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ANALYSIS OF RAE-I INVERSION

CONTRACT NAS 5-20083-2

PREPARED BY

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FOR

NASA GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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FOREWORD

This report was prepared for NASA Goddard Space Flight Center by the Systems Development Division of Westinghouse Electric Corporation, Baltimore, Maryland. It is the final report on Task 2 of Contract NAS 5-20083.

1.0 Introduction

This task was performed in order to obtain a complete description of the RAE-1 spacecraft inversion performed October 31, 1972, based upon the in-orbit dynamical data in conjunction with results obtained from previously developed computer simulation models. The computer simulations used are predictive of the satellite dynamics, including boom flexing, and are applicable during boom deployment and retraction, inter-phase coast periods, and post-deployment operations.

Inversion of the RAE-1 spacecraft was accomplished by retracting the four main booms, coasting for a specified time, and then redeploying the main booms. This operation caused the spacecraft to rotate through 180 degrees about the local vertical, such that the spacecraft was inverted from its original attitude. The inversion operation required approximately 175 minutes, and was accomplished as scheduled with one exception (boom 4 did not redeploy correctly). Attitude data was recorded during the inversion in real time, both manually and on magnetic tape.

These data, as well as boom tip (TV) data, was analyzed in order to obtain a detailed description of the dynamical behavior of the spacecraft during and after the inversion. Runs were made using the computer model (RAE Deployment Dynamics Program), and the results were analyzed and compared with the real time data. Close agreement between the actual recorded spacecraft attitude and the computer simulation results was obtained.

This report describes the nominal inversion operation and the details of the observed results. These are compared with the results of the computer simulation, and the discrepancies are analyzed. Finally, the conclusions derived from this study are reported.

2.0 Nominal Inversion Operation

The method employed to invert the RAE-1 spacecraft involves a retraction of all four main booms to an intermediate length, followed by a coast period, and finally the redeployment of the booms to their original length.

The operations are depicted in figure 1. At time T_o, when the spacecraft is near its equilibrium attitude (Yaw = -15^o, Roll and Pitch = 0^o), the four main booms deployers are turned on to begin retracting the booms. The deployers are turned off when the boom lengths reach L_1 (525 feet).

Since the satellite is gravity gradient stabilized, it has, at equilibrium, zero attitude rates with respect to local vertical. This means it has an attitude rate in pitch, with respect to inertial space, equal to the orbital rate. When the booms are retracted, the pitch moment of inertia is, of course, decreased. In order that angular momentum be conserved, the pitch rate must increase. Given a sufficient increase, the satellite will tumble.

When the satellite has rotated nearly 180^o, at time T_2, the deployers are again turned on, this time to redeploy the booms back to their original length. This decreases the pitch rate back to its original value (orbital rate, or zero with respect to local vertical), and the satellite should be recaptured in a new equilibrium, 180 degrees rotated from the old.

Early studies and computer analysis revealed several pertinent points concerning the operation. (See Ref. 1.) First, the length L1 to which the booms would be retracted could not exceed 550 feet, or the satellite might just oscillate and not tumble. Too short a length would cause too great

