FINAL REPORT

A STUDY OF THE FLEXIBLE BODY DYNAMICS OF THE RAE-A SATELLITE

MARCH 1971

AVSD-0154-71-RR

CONTRACT NAS5-11192

Prepared By

AVCO GOVERNMENT PRODUCTS GROUP
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WILMINGTON, MASSACHUSETTS

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For

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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For
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

TABLE OF CONTENTS

ILLUSTRATIONS

Figures

ILLUSTRATIONS - (cont'd)

Figures

Tables

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This report describes the analysis and technical efforts of R. M. Davis, L. Beltracchi, E. A. Lawlor, and P. L. Bankhead of Avco Systems Division.

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1.0 INTRODUCTION

The RAE-A satellite is dimensionally the largest successful three axis gravity gradient stabilized spacecraft ever flown. Its configuration can be represented as a large X with the spacecraft core structure at the center. The legs of the X are deployable booms measuring 750 feet from center to tip. See Figure 1.0-1. The included angle between the legs of the upper and lower pointing antenna pairs is nominally 60°. The 0.57 inch diameter deployable tubes are interlocked, perforated and silver plated on the outer surface. The temperature gradients across the booms due to solar radiation are minimized by the silver plate exterior and the black interior since perforations allow some fraction of the thermal energy to enter and be absorbed on the back surface.

A dipole antenna, consisting of two 60 foot antennas, bisects the 120° angle between the upper and lower legs of the X and lies in the same plane.

Damping is provided by a libration damper which consists of two deployable booms measuring 315 feet from tip to center. The damper booms are mounted on a damper package which is suspended from the central structure by a torsion wire spring. Energy is dissipated by magnetic hysteresis.

Magnetometers and solar aspect sensors are utilized for attitude determination of the central core structure. Four television cameras are on board to determine the antenna boom tip deflectional position relative to the central core.

The spacecraft is presently in a 12,241 kilometer retrograde nearly circular orbit with approximately 0.001 eccentricity. The inclination of the orbit is 122°.

The overall objective of this contract was to provide definitive data on the RAE-A antenna boom positions as well as increase the knowledge of the RAE-A spacecraft dynamical parameters. These parameters included particularly the antenna boom stiffness and temperature gradient.

The procedure utilized in this study was to compare spacecraft flight data with simulated data computed by the RAE Dynamics Simulator Computer Program and the IMP Dynamics Simulator Computer Program. These computer programs were developed to support the design mission analysis and antenna boom deployment operations of the RAE-A satellite and IMP series of satellites.

The results of this study can be summarized by stating that there was not sufficient flight data available to provide definitive data on antenna boom position to the Radio Astronomy experimenter. There was, however, enough data to indicate the trend if not the actual antenna boom stiffness and temperature gradient. It was possible, by utilizing the IMP Dynamics Simulator, which is a generalized extension of the RAE Dynamics Simulator, to obtain a remarkably good fit of simulated data to measure spacecraft attitude data when the antenna booms were extended to 450 feet. The major result from this study is that the value of the RAE-A antenna boom stiffness appears to be significantly less than the pre-flight ground measured value.

The studies also confirmed earlier indications that an improved simulation could be obtained by using values of the root angles of the antenna booms and the angle of the damper plane of motion, relative to the plane of the antennas, that differed from pre-flight ground measurements.

Most of the results of the studies were obtained using spacecraft data when the antenna booms were extended to the 450 foot intermediate length. At this length, boom tip displacement data was available for both the #1 and #2 antenna although it was not available for the #1 antenna at other boom lengths.
The spacecraft motions were also less sensitive to antenna boom displacement initial conditions at this length providing that they were symmetrical. The

RADIO ASTRONOMY EXPLORER SATELLITE

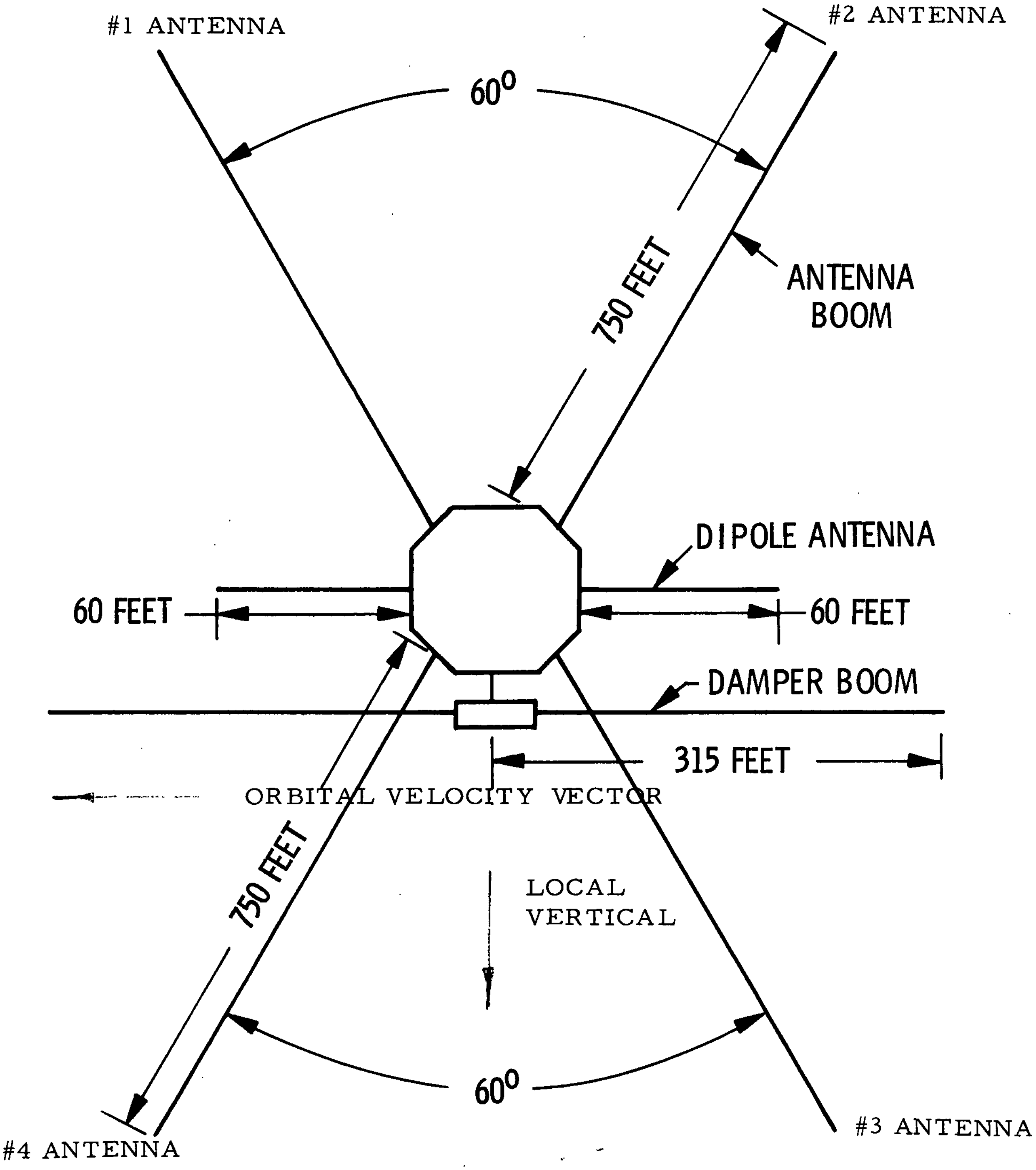


Figure 1.0-1

dynamical motions were, however, dependent on the values used for antenna boom stiffness.

Spacecraft data were also analyzed when the antennas were extended to 750 feet. At this length, only the #2 antenna boom TV was functioning. The time span of data from the #2 boom TV camera was insufficient to be useful in determining antenna boom properties. The spacecraft attitude motions also appear to be more sensitive to boom displacement initial conditions for the 750 foot length. As a result, it was possible to only bound the spacecraft attitude motions. The bounds were narrowed considerably, however, by using a significantly smaller value for antenna boom stiffness than pre-flight ground measurements.

1.1 SUMMARY OF MATHEMATICAL MODELS AND COMPUTER PROGRAMS

The inclusion of a detailed description of the mathematical models and computer program utilized in this study is not feasible in this report. However, a brief description of the capabilities of the Dynamics Simulation Computer programs is worthwhile in order to provide a basis for evaluating the results of this report.

1.1.1 RAE In-Orbit Simulator Computer Program

The RAE In-Orbit Simulator (RAEIOS) computer program is a single computer program composed of several modules that were developed to support the overall flight operations of the Radio Astronomy Explorer - A Satellite. The principal modules which were used in this study were the Dynamics Simulator Module and the Corrector Module. The Data Analyzer Module was also used to convert antenna tip television information into antenna tip deflections and velocities relative to the undeformed axis of the antennas.

Dynamics Simulator Module

The Dynamics Simulator Module of the RAEIOS integrates the equations of motion of the dynamic model that was derived to simulate the RAE satellite. The input of the Dynamics Simulator Module consists of the spacecraft physical parameters and the initial condition of the dependent variables that define the spacecraft's dynamic state. The output of the Dynamics Simulator consists of the time history of the state variables plus other quantities that are derived from the state variables.

Computations of the orbital motion have been uncoupled from the computation of local motions of the satellite about its center of mass. The local motions of the satellite include the three-dimensional large angle rotations of the central core, the deflectional motions of the antenna booms, and the relative rotation of the rigid libration damper. The libration damper employs a hysteresis mechanism which is also simulated.

The satellite ephemeris, which is used to determine the local external force fields, is either calculated internally in the Dynamics Simulator or supplied externally in tabular form from more accurate orbit determination schemes.

The external forces that are simulated include forces due to gravity, solar pressure, and the interaction of spacecraft magnetorquer with the Earth's magnetic field. The internal forces simulated are the forces caused by deformations of the antennas and those induced by temperature gradients across the antenna booms.

A modal approach is used in determining the deformation of the flexible antenna booms. A finite series of shape functions were used to represent the deformed shape of the RAE antennas. These shape functions were specified to be the first three cantilever beam modes. The program will, however, accept other functions that would be applicable to other programs. The coefficients of the shape functions are used as generalized coordinates for both in-plane and out-of-plane displacements. Due to the large deflections of the antennas, it is necessary to account for the axial inertia of a mass element in the antenna booms. The axial motion is derived from the in- and out-of-plane bending by requiring that the length of a differential element along the axis of the boom remain unchanged during deformation. This implies that the stretching deformation of an element along its axis is negligible compared to bending deformation.

When the RAEIOS is being utilized to correlate the measured and simulated data, the Dynamics Simulator Module operates as a subroutine of the Corrector Module.

Corrector Module

The Corrector Module employs a direct search scheme, automatically varying selected satellite parameters in the Dynamics Simulator to minimize deviations between measured and simulated satellite dynamics. The Corrector Module compares simulated and measured state variables over a selected data span. The differences between the simulated and measured dynamics are summed and listed as the performance criterion. Each comparison represents a trial in the search scheme. Each time the parameters that were selected to be optimized are varied, a new simulated history of the state variables is computed by the Dynamics Simulator. The performance criterion is re-evaluated and compared with results of previous trials. A reduction in the performance criterion is considered to be a successful trial. The results of parameter variations for successful trials are used to logically select new values of the parameters for subsequent trials. The entire process is repeated until the performance criterion has been reduced to a level specified by input.

Missing state variables such as boom tip deflections and velocities may be also determined using the Corrector Module. Missing state variables are treated as satellite parameters in the search routine permitting the complete state variable for the satellite to be determined. The search technique was based on a method developed by H. H. Rosenbrock. (Reference 1). Both the Dynamics Simulator and the Corrector Module are described in detail in Reference 2.

1.1.2 IMP Dynamics Computer Program

This computer program was developed to simulate the dynamics of the IMP class of satellites. Generality was retained in its development so that it is applicable to the simulation of the dynamics of a large class of flexible spacecraft including the RAE-A spacecraft.

The program is applicable to both inertially oriented spinning or earth oriented gravity gradient stabilized spacecraft. Internal and external environmental effects developed at orbital altitude are simulated. The effects include gravity gradient forces, solar pressure, magnetic torques and thermal bending due to solar heating. Body torquing devices in the computer program include momentum wheels, a viscous ring nutation damper, magnetic torquer coils and attitude control thrusters. For gravity gradient satellites, an option is available for simulating either a magnetic hysteresis or viscous libration damper.

The computer program has the capability of simulating up to ten flexible tubular elements arbitrarily oriented with respect to the body fixed coordinate frame. A finite series of shape function are used to describe the bending and small twisting motions of the flexible elements. Higher order displacement terms are retained in order to achieve reasonable accuracy for large displacements. The coupling of bending and twisting motions is also simulated. This coupling can be significant when a flexible element has an unsymmetrical cross section.

The equations of motion are derived from variational principles, i.e., the principle of virtual work. The generalized coordinates include the three rotational and three translational degrees of freedom of the body fixed axes and the amplitudes of the shape functions for each flexible element. An additional generalized coordinate is necessary to describe the motions of the libration damper.

Generalized forces were derived and programmed for gravity gradient forces, solar pressure, bending and twisting stresses and structural damping. The induced temperature gradients and solar pressure generalized forces are derived from the instantaneous angle of incidence between the sun line vector and the deformed flexible elements. The temperature gradients are assumed to be developed from a steady state temperature distribution which accounts for the relation between the sun line vector and the overlap or slot if an open cross section element is used.

The equations of motion are transformed into motions with respect to the center of mass. The orbital path of the center of mass is calculated separately in a four body orbit routine which accounts for the gravitational effects of the sun and moon. The orbit routine also calculates the sun line vector and the components of the Earth's magnetic field which are transformed into components in the body fixed coordinate frame. The orbit routine is capable of computing highly elliptical, synchronous or low earth orbits. The effects of aerodynamic drag on the orbit and the flexible motions of a spacecraft is also computed for low altitude orbits.

A special purpose computer program was also developed to compute input data for the IMP Dynamics computer program. This computer program evaluates definite integrals that evolve in the mathematical process of spatially intergrating the internal and external forces acting on the flexible elements of a satellite. The integrals are normalized products of the shape functions and their derivatives evaluated over the flexible elements lengths. For a given shape function, selected to represent the deformed shape of a flexible element, the integrals have to be evaluated only once. The integrals are read into the dynamics program either on cards or compiled into block data. The dynamics simulations can then be made without further recourse to the integral evaluation program. The shape functions are specified by the coefficients of polynominals. For a flexible element with no tip mass, a set of typical shape function used would represent cantilever beam bending modes. Other more appropriate shape functions would be specified for simulating flexible elements with tip masses. The dynamics program can use up to three shape functions or modes in simulation of the deflectional motion of the flexible elements. At times, it is necessary to have different types of flexible elements with different stiffness characteristics on the same spacecraft. The Dynamics program has, therefore, the capability of utilizing two different sets of values as determined by the integral evaluation program for two different families of shape function. An example of the use of this capability would be a spinning spacecraft requiring interlocked closed cross-section elements on the spin axis and utilizing open cross-section elements on the transverse axes.

Reference 3 describes the mathematical formulation that is the basis of the IMP Dynamics Computer program, provides user instructions, flow diagrams of important subroutines and a source listing.

2.0 ANALYSIS OF FLIGHT DATA

2.1 ORBIT

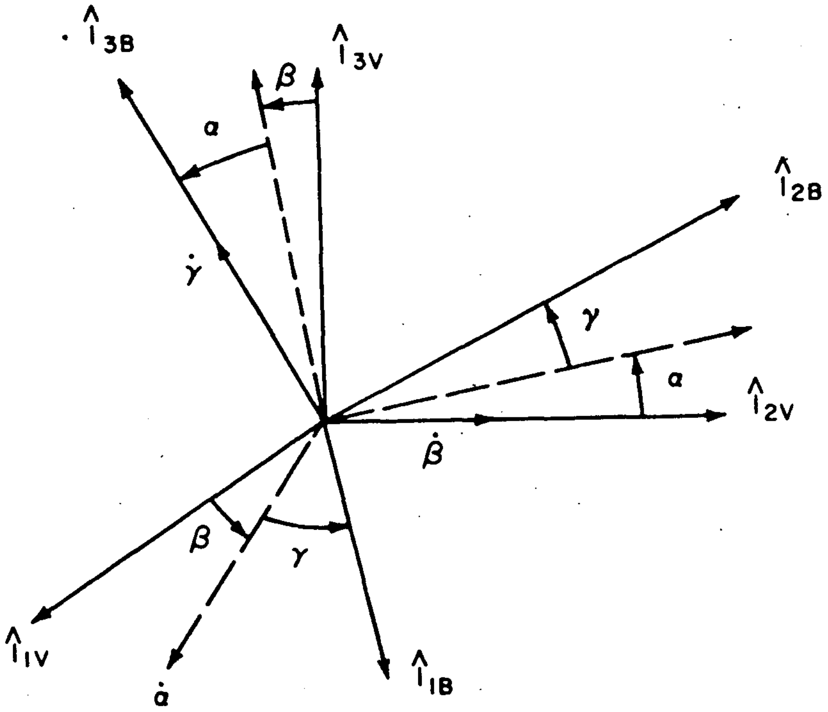
The definitive orbit data used in this study of the RAE-A Satellite were obtained from the Orbit Determination Section at Goddard Space Flight Center. The data were furnished on computer tapes which generally covered a period of two weeks. These data were used as input to the Dynamics Computer programs to define the environment and fields at orbital altitude. These included the gravitational and magnetic field and the components of the sun vector.

No analysis of the effect of errors in the orbital position on spacecraft dynamics was performed since that orbit data has been determined to be accurate to better than 0.5 seconds in a period of one week.

2.2 SPACECRAFT ATTITUDE

Definitive spacecraft attitude data were obtained from the Attitude Determination Office at Goddard Space Flight Center. Spacecraft attitude data for the RAE-A Satellite was derived from measurements made by magnetometers and sun sensors. When received for input to this study, the data had been smoothed and filtered and expressed in engineering units of degrees in pitch, roll and yaw. The definition of these angles and their order of rotation are given in Figure 2.2-1. The pitch, roll and yaw rates were also derived from the basic measurements.

Each file represented a tracking station pass. The attitude data had to be carefully examined prior to being used for comparison with simulated data, since the attitude data were presented on multiple data tapes. At the beginning and end of each file the smoothing and filtering process introduced some errors, particularly in the attitude rates. A singularity in the reduction process also



2-1-3 ROTATION FROM LOCAL VERTICAL FRAME

$\beta - \alpha - \gamma$

$\hat{i}_{1V}$, $\hat{i}_{2V}$, $\hat{i}_{3V}$ UNIT VECTORS, LOCAL VERTICAL FRAME

$\hat{i}_{1B}$, $\hat{i}_{2B}$, $\hat{i}_{3B}$ UNIT VECTORS, SATELLITE BODY FRAME

EULER ANGLES AND EULER RATES
LOCAL VERTICAL - BODY FRAME

79-0131

Figure 2.2-1 EULER ANGLES AND EULER RATES LOCAL VERTICAL - BODY FRAME occurred whenever the magnetic field and the sun vector were either parallel or antiparallel. This singularity could be detected in the data by a rapid change in attitude that would not be physically permissible for a satellite of the RAE configuration. Comparisons of simulated and measured attitude data indicated the possibility of a small amount of bias in roll data. This will be discussed later in Section 4.2.2.

Attitude data was analyzed for the days of July 29 and 30, 1968 and December 2, 1968. These spans of data were selected because of some concurrent antenna boom tip displacement data. Attitude data during other time periods could be analyzed if this study was continued.

2.3 ANTENNA BOOM TIP DEFLECTIONS

Four television cameras were installed in the RAE-A spacecraft to determine the relative displacement of the four antenna boomtips with respect to the central core structure. The cameras were to detect the tip of the antenna booms. The visibility of the tips is enhanced by a lightweight ceramic sphere which diffuses incident sunlight. The location of the boom tip in terms of the position on the vidicon grid was converted to in- and out-of-plane displacement relative to the plane of the undeformed antennas. The conversion process included corrections for optical aberrations and amplifier gain changes.

The vidicon tubes can discriminate four shades of gray. Each television frame requires 13 seconds to record. Four successive frames are recorded from a vidicon and then automatically switched to the adjacent upper or lower vidicon. The operation cycles between the vidicons of either upper or lower pair until commanded to switch to the other pair. Early in the orbital life of the RAE-A satellite, it became apparent that discrimination of the lower antenna boom tip from the Earth's background would not be possible. Data was therefore analyzed only from the upper two vidicons.

The original procedure called for displaying the raw video data on a TV screen. The approximate location of the boom tip target would be indicated by a human operator for subsequent detailed location by a computer. This procedure was not practical since in many instances the tip target could not be readily located because of the noisy picture and reflections from adjacent spacecraft components into the vidicon tube.

The technique was then adopted that utilized a computer printout of the light intensities at the sensitive points on the vidicon screen. There are 240 sensitive positions or dots per vidicon scan line and 252 scan lines. The light intensities were represented by the integers 0, 1, 2 and 3, where 0 represented minimum intensity and 3 maximum intensity. This computer printout was obtained from the Multisatellite Control Center at Goddard Space Flight Center. To reduce the amount of printout, scan lines with no intensity greater than zero were omitted.

The vidicon reticle and antenna boom tip target addresses were located from this data and punched on cards for subsequent creation of a TV data tape. This data tape was used as input to the VIDCOR subroutine of the RAE-IOS computer program (ref. 2). The output of the subroutine was the time history of the in- and out-of-plane antenna tip displacements. The output included both the directly computed displacements and smoothed and filtered data.

Reduced video data sets were obtained for the antenna aspect measurements made during the period from November, 1968 to May, 1969 when the antenna boom lengths were nominally 750 feet. The data spans for each data set varied from two to ten minutes. The dates and times for the data received are given in Table 2.3-1. Only data for the #2 antenna was useful because of a malfunction that occurred in the #1 boom TV camera.

The reduced antenna boom tip displacements data is given in Figure 2.3-1, -2, -3 and -4. Since the data is not continuous, it was necessary to specify the year, month, day, hour and minute for each set of data. It should be noted that the period of time between data sets varies from days to weeks when the reader is observing the plotted data.

The reduced data indicates that the in-plane #2 antenna tip displacements vary between -160 and -82 feet and the out-of-plane tip displacements between -30 and +6 feet. The sign convention for antenna tip motions is given in Figure 2.3-5. The in-plane tip displacements appear to be periodic or at least vary between the maximums and minimums indicated by the available data. The out-of-plane displacements appear to have an overall decreasingly negative trend and even become slightly positive during May, 1969. The out-of-plane deflection appears to be in response to solar effects. An attempt was made to fit the simulated data to this boom tip data, but the results were not meaningful because the data is so sparse. It is quite possible that the trend observed in the out-of-plane tip displacements is merely coincidental because of the many factors involved, such as the frequencies of antenna motion, the particular latitude of the tracking stations which received data and the change of the sunline components with the yaw motions of the satellite.

