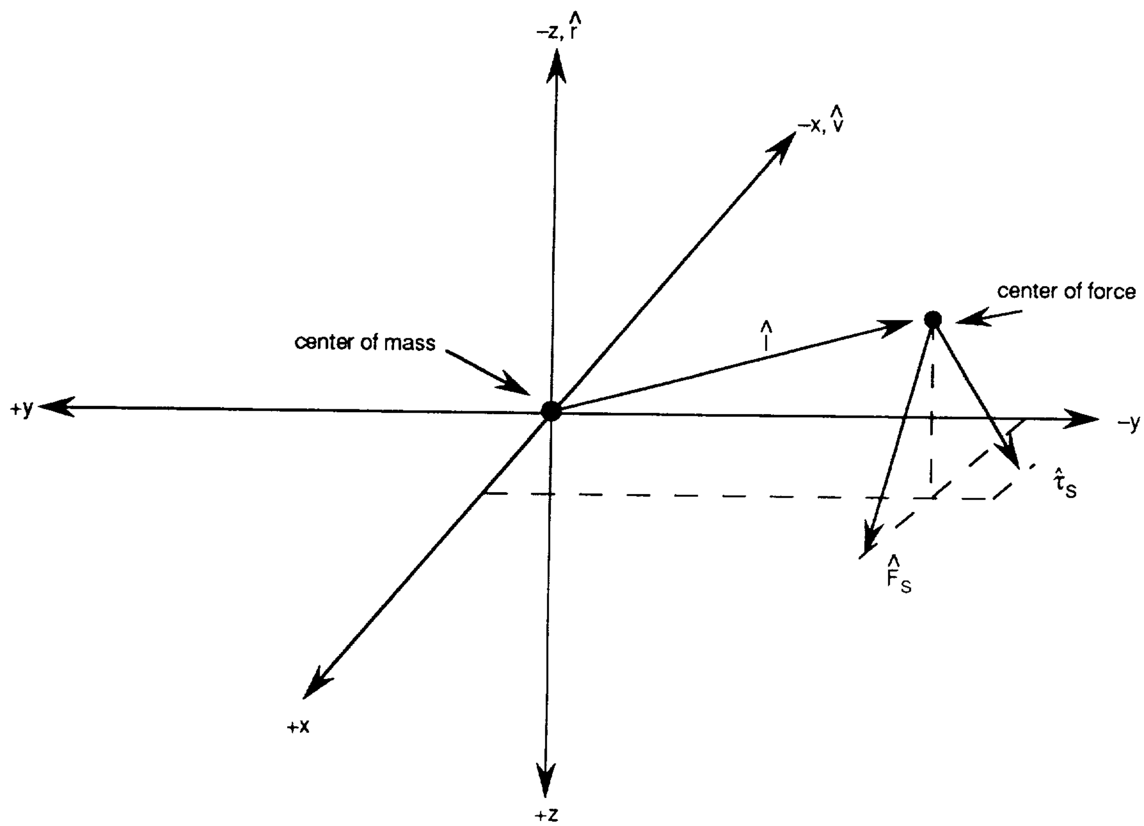
3.2 Magnitude of Attitude Disturbances

The simple model described in Figure 2 can be taken to another level of sophistication using vector analysis. Figure 3 shows the torque that should result from UARS flying backward into the sunset. The spacecraft attitude data agree with the predictions of such diagrams on the direction of the disturbances for any configuration (flying forward or backward at sunset or sunrise). It remains then to examine the magnitudes of the disturbances.

Figures 4 and 5 show the magnitude of the attitude disturbance at various solar beta angles for both sunrise and sunset. The magnitude shown in the plots was derived by examining characteristic signatures of the disturbance in OBC attitude solutions for the time at which the initial disturbance is maximum (Figure 6). Three sunrise and sunset events were examined for each of seven different beta angles ranging from 0 to 65 degrees. The baseline attitude, determined as indicated in Figure 7, was then subtracted from the peak attitude. At each sunrise and sunset the three events were averaged. Generally, the solar array disturbance affects the attitude about all three spacecraft axes. The effect on the pitch axis is often less dramatic; therefore, only the roll and yaw axes disturbances will be discussed here.