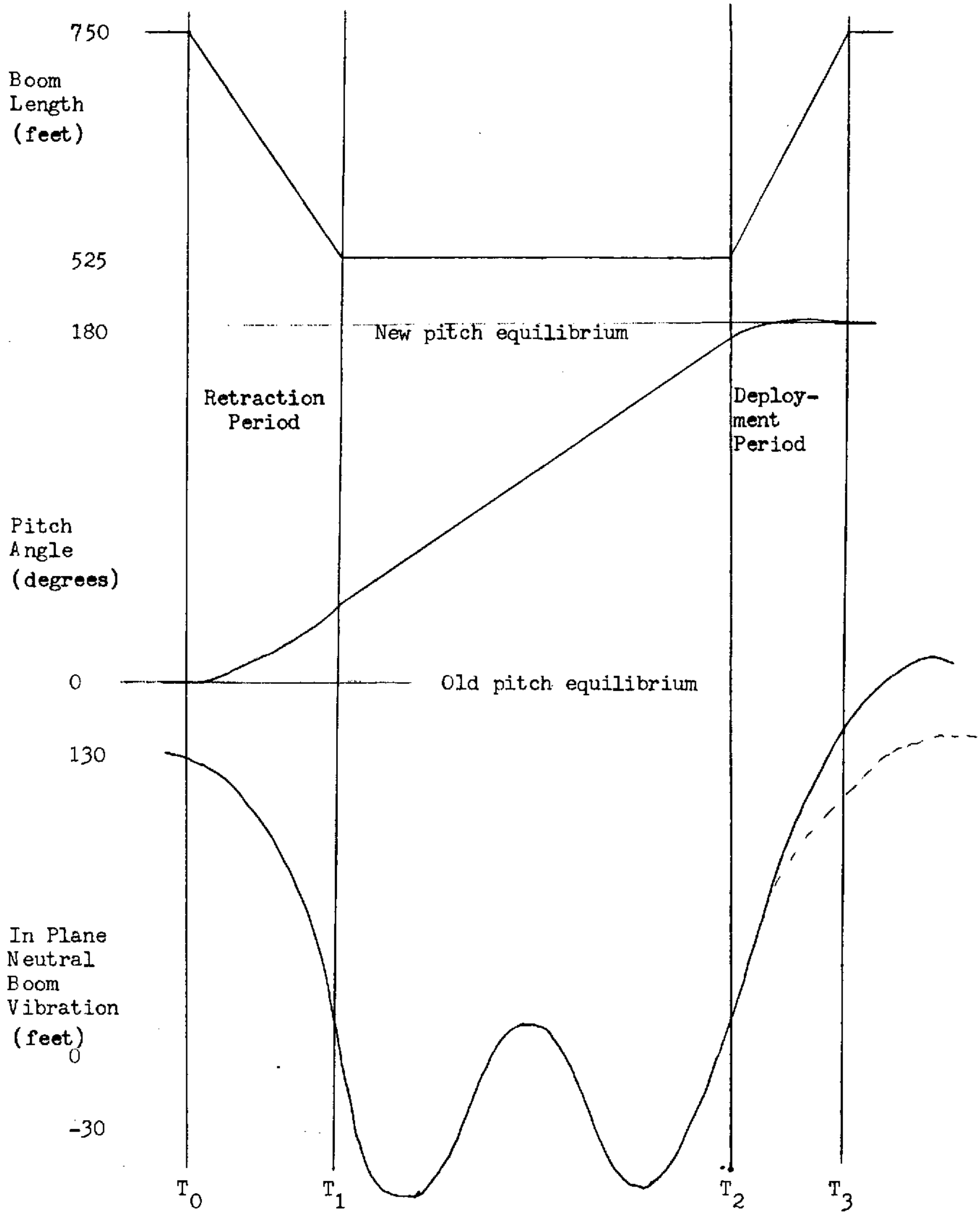

Figure 1. Nominal inversion Maneuver

a pitch rate, complicating the timing of T^2. An intermediate length of 525 feet was felt to be a safe compromise.

Perhaps the most critical part of the operation is the precise timing of T2 such that the pitch angle was 180° at T3. Computer runs indicated sufficient variations in the optimum timing with differing intermediate lengths, initial conditions, and satellite physical parameters (combined with an unknown accuracy of the program to match such severe dynamics), that it was felt necessary to time operations at T1 and T2 on the basis of real time data. T2 would be the time when the pitch angle reached approximately 170-175 degrees.

These preliminary studies also showed that the major boom oscillations would occur in the in-plane-neutral mode, and that their magnitude following T3 would be largely a matter of luck. If T2 happened to fall in the right portion of the oscillation cycle, the oscillations would be very small; if T2 was in the wrong portion, however, the I/P neutral oscillations following T3 could be up to 300 feet peak-to-peak. Even in this worst case, however, a successful gravity gradient recapture was predicted. (An alternate inversion scheme which could potentially resolve the I/P neutral oscillation problem was rejected because it was more complex, time consumming, and required more motor operations.)

The libration damper was to be kept in the locked mode until after T3.

3.0 Observed Results

The inversion operation was performed on October 31, 1972. The plan was, of course, to follow the procedure outlined in the previous section. This section describes the actual operations that took place, and presents the observed data available to describe the results.

3.1 Operation Sequences

The sequence of operations used to perform the inversion maneuver are summarized in Table 1. This data was originally supplied by GSFC, and was recorded at the time of the operations. A comparison with telemetry tape data shows some minor differences in timing, but none of these differences were large enough to have any significant effect on either the results observed or simulation results.

Two time frames are shown. The first is the Universal Time at which each operation was performed. The second is the elapsed time, in seconds, from the first operation. The latter time scale is used for presentation of most of the results in this report.

The first operation was to clamp the damper boom. At 420 seconds, all 4 deployers were turned on to retract the booms, and all were observed to operate normally. The actual initial boom lengths were 740.4, 737.9, 741.4, and 733.0 feet, respectively. At the beginning of the operation, the satellite was in a near equilibrium state with little attitude motion. The yaw angle was -14° to -15° and roll and pitch essentially 0°.

Some confusion exists concerning the commands to unclamp the damper (1238 sec.) and reclamp it (1740 sec.) It is believed these commands may have been sent because the original (0 sec) command was thought not to have been received. At any rate, the state of the damper in the early

Table 1 - RAE-1 Inversion Operation Sequence
October 31, 1972

Time (UT)	Ref. Time (sec)	Operation
14:54:00	0	Clamp Damper
15:01:00	420	Start Retraction of all 4 Booms
15:14:38	1238	Unclamp Damper
15:22:11	1691	Stop Retraction of all 4 Booms
15:23:00	1740	Clamp Damper
16:33:00	5940	Start Redeployment of all 4 Booms
16:37:35	6215	Stop Redeployment of Boom 4 Only
16:47:01	6781	Stop Redeployment of Booms 1,2, & 3
16:47:20	6800	Unclamp Damper
16:48:00	6840	Start Redeployment of Boom 4
16:53:34	7174	Stop Redeployment of Boom 4
16:54:25	7225	Start Redeployment of Boom 4
16:56:30	7350	Stop Redeployment of Boom 4
17:30:00	9360	Start Redeployment of Boom 4
17:31:30	9450	Stop Redeployment of Boom 4
17:33:00	9540	Start Retraction of Boom 4
17:33:33	9573	Stop Retraction of Boom 4
17:35:15	9675	Start Redeployment of Boom 4
17:38:28	9868	Stop Redeployment of Boom 4
17:39:50	9950	Start Retraction of Boom 4
17:40:12	9972	Stop Retraction of Boom 4
17:41:30	10050	Start Redeployment of Boom 4
17:43:45	10185	Stop Redeployment of Boom 4
17:45:20	10280	Start Retraction of Boom 4
17:45:43	10303	Stop Retraction of Boom 4
17:46:50	10370	Start Redeployment of Boom 4
17:48:09	10449	Stop Redeployment of Boom 4

portions of the operation are not known for sure. For the short time involved, however, the damper being clamped or free would have little effect. The data does clearly indicate that the damper was locked during time after 1740 seconds.