#2 ANTENNA BOOM TIP DISPLACEMENTS

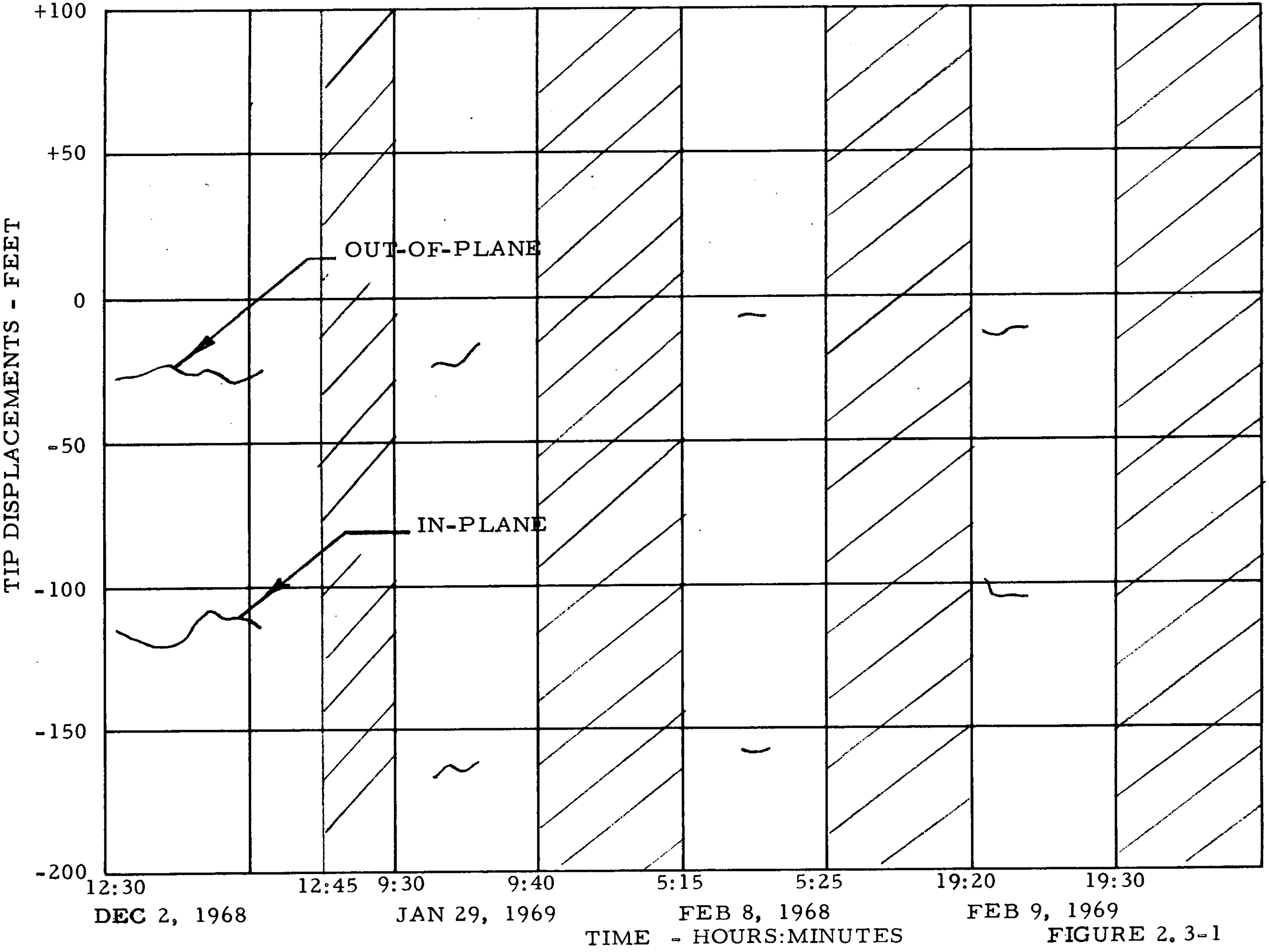


FIGURE 2.3-1

#2 ANTENNA BOOM TIP DISPLACEMENTS

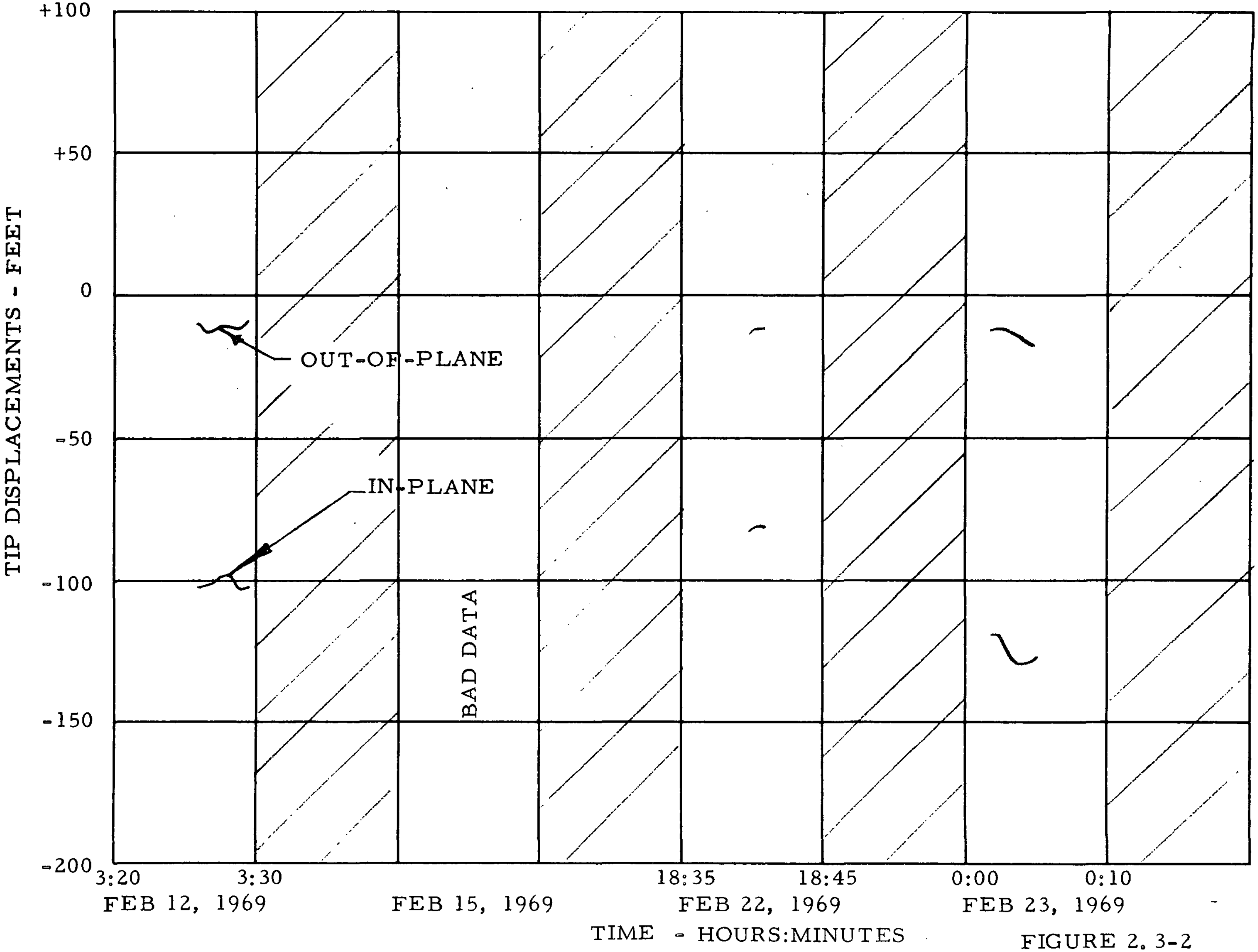


FIGURE 2. 3-2

#2 ANTENNA BOOM TIP DISPLACEMENTS

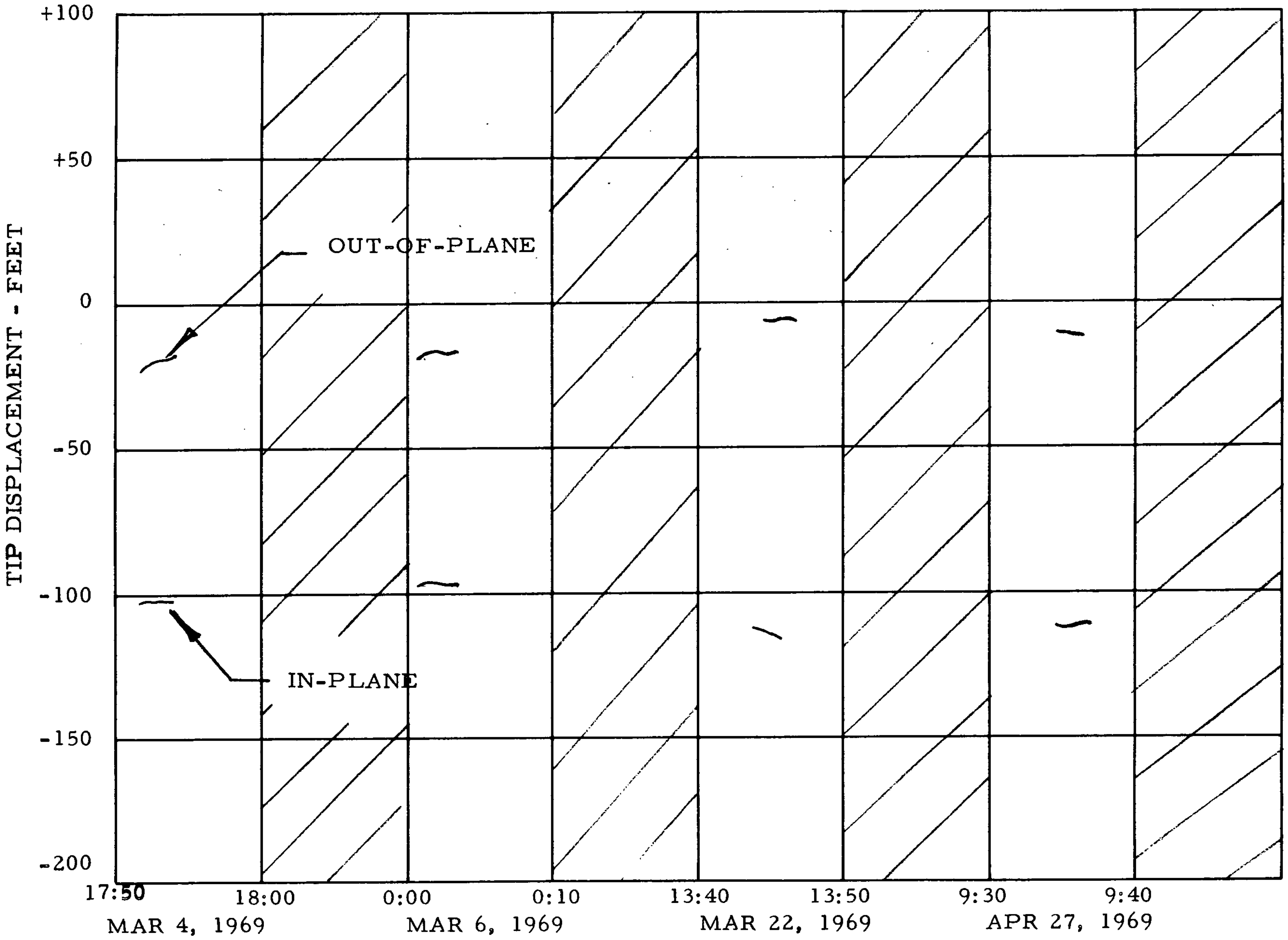


FIGURE 2. 3-3

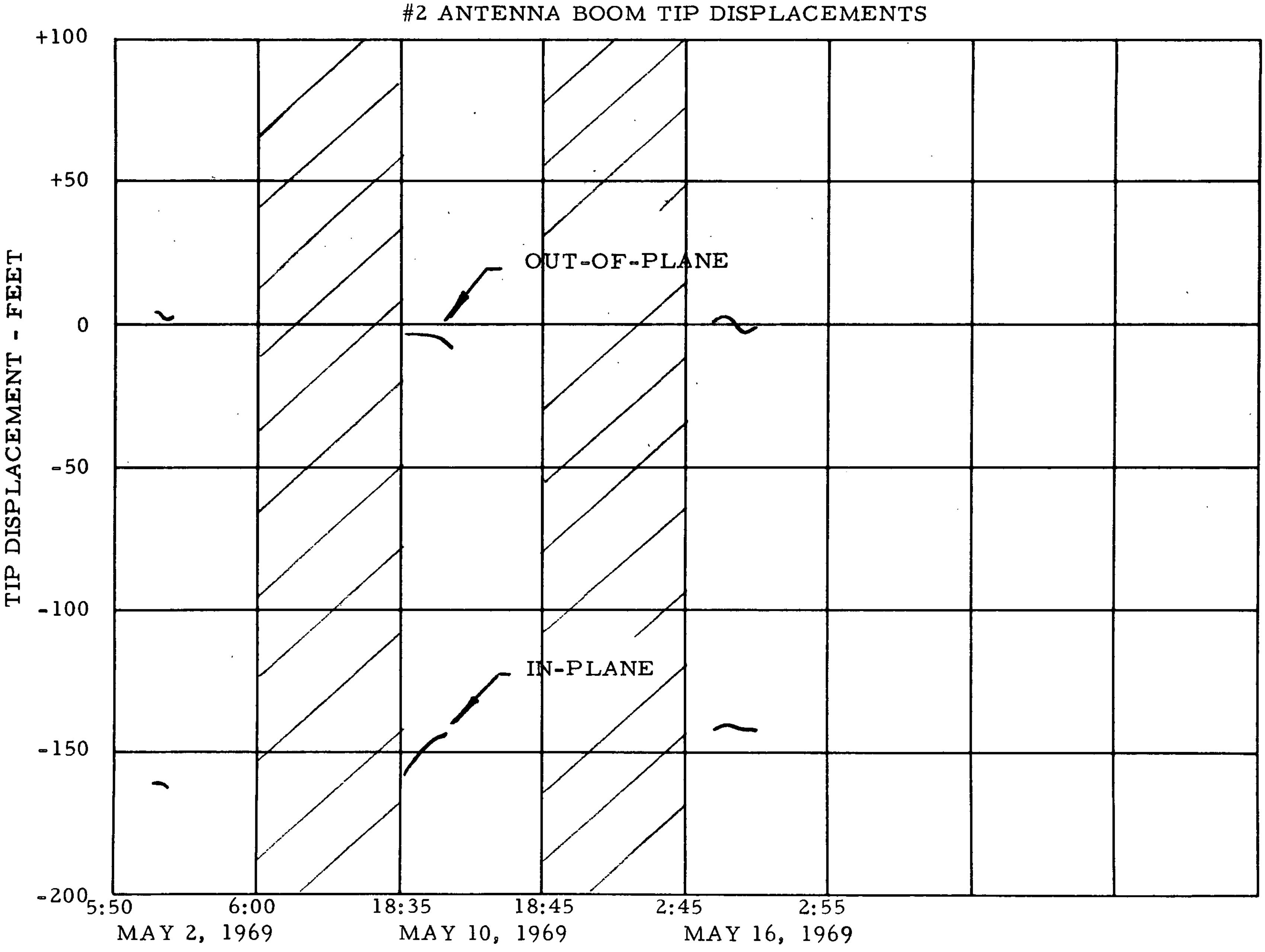
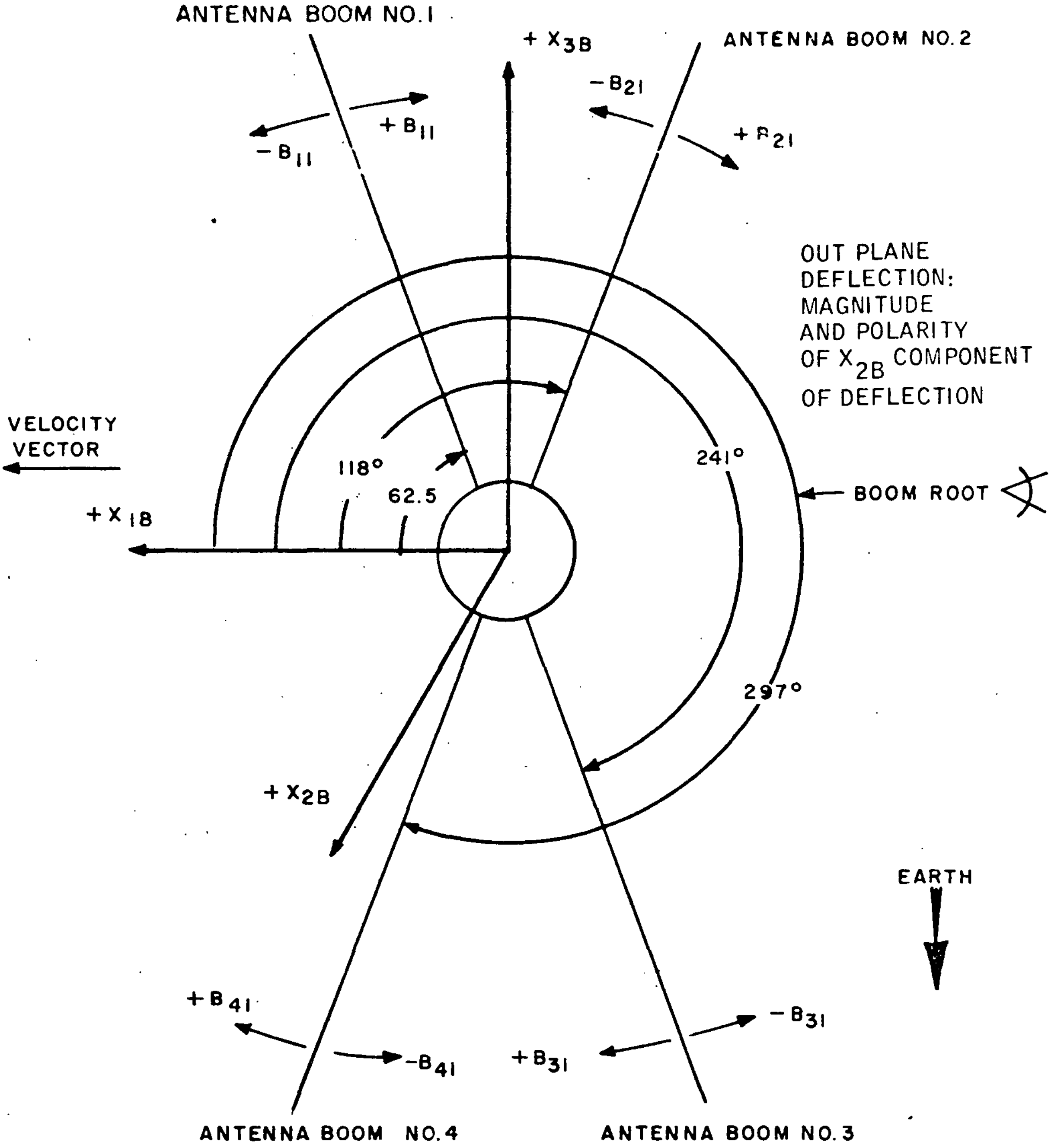

#2 ANTENNA BOOM TIP DISPLACEMENTS

FIGURE 2. 3-4

Table 2.3-1

VIDEO DATA RECORDS - ANTENNA #2

		Time	
Tracking Station	Date	From	To
Tananarive	Dec. 2, 1968	12:30:52	12:41:47
Rosman	Jan. 29, 1969	09:33:07	09:36:24
Rosman	Feb. 8, 1969	05:19:41	05:21:26
Tananarive	Feb. 9, 1969	19:21:08	19:24:24
Santiago	Feb. 12, 1969	03:26:53	03:30:24
Johannesburg	Feb. 15, 1969	10:57:20	11:00:24
Lima	Feb. 22, 1969	18:40:28	18:42:41
Johannesburg	Feb. 23, 1969	20:02:08	22:05:24
Santiago	Mar. 4, 1969	17:52:21	17:54:06
Johannesburg	Mar. 6, 1969	11:01:37	11:04:54
Rosman	Apr. 22, 1969	13:45:26	13:47:10
Rosman	Apr. 27, 1969	09:35:39	09:37:24
Rosman	May 2, 1969	05:53:52	05:54:05
Rosman	May 10, 1969	08:53:52	05:54:05
Rosman	May 16, 1969	02:47:07	02:50:10



X_{1B}, X_{2B}, X_{3B} = BODY AXES

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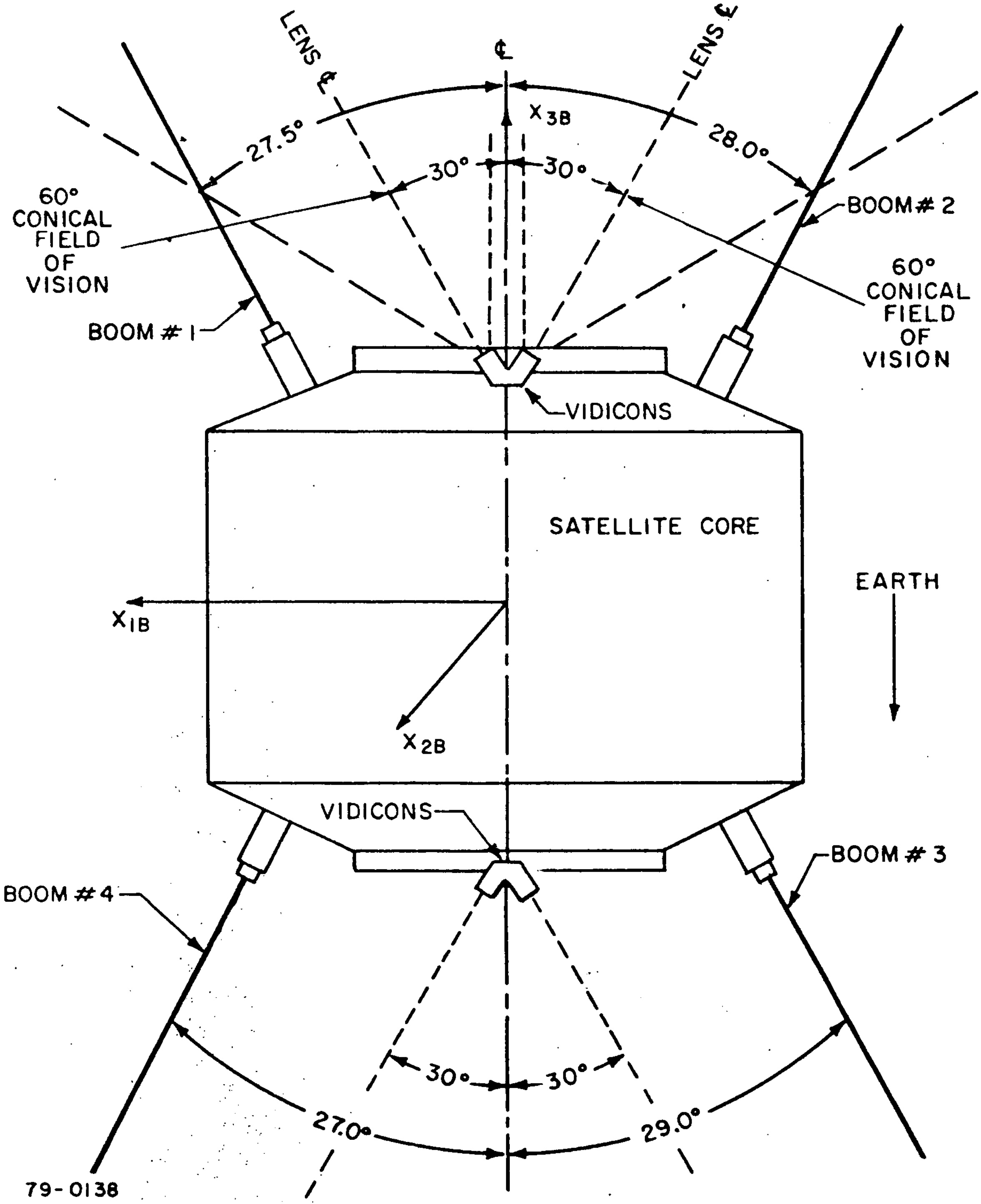
POLARITY OF TIP DEFLECTION

Figure 2.3-5



ASPECT CAMERA

Figure 2.3-6

The out-of-plane tip displacements are also affected by the gravity gradient forces because of the offset of the equilibrium yaw angle from the orbital plane. As a result, the displacement of the #2 antenna would be biased in the negative direction and the #1 antenna be biased in the positive direction.