The peak disturbances are defined when the reaction wheels begin to return the spacecraft to the nominal attitude. They are therefore dependent upon the beta angle in the sense of the total torque input to the spacecraft; upon the solar array drive angle insofar as how the total torque is distributed among the axes; and upon the control system reaction to the position and rate errors computed onboard.

The values listed as Case 1 Table 1 compare well with the disturbances at sunset for an 18-degree beta angle (yaw = 113 arcseconds; roll = 198 arcseconds) although the yaw axis is somewhat overestimated. The mass properties were probably close to the values cited for this case (by inference of interpolation of the beginning-of-mission and end-of-mission mass properties). Case 2 exceeds the values seen in this study, probably because the mass properties resemble the end-of-mission mass properties. It may be a good indication of what to expect at the end of the mission. For comparison to Case 3, flight data for that specific event (occurring on October 5, 1991, around 00h:22m GMT) were examined, indicating 100 arcseconds for yaw and 195 arcseconds for roll. Case 3 is then an overestimate, but it may be that the assumptions in the previous section were incorrect. Generally, it seems that the model used by Freesland, Jasper, and Neste is capable of making reasonable predictions. Some overestimate may be desirable from a conservative standpoint regarding instrument stabilities.



x, y, z = UARS attitude control system

$\hat{r}$ = radial vector

$\hat{v}$ = velocity

$\hat{l}$ = vector from UARS center of mass to center of force

$\hat{F}_S$ = force at sunset

$\hat{\tau}_S$ = torque at sunset

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Figure 3. Torque at Sunset

NOTE: When UARS is flying backward into the sunset at a beta angle of 18°, the solar array drive angle is around 150°. The solar array straightens, creating the force with the resulting torque. This torque has components in the –x, –y, and +z spacecraft axes. The spacecraft responds with positive roll and pitch and negative yaw in order to conserve momentum. A similar analysis for any other configuration yields qualitative agreement with the data.

