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Analysis of RAE-B Attitude Data

Contract NAS 5-20083-1

Prepared by

David A. Hedland
Paul K. DeGonia

Westinghouse Electric Corporation
Systems Development Division
Baltimore, Maryland 21203

for

NASA Goddard Space Flight Center
Greenbelt, Maryland 20771

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 1 of Contract NAS-5-20083.

The GSFC Technical Representative for this contract was Mr. Harvey Walden. The Westinghouse Program Manager was Mr. David Hedland.

TABLE OF CONTENTS

1.0 Introduction

The original objectives of this effort were to obtain as complete as possible a description of the in-orbit dynamical behavior of the RAE-B spacecraft and to account for discrepancies between predicted and actual in-orbit performance. The time period of interest extended from final despin operations in lunar orbit, throughout all deployment operations, and into the final steady-state mission mode. Hence, it was initially expected that this report would include actual and simulated attitude dynamics data for critical phases in this time frame and analysis based on computer simulations utilizing the WEBES program previously developed.

Unfortunately, to a large degree, these objectives have been impossible to meet and the scope of the study was reduced considerably. The main reason for this is that observed attitude and dynamics data for the period in question is unavailable. In fact, only one attitude data tape could be obtained, and it does not cover a period of the greatest use or interest. The only other attitude data available consists of weekly plots covering only a few hours of each week. These data sets are not of sufficient length to attempt a meaningful match with simulated dynamic data, but they do supply attitude equilibrium data throughout the period.

The greatest portion of this effort, then, involved attempting to match the observed attitude equilibrium angles with WEBES simulation results. This attempt was frustrated by the highly non-nominal equilibrium of the spacecraft since the initial deployment, apparently due, at least in part, to a damaged antenna boom.

This report, then, describes the observed data that was available and attempts to match computer simulation results to the observed equilibrium data.

2.0 Background

The RAE-B spacecraft was launched on June 10, 1973, and placed into a near-circular lunar orbit. It is a follow-on to the RAE-1 earth orbiting satellite, and is almost identical in configuration. The satellite's mission is to make directional, low radio frequency measurements to map the galaxy.

Four booms, deployable to a maximum length of 750 feet and arranged in an X configuration, have the dual purpose of serving as antennas and providing gravity gradient stabilization of the satellite's attitude. This configuration is depicted in Figure 1A.

The first phase of boom deployment was accomplished on July 12, 1973. This phase involved deploying the four booms to 600 feet in a single deadbeat maneuver. At the beginning of the second portion of the deadbeat maneuver (from 450 to 600 feet), telemetry data indicated that one of the lower booms was not deploying properly. The other three booms were allowed to deploy to their planned 600 foot lengths, resulting in a successful gravity gradient capture. The damper boom was then deployed to its full 315 foot length. Subsequent efforts finally resulted in deployment of the malfunctioning lower boom to 600 feet also.

Though these operations resulted in a good gravity gradient capture, real time attitude monitoring indicated large resulting attitude oscillations and a large discrepancy between predicted and observed equilibrium attitude values.

Real time monitoring of attitude and boom tip positions indicated that the lower boom was apparently damaged, being bent or perhaps just "hanging" on the spacecraft. This is thought to account, at least in part, for the

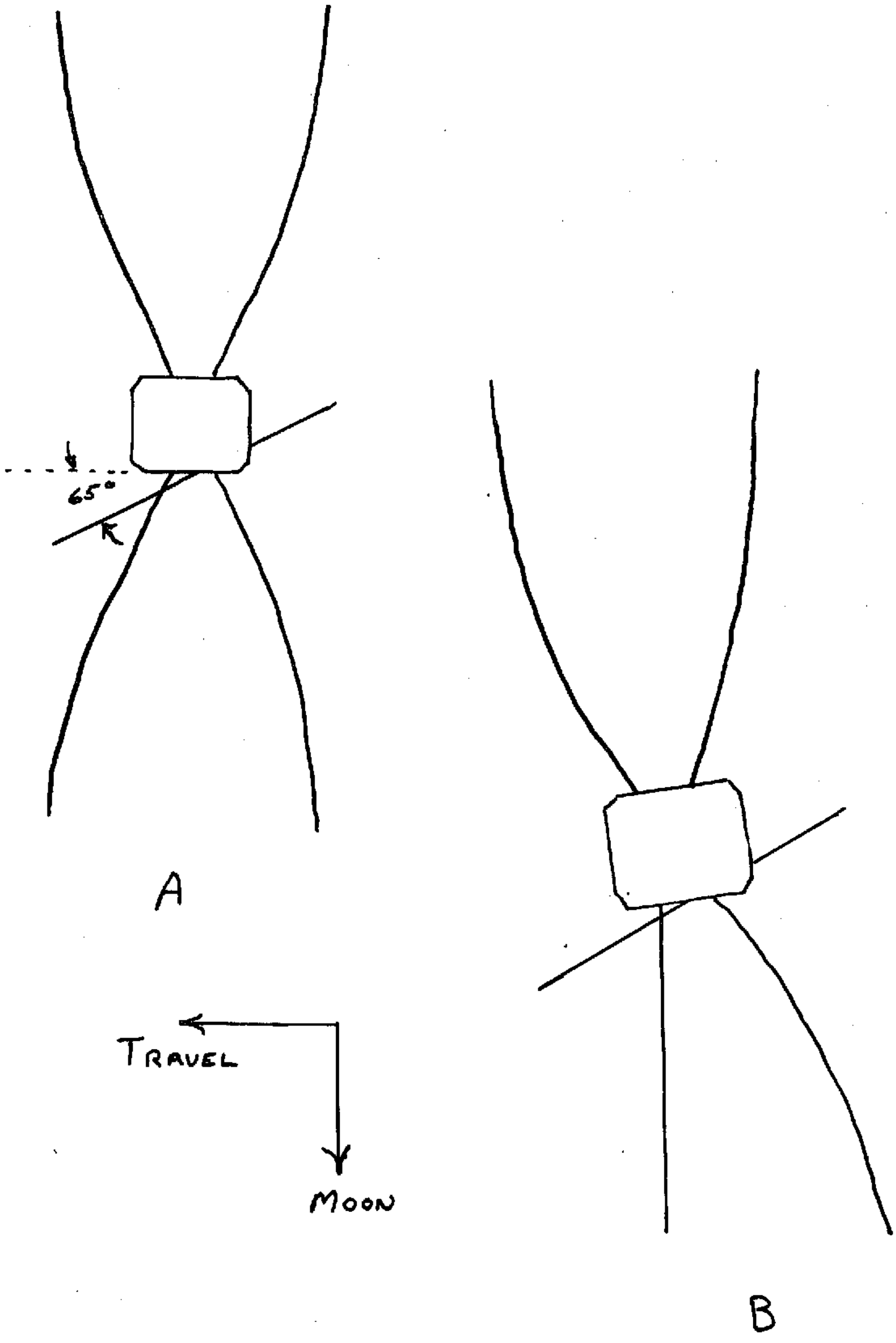


FIGURE 1 - NOMINAL RAE-B CONFIGURATION

equilibrium discrepancy. This configuration is illustrated in figure 1B.

Final deployment of the upper booms to 750 feet was accomplished on November 13, 1973. It was decided to leave the lower booms at 600 feet because of the previous difficulties encountered, and because it would have little effect on the overall mission. No change in the equilibrium attitude resulted from this maneuver.

Late in 1974, the lower booms were inadvertantly also extended to the full 750 foot length. Again, no detectable change in the equilibruim attitude resulted from the operation. Throughout the mission, the equilibrium attitude of the spacecraft has remained pretty much constant at -6, -7 and -40 degrees for roll, pitch, and yaw, respectively. This compares with predicted nominal values of 0, 0, and -16 degrees for 600 foot booms. The reasons for this great discrepancy had not been previously determined, so a major effort of this study became to explain the causes.

3.0 Observed Attitude Data

A major difficulty in accomplishing the objectives of this study has been the extreme sparcity of attitude data. Only two types of data were available for study. The first is a single attitude data tape covering a period of approximately 4 days which was recorded after the initial boom deployment phase (to 600 feet).

While much good data is on this tape, showing large attitude oscillations and covering a long time period, its usefulness is somewhat limited (for comparison with computer simulation results) because of its beginning time. The initial data on the tape is at about 21 hrs. U.T. on July 12, 1973. This is about 4 hours after the final operations of the deployment. At this time, large attitude oscillations were occurring and, undoubtedly, also large damper movements and boom oscillations. The resulting problem is the near impossibility of determining an accurate set of initial conditions to begin a comparison simulation run. (The necessary initial conditions include, of course, attitude and instantaneous attitude rates; damper displacement and rate; and in - and out-of-plane boom displacement and rates.) Meaningful simulation runs can only be made if all these conditions can be determined or (as in the case of previous RAE-1 dynamics studies) if the initial state is in or near equilibrium so that these parameters are known.