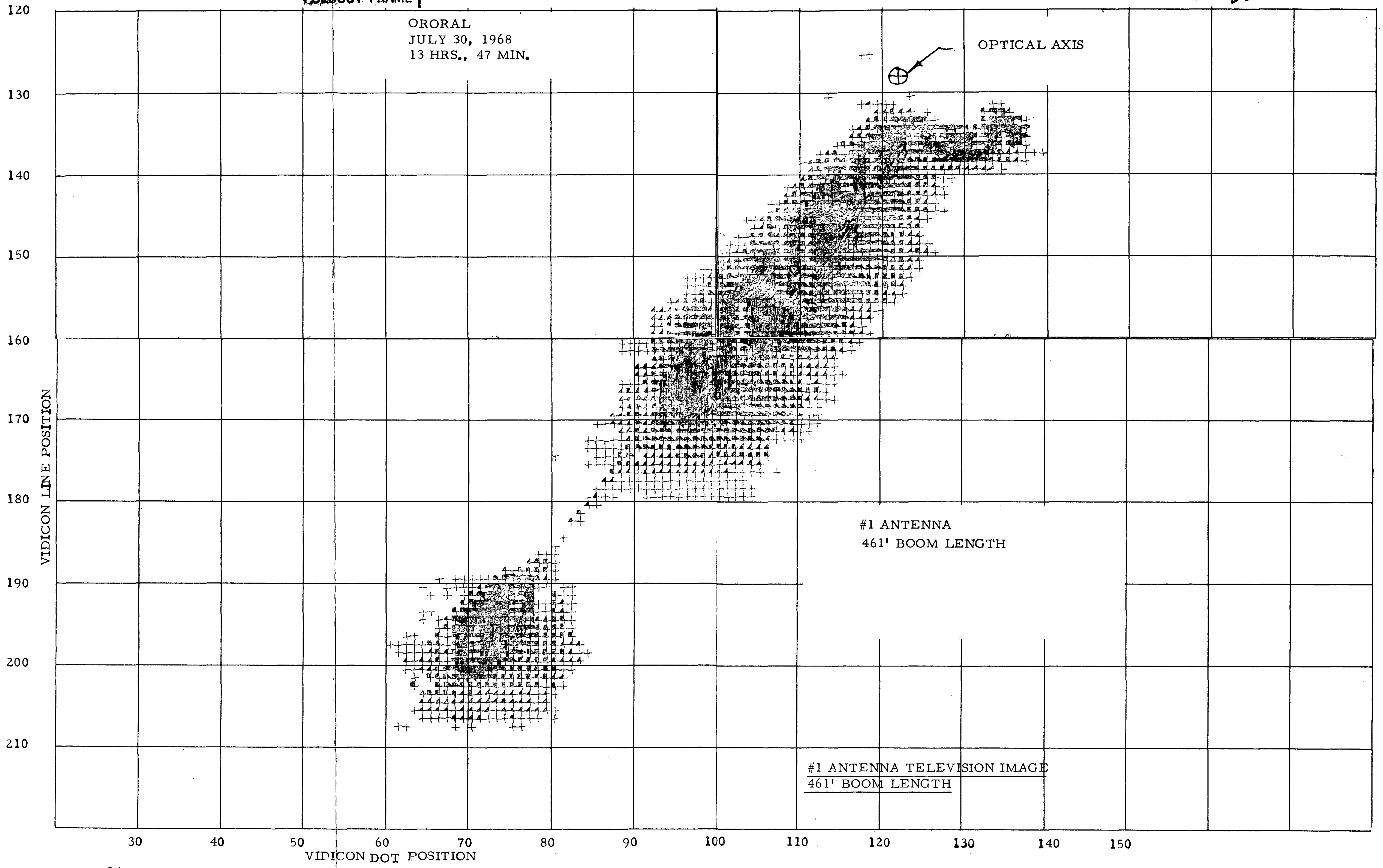
As shown in Figure 2.3-6, the optical axes of the vidicon are parallel to the axes of the undeformed antenna booms when antennas are located at a nominal angle of 30° from the number 3 body axis. Pre-flight ground measurements of these angles indicated deviations from nominal. As shown in Figure 2.3-6, the root angles for number 1 and number 2 antennas were determined to be 27.5° and 28.0° respectively. The video data reduction process was adjusted to accommodate these angular deviations since a 1° error of the optical axis relative to the antenna boom axis causes approximately a 13 foot error in the boom tip displacement data for 750' long booms.

Typical pictures of the #1 and #2 antenna booms, as viewed by the respective vidicons, are shown in Figures 2.3-7 and 2.3-8. The vidicons are offset approximately one foot along the +2 body axis. Because of the offset, the antennas will appear to extend from the lower left hand or right hand corner from the #1 and #2 antenna respectively. If the antennas were undeformed, their tips would be located approximately at the center of the vidicon screen. The polarity of displacement is given in Figure 2.3-5.

The pictures shown in Figures 2.3-7 and 2.3-8 were obtained by superimposing four sequential TV frames. The diameter of the antenna boom at the root appears to be much greater than its actual value. This is probably due to the sun's reflection from the polished silver surface saturating the vidicon tube.

~~FOLDOUT~~ FOLDOUT FRAME 1

FOLDOUT FRAME 2

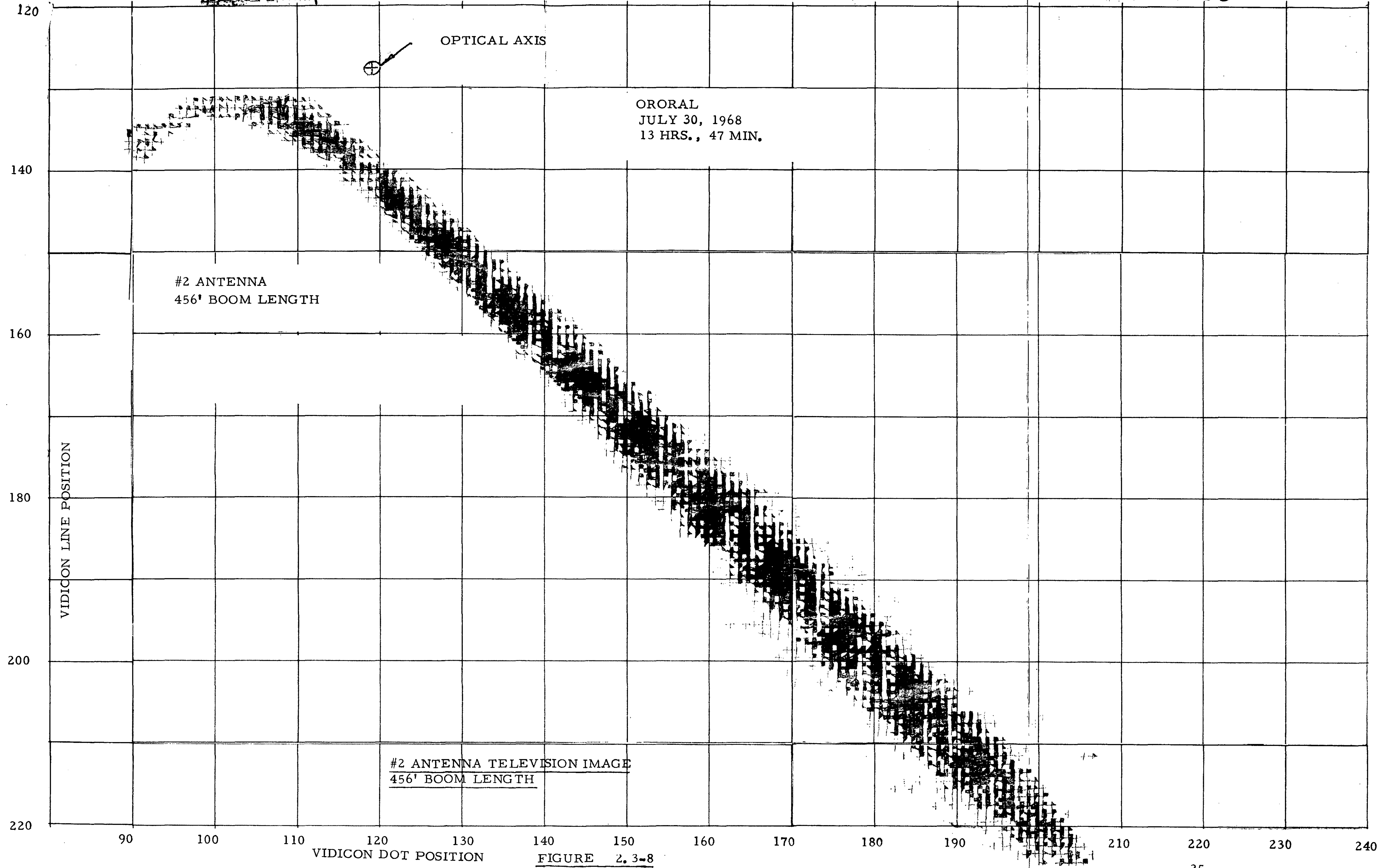


#1 ANTENNA TELEVISION IMAGE
461' BOOM LENGTH

FIGURE 2.3-7

FOLDOUT FRAME 1

FOLDOUT FRAME 2



#2 ANTENNA TELEVISION IMAGE
456' BOOM LENGTH

FIGURE 2.3-8

While it is difficult to determine the actual shape of the antennas, it is worth noting that the shape of the #1 antenna appears to be anomalous. The antenna boom, if deformed into an approximate cantilever bending shape, would have a relatively continuous curvature or at least would not reverse curvature as seen in Figure 2. 3-7. This can be seen in Figure 2. 3-8 and also Figure 2. 3-9 which shows the #2 antenna at a 750 foot length. The #1 antenna seems to have a reversal of curvature which could be caused by a spiraling of the deployed boom. Because of the extreme parallax condition of the vidicon with respect to the antenna, it would be very difficult to determine at what length the anomalous shape of the antenna occurs. It should be noted however that, as shown in Section 4. 1, the deflections of the #1 antenna were more difficult to fit than the #2 antenna when using a mathematical model which assumed cantilever mode shapes and a closed circular cross-section.

FOLDOUT FRAME 1

FOLDOUT FRAME 2

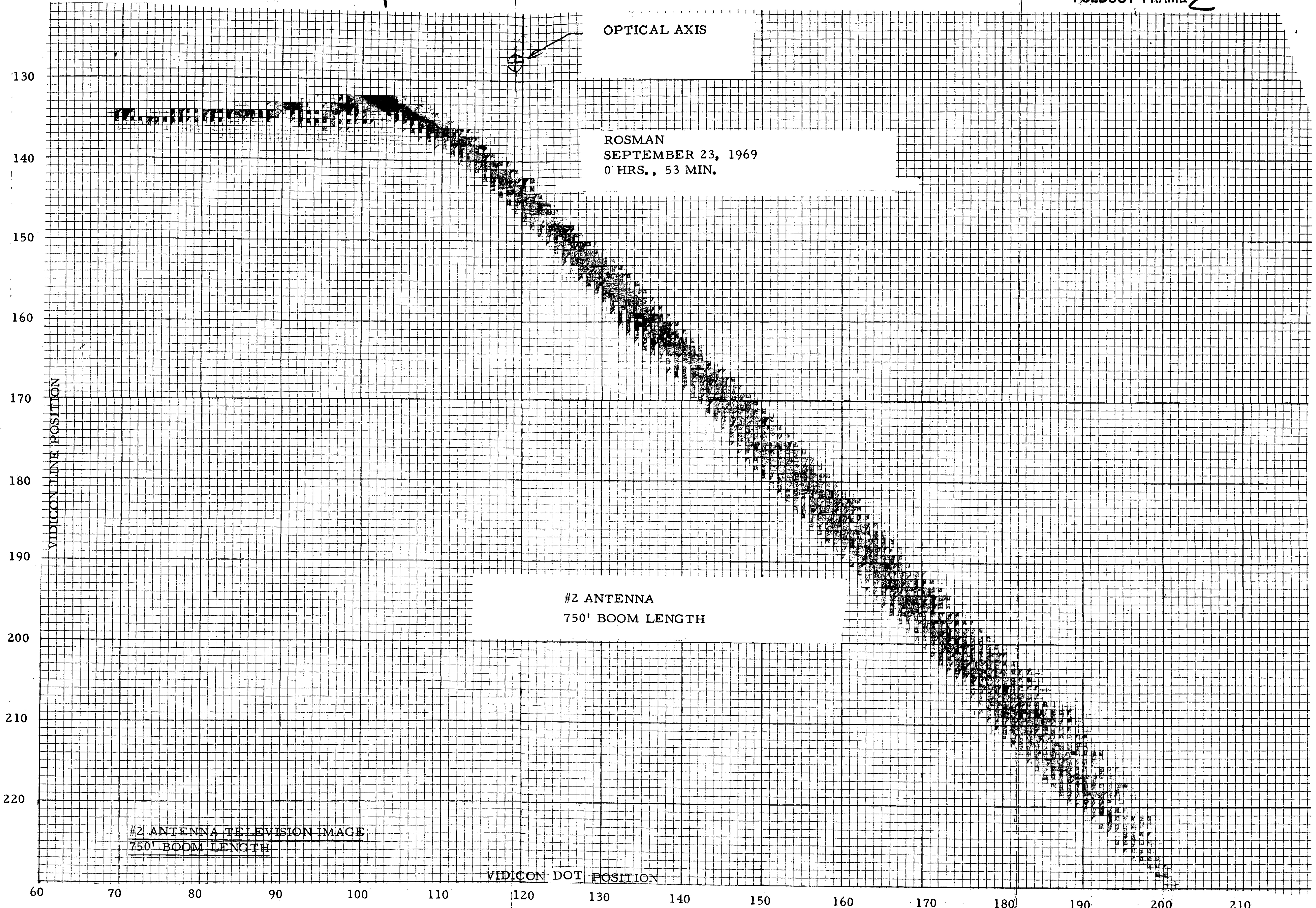


FIGURE 2.3-8

3.0 SIGNIFICANT VARIABLES

3.1 SPACECRAFT PHYSICAL PARAMETERS

The dynamic motions of the RAE-A spacecraft are influenced by a large number of variables. Certain of these variables were more significant with respect to their influence on the dynamic behavior. These parameters were varied in an attempt to improve the fit of the computer simulation to the flight data. It is the purpose of this section to define these variables which are referred to in the later sections.

One of the most significant variables is the stiffness of the antenna booms. The stiffness of an antenna boom is normally expressed as the product of Young's Modulus times the area moment of inertia or EI. This measure of stiffness is only valid if the cross section of the thin-walled tube is closed, i. e., for a simple bending deformation, there will be a linear distribution of stress across the boom.

The theoretical stiffness for the RAE-A booms is 3010 lb-in^2 considering a tube radius of .2935 in., wall thickness of .002 in. and a Young's Modulus of 19 x 10^6 psi for the beryllium copper material. The pre-flight ground measured value for stiffness was 2100 lb-in^2. Even taking into account the presence of perforations, this is a significant reduction from the theoretical value. As will be shown in Section 4, an even lower value for boom stiffness will improve the fit of simulated data. Since E is a material property that is independent of structural configuration and I is property that is fixed by geometry, the indications are that the boom is not behaving simply as a circular cylindrical tube. Over a limited span of boom tip deflection data, it appears that a better simulation can be obtained if there is some coupling between bending and twisting.

Although EI will be varied as a parameter in this study, it is obviously not being used as it normally would be used in a structural problem.

As mentioned previously in Section 1.1, the antenna boom root angles, i.e., the angle between the antenna boom as it emerges from the deployment mechanism and the #1 body axis, has a significant effect on spacecraft motions. The influence manifests itself in the effect on the overall spacecraft configuration, hence the overall moments of inertia.

Root angle measurements were made on the flight hardware and were used for the reference values during deployment operations. The studies performed here indicate the possibility of smaller values for the root angles. These variations are quite possible since it would be difficult to obtain accurate ground measurement for a long antenna length due to the influence of the sea level gravity field.

The angle between the plane of the damper boom motion and the #1 body axis also has a significant effect on the dynamic behavior. This pre-flight ground measurement indicated the angle to be 66.5°. Analysis of data after deployment indicated that a value of 63.5° produced a markedly improved fit of simulated data. This trend was confirmed in this study for using both the RAE and IMP simulation computer programs.

Other spacecraft variables which could be accurately determined by ground measurements or were not varied in this study are given in Table 4.0-2. All of these parameters are necessary, however, to simulate accurately the RAE-A dynamic behavior.

3.2 ORBITAL ENVIRONMENT

The dominating environmental parameter that influences the behavior of the RAE-A satellite is the gravity field, or more specifically the gravity gradient with respect to the center of mass of the satellite. The gravity gradient model used in the dynamics mathematical models is rotationally symmetric with respect to the axis of the Earth, but includes the second spherical harmonic to account for the Earth's oblateness. A comparison of dynamic motions with and without the effect of the Earth's oblateness showed however, that the Earth's oblateness was a very negligible factor in determining the spacecraft's dynamics, i.e., less than 1% difference in the elements of the state vector.

The temperature gradient across the antenna booms induced by solar radiation was the next in the order of importance of environmental factors affecting the spacecraft performance. It was, however, far less important than the gravity gradient as will be shown in Section 4.0. The temperature gradient as used in this report refers to the gradient induced when the sun line unit vector is normal to the axis of the undeformed boom. This temperature gradient is modified to account for the instantaneous angle of incidence as determined by the spacecraft attitude motions and the deformed state of the antenna booms. The variation of magnitude is related to the angle of incidence by a cosine function.

Solar radiation pressure contributes a negligible effect to the spacecraft motions at least for the periods of time studied. These periods spanned at the most 16 hours. For all practical purposes in this study it could be neglected.

Solar pressure could have a long term effect on the satellite orbit and dynamics, but it was not discernible over the periods studied.

Aerodynamic drag at the 6000 km attitude circular orbit was essentially zero and was not considered in this study.

The effects of a residual magnetic dipole moment were not considered in the study. All materials have residual magnetism would reside in the satellite central core structure. As was shown in an earlier study, even the magnetorquer control system would be ineffective after the antenna booms were extended past 20 feet. The residual dipole moments would have torques orders of magnitude less than the magnetorquer system.

3.3 SPACECRAFT STATE VECTOR

If the RAE-A spacecraft is simulated using the first cantilever mode for the antennas and libration damper booms, the spacecraft state vector has a total of 32 independent components. These components include the generalized coordinates and rates associated with the central core attitude, in and out of plane displacement of the four antenna booms and two damper booms and the damper aspect angle. When the spacecraft was in the 450 foot configuration, the central core attitude rates were the most significant variables. The in-plane antenna tip displacements were less dominant providing they were symmetrical with respect to the central core. At the 750 foot boom length, the antenna boom displacement initial displacements had a more significant effect on overall spacecraft motions. It was not possible to fit the spacecraft attitude motions precisely by simply starting the antennas in a symmetrical configuration. An improved fit was obtained, however, by performing permutations on the antenna's initial conditions.

Antenna velocities were not important factors in fitting simulated data to flight data providing the magnitude was less than 1×10^{-2} ft/sec. Tip velocities greater than this value would tend to degrade the correlation of simulated and measured data.

The initial value of the libration damper aspect angle was specified between 2° and 4° for all simulation runs. The computed time history of the aspect angle never exceeded this range for the subsequent computer simulations.

The initial conditions for the libration damper boom tips, when they were considered to be flexible in computer simulation runs, were always set at zero. Since there was no direct measurement of tip motions on the actual spacecraft, it would only be possible to determine the influence of libration damper boom tip displacement initial conditions by observing their effect on the fit of central core attitude data. This study was not pursued due to limitations in time and the belief that other parameters were more significant.

4.0 ANALYSIS OF THE 450 FOOT SPACECRAFT CONFIGURATION

The analysis of the spacecraft flight data consisted of collecting available flight data from the appropriate sources at Goddard Space Flight Center, processing the data into form suitable for input and comparison with the dynamics mathematical models, performing numerous computer simulation runs and subsequent interpretation of the resulting data.

The antenna boom lengths used in the dynamics study were not precisely 450 feet due to different boom deployment rates and the finite time required to command starting and stopping of the deployment motors.

The calibrated boom lengths are given in Table 4.0-1 below.

Table 4.0-1

BOOM LENGTHS

	Length - feet
Antenna #1	461.0
Antenna #2	455.8
Antenna #3	447.1
Antenna #4	449.4
Libration Damper	276.0 (center to tip)

All the other spacecraft physical parameters are defined in Table 4.0-2.

4.1 ANALYSIS OF ANTENNA BOOM TIP DISPLACEMENT DATA

4.1.1 RAE Dynamics Simulation and Optimization

The longest span of compatible attitude and antenna boom tip displacement data was available from 1433 to 1445 on July 30, 1968, while continuous attitude data existed for a longer period.

The search technique developed for optimizing the parameters of the RAE Dynamics Simulator was used in an attempt to improve the fit of the simulation. The principal parameters varied were the antenna boom effective stiffness and temperature gradient. The optimization procedure which is described in detail in Reference 1 is a direct search technique which searches for the minimum performance criteria or error in N dimensional parameter space.

The optimization computer program has four options for constructing the performance criterion from the simulated and measured flight data. The options are time integrated algebraic differences, 2) weighted and normalized algebraic differences, 3) squared differences and 4) weighted and normalized squares of the differences. The option 4 was chosen for this study. The differences between corresponding measured and simulated variables are normalized with respect to the measured parameter unless the measured parameter approached zero. In this situation the measured variable is replaced by a small but finite number. The variables that were utilized in the performance criterion are the pitch, roll and yaw angles, the damper aspect angle and the in and out-of-plane displacements of antenna boom tips. If a variable is missing or there are gaps in the data, the differencing procedure for that variable is blanked out over the appropriate time span.

The weighting for each variable is controlled by input and determines the relative influence of a particular variable in performance criterion and hence in the optimization. The boom tip displacements were weighted more than the attitude data in order to produce steeper peaks and valleys in the performance criterion surface than would occur if the relatively insensitive parameter such as pitch and roll data were equally weighted.

Table 4.0-2

PHYSICAL PROPERTIES OF THE RAE SATELLITE
(Ground Measured Values)

Libration Damper

Damper Boom

Mass/unit length	$.436 \times 10^{-3}$	slug/ft
Effective Stiffness	2420	lbs.-in^2
Radius of tube	.2935	in
Tube wall thickness	0.002	in
Coefficient of thermal expansion	9.3×10^{-6}	in/in$^{\circ}$F
Damping coefficient	0.0	
Projected area/unit length	4.9×10^{-2}	ft^2/ft

Damper Mechanism

Torsional spring constant	1.015×10^{-2}	ft-lbs/deg
Saturation moment for hysteresis damper	1.02×10^{-3}	ft-lbs
Angle between plane of damper boom motion and number one body axis	66.5	degrees
Positive vector of origin of damper mechanism with respect to central core body axis	0.0 0.0 0.0	ft
Inertia matrix of damper mechanism	1.0 0.0 0.0 0.0 1.0 0.0 0.0 0.0 1.0	slug/ft^2
Expotential decay factor for hysteresis	77.0	N.D.

Antenna Booms

Mass/unit length	$.436 \times 10^{-3}$	slug/ft
Effective stiffness	2100	lb-in^2
Radius of tube	.2935	in
Tube wall thickness	.002	in
Coefficient of thermal expansion	9.3×10^{-6}	in/in$^{\circ}$F
Damping coefficient	0.0	
Projected area/unit length	4.9×10^{-2}	ft^2/ft
Undeformed axis of antennas with respect to central core axis in pitch plane		
#1 Antenna	62.5	Degrees
#2 Antenna	118.0	Degrees
#3 Antenna	241.0	Degrees
#4 Antenna	297.0	Degrees

Physical Properties of the RAE Satellite (cont'd)

Central Core

Moment of inertia matrix	15.0	0.0	0.0	slug-ft^2
	0.0	87.9	0.0	
	0.0	0.0	90.3	
Cross-sectional area	14.6			ft^2
Total mass of satellite	13.097			slugs

The direct search technique used for optimization consists of cycling the dynamics simulation over the time span of available flight data. In each cycle, the parameters to be optimized are either increased or decreased depending on the results of the last cycle, i. e., whether the performance criterion has increased or decreased.