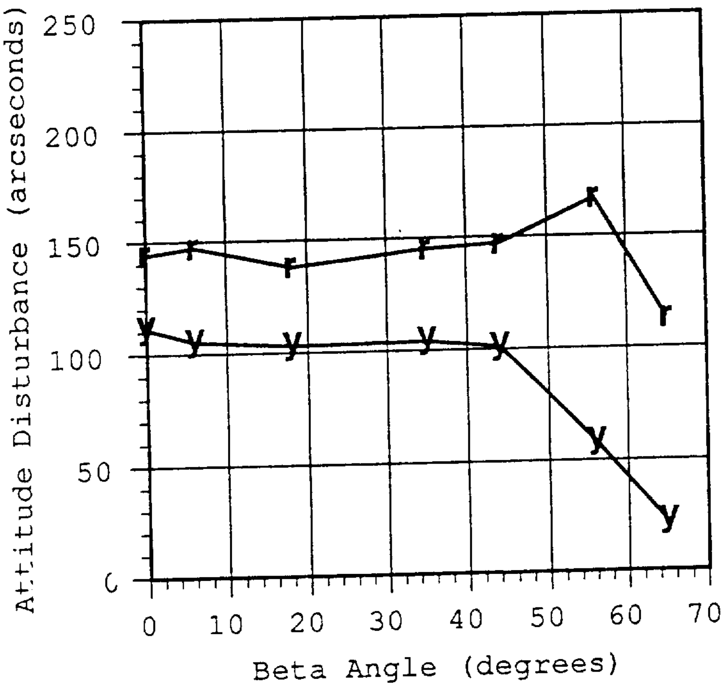

Figure 4. Actual Disturbance at Sunrise; r–roll, y–yaw

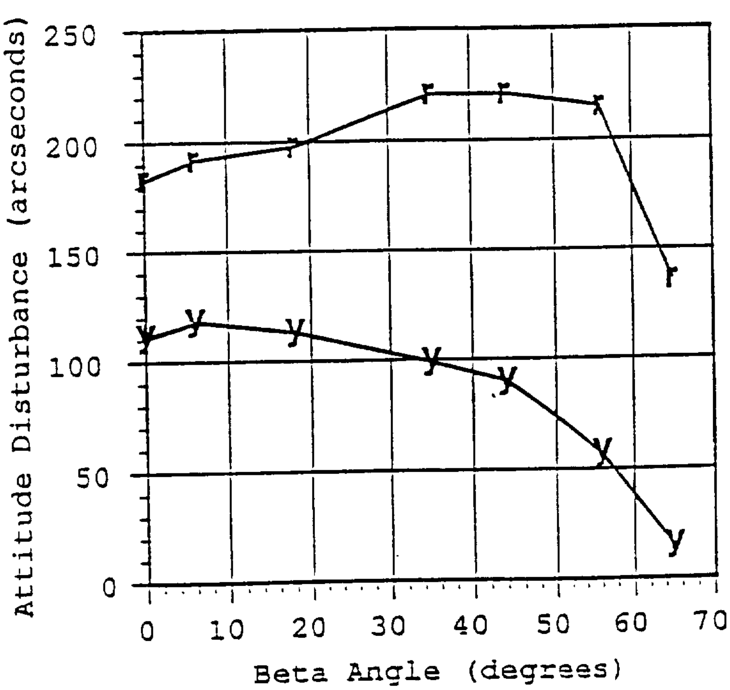

Figure 5. Actual Disturbance at Sunset; r–roll, y–yaw

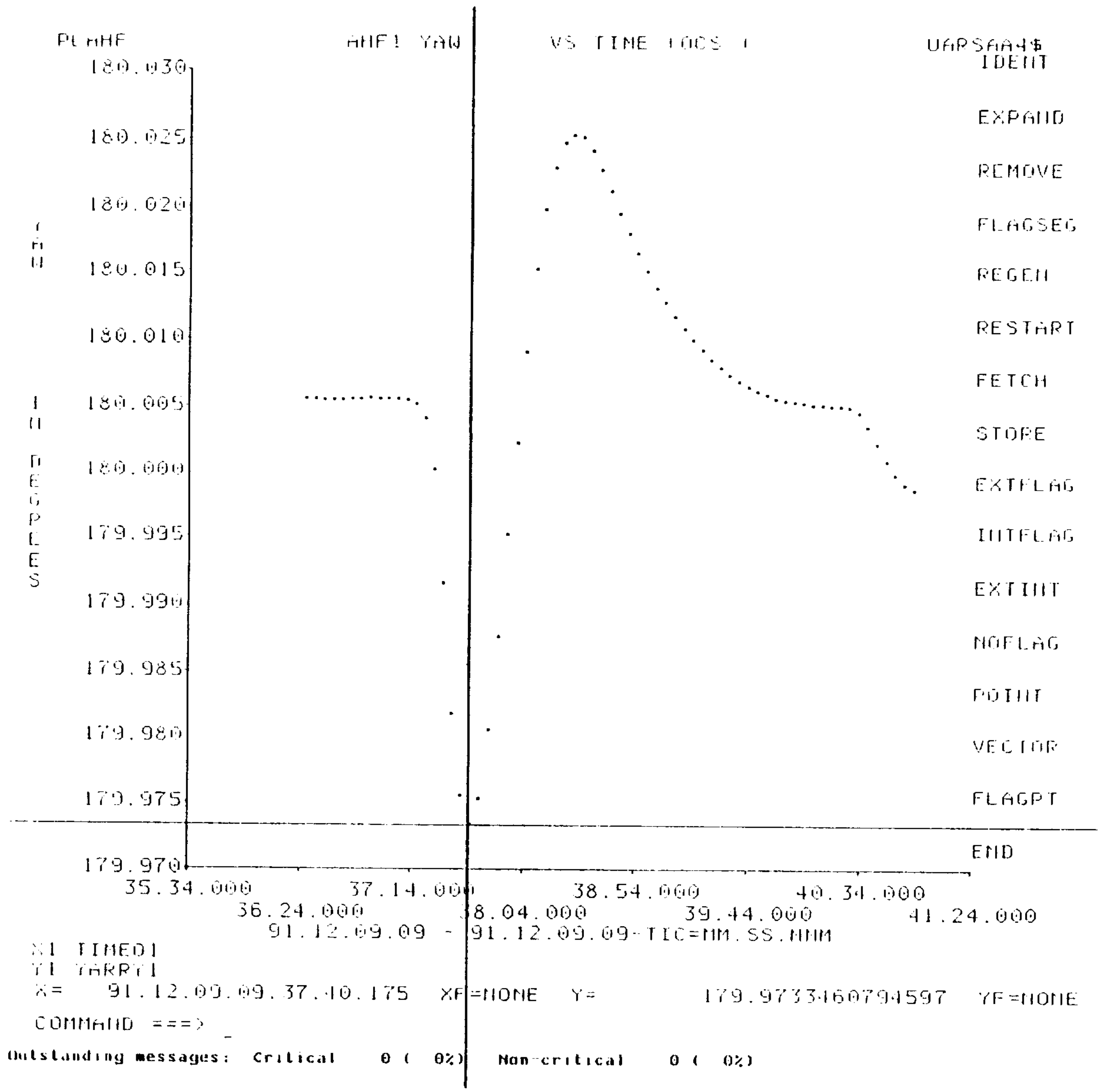

Figure 6. Determination of Maximum Attitude Disturbance

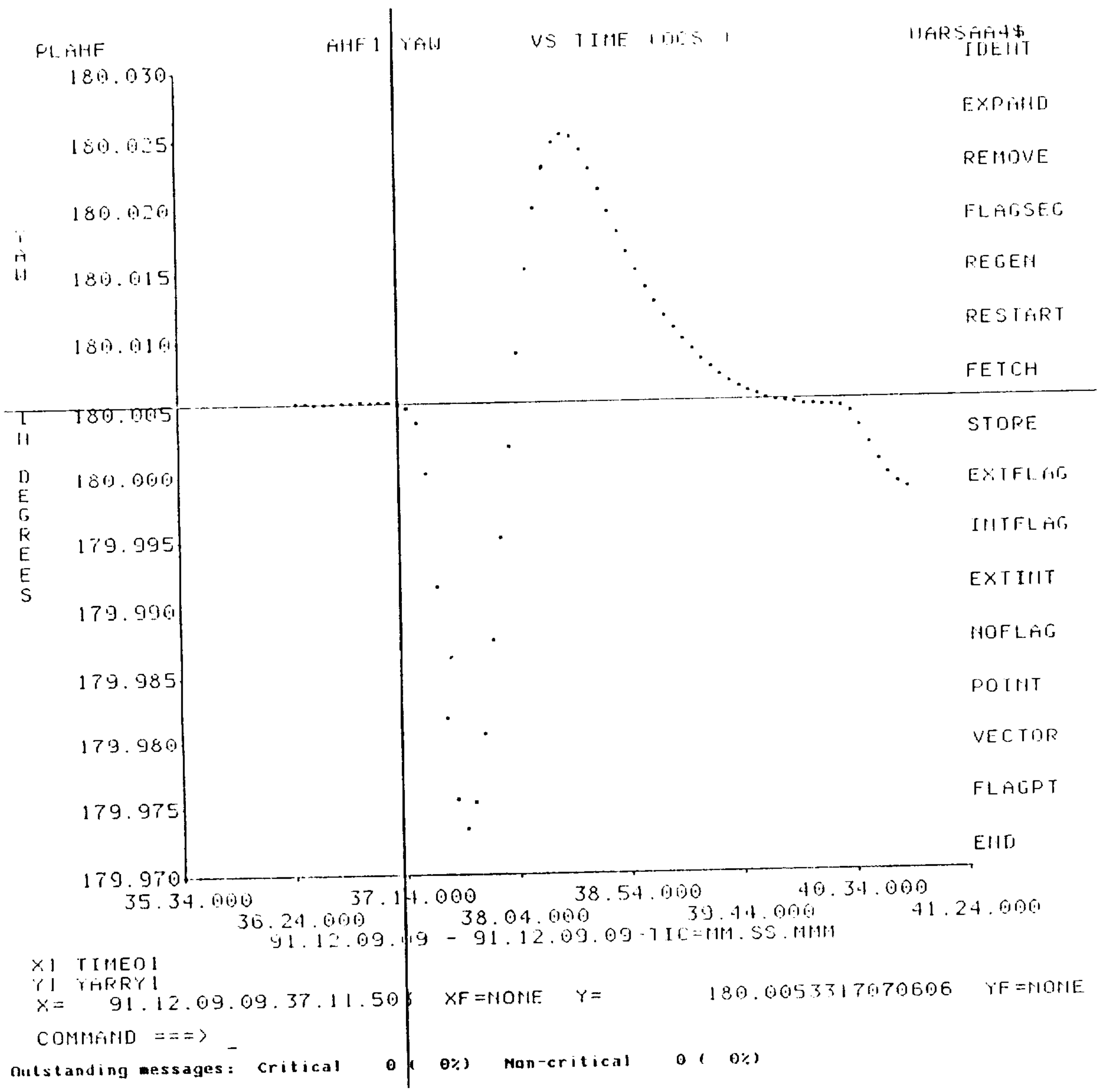

Figure 7. Determination of Baseline Attitude

There are two features in these plots that have not yet been fully explained. First, while the yaw axis shows maximum disturbance at low beta angles (where the total torque should be maximum) as might be expected, the roll axis is disturbed mostly at high beta angles, where the total torque should be falling off. One possible explanation is that, because the solar array drive angle is approaching 90 degrees for high beta angles, more of the total torque should be input to the roll axis, which has a relatively low moment of inertia. Secondly, the roll disturbances for sunset are significantly larger than those for sunrise, while the yaw disturbances are relatively the same. These