Based on real-time boom length data, the deployers were turned off at 1691 seconds. At this time, the boom lengths and resultant retraction rates were:

Boom	1	2	3	4
Length (feet)	529.6	516.7	517.7	519.7
Retraction Rate (feet/sec)	.1659	.1740	.1760	.1678

After a coast period of 4849 seconds, the deployers were turned on again at 5940 seconds to re-extend the booms to their original lengths. The timing was based on near real-time attitude data. The attitude at this time was: Pitch = 172°, Roll = 5.3°, Yaw = -25.1°.

At 6215 seconds, a command was sent to stop redeployment of boom 4 only when real time data indicated a malfunction in the deployer (indicated length of boom 4 stopped at 580.4 feet). The other 3 booms continued to deploy normally. This gave an apparent deployment rate for boom 4 of .2207 feet/second, but the actual rate was undoubtably somewhat higher, since there was a time delay between the movement stoppage and the stop command being sent.

Re-deployment of the other 3 booms was completed at 6781 seconds, for a total redeployment time of 841 seconds. The boom lengths and deployment rates were:

Boom	1	2	3	4
Length (feet)	740.4	737.9	741.4	580.4
Deployment Rate (feet/sec)	.2507	.2630	.2660	.2207

At 6800 seconds, the command was sent to unclamp the damper. Following this, further attempts were made to extend boom 4 to its full length. Commands were alternately sent to start and stop deployment and start and stop retraction. Examination of the telemetry tape data yields the following probable boom 4 lengths at the end of those operations which affected the length:

7174 seconds	650 feet
9573 seconds	640 feet
9868 seconds	700 feet
10185 seconds	714 feet
10449 seconds	721 feet

3.2 Observed Attitude Response

Attitude data during and following the inversion operation was recorded in three forms: Real time data manually recorded at time of maneuver; Mini-Triad data; and, Attitude Tape data. Unfortunately, the third source could not be used because the tape could not be read. However, the other two sources provide sufficient data for the present purpose.

Figure 2 shows the pitch angle response during the actual time of the retraction, coast, and redeployment operations. This is data collected in real time, and is taken directly from Reference 2. The time scale corresponds exactly to that in the first column of Table 1.

As expected, the pitch angle began increasing when the boom retraction was started, and the increase accelerated as the booms became shorter. During the coast period between the retraction and the redeployment, the