Generally, for a 20-minute span of data used in this optimization study, 100 trials will require about 10 minutes of IBM 360-91 computer time.

The results of attempts to optimize the temperature gradient and antenna boom stiffness are shown in Figure 4.1-1. Note that the simulated in-and out-of-plane displacement for the #2 antenna are reasonably close to the measured data. The #1 antenna simulation data shows a considerable deviation, however. Considerable effort was consequentially devoted to determining the reasons for these discrepancies.

The stiffness and temperature gradients as obtained from this optimization are 1610 lb-in^2 and .58 F^o respectively. The search was terminated after 57 trials by the program logic which determines whether a minimum has been reached for the performance criteria.

The nominal spacecraft physical parameters used in computer runs described in the subsequent sections are given in Table 4.0-2. Variations from this table are made for specific parameters as noted in the individual runs.

The integrated error for tip displacements normalized with respect to the #2 in-plane displacements is given in Table 4.1-1. The terminology u_{ij} will be used in the following discussion to define tip displacements, i. e., subscript i refers to antenna boom number and j=1 is out-of-plane and j-2 is in=plane displacements.

Table 4.1-1 - Relative Integrated Error

Displacement	Error
u_{11}	16.6
u_{12}	5.25
u_{21}	5.17
u_{22}	1.0

Obviously, there is a large error in the u_{11} displacement. This error could be 1) the measurement of tip displacement by the vidicon is incorrect or 2) the mathematical model used to simulate the flight data is incorrect. Errors in measurements of tip displacements could be due to uncertainties in the relative angle between the vidicon optical axis or mistakes in the data reduction process. Ground measurements did not indicate out-of-plane error in the boom mechanism. Greater errors could be expected in the in-plane angular measurements however since the seams of the zippered booms were in the plane of the antennas. The reduction process was checked many times and is believed to be error free.

The mathematical model assumes that the antenna booms are closed circular elements and the deformation shape is primarily the first cantilever bending mode. Examination of the television frame for the #1 antenna, Figure 2.3-7, shows an anomalus deformed shape particularly when compared to the #2 antenna both at 450 and 750 foot lengths. This peculiar shape persisted through all television frames that were observed for the #1 antenna.

The studies described in Section 4.1-2 show that, when coupling of bending and twisting is introduced into the antenna simulation, a considerable improvement is gained in fitting antenna displacement data.

It should be noted that the results of the optimization study given above are believed to be a true minimum rather than a relative minimum. Searches were started with different initial guesses for the parameters, but the optimal values always were approximately the same. All results given in later section were also checked in this manner.

Since the weighting of the variables making up the performance criterion could be changed by input to the optimization computer program, it was possible to determine what values of stiffness and temperature gradient would best fit a single antenna or even a particular displacement, i. e., in- or out-of-plane. The results of weighting the displacements variables independently showed however that a single set of stiffness and temperature gradient values was not applicable to both antenna booms. Unfortunately, displacement data was not available for the lower two antenna booms; therefore, no conclusion could be drawn for them. The results for the upper antennas are summarized below:

1. $u_{2,1}$ and $u_{2,2}$ weighted equally in performance criterion. Optimum effective stiffness and temperature gradient are 1550 lb-in^2 and .44°F respectively. See Figure 4.1-2.
2. $u_{1,1}$ and $u_{1,2}$ weighted equally. Optimum effective stiffness and temperature gradient are 2840 lb-in^2 and 1.58°F respectively. See Figure 4.1-3.
3. $u_{1,2}$ greatest weight in performance criterion. Optimum effective stiffness 1352 lb-in^2, optimum temperature gradient 0.80°F. See Figure 4.1-4.
4. $u_{1,1}$ greatest weight in performance criterion. Optimum stiffness 2290 lb-in^2, optimum temperature gradient .975°F. See Figure 4.1-5.

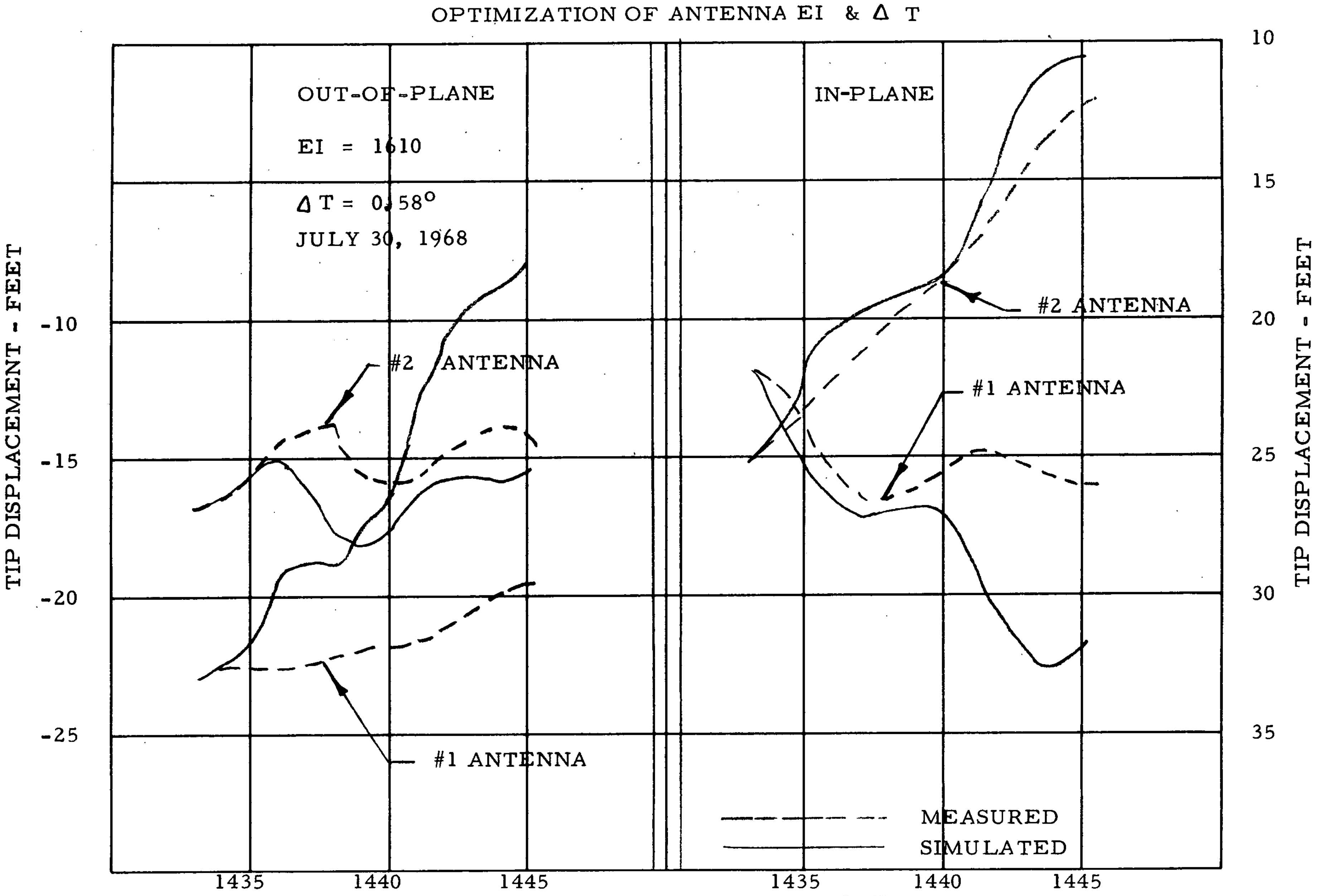

OPTIMIZATION OF ANTENNA EI & Δ T
OUT-OF-PLANE
EI = 1610
Δ T = 0.58°
JULY 30, 1968
#2 ANTENNA
#1 ANTENNA
-10
-15
-20
-25
TIP DISPLACEMENT - FEET
1435
1440
1445
TIME - HR : MIN
IN-PLANE
#2 ANTENNA
#1 ANTENNA
10
15
20
25
30
35
TIP DISPLACEMENT - FEET
1435
1440
1445
TIME - HR : MIN
MEASURED
SIMULATED

FIGURE 4.1-1

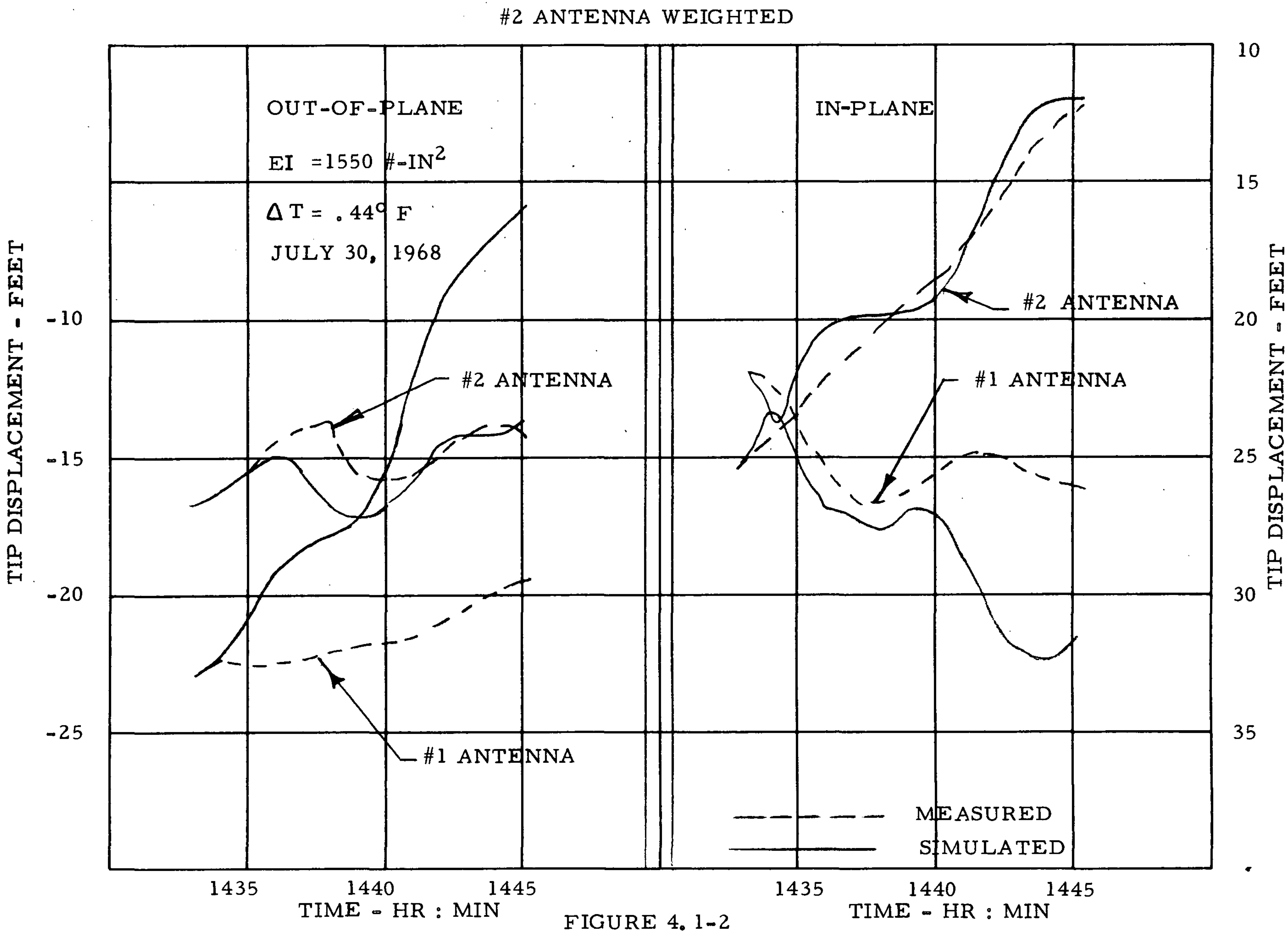

#2 ANTENNA WEIGHTED
OUT-OF-PLANE
EI =1550 #-IN²
ΔT = .44° F
JULY 30, 1968
IN-PLANE
#2 ANTENNA
#1 ANTENNA
#2 ANTENNA
#1 ANTENNA
MEASURED
SIMULATED
TIP DISPLACEMENT - FEET
-10
-15
-20
-25
TIP DISPLACEMENT - FEET
10
15
20
25
30
35
1435
1440
1445
TIME - HR : MIN
1435
1440
1445
TIME - HR : MIN

FIGURE 4.1-2

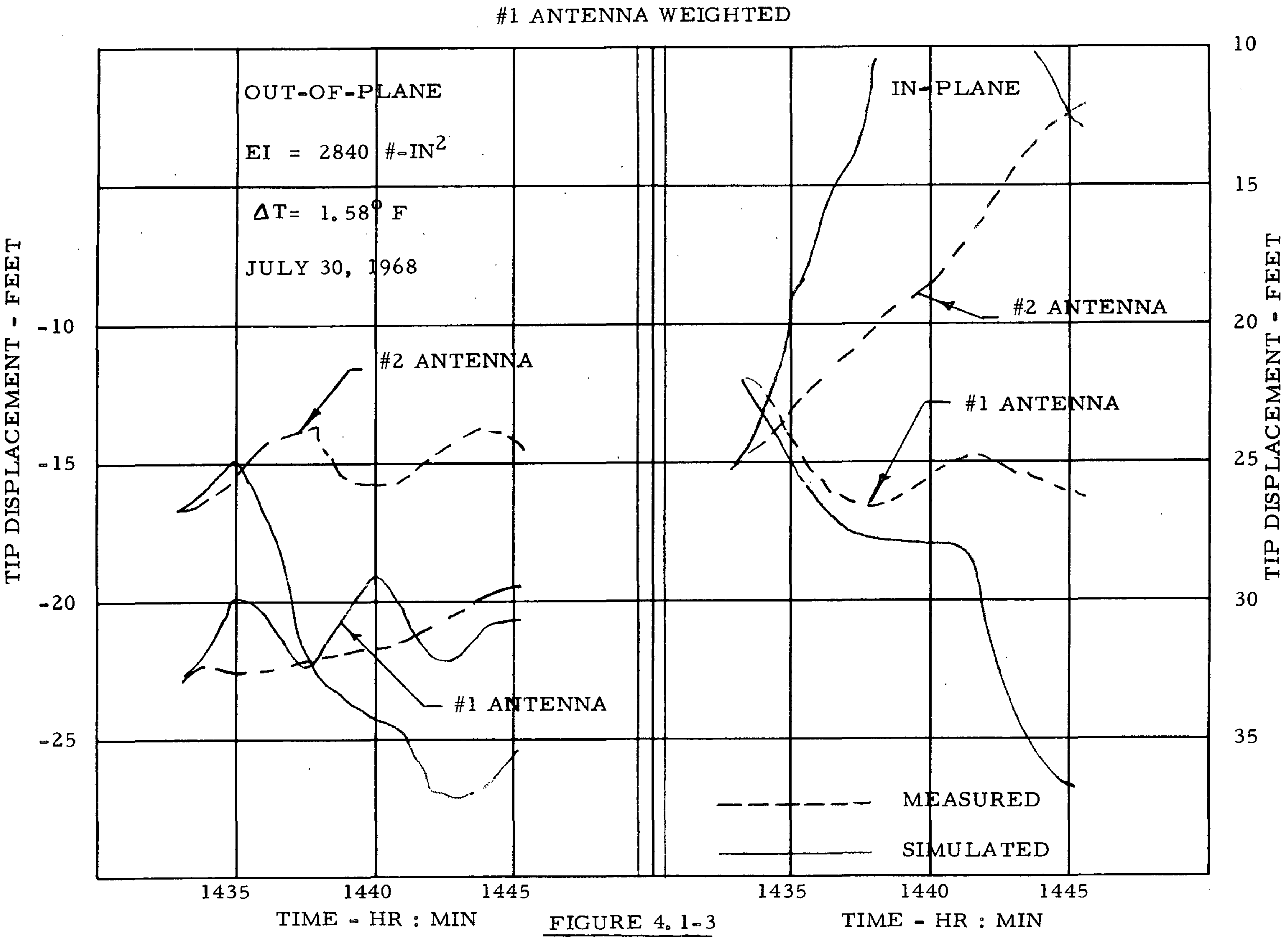

#1 ANTENNA WEIGHTED
OUT-OF-PLANE
EI = 2840 #-IN^2
ΔT= 1.58° F
JULY 30, 1968
#2 ANTENNA
#1 ANTENNA
TIP DISPLACEMENT - FEET
-10
-15
-20
-25
1435
1440
1445
TIME - HR : MIN
IN-PLANE
#2 ANTENNA
#1 ANTENNA
MEASURED
SIMULATED
10
15
20
25
30
35
TIP DISPLACEMENT - FEET
1435
1440
1445
TIME - HR : MIN

FIGURE 4.1-3

#1 ANTENNA, OUT-OF-PLANE WEIGHTED

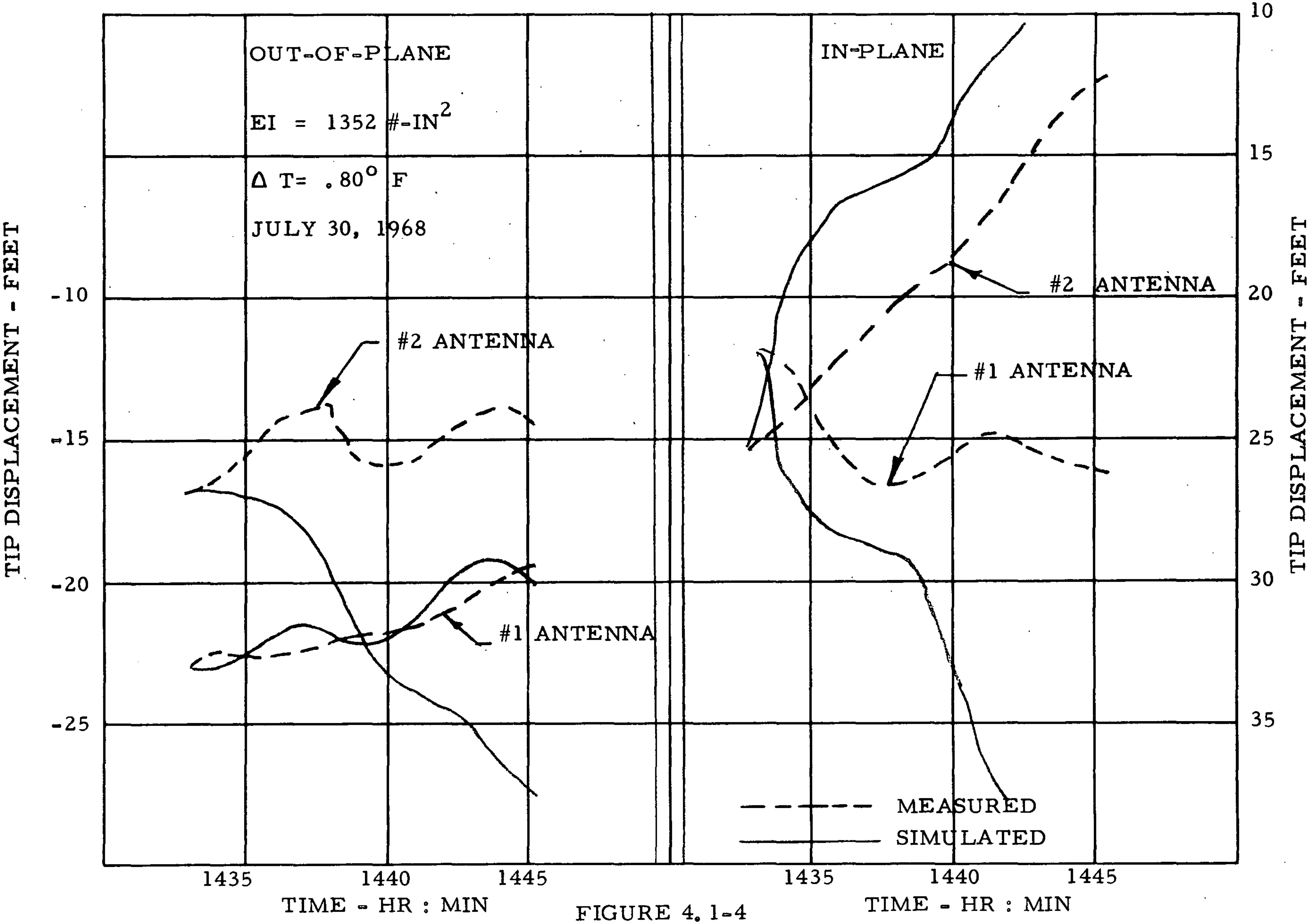


FIGURE 4.1-4

#1 ANTENNA, IN-PLANE WEIGHTED

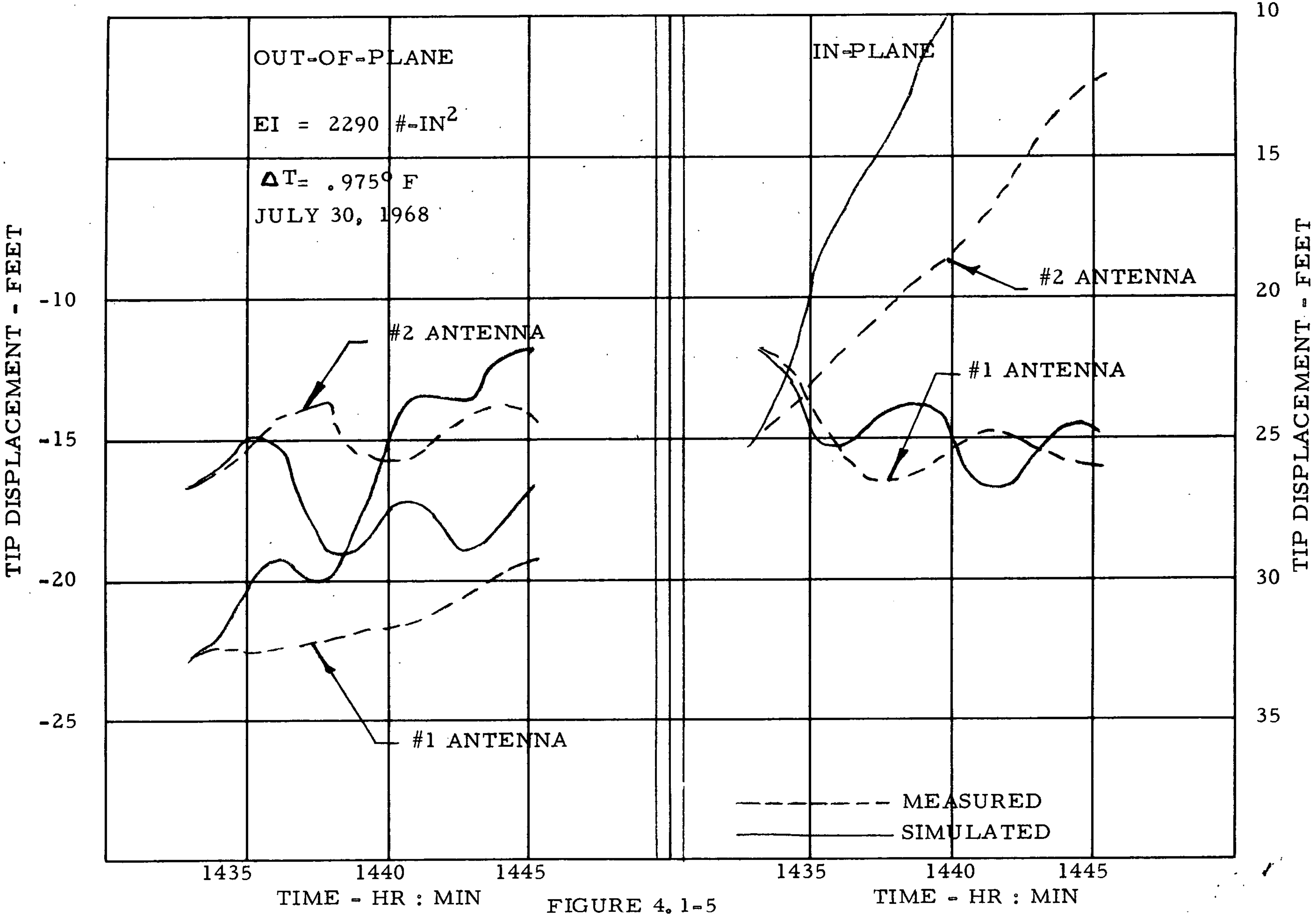


FIGURE 4.1-5

As can be seen in Figure 4.1-1 and Figure 4.1-2, the fit of simulated data is the best for $u_{2,1}$ and $u_{2,2}$ whether $u_{1,1}$, $u_{1,2}$, $u_{2,1}$ and $u_{2,2}$ are equally weighted or $u_{2,1}$ and $u_{2,2}$ are considered independently in the performance criterion. The optimized values for stiffness obtained when $u_{2,1}$ and $u_{2,2}$ are in the performance criterion also provide a superior fit for attitude data when simulated data was compared to flight data over spans exceeding 12 hours.