characteristics of the roll disturbances are likely to be understood only with detailed examination of the control system reaction and possibly with better thermal modeling. It is also possible that there are more dynamics that need to be accounted for, such as motion of the Zenith Energetic Particle experiment boom (in Figure 1, the boom that lies along the Z-axis).

3.3 Timing of Attitude Disturbances

An analysis was undertaken to determine a model for estimating the timing of UARS attitude disturbances due to torques produced by the solar array at sunrise and sunset [Reference 6]. The UARS Flight Dynamics Facility (FDF) attitude task generates a variety of planning aids for the UARS project. Among these aids are predictions of sunrise and sunset times for the spacecraft. More specifically, these are referred to as "zero kilometer" sunset and sunrise events, meaning that the center of the Sun is at the limb of the Earth. When UARS observes a zero-kilometer event, it is at the halfway mark on its path through the penumbra. The peak attitude disturbances as determined above were correlated with the sunrise and sunset times as predicted in the planning aids.

The predicted sunrise and sunset times were then subtracted from the time of maximum initial attitude disturbance for each event. Averages and standard deviations were computed for each event. Because the disturbances in the roll and yaw axes occur at very nearly the same time, only the roll axis plots are included; however, they are valid for the yaw axis as well. The results are tabulated in Table 2 and plotted in Figure 8.

The sunset events show a tendency to move into the day as the beta angle increases. At a beta angle of 0 degrees, the attitude disturbance occurs around 7 seconds after the zero-sunset prediction. At a beta angle of 65 degrees, the snap occurs at 47 seconds prior to the zero-sunset prediction. The sunrise events show a similar tendency to move into the day. At a beta angle of 0, the disturbance occurs about 26 seconds after the zero-sunrise prediction. At a beta of 65 degrees, the disturbance occurs 71 seconds after the prediction.