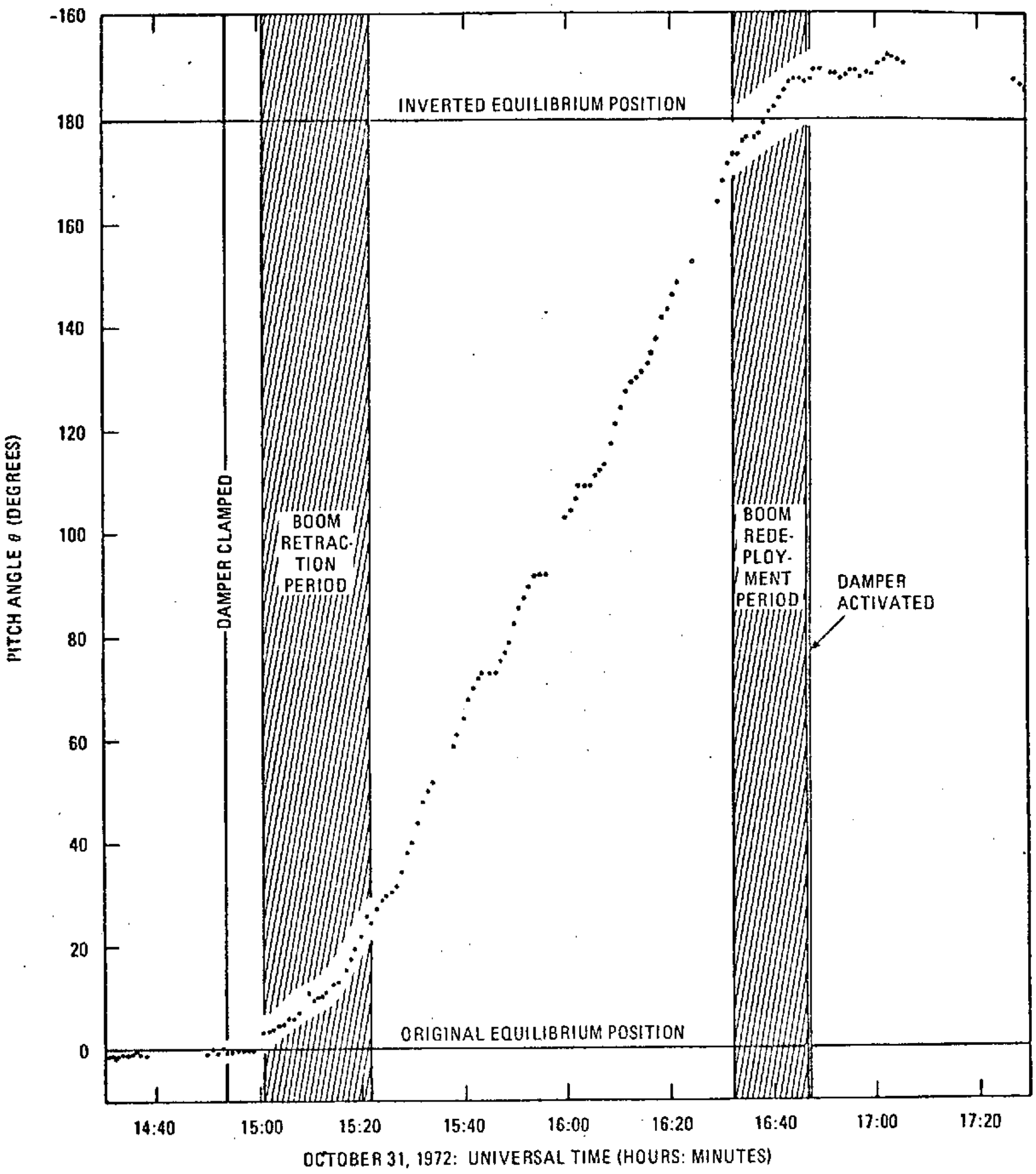

Figure 2. RAE-I Spacecraft Pitch Attitude During Inversion Operation

pitch angle increased almost linearly. The small deviations from a constant rate can be attributed to the change in the relative effect of the gravity gradient torque and the influence of higher frequency boom motions.

The pitch angle was about 172° when redeployment was begun, passed through 180° (or 0° about the new equilibrium) during the redeployment, and overshot the new equilibrium position to a maximum of 10-12 degrees before swinging back. This, of course, constitutes an extremely successful gravity gradient recapture.

It is interesting to speculate on the effect of the boom 4 deployer malfunction. Had that boom deployed normally, the pitch rate would have been slowed even more during redeployment, thus reducing the overshoot and resulting in a more nearly perfect recapture.

The total time period from start of retraction to full inversion was approximately 100 minutes. Considering only the initial pitch (orbital) rate and the change in moment of inertia due to the retraction (that is, considering a case of a rigid satellite) the computed time to accomplish an inversion is about 102 minutes. Therefore, in this (very limited) respect, the satellite appears to have behaved much like a rigid body.

Figure 3 shows the attitude behavior of the spacecraft during the inversion maneuver and for several hours following it. This set of data is Mini-Triad data plotted from cards supplied by GSFC.

Sixty thousand seconds of elapsed time are shown on this and subsequent attitude plots. The zero reference is 14:54:00 of October 31,1972. This is the time when the damper was clamped in preparation for the maneuver. Hence, the absissa time scale corresponds exactly to the

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elapsed time scale of Table 1.

The ordinate of the roll angle plot covers -10 to +10 degrees; the pitch plot from -15 to +15 degrees; and the yaw plot from -35 to +5 degrees. The plots are of central hub attitude, referenced to the local vertical coordinate frame. The pitch plot zero reference is at its equilibrium value. That is, the 180° rotation is removed, so that a $+1^\circ$ value after the inversion is really $+181^\circ$ or -179° with respect to the original equilibrium. Hence, the pitch angle is seen to begin increasing when the booms are retracted, go off scale, and reappear from the negative side during the coast period.

Figure 4 covers the same data for the same time period. This data was taken from Reference 2, and is data that was manually recorded at the time of the operations. It is included because it fills some of the gaps in the Mini-Triad data, particularly the period immediately following redeployment of the booms. This data set was used as the basis for comparison with simulation results. There are no significant differences between the two sets of data.

The major attitude motion occurs in pitch, as expected. Following the 180 degree rotation, the pitch angle overshoots to +10 to 12 degrees at about 8000 seconds, swings back to about -6 degrees at 12-13000 seconds, and reaches another positive peak of 7-8 degrees at 17000 seconds. Another negative peak of 6 degrees is seen at 30-31,000 seconds. An oscillation period of approximately 9000 seconds can be seen quite clearly. The large initial pitch oscillation of 15 to 20 degrees peak to peak damps out considerably after only a few periods. Near the end of the data, the oscillation in pitch has been reduced to about 10

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degrees peak to peak.

Of course, considerable variations from smooth oscillatory motion are seen in the pitch data, as well as in roll and yaw. These can be attributed to two causes: 1) high frequency, low amplitude oscillation of the central hub; and 2) attitude sensor noise.

It is virtually certain that sensor noise accounts for a good deal of the variations. However, it is also likely that some high frequency, low amplitude oscillations did exist. It is not possible to determine what frequency or amplitude these oscillations were from this data, but at no point is there any indication that they exceeded a few degrees in roll, pitch, or yaw. In any case, oscillations of this magnitude and frequency have little or no effect on long term satellite dynamics.

The yaw angle response to the maneuver was also much as expected. Following the boom retraction, the yaw angle increased from its original equilibrium value of -15° to about -25° at the beginning of the redeployment. The suddeness with which this jump appears to have occurred, at the mid-point of the coast period, could again be a result of sensor noise, or from phasing between oscillations of different periods. Following the redeployment, the yaw angle moved to a maximum (negative) value of -34° at about 11,000 seconds, then swung back to about $+1^{\circ}$ at 17000 seconds. These relatively large excursions quickly disappeared, and from around 25,000 seconds on, the yaw angle oscillated about its equilibrium value of -15°. This oscillation had a period of about 2500 to 2600 seconds and an amplitude of about 8° peak to peak. This oscillation can also be seen "superimposed" on the major yaw movement up to about 20,000 seconds. Near the end of the data, it can be seen that even this small oscillation is greatly reduced.