4.1.2 IMP Dynamics Computer Program Simulation

The IMP Dynamics Computer Program simulation is a generalized extension of the RAE simulation. It can simulate a general class of spacecraft including the IMP and RAE satellites. It was not completed at the time of the RAE-A deployment operations. This report represents the first time at which the IMP simulation was used for the RAE configuration with results compared with the RAE Simulator and actual flight data. The Corrector Module of the RAEIOS program was not incorporated into the IMP Computer Program. It was necessary, therefore, to attempt to optimize the parameters of the simulator manually, i.e., by individual computer runs. The procedure followed was to utilize parameters from the RAEIOS optimization studies as initial trials in the IMP Dynamics Computer Program and then improving the estimates with subsequent computer runs. The IMP Dynamics Computer Program permitted the simulation of antenna booms with open cross-sections. In this study, booms with open cross sections were assumed to be circular with a thin slit along one generator of the cylinder.

In general, the results of the IMP Dynamics Computer Program were more accurate than the RAE Dynamics Simulator when compared to flight data. Details of the IMP Dynamics Simulator Computer Program are given in Reference 3.

IMP DYNAMICS SIMULATION - CLOSED TUBE

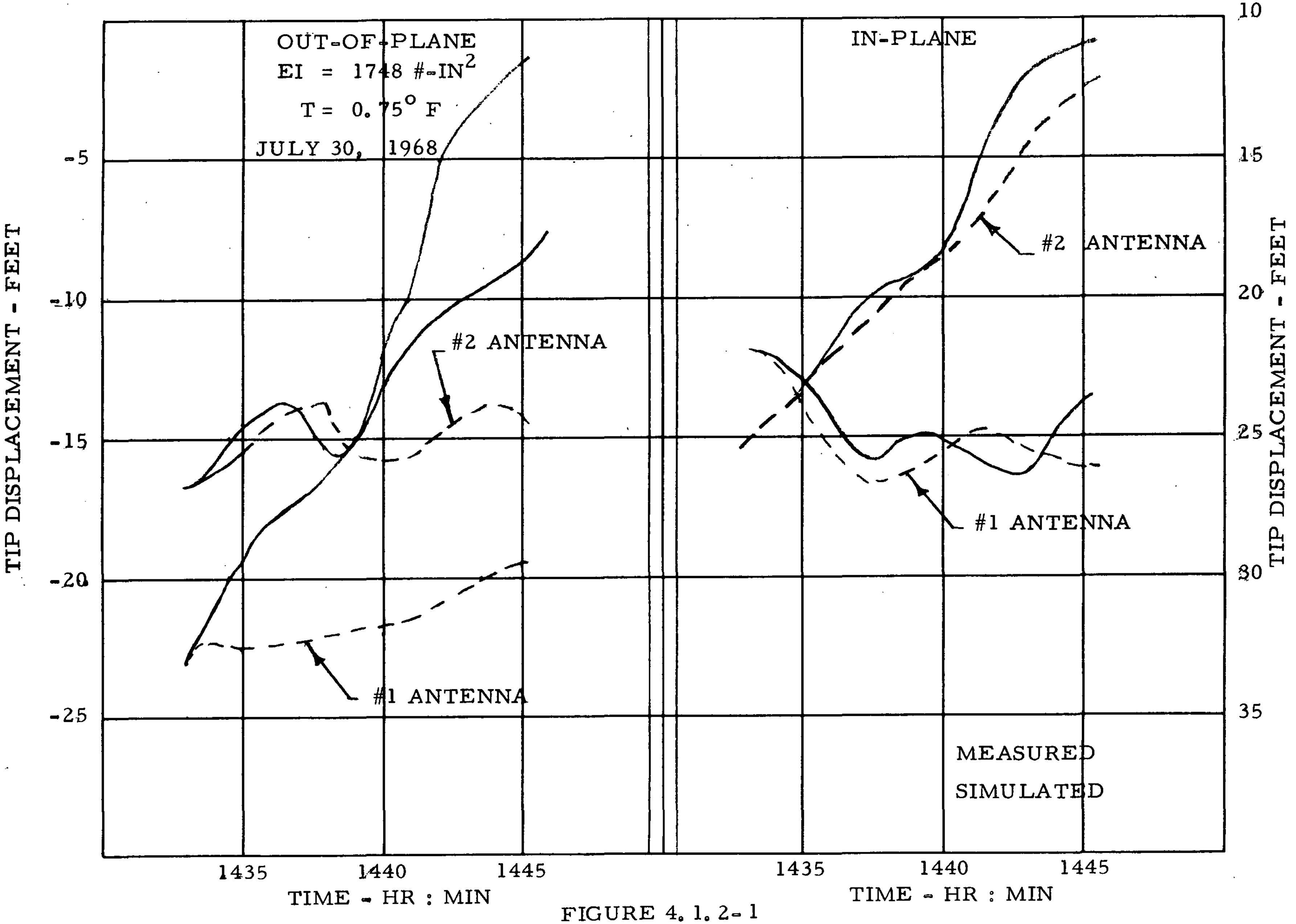


FIGURE 4.1.2-1

IMP DYNAMICS SIMULATION - OPEN TUBE

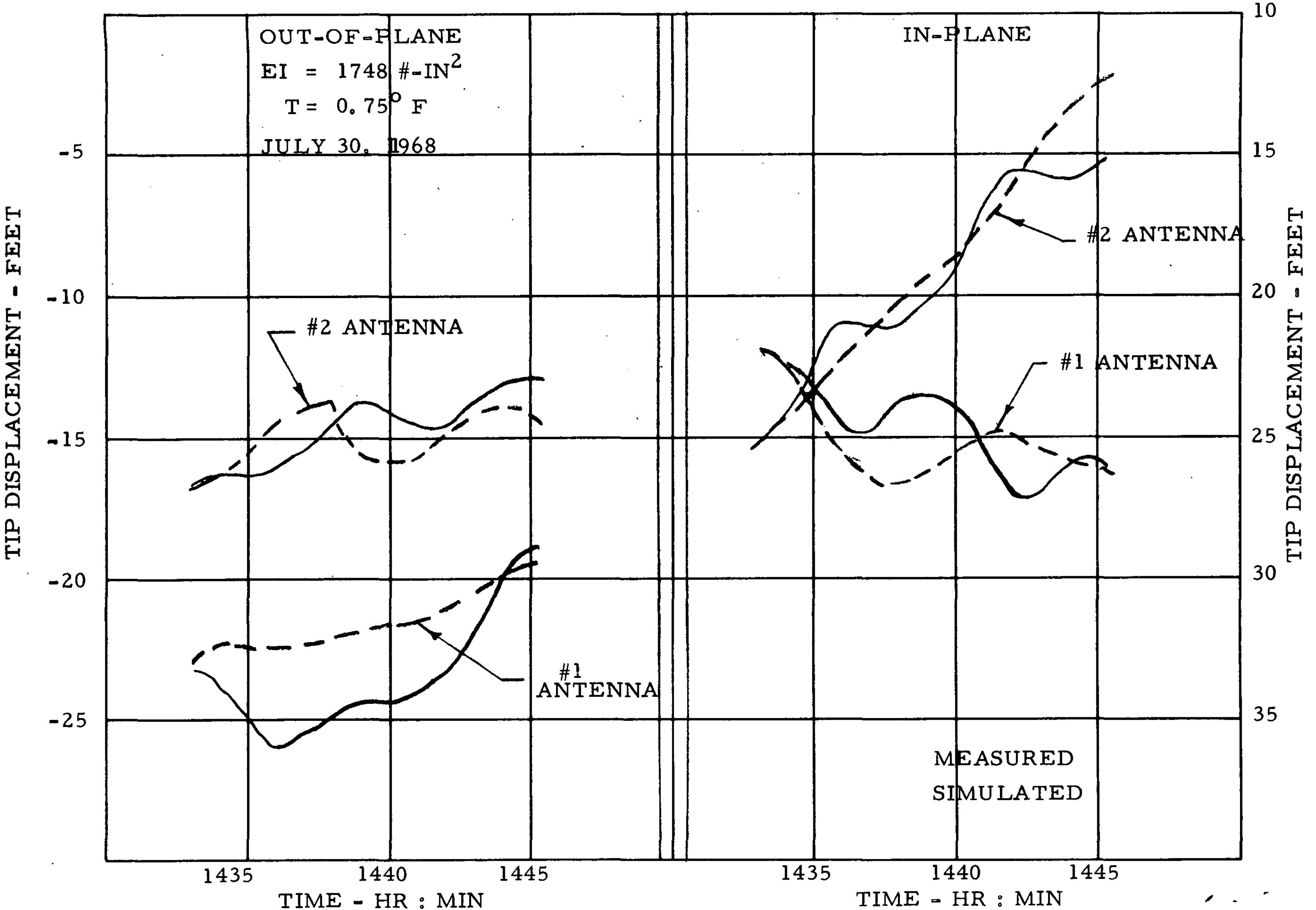


FIGURE 4.1.2-2

Table 4.2-1

INITIAL CONDITIONS - REFERENCE CASE

Libration Damper

Damper Booms Bending Mode			First Cantilever	
Damper Boom Tip Displacement				
	In-plane	#1	0.0	ft
		#2	0.0	ft
	Out-of-plane	#1	0.0	ft
		#2	0.0	ft
Damper Boom Tip Velocity				
	In-plane	#1	0.0	ft
		#2	0.0	ft
	Out-of-plane	#1	0.0	ft
		#2	0.0	ft
Angular displacement of damper mechanism			3.4	degrees
Angular velocity of damper mechanism			0.0	degrees

Antenna Booms

Antenna Boom Tip Displacements				
	In-plane	#1	20.0	ft
		#2	-20.0	ft
		#3	20.0	ft
		#4	-20.0	ft
	Out-of-plane	#1	0.0	ft
		#2	0.0	ft
		#3	0.0	ft
		#4	0.0	ft
Antenna Boom Tip Velocities				
	In-plane	#1	0.0	ft/sec
		#2	0.0	ft/sec
		#3	0.0	ft/sec
		#4	0.0	ft/sec
	Out-of-plane	#1	0.0	ft/sec
		#2	0.0	ft/sec
		#3	0.0	ft/sec
		#4	0.0	ft/sec

Central Core

Attitude Angles			
	Pitch	.95	degrees
	Roll	-3.0	degrees
	Yaw	-10.0	degrees

Initial Conditions - Reference Case (cont'd)

Components of angular velocity vector expressed in body frame with respect to local vertical frame		
#1	-2.0×10^{-3}	deg/sec
#2	-1.67×10^{-3}	deg/sec
#3	1.67×10^{-3}	deg/sec
Satellite Ephemeris		
Components of position vector	1930.8366 -7385.1732 -9570.1040	km
Components of velocity vector	-3.8737852 -3.6438781 2.0210434	km/sec
Date	July 29, 1968	
Start Time	12:00	Hrs

Note: The initial conditions for attitude and damper aspect angles were obtained from flight data.

A significant improvement in fitting the out-of-plane displacements was obtained by including the effect of coupling between bending and twisting of the antenna boom. As discussed in Reference 3, coupling between bending and twisting would only occur if the antenna boom had the characteristics of an open tube. The improvement in the fit of the simulated data using internal force laws associated with open tube structural properties can be seen be comparing Figure 4.1.2-1 and 4.1.2-2. All spacecraft initial conditions and physical parameters are identical for both results except for the treatment of the coupling effect. The parameter EI is used as the structural parameter, however, the torsional stiffness is also a parameter in the open tube simulation.

The improvement in simulated boom tip displacement data using open tube structural properties seems to indicate that the interlocked booms are not as torsionally stiff as a closed circular cylinder. Although the time span of data considered is relatively short, the trend towards antenna boom stiffnesses being considerably less than the theoretical value is also verified by analysis of longer spans of attitude data. This is discussed in Sections 4.2.1 and 5.2

The initial displacements for all of the studies described assumed that the lower antenna booms had 20 feet in-plane displacements and zero feet out-of-plane displacements. Improved estimates were made using the RAE Simulator and Corrector modules. The results of these computer runs were used in the IMP Simulator. The fit-to-flight data is shown in Figure 4.1.2. There is an improvement of the out-of-plane displacements for the #1 and #2 antenna booms and for the #2 antenna in-plane displacement.

Further improvement could undoubtedly be obtained by varying all of the parameters described above simultaneously.

4.2 ANALYSIS OF ATTITUDE DATA

A relatively continuous span of central core attitude data was selected for analysis. This data span was adjacent in time to the boom tip displacement data. The definitive attitude data studied covered the period from 12:00 on July 29, 1968 to 6:50 on July 30, 1968. The antenna and libration damper boom lengths are given in Table 4.0-1. The nominal spacecraft parameters are given in Table 4.0-2. The initial conditions of the time dependent spacecraft variables are given in Table 4.2-1. Unless otherwise stated, these values were used in all computer simulations in this section.

Historically, the analysis of the boom tip displacement data was performed first and the results of the estimates of stiffness and temperature gradient data were used in the study of attitude data.

4.2.1 RAE Dynamics Simulation - 450 Foot Attitude Data

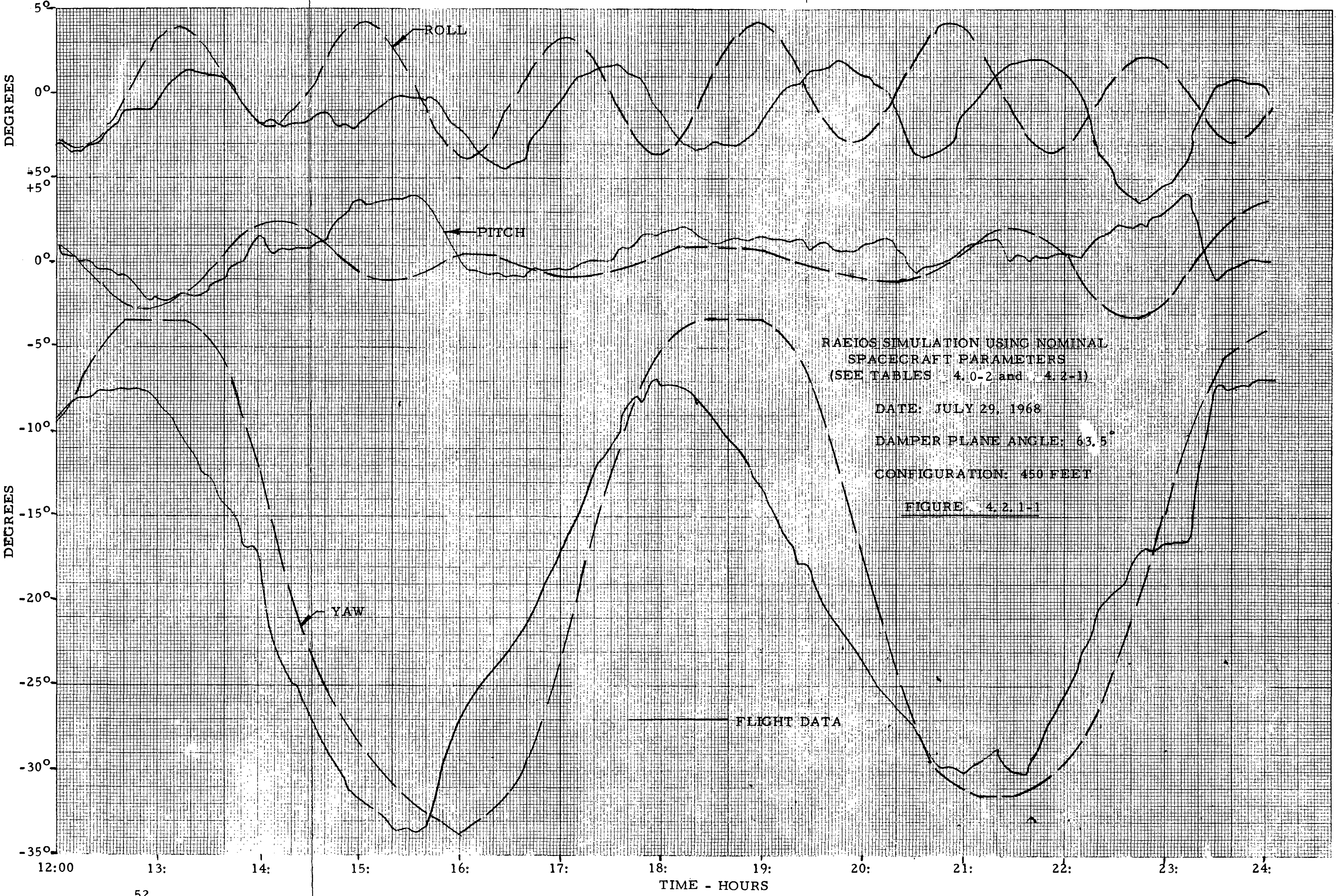
Initial simulations of the RAE dynamics utilized both ground and flight measured spacecraft data. An early result is shown in Figure 4.2.1-1. Both phasing and amplitude fit poorly in this computer run. The only deviation from nominal spacecraft parameters is the angle of the plane of motion of the libration damper boom. Results of previous studies indicated an improved fit could be obtained when a value of 63.5° from the plane of the undeformed antennas was used rather than the nominal 66.5°.

Figure 4.2.1-2 demonstrates than an improvement in the amplitude of the yaw motion could be obtained by modifying the values of the attitude rates, $\dot{\alpha}$, $\dot{\beta}$ and $\dot{\gamma}$ that were obtained from the definitive data tape.

A significant change in the shape and amplitude of the yaw motion develops

FOLDOUT FRAME 1

FOLDOUT FRAME 2



RAEIOS SIMULATION USING NOMINAL SPACECRAFT PARAMETERS (SEE TABLES 4.0-2 and 4.2-1)