The data tape available, then, would probably only have been useful for simulation comparisons if it had begun during or immediately after the original deployment operations. The time period between this "known" data point and the beginning of the observed data is just too great, particularly with the extremely non-nominal deployment and final equilibrium and the uncertainty in the deployment schedule of one boom.

Figure 2 is a plot of the attitude recorded for the first 13 hours of the data tape period. The solid lines are data directly from the data tape. The dashed portions represent "expected" data for portions of time not covered by the tape.

It is immediately apparent from Figure 1 that extremely large oscillations resulted from deployment. The magnitude of these oscillations exceeds any previously seen on the RAE-1 spacecraft during deployments or experiments. However, the attitude does indicate a successful gravity gradient capture with little or no possibility of roll or pitch tumble.

The largest oscillations occur in yaw, with maximum excursions reaching from +30 to, perhaps, -100 degrees during this time period. It is likely that even larger excursions occurred during the time period preceeding this tape. It must be concluded that the possibility of a yaw flip, though it did not occur, was quite high.

Figure 3 shows the attitude recorded during the last 14 hours covered by the tape (July 16, 1973). By this time, the attitude oscillations had decreased to about ± 10 degrees in yaw and ± 5 degrees in roll and pitch. This is very convincing evidence of the effectiveness of the libration damper in reducing large amplitude oscillations. The equilibrium at the end of this period is seen to be about -40 degrees for yaw and between -5 and -10 degrees for both roll and pitch.

The only other type of attitude data available for this study were plots of roll, pitch, and yaw which were produced on a weekly basis since the deployment operations. These plots covered from one to four hours at a given time each week, but often large time gaps within this period were

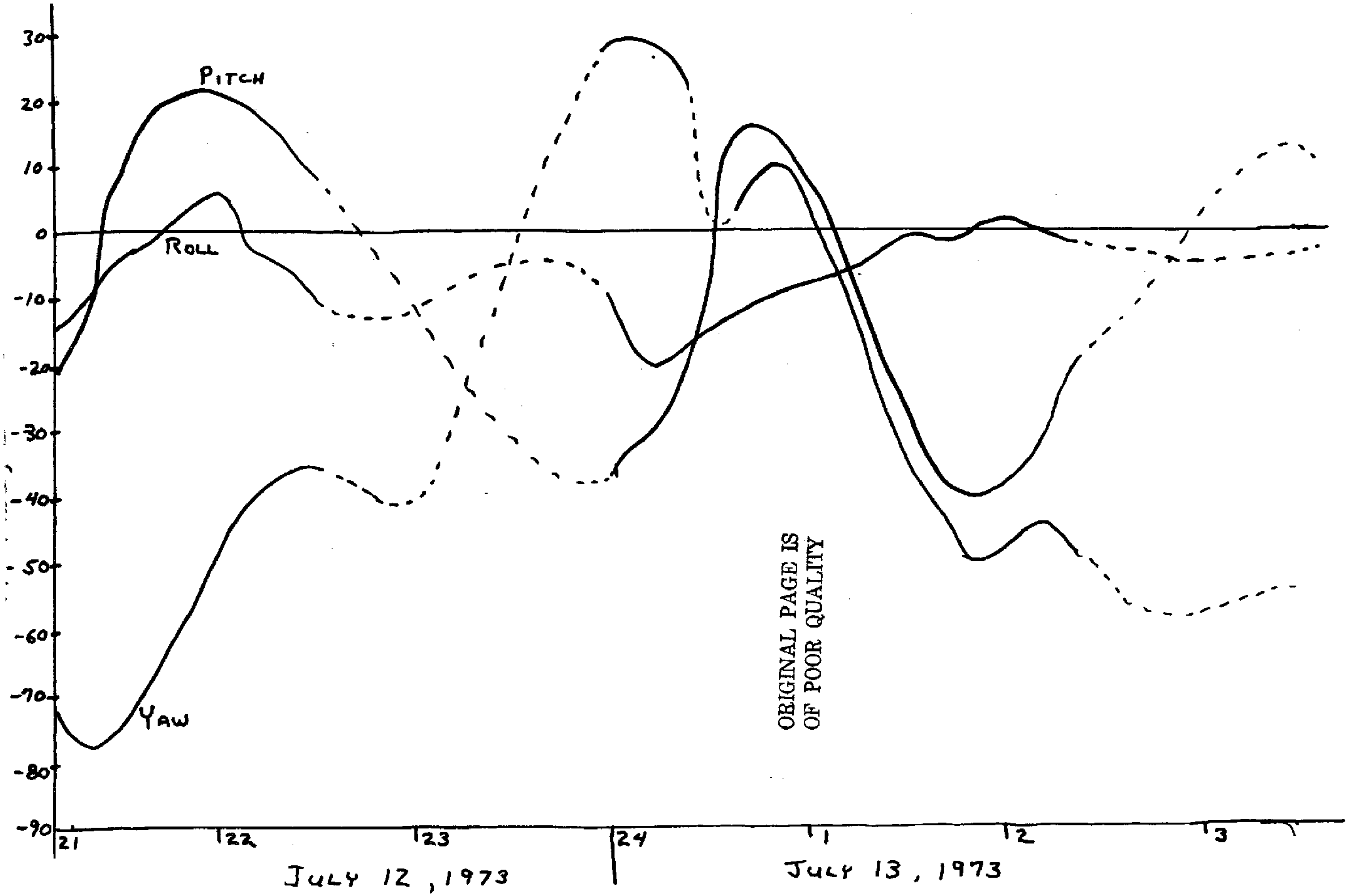


FIGURE 2 - RAE-B ATTITUDE FOLLOWING INITIAL DEPLOYMENT

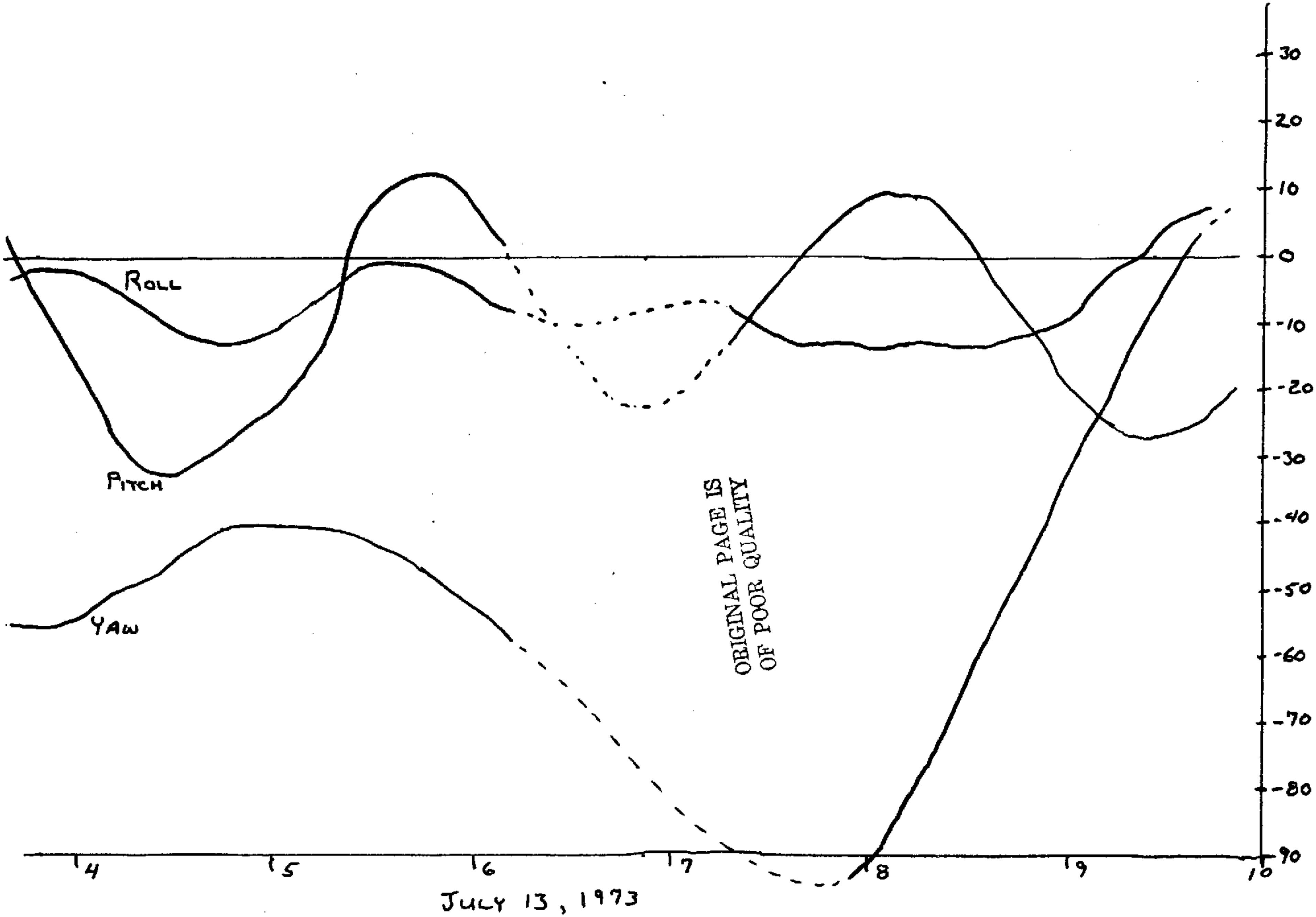


FIGURE 2 (CONTINUED)