The roll angle shows very little response to the retraction - redeployment operations. Maximum excursions following redeployment are only about $\pm 5^{\circ}$, and even this is reduced to only a couple of degrees in the time from 25,000 seconds on. No clear oscillation frequency can be discerned from the data.

3.3 Damper Angle Data

Very little observed damper angle data is available for the time periods of interest here, and what could be found is of questionable validity. In fact, the state of the damper, locked or unlocked, in the early phases of the maneuver could not be determined with certainty. It is thought, however, that the damper remained locked until 6800 seconds, or until just after the main redeployment period.

The only data set containing damper information for this period is the Attitude Data Tape. Throughout most of this tape, the damper angle is either missing or indicated to be zero. From 6800 seconds, when the damper was unclamped, to about 17000 seconds, there is some data thought to be valid, mixed with much data known to be invalid. One problem is that the algebraic sign of the angle is unknown, apparently due to a telemetry problem. The sign often switches on each successive point.

Figure 5 is a plot of the data from the tape considered most likely to be valid. This indicates that the damper swung to about $+21^{\circ}$ after being unclamped, obtaining this peak at about 10,000 seconds. It then reversed its swing, hitting a negative peak of -8° at about 14,000 second, and was back to a positive 10° and increasing at 17,000 seconds. After this time, no data thought to be valid is available. Considering the

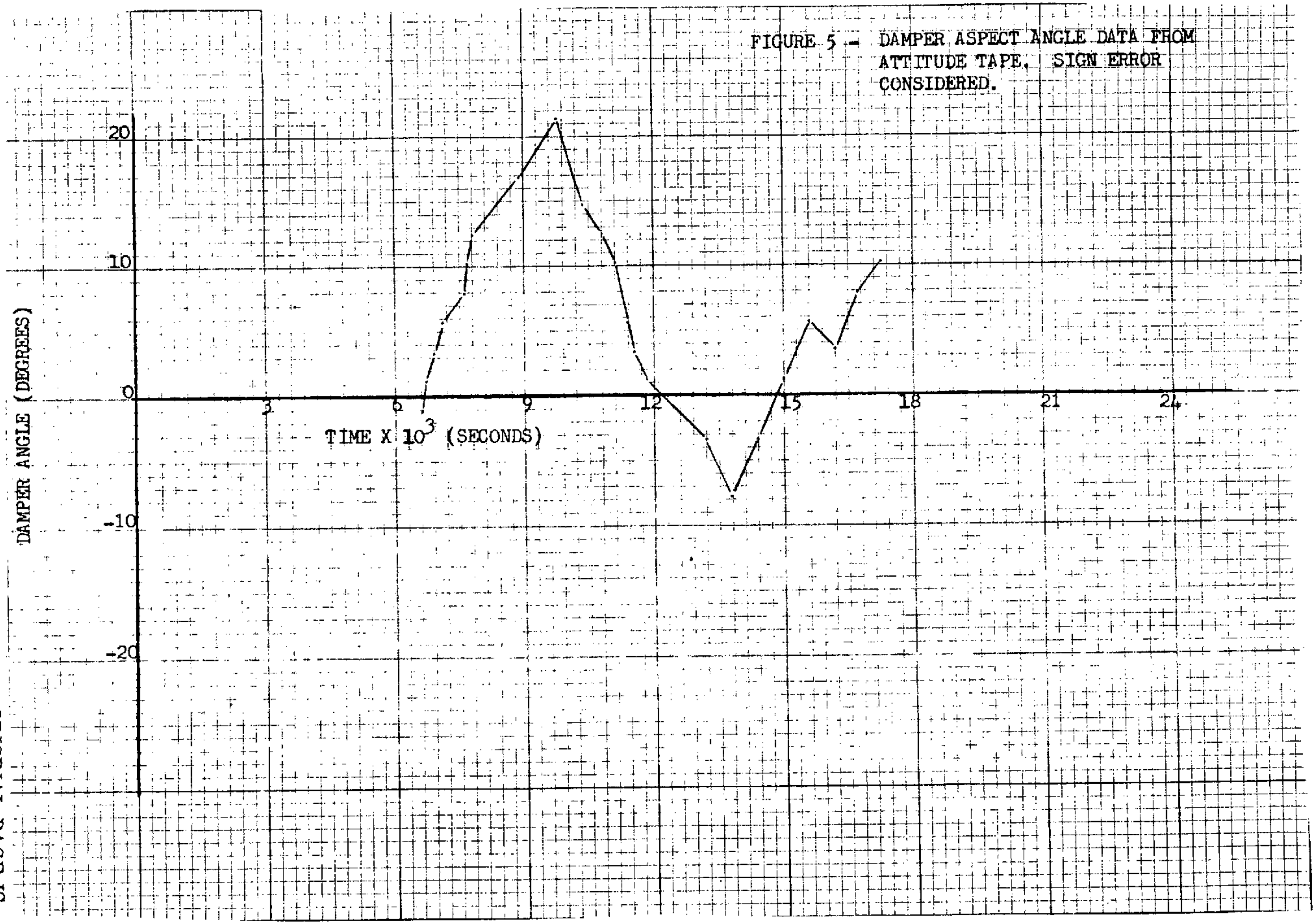

FIGURE 5 - DAMPER ASPECT ANGLE DATA FROM ATTITUDE TAPE. SIGN ERROR CONSIDERED.

obvious errors in the majority of the data, however, even this data must be considered somewhat suspect.