DATE: JULY 29, 1968

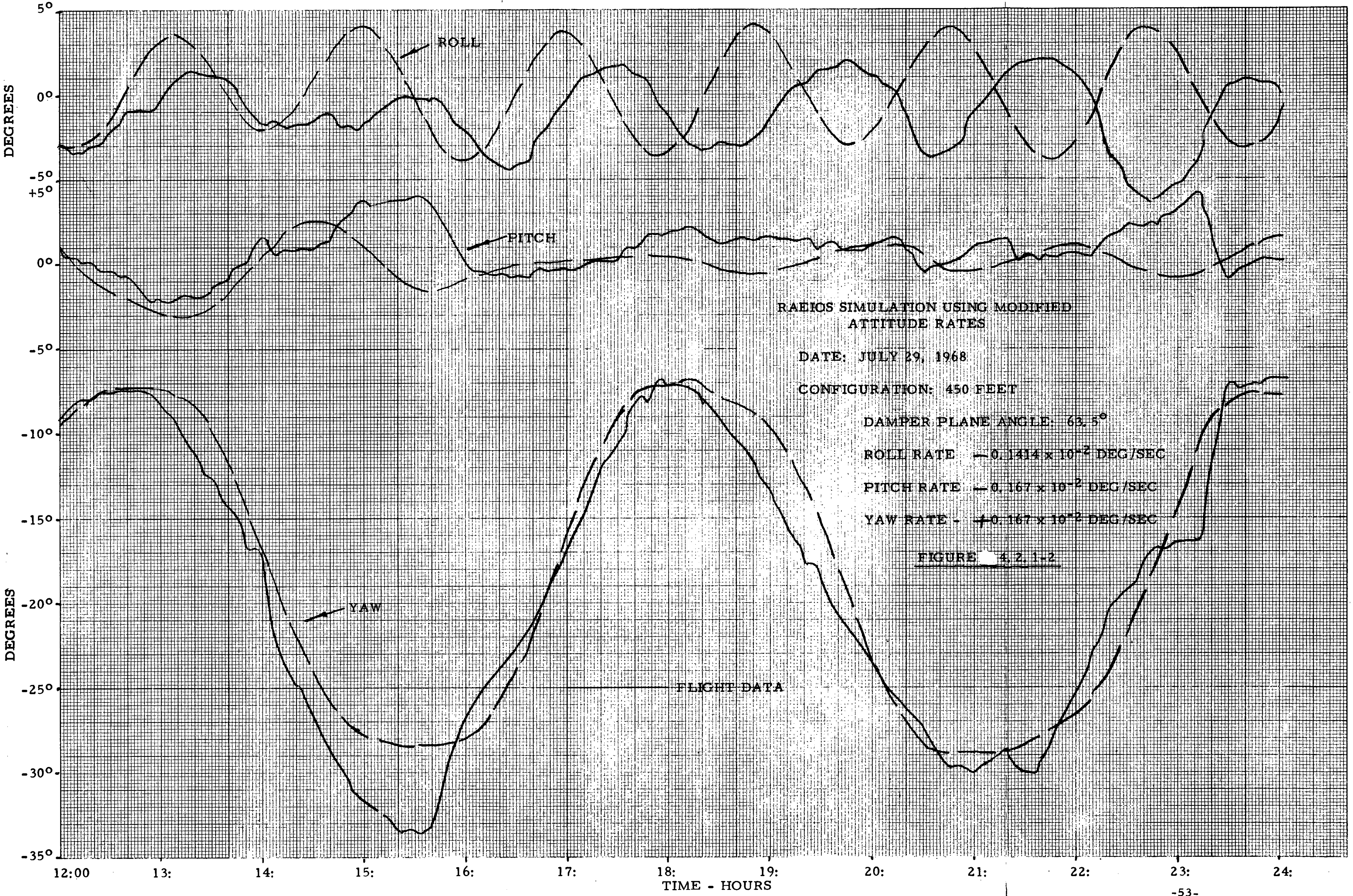
DAMPER PLANE ANGLE: 63.5°

CONFIGURATION: 450 FEET

FIGURE 4.2.1-1

FOLDOUT FRAME 1

FOLDOUT FRAME 2



RAEIOS SIMULATION USING MODIFIED ATTITUDE RATES

DATE: JULY 29, 1968

CONFIGURATION: 450 FEET

DAMPER PLANE ANGLE: 63.5°

ROLL RATE -0.1414×10^{-2} DEG/SEC

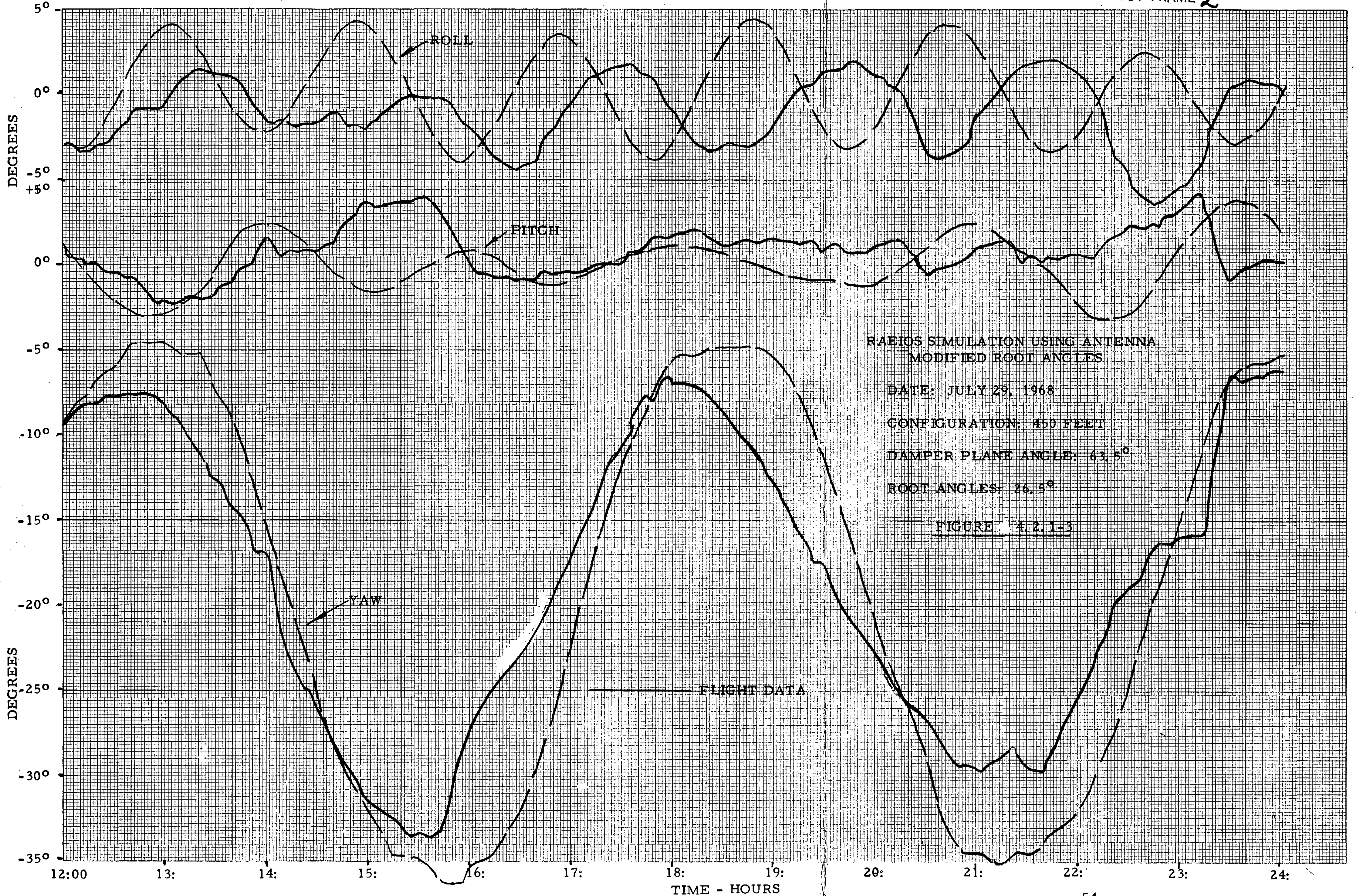
PITCH RATE -0.167×10^{-2} DEG/SEC

YAW RATE - $+0.167 \times 10^{-2}$ DEG/SEC

FIGURE 4.2.1-2

FOLDOUT FRAME 1

FOLDOUT FRAME 2



RAEIOS SIMULATION USING ANTENNA MODIFIED ROOT ANGLES

DATE: JULY 29, 1968

CONFIGURATION: 450 FEET

DAMPER PLANE ANGLE: 63.5°

ROOT ANGLES: 26.5°

FIGURE 4.2.1-3

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Table 4.2.1-1

SUMMARY OF 450 FT. SIMULATIONS

		ANTENNA PARAMETERS						DAMPER PARAMETERS				INTEGRATED ERROR		
	Case No.	Stiffness lbs-in^2	Root Angle	Temperature Gradient F	Roll Rate deg/sec x10^{-2}	Pitch Rate deg/sec x10^{-2}	Yaw Rate deg/sec x10^{-2}	Damper Plane Angles-Deg.	Stiffness lbs-in^2	Temperature Gradient F	Mode	Roll deg-sec	Pitch deg-sec	Yaw deg-sec
	Ref. Data	2080	27.5, 28, 29, 27	.75	-.200	-.167	.167	63.5	2080	.75	0			
RAE Simulation	1						.333					1.212	1.196	1.646
	2				-.1414							1.207	1.115	1.122
	3		26.5, 26.5, 26.5, 26.5				.333					1.241	1.237	1.833
IMP Simulation														
	1		30, 30, 30, 30							3.0		1.015	1.035	1.844
	2		27.5, 27.5, 27.5, 27.5							3.0	1	.986	1.028	1.345
	3	1588	27.5, 27.5, 27.5, 27.5						1588	3.0	1	.956	1.033	1.201
	4	1200	27.5, 27.5, 27.5, 27.5	.275					1200	.275	1	1.0	1.0	1.0
	5	1588	26.5, 26.5, 26.5, 26.5						1588		1	1.001	1.144	1.013
	6							66.5	2380	1.5	1	.974	1.063	1.619
	7	1588	30, 30, 30, 30						1588		1			
	8								2380	1.5	1	.972	1.050	1.414
	9	1588	27.5, 27.5, 27.5, 27.5						1820	1.5	1	.985	1.006	1.199
	10	1588	27.5, 27.5, 27.5, 27.5					66.5	1820	1.5	1	.983	1.052	1.59

when a smaller average value of the root angles of the antenna booms is used. This is shown in Figure 4.2.1-3 where all parameters are the same as used in Figure 4.2.1-1 except for root angles. The phasing of the roll motions is degraded however.

The results of the RAE Dynamics simulation are shown in Figure 4.2.1-1 through 3. These and other computer runs indicated the trends and effects of spacecraft variables. The results are summarized in Table 4.2.1-1. The fit of the simulations to spacecraft flight data was not good however, particularly when compared to later work accomplished using the IMP Dynamics Simulator. An integrated error is also given in Table 4.2.1-1 which is a measure of the goodness of fit of the simulated to measured data.

4.2.2 IMP Dynamics Simulator - 450 Foot Attitude Data

The IMP Dynamics Simulator computer program became operational during the period of performance of this work. It incorporated many improvements over the RAE Dynamics Simulator, particularly in the consistent treatment of higher order terms in the equations of motion and flexible element deformations. It was developed as a generalized spacecraft dynamics computer program so that it could simulate the IMP series of spacecraft as well as gravity gradient spacecraft such as the RAE. However, it does not have some of the features of the RAE Dynamics Computer Program which are available to aid the computerized analysis of flight data. It did prove to be more accurate as a dynamics simulator and hence was used extensively in the remainder of the work effort.

A much improved fit of simulated data to flight data is demonstrated in Figure 4.2.2-1. This comparison of data covers a time span of approximately 16 hours, or roughly 4 orbits. The computer simulation is in phase for the full time span. It is quite possible that the simulation would have remained in phase for a much longer period of time if the time span of the flight data had been longer. The significant spacecraft parameters used for this particular computer run were optimized values obtained from previous computer runs. These parameters were 1) EI = $1200\ \text{lb-in}^2$, 2) average root angles = 27.5° and the angle of the plane of the damper motion $\phi_o = 63.5^\circ$.

Periodically discontinuities occur in the attitude data due to parallel or anti-parallel sunline and magnetic field vectors. This accounts, of course, for some of the deviations of the simulated data from flight data. The measured flight data shows more ripples or noise than the simulated data. This could possibly be due to some slight in-plane unsymmetrical motions of the antenna booms. Since there was no boom tip data available to initiate the computer simulation, a symmetrical antenna deformation pattern was used for the initial conditions. When a computer simulation was inadvertently started in an unsymmetrical configuration, a pronounced ripple was superimposed on the longer period motions. An improved fit of roll attitude amplitude can be obtained by introducing some bias of the sensors relative to the plane of the antennas. This will be demonstrated in the following text.

Subsequent figures will show data covering periods of 12 hours. In many cases, the computer simulations were for longer periods, however.

The result of varying the average stiffness of the antenna boom is shown in Figure 4.2.2-2. The lowest value of EI provides the best fit of yaw motion. Variations of EI do not, however, have a significant effect on the roll and pitch motions. The average root angle for the antennas for all three cases was 27.5°.

A similar trend on simulated data can be observed in Figure 4.2.2-3 where the average root angles of the antennas are 26.5° and the boom stiffness is 1588 lb-in^2. This should be compared to Case II of Figure 4.2.2-2. Obviously it is difficult to separate the effect of these two important variables, i.e., stiffness and root angles.

If the previous case shown in Figure 4.2.2-3 is varied by rotating the plane of the underformed antennas by 1° relative to the roll axis, an improved fit of the roll attitude motions is obtained. This is shown in Figure 4.2.2-4 where an apparent bias possibly due to sensor misalignment has been removed from the roll data.

The computer simulation using ground measured values of average antenna boom stiffness (2080 lb-in^2), and the angle of the plane of the damper boom motion ($\phi_o = 66.5^\circ$) is shown in Figure 4.2.2-5. Comparing this to Case I of Figure 4.2.2-2 clearly demonstrates that the effective value of ϕ_o is closer to 63.5 than 66.5°.

The results described above are also summarized in Table 4.2.1-1. The values for the integrated errors given in the table were obtained by computing the square root of the time integrated squares of the difference of the measured and simulated data. The error for each state variable was normalized to a reference case so that the relative error for each variable could be readily observed.

The temperature gradient across the antenna boom is also considered to be an important spacecraft physical parameter. Its determination was one of the principal objectives of this study; accordingly, variations of the temperature gradient were made in several computer runs holding every other variable constant. The important variables of stiffness and root angles were set at

1200 lb-in^2 and 27. 5° for these cases. The temperature gradient was varied from -0. 75° to +2. 25°. The temperature gradient is expressed as the gradient that would be developed when the sun vector is normal to the axis of a flexible element. The magnitude of the gradient would vary as a cosine function with the angle of incidence. The temperature gradient at any point along an antenna boom is dependent, in the computer simulation, on the instantaneous local angle of incidence. A positive temperature gradient would cause the antenna booms to bend away from the sun.

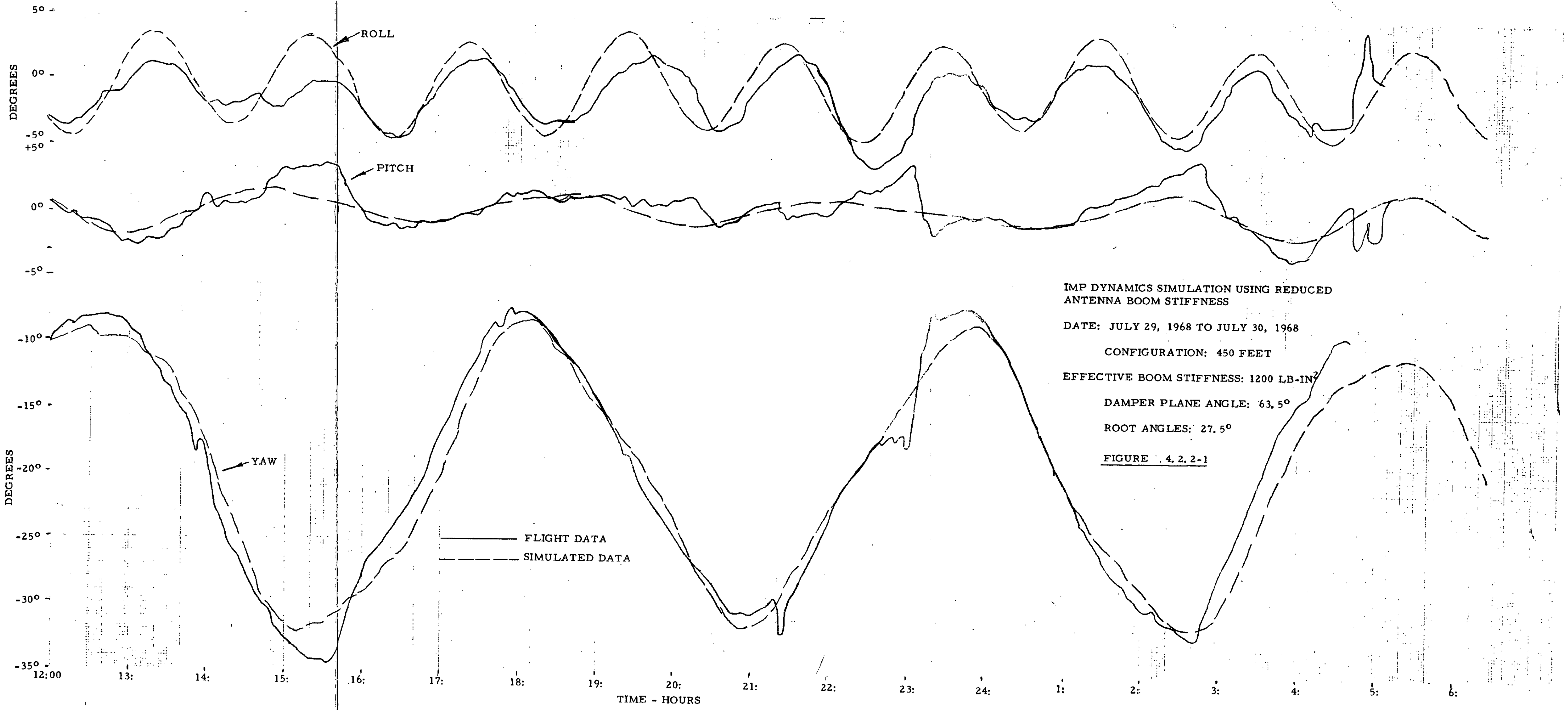
The results of the parametric variations of temperature gradient are shown in Figure 4. 4. 2-6. It is apparent in this figure that the central core attitude motions are relatively independent of the antenna boom temperature gradient. This is true at least for sun angles that the spacecraft is experiencing during this period of time.

In Section 4. 1. 2, it was shown where an improved fit of boom displacement data could be obtained if the flexible elements were assumed to have open cross sections and coupling was introduced between twisting and bending deformations. Using a bending stiffness of 1200 lbs-in^2, the corresponding attitude simulation is given in Figure 4. 2. 2-7. Only minor differences are observable between the equivalent closed tube simulation (Case III of Figure 4. 2. 2-2) and the open tube case of Figure 4. 2. 2-7.

Typical antenna boom flexural motions for computer simulations corresponding to Figure 4. 2. 2-2, Case I and Case III, are shown in Figures 4. 2. 2-8 and 4. 2. 2-9. The in- and out-of-plane deflections for the #1 antenna are shown for boom stiffness of 2080 and 1200 lb-in^2.

FOLDOUT FRAME 1

FOLDOUT FRAME 2



IMP DYNAMICS SIMULATION USING REDUCED ANTENNA BOOM STIFFNESS

DATE: JULY 29, 1968 TO JULY 30, 1968

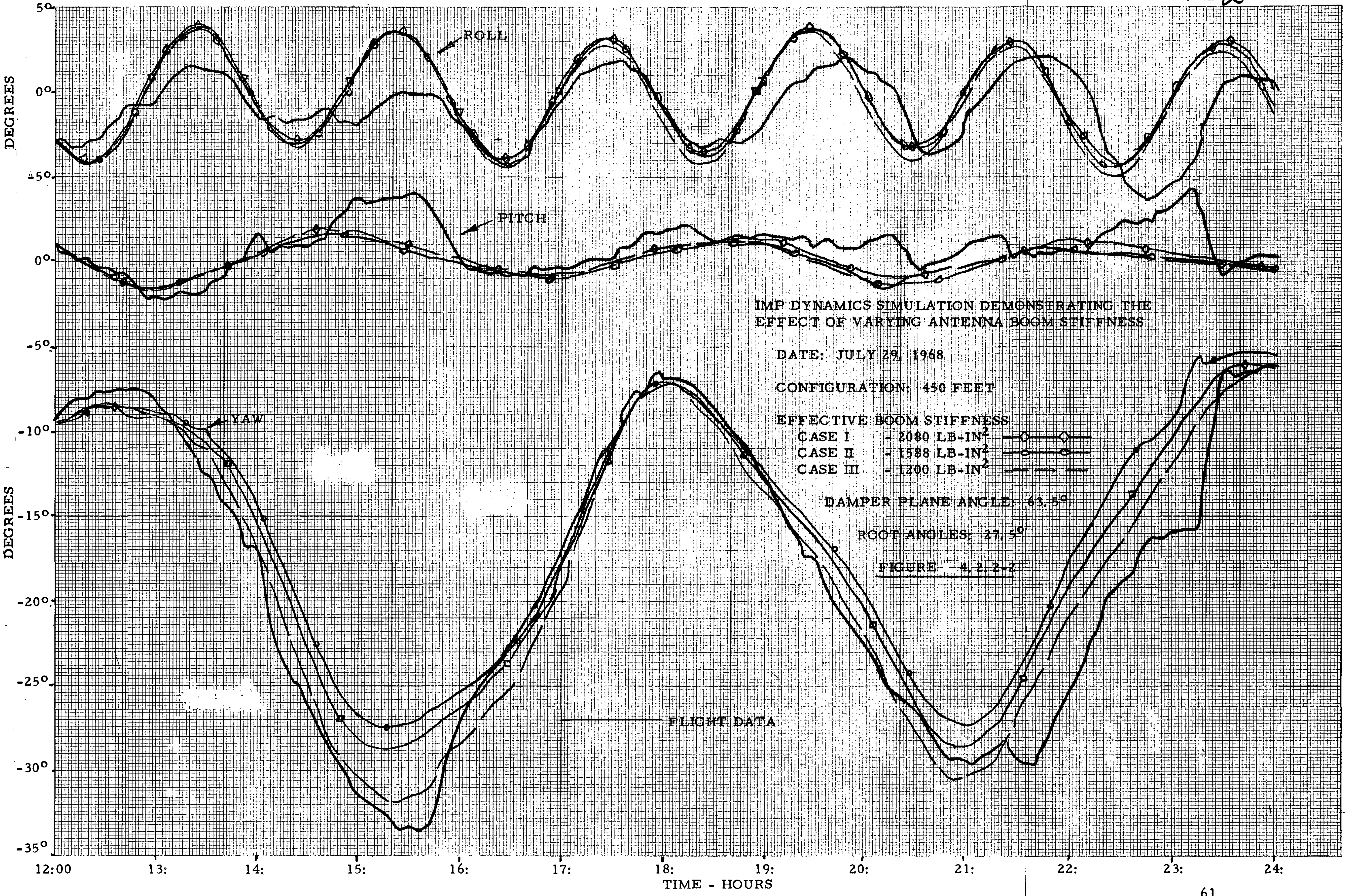
CONFIGURATION: 450 FEET

EFFECTIVE BOOM STIFFNESS: 1200 LB-IN^2

DAMPER PLANE ANGLE: 63.5°

ROOT ANGLES: 27.5°

FIGURE 4.2.2-1



IMP DYNAMICS SIMULATION DEMONSTRATING THE EFFECT OF VARYING ANTENNA BOOM STIFFNESS

DATE: JULY 29, 1968

CONFIGURATION: 450 FEET

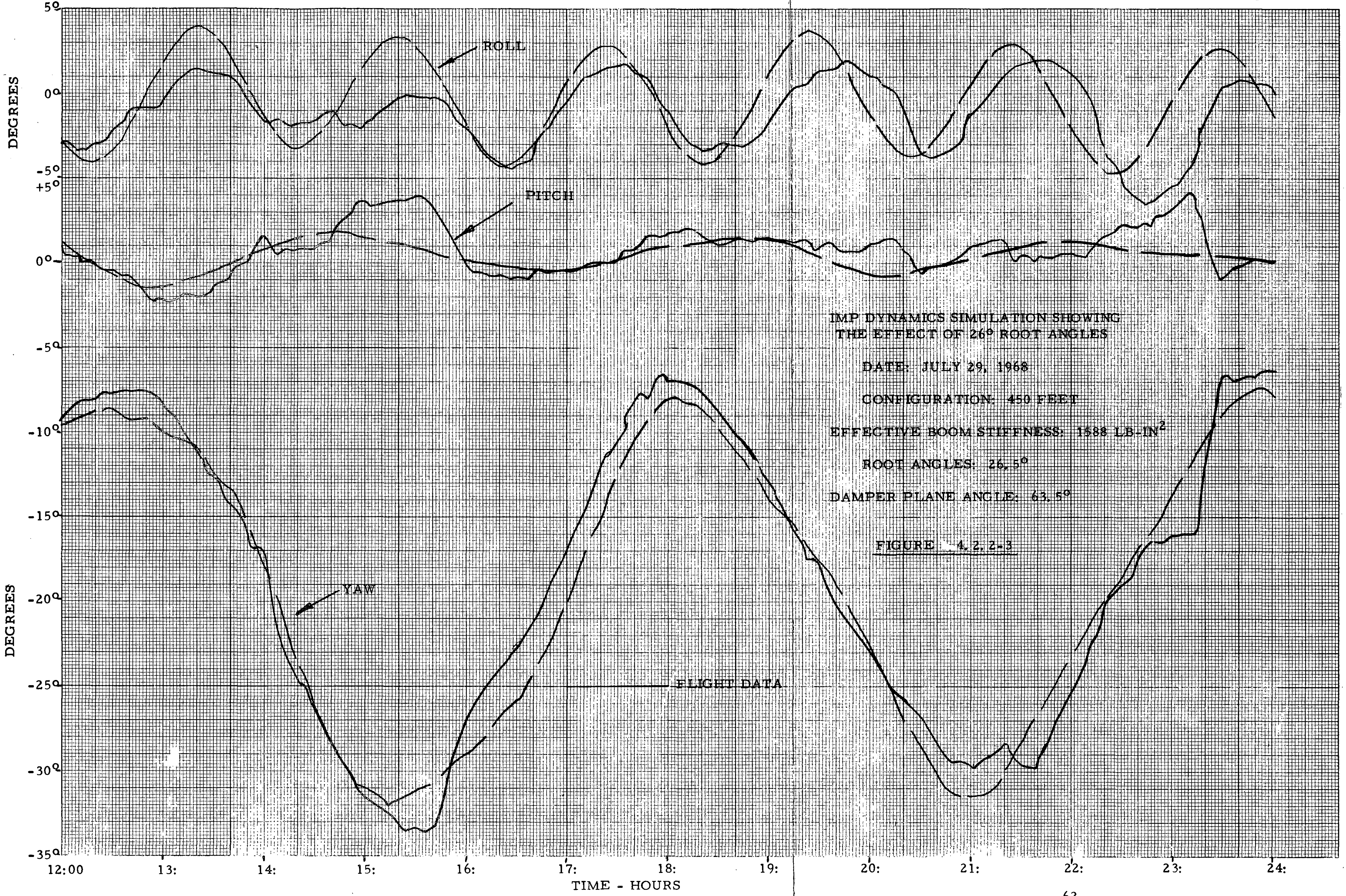
EFFECTIVE BOOM STIFFNESS
CASE I - 2080 LB-IN^2 ◇
CASE II - 1588 LB-IN^2 ○
CASE III - 1200 LB-IN^2 — —