As noted in Section 2.2, the plots of gradients indicate that the solar snap should occur at the entrance to the penumbra for both sunset and sunrise events. At sunset and sunrise, the spacecraft enters the penumbra increasingly earlier than the zero-kilometer event as the beta angle increases. The data for the sunset events appear to agree with this model; the solar snap occurs increasingly earlier than sunset as the beta angle increases. However, the sunrise events show the opposite behavior: they occur later and later than sunrise as the beta angle increases. It should be remembered that the differences presented here are based on the times of the peak disturbance, which are ultimately determined by the control system. It would be perhaps more correct to examine the predictions in terms of the timing of the "shoulder time" (i.e., the times at which the attitude begins to be disturbed as shown in Figure 7) or in terms of the peak torque due to solar snap. But a casual survey of shoulder times indicates the same trend. A torque analysis had not been completed at the time of this writing. This discrepancy indicates the need for a detailed understanding of the thermal behavior of the array.

3.4 Predicted/Actual Effects on Propagation

The UARS FDF attitude task routinely computes attitude solutions using Fixed-Head Star Tracker (FHST) and digital gyro telemetry in a batch least squares algorithm for confirmation of the attitude computed onboard UARS.

Table 2. Timing of Roll Attitude Disturbance With Respect to Zero-Kilometer Sunset/Sunrise Predictions

SUNSET		
Solar Beta Angle (degrees)	Timing Difference (seconds)*	Standard Deviation (seconds)
0	9	1
6	9	1
18	9	1
35	6	1
44	4	1
56	-7	1
65	-41	4
SUNRISE		
inertia values (ft.lb.sec^2)	Timing Difference (seconds)*	Standard Deviation (seconds)
0	26	1
6	26	1
18	26	1
35	29	2
44	31	2
56	40	1
65	71	4

*Maximum attitude disturbance minus predicted zero-km Sunrise/Sunset.