3.4 Boom Tip (TV) Data

As with the damper data, the TV boom tip data available is very sparse and of poor quality. TV pictures of three of the booms were taken at three times following the operation. The times were at approximately 32,200 seconds, 42,400 seconds, and 90000 seconds after the reference time of 14:54:00.

The digital print-out of these pictures were examined in an attempt to locate the boom tips. In some pictures, no boom could be distinguished from the background noise. In others, two images could be seen, either of which may have been the boom. In cases where a boom could be seen, it is unknown if the end of the image was actually the boom tip or just some intermediate point on the boom, with farther points invisible.

Table 2 summarizes the best estimate that could be made of the boom tip position in each picture. The values shown are the estimated tip displacement, in feet, from the nominal undeformed cruciform.

Table 2 - Boom Tip Positions from TV Data

Time	I/O Position	O/P Position
	Boom 1	
32201	-155	-80
32268	-155	-80
42361	-137	-69
42443	-122	+12
42469	-119	+18
89987	-137	-74
90003	-143	-80
90026	-137	-80
	Boom 2	
32281	149	54
32320	143	49
42401	128	42
42482	134	46
42499	128	42
89974	134	46
89987	131	42
90000	128	39
	Boom 4	
32830	134	89
32843	131	86
32846	134	89
42918	Boom Totally Obscured	
42953	Boom Totally Obscured	
90717	47	3
90730	47	3

3.5 Post Inversion (Steady State) Behavior

Figure 6 is a plot of the satellite attitude behavior of November 1, 1972 the day following the inversion operations. The starting time of the data (zero reference of the abscissa) is 7:35:07, or about 16 hours after the inversion.

The plots clearly show that little, if any attitude motion resulting from the inversion still existed. The roll angle varies only slightly from its 0° equilibrium value. Small oscillations of ± 5 degrees can be seen in pitch, again about an equilibrium of 0° (or 180° with respect to the pre-inversion equilibrium). The yaw equilibrium is about -15°, and again, only a few degrees variation exists.

Additional attitude data collected during November and December of 1972 confirm that the spacecraft maintained this attitude behavior. These data sets are not long enough to present in a meaningful graphical form, however.

Two conclusions can be drawn from the steady state attitude behavior. First, since the new equilibrium attitude values are essentially identical to the pre-inversion values, and the oscillations are of the same size, it is obvious that the inversion and relatively violent attitude motions had no detremental effect on the spacecraft structure. Any significant bending or kinking of the booms would have affected the new equilibrium values. Secondly, the low magnitude of the pitch and yaw oscillations so soon after the inversion indicate the effectiveness of the damper system. The initial oscillations following the inversion were nearly 20° and 35° peak to peak for pitch and yaw, respectively. Within a day, they were reduced to less than 10 degrees apiece.

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4.0 Computer Simulation Results

To gain further insight into the inversion maneuver and the ability to simulate it, an effort was undertaken in an attempt to match simulation results to observed data. This section describes the results of this effort.

4.1 WEBES Program

The main computer simulation used in this effort is the Westinghouse Elastic Boom Extension Simulation. This program is documented in detail in Reference 3. The major program capabilities of interest in this study are reviewed below.

WEBES is a predictive simulation of total satellite dynamics, including boom flexing, and is applicable during boom deployment or retraction, interphase coast periods, and post-deployment phases.

Program inputs, which specify the initial satellite state, include initial attitude and attitude rates, boom flexing and rates, and boom deployment and retraction schedules. Deployment rates and schedules can be varied for each of the four main booms and the damper boom individually.

The program has provisions for simulating the damper boom in the locked or unlocked mode. Either of two damper models can be used in the unlocked mode. One is a viscous damper model and the other a magnetic hysteresis damper model. The latter was used in this study.

One to three modes of booms flexing can be simulated. Physical constants describing the satellite can also be varied.

4.2 Equilibrium State Determination

The observed yaw equilibrium angle, both before and after the inversion operation, is about -15 degrees. It has, in fact, remained near that value throughout the mission. This is about 5 degrees greater than is predicted by the WEBES program (and several other models, as well) for a completely "nominal", spacecraft configuration. To the writer's knowledge, this difference has never been fully explained. However, several possibilities exist that could result in the difference. Some of these are:

a) A greatly lower flexural rigidity in the main booms than thought.

b) A semi-vee angle significantly less than nominal.

c) A damper skew angle greater than 65°.

d) One or more bent or warped booms.

e) A smaller value of main boom density than thought.

f) A greater value of damper boom density than thought.

g) A misalignment of the attitude sensors, giving an inaccurate yaw angle.

h) Any combination of the above.

All the causes a-f would have, to a greater or lesser degree, an effect on the dynamic results of the simulation as well as the static equilibrium yaw angle. However, past and present experience with the WEBES simulation indicates that whatever the reason, it has little effect on its ability to accurately simulate attitude dynamics of the spacecraft. Reason (g) seems highly unlikely, and (h) presents too bewildering an array of possibilities to be considered.

Several of the possibilities (notably a, b, and e) were simulated, and rejected on the basis of having too great an effect on the dynamical behavior of the satellite.