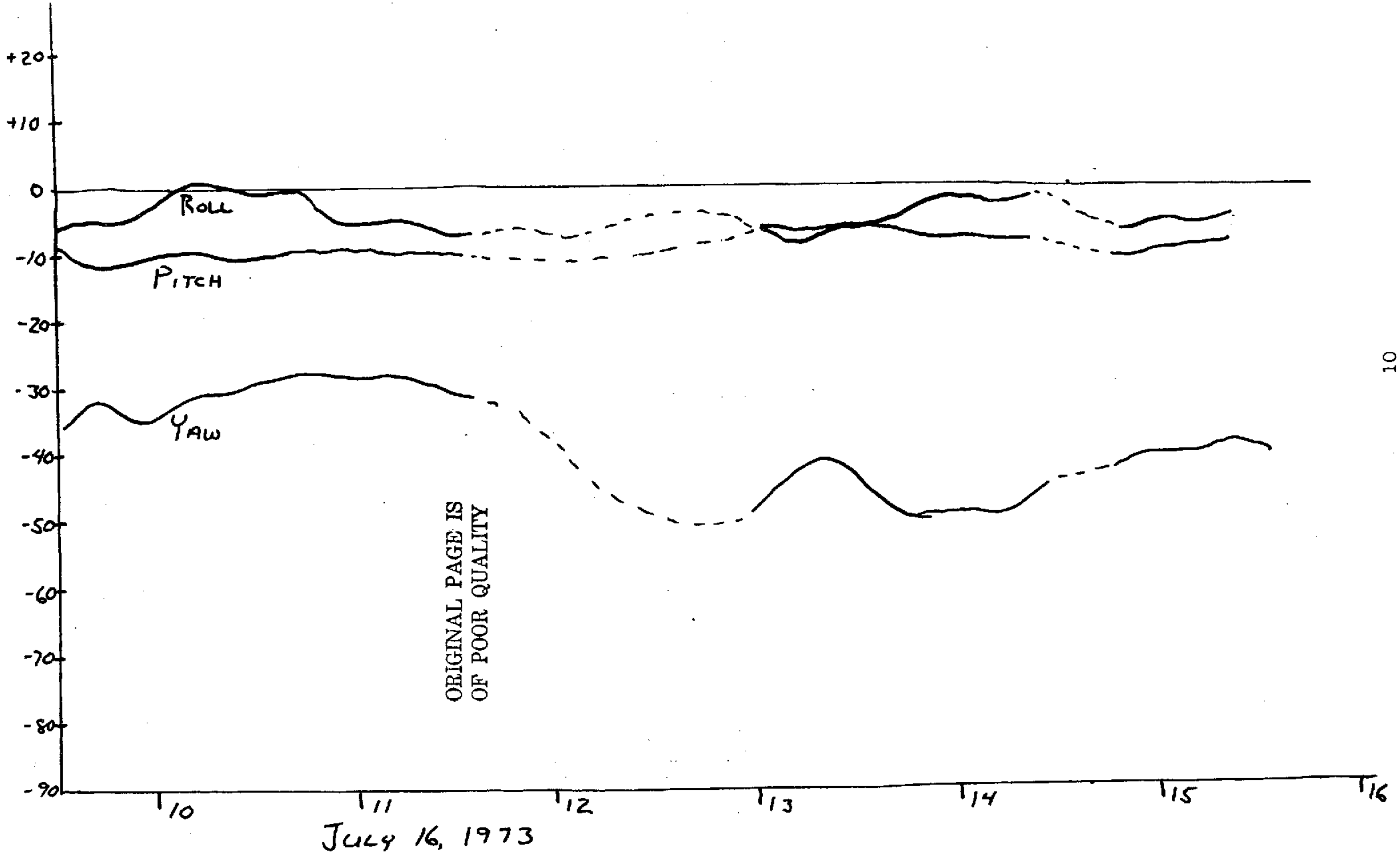
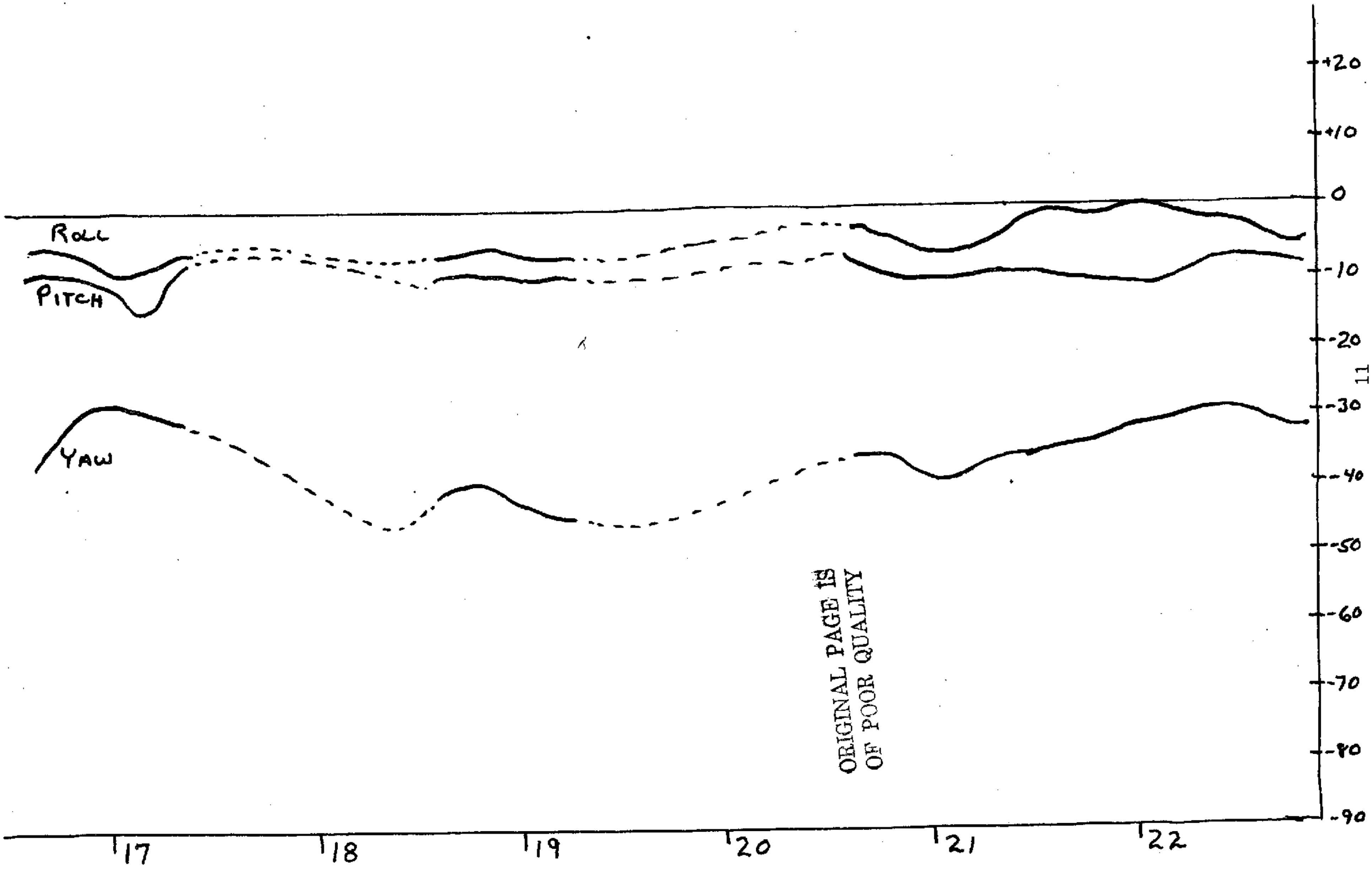