DAMPER PLANE ANGLE: 63.5°

ROOT ANGLES: 27.5°

FIGURE 4.2.2-2

FOLDOUT FRAME 1 FOLDOUT FRAME 2



IMP DYNAMICS SIMULATION SHOWING THE EFFECT OF 26° ROOT ANGLES

DATE: JULY 29, 1968

CONFIGURATION: 450 FEET

EFFECTIVE BOOM STIFFNESS: 1588 LB-IN^2

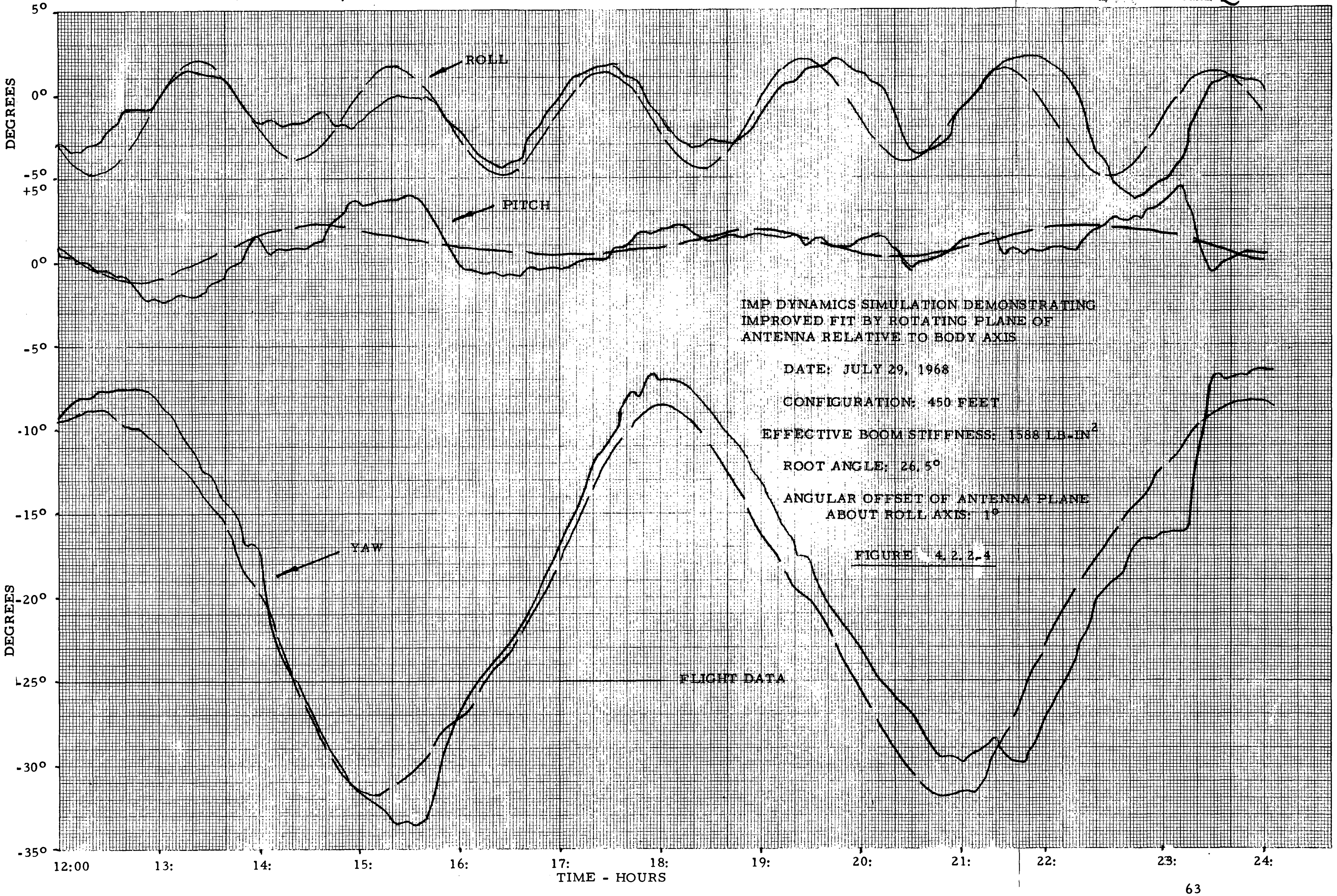
ROOT ANGLES: 26.5°

DAMPER PLANE ANGLE: 63.5°

FIGURE 4.2.2-3

FOLDOUT FRAME 1

FOLDOUT FRAME 2



IMP DYNAMICS SIMULATION DEMONSTRATING IMPROVED FIT BY ROTATING PLANE OF ANTENNA RELATIVE TO BODY AXIS

DATE: JULY 29, 1968

CONFIGURATION: 450 FEET

EFFECTIVE BOOM STIFFNESS: 1588 LB-IN^2

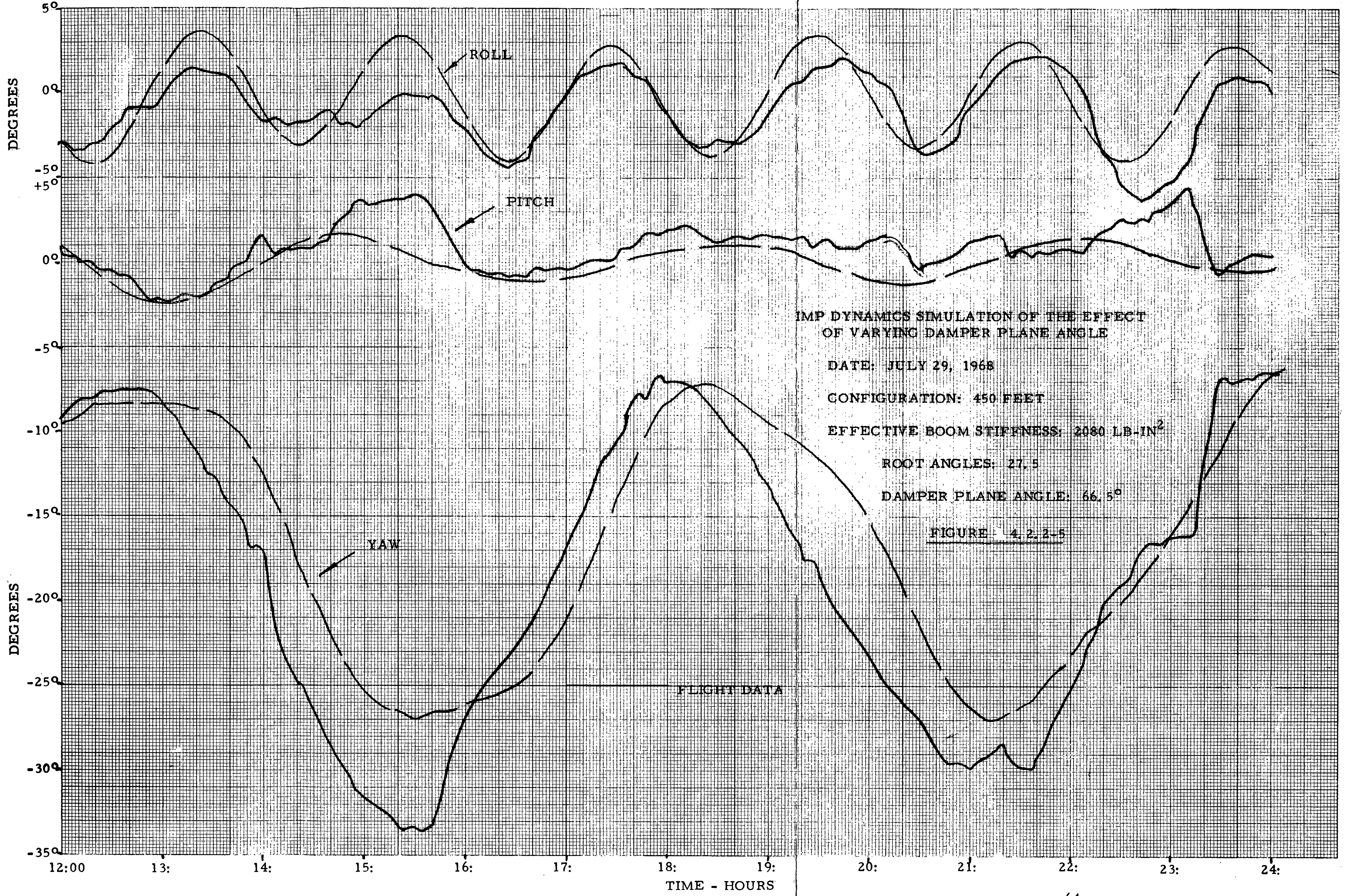
ROOT ANGLE: 26.5°

ANGULAR OFFSET OF ANTENNA PLANE ABOUT ROLL AXIS: 1°

FIGURE 4.2.2-4

FOLDOUT FRAME 1

FOLDOUT FRAME 2



IMP DYNAMICS SIMULATION OF THE EFFECT OF VARYING DAMPER PLANE ANGLE

DATE: JULY 29, 1968

CONFIGURATION: 450 FEET

EFFECTIVE BOOM STIFFNESS: 2080 LB-IN^2

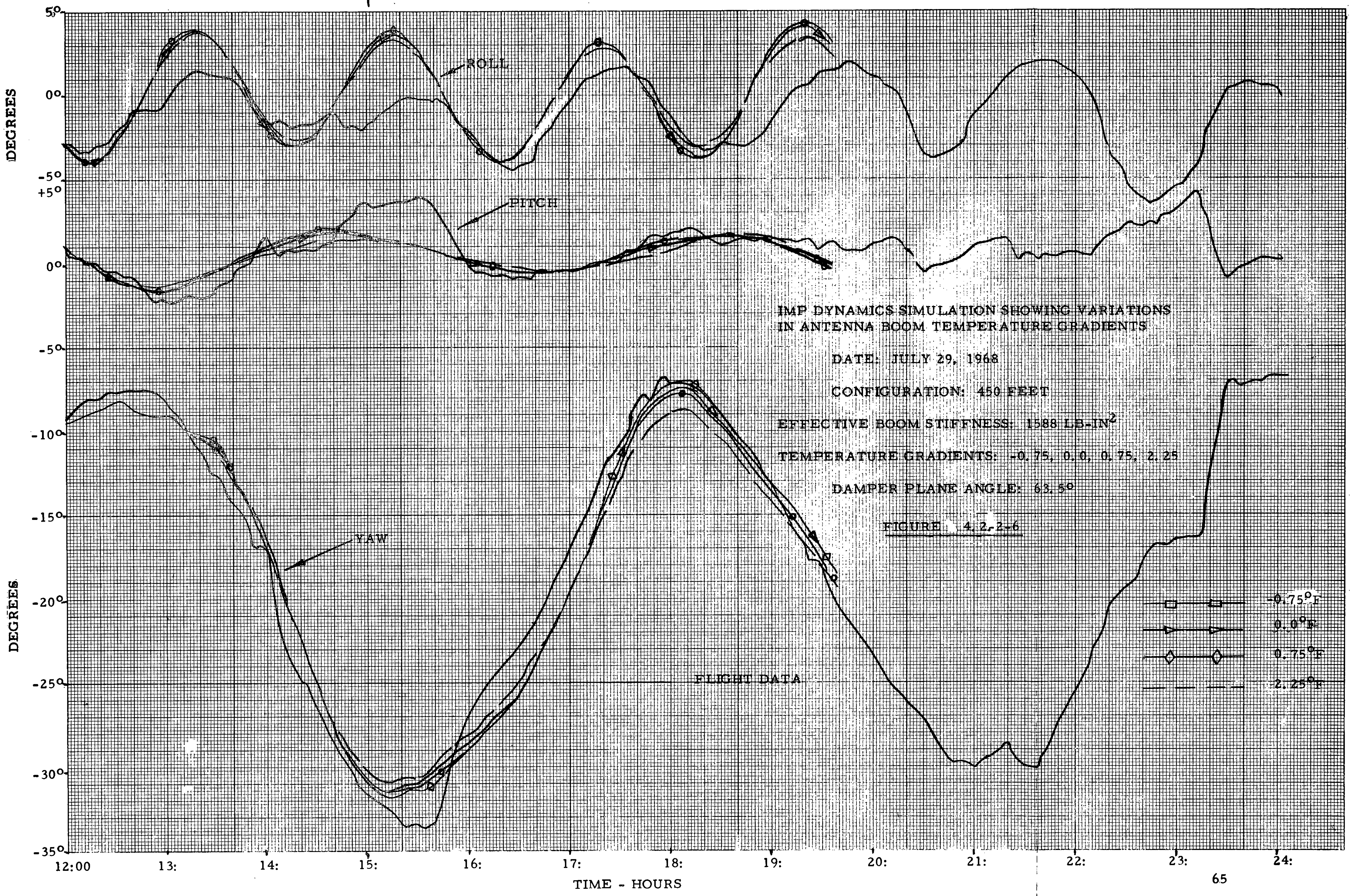
ROOT ANGLES: 27.5

DAMPER PLANE ANGLE: 66.5°

FIGURE 4.2.2-5

FOLDOUT FRAME 1

FOLDOUT FRAME 2



IMP DYNAMICS SIMULATION SHOWING VARIATIONS IN ANTENNA BOOM TEMPERATURE GRADIENTS

DATE: JULY 29, 1968

CONFIGURATION: 450 FEET

EFFECTIVE BOOM STIFFNESS: 1588 LB-IN^2

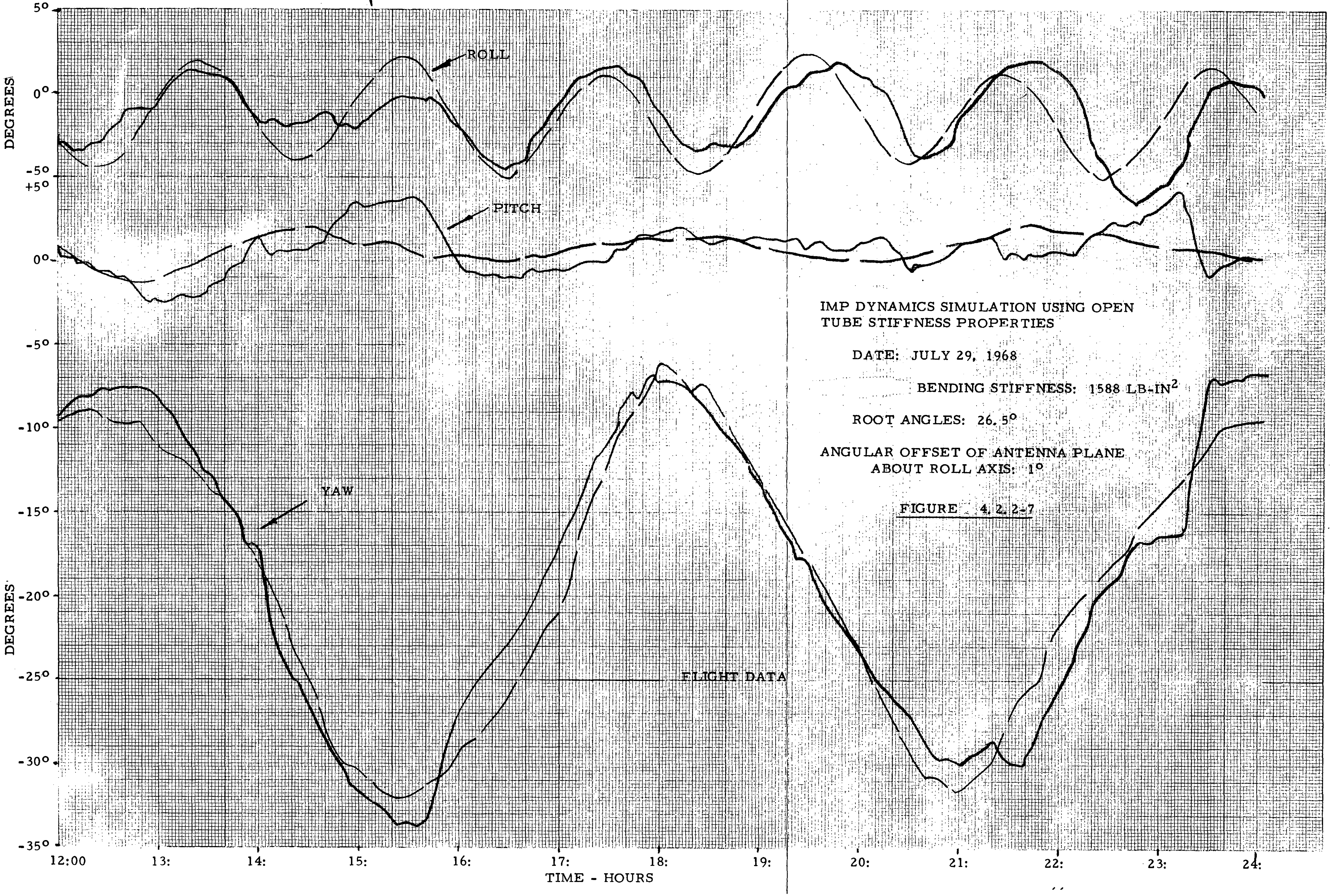
TEMPERATURE GRADIENTS: -0.75, 0.0, 0.75, 2.25

DAMPER PLANE ANGLE: 63.5°

FIGURE 4.2.2-6

FOLDOUT FRAME 1

FOLDOUT FRAME 2



IMP DYNAMICS SIMULATION USING OPEN TUBE STIFFNESS PROPERTIES

DATE: JULY 29, 1968

BENDING STIFFNESS: 1588 LB-IN^2

ROOT ANGLES: 26.5°

ANGULAR OFFSET OF ANTENNA PLANE ABOUT ROLL AXIS: 1°

FIGURE 4.2.2-7

SIMULATED #1 ANTENNA BOOM DISPLACEMENT HISTORY

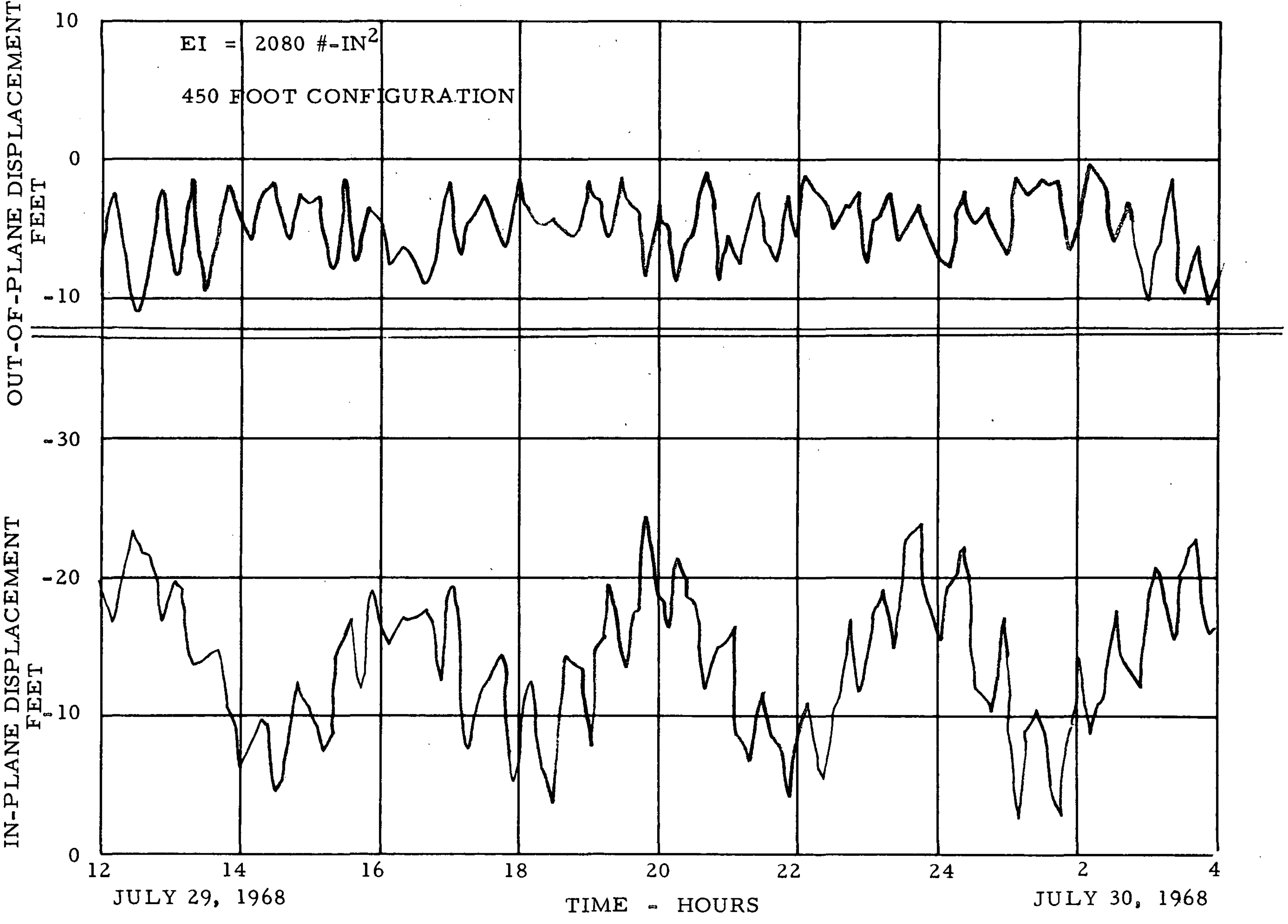


FIGURE 4.2.2-8

SIMULATED #1 ANTENNA BOOM DISPLACEMENT HISTORY

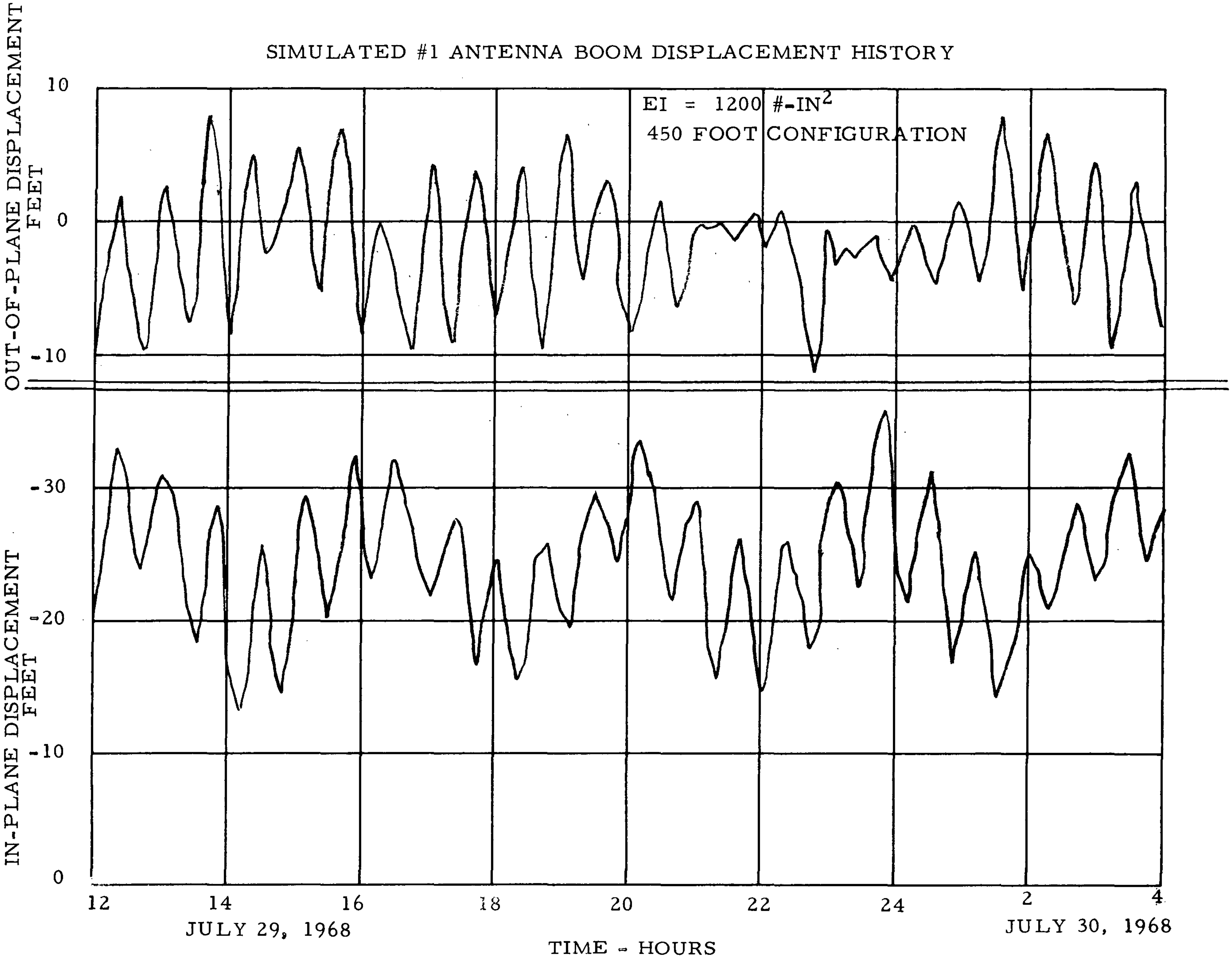


FIGURE 4.2.2-9

5.0 ANALYSIS OF THE 750 FOOT SPACECRAFT CONFIGURATION

The analysis of the RAE-A spacecraft flight data, when the booms were deployed to 750 feet, was more difficult than the 450 foot data because of the reduced amount of boom tip deflection data available.