To achieve an accurate yaw angle match in this effort, the damper boom density was increased in the simulation about 20% (reason f). This method was chosen not so much because it is the most likely actual cause, but because it has little effect on overall satellite dynamics except for the yaw equilibrium angle.

4.3 Simulation Run Conditions

Besides the equilibrium state described above, several conditions for the simulation runs were set. All dynamics simulation runs were designed to duplicate as closely as possible the known actual conditions. Hence, the schedule of events described in Table 1 was followed, with only minor variations.

All runs were begun at the zero reference time when the damper was locked. The satellite was presummed to be in an equilibrium steady state at this point. Hence, the initial yaw angle was -15°, and roll and pitch angles were 0°. Each boom had an initial in plane deflection of 130 feet and no out of plane deflection. Boom warpage and thermal bending were not included.

The damper was initially in the locked mode for all runs, and was unlocked at 6800 seconds. While in the locked mode, the damper angle was zero.

Because of the deployer mechanism failure for boom 4 and the resultant attempts to redeploy this boom, the exact schedule and deployment rates were unknown for the redeployment from 580 feet on. Initially, only the final length of 721 feet at 10,449 seconds was known. For the sake of simplicity, the simulation runs were set up to deploy boom 4 from 580 to 721 feet in a single sequence at the same redeployment rate observed for deployment to 580 feet (.2207 feet/second). This redeployment sequence was done in the time interval from 9360 to 9997 seconds. The boom length data reported at the end of paragraph 3.1 became available after several simulation runs were made. However, since the differences between the schedules were small and affected only one boom, the original redeployment schedule assumption was used for all runs.

As explained in Ref. 3, provisions are made in the WEBES program to artificially increase the satellite hub moment of inertia. This nearly eliminates the very high frequency oscillations in the simulation results while having almost no effect on the longer term dynamics. For this effort, the hub moments of inertia were increased by a factor of 20. This, coupled with the obvious lack of sensor errors, explains why the simulation results are generally much smoother curves than the observed results.

4.4 Best Match Attitude Comparison

Figure 7 shows the attitude response to the inversion maneuver for the WEBES run which most nearly matched the observed data. This run was made simulating 3 vibration modes per boom and a flexural rigidity of 14.5 $lb\text{-}ft^2$ (2088 $lb\text{-}in^2$). A comparison with Figure 4 shows the similarities and differences between the observed and simulated results.

The simulated roll angle response to the operations is a small oscillation of about 5 degrees peak to peak about a zero equilibrium. The period is about 7500 seconds. The oscillation decreases to only a couple of degrees by the end of the data. Although the observed data does not clearly show the oscillation period, the observed and simulated results are very similar.

Larger attitude oscillations occur in pitch following boom redeployment. The pitch angle at the beginning of boom redeployment was about 169° in the simulation compared with about 172° in the observed data. The pitch overshoot in the simulation, about 6°, is somewhat less than observed, but the oscillation resulting is slightly greater. The observed pitch oscillation appears to be 15-20° peak to peak, while the simulation shows about 25° peak to peak oscillation. The observed pitch period of 9000 seconds is matched nearly perfectly by the simulation. In both the observed and simulated data, the oscillation is decreased considerably after a few periods.

The yaw angle response of the simulation is also quite close to the observed data. In both cases, the yaw angle increases from its initial -15° equilibrium to -25° at the beginning of the redeployment, although some higher frequency oscillations are seen in the observed data. The minimum and maximum yaw angle excursions following redeployment were about -34° and $+1^{\circ}$; the simulation showed excursions of -30° and -2°. As with the observed data, these large oscillations quickly disappeared and an 8° p-p, 2500 second period oscillation is seen. This is reduced even further near the end of the simulation, as it was in the observed data. The equilibrium angle is about -15° in both cases.

Although there are minor differences between the simulated and observed attitude results, the WEBES program did simulate the overall attitude dynamics quite accurately with the run conditions reported above.

4.5 Effect of Boom Flexural Rigidity Variations

Some previous studies and observed data have suggested that the boom flexural rigidity (EI) is lower than the nominal values measured before launch. This hypothesis was tested by simulating the inversion with WEBES using a lower value for EI.

Figure 8 shows the attitude response obtained under conditions identical to those in the previous case but with EI lowered to 13 lb-ft^2. The attitude response is not greatly different from the previous case except that the pitch oscillation has less tendency to damp out and the maximum yaw excursions are slightly greater. Overall, it could be considered nearly as good a match as the EI=14.5 case.

Lowering EI even further to 11 lb-ft^2 (1656 lb-in^2), however, had a disasterous effect on the accuracy. This case did not even simulate a successful gravity-gradient recapture. It is concluded, therefore, that if the EI is actually lower, it is not more than about 10% lower than originally thought.

4.6 One Vibrational Mode Simulation

The two simulations described above used three vibrational modes per boom. Figure 9 shows the attitude response obtained when only one mode per boom is used. The potential advantage of using one mode is, of course, a savings of computer time. A one mode run takes only about one tenth the computations that a threemode run does, and previous studies have indicated that one mode is sufficiently accurate when the satellite is near its steady state equilibrium.

Figure 9 clearly indicates that this cannot be said for cases when attitude and boom dynamics are as severe as they were during the inversion.

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The run conditions of Figure 9 are identical to those of Figure 7 except that only one mode is simulated.

The Figure 9 simulation is obviously not even close to representing the actual data. The initial inaccuracy,which naturally results in later inaccuracies, is that only about 130° of pitch rotation had been simulated when redeployment began, rather than the actual 172°.