Fig. 3 - RAE-B Attitude



JULY 16, 1973

FIG. 3 (CONTINUED)

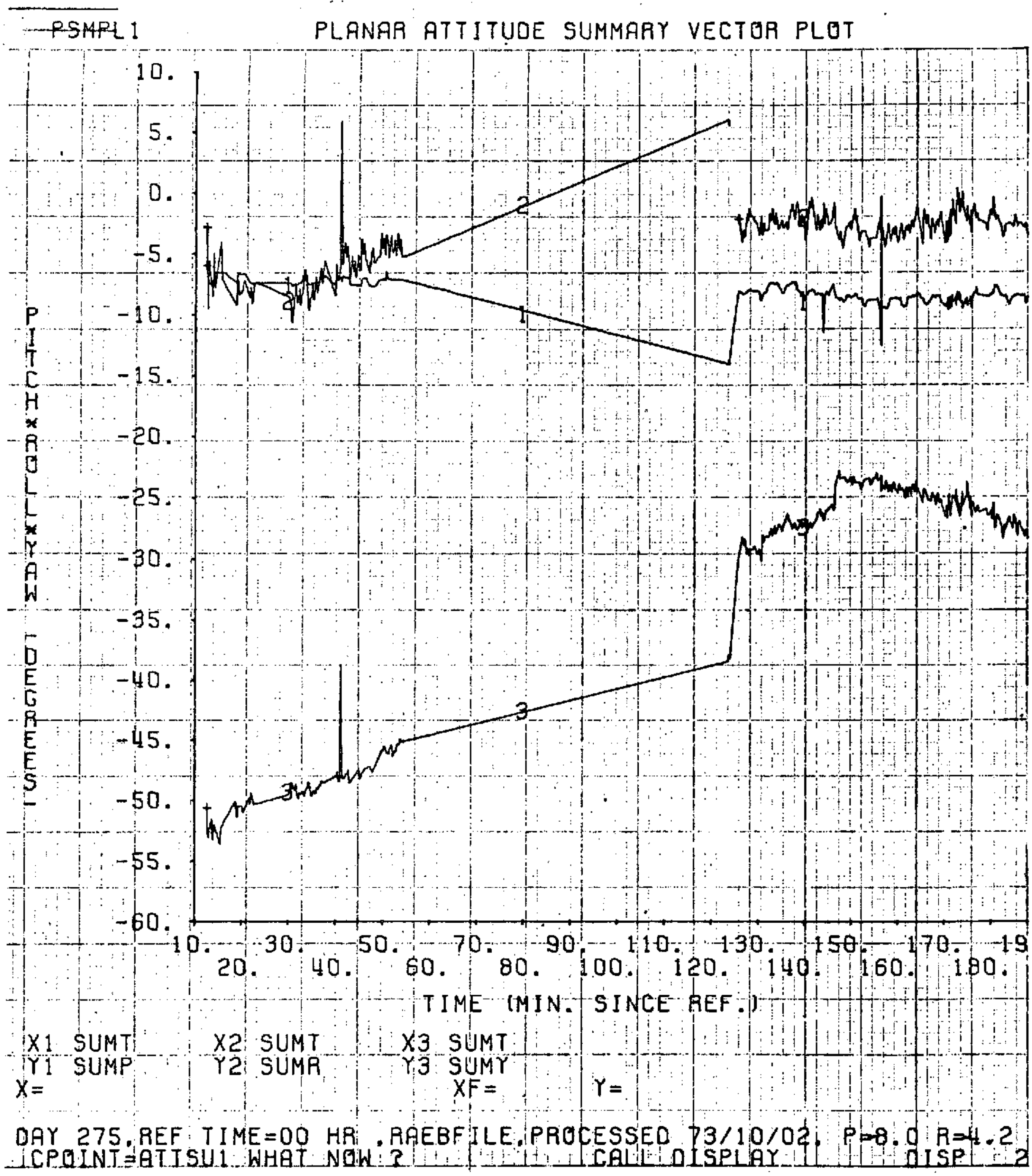
not covered. Considerable noise was present in most of the data.

Four representative examples of this data are reproduced in Figures 4-7. These four are more or less typical of the total of about 75 data sets available, and cover each of the satellite boom length configurations. Figure 4 was recorded October 1, 1973, when all four booms were at a length of 600 feet. Figures 5 and 6 were recorded on June 6, 1974 and June 10, 1974, respectively, when the lower booms were 600 feet long and the upper booms had been extended to their full 750 foot lengths. Figure 7 was recorded on January 6, 1975, when all four booms were 750 feet long.

Obviously these data sets are neither sufficiently lengthy or accurate to yield much information on satellite dynamics. However, they do provide good information concerning the equilibrium attitude of the satellite.

The data of figures 4-7, and, in fact, all the other data sets of this type, show that the equilibrium attitude has remained pretty constant for all the configurations. The yaw equilibrium has been about -40 degrees, and the roll and pitch equilibriums have averaged about -6 and -7 degrees, respectively. Maximum excursions from these equilibrium values has seldom exceeded a few degrees in roll and pitch and 15 degrees in yaw.

The equilibrium conditions shown by these plots is in very good agreement with the conditions seen on the attitude data tape, so each data type tends to confirm the other. Perhaps the only new, and quite surprising, result obtained from the plots is that the equilibrium state did not change measurably after the second deployment (upper booms to 750 feet) and third deployment (lower booms to 750 feet). The reason for this remains unknown. The level of expected change due to these maneuvers is discussed at the end of section IV.



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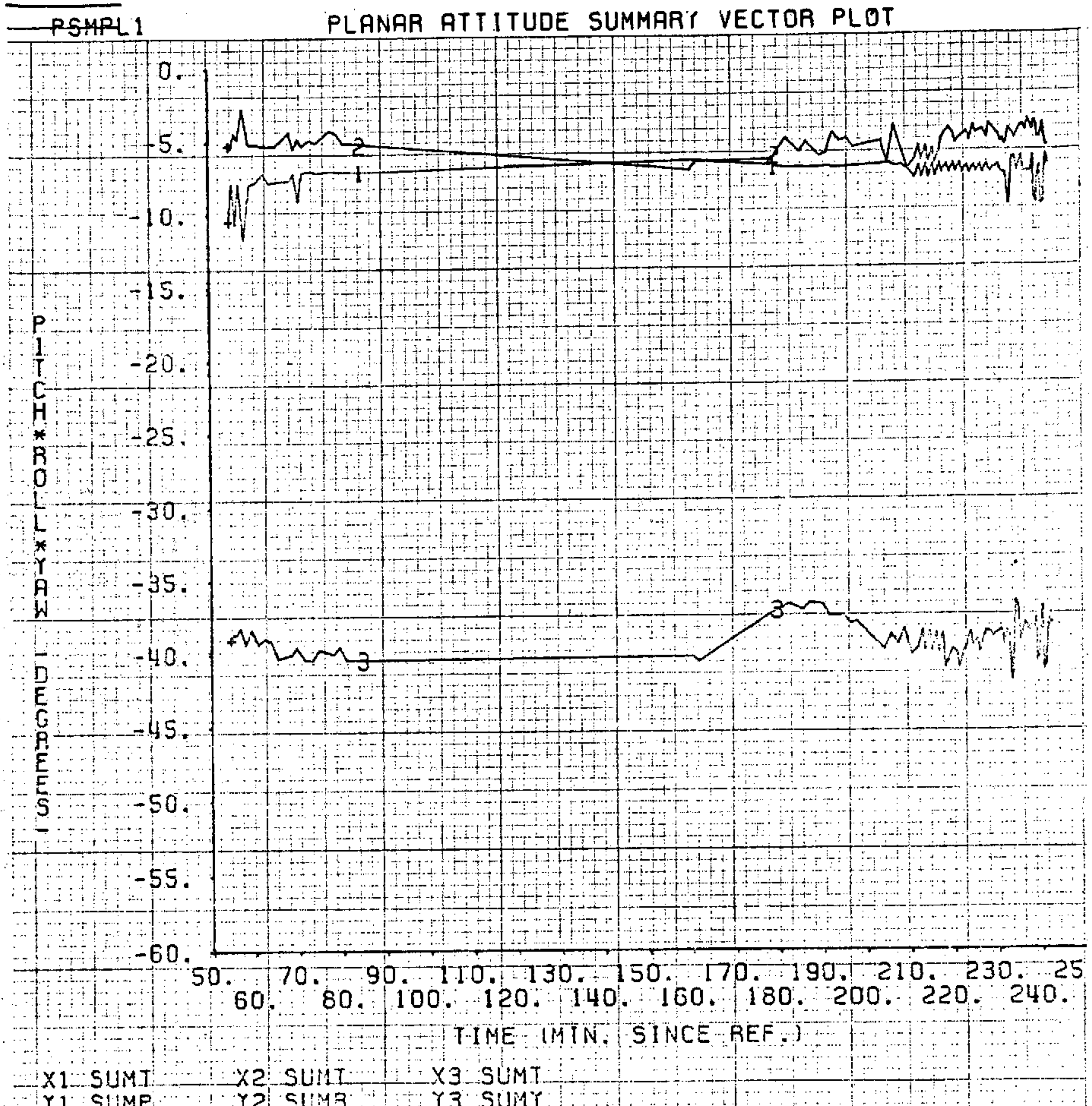
X1 SUMT        X2 SUMT        X3 SUMT
Y1 SUMP        Y2 SUMR        Y3 SUMY
X=                            XF=          Y=
DAY 275,REF TIME=00 HR ,RAEBFILE,PROCESSED 73/10/02, P=8.0 R=4.2
 CPOINT=ATISU1 WHAT NOW ?                 CALL DISPLAY          DISP  2
```

Figure 4 - RAE-B Attitude, October 1, 1973