The lack of boom tip data was unfortunate because simulations of attitude motions of the spacecraft were considerably more sensitive to boom tip initial conditions than simulation of the 450 foot configuration. An attempt was made to search for an optimum set of initial boom tip displacements using the Corrector Module of the RAEIOS computer program. No conclusive results were obtained from this attempt because of the difficulty in obtaining a sufficient span of computer time for more than one stage of the search program. As much as 1 hour of computer time would be required for the search to converge since a minimum of 8 variables must be varied simultaneously. The minimum variables are the in- and out-of-plane tip displacements of the four antenna booms.

The emphasis of the analysis was therefore directed towards determining the influence of such variables as effective boom stiffness, antenna boom root angles and temperature gradients on attitude motions.

Spans of reduced attitude data covering the period from 0:00 to 12:00 and from 12:00 to 20:00 on December 2, 1968 were used as the reference data sets. The initial conditions for the antenna boom tips used in the simulations are given in Table 5.1.1-1. The spacecraft physical parameters are the same as those given in Table 4.0-2, except that the antenna boom lengths are 750, 750, 738 and 750 feet long for the #1, 2, 3 and 4 antennas respectively, and the reference value for the effective boom stiffness is 1380 lb-in^2. The initial conditions for the antenna boom tip displacements were the best estimate obtained from the search procedure described earlier.

Table 5.1.1-1

ANTENNA BOOM TIP INITIAL CONDITIONS

In-Plane Displacements

#1	135.0 ft.
#2	-116.8 ft.
#3	116.8 ft.
#4	-135.8 ft.

Out-of-Plane Displacements

#1	9.0 ft.
#2	29.0 ft.
#3	29.0 ft.
#4	9.0 ft.

5.1 PARAMETRIC ANALYSIS OF ATTITUDE DATA

The analysis performed on the flight data obtained from the 450 foot configuration indicated that variation of the effective boom stiffness and antenna root angles had a significant effect on the fit of the simulated data. Similar trends were observed in the analysis of attitude data from the spacecraft in the 750 foot configuration. This is demonstrated in Figure 5.1-1 where the best fit to flight data is obtained when using an effective boom stiffness of 1380 lb-in^2 and an average antenna root angle of 27.5°. The data span covers a period from 12:00 to 20:00 hours on December 2, 1968. The fit is not as good as that obtained for the 450 foot configuration, since the initial conditions of the 750 foot antenna boom tips have a greater influence on the attitude motions.

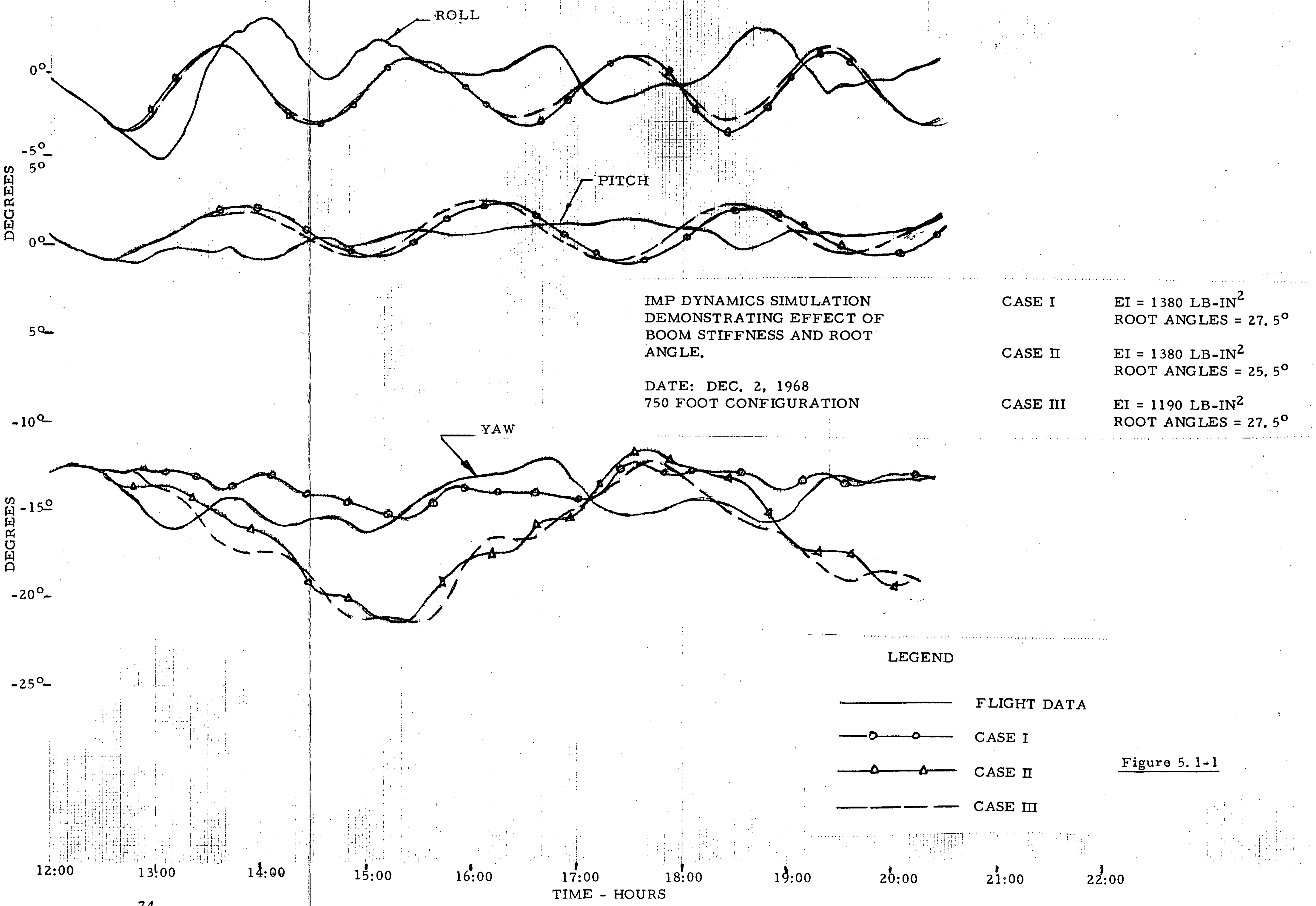
Independent variations of the effective boom stiffness and average antenna root angles to 1190 lb-in^2 and 25.5° respectively, increase the deviation of the simulated yaw data. The amount of deviation is nearly the same for both cases. The two parameters apparently have the same effect on contribution of the antenna boom to the spacecraft overall yaw inertia. Reducing the antenna boom stiffness or reducing the root angles shifts the equilibrium position of the antenna booms towards the #3 body axis. The equilibrium yaw angle will therefore tend to increase negatively since the moment of inertia of the libration damper is unchanged. The changes in the pitch and roll moments of inertia will be much smaller. This is also exhibited in Figure 5.1-1 where only minor changes in roll and pitch amplitudes are shown.

Variation of stiffness and root angles were also made for the time period from midnight to noon on December 2, 1968. Again the best fit appears to occur when an effective boom stiffness of 1380 lb-in^2 and antenna root angles of 27.5° are used. Note that the damper boom was considered to be rigid for this case. There was no significant difference between results for a flexible or a rigid damper.

Decreasing the antenna root angles increases the average yaw angle in the same manner demonstrated in Figure 5.1-1. Increasing the antenna boom stiffness decreases the average yaw angle. This is also consistent with results given in Figure 5.1-1. In fact, increasing the antenna boom stiffness to 1905 lb-in^2 produces a significant deviation of the simulated data from the flight data, particularly in yaw, but also for pitch data.

Several computer simulations were made to determine the influence of temperature gradients on the attitude motions of the spacecraft. As shown in Figure 5.1-3, the effect of relatively major changes in temperature gradients produces minor deviations of simulated data from flight data. The deviations are only evidenced in the yaw motions. This can be attributed to the fact that the sun line vector is nearly perpendicular to the plane of the undeformed antennas. The average value of the projection of the unit sun line vector on the spacecraft #2 body axis is 0.91.

The deformations of the antenna booms, due to the temperature gradient, are principally out-of-plane or in the direction of the negative #2 body axis. As a result, the thermal deformations, even though they can be large, i.e., approximately 140 feet for a temperature gradient of 2.25°, have a minor effect on the yaw as well as the pitch and roll moments of inertia. The largest temperature gradient does, however, produce the largest amplitude yaw motions. The results indicate that the temperature gradient is less than 2.25°, but the precise value would be difficult to determine from attitude motions alone with this particular sun-line antenna plane geometry.



IMP DYNAMICS SIMULATION DEMONSTRATING EFFECT OF BOOM STIFFNESS AND ROOT ANGLE.

DATE: DEC. 2, 1968
750 FOOT CONFIGURATION

CASE I EI = 1380 LB-IN^2
ROOT ANGLES = 27.5°

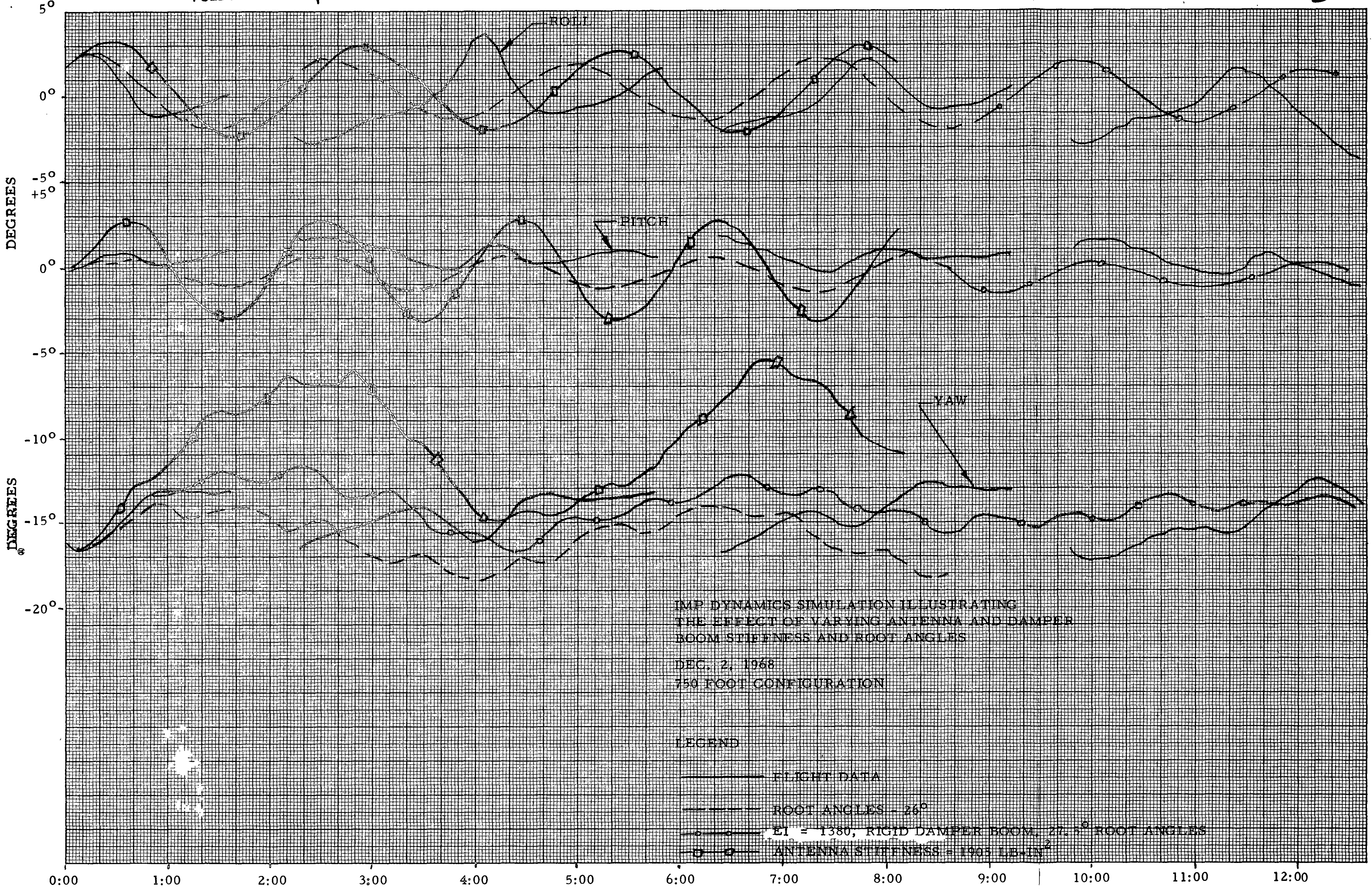
CASE II EI = 1380 LB-IN^2
ROOT ANGLES = 25.5°

CASE III EI = 1190 LB-IN^2
ROOT ANGLES = 27.5°

Figure 5.1-1

FOLDOUT FRAME 1

FOLDOUT FRAME 2



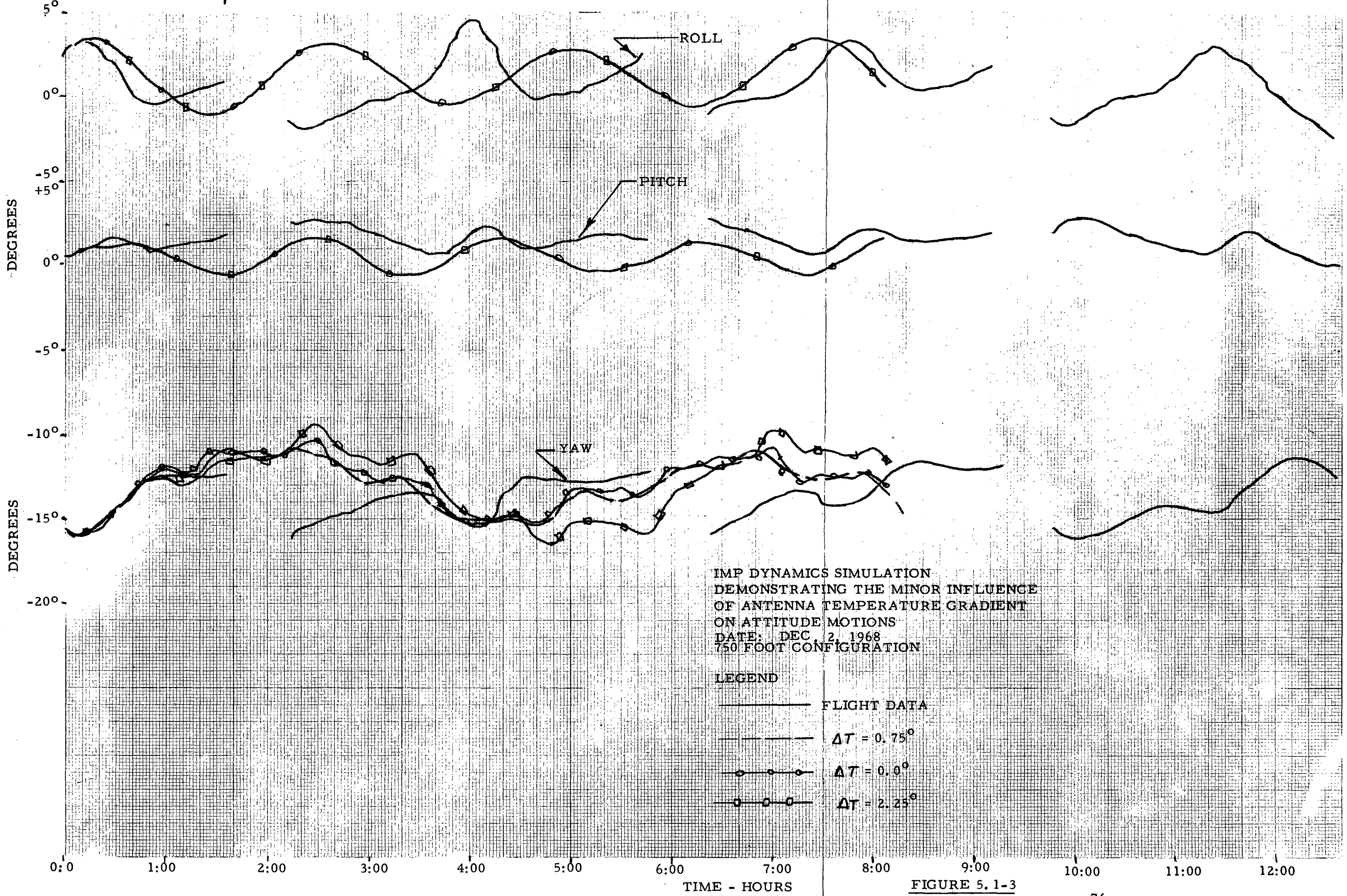
IMP DYNAMICS SIMULATION ILLUSTRATING
THE EFFECT OF VARYING ANTENNA AND DAMPER
BOOM STIFFNESS AND ROOT ANGLES

DEC. 2, 1968
750 FOOT CONFIGURATION

FIGURE 5.1-2

FOLDOUT FRAME 1

FOLDOUT FRAME 2



IMP DYNAMICS SIMULATION
DEMONSTRATING THE MINOR INFLUENCE
OF ANTENNA TEMPERATURE GRADIENT
ON ATTITUDE MOTIONS
DATE: DEC 2, 1968
750 FOOT CONFIGURATION

FIGURE 5.1-3

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Several important conclusions can be drawn from this analysis of the RAE-A satellite flight data. The most important conclusion, from the point of view of future flight operations of the RAE-A and perhaps the RAE-B satellite, is that there is a significant deviation of boom stiffness and antenna root angles from pre-flight ground measured values. By using combinations of reduced antenna boom effective stiffnesses and root angles, the fit of simulated to flight data is significantly improved. The best fit of flight data occurred using effective boom stiffness ranging from 1200 to 1380 lb-in^2. The pre-flight ground measurement was 2100 lb-in^2. Ground measurements of the root angles of the antenna booms were 27.5°, 28°, 29° and 27° for the Nos. 1, 2, 3, and 4 booms respectively. Computer simulations indicate that an average value between 26.5° and 27.5° is more appropriate.

The simulated data was generated by the IMP Dynamics Computer program which was also demonstrated in this study to be remarkably accurate when the spacecraft physical parameters were appropriately selected. The simulation remained in phase with flight data for at least 16 hours. The phase lock probably would have been for longer if a longer span of flight data had been available. The ability to simulate actual flight data using the modified values of antenna boom properties and the IMP Dynamics Simulator increases the confidence level associated with prediction of spacecraft dynamical behavior both for the RAE-A Dynamics Experiment and for the RAE-B Lunar flight in 1972.

The analysis of the reduced antenna boom tip deflection data obtained from the antenna boom television cameras indicated that the antenna stiffness properties are not identical at least when comparing the #1 and #2 antennas. This result was concluded both from attempting to fit the deflectional motions using both the RAE

Dynamics and IMP Dynamics Simulators and by direct examination of the television frames.

The analysis also confirms the result obtained in earlier work that an improved fit of simulated data can be obtained by changing the angle of the plane of motion of the libration damper from 66.5° to 63.5°. The angle is measured in a positive direction from the plane of the undeformed antennas.

The average antenna boom temperature gradient is estimated to be between 0.44° F and .80° F. This estimate was obtained from the analysis of antenna boom deflection data. Central core attitude data was relatively insensitive to variations in antenna boom temperature gradients. The amplitude of simulated yaw motions was, however, more reasonable with a temperature gradient of 0.75° than an extreme of 2.25° F.

Bias in the roll attitude was indicated by the improvement in the fit of the amplitude of simulated roll data. This improvement was obtained by rotating the plane of the undeformed antennas by 1° with respect to body roll axis.

The average yaw angle is sensitive to the effective antenna boom stiffness and antenna root angle used in the dynamics simulation. Variations of these parameters change the relative contribution to the yaw moment of inertia of the antenna booms with respect to the skewed libration damper boom. As a result, it was possible to obtain an estimate of these parameters from the analysis of attitude data alone. Analysis of pitch and roll data does not yield as useful information since for a stable symmetric configuration average values should be zero. The concept of analyzing a non-zero equilibrium position can be used to advantage in the RAE-A Dynamics Experiment. Here a partial retraction of one antenna boom will create a non-zero equilibrium pitch angle. This equilibrium angle will then be sensitive to parameters which affect the spacecraft's overall moments of inertia.

The Corrector Module of the RAEIOS Computer program has proven to be a feasible tool for optimizing the parameters of the non-linear RAE Dynamics Simulator when fitting the flight data. Merging the Corrector Module with the more accurate IMP Dynamics Simulator would undoubtedly permit a more accurate estimation of significant spacecraft parameters.

6.2 RECOMMENDATIONS

Further analysis of flight data is recommended in order to improve estimates of individual antenna boom stiffnesses, temperature gradients and antenna root angles. The additional analysis should be performed utilizing post-deployment attitude and boom tip displacement data. The post deployment data could also be examined to determine whether estimates can be made of damping in the antenna booms.

A study could be made of the attitude data during a shadow phase of the flight in order to determine the sensitivity of the antenna booms to the transient temperature pulses. This would permit an opportunity to obtain a more accurate estimate of the antenna boom temperature gradients.

Incorporation of the Corrector Module into the IMP Dynamics Computer program is recommended. The Corrector Module should also be expanded to include additional variables such as antenna root angles and boom damping.

This would permit the efficient utilization of the more accurate IMP Dynamics Computer program in support of dynamics analysis.

REFERENCES

1. Rosenbrock, H. H., "An Automated Method for Finding the Greatest or Least Value of a Function", The Computer Journal, Volume 3, October 1960, pages 175-184.

2. "User's Manual for RAE In-Orbit Simulator Computer Program", Avco Systems Division, January 1969, AVSSD-0017-69-CR, NASA Contract NAS5-11050.

3. "User's Manual for IMP Dynamics Computer Program", Avco Systems Division, (to be published in January 1971), NASA Contract NAS5-11149.