It is interesting to note that more than one mode is required for accurate simulation of severe attitude dynamics in spite of the fact that higher mode vibrations are extremely small compared to the first mode. In the run shown in Figure 7, the second mode of vibration never exceeded 6 feet either in-or out-of-plane, for any boom, and the third mode never exceeded one foot. The first mode vibrations varied from -50 to +150 feet in plane and $\pm$ 30 feet out-of-plane for all booms.

4.7 Antenna Boom Flexing

As discussed in Section 3.4, little or no reliable data concerning boom flexing as a result of the inversion maneuver is available. However, since the observed attitude data is closely matched by the WEBES simulation, it is likely the actual boom flexing is also closely matched by the simulation. If the simulation boom motions differed greatly from the actual motions, it would have also been reflected in the attitude results.

The greatest boom motion in the simulation runs occurs in the in-plane-neutral flexing mode. The upper plot of Figure 10 shows the in-plane-neutral flexing for the run described in Section 4.4 (EI=14.5,3 flexing modes simulated). The initial retraction induces a large I/P flexing, causing the average I/P position to change from the original equilibrium of +130 feet

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feet to -60 feet. At the intermediate coast lengths, this I/P vibration has a period of about 2300 seconds. Because the satellite is rotating in pitch, the equilibrium I/P flexing value is constantly changing. The boom redeployment is initiated after about two complete periods of I/P flexing. At the completion of the redeployment and gravity gradient recapture, the new equilibrium is again near 130 feet. About a 50 feet peak to peak vibration still exists after redeployment with a period of 4200 seconds. This low value of remaining flexing is due to a favorable time phasing between the initiation of redeployment and the flexing during the interphase coast period. As noted in Section 2, an unfavorable phasing could have resulted in as much as a 300 feet p-p I/P vibration.

Vibrations in the other flexing modes is relatively small. The maximum excursions in each mode were approximately:

Roll	± 18 feet
Pitch	± 20 feet
Yaw	± 30 feet
Longitudinal	± 45 feet
Lateral	± 10 feet
Vertical	± 40 feet
O/P Neutral	± 25 feet

None of these vibrations would have much effect on attitude dynamics with 750 foot booms, because of their relatively small amplitude and high frequency.

The largest of the vibrations, longitudinal and vertical, are due in large part to the non-symmetry of the redeployment caused by the boom 4 deployer malfunction. Without the non-symmetry, these modes could have been expected to remain within about ± 10 feet.

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The largest instantaneous deformation of any boom following redeployment is about ± 70 feet out-of-plane and 50 to 200 feet in-plane.

The upper plot of Figure 11 shows the in-plane-neutral for the simulation case when EI was lowered to 13.0. With the lower EI, the period of the interphase coast vibrations is greater and the redeployment phasing less favorable. This results in a residual I/P neutral vibration of about 150 feet p-p at the end of redeployment. This vibration decreases to about 50 feet after 8 or 10 periods. The effect on attitude (Section 4.5) is seen in the greater yaw motion. While the match with observed yaw attitude is still close, the yaw motions are somewhat larger in this simulation than the observed. It can therefore be concluded that the 150 foot resulting p-p I/P vibration is probably greater than actually existed, and that the I/P vibration - redeployment phasing was favorable.

The observed antenna tip data reported in Table 2 shows maximum excursions of 47 to 155 feet in-plane and ±89 feet out of plane. The in-plane positions are plausible in light of the simulation runs, but the out-of-plane displacements are larger than expected. It is felt that this is more of an indication of errors in the observed data than inaccuracies in the simulation.

4.8 Damper Boom Motions

The bottom plots of Figures 10 and 11 show the damper boom motion for the cases using EI's of 14.5 and 13.0, respectively. Both show large damper boom movement after unlocking at 6800 seconds. Because of somewhat larger attitude motions in the second case, the damper motion is also greater. Neither case indicate motion large enough to hit the limit stops.

Neither case closely matches the small amount of observed data shown in Figure 5. However, more important than matching this data is observing the overall effect of the damper on the satellite dynamics. Both the observed data and the simulation runs show a significant reduction in the magnitude of the yaw and pitch oscillations resulting from the operations after, say, 50,000 seconds. The simulation runs show that after the large oscillations have been damped out the damper motion is reduced greatly and stays near its zero equilibrium.

5.0 Conclusions

The inversion maneuver of the RAE-1 satellite was successfully accomplished with results very close to those predicted before the maneuver. In spite of the age of the satellite, with minor exceptions all on-board systems worked well. A malfunction of the deployer mechanism of boom 4 during redeployment had little effect on satellite dynamics.

There is no indication of any mechanical damage to the satellite resulting from this maneuver, which is by far the most severe it has experienced. A favorable time phasing between the redeployment and boom flexing probably kept boom vibrations relatively small.

The available observed data for boom tip positions and damper angle is not sufficient to reproduce an accurate or reliable time history of these variables. However, there is no question that the damper system was effective in reducing the attitude librations resulting from the maneuver.

The WEBES program has proven its ability to accurately reproduce, and hence to predict, the satellite dynamic behavior even for dynamics as severe as encountered in the inversion. However, three boom vibration modes are required for accuracy under such severe dynamics, in spite of the fact that the second and third mode vibrations are very small when compared with the first. One mode has been previously shown to be adequate for conditions close to static equilibrium.

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