```
X1 SUMT          X2 SUMT          X3 SUMT
Y1 SUMP          Y2 SUMR          Y3 SUMY
X=            70.4508666992188  XF=NONE  Y=          -5.0000000000000

DAY 157,REF.TIME=1100 HR.,RAEB TAPE-2,PROCESSED 74/06/07
CPOINT=ATTSU1 WHAT NOW ?                  CALL DISPLAY           DISP    2
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Figure 5 - RAE-B Attitude, June 6, 1974

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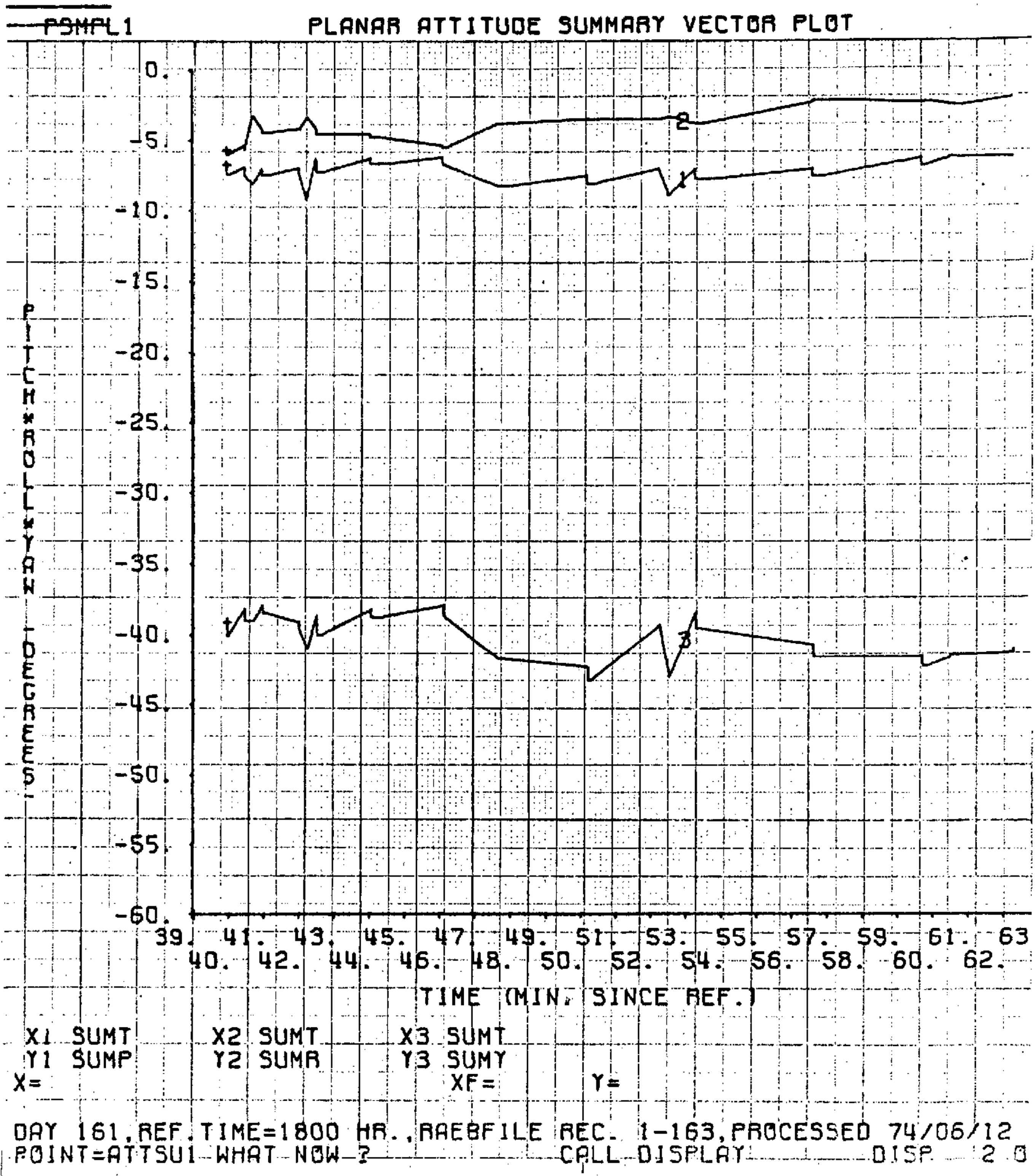

```
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Y1 SUMP        Y2 SUMR        Y3 SUMY
X=                            XF=          Y=
DAY 161,REF.TIME=1800 HR.,RAEBFILE REC. 1-163,PROCESSED 74/06/12
POINT=ATTSU1 WHAT NOW ?                CALL DISPLAY              DISP  2 0
```
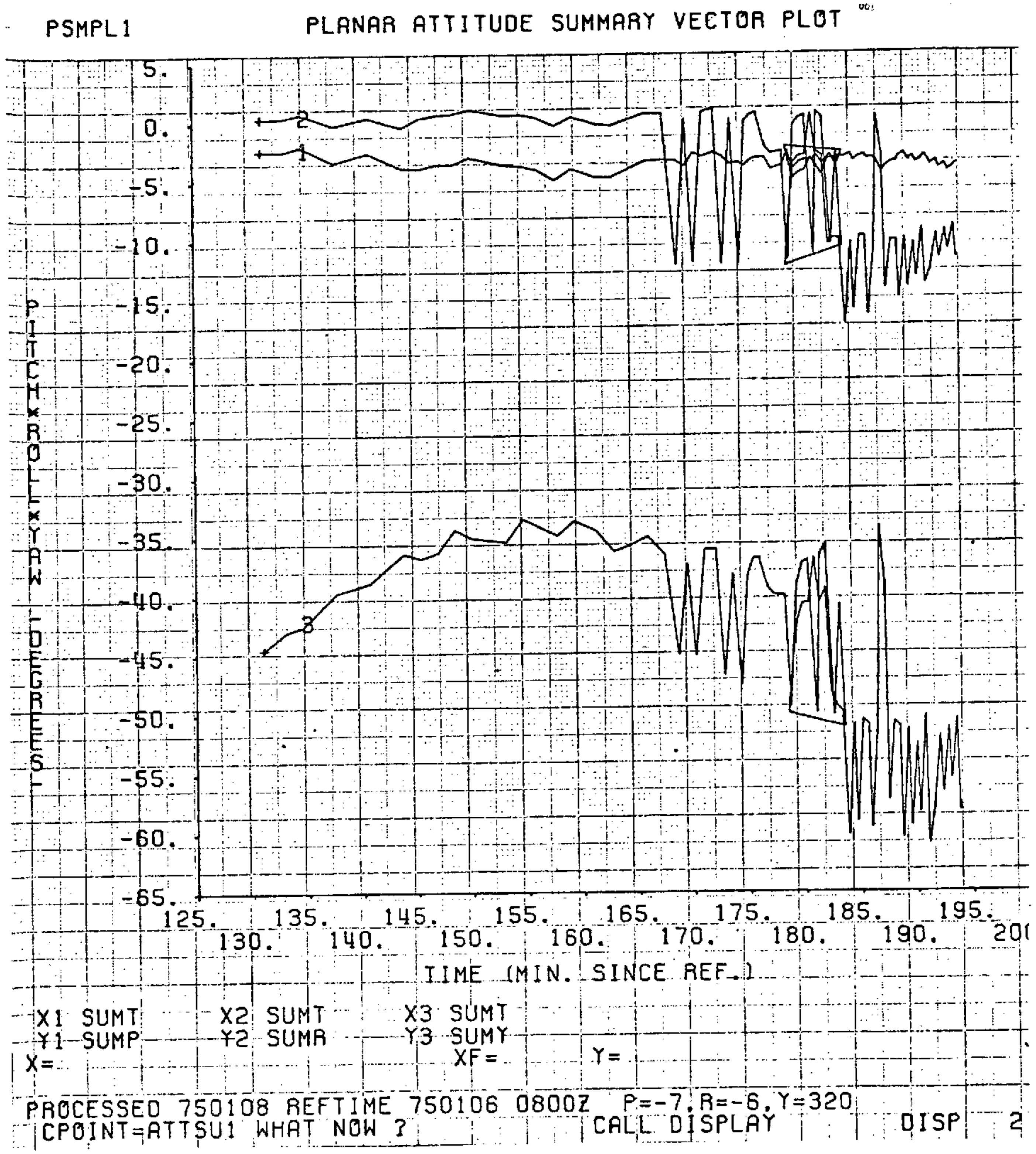