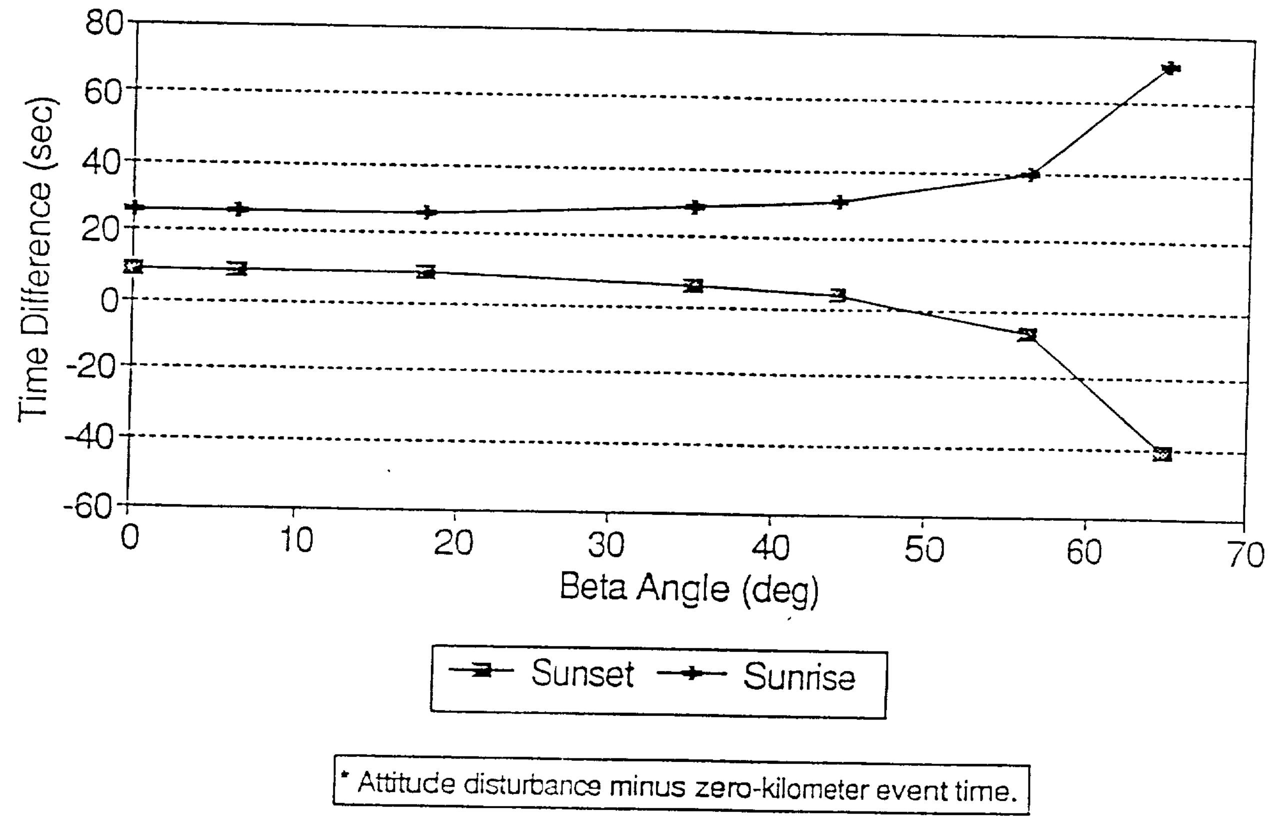

Figure 8. Times of Attitude Disturbance for Sunrise and Sunset versus Solar Beta Angle

To obtain an analytical expression for the attitude propagation matrix, one assumes that the angular velocity is constant over the sampling interval. In reality, there are accelerations in the angular velocities due to a variety of factors. Since the gyro sampling rate is very small, 1/8 second, most of these accelerations do not present a problem. In the case of thermal snap, however, the disturbance is relatively large and occurs over a short period of time (i.e., less than one minute). One concern was that the ground-computed attitudes would not properly model the thermal snap. Errors could even accumulate when spacecraft nights are short.

An analysis was performed to determine whether the attitude ground support system (AGSS) is able to meet the 60-arcsecond-per-axis attitude determination requirement. Attitude solutions for periods just prior to and during sunset were generated using the AGSS. The results were compared with the OBC attitude solutions over the same time period. The magnitude of the residuals from the attitude solutions prior to sunset are of the same magnitude as those during sunset. Table 3 gives the root mean square (RMS) values for the comparison. This indicates that the UARS AGSS is able to propagate attitude solutions during periods of thermal snap without compromising the attitude determination requirements.

Table 3. **Comparison of OBC and Ground Attitudes**

	RMS VALUES (ARCSEC)		
	Yaw	Roll	Pitch
Before Snap	5	9	27
During Snap	12	12	18

4. CONCLUSIONS

From this analysis and the prelaunch studies, it can be concluded that the attitude disturbances experienced by UARS are caused primarily by bending of the solar arrays as the spacecraft enters and exits sunlight.

The disturbances were predicted to occur for UARS based on its design similarity to the Landsats (i.e., an asymmetric solar array configuration). The disturbances are not reported to the same extent for satellites with smaller solar arrays or more symmetric configurations.

The direction of the attitude discontinuities for UARS confirms that the torque being applied as the spacecraft enters and exits sunlight coincides with the predictions from the model described in Section 2.2. In addition, the magnitude of the thermal snap modeled by the spacecraft builder in References 2 and 5 is a fairly good predictor of what the actual magnitudes are, as described in Sections 3.1 and 3.2.

On the other hand, there remain some questions concerning the magnitude and timing of the disturbances. Specifically, why are sunset roll disturbances so much larger than those at sunrise? Why do the roll disturbances become larger at high beta angles? And why does the timing of the sunrise disturbances appear to be opposite of that predicted? A key to answering these questions may be provided by the TOPEX satellite, which will be flown with temperature sensors on either side of the array, allowing observational checks for the thermal modeling. Jasper and Neste have also proposed using strain gauges for direct measurements of solar array bending.

Whatever the details are of the process taking place, the Landsat-design spacecraft have demonstrated that there is a potential for large attitude disturbances at sunset and sunrise. It is important that this process be better understood. It should be considered in stability analysis for any satellite, even ones with small symmetric arrays.

Because the UARS moments of inertia will continue to decrease (due to cryogen boiloff and propellant use), efforts should be made to determine any trends in the disturbances.

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