Figure 6 - RAE-B Attitude, June 10, 1974



```
X1 SUMT      X2 SUMT      X3 SUMT
Y1 SUMP      Y2 SUMR      Y3 SUMY
X=                           XF=        Y=
PROCESSED 750108 REFTIME 750106 0800Z  P=-7,R=-6,Y=320
CPOINT=ATTSU1 WHAT NOW ?          CALL DISPLAY        DISP   2
```

Figure 7 - RAE-B Attitude, January 6, 1975

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4.0 Simulation Results

This section reports on the results of computer simulation runs made to gain insight into the state of the RAE-B satellite in orbit.

The simulation program used is called WEBES (for Westinghouse Electric Boom Extension Simulation) and has been used extensively and successfully for several years in support of both the RAE-1 and RAE-2 missions. As noted earlier, sufficient attitude data to make useful comparison runs to attitude dynamics was not available. However, since the equilibrium state of the satellite was so far from that expected, considerable effort was spent to match these conditions.

The factors affecting the equilibrium attitude of the satellite are relatively simple, and can be seen in Figure 1. The satellite is symetrical (with respect to moments of inertia, which, in turn, determines the equilibrium) about the roll and pitch axes. Hence, the expected roll and pitch equilibrium angles are each zero degrees. The damper boom is skewed out of the plane of the main booms (which determines the body reference axes) by 65 degrees. This results in the principal inertia axes (and hence the yaw equilibrium) differing from the body reference axes. Previous studies have determined that for a nominal configuration (figure 1A), the expected yaw equilibrium should be about -10 degrees for 750 foot main booms and 315 foot damper booms. For 600 foot booms, an equilibrium of about -16 degrees is expected.

In the previous section, it was seen that the actual equilibrium attitude has remained near -6, -7, and -40 degrees for roll, pitch, and yaw, respectively. This indicates that the moment of inertia of the skewed damper has a much greater effect than expected or, equivalently, the composite yaw inertia of the satellite without the damper is much less than expected. The same result was observed in RAE-1, but to a much lesser degree. The RAE-1 yaw equilibrium was only about 5 degrees greater than predicted.

Variations in any of several physical parameters of the satellite can be expected to affect the attitude equilibrium. These parameters were varied in simulation runs to determine to what degree they affected equilibrium values and, hopefully, to explain the discrepancies. The suspected possible causes are listed here, in roughly the order of their likelihood:

A. One of the lower booms is known to be damaged and not in its nominal position. It is thought to be either bent inward, or possibly to be "hanging loosely" from the satellite. This situation is shown in Figure 1B. Telemetry data is not sufficiently consistent or accurate to determine the exact orientation of this boom, however. Bending the boom inward would,of course, decrease its contribution to the satellite yaw moment of inertia and also affect the pitch angle in the manner required to match equilibrium. Bending of one boom out of plane has a smaller, and less easily predicted effect.

B. If the structural rigidity (EI) were less than the nominal value measured before launch ($\sim$ 14 lb ft^2), static gravity gradient bending would be greater, thus reducing yaw moment of inertia.

C. If the in-plane semi-vee angles of the three "good" booms was less than the nominal 30 degrees, the yaw equilibrium angle would be greater.

D. Main boom densities less than the pre-launch values or a damper boom density greater than expected would affect the equilibrium in the observed manner.

Simulation runs were made testing each of the above possibilities and combinations of them. Most runs were made with main boom lengths of 600 feet, since more data was available for comparison. Also, if the equilibrium could not be matched for the 600 foot case, there was no hope for doing so at longer boom lengths since the longer lengths result in greater composite yaw moment of inertia. Some runs were made in each configuration, though.

The major emphasis was on matching the -40 degree yaw equilibrium since this was the greatest discrepancy from nominal. It was found that nearly any variation causing a greater yaw equilibrium would affect the roll and pitch equilibrium in the desired manner; that is, to cause small negative roll and pitch equilibriums. All the results reported here matched the roll and pitch equilibriums to within 2 or 3 degrees.

Initial runs quickly indicated that none of the possibilities listed above could, alone, account for the discrepancies with any reasonable variations from nominal parameters. Hence, most of the runs reported here have several of the effects taken into account.

Figure 8 illustrates the effect of displacing one lower boom in the in-plane direction only, as described in cause A. In these runs, the EI was 14 lb. ft.^{2} (nominal) and the semi-vee angle of the remaining three booms was 24 degrees. Boom densities were set at the nominal values. The maximum yaw equilibrium occurred with the semi-vee angle of the single boom at -5 or -6 degrees, and was -34.2 degrees. At this point, roll and pitch were -5 and -7 degrees, respectively, which is very close to the observed values. The yaw is still off by 6 degrees, however.

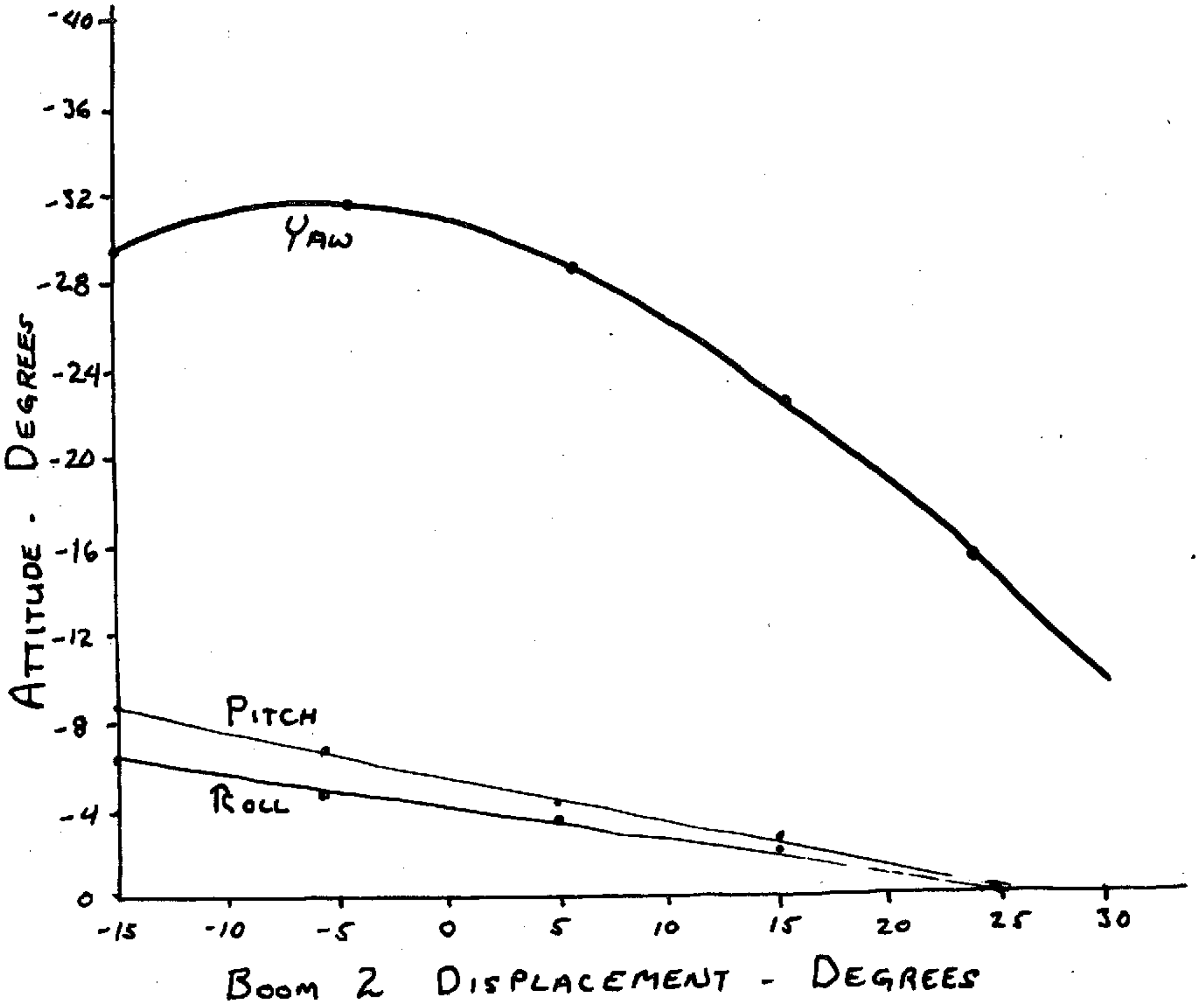

Figure- 8 Effect of Displacing 1 Boom

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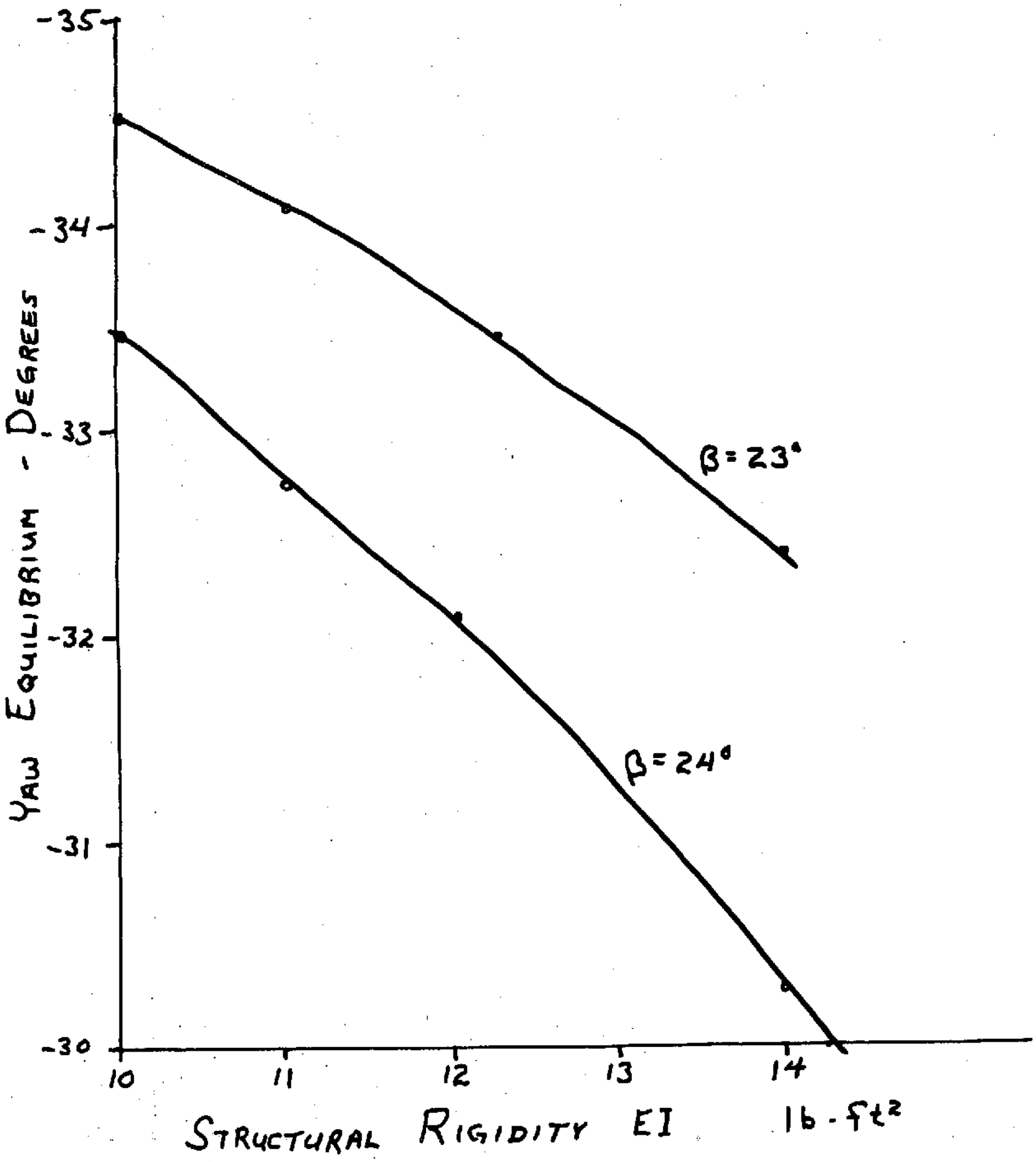

FIGURE 9- EFFECT OF EI VARIATIONS

The point at which the maximum yaw angle occurs is, as expected, the point at which the boom is directed along the radial (or -Z) axis, and hence, contributes the least to the composite moment of inertia. The -6 degree orientation corresponds to the -6 degree pitch equilibrium. It is apparent from Figure 8 that adjusting the in-plane location of a single boom will not effect the yaw equilibrium sufficiently, even when the semi-vee angle of the other three booms is lowered to 24 degrees.

The only way to simulate an out-of-plane dislocation of a boom in the WEBES program is to simulate static, or force free, bending of the boom. The shape simulated is a first vibrational mode shape, and thus may be an imperfect way of representing a damaged boom. Nevertheless, several runs were made to determine if out-of-plane bending of the damaged boom could account for the yaw discrepancy. Bending as great as a 200 foot tip displacement had less than a 3 degree effect on the yaw equilibrium, but had greater affects on roll and pitch, but not in the desired direction.

Figure 9 shows the effect of variations in the boom's structural rigidity on the yaw equilibrium for semi-vee angles of the three undamaged booms of 23 and 24 degrees. Reducing EI from a nominal value of 14 lb ft^2 to only 10 lb. $ft.^2$ increased the yaw-equilibrium angle only about 3 degrees. Runs with EI's of less than 10 became unstable.

Figure 10 shows the effect on the yaw equilibrium of varying the semi-vee angle of the three undamaged booms. These runs were made with the damaged boom at -6 degrees, which yielded the maximum yaw, and nominal boom densities. This variation is seen to have the greatest affect on the yaw equilibrium of the possibilities tried. By reducing the semi-vee angle to 20 degrees, the simulated yaw equilibrium finally matches the observed value. However, an

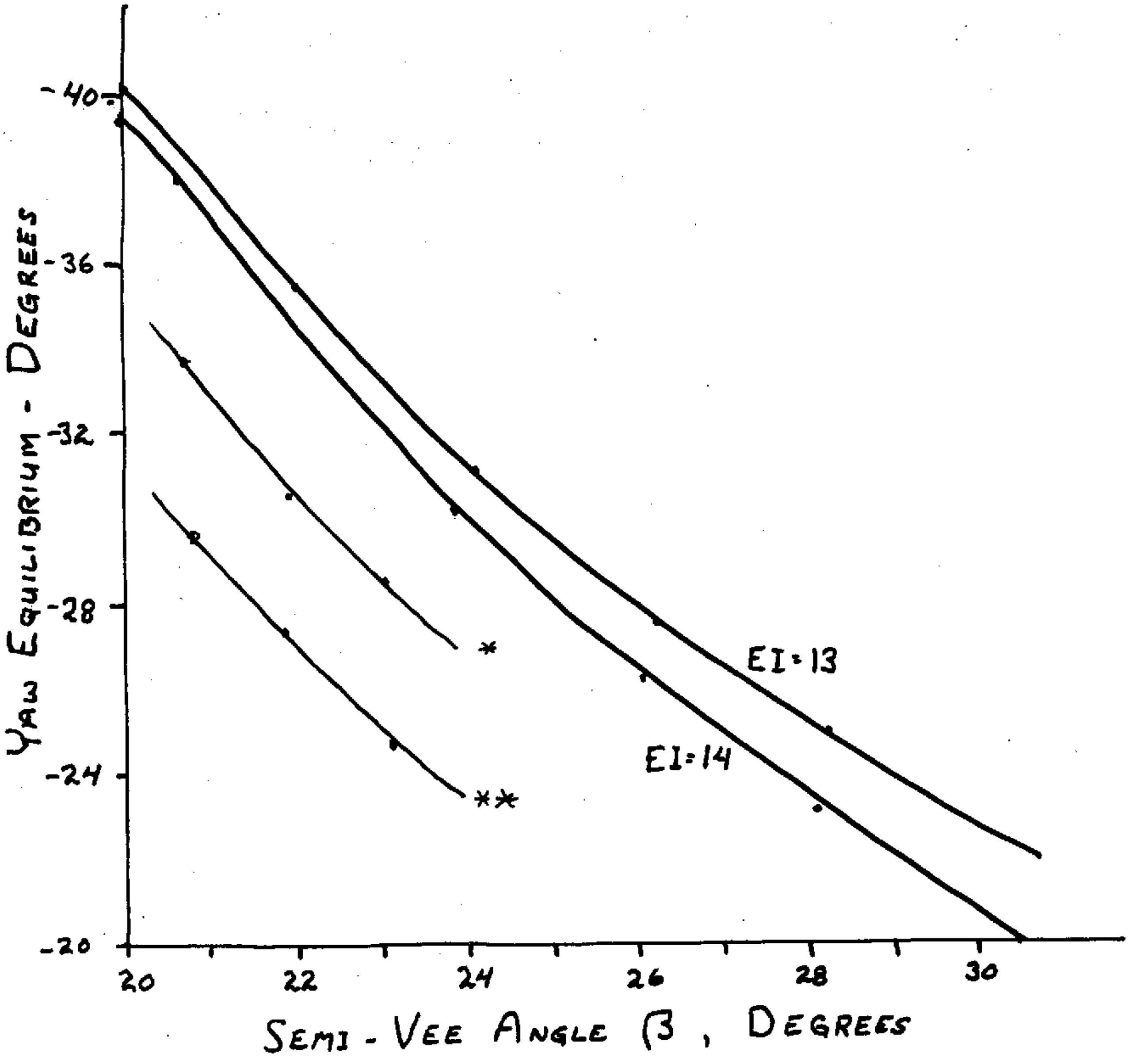

FIGURE 10 - YAW EQUILIBRIUM VS. β

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error of 10 degrees in manufacture and measurement of this parameter is inconceivable, so that this cannot be considered a reasonable explanation of the discrepancy.

Figure 11 shows the effect of variations in boom density for several semi-vee angles. These data reflect variations when the damaged boom is in the location yielding the greatest (negative) value. In these runs, the densities of the main booms were decreased and the density of the damper boom increased by the indicated percentage. In general, a change of 10 percent, which might be considered about as great as could reasonably be justified, increases the yaw-equilibrium by only about 2 degrees. The dominant variation remains the semi-vee angle, ϵ .

To summarize these results, the WEBES program has been unable to accurately match the observed attitude equilibrium state with any reasonable set of physical parameters.

One final possibility should perhaps be considered. That is that the observed attitude data is unreliable or incorrect, and would continue to indicate an equilibrium of -6, -7, and -40 degrees whatever its actual attitude. This possibility seems remote, and if it were true, would probably have been determined by other investigators by now.

Nevertheless, the fact that the observed equilibrium did not change with subsequent deployments tends to support the possibility. Several runs were made to determine what the expected change due to the deployments is. The results are shown in Figure 10. The curve marked with "*" represents the yaw equilibrium expected when the upper booms were extended to 750 feet; the curve marked with "**" represents the expected value with all four booms at 750 feet. The runs were made with an EI of 13. A total of 7 or 8 degrees change is predicted after both operations. No such

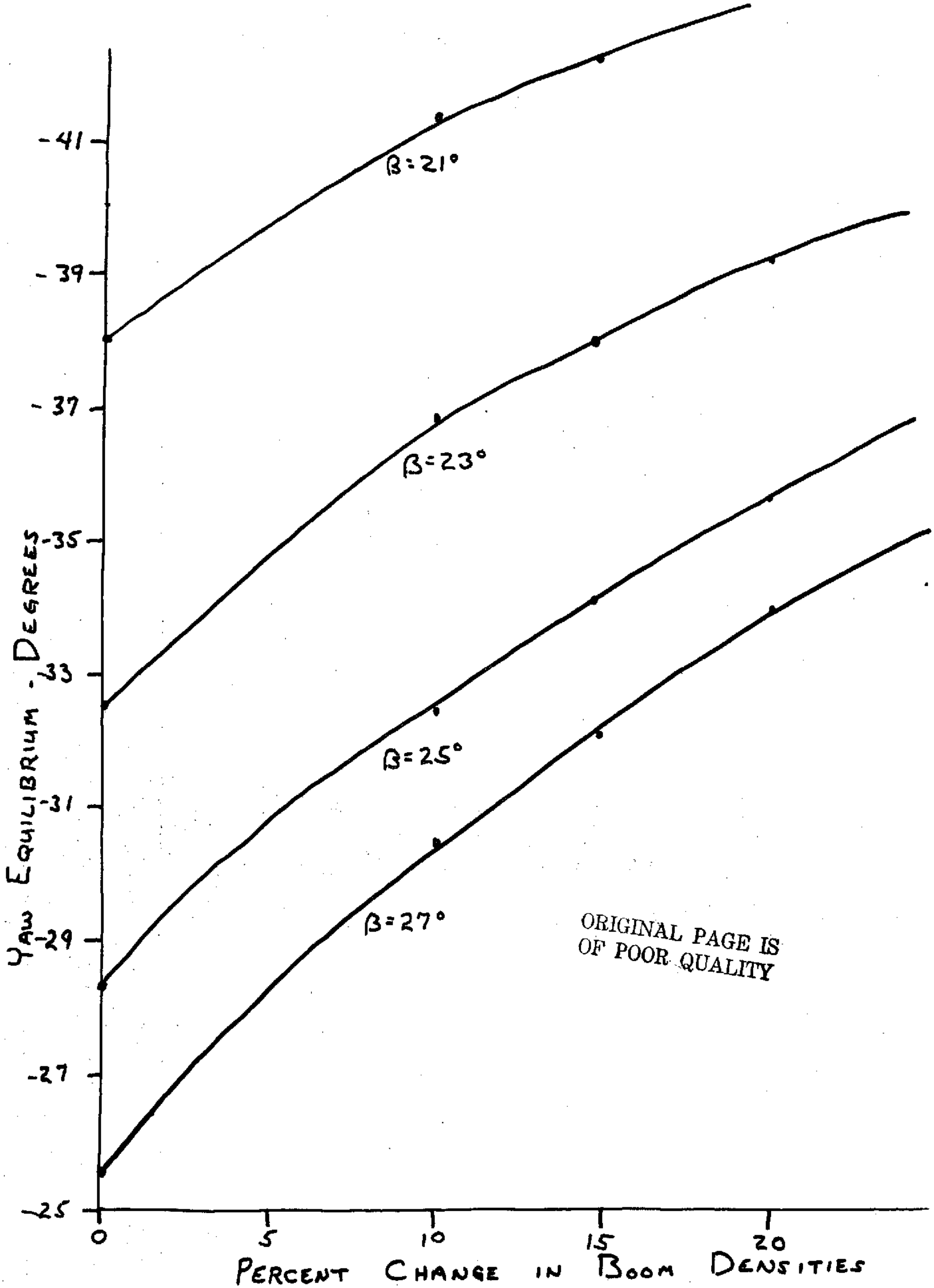

Figure 11 - Effect of Boom Density Variations

change is reflected in the observed data.

This, of course, could hardly be considered proof of the possibility mentioned, though it does support it. The hypothesis could perhaps be tested if future dynamics experiments were conducted.

5.0 Conclusions

The following conclusions can be drawn from the data studies in this effort:

1. The boom deployment operations resulted in a successful gravity gradient capture and attitude stabilization, which allowed the satellite to pursue its primary experiments.

2. Certain abnormalities occurred in the deployment of one of the lower pair of booms. When finally deployed, the boom was in a damaged condition.

3. Extremely large residual attitude oscillations followed the initial deployment sequences. These were undoubtedly at least partially a result of the deployment problems. The residual yaw oscillation was probably nearly large enough to cause a yaw flip, but no flip occurred.

4. The libration damper system was very effective in reducing the deployment induced oscillations. After 100 hours, the remaining oscillations were on the order of a few degrees.

5. The indicated equilibrium attitude of the satellite has remained at about -6, -7, and -40 degrees for roll, pitch, and yaw, respectively, compared with a predicted 0, 0, and -10 to -15 degrees, for a nominal configuration. This is probably at least in part due to the damaged boom.

6. Studies with the WEBES computer simulation have failed to match the observed equilibrium values with any reasonable set of satellite physical parameters, and so have not explained the discrepancies between predicted and observed equilibrium.

7. The fact that the equilibrium did not change measurably after the 2 subsequent deployment operations suggests the possibility that the observed data is unreliable. Physical theory and computer simulations indicate that the two operations should have changed the yaw equilibrium by about 7 degrees.